Seasonality of flooding in Scottish rivers

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Declarations

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Abstract

The study considers the seasonal distribution of non-tidal peak flows on a large number of rivers draining varied catchments across Scotland and Northumberland. Peaks over threshold (POT) flood series from 156 gauging stations are used, and are subject to two quality control measures. Firstly, threshold values are standardised to give 45 peaks over a ten year period and secondly, records are adjusted to compensate for non-stationarity in the sampled data. The database assembled consists of 3458 station-years of record.

A comprehensive description of the seasonal patterns found is presented, based on these quality-controlled data and utilising a number of methods of characterisation. Directional statistics are employed to indicate the central tendency of time-of-year values for each station, a six-season analysis gives more detailed information, and the seasonality of large peaks is compared with that of full POT series. Finally, a classification analysis is used to summarise these patterns.

These patterns are related to five catchment characteristics: the seasonality of rainstorms; soil moisture deficit lengths; catchment size; lake storage and snowmelt, although the effect of the last of these is unclear as suitable data were not available for analysis. A discriminant analysis is employed to relate the five physical factors to flood seasonality.

The study concludes with a discussion on the implications of its findings. A method of assessing seasonal flood risk using POT series is presented, offering an accurate means of relating flood magnitude to recurrence interval for any period of less than one year. The implications of seasonal heterogeneity, both within and between flood records, are also discussed. The suitability of the exponential model for use with POT records is questioned and it is suggested that explicit recognition of the seasonality of flooding may be necessary in order to make accurate design flood estimates.

To my parents

Frontispiece: Flooding on 1 April 1992 on the River Eden at Dairsie Bridge, Fife. The river left its banks in many places, resulting in the erosion of topsoil in the field shown in this view and much damage to property was caused in Cupar, 5 km upstream. Fortunately, the flood-waters did not enter the houses in the foreground. The peak flow recorded at station 14001 Kemback immediately upstream was the highest in 25 years of record.

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GLOSSARY OF TECHNICAL ABBREVIATIONS

AM	Annual maximum, see pp 41-43.
AMAF	Arithmetic Mean Annual Flood
AREA	Catchment area (km^2)
BFI	Baseflow index[1]
CTROIDY	National Grid northing of catchment centroid
DRZ	Day of first return to zero SMD after summer maximum (Hewson 1983a)
EV1	Extreme Value 1 distribution
GSN	IH Gauging Station Number
IH	Institute of Hydrology
LAKE	Proportion of catchment draining through significant loch or reservoir (NERC 1975)
LOCH	Proportion of catchment area covered by loch and reservoir storages (Acreman 1985a,b)
Mean day	Mean day of year for flood or peak rainfall occurences. Values are given as days after 31 May viz:

Date	Value	Date	Value
June 1	1	December 1	184
July 1	31	January 1	215
August 1	62	February 1	246
September 1	93	March 1	274
October 1	123	April 1	305
November 1	154	May 1	335

(See pp 88-90 for theory of directional statistics)

MDOY	Mean day of year (Hewson NDa)
NERC	Natural Environment Research Council

[1]Institute of Hydrology (1980) *Low Flow Studies Report*, Wallingford: Institute of Hydrology.

POT	Peaks over threshold, see pp 41-43
PTxMAF	Mean Annual Flood based on POT series with an average of x peaks per year (x = integer) (NERC 1975)
Q	Discharge, usually the peak flow of a flood event (m^3s^{-1})
$\overline{Q}$	Mean annual flood (m^3s^{-1})
Q_T	Peak discharge of flood of *T*-year return period (m^3s^{-1})
r	Clustering index to inidicate degree of clustering of events about a mean time of year. Values range from 0 (no clustering) to 1 (total clustering), see pp 88-90 for details.
RPB	River Purification Board
RSMD	1-day rainfall of 5-year return period less effective mean SMD (mm) (NERC 1975)
S1085	10-85 percentile mainstream slope (m km^{-1}) (NERC 1975)
SAAR	Standard Average Annual Rainfall 1941-70 (mm) (NERC 1975)
SMD	Soil Moisture Deficit (mm)
SOIL	Soil index based on Winter Rainfall Acceptance Map (NERC 1975)
T	Return period (years)
STMFRQ	Stream frequency (junctions km^{-2}) (NERC 1975)
URBAN	Proportion of catchment urbanised (NERC 1975)
WRAP	Winter Rain Acceptance Potential (NERC 1975)

Chapter 1

Introduction

1.1 On flooding

Flooding occurs on every watercourse in Scotland, from the smallest stream to the largest of its great rivers. The magnitude of any given flood is determined by the interaction of many factors, the size of catchment, the rainfall received therein, the steepness of the catchment, and the wetness and permeability of its soils being amongst the most important. The interaction of these factors in any river basin is a constant process, with the outflow of water down the river at any point in time attaining a dynamic equilibrium. As such, floods can be regarded as expressions of this equilibrium like any other river flow, being differentiated from other flows only on the basis of their relatively high magnitudes; indeed for the purposes of this study, a flood is simply defined as the exceedance of some specified flow threshold at a particular point, as opposed to the geomorphic definition of the exceedance of bank-full stage.

That such high flows occur only over quite restricted periods of time, with the flow of water in a river rising in response to an input of precipitation before reaching a peak and then receding to lower values, allows floods to be regarded as individual events. While river flow minute by minute is the ever-changing output of a complex system, high flow values occur over periods of only a few hours or perhaps a few days in the case of large rivers, and the locus of these values constitutes a flood. In the natural course of events, floods will vary in their magnitude according to the various factors described above, and it follows that if a flood is defined for any given point on a river as the exceedance of a particular flow value, then the greater that value, the rarer will be the occurrence of floods. In order to study floods on the many rivers of Scotland as a whole, it is necessary to define floods as the exceedance of such a flow value, defined for each place on each river, on the basis of its average frequency of exceedance. All that follows in this thesis is based on such a concept of a flood.

With the development of much of Scotland's settlement in close proximity to watercourses for reasons of water supply and, historically, also for transport and power, the occurrence of flooding is of considerable importance to man. The incidence of a great flood inevitably captures the public imagination, with the gushing of waters a great spectacle to see and hear. However, there are also practical consequences of a flood, as illustrated by the following chronicle excerpt:

> "Then, after the feast of St. Peter ad Vincula (1st August, 1294) there happened a stupendous flood in the river of Scotland called Teviot, prognosticating future events at hand, such as we have witnessed before our eyes. For the waters of the Teviot suddenly waxed without much rain, over flowing bridges and lofty rocks, sweeping away the mill below Roxburgh castle and others, besides everything else that was in their way."
>
> *(Chronicle of Lanercost, Maxwell, 1913, 108, cited in McEwen 1990)*

In built-up areas, damage to the extent of millions of pounds can be done to property, both domestic and commercial; and, even away from settlement, to fields, crops and livestock. In the worst cases, lives have been lost. During the course of a flood, considerable inconvenience is also caused in addition to the damage which may be done: people living in houses threatened by floodwaters must be evacuated, communications are often disrupted when water crosses roads and railway lines or cuts telephone lines, and, if bridges are swept away, the effects are felt for some time afterwards.

It is not surprising, therefore, that considerable effort has been devoted to the study of floods as these are problems which are felt the world over. One key aim in this has been to develop methods of accurately assessing how often flooding of a given magnitude may be expected to occur at a given site. Flood defences can be built to protect property, effectively increasing the capacity of the channel and thus preventing water from spilling onto adjacent areas. However, the cost of such works increases with their capacity, so it is desirable to find the optimum level of protection at which the cost of protection plus anticipated damage is minimised. Further, a sound understanding of the magnitude-frequency relationship of floods at a specified point will allow the planning of other future developments to be done on the basis of an accurate assessment of risk. Such information is often required by engineers in the design of dams, bridges, culverts and buildings of many types. The effort put into understanding how flood magnitude varies with recurrence interval is reflected by a substantial literature on the subject, and is referred to throughout this thesis. The place occupied by the present study within that broader field will be outlined over the course of this chapter.

1.2 Scotland and its great floods

The rivers of Scotland show a great diversity in their character. Indeed, the country as a whole is characterised by many contrasts in its physical terrain, from the rugged highlands of the north and west, a steep mountainous landscape bearing witness to the erosive power of glaciation as recently as 10,000 years ago, to the relatively smooth lowlands found in such areas as Caithness, Buchan, Fife, the East Lothians and The Howe of the Mearns in Angus. These areas too owe much of their character to events of the last glaciation, though in a different sense, and are therefore characterised by rivers of an altogether different nature: gradients are low, the rivers never gain any great size before reaching the sea, and often drain catchments covered with soils much thicker and more permeable than are generally found in upland areas. Climate also varies dramatically between these different environments, not least in terms of precipitation and evapotranspiration. Accordingly, flooding must be expected to show a great diversity amongst these very varied rivers, particularly in terms of their peak magnitudes and volumes, flashiness and causal mechanisms.

Over the past centuries for which documentary records are available, some memorable floods have occurred in Scotland. Some have been regional in character, causing all major rivers and their tributaries across a wide area to record extremely rare peak flow values. The floods of January 1849 in Inverness-shire and its surrounding area provide one such example (Nairne 1895). They lasted over three days, affecting the whole of the Ness basin, the Conon and Beauly to the north and west, and the Spey to the east, as well as the other rivers in the region. The flooding was caused by heavy rain over the whole area combined with the rapid thaw of a deep snowpack on the mountains. Great damage was inflicted on Inverness, with a third of the town being submerged and an important bridge being lost; upstream, multiple breaching of the Caledonian Canal occurred, and roads, fields and plantations were devastated, according to Nairne's dramatic account. In early 1989, widespread flooding occurred again on the Ness and surrounding rivers (Inglis 1989), causing considerable damage which this time included destruction of the railway bridge over the Ness at Inverness.

Major flooding of Scotland's larger rivers generally attracts attention in the literature, so there is much information also on the Tweed floods of August 1948 (Glasspoole 1949, Learmonth 1950) and August 1956 (Common 1956). 158 mm of rainfall was recorded at Floors Castle, Kelso on 12 August, 1948, and again great damage resulted from the ensuing floods over a wide area, including the removal of many road and rail bridges. Both rainfall and floods were less extreme in 1956, but still property and farmland was flooded, and communications disrupted. Mention must also be made of the Tay, Britain's largest river, which has also produced some notable floods: in 1210, "half the town of Perth was said to have been swept away and 'the King's son and at least 14 others perished'"(Falconer and Anderson 1992); more recently in February 1990 a major flood caused inundation of 42 km^2 of land in the Tay and Earn catchments with about 50 properties affected, the direct cost of damage exceeding £3 million. However, a flood in February 1814 reached a peak level in Perth more than one metre above that of the 1990 event, and if repeated today would cause damage on a colossal scale (Falconer and Anderson 1992). Like the three rivers mentioned above, the River Spey has also recorded many great floods, and in recent years with a greater frequency than any of these others, since major flooding has occurred in 1989, 1990 and again in 1992. As the Spey valley is not as heavily populated as the Ness, Tweed or Tay valleys, damage to property does not seem to have been as severe, but dramatic scenes have been seen nonetheless, and concern over the damage caused by floods has been expressed (Robert H Cuthbertson & Partners 1990, Sprott and McKenna 1992).

At the other extreme, equally or perhaps even more dramatic flooding has been known to occur with only a very limited spatial extent. On 25 July 1983, a severe thunderstorm produced a flood on the Hermitage Water near Newcastleton, Roxburghshire, of almost 170 m^3s^{-1} from a catchment of only 36.9 km^2, while adjacent catchments experienced no flood whatsoever (Acreman 1991). Similarly, McEwen and Werritty (1988) report a flash flood on the Allt Mor which drains north from the Cairngorm Mountains. On 4 August 1978, a convective rainstorm occurred with a recorded peak intensity of 33.5 mm hr^{-1}, and the resulting peak discharge was estimated at 55 - 66 m^3s^{-1} from a catchment of only 16.4 km^2. In both cases, there was significant geomorphic impact, both in and outwith the fluvial channel. These examples are just a few of the notable floods to have occurred in large and small Scottish catchments. Werritty and Acreman (1985) provide a useful summary of Scotland's greatest floods, constructing envelope curves to show the variation of maximum recorded specific discharge with catchment area.

1.3 The seasonality of flooding in Scotland: aims of the study

A striking feature of the flooding described in the examples above is the seasonal distribution of events. The three recent large floods on the upper Spey all occurred in the winter months, as did the two floods described for the River Ness. On the other hand, both the 1948 and 1956 regional floods in the Tweed basin occurred in the summer month of August, and the two localised thunderstorm-generated floods described also occurred in summer. Another good example of marked flood seasonality can be found on the River Findhorn: Green (1958, 1971) reports two great floods on this river, in 1956 and 1970, both of which occurred in August, and under very similar meteorological conditions. The latter is the largest flood peak to have been recorded at any flow gauging station in Britain (station 07002 Forres), but is still thought to be rather smaller than the 'muckle spate' of 1829 which affected all the rivers of north-east Scotland (Lauder 1830), again an August event.

The purpose of this thesis is to specifically address and investigate this seasonal aspect of flooding in Scotland. Seasonality has rarely been addressed explicitly in studies of flooding, but that work which has already been done, and the examples given above suggest that this is a phenomenon which is interesting and deserving of further study. The general neglect of seasonality may in part result from a tendency to regard it as being largely irrelevant to the understanding of flood magnitude-frequency relationships. Perhaps too the preference of hydrologists to use annual series data in their investigations - largely the result of recommendations in the

Flood Studies Report (NERC 1975), see Chapter 2 - has masked the wealth of interesting information on seasonality which can be uncovered by use of peaks over threshold series, considering every exceedance of a threshold level to constitute a flood of interest (the choice of flood series to be used is discussed in Chapter 3). Whatever the reasons, this study sets out from the premiss that seasonality is worthy of investigation, and in view of the considerable diversity amongst the rivers of Scotland as described above, it is felt that Scotland provides an excellent geographical context within which such a study can usefully be undertaken.

The study has three broad aims. The first is to undertake a comprehensive survey of the seasonality of flooding in Scotland, working from the definition of a flood outlined earlier. The results of previous research, whether specifically investigating seasonality, or simply just reporting on the occurrence of significant floods, suggest that there is considerable diversity in the seasonality of flooding amongst the rivers of Scotland, and therefore encourage such an investigation. It will provide a new body of knowledge, since hitherto no such study has been undertaken. It is hoped that the information thus yielded will be of interest in its own right, and also provide some useful insights into other aspects of flood studies.

The second aim follows logically from the first, being to identify the factors responsible for producing the patterns of seasonality identified under the first aim. Some factors have already been suggested in previous work, but the results of a comprehensive survey will form a much improved basis for evaluating the importance of these previously suggested influences, as well as identifying additional factors which seem to affect the seasonality of flooding. Again, it is hoped that use of a flood database incorporating information from rivers of such diverse character as are found in Scotland should be of benefit in this.

The third aim is to consider the wider implications of the findings reached under the first two aims, and two particular themes are to be investigated. One is to examine how an appreciation of seasonality can be of use in assessing seasonal flood risk on a given river, which is a question likely to be of some practical importance to engineers. The second is to review the implications of seasonality for flood frequency analysis in general. Conventional methods of estimating design floods do not recognise the seasonal variation of flood probabilities, but this study will assess the potential benefits of an approach to flood frequency analysis which specifically takes account of seasonality. This approach follows the results of investigations carried out in Canada and Italy which have shown the benefit of identifying separate flood generating mechanisms, identified by their season of occurrence.

In undertaking this investigation, it is hoped to fill a gap in present knowledge, and in the process contribute to the further development of the general field of flood hydrology. A view of flooding in Scotland from a previously neglected perspective leads to the hope of improving our understanding of flood generation, and may well assist the development of methods by which to improve upon the estimation of design floods.

1.4 Structure of the thesis

The thesis is divided into seven chapters. To familiarise the reader with its organisation, the main topics covered in each chapter are briefly described below. The first chapter discusses flooding in a general sense, then also in a more specifically Scottish context, before introducing the specific subject of this thesis, the seasonality of flooding in Scotland.

Chapter 2 provides a background to the study, outlining all pertinent literature, as well as describing its geographical context. Previous studies of seasonality, whether addressing the topic directly or otherwise, are described, and factors which have been identified as important determinants of seasonality are given. Methods of flood frequency analysis are described, and the potential importance of seasonality in relation to flood frequency analyses explained. Specifically Scottish aspects to the study are also explored, both in terms of previous work on flood frequency analysis with a particularly Scottish perspective, and also discussing in some detail river catchments' physical characteristics which are thought to be of interest in this study.

In Chapter 3, the methods of data collection for the study are described. Data sources are outlined and the choice of data type (peaks over threshold series) to be extracted from the available records is justified. The selection of gauging stations from which data were to be extracted is explained, along with the detailed data extraction methods used and the strategy used for quality control of the data.

The patterns of seasonality found from the resulting database are described in Chapter 4. The use of a number of methods is deemed to be necessary in order to fully explore the patterns in the data; each method is outlined in turn before a description of the patterns found. Maps are used to convey much of the information and a method is presented which enables a simple summary description of seasonality to be given for each gauging station used.

These patterns of seasonality are explained in Chapter 5: a number of controlling variables are identified and the influence of each on seasonality is examined in turn before a multivariate statistical analysis is applied in order to bring together the effects of these disparate influences. The value of this method is discussed and this is followed by an examination of the findings of this investigation in relation to those of other studies.

The penultimate chapter of the thesis, Chapter 6, then takes a critical look at the significance of the whole study and considers some of the wider implications of seasonality in flooding. Two main topics are considered: implications for the assessment of seasonal flood risk, with direct benefits for practising engineers; and the rôle of distinct generating mechanisms - as identified by Lamb weather types - in flood frequency analysis more generally. Again, other relevant studies are brought into the discussion.

Finally, Chapter 7 gives a summary of the findings of the study as a whole, and conclusions are presented. The strengths and weaknesses of the work are evaluated, and specific recommendations are made for future studies.

1.5 Conventions

Throughout the thesis it is necessary to refer to individual river gauging stations and also to particular areas of the study area, and conventions have been adopted for both of these. Gauging station names are given with their Institute of Hydrology Gauging Station Numbers (GSNs) except where repetition seems undesirable, allowing speedy location on maps (see Figures 3.3a-3.3e) and also facilitating ready access to relevant information in the appendices to this thesis. Station numbers are given in five-digit format, the first two digits denoting the hydrometric area of the gauge, giving a broad indication of the area in which it is found (see

Figure 1.1), with the following three digits being used to create a unique number for each station. In normal circumstances, both the river and station names then follow this number, e.g. 08004 Avon @ Delnashaugh. For the description of areas containing a number of rivers, the pre-1975 county names have been used rather than the system of regions which has subsequently formed the basis of local government in Scotland; these are shown in Figure 1.2.

Finally, a further convention is adopted for reference to specific sections of the *Flood Studies Report* (NERC 1975). This is an extensive document, and in order to refer the reader to particular sections of it, references are given in the form V.s.s.s where the first numeral, V, is the volume number and the remainder, s.s.s, is the section within that volume, *eg* I.4.2.7.

Figure 1.1
Hydrometric areas and main rivers: Scotland and northern England

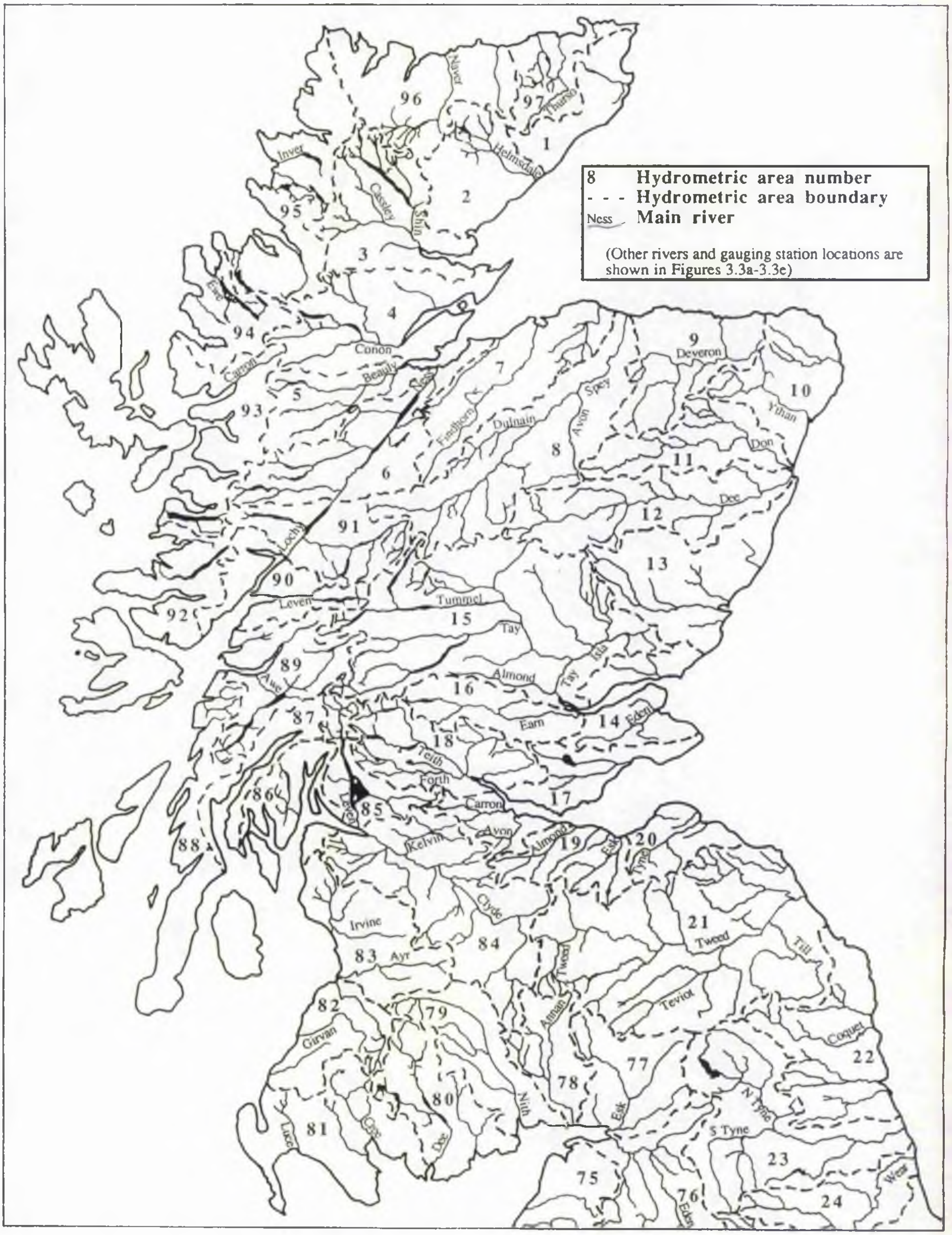


Figure 1.2
Counties of Scotland and Northern England

Chapter 2

Background to the study: thematic and geographical context

2.1 Introduction

The purpose of this chapter is to set the study into context. This is done in two ways: first, the literature pertinent to the investigation is described, both as a means of explaining some of the important ideas surrounding it and also in order to describe the current state of research in this field. This will allow an explanation to be made of how the present study relates to existing work and how it will contribute to the understanding of flood hydrology.

Second, the geographical context of the study is outlined. Some attention must be directed towards the physical characteristics of the study area, and as this investigation is concerned with catchments covering a large part of mainland Scotland, the considerable variety of catchment characteristics found across the country must also be described. All physical factors considered to be of relevance to the study are addressed.

While it has been suggested here that there are these two distinct aspects to setting the study into context, many of the physical characteristics of interest are best introduced through the literature, so the two are handled simultaneously to a certain extent. Over the course of the chapter, the reader will see how the present study seeks to build on existing work and thereby contribute towards an enhanced understanding of flood frequency analysis.

2.2 Previous studies of seasonality

The most suitable body of literature to review first in this chapter is that work which specifically addresses seasonality of flooding for its own sake. As far as is known, the only work to have done this was undertaken by A D Hewson at the Institute of Hydrology in the early 1980s, though mostly with an overall British context rather than being specifically Scottish in outlook.

Hewson's earliest work on this topic (Hewson NDa) was an exploration of time of year of peak flows based on annual maximum series. He found that peak flows tended to occur later in the year in the east of Britain relative to the west, and also that on an annual basis there was considerable stability in the date of peak flow between neighbouring catchments, *ie* the annual maximum flow on one river often occurred on the same date as for many adjacent others. The map of mean day of year (MDOY) values presented in this first of Hewson's papers is rather generalised in its description of patterns for Scotland, but the general tendency is also for later values to be found in the east of Scotland than in the west.

In this initial study, Hewson suggested that the spatial pattern of MDOY values might be explained to a significant extent by reference to mean annual rainfall totals, areas with high annual totals appearing to be generally correlated with an earlier mean time of flood than otherwise, a view maintained in his later work. Anomalous behaviour in the London area was thought to reflect the seasonal distribution of both rainfall totals and storm events in combination with an urbanisation effect. A possible similar effect suggested for the Edinburgh area seems unlikely to be associated with urbanisation since very few of the gauged catchments in that area are actually urbanised to any great extent; indeed no Scottish catchment is found to reach the degree of urbanisation sometimes found in England. An analysis based simply on correlation also suggested that catchment permeability was an important determinant of MDOY value, being characterised by base flow index (BFI), soil index (SOIL) and proportion of catchment urbanised (URBAN) (see NERC 1975); catchment steepness (S1085) and drainage density (STMFRQ) were also considered relevant controls.

However, application of a regression analysis was somewhat unsuccessful in this study, with less than 50% of the variance of MDOY values being explained. The two most important catchment characteristics identified were RSMD (one day rainfall of five year return period less effective mean soil moisture deficit) and URBAN yet, as Hewson recognises, most catchments have very little urbanisation, making an apparently high importance of this characteristic rather puzzling. One suggestion not made in Hewson's work is that it is unreasonable to expect a circular variable such as MDOY to be well explained in a multiple linear regression analysis; this idea is developed in Chapter 5.

In a development of this work, Hewson (NDb) identified the rôle of soil moisture deficit (coupled with the seasonality of storm rainfalls) in explaining patterns of seasonality, this time using POT records as a basis for his work. He also identified small, upland catchments as being more likely to exhibit unusual seasonality than most others, while maintaining a similar opinion about heavily urbanised catchments. Furthermore, he focused specifically on some unusual patterns in and around the Spey valley in northern Scotland, a feature taken to be of great interest in this study. Hewson suggested that "the unusual prevalence of heavy rainfalls in August in this area and perhaps also ... the extensive snow cover at high levels throughout the winter" were important here. An explanation of seasonal patterns, including a specific consideration of the Moray-Nairn area, is attempted in Chapter 5, but in the interim it must be emphasised that the observation of such interesting patterns in this area by Hewson has served as a significant encouragement for the study of seasonality through this investigation.

Further work by Hewson (1982a) again illustrates the difficulty of using regression analysis to explain seasonality; using two different indices of seasonality, S1085 appeared to be the most important predictor, while a physically meaningful index of soil moisture deficit was excluded from the finally chosen expression due to its strong correlation with annual average rainfall. CTROIDY (catchment centroid northing) was also found to be statistically useful, such that Hewson's explanation of seasonality was very indirect, rather than making direct reference to the specific physical factors which he had already identified as important, particularly soil moisture deficits, the seasonality of storm rainfalls and catchment permeability. The obsessive use of regression analysis certainly seems to have been unproductive here. However, in a later working paper (Hewson 1983a), the value of soil moisture deficit data was shown by an analysis using a day of return to zero SMD statistic (DRZ). When mapped, values of this statistic produced a very similar pattern to the MDOY map for flood seasonality, and Hewson places great importance on linking the time of return to field capacity with a seasonal analysis of intense rainfalls in explaining the seasonality of flooding.

The effects of urbanisation were specifically investigated by Hewson in a study based on London and Manchester (Hewson 1982b), in which it was concluded that the interaction between soil type and urbanised fraction was of prime importance. However, as has already been stated, the degree of urbanisation in Scottish catchments never reaches the levels associated with some English cities, and is not considered to be of importance in a Scottish study.

Hewson's interest in flood seasonality in the Moray area was written up in a short working paper exclusively devoted to that area (Hewson 1983b). He found that on the lower Spey, the Findhorn and the Deveron, the largest floods on record are summer events. He suggested that such a seasonal pattern was not found anywhere else in Britain, with the possible exception of two (unnamed) catchments in western Scotland. This unusual seasonality is shown to be a localised phenomenon, with records from the upper Spey and other adjacent catchments showing a more usual domination of winter events; the River Spey itself, with nine gauging stations (including those on its tributaries), therefore shows a remarkable amount of diversity in the seasonality of flooding within a single river system. Hewson makes some very useful observations in interpreting these patterns, and these are discussed at the appropriate point in Chapter 5.

Hewson's work is valuable as an exploration of the seasonal patterns of flooding which are to form the focus of this study, with his examination of the Moray area phenomenon being of particular interest. However, compared with Hewson's (presumably) relatively brief studies, this investigation aims to describe such patterns in a much more thorough and comprehensive way. The analysis subsequently attempted here also aims to investigate more fully the factors which determine the seasonality of flooding at a given site.

Furthermore, the motivation for Hewson's work must be considered at this stage. At one point, Hewson (1982a) suggests that it would be desirable to be able to predict the mean day of flood for any given return period at an ungauged site. The precise purpose of this is unclear, and can surely have little practical benefit, but underlying his work there seems to be the conviction that an understanding of seasonality might help explain variation in flood frequency curves, and indeed that "it might prove possible, for example, to define a single national flood frequency curve and adjust it according to the seasonal characteristics of the area within which [a given] catchment lay" (Hewson 1982a). More specifically, he suggested in his final paper on this subject (Hewson 1983c) that DRZ was a fundamental cause of the differences found in growth curves between regions. It is unfortunate that Hewson did not continue with this work as it held considerable promise for the development of flood frequency analysis methods, but Chapter 6 of the present study aims to realise something of that potential.

2.3 Indirect references to seasonality

Probably the most important work to recognise flood seasonality while addressing flood frequency more generally is that of Todorovic. Initially, only the seasonal variation of flood frequency was addressed (Todorovic and Zelenhasic 1970), but in a subsequent development (Todorovic and Rousselle 1971) this was extended to a model which also considered variations in the distribution of peak magnitudes with season. Hewson (1982a) refers to some of this work which is also cited in the UK *Flood Studies Report* (NERC 1975 I.2.7.3) in a discussion of the various POT models available for design flood estimation. However, practical application of Todorovic and Rousselle's 1971 model is not discussed at all in the *Flood Studies Report* and even the earlier model (Todorovic and Zelenhasic 1970) seems not to have received any great attention in practice in Great Britain. Indeed, the emphasis placed on peaks over threshold models in the *Flood Studies Report* is relatively minor in comparison with annual maximum methods, the former only being suggested as a possibility when design flood estimation is to be attempted on the basis of a short gauged record (NERC 1975 I.A.3). This has been reflected by a general lack of interest in POT methods in both practical engineering and in the flood frequency analysis literature.

Developments of this approach have, however, shown themselves to be of some practical worth outside Great Britain. Using annual maximum series for rivers in south-west Canada, Waylen and Woo (1982) found that the application of a Gumbel distribution was grossly inadequate on account of the mixed processes generating floods in the rivers of that region. Annual floods on these rivers were found to be generated both by rainfall and by snowmelt, the relative frequencies and magnitudes of floods belonging to each group varying spatially (Waylen 1985). Where both processes contributed a significant proportion of the annual floods, the distributions of the individual groups had to be compounded before a good fit to the full annual series could be obtained. In essence, as with the work of Todorovic and Rousselle (1971), the floods of individual seasons were regarded as nonidentically distributed, and a satisfactory model was arrived at only by specifically identifying separate subpopulations within the whole flood series. Waylen (1985) subsequently extended this analysis to the use of partial duration series, arguing that it provided a flexible, physically meaningful, yet simple method.

A similar situation to that in south-west Canada exists in some Italian rivers, with flood series again being readily separable into groups generated either by the spring snowmelt or extreme rainfall events. Rossi *et al.* (1984) therefore devised a Two Component Extreme Value distribution to handle these two often differing distributions, again showing a considerable improvement in fit when compared with application of a Gumbel method; the latter tended to show extreme rainfall-generated floods as very extreme outliers whereas the new model was able to produce distributions which appeared to fit the data well. This work was developed to include a regional analysis in order to improve parameter estimation (Fiorentino *et al.* 1985) and thus increase the accuracy of design flood estimation at both gauged and ungauged sites, although Arnell and Gabriele (1988) point to some drawbacks with the method, and Rasmussen and Rosbjerg (1991) suggest that the large number of parameters required in a multi-seasonal model detracts significantly from its usefulness.

These two sets of work demonstrate the potential importance of seasonal variation in flood generation: in both cases, flood series could be satisfactorily modelled only by separating out two distinct groups according to their generating mechanisms. In Scotland, flood series are not seen to readily separate out into such distinct components as is the case in Canada and Italy. Snowmelt is certainly a recognised contributor to flooding in Scotland (see below), but snow accumulations nowhere amount to the extent of being able to produce an annual snowmelt flood. It might therefore be argued that such an approach of separating floods into distinct generating process groups is not justified in Scotland. However, if it can be shown despite this that seasonal diversity does exist in the generation of floods in Scotland, then the separate treatment of distinct groups within whole flood series would still be perfectly valid. Observations of the seasonality of flooding on the River Findhorn, and the similarity of meteorological conditions causing its great

August floods (Chapter 1), illustrate clearly the potential for this argument. Accordingly, this study will seek to investigate the possibility that the successful analysis of Scottish flood series requires such overt recognition of the diversity of generating mechanisms which may be present within such series.

Mention should also be made at this juncture of a study by Archer (1981a) which, in a more pragmatic sense, also takes advantage of Todorovic's work illustrating the seasonal variability of flood generation. Archer produced a simple model for the assessment of seasonal flood risk which simply adjusted an initial estimate based on an homogeneous within-year distribution of floods above a given threshold according to the proportion of events occurring in the 'season' of interest. This makes no direct reference to the rôle of separate generating mechanisms but, if the purpose of an analysis is to calculate the risk of exceedance of a threshold in a given period of months, such disaggregation is quite unnecessary and Archer's method seems to be an efficient means of obtaining directly useful information. Data collected in this study are applied directly to the question of seasonal flood risk in Chapter 6.

2.4 Controls on flood seasonality

Controls of seasonality have already been mentioned in some of the studies discussed above. In order to provide a background to the explanation of seasonal patterns attempted in Chapter 5, a summary of their findings, along with discussion of other work of relevance to flood generation, is provided here. Each of the various controls is discussed in turn.

Soil moisture deficit is a much-discussed factor in this context. Unlike rainfall magnitude, which affects flood magnitude by means of an essentially direct relationship, soil moisture deficit acts as a constraint on flood generation: a very dry soil can cause a relatively large storm rainfall to produce only a very modest runoff response. Hewson was aware of the importance of SMD in seeking to explain the patterns of flood seasonality which he observed, noting the similarity of patterns in his maps of mean day of flood and day of return to zero SMD (Hewson 1983a), as explained above.

Given the nature of the seasonal variation of soil moisture deficit values, it can be expected that soil moisture should have a major impact on the seasonal distribution of floods. SMD values change only relatively slowly on a time-scale of days, and large soil moisture deficits are maintained only over the summer period, though the length of that 'season' and the magnitude of the deficit vary significantly between places. Irrespective of the typical length of significant SMD at any place, and all other things being equal, the normally discrete nature of a SMD season must produce a significant variation in the probability of flood occurrence between seasons. This is recognised in a number of studies, three examples being Archer's (1981a) study of seasonality in north-east England; the development of a model by Ettrick *et al.* (1987) for estimating seasonal flood risk in summer months on the basis of start-of-month baseflow as an indication of catchment wetness, and a recent study by Reed (1992) which examines the seasonal pattern of flooding in the development of a trigger model for reservoir safety assessment. There can be little doubt that soil moisture deficit has an important rôle in the determination of patterns of seasonality of flooding.

In seeking to explain the seasonality of flooding, both Archer (1981a) and Reed (1992) place considerable emphasis also on the importance of storm rainfall seasonality. This must be differentiated from the seasonal distribution of rainfall totals, since a season with a high total will have very few floods if that total is evenly distributed amongst a large number of small rainfall events; it is only the occurrence of relatively high rainfall intensities which causes flooding. Archer and Reed therefore argue that it is an analysis of the seasonal distribution of peak rainfalls, tempered by the effect of soil moisture deficit, which is necessary to explain the seasonality of flooding.

This is well illustrated in Archer's study of north-east England where he found that late summer was the season of greatest storm rainfalls throughout the region but that the corresponding flood frequency was strongly affected by soil moisture. In the west of the region, where high rainfall totals and thin soils were responsible for low soil moisture deficits, flood seasonality matched the late summer maximum of the storm rainfall seasonality quite well, whereas in the drier east, also characterised by more permeable soils, summer flooding was much less frequent. In fact, the maximum frequency of heavy rainfalls in late summer was reflected only in maximum frequency late summer (September) flooding at one station, Trout Beck at Moor House, the wettest catchment in the study, thus reflecting the great importance of soil moisture deficits on flood seasonality.

Reed's (1992) study analyses the seasonality of storm rainfalls in rather greater depth, attempting to use various combinations of one-day rainfall depths and antecedent conditions to explain the seasonality of flooding in two specific catchments. Reed considered the apparent difference in the influence of soil moisture between the catchments to be significant, and was able to achieve a considerable level of success in explaining the seasonality of flooding. Rainfall inputs to his models were based simply on a peaks over threshold analysis of daily rainfall totals, and illustrated some differences in peak rainfall seasonality between the two catchments.

In various parts of his work, Hewson (*eg* 1983c) too recognised the seasonality of storm rainfall as being important in explaining the patterns of flooding found across Great Britain, particularly in relation to urban catchments (1982b) and in the Moray area (1983b). Along with the two previously mentioned authors, he finds evidence to suggest that although the interaction between storm rainfalls and soil moisture lies at the centre of explaining seasonal patterns, the occurrence of extreme rainfall is capable of producing very large floods, irrespective of soil moisture. Some further aspects of rainfall seasonality in Scotland are discussed in Section 2.6.

For the sake of completeness, urbanisation should again be mentioned here, as Hewson (*eg* 1982b) argues that it is important in producing markedly different flood seasonality to that found in other areas, a view supported by Bayliss and Jones (1992). In their work, catchments with a high urbanised fraction are shown to have a substantially earlier average seasonality of flooding than other catchments in a study based on 687 stations with POT records across the United Kingdom. As mentioned above, Hewson's more detailed work considers urbanisation to be important in a wider sense of catchment permeability, as well as relating it to the seasonality of storm rainfalls and soil moisture deficit. He found urban catchments in Manchester differed little in their flood seasonality from neighbouring non-urbanised basins, but those in London did differ markedly from non-urban neighbours. This difference was attributed to the fact that soils in Manchester were generally wetter through the year so that urbanisation did not seriously alter the seasonal distribution of catchment wetness, whereas in the London area, summer soil moisture deficits can be great so that urbanised catchments will produce much more runoff from a given summer rainstorm than would non-urbanised ones. It must be repeated, however, that major urbanisation is not a feature of Scottish catchments, and is thought to have little relevance to this study.

As well as recognising that some urbanised catchments show unusual patterns of seasonality, Hewson (NDb) noted that the same was true of many small, upland catchments, though as with urbanisation, the effect was not found to be a regular one. In particular, he noted that many of the catchments with a high proportion of June, July and August events were small, upland basins. This suggests an influence of catchment size on flood seasonality, but runs counter to the interpretation of Archer who finds that "there appear to be no significant differences [in seasonality] ... resulting from catchment size" (Archer 1981a p1032). The data he presents do not contradict Hewson's view that small, upland catchments are more likely to have unusually high late summer flood frequencies; indeed they support it, but Archer explains their seasonality by reference to the fact that these small catchments lie in the uplands, which experience high rainfall totals, and thus have antecedent conditions which will be more likely to reflect the seasonality of peak rainfalls than elsewhere. Catchment size is therefore considered to be unimportant; instead it is the upland location of catchments which is argued to be of relevance, although it must be recognised that catchments in the uplands must be relatively small since the uplands contain the head-waters of larger rivers. Archer's data show that while some of the highest August-September flood percentages are found in small, upland catchments, somewhat larger catchment areas further downstream of these can also have high late summer flood frequencies where these are found in essentially upland areas. It would therefore seem that while Hewson's observation is still correct, catchment area in its own right might not be an important determinant of flood seasonality. However, it must be noted that Archer's study includes data from only one moderately small (<50 km^2) lowland catchment, so that unusual seasonality in other such catchments might go undetected.

Beyond these four influences - soil moisture deficits, rainfall seasonality, urbanisation and the possible effects of basin area - no other controls on seasonality have been suggested in the limited literature on flood seasonality. However, there are two further factors which would seem to be relevant, and will also be dealt with here.

Snow is arguably the more important of these two factors. It has been recognised for many years that snowmelt can contribute significantly to flood peaks, either producing a peak entirely from melt, or supplementing runoff generated from rainfall. An early statement was provided by Johnson and Archer (1972) who suggested that snowmelt contributed to a significant number of flood events on the

River South Tyne in Northumberland (14% of the largest 150 events in a 10-year period), and that it also exercised an important effect on monthly flow values. More recently, Ferguson (1984) has shown snowmelt to have a major impact on runoff in the Cairngorm mountains, an area characterised by great depths and durations of lying snow (Jackson 1978). The *Flood Studies Report* (NERC 1975 I.7.2) took account of the possibility of snowmelt augmentation of flood magnitudes by suggesting that a maximum melt rate of 42 mm day^{-1} be added to the probable maximum precipitation value in calculating probable maximum flood values for the winter season. However, Archer (1981b) has subsequently argued that this maximum figure is too low on the basis of flood observations in north-east England; Mawdsley *et al.* (1991) have supported this contention on the basis of theoretical energy-balance studies with a broad applicability for the whole of the UK, but Reynolds (1985) has suggested that the originally proposed figure of 42 mm day^{-1} is too high for Scotland. On the basis of results from a mathematical model, Futter (1991) shows that snowpack presence can lead to great increases in the risk of flood exceedance of a given magnitude, conditional upon input precipitation and baseflow levels, but that the storage potential of a snowpack may also produce a flood peak attenuation effect. Nonetheless, snow is shown by all the studies to have the potential to increase flood magnitude, whether or not accompanied by rainfall, and must therefore be considered to be of relevance to this study. Unfortunately, a lack of comprehensive data produces practical problems, and this is discussed in Chapter 5.

The second factor which may also affect flood seasonality but has not received any attention in the seasonality literature is the effects of lake or reservoir storage. The statistic LAKE was used in the *Flood Studies Report* (NERC 1975 I.4.3) to describe the proportion of a catchment draining through lakes and reservoirs, and was included in the final equation recommended to predict mean annual flood. Subsequently, Acreman (1985b) refined this equation for application to Scottish catchments and found that the statistic LOCH, the proportion of the basin area covered by such storages, improved prediction of the index flood. Both of these studies are concerned with estimation of index flood magnitudes, and show lake and reservoir storage to be important in this respect, but it must also be expected that such storages should affect the time of year of floods downstream of a lake or reservoir if flood hydrographs upstream vary seasonally. Other physical characteristics might also affect flood seasonality, for example catchment slope or soils, though these do not appear to be obvious influences and have received no attention in the specific literature. The effects of all of these factors are discussed fully in Chapter 5.

To summarise the literature on these controls, soil moisture and storm rainfall seasonality appear to be accepted as the most important influences on flood seasonality. Urbanisation is recognised as an important modifier of flood seasonality but is considered to have little relevance to Scottish flood records; and catchment area may also be important, though Archer's work suggests that this may not be so much a physical influence in its own right as an expression of other factors, particularly soil moisture and catchment permeability. The effects of snow and loch or reservoir storage are also identified as being potentially important. These factors can be usefully divided into two groups: catchment area and loch or reservoir storage are static catchment characteristics, while soil moisture levels, the incidence of storm rainfalls, and snow storage amounts are all temporally variable and can therefore be described as dynamic characteristics, at a range of time-scales. Individual catchments have their own particular characteristics in terms of all of these factors, whether static or dynamic; it is their interaction which determines the flood seasonality characteristics of each.

2.5 Methods of flood estimation

The purpose of this section is to introduce the reader to some of the background to flood estimation, since this is the wider context within which this study arises. From the objectives set out in Chapter 1 it can be seen that this study is in part simply an exploratory one, but it has also been explained that it could be of significance in the wider field of flood frequency analysis. The various approaches to flood estimation are therefore outlined here, giving an indication of the historical development of ideas and presently accepted methods.

The justification for flood estimation has always lain in the need to estimate the magnitude of floods for the design of structures. These include bridges, culverts, spillways, flood protection works and any other structures which might lie within reach of a flooding river. Either the probable maximum flood, the magnitude of a given recurrence interval flood or the recurrence interval of a given flood magnitude may be required. Generally, the peak instantaneous discharge of the flood is the quantity of interest, but peak stage may alternatively be sought, derived from a stage-discharge relation at the site of interest, or occasionally, perhaps when storage reservoirs are involved, a flood volume may be required. Attention in this study will be focused exclusively on peak discharge values.

In a review of work from the early part of the present century and the latter part of the 19th, Wolf (1966) explains that early approaches to flood estimation were based on surveys of the largest known floods in many parts of the world, and aimed to estimate the maximum possible flood to be expected for any given site on a river, Q_{max}. Empirical formulae were used, with catchment area being the prime determinant, but Wolf also lists catchment length and width, rainfall, runoff volume and various indices to represent catchment soils, geology, drainage pattern, etc as having been proposed for use. Amongst these relations is the well-known 'rational method' originally due to Kuichling (1889), given by

$$Q_{max} = CAi$$

where C is a coefficient of runoff, A is catchment area and i represents a mean intensity of precipitation.

A major advance in the UK was the publication in 1933 of the *Interim Report* of the Institution of Civil Engineers' Committee on Floods in Relation to Reservoir Practice (Institution of Civil Engineers 1933). This gave envelope curves showing highest recorded specific discharge values against catchment area, and made numerous design recommendations for practising engineers. The concept of return periods was not in use at this stage; 'normal maximum flood' and 'catastrophic flood' magnitudes were the focus of concern for engineers at this time. In 1960, following the receipt of many further flood observations from throughout the UK, a subsequent report, *Floods in the British Isles*, was issued (Institution of Civil Engineers 1960) to improve upon the Interim Report's inability "to put forward any rules for arriving at the probable maximum flood discharge". However, despite envelope curves again being produced as in the 1933 report, reference is made to the potential use of gauged records, and the concept of recurrence interval is introduced, although the desirability of defining 'normal maximum' and 'catastrophic' flood values still appears to be of paramount importance. Return period-based analyses are now much more important than previously, but envelope curves showing the variation of maximum recorded specific flood discharges with return period are still useful; Werritty and Acreman (1985) provide such a curve specifically for Scotland.

An alternative approach to flood estimation has been to work from a maximum estimated rainfall over a catchment (probable maximum precipitation (PMP)) in order to derive a maximum flood value. Perfect application of this method requires that the processes by which rainfall is converted to runoff are understood in every detail, and that their highly complex behaviour can be represented in a model. Unit hydrograph theory, initially developed by Sherman (1932) and Bernard (1935), provides a useful approximation to this, hydrograph ordinates being taken to be directly proportional to storm rainfall. This method can be used for the calculation of design floods by the input of a maximum calculated storm rainfall, and in practice can be used for comparison with the results of flood frequency methods, the discussion of which forms the basis of the remainder of this section.

In present-day hydrology, there are two broad approaches to design flood estimation, rainfall-runoff methods represent one approach and flood frequency analyses the other. The latter involve the definition of flood magnitude-frequency relationships for application at any given site of interest, such that a flood peak magnitude can be related to a specific return period.

One of the earliest publications to outline the application of this method is Dalrymple's *Flood-Frequency Analyses* (Dalrymple 1960), being a manual of methods used by the United States Geological Survey. An index flood, the mean annual flood, $\overline{Q}$, was derived from a curve showing its relation with basin area (and possibly other catchment characteristics), and the magnitude, Q_T, of a flood of a greater, T-year, return period was then found from a second curve relating $Q_T/\overline{Q}$ to recurrence interval. While Dalrymple's method may appear somewhat simple in comparison with later developments, the basic approach of calculating an index flood and then applying a scaling factor to obtain a flood of higher return period still lies firmly at the heart of current flood frequency analysis.

In Britain, the publication of the five-volume *Flood Studies Report* (NERC 1975) after much research at the then recently-established Institute of Hydrology represented a further major step in this direction for design flood estimation. The *Flood Studies Report* has already been referred to on a number of occasions in the preceding sections; this is indicative not only of the great amount of work presented in it, but also of the importance with which its recommendations have been viewed in subsequent years (a useful guide to its recommendations is given by Sutcliffe (1978)).

A number of methods were presented for the estimation of the mean annual flood, both for gauged and ungauged sites (Figure 2.1). Where data from a gauging station were available, several methods could be used, the preferred choice depending on record length. Methods for both annual maximum and partial duration series data were described, though use of the former type dominated the recommendations, largely reflecting the development of the statistical theories underlying their analysis. For ungauged sites, the index flood was to be estimated by reference to catchment characteristics using a six-term regression equation:

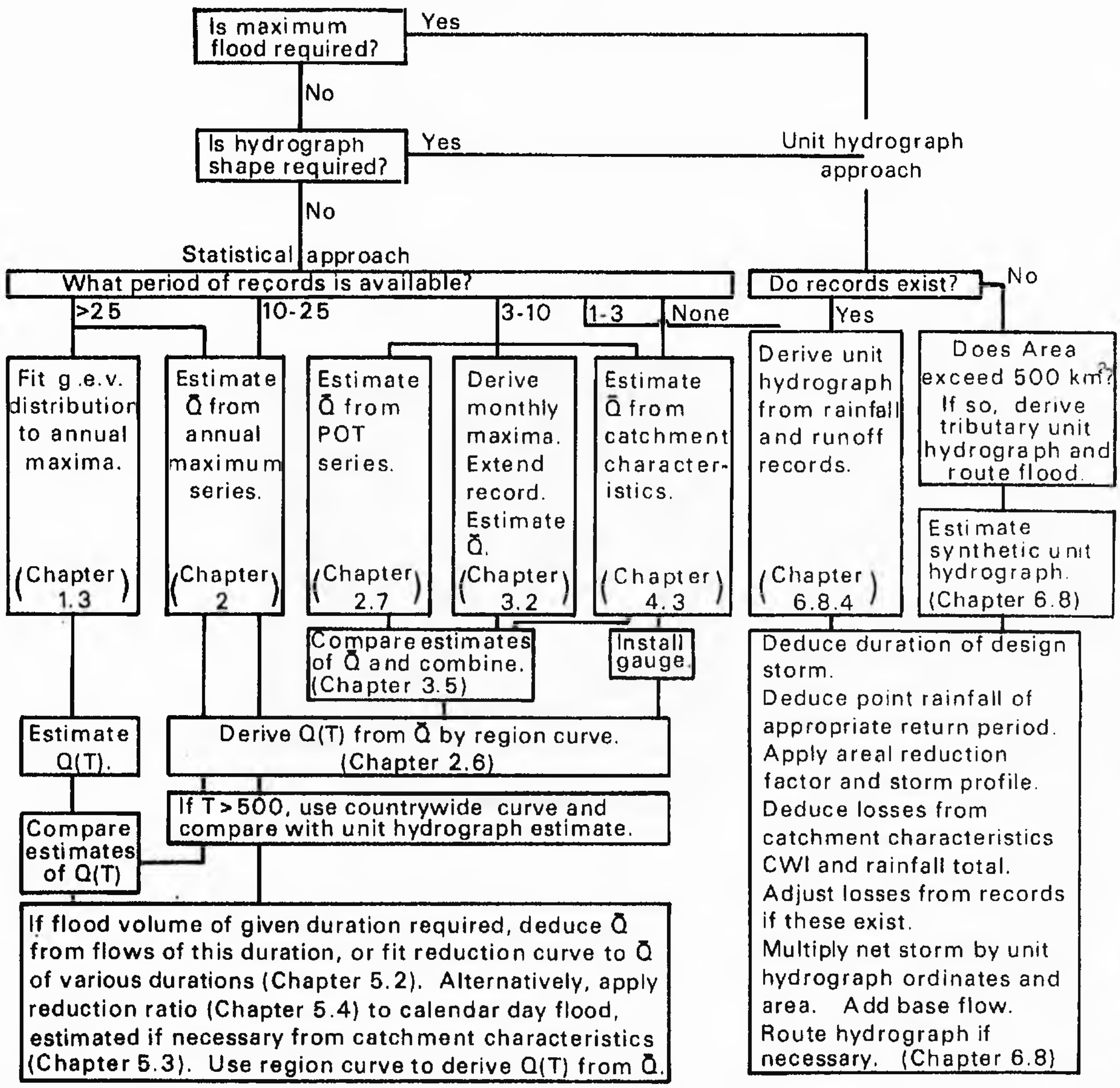
$$\bar{Q} = m\ AREA^{0.94}\ STMFRQ^{0.27}\ S1085^{0.16}\ SOIL^{1.23}\ RSMD^{1.03}\ (1+LAKE)^{-0.85}$$

where m = a regional multiplier
AREA = catchment area (km^2)
STMFRQ = stream frequency (junctions km^{-2})
S1085 = 10-85% mainstream slope (m km^{-1})
SOIL is a catchment soil index representing its winter rainfall acceptance potential
RSMD = maximum one-day rainfall of five year return period minus SMD (mm)
LAKE = proportion of the catchment draining through a significant loch or reservoir.

The estimation of high return period flood magnitudes was in most cases to be made using a regional growth curve relating $Q_T/\bar{Q}$ to return period. Ten significant geographical regions were identified for this purpose; the appropriate map and growth curves are shown in Figure 2.2. Where more than 25 years of annual maximum series were available, however, it was recommended that magnitudes could be estimated by fitting a general extreme value distribution without the need to calculate mean annual flood first.

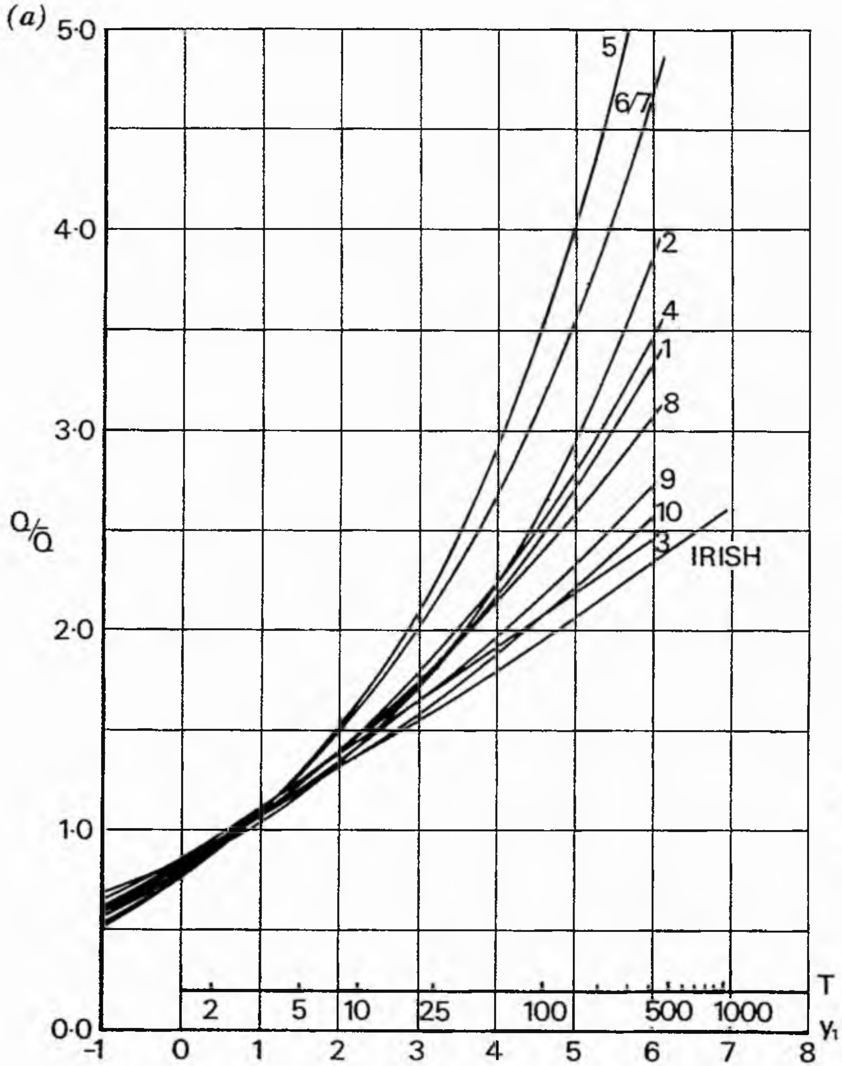
The selection of statistical distributions for flood series is a key issue in flood frequency analysis, since the distribution chosen will determine the value of a design flood estimate, and this applies equally to empirically derived regional growth curves and to curves derived directly from extreme value theory for application at an individual site. The appropriate choice might be made on the basis of graphical inspection of the fit of points from any one station; alternatively the *Flood Studies Report* suggests goodness-of-fit tests which might be applied. The

Figure 2.1
Estimation of design flood



Source: NERC (1975) Figure A.1

Figure 2.2 (a) Region curves showing average distribution of $Q_T/\overline{Q}$ in each region and (b) geographical extent of regions



Source: NERC (1975) Figure 2.14

Based on NERC (1975) Figure 2.4

work of Waylen and Woo (1982) and Rossi *et al.* (1984) described in Section 2.3 is of relevance here: these studies present two individual, though similar, models of the form of flood magnitude-frequency distributions, both being derived from areas with particularly unusual seasonal flood regimes. The basic problem faced by flood frequency analysis is that the correct distribution of flood peaks for any site, whether using annual maximum or partial duration series, is not known, and hydrologists must strive to describe the magnitude-frequency relationship of floods for a specified site or in a more general way as best they can on the basis of the available information. A study by Ahmad, Sinclair and Werritty (1988) addresses this problem in a specifically Scottish context, but it is hoped that the present study, considering flood seasonality in Scotland, may make some further significant contribution towards resolving this problem.

It is also worth noting that since publication of the *Flood Studies Report*, Acreman and Sinclair (1986) have argued in a Scottish study that geographical regions as used in the *Flood Studies Report* and in other studies before it (*eg* Dalrymple 1960) should be superseded by groups of catchments which are defined by their catchment characteristics (non-geographical 'regions'). They argued that flood frequency behaviour was much more likely to be homogeneous within groups of physically similar catchments, such as small, steep ones or those with large lochs, than within geographically-defined groups of catchments which might have greatly differing physical characteristics. More recently, Acreman and Wiltshire (1989) have suggested that the placing of catchments into distinct groups is unhelpful since there will always be a certain degree of heterogeneity within groups. They proposed instead a method by which every catchment would define its own 'group' while its flood frequency behaviour was deduced by reference to other physically similar basins, weighting the importance of various physical similarities. In all these more recent developments, however, the benefit of using 'regions' of one sort or another in effectively pooling the records of many gauging stations to yield more information than would be available from a single site has been maintained. Considerable attention is directed towards the fitting of frequency distributions to partial duration series in Chapter 6, and a recent review of the various methods of flood frequency analysis currently available is provided by Cunane (1989).

2.6 Physical characteristics of Scottish catchments

To complete this background to the study, attention must be directed towards the physical characteristics of catchments in Scotland. Mention has already been made of the great diversity which exists in the characteristics of Scottish catchments. The purpose of this final Section is to describe more fully these varying characteristics. By reference to literature and to tabulated statistics, it aims to discuss all the physical characteristics which might affect flood seasonality.

A useful starting-point in considering the diverse character of Scottish catchments is Acreman's classification of 168 Scottish basins on the basis of six catchment characteristics (Acreman 1985a, Acreman and Sinclair 1986). Acreman identifies five groups, though only three of these are described in physical terms, the other two still containing a considerable amount of variation in their physical characteristics. The three described, however, are: those containing large lochs; shallow-slope lowland basins; and small, steep, upland basins. Acreman's interest was in identifying more appropriate groups of catchments for the purpose of flood frequency analyses, and he was able to show that his regions, defined in terms of their physical characteristics, did have significantly different flood frequency distributions. His cluster of basins with large lochs, for example, has a relatively low variation of flood magnitude with return period (small growth factors, *ie* low rate of increase of $Q_T/\overline{Q}$ with T), while his shallow-slope lowland basins which are "located on the better drained soils of eastern Scotland which experience a more variable soil moisture deficit ... are subject to a greater proportion of summer floods" (Acreman and Sinclair 1986, p 376) and were shown to have high $Q_T/\overline{Q}$ growth factors. These findings were explicable in physically reasonable terms.

Such groups of catchments could also be seen as possessing significant differences in terms of seasonality. The flood attenuation effect of lochs will lead to rivers downstream of such storages responding to rather longer rainfall durations than would otherwise be the case, while small catchments will be expected to flood in response to much shorter peak rainfall durations. If the seasonality of peak rainfall amounts varies with duration, then it follows that these different groups of catchments will be expected to have different flood seasonalities. Furthermore, the lowland distribution of catchments in one of Acreman's groups, synonymous with strong seasonal variations in soil moisture deficit, is also likely to have implications for flood seasonality.

Turning to the characteristics of actual Scottish catchments, basin size is one characteristic which obviously varies greatly between one catchment and another. Scotland's two largest river basins are those of the River Tay, draining an area of 4587 km^2 to the gauging station at Ballathie, and the River Tweed, draining 4390 km^2 to Norham. The Rivers Spey, Clyde and Ness also drain areas exceeding 2000 km^2, and on all of these, flood hydrographs extend over periods of days rather than the rather fewer number of hours characteristic of smaller rivers. Amongst them, these five rivers drain about one-fifth of Scotland's land area, being fed by many successively smaller tributaries. At the other extreme of the range of basin sizes, it is difficult to know what might constitute the minimum of basin size. In calculating stream lengths, the appearance of a blue line on a 1:25,000-scale Ordnance Survey map (2nd edition) is taken to define a watercourse, so the area upstream of any such line could be taken to be a drainage basin. However, gauged catchments are of rather more practical interest for the purposes of this study, since it is from these that recorded flow information will be derived (see Chapter 3), and it can be observed that very few catchments of less than 50 km^2 are gauged. In this investigation, only 10% of the catchments to be used are smaller than this, and only 2% are smaller than 10 km^2. Assuming that large drainage basins are composed of many smaller basins which can be identified as entities in their own right, the relative rarity of gauging small catchments can be seen as a bias in the gauging network, and should be borne in mind through the following chapters.

It is also worth noting that because of their great size, there can be little variation in the character of Scotland's largest drainage basins: each of the five large basins mentioned above drains a varied area which extends from the uplands in the centre of the country down to the coast. On the other hand, small catchments may have a great variety of characters, depending on their location. In the uplands, they are likely to experience high rainfall amounts around the year with little opportunity for soil moisture deficits to develop; their soils might typically be thin and translate rainfall rapidly into runoff, with generally steep slopes encouraging this tendency. In the lowlands, however, catchments are more likely to be relatively flat, draining well-developed, highly permeable soils (especially in the east of Scotland), and experiencing a quite different rainfall regime, both in terms of annual totals and temporal distribution.

To take two contrasting examples, one might compare the West Peffer Burn at Luffness Mains, draining a mostly arable area of 26.2 km^2 in the East Lothians into the Firth of Forth with the Allt Leachdach on the north-west flank of Ben Nevis, another small catchment (6.5 km^2) which was gauged for many years at an intake works for a hydro-electric scheme. Their small catchment areas are one of their few common features: the West Peffer catchment receives a mean annual rainfall of only 643 mm while the Allt Leachdach receives 2375 mm; the former has a very shallow slope of 1.56 m km^{-1} over its 10-85 percentile length while the latter is much steeper at 17.73 m km^{-1}; and the drainage density of the two basins also contrasts greatly, their values being 0.15 and 3.09 junctions km^{-2} respectively. One common feature to both basins is their relatively clayey soils, though these are still sure to be better developed on the coastal plain than at considerable altitude on Ben Nevis. Differences in rainfall will still, however, ensure that the typical soil moisture status and corresponding runoff response to a given rainfall input will differ between the two at certain times of year, and therefore affect their respective flood seasonalities. Thus it can be seen that although the range of catchment sizes found in Scotland is likely to contribute to differences in flood seasonalities, there are many other factors which might be responsible for other differences.

The general topographic structure of Scotland is responsible for the spatial distribution of many of the characteristics which affect flood generation (Figure 2.3). The concentration of upland areas in the west of Scotland, coupled with the preponderance of rain-bearing weather systems to arrive over Scotland from the west, results in much higher annual rainfall totals in the west than in the east, as shown by the Meteorological Office 1941-1970 standard period map (Figure 2.4, Meteorological Office 1977); the direct influence of altitude is also quite apparent. This is important in affecting the likely antecedent conditions preceding storm events, as the variation in annual rainfall totals clearly gives the development of high soil moisture deficit values in the east a much higher probability than in the west. The spatial distribution of maximum 24-hour rainfall values (Figure 2.5a) is broadly similar to that of mean annual totals, but that for maximum 2-hour durations (Figure 2.5b) is somewhat different, and these variations with duration, especially when related to catchment size, have implications for flood generation.

Soils are also affected by this general topographic structure. High rainfall totals and wind speeds, coupled with low temperatures and sunlight hours at high altitudes, ensure that soils in this environment have developed only slowly since deglaciation, and as a consequence are thin and relatively impermeable. Altitude is not the only control on soils, however, and the *Flood Studies Report* WRAP (Winter Rain Acceptance Potential) map (Figure 2.6, NERC 1975 Figure I.4.18) shows, with

Figure 2.3
Upland areas of Scotland

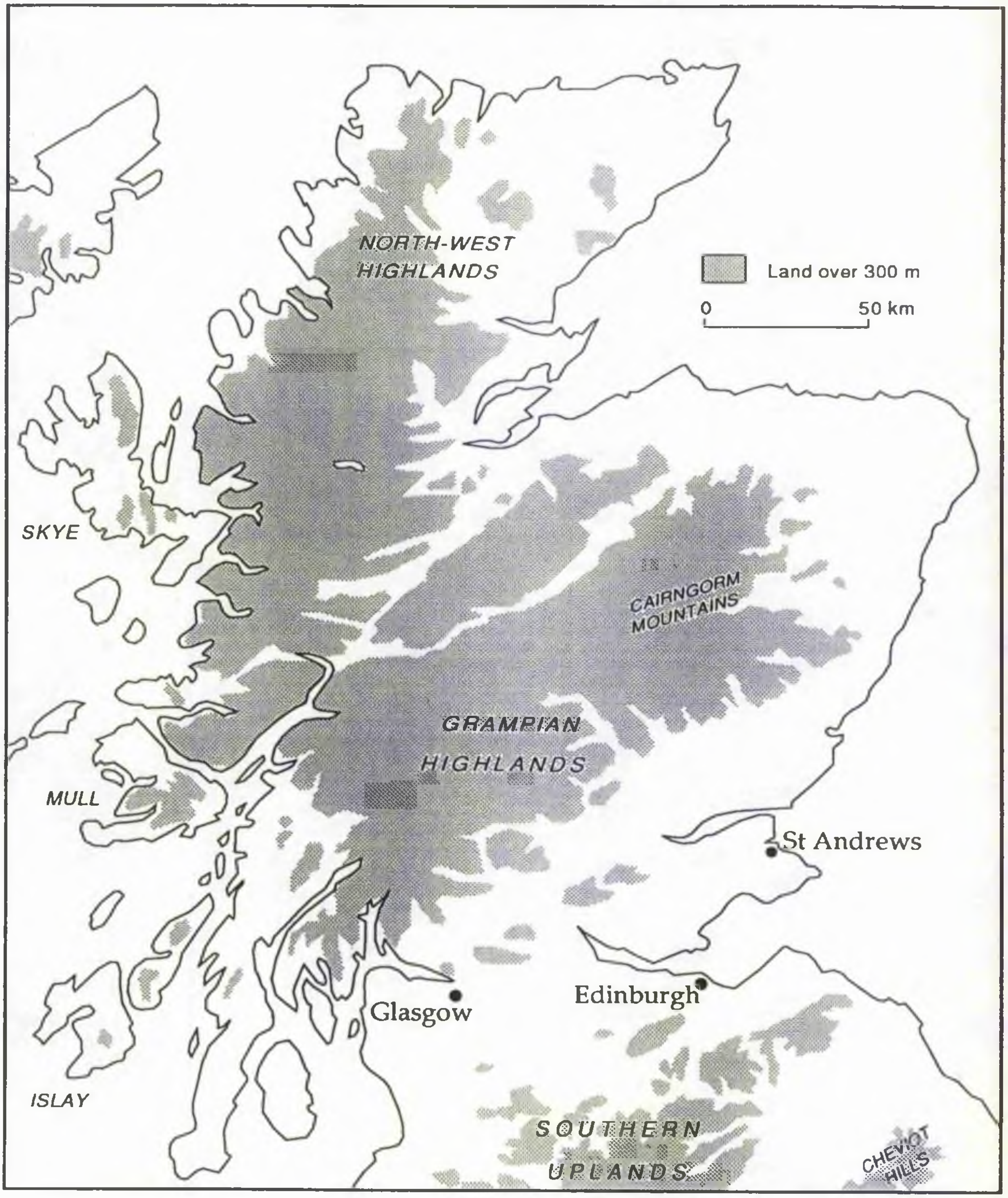
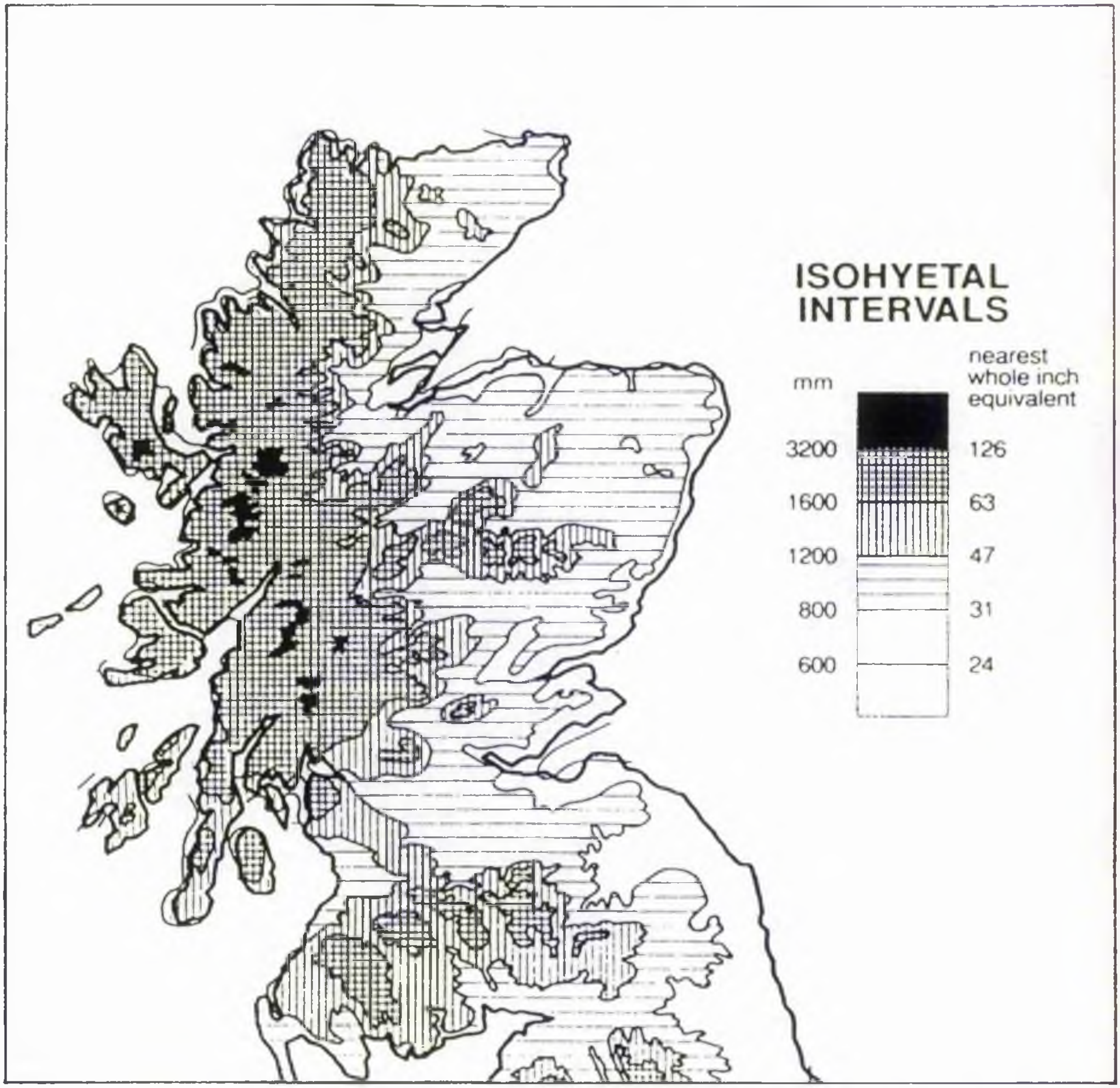


Figure 2.4
Average annual rainfall (1941-70)



Based on Meteorological Office (1977)

Figure 2.5

(a) Maximum 24-hour rainfall (mm)

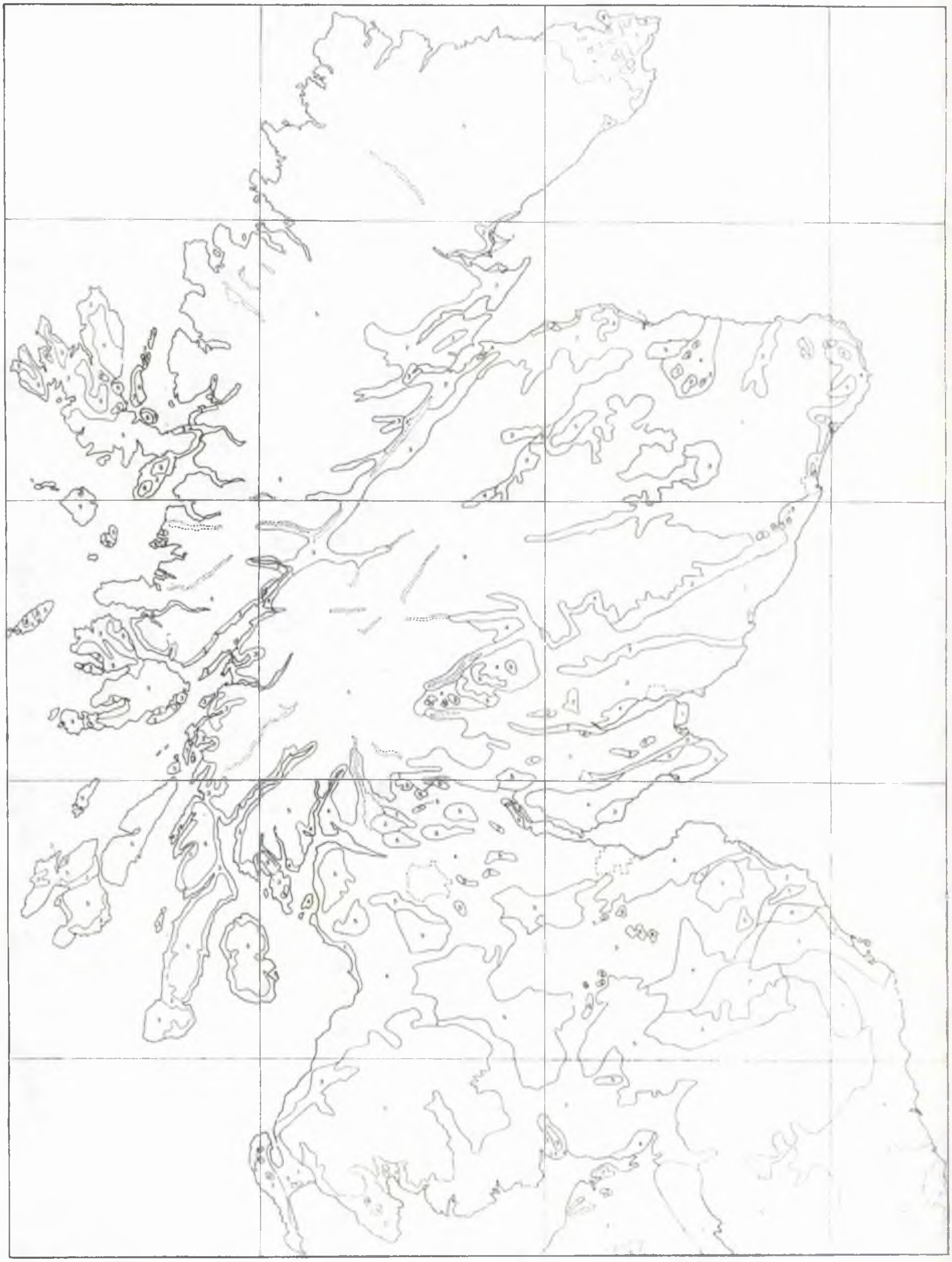
(b) Maximum 2-hour rainfall (mm)

WRAP Classification

Class 1 Very high
Class 2 High
Class 3 Moderate
Class 4 Low
Class 5 Very low

Figure 2.6
Winter Rain Acceptance Potential

Source: NERC (1975) Figure I.4.18



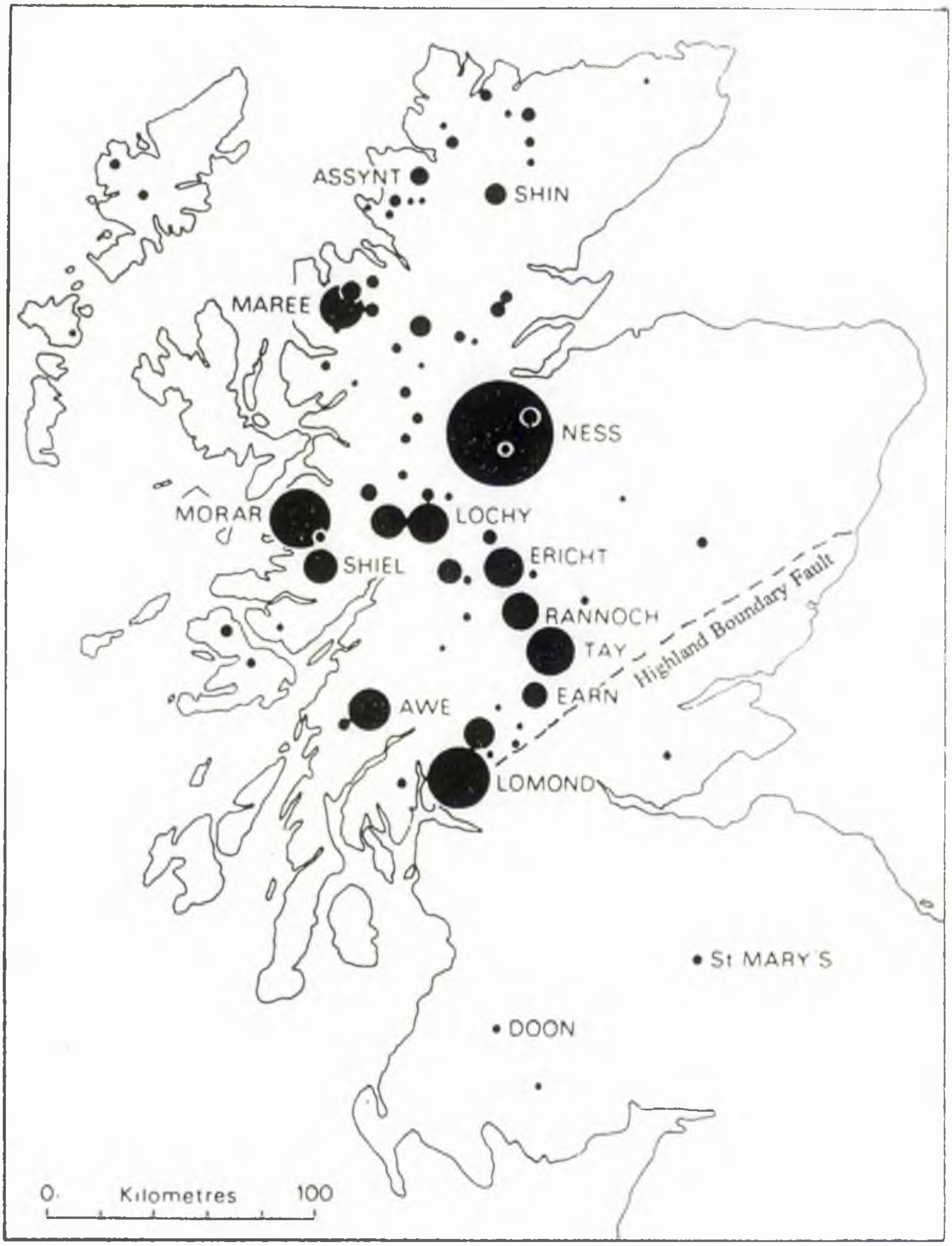
direct relevance for flood generation, how the character of soils varies across Scotland. Acceptance potential values in Scotland are generally low, though a significant area of higher values is found in north-east Scotland, and values are also generally higher along coasts.

Drainage density, another variable which is of direct relevance to flood generation, is dependent on both rainfall and soils. With increasing rainfall, the density of the stream network will increase to evacuate greater amounts of runoff, and as soils become less permeable, so again a greater drainage density will evolve to accommodate a greater proportion of quickflow relative to slowflow (Richards 1982). Catchment slope too can be expected to affect drainage density, since steeper slope will cause faster runoff and result in a denser channel network. Therefore the catchments with greatest drainage density, and hence also the flashiest runoff, are found in upland areas, particularly in central and western Scotland.

Finally, snowfall is also heavily influenced by topography, particularly altitude. Snow has already been mentioned for its property of either suppressing flooding, through causing precipitation to be stored on a catchment surface, or directly contributing to it when such storage is released, often in combination with rainfall. Once again, this factor assumes greatest importance in catchments with significant proportions of their total areas in upland areas, *ie* central and western areas. The Cairngorm Mountains deserve special mention here, since these form the largest contiguous upland area in Scotland (Ferguson 1984) and it can be seen that snow lies longer in this area than anywhere else in the UK (Meteorological Office 1975). The greatest effect of snow in such catchments is arguably its melt supplementing daily flow values in spring, but snowmelt floods generated without any rainfall are reported and are of greater interest in this study. It is expected that similar behaviour will be observed in rivers draining other upland areas, particularly in the west, although there appears to be a lack of suitably specific studies. The modification of seasonal flood regime by snow can be expected to vary from a minimum in small, coastal catchments which lack any high ground, to a maximum in those draining only mountainous areas such as the Cairngorms or other parts of the Grampian Mountains.

The occurrence of lochs, although mentioned above, should also be considered a little further here, simply to add a description of their geographical distribution (Figure 2.7). Scotland's largest lochs are found to the north of the Highland Boundary Fault which runs from Stonehaven to Balmaha Loch Lomond), the

Figure 2.7
Scottish freshwater lochs exceeding 20×10^6 m^3 in volume
(Circles proportional to loch volume)



Source: Sissons (1976) Figure 3.3

geological differences across this fault having being responsible for differences in evolution of the landscape during glaciation. Smaller lochs are also found to the south of this line, however, so the effects of loch and reservoir storage on flood attenuation cannot be said to have a particularly clear regional pattern.

These are the various factors which are thought to be of relevance in setting this study into its geographical context. It has been demonstrated that topography exerts an important control on many of the factors relevant to flooding and its seasonality, but the interaction of these factors, along with the great variety of sizes of gauged catchment is likely to ensure that this study will find considerable variation in the seasonality of flooding across Scotland. In Chapter 4, the actual patterns of seasonality in Scotland will be described, and in Chapter 5, an attempt will be made to determine how the factors described above interact to produce them.

2.7 Summary

Seasonality of flooding has received little attention in the wider study of flooding in Scotland or elsewhere. Only the exploratory work of Hewson at the Institute of Hydrology in the early 1980s has directly addressed the seasonality of flooding as a matter of interest in its own right.

However, the seasonal distribution of floods has been found to be of some importance in regions where floods appear to belong to distinct genetic groups, their identification on a seasonal basis enabling more appropriate flood frequency models to be developed. In acknowledging that modelling of flood frequency distributions is a complex field, it is felt that study of the seasonality of flooding in Scotland may provide useful information which could lead to a greater understanding of flood magnitude-frequency relationships and thus an improved ability to predict flood quantiles at a given site of interest.

Many physical factors have been identified as important determinants of seasonality, both by studies specifically addressing seasonality and others. The seasonality of peak rainfalls and catchment wetness appear to be the most important of these, but catchment size, soils, slope, drainage density, snow cover and the presence of loch or reservoir storages are all recognised as potential influences on flood seasonality. The effect of each of these remains to be identified in the course of the present investigation.

These catchment characteristics vary considerably amongst the river basins draining Scotland's land surface, some showing a certain interdependence, but others not. It is felt that a considerable diversity in flood seasonalities may well be found to result from the interaction of these influences across Scotland, from the mountainous Highlands, through less rugged environments as are found in much of southern Scotland, to the gentle lowland areas found especially along the east coast. The study sets out against this background to pursue the aims set out in Chapter 1.

Chapter 3

Flood Database Preparation

3.1 Introduction

In order to gain a good understanding of the nature of seasonality in flooding across Scotland, data were required to detail the flooding behaviour of individual rivers throughout the country and from this to describe spatial patterns of seasonality. The data to be collected required both a spatial and temporal registration: the location of the individual sites from which data were to be collected was important in placing each data set in a spatial Scottish context, while within each of these data sets the time of year at which floods occur is important in describing the overall seasonality of flooding at that site. The primary aim was to establish a database of flood information for sites across the whole of Scotland, at each site using the full period of record available whenever possible. This database would hold dates of floods in order to describe seasonality and would also include peak flow values for each flood to describe flood magnitudes in connection with seasonality.

Two possible types of database could be collected in furtherance of these aims. Known as annual maximum (AM) and peaks over threshold (POT) series respectively, each offers advantages and disadvantages (Figure 3.1). The former is a listing of the date and peak flow of the largest flow event in each year and may be based on calendar years (January - December), or more traditionally 'water years' (October - September in Britain). Irrespective of the definition of the year, an

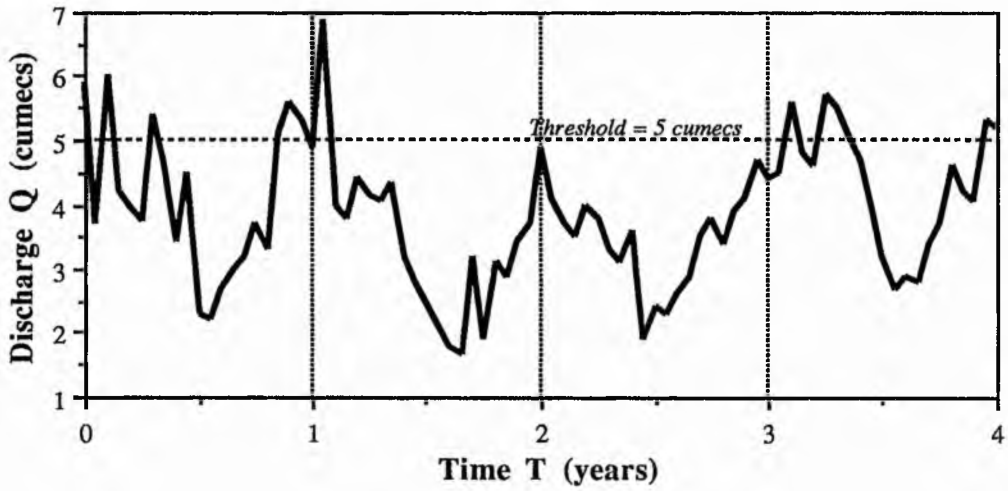


Figure 1

	Year 0	Year 1	Year 2	Year 3
Ann Max	Feb 6.0	Jan 6.9	Jan 4.9	Mar 5.8
P.O.T.	Jan 5.9 Feb 6.0 Apr 5.4 Nov 5.5	Jan 6.9		Feb 5.6 Mar 5.8 Dec 5.3

Figure 3.1

Simplified representation of annual flooding behaviour to illustrate annual maximum and peaks over threshold series: POT data give a much more detailed description of flooding and are therefore preferred for use in seasonal analysis.

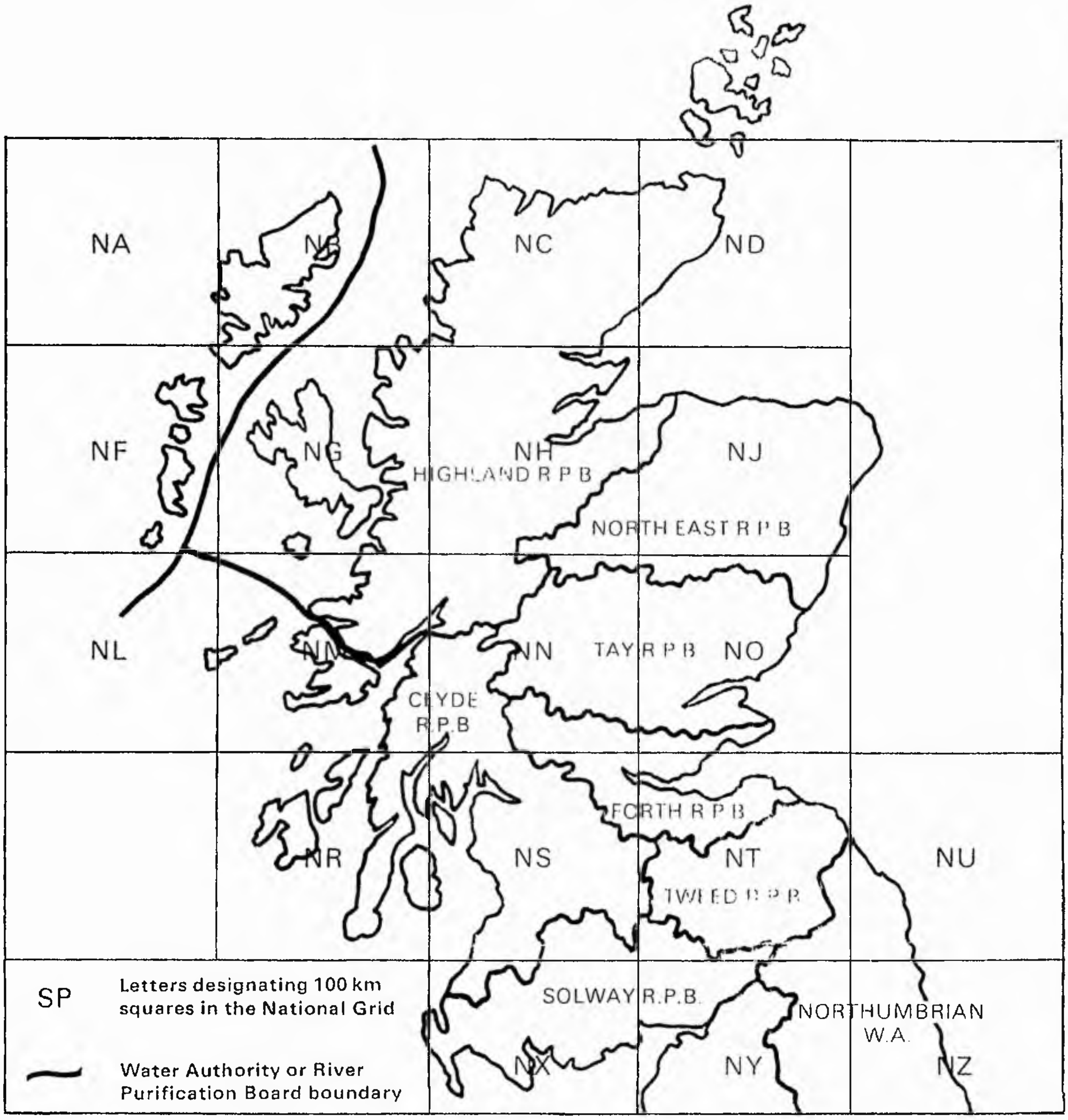
annual maximum series represents each year with the date and peak flow of one flood. This may be very convenient for subsequent statistical analysis and is also quite easily performed in terms of data extraction, but it fails to describe fully the flooding behaviour of a river in any one year: it gives no indication of the frequency of flooding within a year, nor does it describe the season of occurrence of any but the biggest flood of each year. By contrast, peaks over threshold data comprise details of all floods equal to or greater than a given flow magnitude at a site. In a 'flood-poor' year, this may mean that no events are recorded at all, while in 'flood-rich' years there may be many floods - perhaps a dozen or more - recorded in a POT series. This lacks the regularity of an AM series but does give a much fuller picture of the seasonal nature of flooding at a particular site while also showing the annual variations in flood frequency which occur. A POT series gives a much more comprehensive description of flooding than does an AM series and for this reason, the former was selected as being appropriate for use in this study.

3.2 Scottish river flow data collection

Before proceeding to describe the methods adopted for identifying and collecting flood data, brief mention must be made of the sources of river flow records from which flood data are extracted. River flow measurement first began in Scotland in 1913 when Capt W N McClean started work at his own initiative on the establishment of a network of rain gauges and river flow gauges in northern Scotland (McClean 1927, Werritty 1987). Since that time, river flow records have been recognised as having much wider importance in the field of water resource management, both for provision of water to industrial and domestic consumers as well as for the safe disposal of waste water. Today, recording of river flows is commonplace and in Scotland after an initial period of involvement of the Scottish Development Department, seven River Purification Boards (RPBs) now have a public responsibility as guardians of the water environment which includes a duty to monitor flows in all major watercourses within their respective areas (Poodle 1987). These areas are shown in Figure 3.2, and the data from the Boards' gauges form the great majority of the database to be studied in this thesis.

Flow measurement is achieved by the use of gauging stations whereby a recorder located at a particular point on a watercourse continuously records the level of the river (see Plates 3.1-3.4). Gauging stations are distributed widely throughout

Figure 3.2
River Purification Board areas



Source: IH/BGS (1988)

Plate 3.1 Station 15008 Dean Water @ Cookston
Straight, 10 m wide section with all flows up to 52 m^3s^{-1} contained within banks. A cableway is provided for the suspension of a current meter in order to measure velocity across the section.

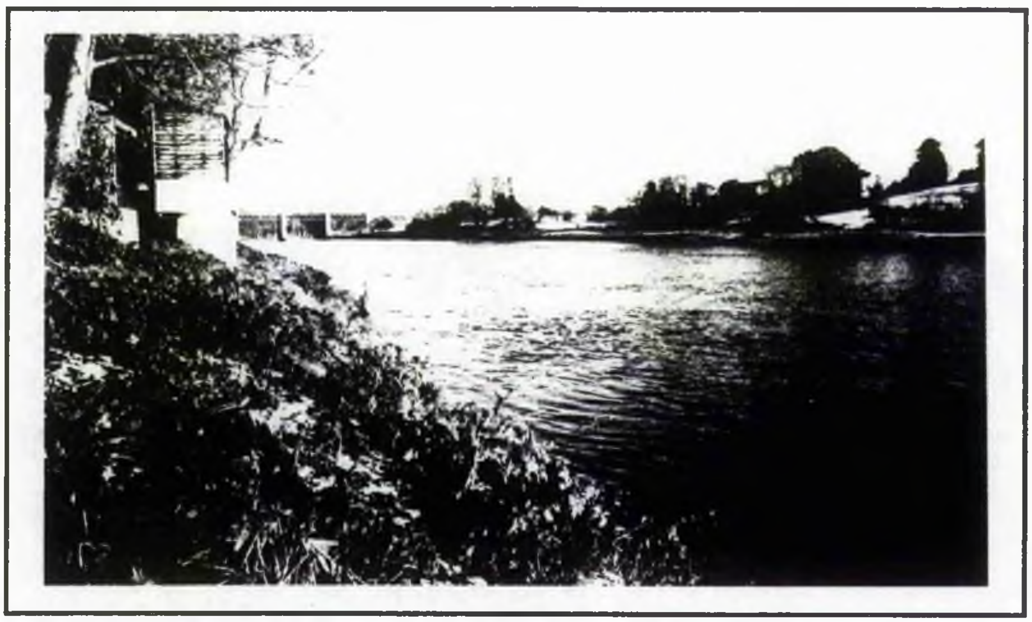


Plate 3.2 Station 15006 River Tay @ Ballathie
90 m wide section - the Tay is Scotland's largest river, at this point draining a catchment of 4587 km^2. Instruments are housed in the wooden hut built on top of a giant stilling well which exceeds 6 m in depth.

Stage recorders

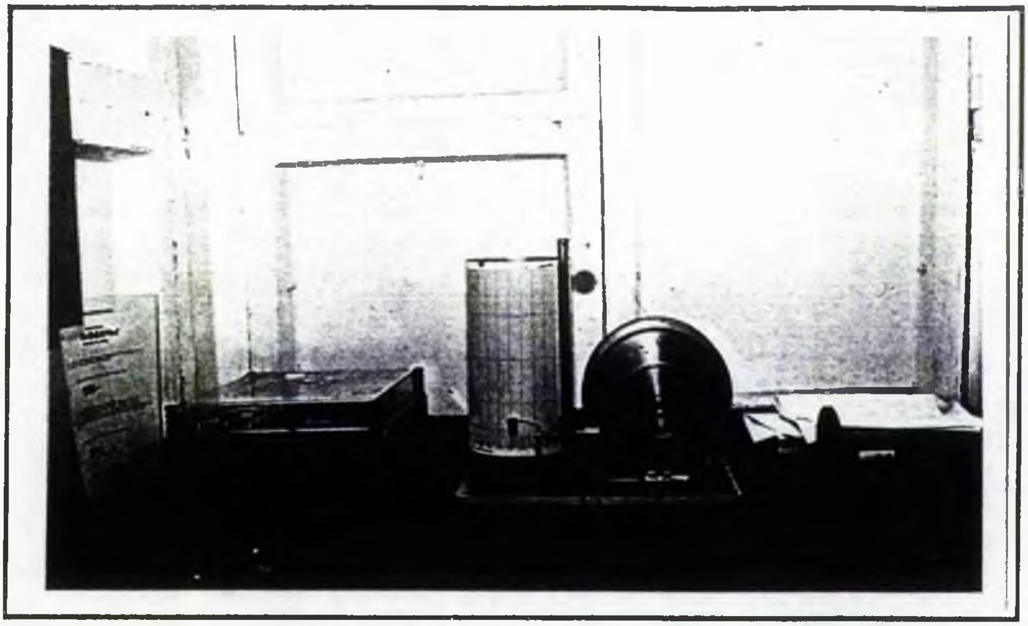


Plate 3.3 Munro rotating drum recorder (centre) and DTS digital recorder (left) at station 19010 Braid Burn @ Liberton. The paper chart is changed weekly, corresponding to one rotation of the drum. The digital recorder may be connected to a telemetry unit, allowing remote interrogation.

Plate 3.4
Strip-chart recorder at station 80003 White Laggan @ Loch Dee. This type of recorder uses charts several metres long which only need changed once per month. The stilling well is a length of narrow-diameter plastic pipe.

Boards' areas to give a good overall measurement of flows, and are also sited to yield specific flow information concerning, for example, confluences of major rivers, artificial influences, or areas of particular flood hazard. Water level is continually measured by a float in a stilling well constructed in the river bank, and the measured stage can then be converted to a discharge value using a stage - discharge relationship or 'rating' (see Section 3.5 below). Gauges are located at stable cross-sections on a river in order that the rating will not change significantly with time, and ideally at sites where even the highest floods can be expected not to rise above the level of the river banks; the gauge can then be expected to provide accurate flow data. In order to improve cross-sectional stability or the accuracy of measurement (Ackers *et al.* 1978), artificial structures for which theoretical ratings are available may be built into the river bed (see Plates 3.5-3.6). However, gauging authorities often find such ratings to be in error and compute more accurate equations on the basis of current meter measurements (see IH/BGS 1988).

Stage data are recorded by one of two types of device, both actuated by a float in a stilling well. Chart recorders employ a rotating drum onto which a (typically weekly) chart is placed, and a pen which records water level changes detected by the float. However, in recent years digital recorders have become more common and record levels at fixed time intervals (usually 15 minutes) onto either punched tape or more robust magnetic tape which is also preferred for its ease of processing (see Shaw 1983). For the purpose of assembling a POT database, autographic chart records are preferred because it is felt that peak levels can be found more accurately from charts than from digital records where the peak level is likely to occur between the 15 minute measurement intervals. Where digital recorders have been installed by RPBs, they are generally found to operate alongside pre-existing chart recorders, so this choice did not limit data availability in any way.

In addition to the hydrometric data collection undertaken by the RPBs and their predecessors, some additional records have been collected by other bodies, generally industrial concerns which need information regarding the flow behaviour of adjacent watercourses: the record for the River Irvine at the Glenfield & Kennedy Works in Kilmarnock (station 83802) is one such (recently transferred to operation by the Clyde RPB) and provides the longest flow record in Scotland. The product of the operation of all these gauging stations is a database providing data from all parts of Scotland although stations are much more closely spaced in the more heavily populated parts of the country than in remote areas and data availability in terms of record length shows a similar pattern.

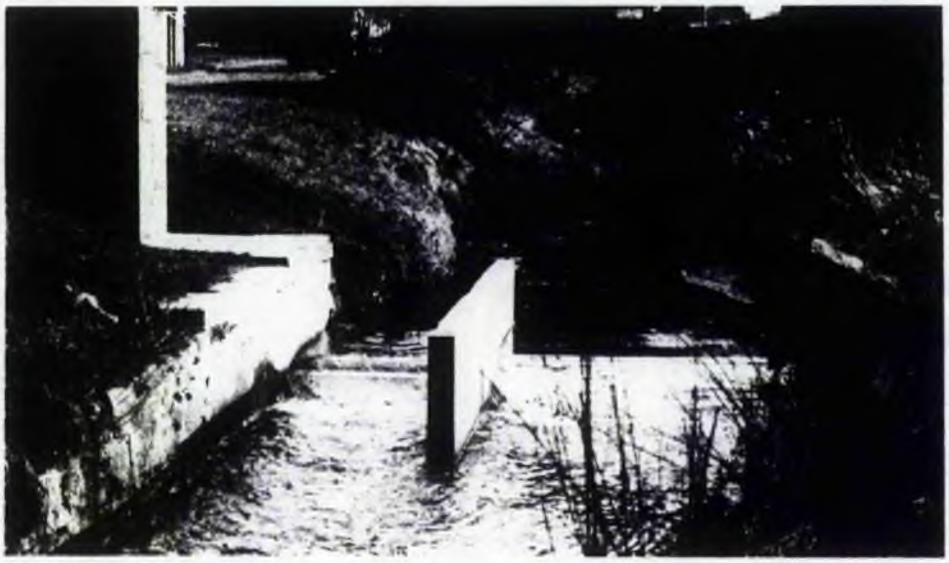


Plate 3.5 Twin-crest crump weir at station 19010 Braid Burn @ Liberton
The two crests are set at different heights to provide an effective hydraulic control at both low (left) and higher (right) stages, thus enabling an accurate stage-discharge calibration to be established for a wide range of flow conditions.

Plate 3.6 Broad-crested weir at station 19002 Almond @ Almond Weir
Vertical retaining walls ensure that flow is contained within the structure up to stages of 1.4 m, a level which has been exceeded only three times in 27 years of record.

3.3 Site selection

In planning the assembly of the database, it was recognised that time constraints would limit the number of chart records which could be read: it would not be possible to extract data from all available records. A number of factors were therefore taken into account in deciding which records would be used in the study.

Maps showing the locations of present and past gauging stations were consulted in order to identify stations which could be used to give a basic coverage of the whole of Scotland: it was a primary aim that all major drainage basins should be represented within the database. In conjunction with these maps, the length of record available at each of these stations was considered, including the length of previously collected POT data which would be available in computer disk files thus obviating the need to consult charts. Where a number of gauges could be used to provide data for an area, stations with long records and previously collected data were preferentially selected. Much of the data previously collected was a result of the preparatory work for the *Flood Studies Report* (NERC 1975) and had subsequently been updated to the end of 1982 by Acreman in the course of his PhD studies (Acreman 1985a).

Beyond the aim of ensuring that data from all major drainage basins were included in the data set, detail within individual basins was sought and again length of available record was taken into consideration. These additional stations were used to provide data from the larger tributaries of rivers and were selected such that significant gaps between stations already chosen might be eliminated wherever possible. It was difficult to specify rigid criteria to define such gaps, as data availability varies widely between regions of Scotland. In the area north and west of the Great Glen, gauging stations are sparse and most records from that large area are only quite short. Every effort was therefore made to incorporate all such available data in order to provide as great a density of data points as possible. In contrast, much of Lowland Scotland, such as the Clyde basin, is characterised by a relatively high density of gauging stations and consequently it was possible to select stations for which long POT records were already available.

In addition to the general aim of providing a good overall description of flooding behaviour, specific attention was focused on areas where it was felt that interesting seasonal phenomena existed. Hewson (1982a) shows maps of mean day of flood for the whole of the British Isles and notably low values are found in the Moray-

Nairn area (see Chapter 2) so it was felt important that sufficient data were collected to describe in good detail the seasonality of flooding in this area.

Also, it was deemed desirable that any long-term trends in seasonality should be detected, *ie* particular attention should be directed towards any non-stationarity which may be present within the data, and therefore it was again considered important to include long records within the data set. The length of record for all stations used is shown in Appendix A and the investigation of non-stationarity is described in Section 3.8.

Finally, it was recognised that data from certain gauging stations should be omitted from the study because of extreme human alteration to flow regimes. This point concerns the ability of a relatively empty storage reservoir to absorb the water of a flood peak so that the watercourse downstream might not experience a flood event which would have occurred if the dam were not present. This would have the effect of omitting summer floods from a record because of the normally low storage of reservoirs in summer, while allowing winter peaks to be transmitted downstream of a reservoir because of typically high storage levels and hence a lesser ability to absorb the volume of a flood wave. While it was felt that this problem primarily affected areas of Scotland with a high level of hydro-electric development, it was also recognised that public water supply reservoirs have similar effects on flow regimes. River purification board hydrologists were therefore consulted, and where the effects of dams were clearly manifested in the flow record, stations were excluded from the analysis. As a result, data from most of the gauging stations in the extensive Tay system (Scotland's largest river basin after the Tweed) were classed as unusable and several further stations in other parts of Scotland, especially the Highlands, were also excluded. Relatively high population pressure in the central lowland valley of Scotland is reflected in a large number of reservoirs for water supply purposes and this too caused notable omissions from the list of acceptable stations.

Taking all the above factors into consideration, a list of priority stations was produced to ensure a good basic description for the whole of Scotland and, following collection from all of these stations, as much data as possible was to be collected from the remaining stations within the time limit. Following identification of a possible seasonality anomaly around the Cheviot Hills at the eastern end of the

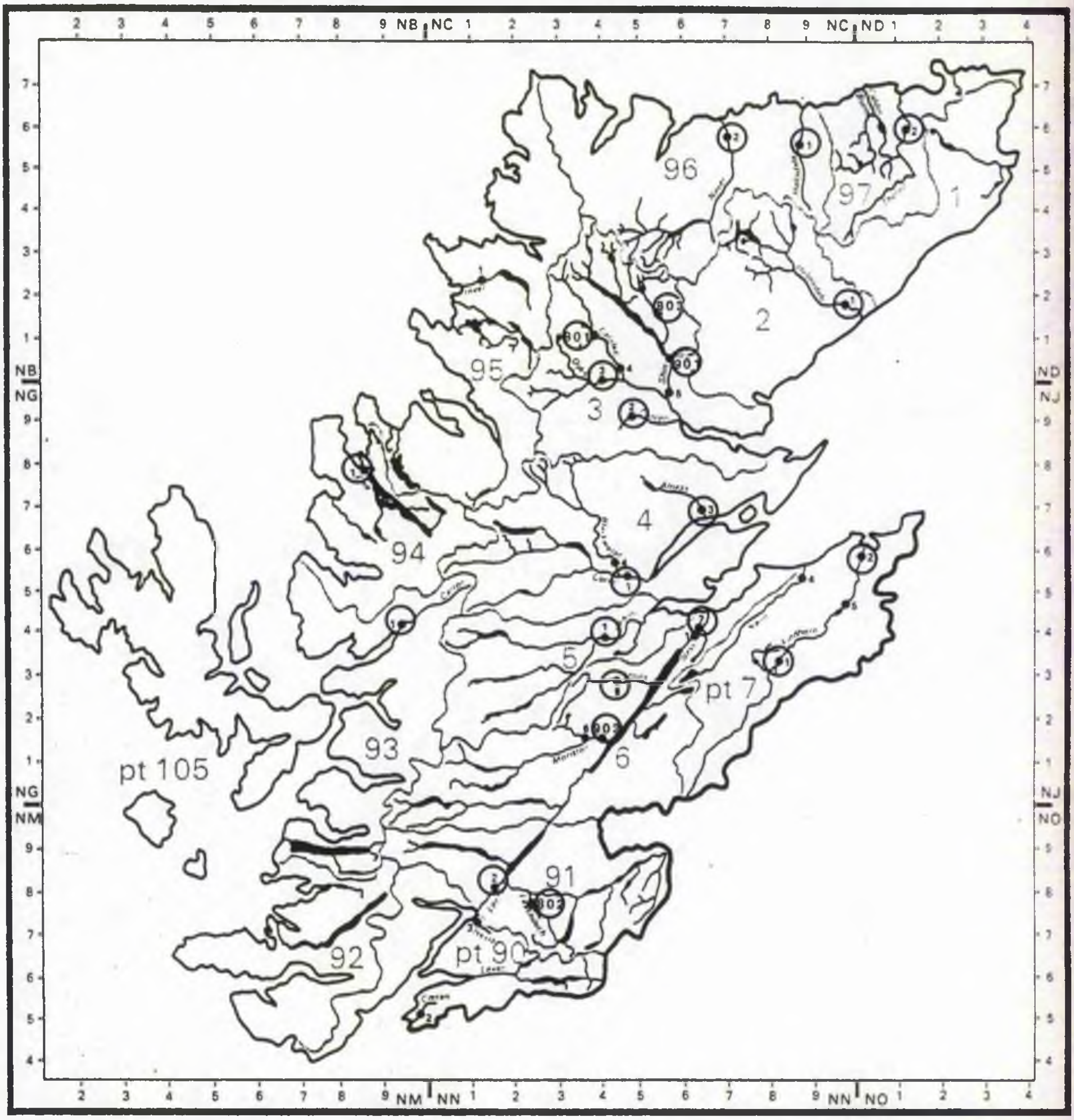
Anglo-Scottish border (Hewson 1982a (Figures 3 and 4)), it was also decided to collect data from gauging stations in Northumberland in order to provide a full description of seasonality in this area. The location of all gauging stations used in this study are shown in detail in Figures 3.3a-3.3e, with record lengths being shown in Figure 3.3f, and full details also being given in Appendix A.

3.4 Data extraction

Having identified the sites for which data were required, the availability of previously collected data for them was established. Much of the work of data collection was then to be in reading flood event information from chart records. This is a very laborious process, demanding the examination of all charts from a station in order to identify no more than about five peaks per year on average. Consultation of charts was only possible at River Purification Boards' offices and practical considerations would have severely limited the amount of time available for collecting data in this way. However, microfilm copies of charts had previously been made for most stations, either by the Institute of Hydrology or by the individual Boards themselves. Use of these microfilms enabled charts to be read at a relatively high speed and the data extracted from them could be entered directly onto a computer without the need to write data onto paper and then copy it to computer at a later stage. Furthermore, finance made available by the Institute of Hydrology enabled these microfilm records to be brought up to date with the help of the RPBs in making charts available for this purpose. This arrangement allowed data extraction to be done in the most efficient way possible.

The first stage in extracting data for a station was to establish a threshold discharge to be used. In the case of a station for which records had already been collected, this value had already been set. Where a new station was to be used, the best method of establishing a threshold was simply to scan through one year's microfilm in order to identify a suitable threshold value which could be used to collect at least ten peaks per annum for the first few years of record, and with further reading of the record, the threshold could be adjusted upwards to prevent the collection of too many data while ensuring that the requirement of a long-term average of five peaks per year was still met. Section 3.7 below discusses an adjustment of thresholds, but at the stage of data extraction from microfilm, achievement of the average of

Figure 3.3a
Gauging station locations: Highland RPB area

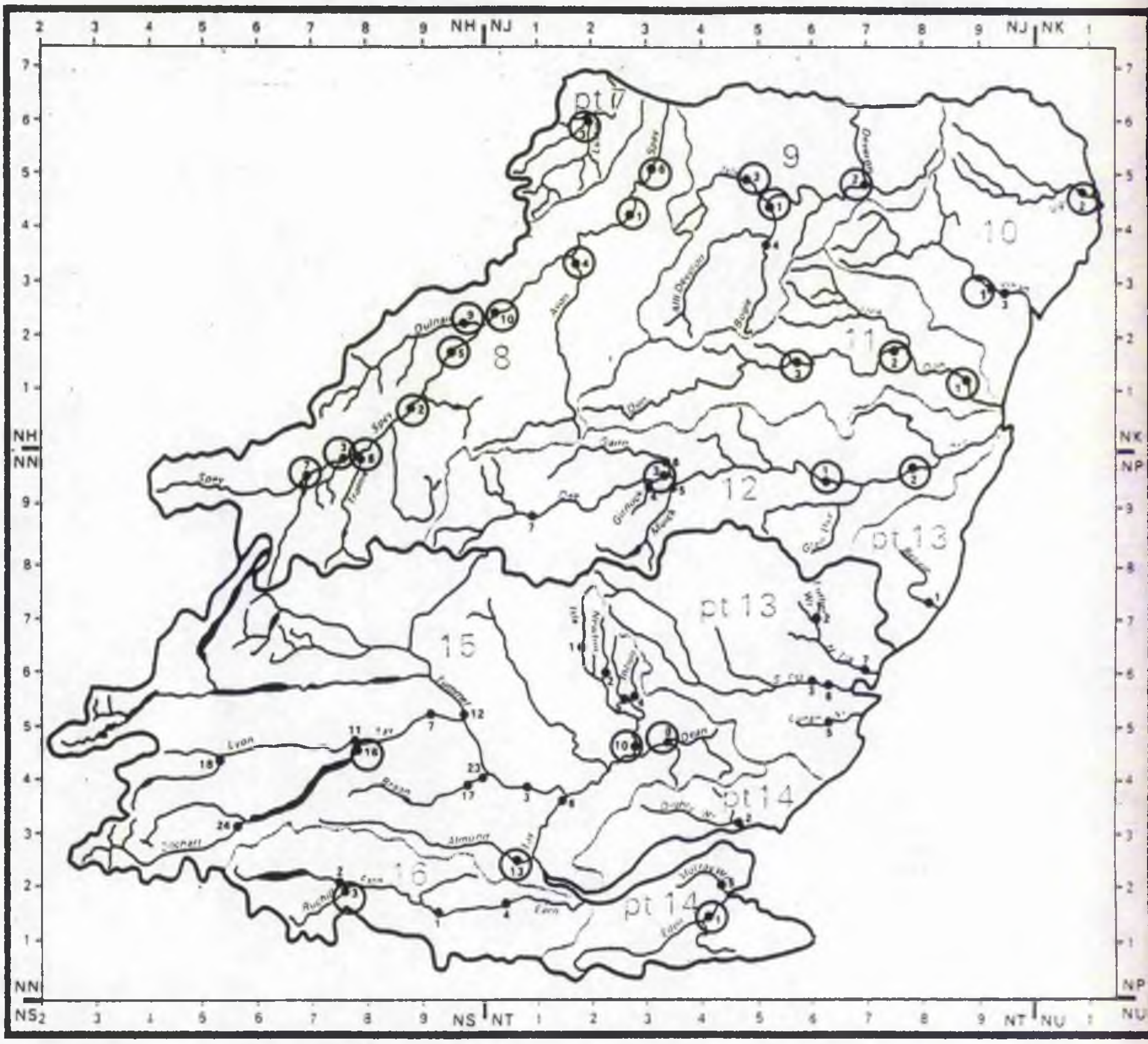


Based on IH/BGS (1988)

—	River Purification Board boundary
---	Hydrometric area boundary
6	Hydrometric area number
•2	Gauging station
(•2)	Gauging station used in this study (see Appendix A)

5-digit gauging station numbers are produced by using the hydrometric area number as the first two digits, followed by the station number shown as the following three digits.

Figure 3.3b
Gauging station locations: North-East and Tay RPB areas

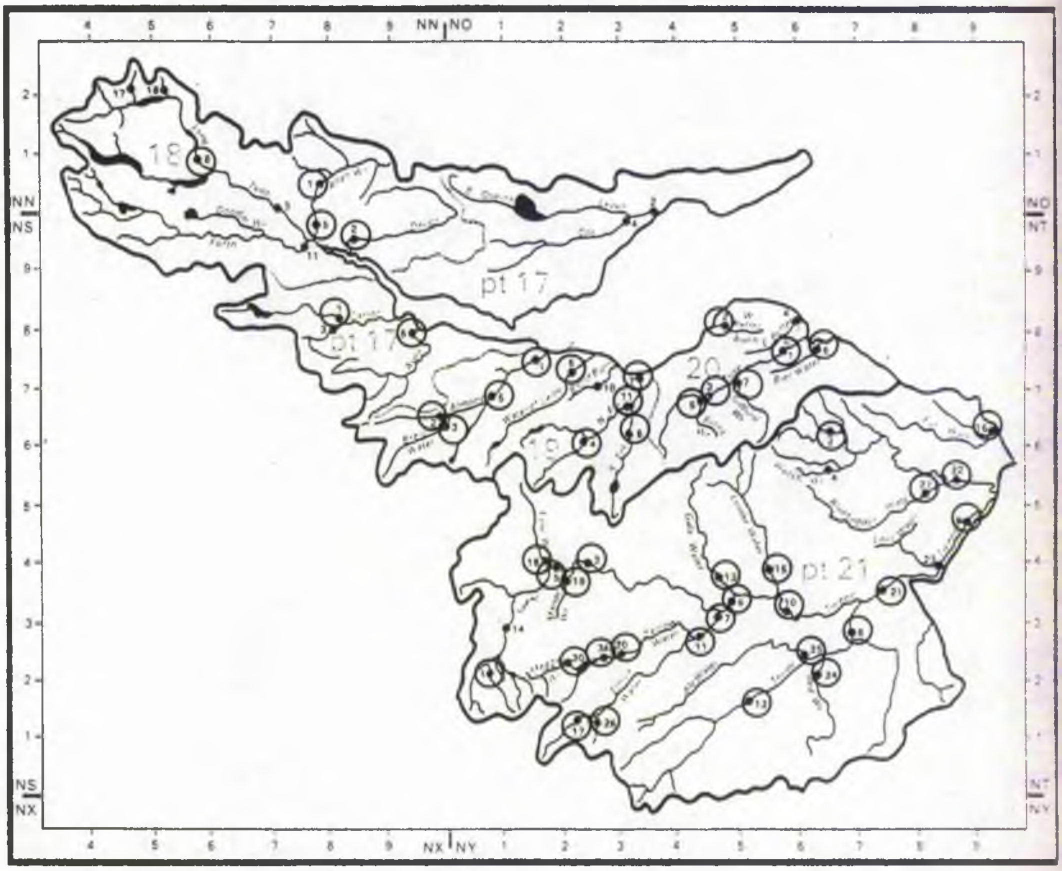


—	River Purification Board boundary
- -	Hydrometric area boundary
12	Hydrometric area number
•2	Gauging station
(•2)	Gauging station used in this study (see Appendix A)

5-digit gauging station numbers are produced by using the hydrometric area number as the first two digits, followed by the station number shown as the following three digits.

Based on IH/BGS (1988)

Figure 3.3c
Gauging station locations: Forth and Tweed RPB areas

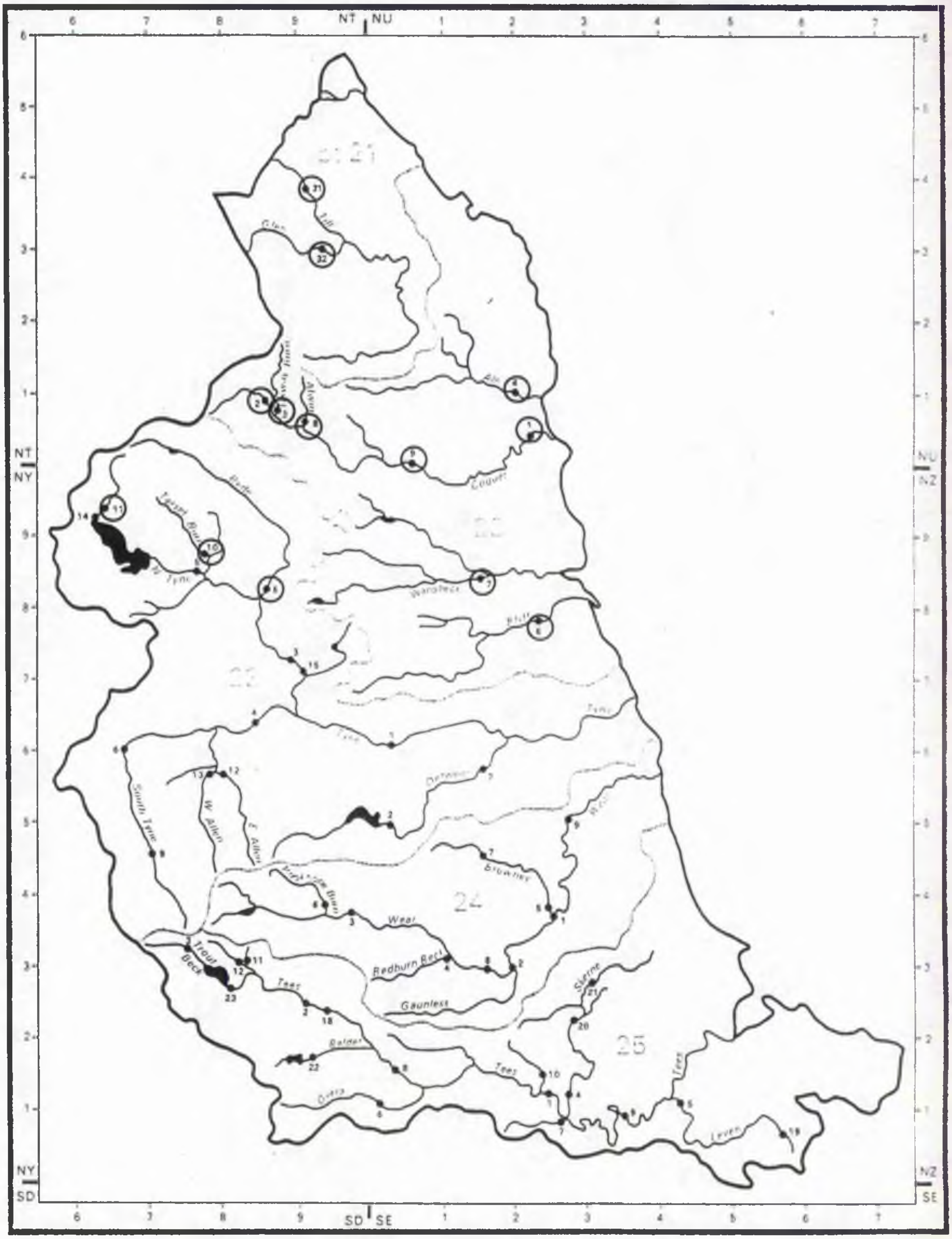


Based on IH/BGS (1988)

——	River Purification Board boundary
	Hydrometric area boundary
21	Hydrometric area number
•2	Gauging station
(•2)	Gauging station used in this study (see Appendix A)

5-digit gauging station numbers are produced by using the hydrometric area number as the first two digits, followed by the station number shown as the following three digits.

Figure 3.3d
Gauging station locations: National Rivers Authority (Northumbria) area

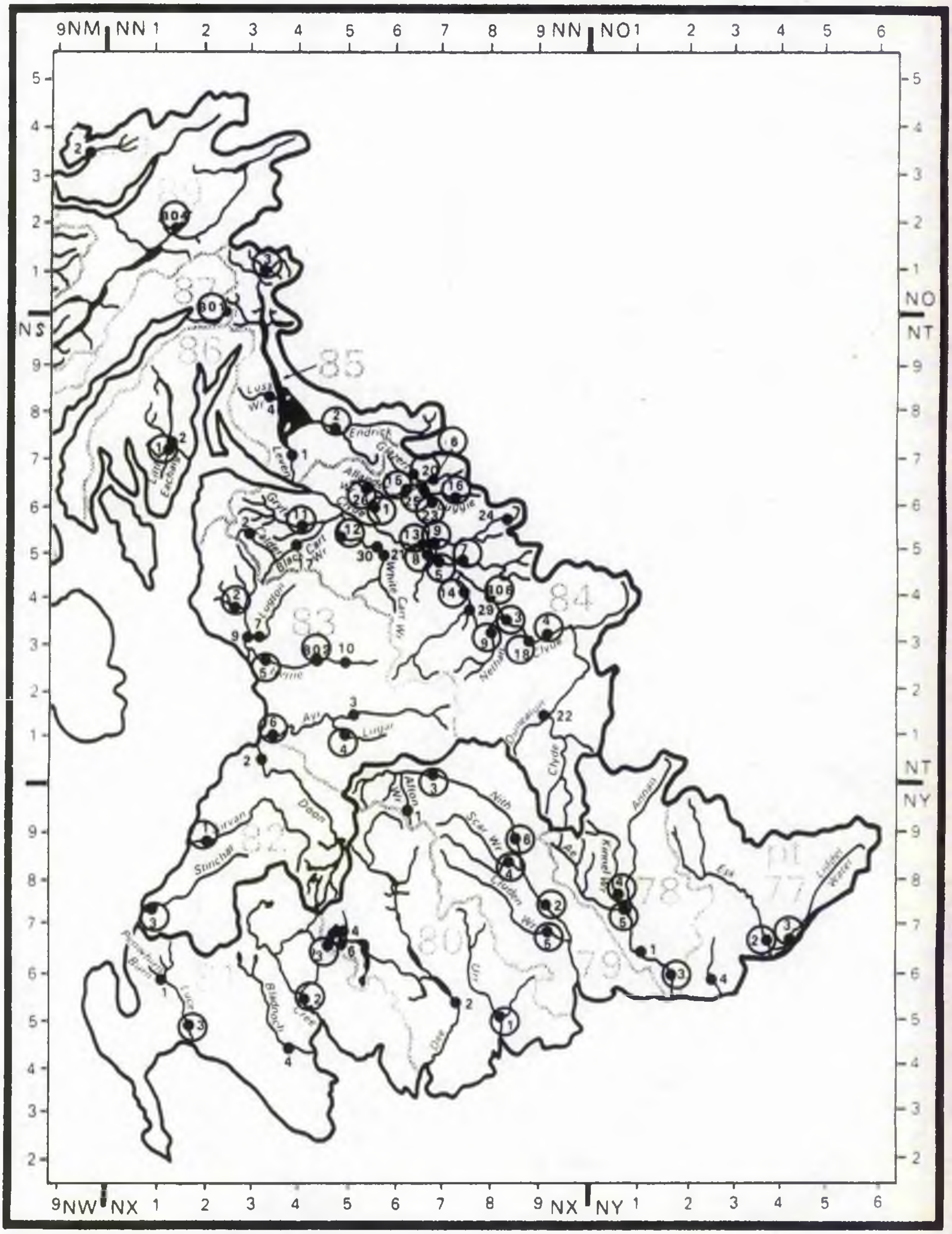


Based on IH/BGS (1988)

—	NRA (Northumbria) boundary
	Hydrometric area boundary
22	Hydrometric area number
•2	Gauging station
(•2)	Gauging station used in this study (see Appendix A)

5-digit gauging station numbers are produced by using the hydrometric area number as the first two digits, followed by the station number shown as the following three digits.

Figure 3.3e
Gauging station locations: Solway and Clyde RPB areas

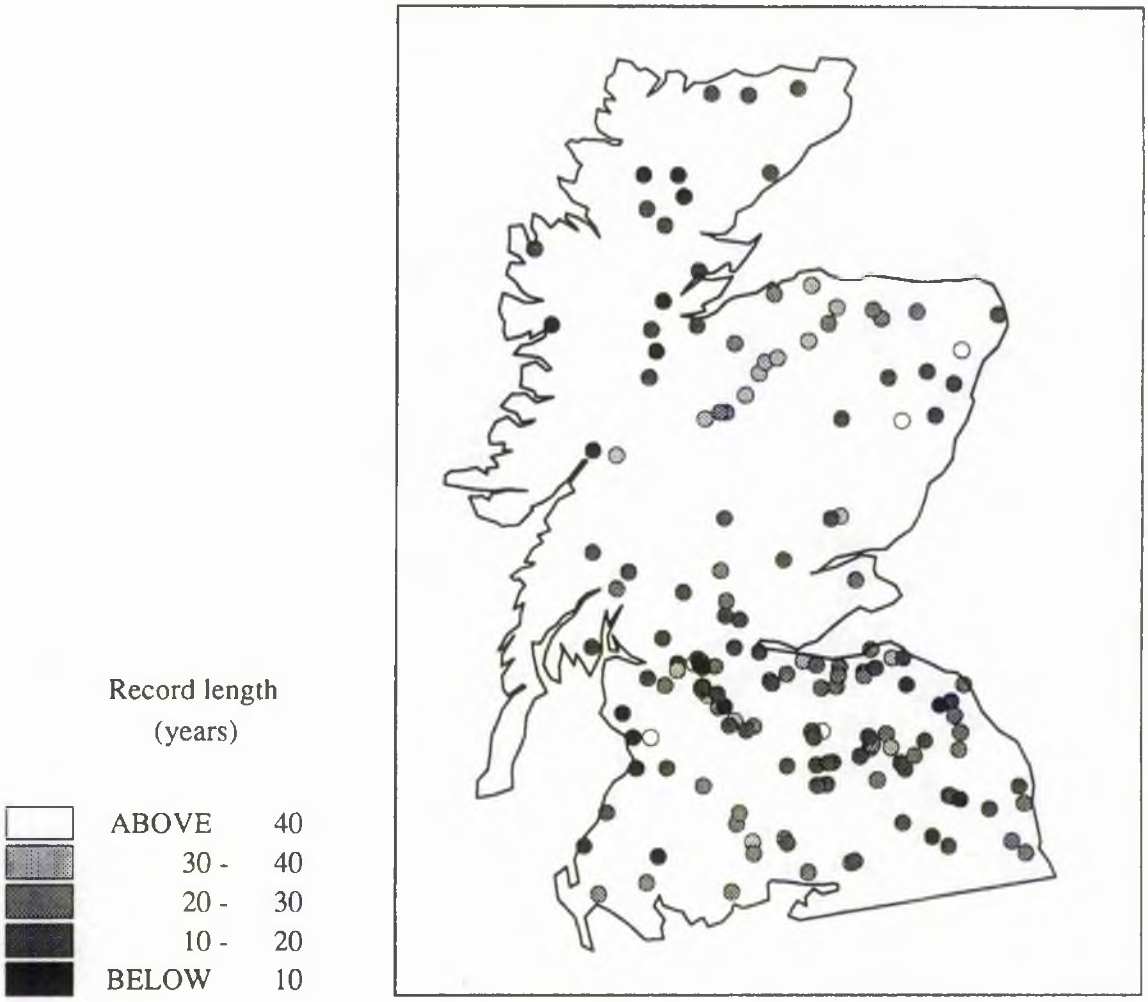


▬	River Purification Board boundary
	Hydrometric area boundary
84	Hydrometric area number
•2	Gauging station
(•2)	Gauging station used in this study (see Appendix A)

Based on IH/BGS (1988)

5-digit gauging station numbers are produced by using the hydrometric area number as the first two digits, followed by the station number shown as the following three digits.

Figure 3.3f
Length of gauging station records collected



five peaks per year established in the *Flood Studies Report* (NERC 1975 IV.2.1.2) was sought so that data from new stations would be compatible with the POT series already collected.

Discharge thresholds having been established, the data extraction process demanded the relatively simple task of recording the date of occurrence ('water days' starting at 0900 hrs were used) and peak river level for all events equal to or greater than the chosen threshold (and conversion into stage terms). However, interdependence between adjacent peaks introduced some confusion into this process as it was recognised that if a number of peaks occurred in close succession, it would be unreasonable to regard each one as an individual event in subsequent analyses when the rising or falling limb of one flood hydrograph could be seen to contribute to the magnitude of another. Procedures for eliminating such interdependence have been developed through the experience and expertise of the Institute of Hydrology and as these procedures were used in producing the previously collected data, it seemed only sensible to use the same methods in the present data extraction process. The rules used to define independence between peaks state that two requirements must be met:

1. discharge must fall by at least one-third of a peak value before rising to another, and

2. the time between successive peaks must be at least three times the mean lag time of the river.

If both of these rules are not met, then only the largest peak of a group is recorded as an independent one (see Figure 3.4). In order to operate this system, lag times for at least the first five floods in each record were noted for subsequent reference.

Occasionally, chart traces would be damaged or even unreadable on microfilm; in such cases, the charts were often annotated and this enabled many ambiguities to be clarified. However, some charts were completely unintelligible and in such cases, peak values from other recorders or estimates were made available by RPB staff. Annotation of charts was especially useful when charts had been set high or low relative to their correct positions and in this way inaccuracies in level readings were avoided.

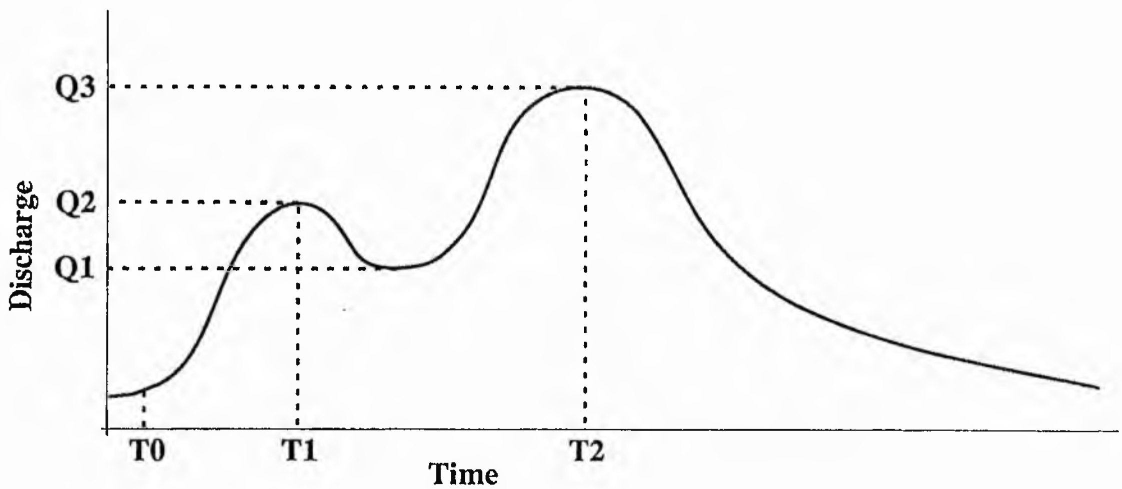


Figure 3.4: Independence rules
If either a) time T2 - T1 < 3 times mean time to peak (e.g. T1 - T0), or
b) Q1 > Q2 x 2/3,
then only the larger of the two peaks will be considered independent of the other.

All microfilm records were checked for continuity: the end date for each chart was checked against the start date of the next chart and any gaps in the record noted. If more than one whole week in any year was found to be missing, the whole year's data would be omitted from the record in order to avoid the possibility of altering the seasonality of the data through omitting peaks which may have occurred during the missing period. However, gaps were discounted if records from other stations on the river in question, and those in the surrounding area, suggested that no flood had occurred during the period of the gap. For the same reason, each record used was a whole number of years in length rather than including a part-year.

Data for the few stations in Northumberland were obtained directly from the National Rivers Authority (Northumbria Region) as POT series and were understood to be free of gaps and had been collected using IH independence rules. The data were therefore in a ready to use form and required none of the above checks, although they were included in the final data checking process described below.

The concluding stage of the extraction process was to check the computer files created for each station by running an Institute of Hydrology data checking program. This was useful in finding date errors by assuming that all dates in each file would be in chronological order but also detected inconsistencies with summary information and a variety of other mainly typographical errors in the files. Output was used to correct mistakes and indeed proved useful in identifying errors in the previously collected data. While it would be dangerously unrealistic to claim that this checking program resulted in error-free data being produced, it is felt that most errors in the data set were eliminated. Use of Institute of Hydrology standard procedures throughout this exercise avoided any internal inconsistencies within the data set, but more importantly enabled high data quality to be achieved: threshold setting, independence assessment, gap checking and error detection all used accepted IH methods developed over many years and with the benefit of considerable expertise. Consequently, the data would also be compatible with England and Wales data in any future comparative studies. Full details of the records collated at the end of this process are tabulated in Appendix A.

3.5 Stage - discharge conversion

Reference has been made on a number of occasions in the preceding sections to the relationships used in converting stage measurements to discharge values This section aims to describe the methods used and problems encountered in producing accurate rating relationships.

It is common practice amongst gauging authorities to use a rating equation to describe the relationship between stage and discharge, the equation normally being of the form

$$Q = a\,(h + c)^b$$

where:

Q = discharge (m^3s^{-1})
h = stage (m)
a, b and c are constants

Such an equation is always accompanied by a stage range for its applicability, and ideally, should only be used within that range. If the stage-discharge relationship cannot be described adequately by one equation within the desired limits, two or more equations may be used, each with its own stage range (*eg* Figure 3.5a). Gauging authorities regularly check the accuracy of rating equations and make revisions if necessary so that accuracy of flow values is maintained. However, most changes in rating are necessary to take account only of relatively small changes in channel geometry while the stage - discharge relationship at high flows remains relatively unchanged. Therefore in order to avoid unnecessary application of rating changes to the POT stage data, specially derived flood rating equations (*ie* applicable at stage/discharge values equal to or above threshold values) were preferred in this study and changes in rating were needed only when major changes to the rating relationship had occurred. As an example, Figure 3.5b shows a number of equations used at station 89804 River Falloch @ Glen Falloch by the Clyde RPB along with a flood rating. The flood rating is valid only above the threshold discharge of 104 m^3s^{-1} and it is noticeable that at flow values greater than this, the flood rating cuts across the other rating curves. However, the curve has been plotted using only high discharge measurements and it is felt that it can more accurately reflect the stage - discharge relationship for high values than can the other lines which must also describe the relationship at lower flows. Provided that

Figure 3.5a: 2-part stage-discharge rating for station 84015 Kelvin @ Dryfield

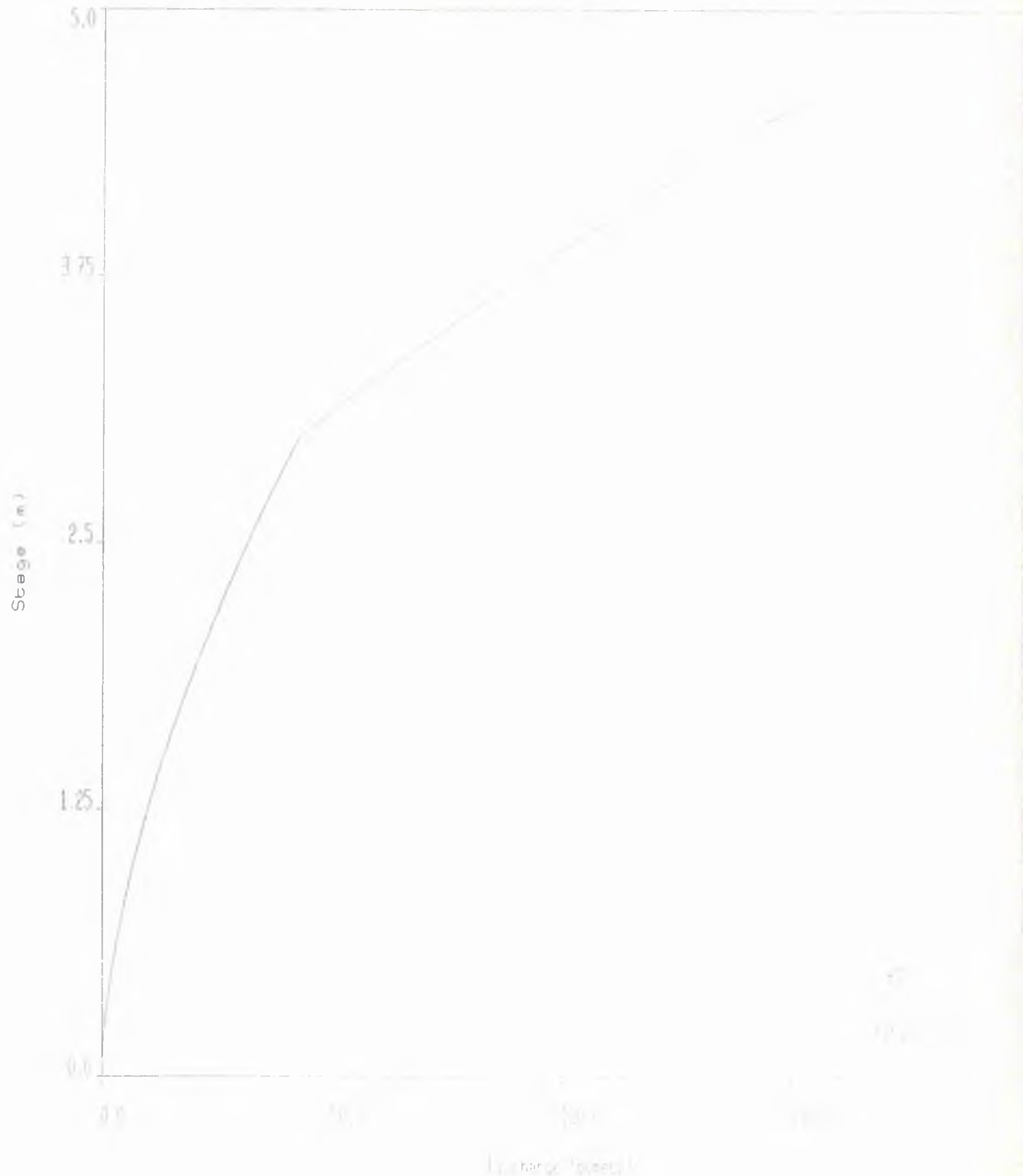
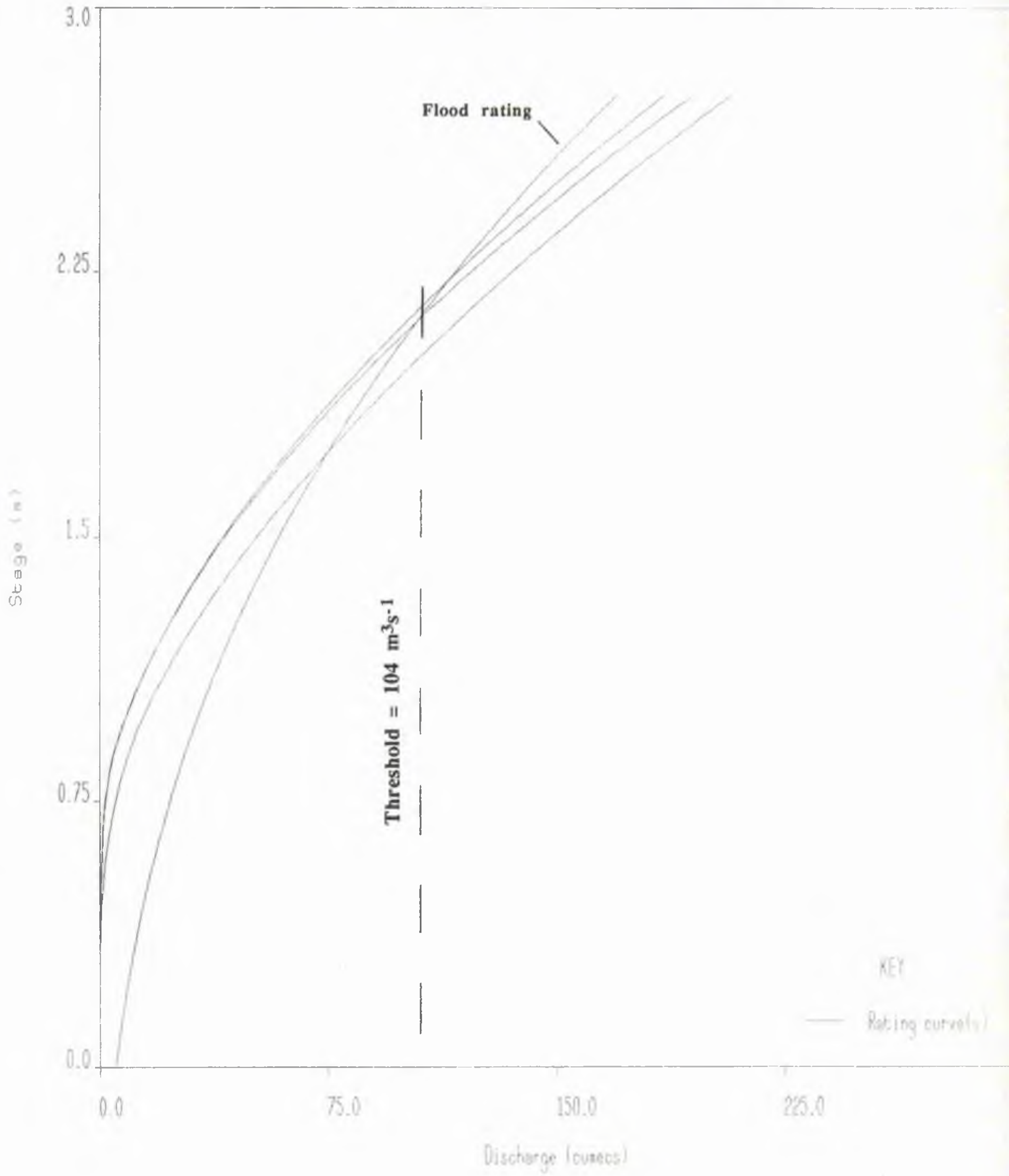


Figure 3.5b: Full-range ratings and flood rating for station 85003 Falloch @ Glen Falloch



significant changes in rating were always applied to the data, this method avoided internal inconsistencies in the discharge data which might otherwise have resulted from the application of all rating changes made by gauging authorities.

A set of such flood ratings produced for most Scottish gauging stations by M C Acreman was made available through the Institute of Hydrology, and these were used as the basis of stage - discharge conversion for most gauging stations in this study. The ratings had been produced in the early 1980s and it was therefore necessary to check on their continued validity for data which extended until the end of 1989. To this end, all available stage/discharge measurements and rating equations were collected from the RPBs and used to assess the suitability of continued use of these equations. Checks were also made on the applicability of the equations used in the early 1980s where data were available. Where it was found that changes in ratings had taken place, the data supplied by the RPBs were used to derive new flood ratings, this being done with the use of HYDATA, a multi-purpose hydrological database program produced at the Institute of Hydrology.

Single equation ratings could normally be fitted to data for stations where flows do not exceed bank-full stage but, at some stations, out-of-bank flooding occurs and the rating curve undergoes a major change such that the fitting of a single flood rating becomes more difficult (see Figure 3.5a). Furthermore, accurate measurement of discharge at high levels is difficult, both in practical terms and because opportunities for making such measurements are rare. The high part of the equation must therefore be fitted around discharge estimates made by gauging authorities. Because of the scarcity of, and uncertainties surrounding, such information, out of bank ratings proved to be the most contentious part of the data collection process. It is unfortunate that it was with the largest flow values that inaccuracies in stage - discharge had the greatest effects since a small percentage error in flow estimation leads to a large absolute error when applied to a high flow value. For this reason, a programme of data validation was embarked upon.

3.6 Data validation

This stage in the data collection process was introduced in order to check for the effects of any significant errors in the rating equations used. While it was felt likely that the greatest errors would affect the highest flows through inappropriate extrapolation of ratings derived from lower stage - discharge measurements, it was decided that at each station, sample checks would be made for all flows above the threshold value. A database of POT series for all primary gauging stations at the Institute of Hydrology was used as a source of flood peak values supplied by gauging authorities and checked by the Institute of Hydrology or its predecessors, against which flow values produced by application of flood ratings adopted in this study could be checked.

The database extends only to the early 1980s (although it is more up to date for gauging stations in England and Wales) but within this constraint, the highest value on record, one just above the threshold and an intermediate value were always used for comparison. Where records on the IH database exceeded ten years in length, care was taken to ensure that good comparison between the two data sets obtained for their entire common period by making additional checks according to the length of record. Where differences of discharge value in excess of twenty per cent were found between the two data sources, this was taken as an indication that a rating error had been applied to one of the records. RPBs were duly consulted in order to establish the reasons for such disparities and the database amended accordingly. Following completion of microfilm data extraction (and prior to this validation exercise), copies of the data extracted for each RPB area were forwarded to the respective Boards and feedback from some of them, identifying certain errors, was also useful in improving the quality of the data still further. The lack of opportunity to compare mid- to late 1980s data with an alternative database is not seen as problematic: checks for rating errors were made for all stations using earlier data, and out of bank ratings are only likely to change in most unusual circumstances - most probably as a result of human interference - and no RPB reports any such changes other than more extensive changes to channel geometry where it has been necessary to re-site or abandon a gauge.

As a result of this validation exercise, it was found that at some stations the rating equations which had been thought to be applicable throughout the entire range of flood flows were as much as 45% in error. At most stations, after comparison with the IH database, it was felt that the flood ratings used were of acceptable accuracy as disagreements with the IH data were only minor but ratings were revised for a total of 56 gauging stations. This procedure must be seen as having made a valuable contribution to improving the quality of the database.

3.7 Threshold adjustment

Upon completion of the data collection process, it became apparent that the threshold discharge values used for the POT series produced markedly more floods per year on average at some stations than at others. At one extreme, the 25 years data extracted for station 18001 Allan Water @ Kinbuck contained an average of only 3.12 floods per year; at the other, a 20 year record for 84016 Luggie Water @ Condorrat produced an average of 9.85 floods per year and between these two poles there existed a continuum of average frequencies. In the interests of producing an objective description of the seasonality of flooding across the study area, it seemed undesirable that such variation should exist since a low threshold would lead to the inclusion of relatively small floods in the data set, *ie* floods which may be produced under different conditions to those causing larger events and which may also have different seasonal characteristics. It was therefore decided to take steps to reduce these variations, in spite of the inevitable loss of data which would result.

In order to make records comparable, it was decided that each should be standardised to the same average number of events per year. This would involve the elimination of smaller peaks from flood series by threshold raising until only the required number of peaks remained in each record. Adjusting thresholds in this way while retaining all stations in the data set would require the new thresholds to be set at the frequency of the station with the lowest average number of peaks per year. However, this would result in a drastic reduction in the number of peaks remaining, so instead it was decided to remove from the database those stations with the very lowest average flood frequencies and then set the threshold as the minimum annual average frequency found in the remainder. In doing this, it was recognised that flood frequencies vary between years and that the frequency used for threshold standardisation must therefore be made specific to a given period. The period 1979-88 was specified for this purpose as the ten years found at most stations. A longer period would have been desirable but since such a requirement could only have been met by fewer stations, a single decade was reluctantly accepted. The frequency required for threshold adjustment was set at 45 peaks over the 1979-88 period as this offered the maximum number of peaks remaining above revised thresholds while losing only 13 records and with these only a limited amount of spatial detail since just one (10001 Ythan @ Ardlethen) lay more than 15 km from another station able to satisfy the new threshold requirement.

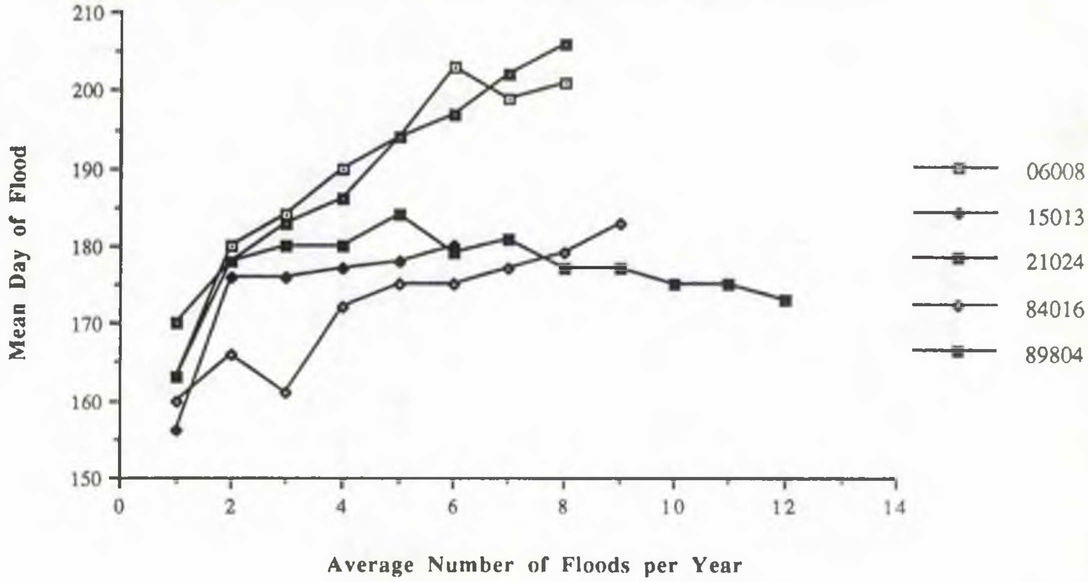
At stations where a full record did not exist for the period 1979 - 88, neighbouring stations whose thresholds had been successfully adjusted to include 45 events for that period were used to indicate the number of floods which should be found in the record over that period common to both stations. If more than one neighbouring station was suitable for use on the basis of proximity to the station in question, then an average number of floods could be found over a common period from all the neighbouring records. However use of additional neighbours often resulted in the use of much more limited common periods and, as it was felt important not to use data from too distant stations, it was decided to use no more than two neighbouring stations in determining threshold values for stations without a complete 1979 - 88 record. It is felt that selection of this threshold value enabled a good degree of detail to be maintained for individual records without losing significant spatial resolution.

It must be acknowledged that the method used for setting thresholds is not a perfect one in that the ten year period used may have been more of a flood-rich decade in one region than in another, but over a period of such length, it seems reasonable to state that these differences will not detract significantly from the positive value of standardising thresholds as described above. Figure 3.6 shows the results of a sensitivity test conducted for five gauging stations in different parts of Scotland, whereby changes in mean day of flood for a record (this concept is described fully in Chapter 4, see also Glossary) due to adjustment of threshold values are shown. It is suggested that reduction of the range of average annual flood frequencies has led to an acceptably small effect of frequency on seasonalities.

3.8 Preliminary testing of data

The final phase of the data collection process was to conduct a basic examination of the data collected in order to check for possible unwanted influences on its seasonal characteristics. In addition to the effect of threshold value on seasonality discussed

Figure 3.6
Variation of mean day of flood with discharge threshold



Mean day of flood shown as days after 31 May

Station details:
06008 Enrick @ Mill of Tore
15013 Almond @ Almondbank
21024 Jed Water @ Jedburgh
84016 Luggie Water @ Condorrat
89804 Strae @ Duiletter

in the previous section, the possible effects of non-stationarity were considered to be important. Because of acknowledged long-term variations in flood frequency at any site, it also seemed possible that long-term changes in seasonality might be found in flood records and it was considered important to examine any such changes.

If there are long-term variations in seasonality present within the records of individual gauging stations, analysis will not be able to proceed using the assumption that the data collected are of general applicability in description of seasonality at a site, but rather are only specific to one particular period of time. Following from this, comparison of seasonal characteristics between records collected over different periods would be invalid as records would not be compatible with each other. It is therefore important to assess whether any non-stationarity is present within the data.

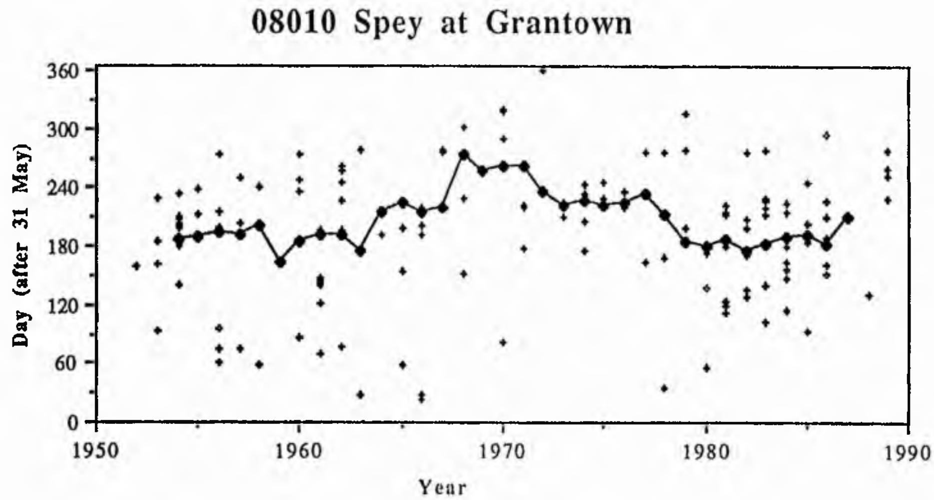
It is widely accepted in all flood frequency work that there is a year-to-year variation in the occurrence of floods and this may contribute to a year-to-year variation in the seasonality of flooding. Variations in seasonality may also occur irrespective of changes in annual flood frequency. To examine whether such changes are present, eleven long-record gauging stations from around Scotland were chosen, and for each record all flood events were plotted on a graph showing year and season of occurrence (Figure 3.7). A five-year running mean day of flood value is plotted on each graph to show the variation in overall seasonality with time. Typically the mean day of flood values, after smoothing by use of the five-year mean, had a range of about 100 days, *ie* the mean time of flood occurrence within the year varied by about a quarter of a year. The records do not show long periods with steady mean day of flood values but instead show considerable variation from one year to the next, even after smoothing with a five-year mean. Despite the irregular nature of the values, such annual variation must affect any overall characterisation of the seasonality of flooding within a record.

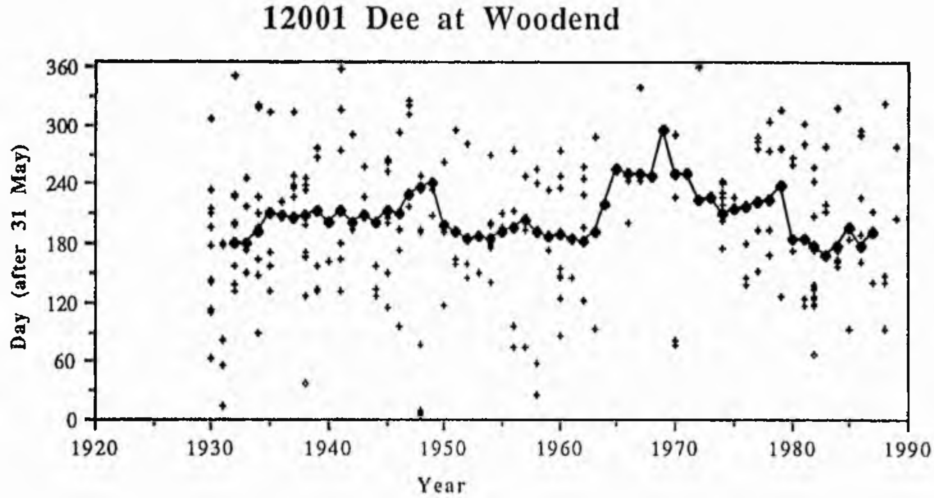
Figure 3.8a shows, for four selected stations, the number of events in each five year period alongside the five year mean day of flood values, suggesting at least for the two east coast stations, 08010 and 12001, that an inverse relationship may exist between the two variables although the data for the two west coast stations, 83802 and 91802, show this much less clearly: differences in the relationships between these variables may exist between east and west coast areas. Figure 3.8b allows closer examination of these relationships by showing the variation of mean day of

Figure 3.7

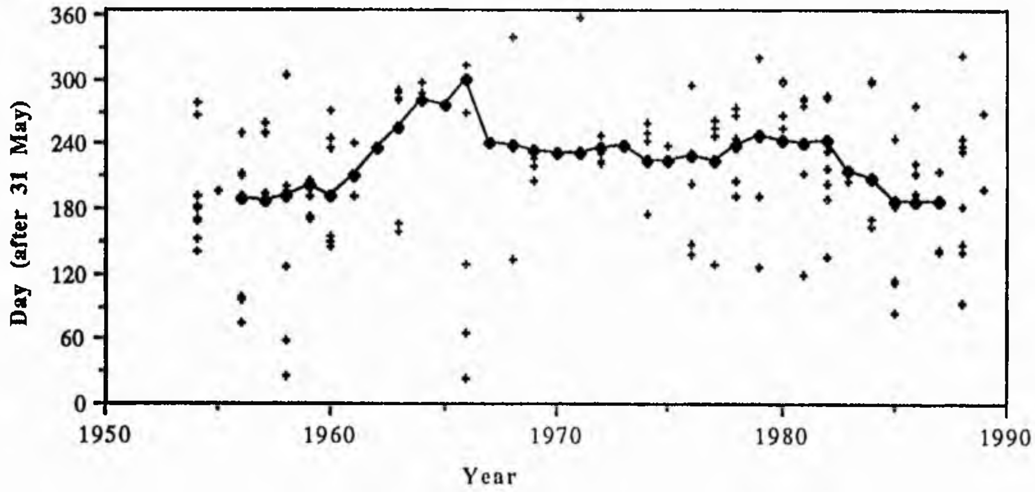
Graphs to show season and year of occurrence for all floods above revised thresholds at eleven long-record gauging stations across Scotland; solid line shows 5-year running mean.

Graphs enable detection of any long-term shifts in seasonality.

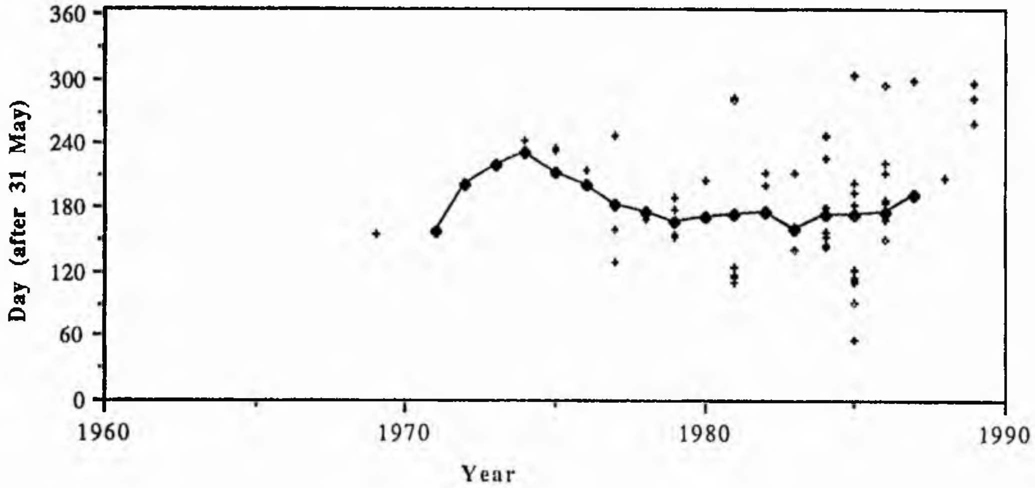




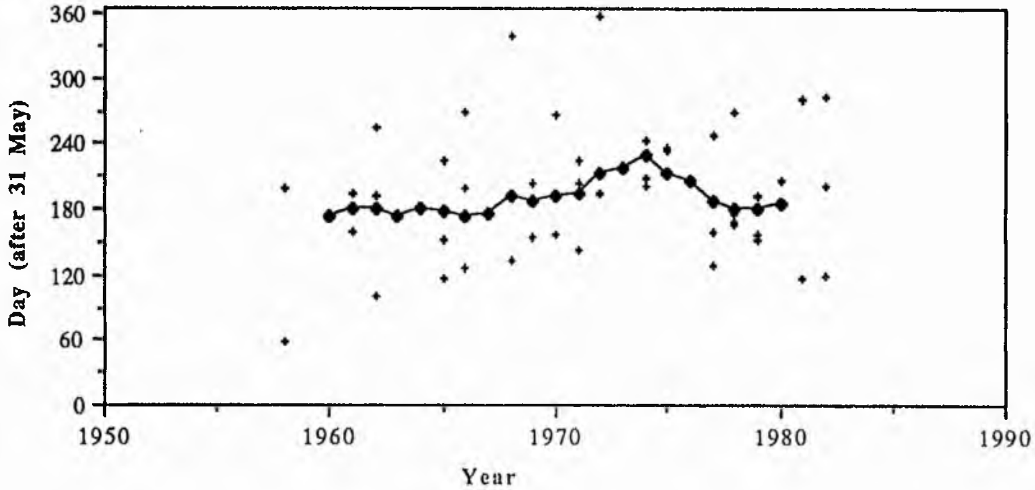
15008 Dean Water at Cookston



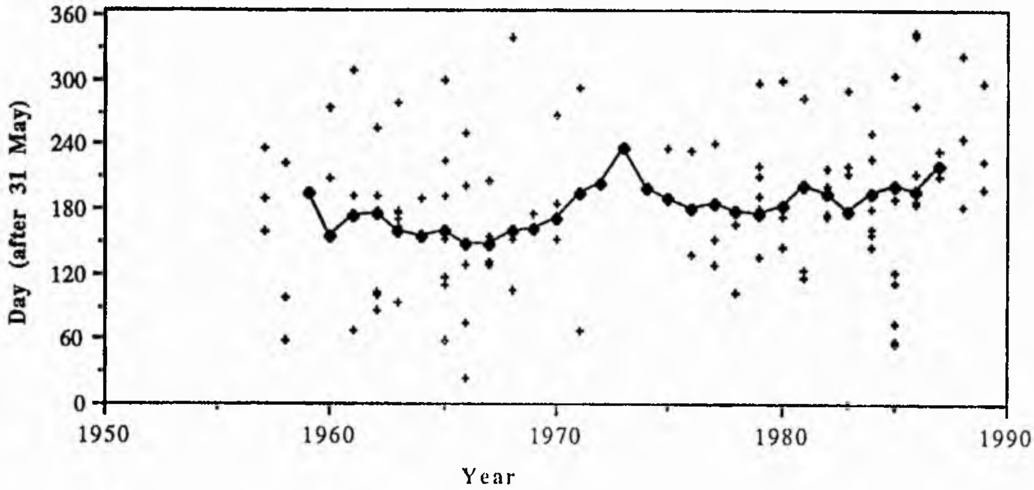
17001 Carron at Headswood



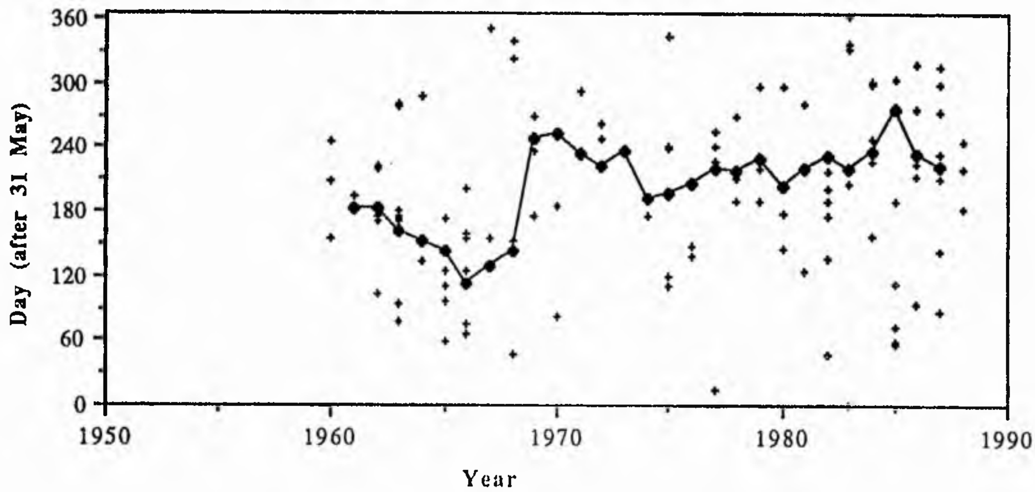
18001 Allan Water at Kinbuck



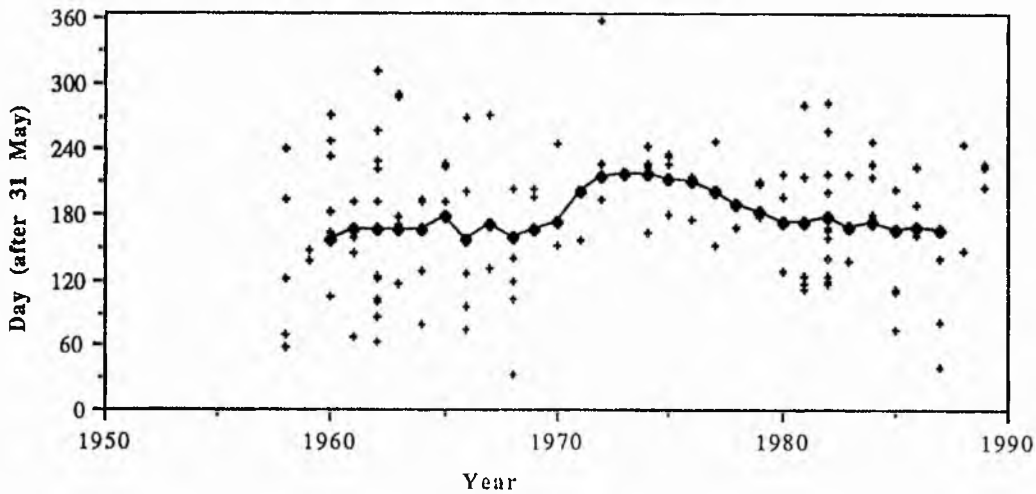
19001 Almond at Craigiehall



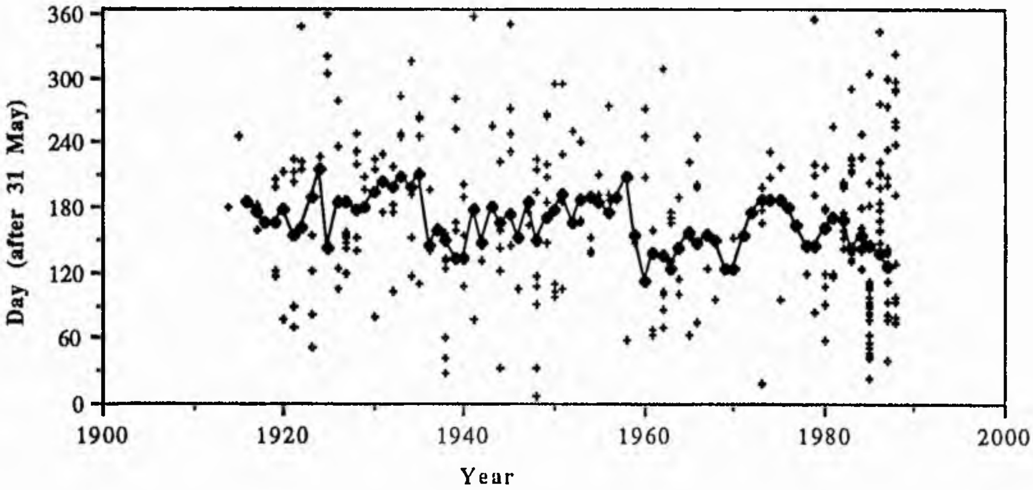
20001 Tyne at East Linton



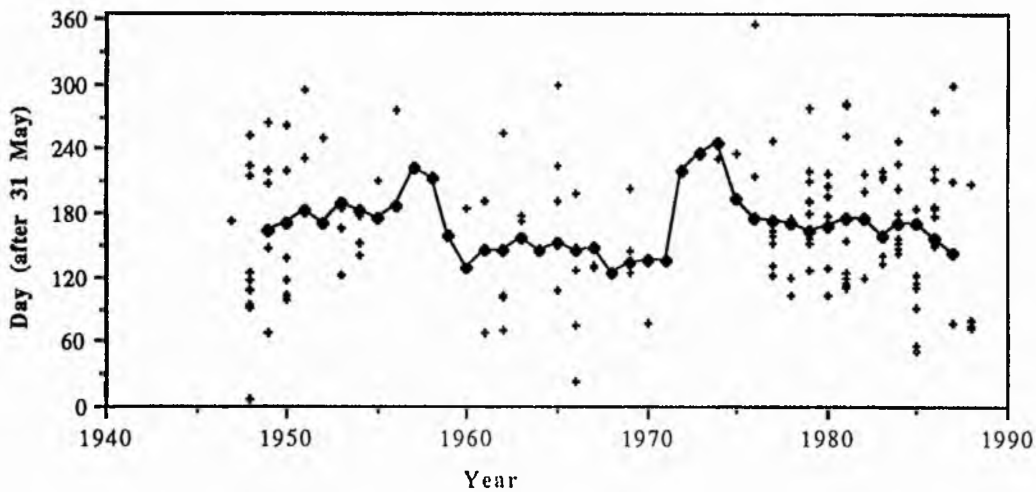
79002 Nith at Friar's Carse



83802 Irvine at Glenfield (Kilmarnock)



84015 Kelvin at Dryfield



91502 Allt Leachdach at Intake

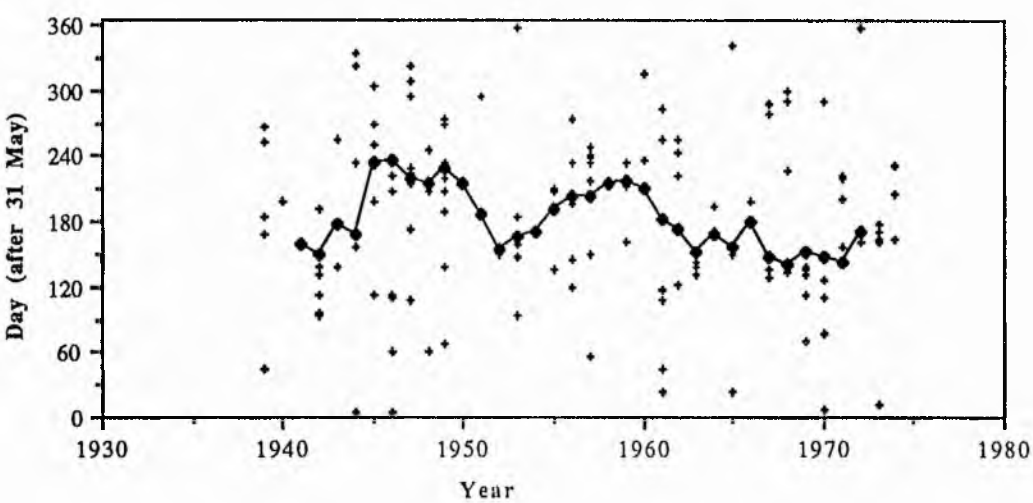


Figure 3.8a
Variation with time of five-year running means of flood frequency and mean day of flood for four Scottish gauging stations

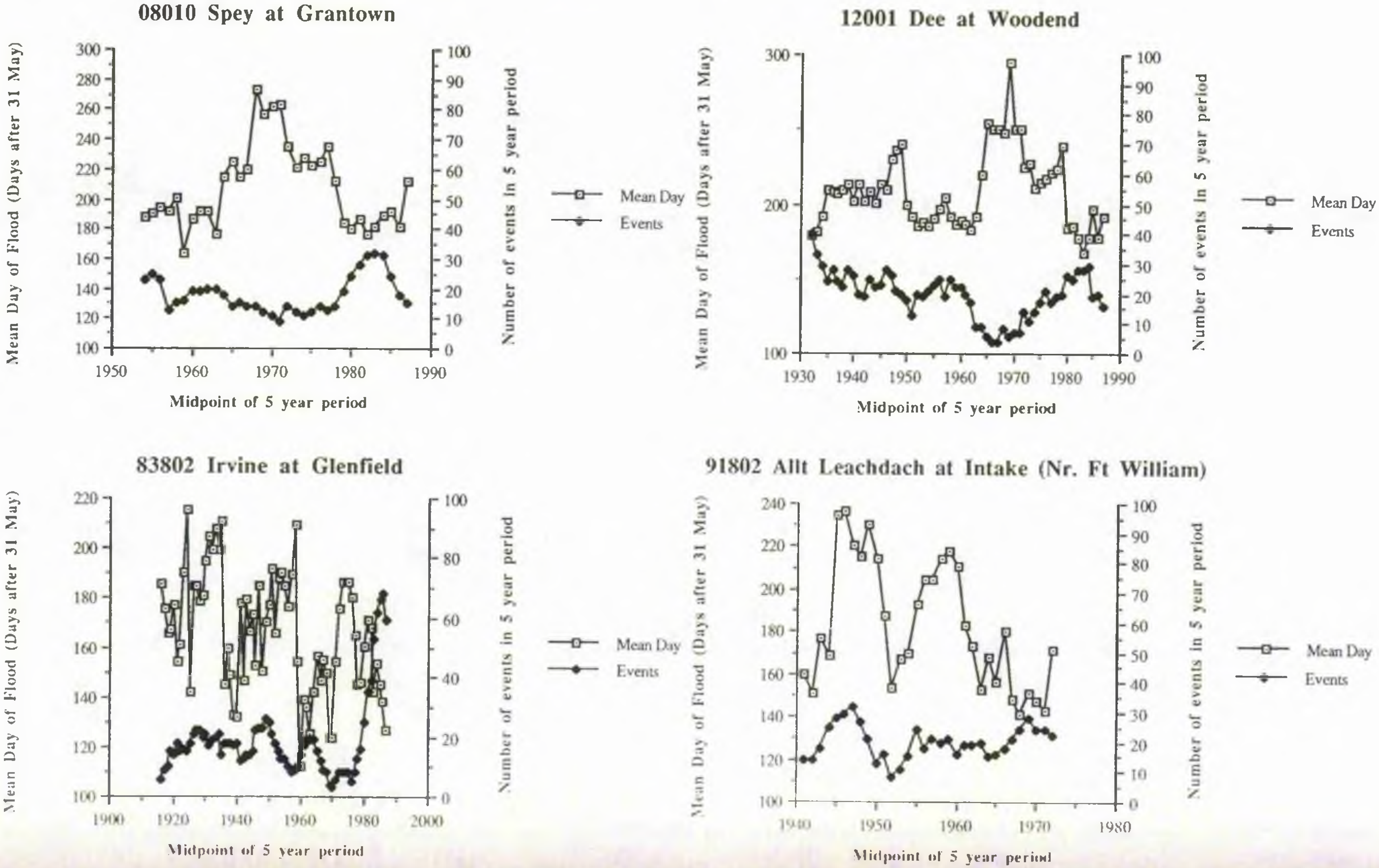
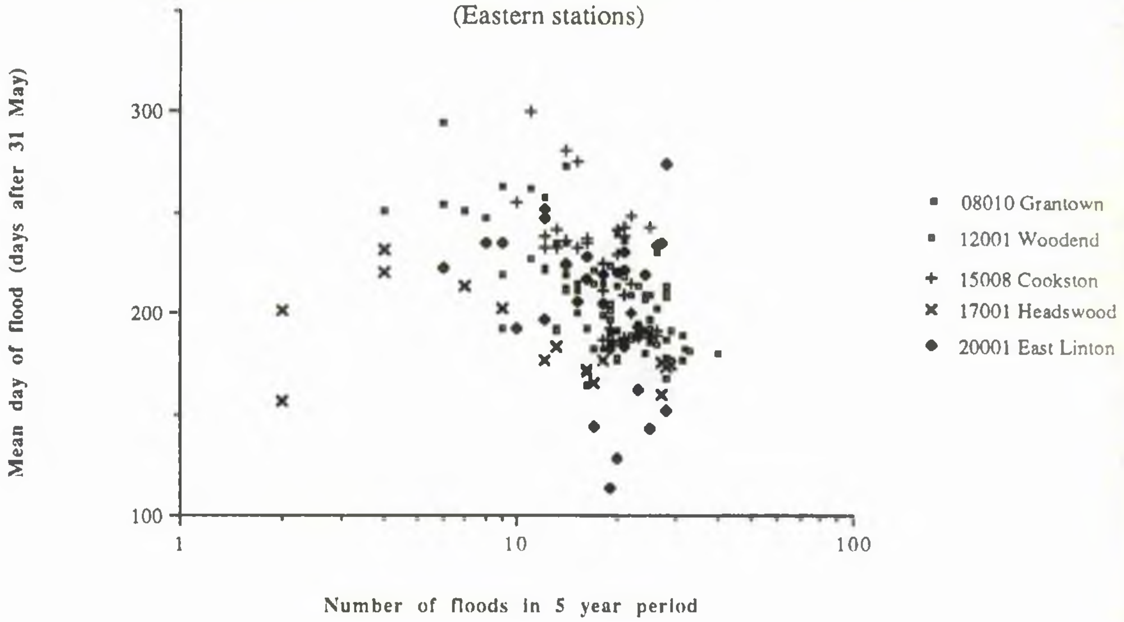
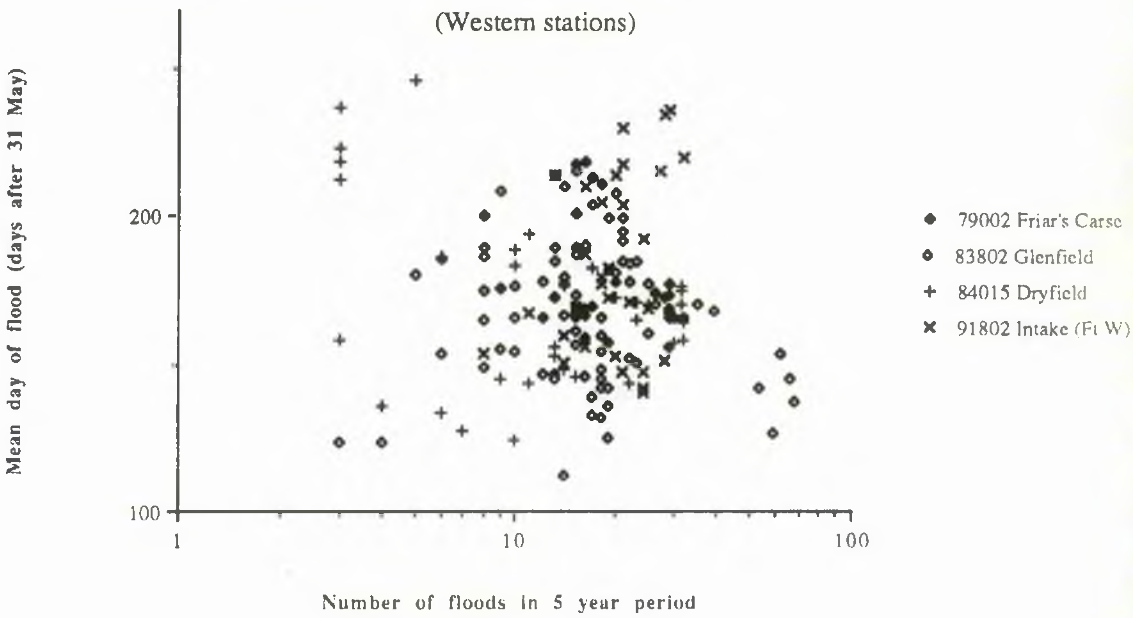


Figure 3.8b

Variation of Mean Day of Flood values with Flood Frequency



Variation of Mean Day of Flood values with Flood Frequency



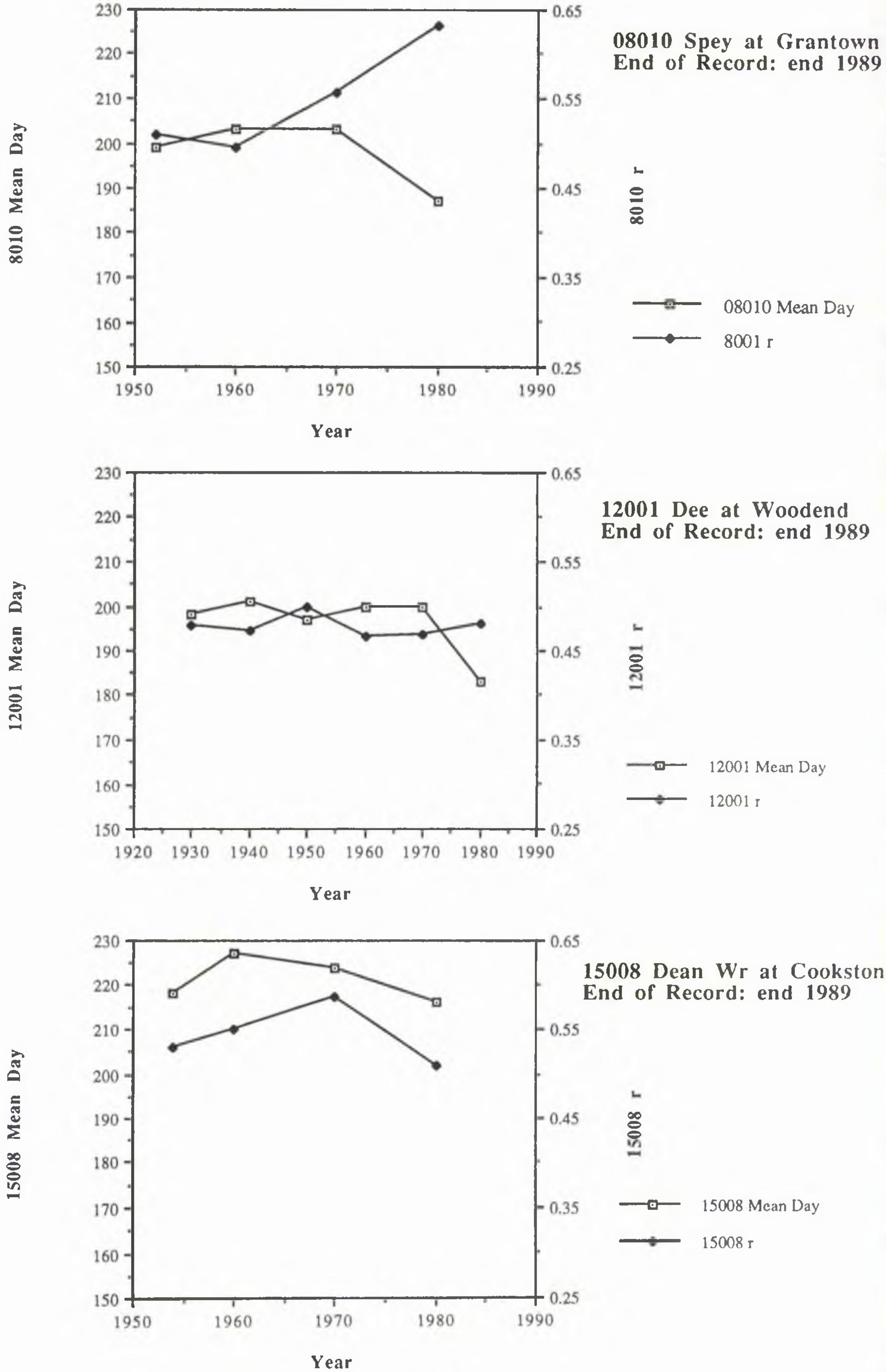
flood with five year flood frequency for selected long-record eastward and westward draining rivers. The distribution of points on the two graphs again suggests that flood frequency does exhibit a rather different relationship towards seasonality at eastern stations compared with western ones. Irrespective of its cause - flood frequency or other influences - the variation of seasonality with time may be an issue of some concern, especially when considering relatively short records, for while there is no apparent long-term trend in the data (neither a general trend towards higher nor lower mean day of flood values) the variation is considerable and the overall description of seasonality at a station will be influenced by the period of data used to represent it.

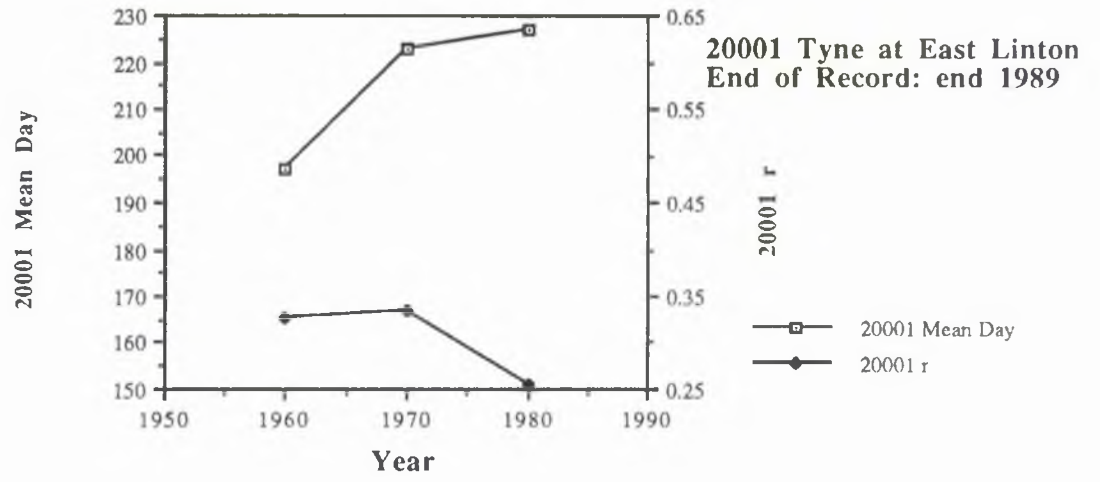
To evaluate the extent of the influence which might be exerted by the period of record used, nine of the longest records available were selected to represent all parts of Scotland, and mean day of flood values and *r* values were calculated for different periods. The variation in these values is shown in Figure 3.9, and it can be seen that while the mean day of flood value at some stations is almost invariant with the length of record used, at others the mean day value varies by as much as 30 days depending upon the length of record analysed. The figure shows a variety of behaviours in response to increasing record lengths: it was expected that as record length increased, the mean day of flood for the sample analysed would approach the mid-point of the range of all values in the station record, but at some stations the mean day of flood for the full length of record available differs considerably from the value found from later parts of them (20001, 91802). Plots for stations 08010 and 12001 suggest a danger in using too short a length of record to represent seasonality at a site; mean day values for the last ten years of record for these stations are considerably lower than for greater lengths of the available record.

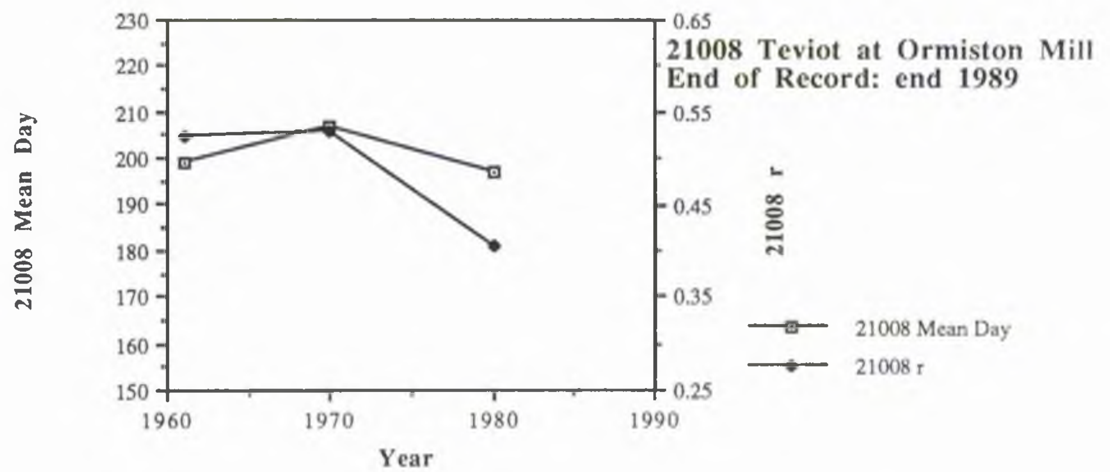
The effects of this long-term variation in the seasonality of flooding can be observed by comparison of the maps in Figure 3.10, which are derived from continuous records for the period 1962 - 88 for 22 stations. While the accompanying *r* values often indicate that there is a considerable amount of scatter about the mean day of flood values shown, differences in mean day of flood value between the periods shown often exceed 30 days at individual locations. It is noticeable that both the form of the isolines on the maps as well as their range of values differ quite significantly between consecutive nine year periods.

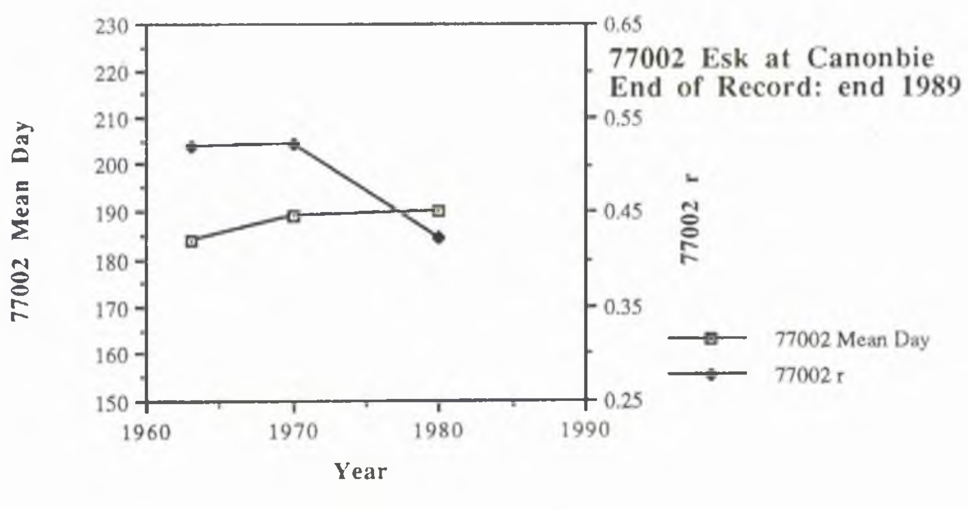
The conclusion must be drawn from these data that seasonal behaviour in flooding does vary considerably through time within the records held and this must be

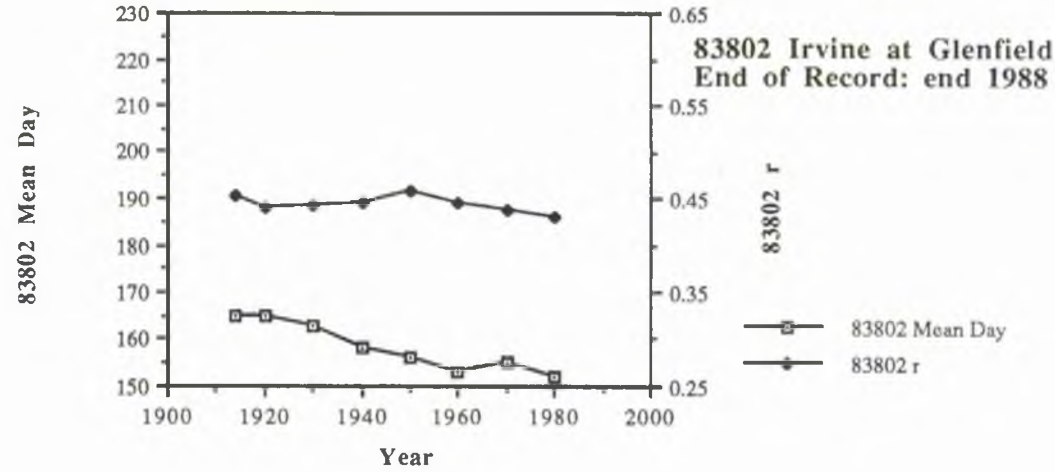
Figure 3.9 Mean day of flood and *r* for x-axis value to end of record (Mean day values as days after 31 May)

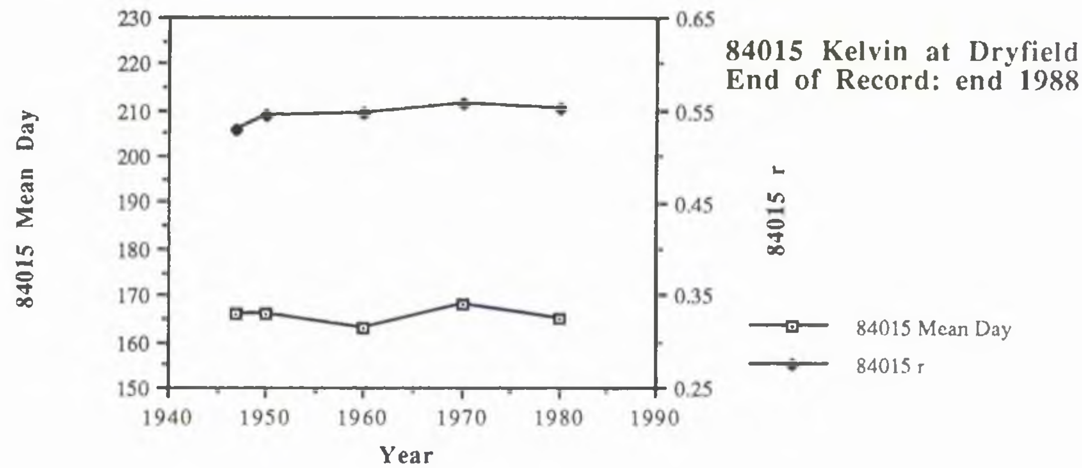



20001 Tyne at East Linton
End of Record: end 1989
20001 Mean Day
20001 r
20001 Mean Day
20001 r
Year
230
220
210
200
190
180
170
160
150
0.65
0.55
0.45
0.35
0.25
1950
1960
1970
1980
1990


21008 Teviot at Ormiston Mill
End of Record: end 1989
21008 Mean Day
21008 r
21008 Mean Day
21008 r
Year
230
220
210
200
190
180
170
160
150
0.65
0.55
0.45
0.35
0.25
1960
1970
1980
1990


77002 Esk at Canonbie
End of Record: end 1989
77002 Mean Day
77002 r
77002 Mean Day
77002 r
Year
230
220
210
200
190
180
170
160
150
0.65
0.55
0.45
0.35
0.25
1960
1970
1980
1990


83802 Irvine at Glenfield
End of Record: end 1988
83802 Mean Day
83802 r
Year
83802 Mean Day
83802 r


84015 Kelvin at Dryfield
End of Record: end 1988
84015 Mean Day
84015 r
Year
84015 Mean Day
84015 r

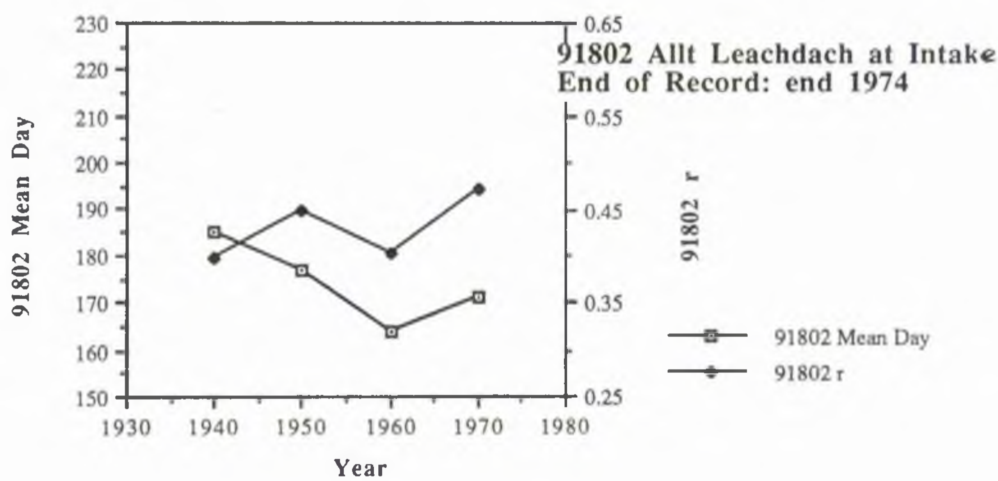
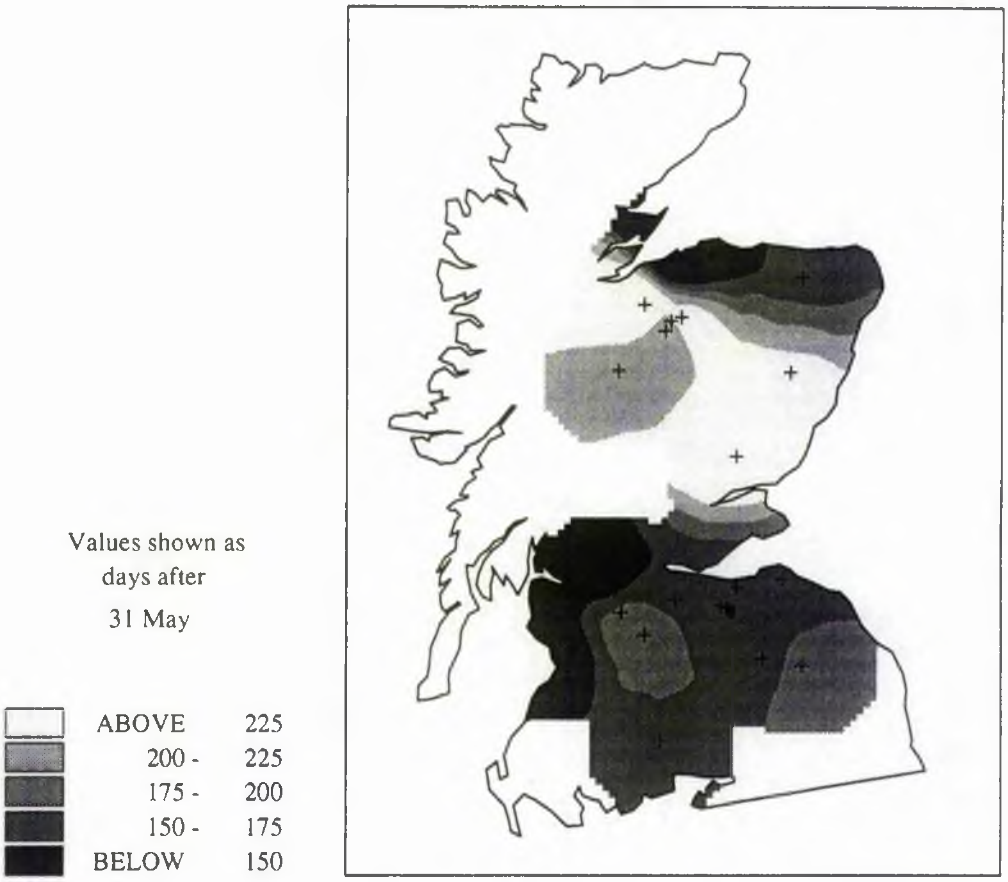
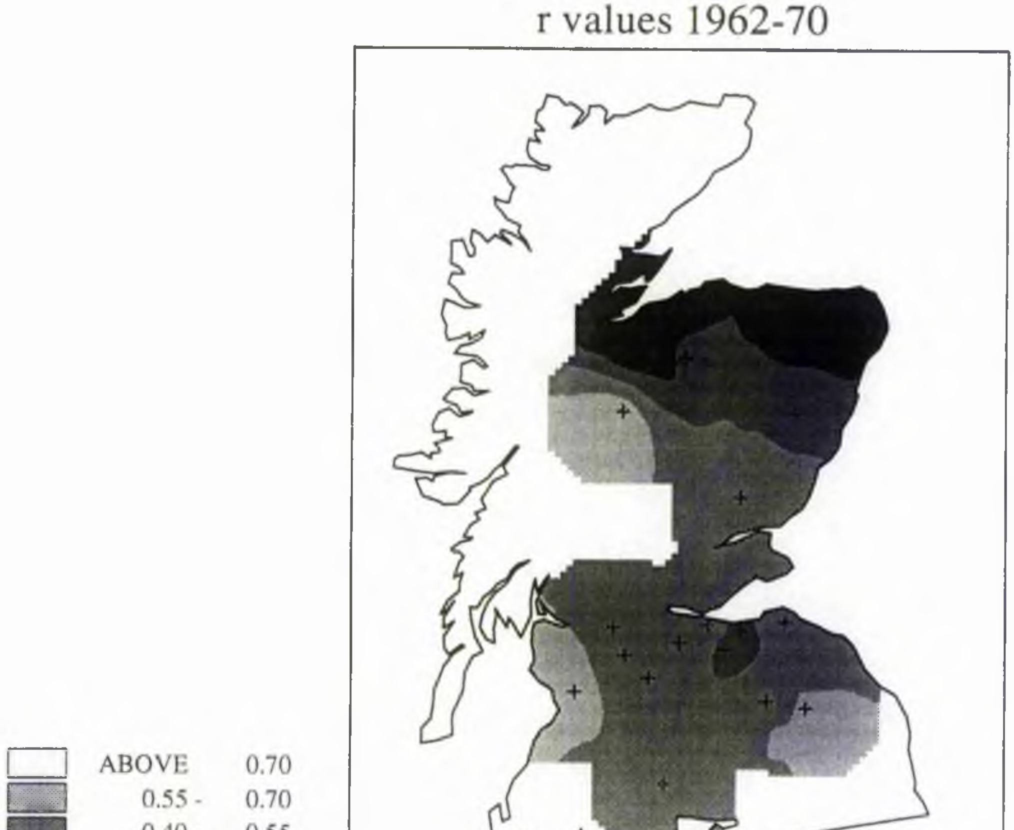

91802 Allt Leachdach at Intake
End of Record: end 1974
91802 Mean Day
91802 r
Year
91802 Mean Day
91802 r

Figure 3.10

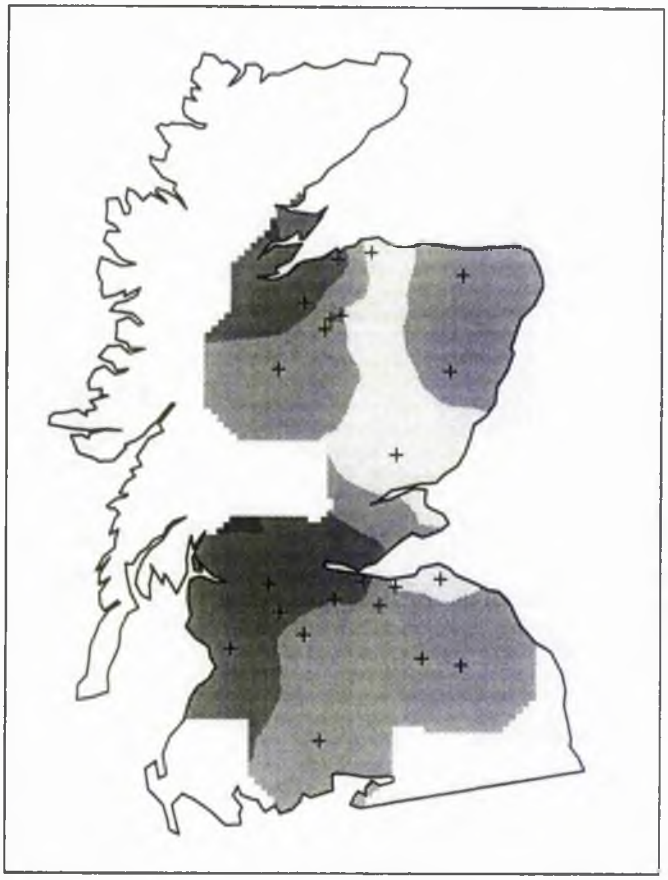
Variation in seasonal patterns with record sampled

Mean day of flood 1962-70




r values 1962-70
ABOVE 0.70
0.55 - 0.70
0.40 - 0.55
0.25 - 0.40
BELOW 0.25

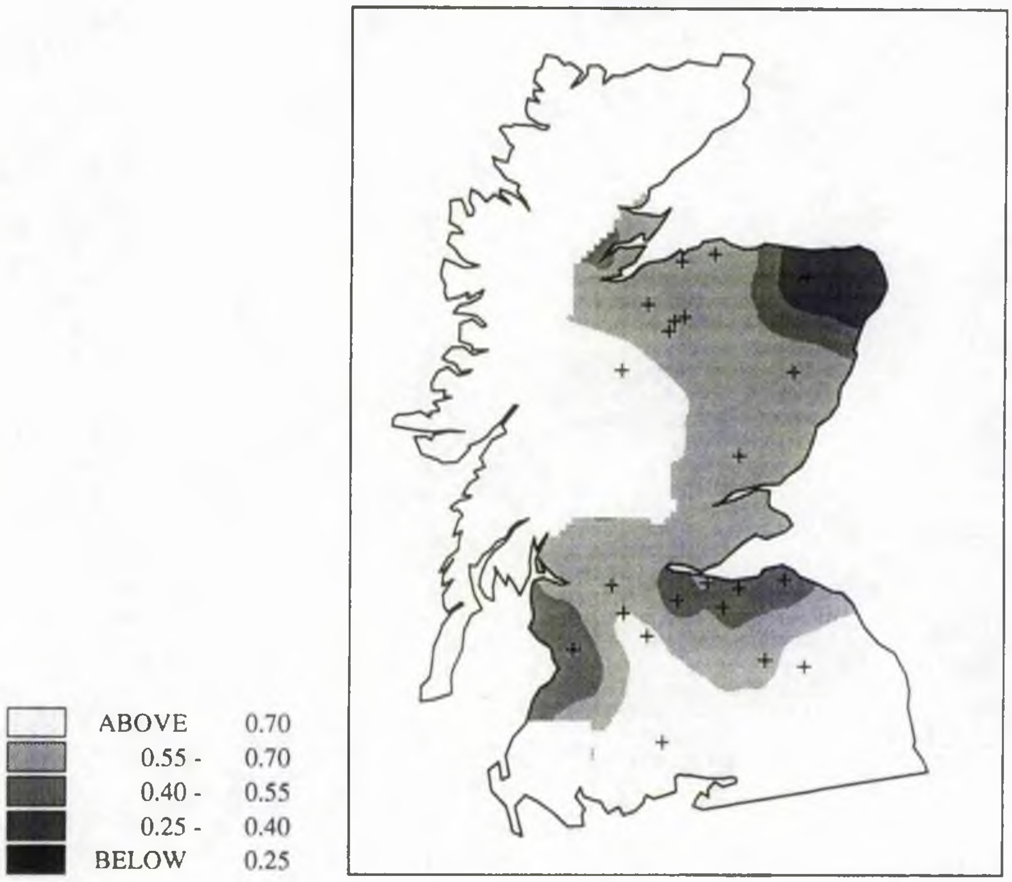
Mean day of flood 1971-79



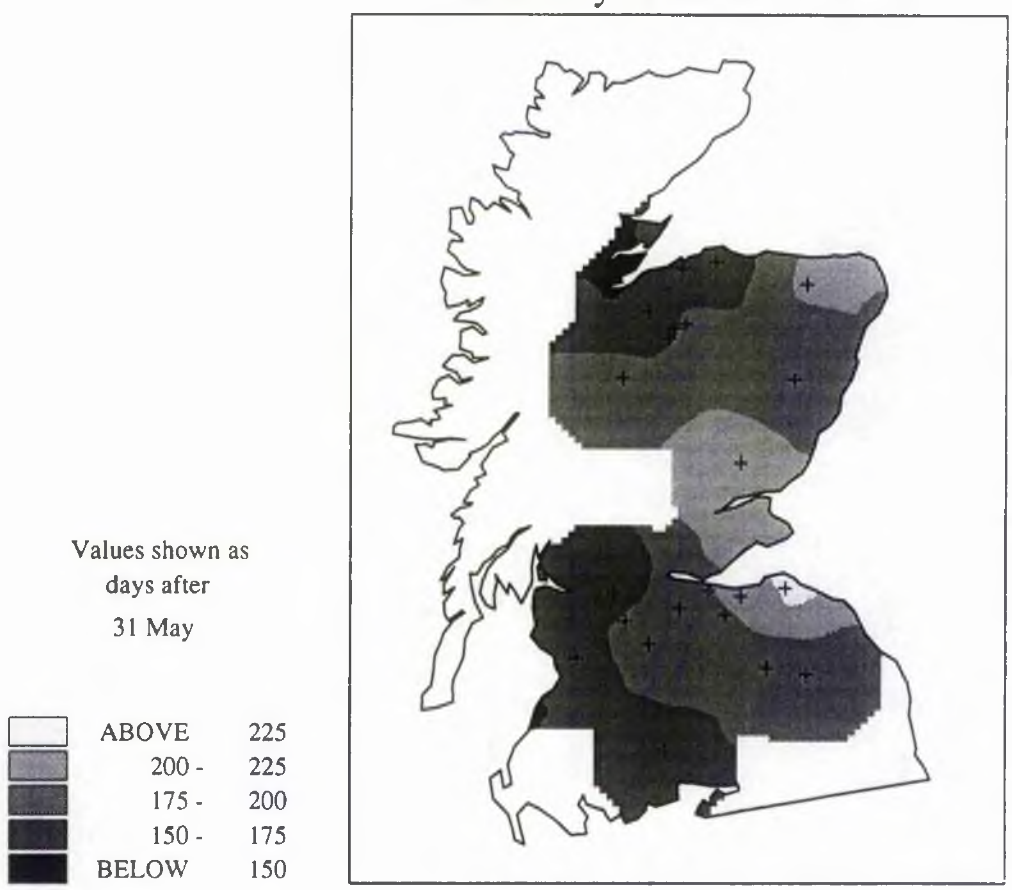
Values shown as days after 31 May

ABOVE		225
	200 -	225
	175 -	200
	150 -	175
BELOW		150

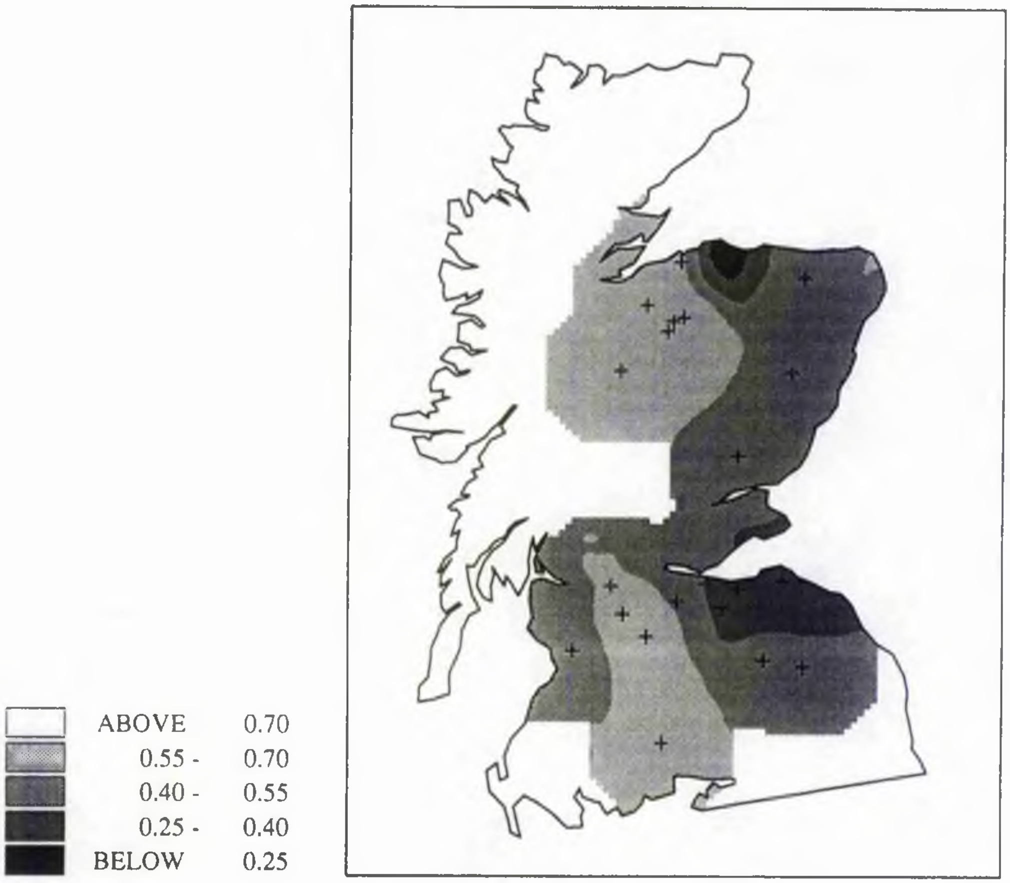
r values 1971-79



Mean day of flood 1980-88



r values 1980-88



recognised as a limitation in analysis of the data. Means of reducing this limitation will be considered along with the analysis of the data in Chapter 4.

In summary, the period of data collected for a station must be seen to influence the seasonal characteristics of the sample. Even in the longest record held, that for station 83802 Irvine @ Glenfield, the mean day of flood for the entire record held seems surprisingly uncharacteristic of smaller samples taken from later parts of the record, suggesting that a shift during its 75 years length has occurred in the direction of progressively earlier floods. Great care will therefore be required in analysis of these data.

3.9 Summary

The peaks over threshold database collated contained over 4000 station-years of record derived from chart records produced at gauging stations across Scotland and into north-east England, giving what was considered an optimum spatial and temporal resolution of records. Data were collected using Institute of Hydrology standard procedures for peak independence, gap detection and error checks and was totally consistent both internally and with other data collected using IH methods. Flood ratings were used to ensure a sensible approach to the conversion of stage data to flow values and checks with an independently produced Institute of Hydrology database were carried out to enable errors in rating relationships to be identified and acted upon. Threshold values for each station were adjusted in order to ensure comparability between records. However it would appear that the seasonality of flooding at a given site is prone to change with time, more so at some stations than at others, thus suggesting that comparison of records collected at individual gauging stations is not possible unless it is done only for common periods. This may present a major problem for the subsequent analysis of the database.

Chapter 4

Spatial patterns of seasonality

4.1 Introduction

This chapter is a spatial description of the seasonality of flooding throughout the study area. Overall patterns of general applicability are identified, along with exceptions to them. The data used are the POT series described in the previous chapter, having been standardised to a discharge threshold of 45 events in the 10 years 1979-88 or equivalent. Details of the data are given in Appendix A while threshold adjustments are shown in Appendix B.

In order to fully describe the spatial patterns of seasonality, three methods of data presentation were selected for use. In order of decreasing generalisation, the first is a pair of maps showing mean day of flood and an associated clustering statistic, *r*, for gauging stations in the study area (Section 4.2; Figures 4.2a, 4.2b). These maps give a broad indication of the annual distribution of events at individual stations and allow comparisons to be made between regions. The second method uses a set of maps to show relative frequencies of events in two-monthly periods by displaying at each gauging station location the number of events in each two month period as a proportion of the total number of events at the station (Section 4.3; Figures 4.3a - 4.3f). This presentation therefore shows the seasonal distribution of events in greater detail than the mean day of flood and *r* statistic maps, allowing the importance of individual 'seasons' in the overall seasonal regime of a catchment to be evaluated. In Section 4.4, the description of seasonality is extended to include a consideration of discharge in the seasonal distribution of events, with the seasonality of only the larger peaks in each record being compared with that of each record as a whole. During the course of the chapter, records which show anomalous seasonalities are highlighted and possible reasons for these are suggested. Finally, in Section 4.5, a classification method is described which allows these patterns to be condensed into a readily understandable form, the seasonality of flooding at any station being represented simply by its class membership. This allows a general summary of the spatial patterns of seasonality across the study area to be made.

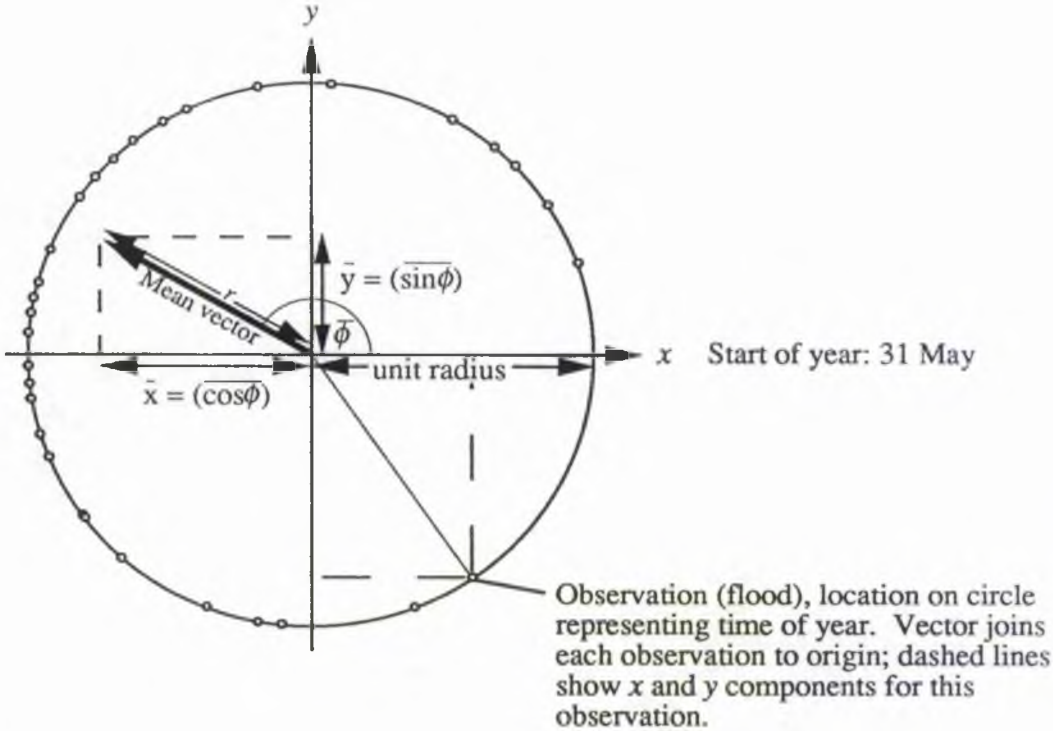
4.2 Mean day of flood and *r* statistics

Figures 4.2a and 4.2b show values of mean day of flood and *r* statistics for all gauging stations meeting the threshold frequency requirement referred to above. Values are plotted at the gauging station locations themselves as opposed to the centre of their respective catchments, since the values refer to the seasonality of flooding at those points rather than being representative of flooding behaviour at all points upstream of them. It will be shown that seasonal behaviour does vary within catchments.

4.2.1 Directional Statistics

The statistics presented are directional statistics, used to overcome the circular nature of the data (Mardia 1972, Batschelet 1981). Linear techniques would lead to misleading representation of the data, *eg* the arithmetic mean day of occurrence of two flood events occurring on day 1 and day 365 of a year is day 183, whereas a value of day 0.5 is much more helpful in such a context. In order to derive a mean day of flood value which would give a measure of central tendency for the season of occurrence of all events at each station, the date of each event must be considered as an observation on the circumference of a circle of unit radius: direction from the centre of the circle relative to a fixed axis therefore represents season relative to a fixed start of year date (Figure 4.1). Events are treated as unit vectors which can be resolved into components with respect to x and y axes; a mean vector $\bar{\phi}$

Figure 4.1
Mean vector to represent season of occurrence of flood events



Based on Batschelet (1981), Fig.1.3.3.

(expressed in degrees relative to the x axis) to represent the mean day of flood can then be found by

$$\bar{\phi} = \begin{cases} \arctan(\bar{y}/\bar{x}) & \text{if } x < 0 \\ 180° + \arctan(\bar{y}/\bar{x}) & \text{if } x > 0 \end{cases} .$$

(Batschelet 1981 p10)

$\bar{\phi}$ can then be translated to a mean day of flood statistic, which is plotted in Figure 4.2a showing spatial variations in the overall annual distribution of flood events. The index has been computed as a number of days after 31 May, this date being chosen as a convenient one at the time of year when fewest events are found in the POT database.

A second statistic, *r*, the length of the mean vector (Figure 4.1), can be computed to indicate the amount of clustering of points about the mean vector. As the individual events are represented as unit vectors, the value of *r* must range from a minimum of 0, representing no clustering (equal distribution of vectors in all directions) to 1, representing total clustering, *ie* all vectors in the same direction from the centre. *r* is calculated as $r = (\overline{x^2} + \overline{y^2})^{1/2}$ (Batschelet 1981 p10). POT records with low *r* values must therefore have events widely distributed throughout the year with little clustering around the time of year indicated by the mean day of flood statistic, while those with high *r* values have a strong concentration of events about the mean day of flood. *r* values can therefore be used as a means of qualifying the information provided by the mean day of flood statistic: a high *r* value indicates that the season indicated by the mean day of flood is a dominant season of flooding, while a low *r* value indicates that the mean day of flood does not represent a dominant time of year in the flood record. In such cases, events may be distributed widely throughout the year, or a bimodal distribution with two modes separated by six months may apply. *r* values for the stations used in this study are shown in Figure 4.2b and discussed in detail in Section 4.2.3.

4.2.2 Period of record standardisation

In Section 3.8, it was demonstrated that the period of record used could influence seasonality statistics as the seasonality of flooding on any river may vary significantly through time; this was thought to be a particular problem in the use of short records. To make a useful description of spatial patterns of seasonality it is therefore important to suppress this period of record sampling error as much as possible, although the advantages offered by any measures which involve exclusion

Figure 4.2a

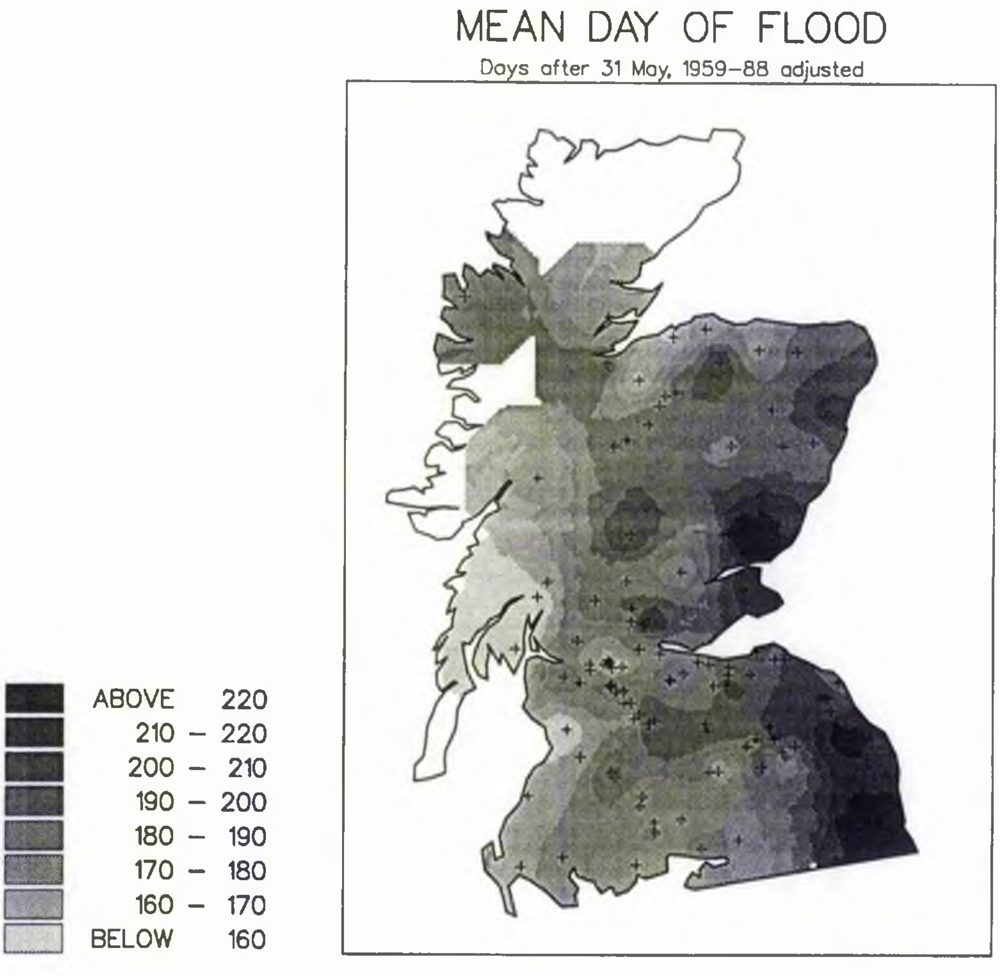
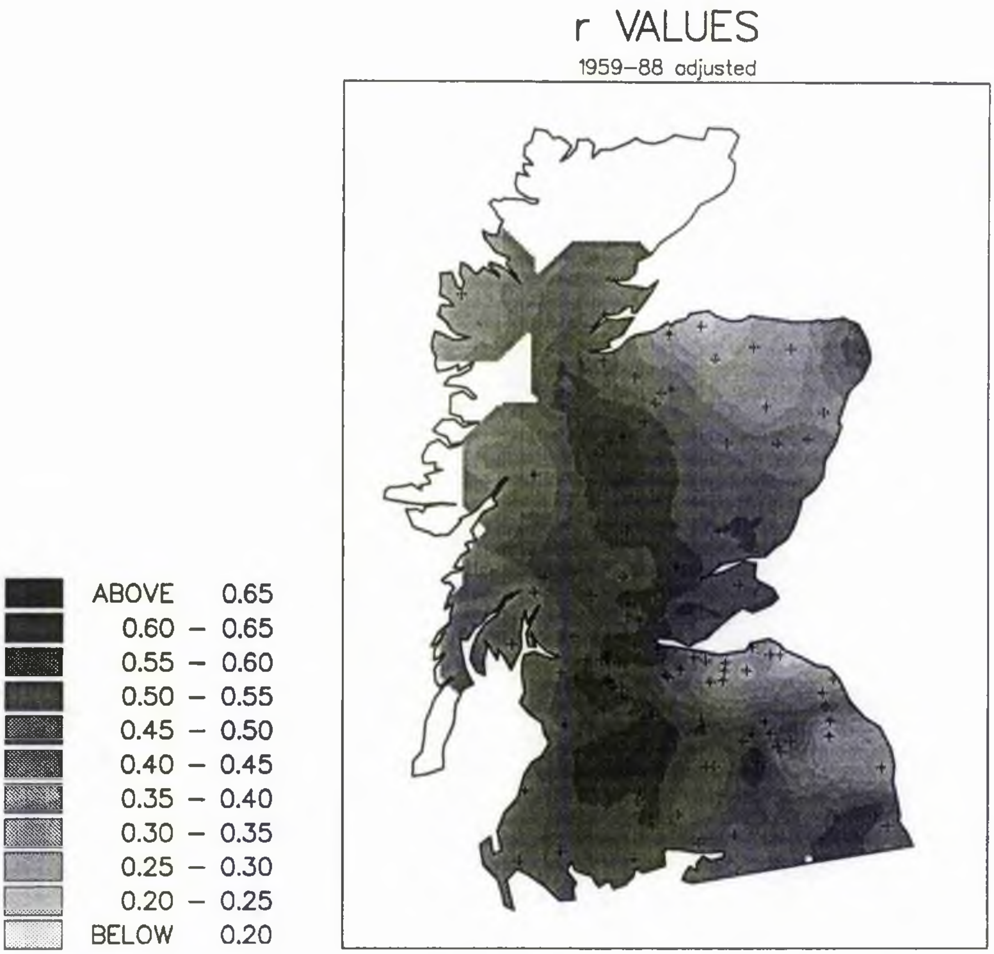

MEAN DAY OF FLOOD
Days after 31 May, 1959–88 adjusted
ABOVE 220
210 – 220
200 – 210
190 – 200
180 – 190
170 – 180
160 – 170
BELOW 160

Figure 4.2b


r VALUES
1959–88 adjusted
ABOVE 0.65
0.60 – 0.65
0.55 – 0.60
0.50 – 0.55
0.45 – 0.50
0.40 – 0.45
0.35 – 0.40
0.30 – 0.35
0.25 – 0.30
0.20 – 0.25
BELOW 0.20

of data from the database must be weighed carefully against the loss of detail which this would involve. With this in mind, it was decided that mean day, r and any other statistics used should be standardised to a 30 year period, and 1959 - 88 was selected as the 30 year period for which there was the greatest number of stations in the database with a complete record. For these stations, statistics were calculated for this 30 year period only. For stations without this complete record, it was necessary to adjust the statistics for the period of record available to values which might be expected for the standard period.

The method employed to make this adjustment was based on the assumption that any shift in seasonality (characterised by whatever statistics) between the period of record held at a station and the standard period would be matched at neighbouring stations. Further, it was assumed that the similarities between neighbouring stations in such shifts would become weaker with increasing distance between them, *eg* in attempting to adjust the seasonality statistics of a short record to those for the 30 year standard period, a neighbour 20 km distant would give a better indication of the shift in seasonality than would one at a distance of 200 km. Finally, it was also assumed that a greater length of overlap period between a station and a neighbour would increase the accuracy with which seasonality statistics could be adjusted; this overlap period need not necessarily be within the standard period. Use of two neighbouring stations, preferably in opposite directions from the station of interest ('target' station), would further enhance the accuracy of the method by providing more information on which estimates could be based. Similar assumptions are made and similar methods employed in the artificial extension of records and in the prediction of other hydrological statistics (*eg* Vogel and Kroll 1991).

In order to evaluate the applicability of this method, a test was devised whereby all complete 1959 - 88 records were used in all possible combinations of periods of record and pairs of neighbours, to predict 30 year statistics for all of the stations within this group. Each prediction of mean day and r was based on estimates from two neighbours (i = 1, 2) at distances d_1 and d_2 from the target station, the weightings assigned to each neighbour being calculated as

$$w_i = \frac{\frac{1}{d_i}}{\frac{1}{d_1} + \frac{1}{d_2}}.$$

The predicted statistics were then compared with the known values, and from these results a confidence limit was produced to define the minimum record overlap length and maximum neighbour distance combinations within which mean day of flood and *r* could be predicted with 95% confidence to be within an error of 15 days and 0.15 respectively. Weighting of estimates by an inverse distance squared method rather than by inverse distance resulted in no improvement in performance, the latter therefore being employed.

Within this confidence limit, standardised mean day of flood and *r* values were calculated for all stations lacking a complete 1959 - 88 POT record. For those stations to which too short an overlap period applied, or too far from any neighbour with a complete standard period record, it was deemed unsafe to attempt to predict standardised statistics; Figures 4.2.a and 4.2b are therefore constructed only on the basis of complete 1959 - 88 records and those for which adjustment could be made within the 95% confidence level. In this way 36 of the 143 stations for which threshold revision was possible were lost from the database available for the production of these maps.

4.2.3 Mean day of flood and *r* statistic maps

Figures 4.2a and 4.2b are choropleth maps based on mean day and *r* values with interpolation to show values of these statistics in areas between gauging station locations. Areas more than 40 km from any data point have been left unshaded as interpolation cannot be made with great confidence. It is important to note that the patterns shown are based on interpolation of values from only a finite number of data points; values indicated between these points are based only on values at neighbouring points and do not necessarily reflect the nature of seasonality at every point on the map. Also, in a few exceptional cases where data points close to each other have markedly different values, the choropleth shading is unable to show this; Appendix D however gives mean day of flood and *r* values for all stations before and after standardisation. Despite these two minor limitations, sufficient data are available to allow a number of spatial patterns of seasonality to be identified with absolute certainty.

The most striking feature of the mean day of flood map is an east - west gradient, with the highest values (latest mean day of flood) on the east of the map and the lowest (earliest) in the west. 21 east-draining catchments record adjusted mean day of flood values greater than or equal to 200 days after 31 May; only one west-draining catchment exceeds this value (84018 Clyde @ Tulliford Mill: adjusted mean day = 200.2). Of catchments with adjusted mean day values less than 170 days, 4 drain east and 16 drain west. In some parts of the map, this gradient shows itself very well, but the pattern is by no means uniform.

Furthermore, the map of *r* values shows significant information which should be considered in conjunction with these patterns: higher *r* values (>0.55) suggesting dominance of one particular season tend to be found in inland areas but are associated with a considerable range of mean day values; low *r* values (<0.35) indicating a wide distribution of events throughout the year are found on the south Moray Firth coast and in East Lothian, with other low values also being found in parts of the Tweed basin and Northumberland. Few stations on the west coast show low *r* values (only 87801 Allt Uaine @ Loch Sloy Intake has a value of less than 0.4); this indicates that the generally earlier flooding found on the west coast exerts a greater dominance in the year as a whole, whereas lower *r* and higher mean day values in the east suggest a wider distribution of events throughout the year with a general tendency for events to occur slightly later in the annual cycle.

The south coast of the Moray Firth is perhaps the single most outstanding anomaly on the mean day map. The two stations on the River Findhorn (07001/07002) record very low mean day values, while on the adjacent River Spey, a significant gradient in mean day values can be observed, with the mean day of flood becoming progressively earlier up-river. The low Findhorn and high Spey mean day values are associated with a considerable scatter of events through the seasons and are further discussed in Section 4.4. In Angus, station 15008 Dean Water @ Cookston records a mean day of flood value (224.0) 30 days greater than its neighbour 15010 Isla @ Wester Cardean draining an adjacent catchment area. In the Tweed basin, clusters of data points on the map show an uneven pattern; again adjacent catchments do not always have similar mean day statistics.

In the west of Scotland, while it has already been stated that the mean day statistic shows that flooding generally occurs earlier in the year than in the east, there are some notable values to be mentioned. The most exceptional of these is station 80003 White Laggan @ Loch Dee: while its record is too short to allow standardised statistics to be calculated, the mean day of flood value for its nine years of record is 108, with a not insignificant *r* value of 0.560. This is a remarkably early mean, two or three months earlier than most other stations, but also in south-west Scotland stations 83002, 83005 and 83006 all show early mean day values at moderate to high *r* values: while these are all based on short records, they are over different periods of time so it would seem that some rivers in this area are normally characterised by very early flooding. At a lower *r* value, the longest POT record in Scotland, 83802 Irvine @ Glenfield, shows a low mean day value of 165.3, reduced to 152.4 for the standard period. Further north, these low west coast mean day values are complemented by values of 154.1 and 152.0 at stations 86001 and 87801 respectively: although *r* values here are low, the early mean day statistics do reflect significant concentrations of flood events in the autumn months. Finally on the west coast, a noticeable feature in the map of mean day values is a clustering of low values in the Kelvin basin: values on the nearby mainstream Clyde and on its other tributaries are clearly much later in the year by a margin of 20 - 30 days.

The values of these statistics are the result of varying distributions of events through the seasons at individual stations. Section 4.3 examines the frequency of occurrence of events in 2-monthly periods in order to gain further detail on this, while Section 4.4 considers in addition discharge values of events. However, the east - west gradient of mean day values identified here, along with anomalies within this pattern should be taken to be significant in their own right, as should the map of *r* values, distinguishing those areas with flood events widely distributed through the year (especially the Moray-Nairn and Lothian areas) from those where flooding is more concentrated in particular seasons (upland and more generally west coast areas). Nevertheless, it must be noted that drainage basins in close proximity to each other do not necessarily exhibit similar seasonal characteristics; the reasons for this will become the focus of attention in later chapters.

4.3 2-monthly percentages

Six maps were constructed to show spatial variation in the proportion of floods occurring within two-month periods of the year (Figures 4.3a - 4.3f). It was decided to split the year into six parts for this purpose since it was felt that any finer division of the year would result in sample sizes which were so small as to increase unacceptably the risk of inaccuracy, while a coarser division would lead to an unhelpful loss of detail. The starting point of the year was defined as June 1 as this ties closely with the May 31 start date used for the mean day of flood statistic and,

Figure 4.3a

JUNE — JULY FLOODS AS PERCENTAGE OF TOTAL

1959–88 adjusted

Figure 4.3b

AUGUST – SEPTEMBER FLOODS AS PERCENTAGE OF TOTAL

1959–88 adjusted

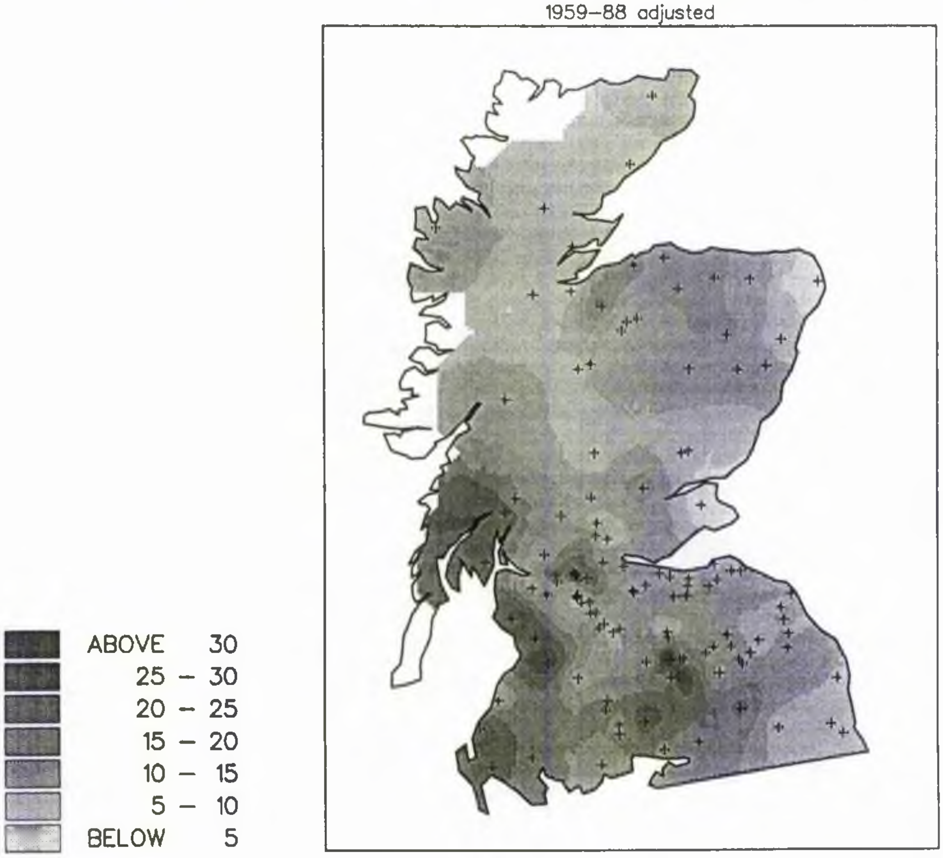


Figure 4.3c

OCTOBER – NOVEMBER FLOODS AS PERCENTAGE OF TOTAL

1959–88 adjusted

Figure 4.3d

DECEMBER – JANUARY FLOODS AS PERCENTAGE OF TOTAL

1959–88 adjusted

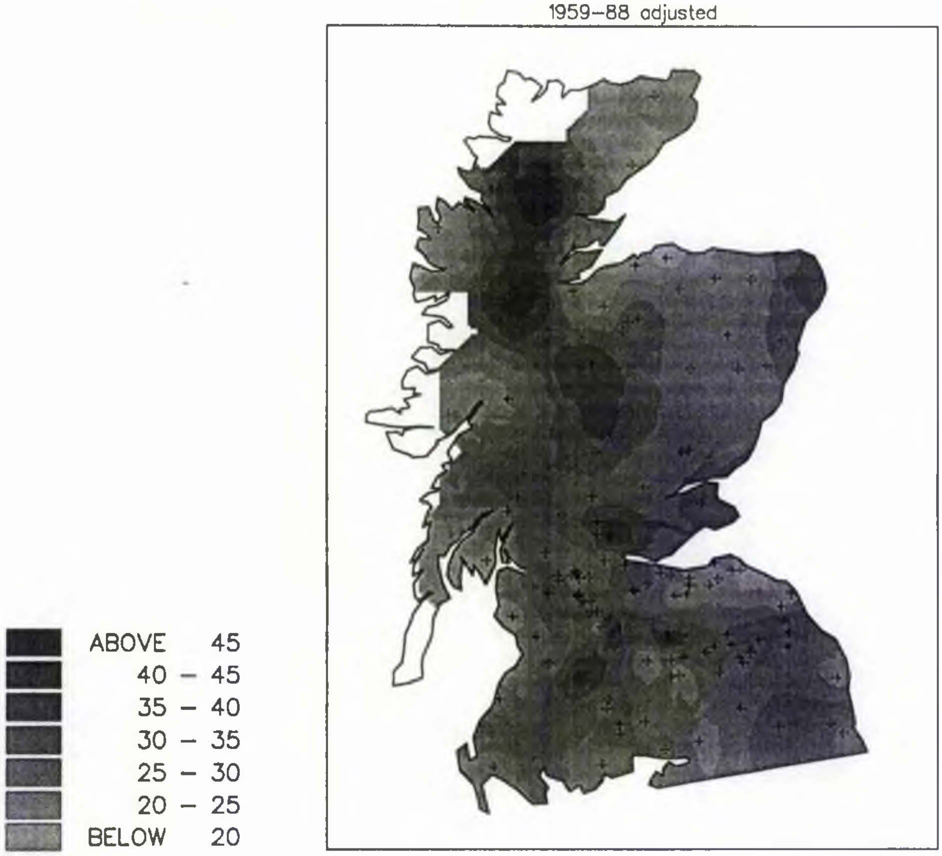


Figure 4.3e

FEBRUARY – MARCH FLOODS AS PERCENTAGE OF TOTAL

1959–88 adjusted

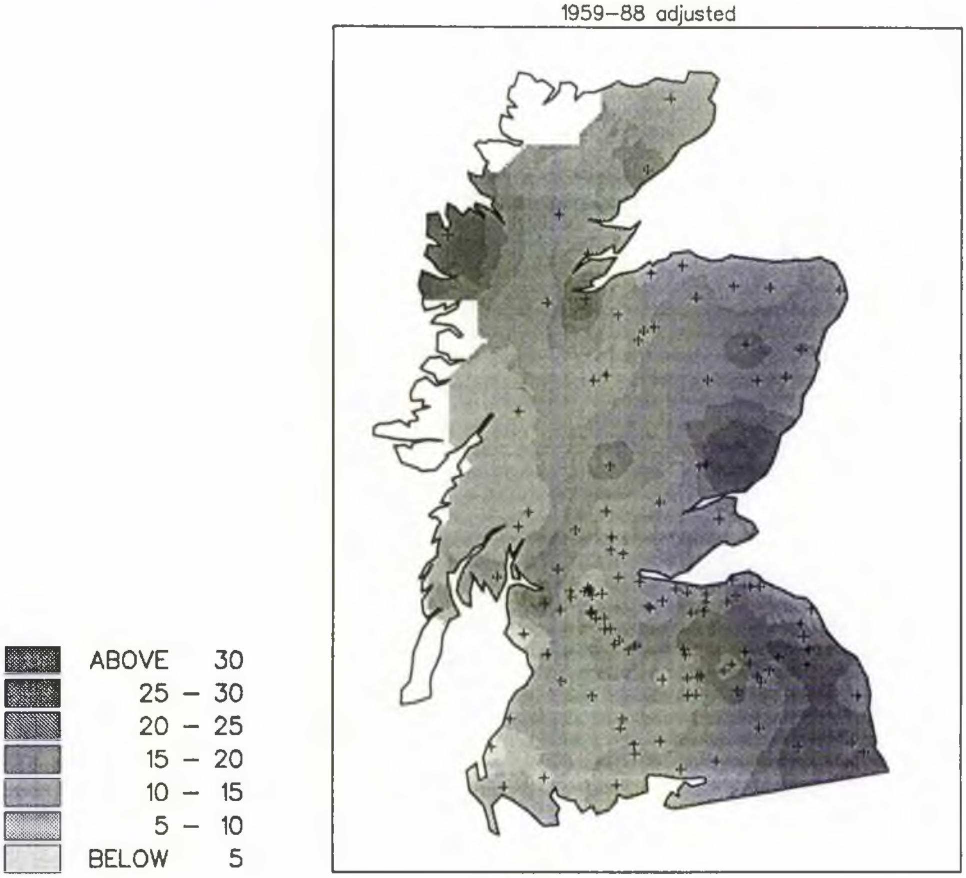


Figure 4.3f

APRIL – MAY FLOODS AS PERCENTAGE OF TOTAL

1959–88 adjusted

more importantly, the differences between months within each pair arising from this start date were less than for the alternative set of pairs (*ie* start 1 July). All but one of the two-monthly maps were based on 61-day periods rather than the actual lengths of each pair of months in order to make maps as comparable as possible, the exception being the February - March map which used an average of 60.25 days accounting for leap years.

4.3.1 Period of record standardisation

Records were standardised to the same common period (1959 - 88) as used for the mean day and *r* statistics described in Section 4.2 above. The interpolation requirement was set at a confidence of 90% of adjustments causing no more than a 12% error in the 2-monthly percentage frequencies. This allowed 119 stations out of the 143 with adjusted thresholds to be used in plotting the maps, thereby giving a rather better spatial coverage than in Figures 4.2a and 4.2b. As with the mean day and *r* maps, interpolation was limited to 40 km from any data point. Predicted 1959 - 88 frequencies were corrected such that the sum of all six periods' frequencies always totalled 100% at each station. As with the maps of mean day and *r*, values differing considerably from those at close neighbour stations cannot always be shown on the maps, but values of the 1959 - 88 adjusted frequencies for each two month period at each station are given in Appendix E. Description of the maps is based entirely on these adjusted values.

4.3.2 Two-monthly percentage maps

4.3.2.1 June - July (Figure 4.3a)

This is the period which is generally characterised by the lowest number of flood events in the year (mean = 3.6% of all events, median = 2.4%), followed closely by April - May (mean = 4.2%, median = 3.1%). With such a low proportion of events occurring in this period there is little scope for identifying important spatial patterns, other than to identify those areas where there is a significantly higher incidence of June and July flooding than elsewhere. Considering the low mean and median percentages, it is perhaps surprising to find four stations with more than 10% of events in these two months.

In north-east Scotland, most stations on the east of the country north of Inverness and all those to its east in a band extending approximately 50 km from the north-facing coast have values between 5% and 10%. There are only two exceptions where more than 10% of events are recorded, these being the coastal Morayshire stations 07002 Findhorn @ Forres and 07003 Lossie @ Sherriff Mills, while at 10002 Ugie @ Inverugie, no events are recorded at all. It should also be noted that stations 05901 Beauly @ Erchless and 06007 Ness @ Ness-side record very low values (0% and 1.4% respectively) despite close proximity to this area of higher values; all three River Dee stations also record zero values.

The Lothian - Borders area shows a very well defined pattern of higher values, with all stations between 19001 Almond @ Craigiehall and 21022 Whiteadder @ Hutton Castle in a coastal strip 25 km wide recording values in excess of 5%. The area defined by this 5% isoline does seem remarkably well defined, and with other high values at 21032 Glen @ Kirknewton and 22004 Aln @ Hawkhill, it might be appropriate to extend this area of more prominent June and July flooding further south along the coastline. Contrary to the interpolation on the map, 21024 Jed Water @ Jedburgh seems most likely to be an isolated high value (11.0%) on this map; the low value of 1.6% for the nearby 21025 Ale Water @ Ancrum catchment makes this a most notable anomaly.

Only three west-draining rivers in the whole of Scotland record values greater than 5%, indicating that June and July floods are much more characteristic of east coast catchments, though still at a relatively low frequency. These three west coast stations are 83802 Irvine @ Kilmarnock (6.3% of all events in these two months), 87801 Allt Uaine @ Intake (13.9%) and 91802 Allt Leachdach @ Intake (7.7%). The latter two catchments are very small mountainous ones; the first is a somewhat larger lowland basin.

June and July can therefore be summarised as months of infrequent flooding, but with two well defined areas of more frequent flood activity, namely north-east Scotland and the east coast south of Edinburgh to north Northumberland. In addition, one isolated basin in the Tweed catchment, one in Ayrshire and two small mountainous others on the west coast also experience a greater frequency of events.

4.3.2.2 August - September (Figure 4.3b)

The months of August and September see a much greater range of flood frequencies, from a minimum of 2.1% at 10002 Ugie @ Inverugie, a station with a notably low flood frequency in the previous two months also, to a maximum of 38.5% at 21026 Tima Water @ Deephope. The mean frequency is 15.5% of events with a standard deviation of 7.4%. This greater range of frequencies is characterised by more pronounced spatial patterns than in June and July.

Most of the far north of Scotland is characterised by relatively low frequencies of events; values are less than 10% at most stations and reach a regional maximum of 14.7% at Poolewe. Slightly higher frequencies are found in the area from 07001 Findhorn @ Shenachie to 12002 Dee @ Park Bridge, with the highest values in this region being found locally on the River Findhorn and an anomalous low centred on 10002 Ugie @ Inverugie. The southern part of this area can be considered to be bounded by a 'trough' of lower values (less than 10%) running north-west from the Firth of Tay to south-east Ross-shire. Further to the south of this line, only a few stations record such low values; most are in parts of the Tweed basin or the south of Northumberland, and only two (84008 and 84018) are west-draining catchments.

The highest August - September frequencies are found far to the south of this trough, occurring in distinct areas: two small catchments in the upper Tweed (21026 and 21030, values greater than 35%), 28.8% at 78004 Kinnel @ Redhall and 27.0% and 33.3% at 81003 Luce @ Airyhemming and 82003 Stinchar @ Balnowlart respectively at Scotland's south-western extremity. 43% of all events in the non-standardised 80003 Loch Dee record occurred in these two months, giving its extremely early mean day of flood value. Catchments in the Kelvin basin experienced a markedly higher frequency of events in these two months than did neighbouring stations on or near to the adjacent mainstream Clyde. Also in south-west Scotland, stations 83004, 83802, 83002, 86001 and 87801 all show frequencies of at least 28% in August and September, thus defining a zone of high frequency along the west coast from Wigtownshire to the head of Loch Long.

The distribution of flood frequencies for August and September is best summarised by reference to a north-west to south-east parallelism to its features. An axis of low frequency values runs from the Firth of Tay to south-east Ross-shire; to the north, higher values are found concentrated on the south coast of the Moray Firth and especially on the River Findhorn, but values remain quite low to the north of

Inverness. To the south of the axis, the pattern of values is by no means simple, but the highest values are found on the west coast southwards from the head of Loch Long, in the Kelvin basin and also in places in the hills of the far south-west and upper Tweed valley. Flooding is less frequent on the mainstream Clyde, in south Northumberland and parts of the Borders.

4.3.2.3 October - November (Figure 4.3c)

Flood frequencies in October and November are considerably higher than in the preceding two month period, and are only slightly lower, with a mean of 29.7%, than in December and January (30.7%). A standard deviation of 5.2% indicates a tight clustering of values about this mean: 85% of stations experience at least 25% of events in these two months, but only 15% experience more than 35% over the same period. It therefore seems sensible to accept the range of 25 - 35% of events as typical of the study area as a whole, and focus attention on the spatial distribution of values outwith this range.

Working clockwise around the study area, starting from the north-east tip of Scotland, the first stations to be encountered with values outside this range form a narrow band running from 07002 Findhorn @ Forres to 11001 Don @ Parkhill. To the south, the Tay basin contains one catchment, 15013 Almond @ Almondbank, with a high frequency (38.6%) and one with a low value, 15008 Dean Water @ Cookston (22.4%). Further south along the east coast, there is an increased incidence of stations with low October - November frequencies, nine stations between 18002 Devon @ Glenochil and 22006 Blyth @ Hartford Bridge recording values of less than 25%. Interspersed with these, however, are five catchments recording high (greater than 35%) frequencies, four of them in the Tweed basin, and it cannot therefore be suggested that any well defined area of lower frequency October - November flooding exists in this area. Stations with exceptionally high or low flood frequencies in these two months occur in isolation from others with similar values, and it should be noted that the Tweed basin includes both the station with the greatest proportion of events in this period, 21001 Fruid Water @ Fruid (49.4%), as well as the two stations with the lowest such percentages, 21031 Glen @ Kirknewton (17.9%) and 21030 Megget Water @ Henderland (18.3%). All east coast stations other than Fruid with values exceeding 35% record rather less exceptional values of less than 39%, and as only one west draining catchment, 91802 Allt Leachdach @ Intake, exceeds this value with 41.3%

of events in October and November, then the 49.4% recorded at Fruid does indeed seem exceptionally high.

On the west coast, an isolated low frequency of 23.4% is found at 82003 Stinchar @ Balnowlart, while high values of 37.4% and 39.1% are found at nearby 82001 Girvan @ Robstone and further to the north 83002 Garnock @ Dalry respectively. The Clyde basin contains an interesting clustering of values outside the 25 - 35% band: four of the five left bank tributaries for which data are held record high values (the fifth records a lower than average value of 28.2%), one right bank tributary, 84019 North Calder @ Calderpark, also records a high (36.0%) value, yet the right bank tributary immediately upstream, 84007 South Calder @ Forgewood, records a low value of 24.6%. Further down the Clyde, four catchments in the right bank Kelvin catchment also record high values. No stations on the mainstream Clyde record values outside the 25 - 35% range. Finally in the west, as previously mentioned, 91802 records the second highest frequency of 41.8%, while the similarly mountainous and small catchment 87801 Allt Uaine @ Loch Sloy Intake records a low 21.5% and 94001 Ewe @ Poolewe in the northwest records 22.8%.

The spatial distribution of the abnormally high or low frequencies of October and November floods described above can be used to produce a general characterisation of the patterns of flooding in these two months. Higher frequencies of October - November floods occur in the south and west of the area, while low frequencies occur most commonly in the east. Extreme values often occur in isolation rather than forming part of any area of generally high or low frequencies, so as in previous two-month periods, smooth patterns tend not to be found. For all stations, however, this period is one of the most important in the year for flood occurrence.

4.3.2.4 December - January (Figure 4.3d)

The frequency of flooding in December and January is, for the study area as a whole, slightly higher than for the previous two months and the average frequency of 30.7% is the highest of all the two-month periods. A standard deviation of 6.2% indicates a close distribution of values about this mean, and a similar distribution to the previous period. In describing the spatial distribution of values, a similar approach is therefore employed, and attention will be focused on frequency values more than one standard deviation above or below the mean, *ie* values greater than 36.9% or less than 24.5%.

High flood frequency values for this period are found predominantly in inland areas. These form a 'ridge' of values in north and central Scotland from 03002 Carron @ Sgodachail to the Forth basin, and in southern Scotland, high values are rather more isolated, being found in the Tweed, Nith and Clyde basins. The highest of these values occurs at 21019 Manor Water @ Cademuir (48.1%) and the next highest at 18002 Devon @ Glenochil (46.5%). The latter station lies only 3 km from the Firth of Forth and as such might appear to be a coastal station. However, open coastal waters lie more than 50 km to the east, so this can still be considered to be something of an inland catchment. The four next highest values (42.9% - 46.0%) are all found in the north - south oriented area of high values between the Carron and the upper Spey. The River Spey shows quite a smooth downstream decrease in December - January frequencies from 43.2% at 08903 Ruthven Bridge to 31.4% at 08001 Aberlour. The two exceptions to the generally inland distribution of high values are found on the east coast: 14001 Eden @ Kemback records 38.0% and 10002 Ugie @ Inverugie, 42.7%, making it again a somewhat exceptional station.

The corollary of this pattern of high values is that low frequencies are found more commonly in coastal areas, though the part of the east coast containing the two high values noted above is one exception to this. In the east, only one station north of the Forth records less than 24.5%, this being 07003 Lossie @ Sherriff Mills, although the two neighbouring stations on the River Findhorn do record lower than average values of about 28%. These values are best explained by the high frequencies recorded there between June and September.

To the south of the Forth, a quite pronounced area of low frequencies is found extending from 19004 North Esk @ Dalmore Weir to 21022 Whiteadder @ Hutton Castle, with some other lower than average values further south. Like the Lossie and Findhorn stations, these may also be considered to be the result of higher frequencies in other parts of the year (especially between April and July) , but it is difficult to determine whether these low values are simply an unwanted effect of using percentages to express frequency, or whether December - January frequencies in this area are genuinely low. Three remaining low values are found well inland in the southern part of the Tweed basin, at 21001 Fruid @ Fruid, 21024 Jed @ Jedburgh and 21026 Tima Water @ Deephope. All three of these record abnormally high frequencies in other seasons.

On the west coast, some of the low frequencies are found to occur at coastal stations, while others are quite far inland. In the south-west , 77002 Esk @ Canonbie, 83802 Irvine @ Glenfield and 83002 Garnock @ Dalry are all coastal stations with low values. In the Clyde basin, low values are found at 84020 Glazert Water @ Milton of Campsie and 84023 Bothlin Burn @ Auchengeich both within the Kelvin sub-catchment, and at 84009 Nethan @ Kirkmuirhill further inland. Finally, stations 86001, 87801 and 94001, which all record high frequencies in August - September or October - November also show low December - January frequencies.

Description of the distribution of values of December - January frequencies does highlight the interdependence of all these two-monthly frequency values. Most of the low frequencies identified in this period are associated with high frequencies in other periods, and *vice versa*. The lowest frequency of events in this period is 17.7%, still slightly greater than the proportion which would arise from a totally even seasonal distribution, and with 81.5% of stations recording at least 25% of all events in these two months, it can be stated with certainty that frequencies in this period are generally high, even if sometimes reduced by the effect of higher frequencies of flooding in other months. The patterns found are generally rather smoother than those for other two month periods, and are characterised by higher December - January flood frequencies in a substantial inland area in the north of Scotland and in more localised areas in the south, but only rarely in the west. Low frequencies for this period occur in the Moray-Nairn area, one very well-defined part of East Lothian, part of the Tweed basin and in a few more scattered catchments in the west.

4.3.2.5 February - March (Figure 4.3e)

The mean frequency of occurrence of February and March flood events is, at 16.5%, about half that of either of the previous two two-monthly periods, and is quite similar to that for August - September (15.5%). However, the standard deviation of 5.9% is very similar to that for December - January, but because of a significantly lower mean indicates a proportionately greater distribution of values. The two lowest frequencies for the two months are 3.0% at 82003 Stinchar @ Balnowlart and 3.7% at 83002 Garnock @ Dalry; the highest is 33.2% at 06007 Ness @ Ness-side, this station experiencing 89.8% of its events between October and March.

The map of February - March frequency values (Figure 4.3e) shows a strikingly clear east - west gradient, with relatively few anomalies to this pattern. High frequencies are found on the east of the study area, most especially in parts of the Tweed basin and Northumberland. Sixteen stations record frequencies greater than one standard deviation above the mean, and of these only two drain to the west coast. One, 84011 Gryfe @ Craigend is quite close to a number of stations with low February - March frequencies, both on the coast to the south and in the Kelvin basin, with both these groups of low values being quite pronounced. The other is 94001 Ewe @ Poolewe which appears as a definite anomaly on the map, although the lack of other stations nearby makes this difficult to qualify. However, it may prove significant that both this station and 06007 which records the highest proportion of February - March events both lie below large lochs. This idea will be developed at a later stage. Station 15008 Dean Water @ Cookston also stands out as an anomaly with 31.8% of events in this period, again contrasting sharply with the percentage recorded at nearby 15010 Isla @ Wester Cardean (16.6%).

Low February - March frequencies clearly dominate on the west of the map, with only the previously mentioned exceptions of 84011 and 94001 breaking this pattern. Values in Ayrshire are noticeably low, especially those already mentioned at stations 82003 and 83002. The cluster of low values in the Kelvin basin also seems conspicuous; both of these areas of low values have previously been identified as areas of high frequency in the autumn months. None of the low values on the east coast is nearly as low as some of those on the west, the only noticeable cluster being between the River Findhorn and the River Dulnain tributary of the Spey.

February and March can therefore be summarised as months of less frequent flooding than the previous two two-month periods, the general spatial distribution of values being one of increasing flood frequency from west to east, the most significant area of high frequencies being in the south of the Tweed basin and into Northumberland, and the areas of lowest frequencies being on the south-west coast and in the Kelvin catchment. Anomalous high flood frequencies within this period occur below large lochs at Poolewe and Ness-side. It is again felt that some of the incidences of low percentage frequencies arise from high frequencies in other months.

4.3.2.6 April - May (Figure 4.3f)

The mean percentage frequency of April - May floods is 4.2%, with 16 stations having zero frequencies and 68% of stations recording less than 5% of events in this period. Therefore much of the map shows either zero or nominal frequencies; only 8% of stations experience more than 10% of their floods in this period. The highest frequency recorded is 15.2% at 19005 Almond @ Almondell.

The spatial distribution of higher frequencies is quite a clear one, being based almost entirely on the east coast. Indeed, only a small part of the east coast displays values less than 5%, this being around the Moray Firth, Black Isle and Caithness. In north-east Scotland, the area of greater than 5% frequencies extends well inland, but other than this, such values are confined essentially to coastal areas. Areas with values above 10% are somewhat limited, occurring in West Lothian, East Lothian, Berwickshire and south-east Northumberland. On the west coast, two isolated catchments record values exceeding 5%, namely 86001 Little Eachaig @ Dalinlongart and 94001 Ewe @ Poolewe. In inland areas, values tend to be lower than at either coast. In summary, this period of the year is one of generally low flood frequency, with a tendency for slightly more frequent occurrences on the east coast and lowest frequencies in inland areas. This pattern is quite similar to that for the months of June and July.

4.3.2.7 Summary of patterns in two-monthly maps

To summarise this section, it seems useful to list the most prominent spatial patterns found in the two-monthly data. A general symmetry exists in the two-monthly frequency values, with April - May and June - July experiencing low flood frequencies, October - November and December - January showing high frequencies, and the intervening August - September and February - March periods having intermediate frequencies. However, within this overall seasonal distribution, considerable spatial variation is found.

The two pairs of low frequency months exhibit quite similar spatial patterns, with the highest frequencies occurring on the east coast although these rarely account for more than 10% of events in either two-month period. In August and September, the highest frequencies are found in parts of south-west Scotland and decrease towards an axis of low frequencies stretching from the Firth of Tay to south-east Ross, beyond which some further high values are found in the north-east. Events are again more frequent in the south and west in October and November, with lower frequencies in the east of the country. However, stations with extreme values in this period are often quite isolated and patterns are not particularly smooth. December and January show a pattern of values where proximity to coastlines seems to correlate with values, higher frequencies being found inland and also in the east. Lower December - January frequencies are conspicuously concentrated in the Lothians and to the south of the Moray Firth. Both high and low frequencies in this period seem to correlate inversely with extreme frequency values in other periods. Finally, frequencies in February and March are highest in the east, particularly the south-east, and lower in the west, most especially along the south-west coast.

The combination of all these distributions is seen in Figures 4.2a and 4.2b showing the spatial distribution of mean day of flood and *r* values: the mean day of flood is seen to be later at stations in the east of the area than in the west, and *r* values are notably low around the Lothians and to the south of the Moray Firth reflecting a propensity for events to occur relatively evenly around the whole year rather than being heavily concentrated only in the winter months. These maps provide a condensed summary of the information presented in the two-monthly maps.

Finally, it is worth concluding this section on the two-monthly data by noting some stations which regularly provided anomalies to the more general patterns presented in Figures 4.3a - 4.3f. A number of catchments within the Kelvin basin record anomalously high flood frequencies between August and November and low frequencies later in the year. The south-west coast sees some most unusual seasonal distributions, station 83002 being the most exceptional with 75.4% of events occurring between August and November while the short 80003 Loch Dee record witnesses 43% of events in August and September. Stations 06007 Ness-side and 94001 Poolewe, which both lie below large loch storages, often provide anomalies: especially high frequencies are found in February - March, and the mean day of flood values found are significantly higher than those at neighbouring stations. Like Ness-side, station 10002 Ugie @ Inverugie, in the north-east extremity of Scotland, records 90% of its events between October and March. Lastly, stations 86001, 87801 and 91802 on the west coast must be mentioned, with numerous notably high and low frequencies noted earlier indicating some rather unusual seasonal distributions. All three of these catchments lie in quite mountainous areas, but rather than having similar seasonalities of flooding as might be expected from stations in similar environments, significant differences between them have been observed. Reasons for these anomalies will be sought in the following chapters.

4.4 Discharge considerations

It would be both tedious and impractical to give an individual description of each of the rose diagrams presented in Appendix C. However, to examine them reveals that each is different, and considerable variation appears within spatial groupings of stations. The preceding sections of this chapter have examined variations between stations in the frequency of events occurring in different periods of the year. This final section considers event magnitudes by the identification of those stations where larger flood events have a different seasonality to that of the full flood record at a station.

Section 4.3 of this chapter has shown that with only the rarest of exceptions, the months between October and January are absolutely dominant in terms of the proportion of events occurring in this period, although start and end points to this season cannot easily be defined. These events may be considered as a spatially invariant base population within the total set of all flood events, *ie* dominance of winter flooding is assumed to apply at all stations. It can also be seen from Appendix C that smaller events within this season are more common than larger ones, as would be expected from an understanding of magnitude - recurrence interval relations. However, inspection of the rose diagrams in Appendix C reveals that such winter events are not always the largest in any one record. In order to identify the occurrence of significant populations of high magnitude, non-winter events, the modal month of the twenty largest floods in each record was found and compared with the modal month of the whole record. Comparison of modes in this way allowed the identification of stations where non-winter floods were of importance at high magnitudes while being less important in the overall seasonality of flooding on a river. These differences, along with the modal month values from which the differences are derived, are plotted in Figures 4.4a - 4.4c. Patterns within the modal difference values are described in the following paragraphs.

Figure 4.4a

MODAL MONTH: ALL EVENTS

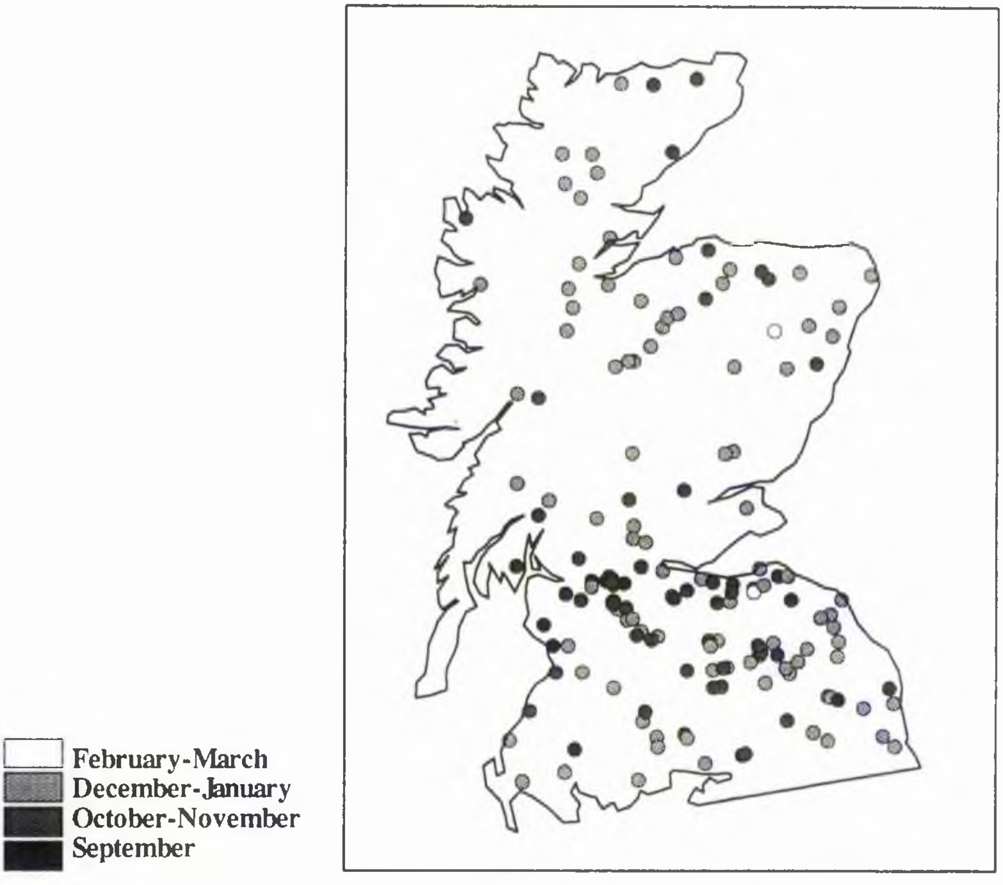


Figure 4.4b

MODAL MONTH: LARGEST 20 EVENTS

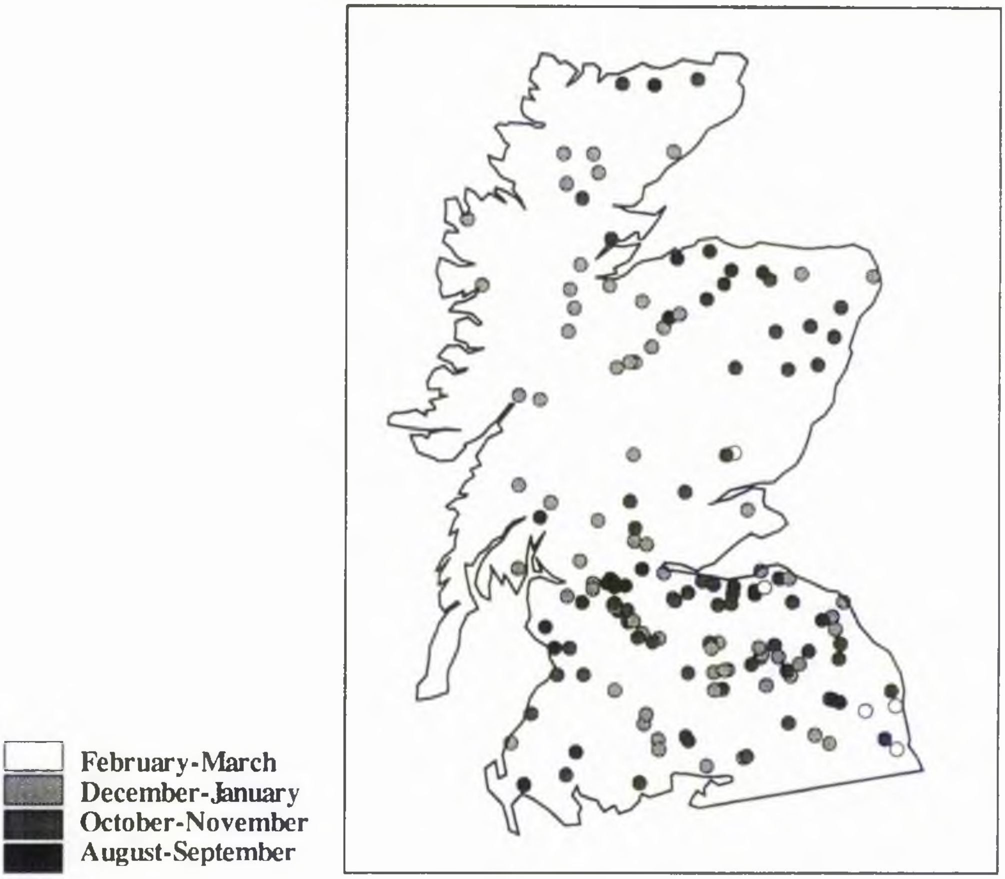
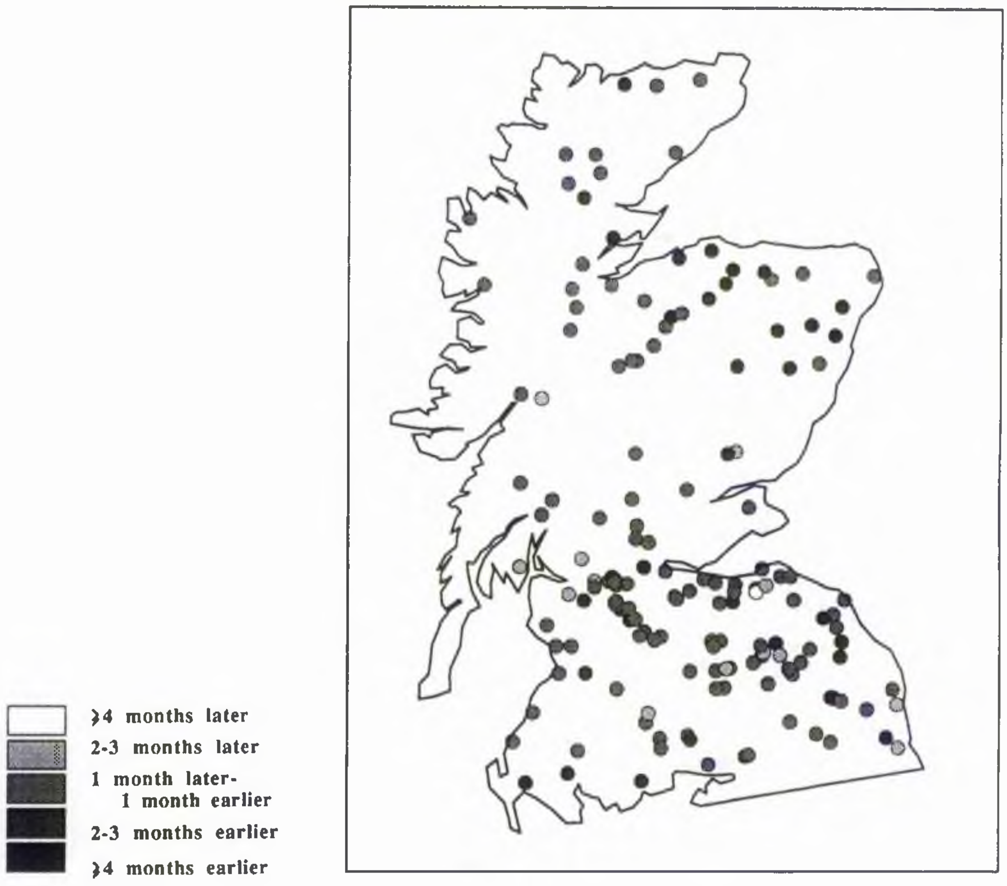


Figure 4.4c

SHIFT IN MODAL MONTH

20 LARGEST EVENTS RELATIVE TO FULL RECORD



In the far north of Scotland, three stations are found where the modal month of the largest events is two or three months earlier than that of the overall population, these being 96002 Naver @ Apigill, 03002 Carron @ Sgodachail and 04003 Alness @ Alness. The modal month for the largest events at 96001 Halladale @ Halladale is September, early in comparison with other stations in this area, but the overall mode is October (the station also has a relatively early mean day of flood of 172), so autumn flooding can be said to be important at high discharges at the three first-mentioned stations and more generally at Halladale.

A more marked departure from the overall modal month of flooding occurs on the River Lossie, lower Findhorn and lower Spey. August and September are the modal months for larger events in this area, compared with an overall December mode at most stations. It is noticeable that this area is quite sharply defined, stations above Grantown on the mainstream Spey being completely winter-dominated, although 08009 Dulnain @ Balnaan Bridge shows an August mode for larger events, and it is thought that this river and the Avon further downstream are influential in producing summer modes at 08001 Aberlour and 08006 Boat o' Brig on the mainstream. To the east, the modal month for the twenty largest events is generally October, still considerably earlier than for the overall POT series at these stations. This area extends from the north coast to the Firth of Tay. 15008 Dean Water @ Cookston is once again exceptional, with its high discharge modal month, March, two months later than for its overall record.

South of the Tay, differences in modes are generally smaller; where a difference in modal month exists, the mode for large events is in most cases slightly earlier than for the whole record. 20005 Birns Water @ Saltoun Hall appears as a major isolated anomaly on the map, with a difference of five months. This is due to an overall mode of March - this month is important at other East Lothian stations but is never the month of most frequent flooding elsewhere in the area - combined with an August mode for large events, this being repeated nowhere else in the Lothians. Further south again, difference in modes are more variable in the Tweed drainage basin and in Northumberland, with the mode for large events occurring both before and after the mode for whole records. Spatial variation in these values seems to be without any easily defined trend.

In the south-west, a number of stations along the Solway and Ayrshire coasts show relatively early modal month values for large events as a result of high peaks occurring in September and October. The large difference in modes (three months) at 78005 Kinnel @ Bridgemuir is of little importance, as 18 of the largest 20 events are distributed evenly among six months. In the Clyde basin, some stations both on the Clyde itself and on its tributaries show earlier modes for large event populations, while around the Firth of Clyde, four stations show the large event mode being two or three months after the overall mode. Finally of note is 91802 Allt Leachdach @ Intake, where the large event mode of January occurs three months after an early overall mode of October.

The foregoing observations demonstrate that at some stations, and sometimes in clear geographical regions, the largest flood events in a record do have significantly different seasonal distributions to the overall pattern of seasonality for the corresponding whole POT record. Use of the mode to investigate this is a simple method, but the patterns identified here suggest it is nonetheless an effective one. The area around Morayshire and the whole of the area from Buchan to Tayside have been identified as having significant populations of late summer or early autumn events of high magnitude, and similar behaviour is found around the coast of south-west Scotland. In other areas, differences in modal months are more variable: in the far north, a few stations show earlier events to be important at high discharges, and in the Tweed basin and southwards, the highest monthly frequencies of large events can differ in either direction from the overall mode. This consideration of magnitude therefore adds significantly to the description of patterns made in previous sections which dealt only with season of occurrence of flood events.

4.5 Classification analysis

By using three separate methods of describing seasonality, a large amount of information has been produced in the preceding sections of this chapter. The three methods can be seen as complementing one another, as each provides information not revealed by the others. This amounts to a very comprehensive description of the patterns of seasonality across Scotland. However, it is difficult to assimilate all the information provided to gain a general picture of how seasonality varies across space. A method of condensing the appropriate information was required to simplify the many patterns which have been described and, to this end, a classification analysis was employed. This enables the seasonality of flooding at each site to be described by reference to one of a small number of seasonality groups, and, by plotting the group membership of individual stations on a map, allows spatial patterns to be easily understood. The greatest advantage of a classification analysis was seen to be the ability to condense several sources of information into a single-term description of seasonality for each site, since values of a large number of scalar variables can be used to determine group membership.

To implement the classification analysis of the seasonal data, a computer package, CLUSTAN (Wishart 1987), was used. Four separate aspects of the classification had to be determined: the choice of input variables to describe seasonality; the classification method to be employed; the similarity measure to be used and the final number of groups (clusters) to be arrived at.

It was decided that the analysis should be based upon the two-monthly flood frequency data described in Section 4.3 as this provided a detailed source of information for the analysis. Mean day of flood and r values would not be needed in addition, since these can be seen as summarising the two-monthly data. It was also decided not to include the modal month data produced for high discharge events, as it was felt that at stations with relatively short records, the small number of events exceeding a low frequency threshold would make the use of such data somewhat unreliable. However, the data set did include all stations which satisfied the requirements of the threshold revision, including those where standard period-adjusted two-monthly frequency values were not available. In such cases, unadjusted values based simply on the period of record available were used, thus enabling an improved spatial coverage to be achieved.

A classification analysis involves the allocation of cases (in this instance catchments) to clusters, and this can be done using a great variety of methods. The choice of method determines the specific means by which cases are combined to form clusters, and the CLUSTAN user manual recommends a two-part method for a study with this number of cases (143). Initially, Ward's method, which involves a hierarchical fusion of clusters at each step in the classification, is to be used. At the first step, each case is considered to constitute a one-member cluster, and, at each subsequent step, the two closest clusters are merged with each other, distances being calculated in terms of euclidean sum of squares which is a standard method of calculating distance in multivariate space (principal component values were used, as recommended, rather than the actual values of the six original variables). This method was used to produce ten clusters after which point a second method is recommended. This involves iterative relocation of cases from within their existing groups to new groups wherever this results in a reduction in within-group variation (distance between members of a group) and an increase in between-group variation (distance between groups). In this way, groups become better-defined than is possible by a hierarchical method in which no relocation is possible after initial fusion of clusters. Fusion then proceeds until the desired number of clusters is produced, and in this case the classification was terminated with four clusters since these appeared to represent four physically meaningful models of flood seasonality.

Figure 4.5 shows two-monthly flood frequency values for the members of each of these four groups; actual values are presented in Figure 4.5a, while a more accurate picture of the typical seasonality of flooding in each can be gained from Figure 4.5b where 25, 50 and 75 percentile values of the two-month frequencies are given. Taking each group in turn, Group A is characterised by a strong winter seasonality, with the highest two-monthly percentage occurring in either October-November or December-January at all but one of its stations, and 69% recording over 50% of events in these four months.. Flood frequencies in the remaining months of the year are therefore rather low, and it can be seen that frequencies in August-September and February-March are considerably lower than in the intervening two two-month periods. Group A may therefore be considered to be composed of stations with winter-strong seasonality.

Group B is distinguished by the unusually high number of events occurring in late winter, with February-March frequencies being considerably higher than for any other group, and generally only a little lower than for December-January. Frequencies in this group are low in April-May and June-July - as is generally the case - but then gradually rise through August-September and October-November to a maximum in December-January or occasionally February-March. This group has less pronounced seasonality than Group A (mean r value 0.491 compared with 0.564 in Group A), but still the high proportion of events occurring in late winter is a strong characteristic.

Group C is characterised by a much less pronounced seasonality than any of the other three groups and is therefore composed of the stations with the lowest r values (mean=0.355). Only rarely does the number of events occurring in any two-month period exceed 30% of the total, and June-July frequencies are conspicuously high. Unexpectedly perhaps, the opposite is found in August-September for most stations in this group, but the lack of any season with unusually high flood frequency defines this group clearly as one with a very weak

Figure 4.5a
Two-month frequency
values for Groups A-D
JJ=June-July; AS=August-September; ON=October-November; DJ=December-January; FM=February-March; AM=April-May

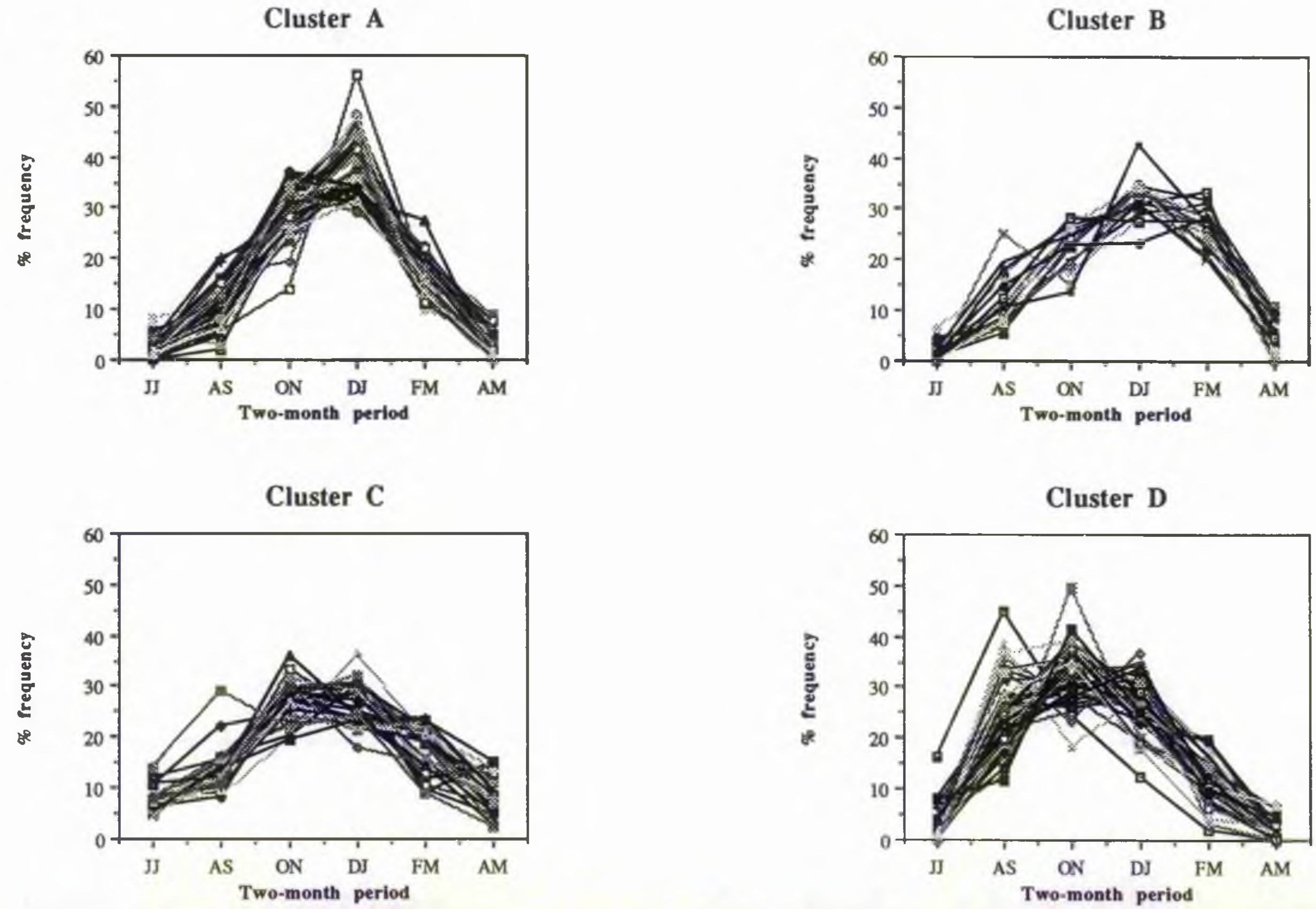
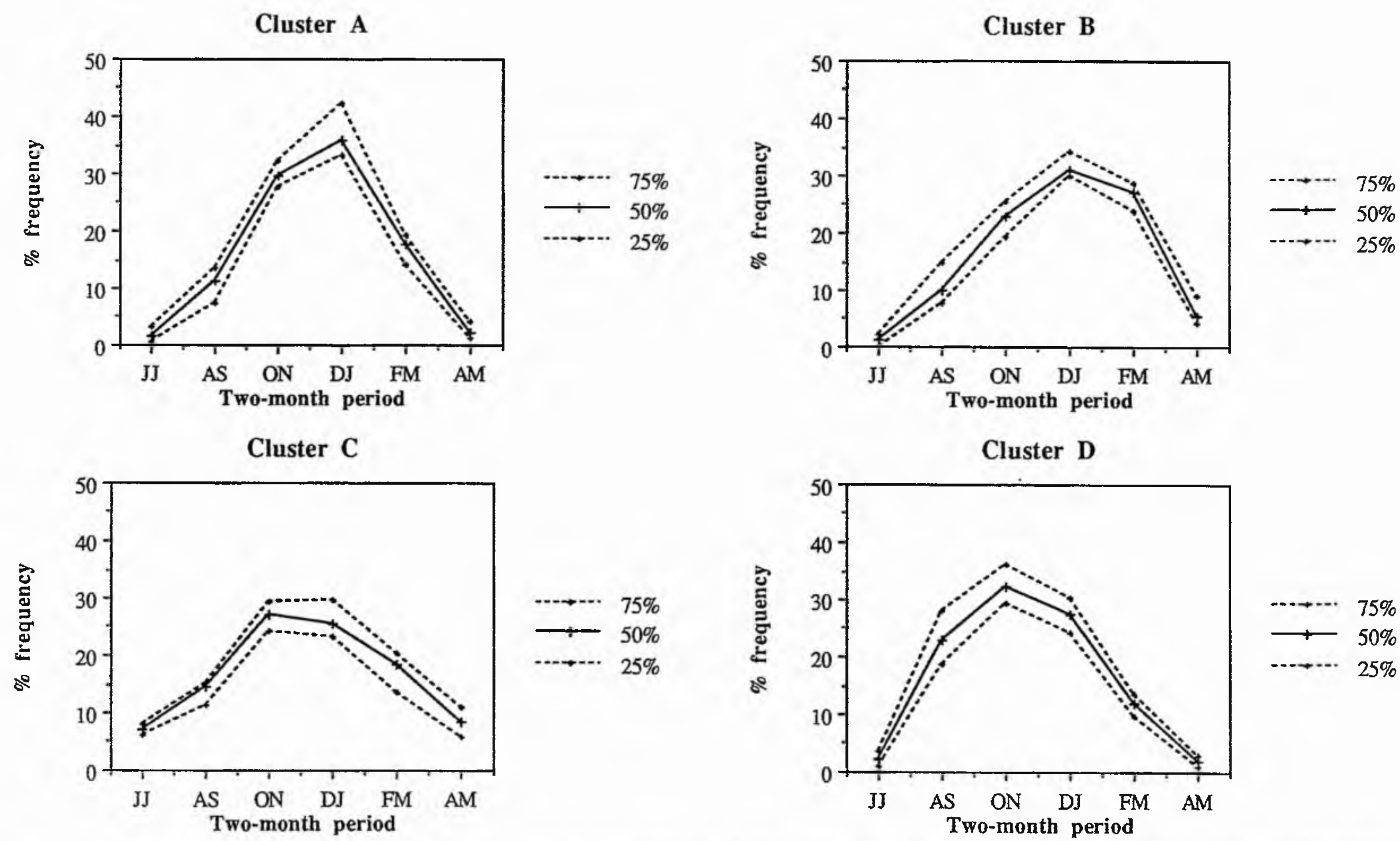


Figure 4.5b
Median and quartile ranges for two-month frequency values in Groups A-D
JJ=June-July; AS=August-September; ON=October-November; DJ=December-January; FM=February-March; AM=April-May



seasonal signature, and a rather earlier mean day of flood than Group B which has only a relatively modest seasonality.

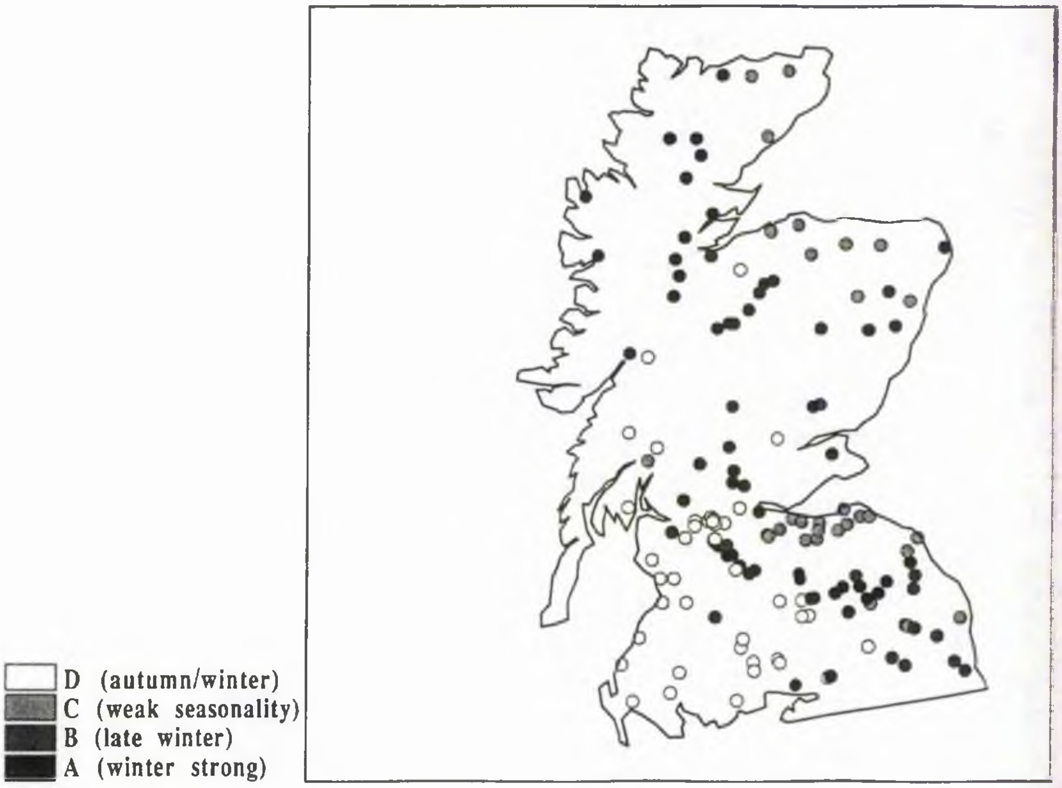
Finally, Group D is characterised by a relatively strong early seasonality. August-September frequencies are unusually high at stations in this group, and the season of maximum frequency is no later than October-November at 78% of its members. Though there is a strong seasonality at these stations, Group D stations are clearly differentiated from those of Group A by their significantly earlier bias.

The spatial patterns in group membership can be seen in Figure 4.6, and it is immediately apparent that each of the groups has its own spatial distribution of members. Beginning with Group A, these stations with winter-dominated seasonality are generally found in inland areas and often on rivers draining large catchments: many Group A stations are found on the Rivers Clyde, Tweed, Dee and Spey and some of their larger tributaries. Group B stations are heavily concentrated on Northumberland and the Borders, with only six of the seventeen members occurring outwith this area. Of these, two occur below two of the largest loch storages in the study (06007 Ness @ Ness-side below Loch Ness and 94001 Ewe @ Poolewe below Loch Maree), but the concentration of Group B stations in the south-east of the study area is striking.

Even more striking, perhaps, is the spatial distribution of the members of Group C, which are essentially confined to two geographic areas. In north-east Scotland, a cluster of these stations with especially weak seasonality is found in a coastal area extending from the River Dee to the lower River Findhorn and across the Moray Firth to Caithness. Further south, a larger and more concentrated cluster of stations is found on the south shore of the Firth of Forth, encompassing the rivers between the Almond and the Tyne, with a further four examples being found further south in Berwickshire and Northumberland. None of the stations on rivers along this stretch of the Firth of Forth belongs to any other group. Finally, the members of Group D, showing a pronounced early seasonality, are found most predominantly in south-west Scotland. Only three of the 21 stations in hydrometric areas 77-83 belong to any other group; a strong cluster of Group D stations is also found in the Kelvin sub-catchment of the Clyde, but only five examples are found north of the Forth-Clyde valley.

This classification analysis allows a succinct description of the seasonality of flooding across Scotland to be made. It has been possible to identify broad spatial

Figure 4.6
GROUP MEMBERSHIP FOR 143 STATIONS



patterns, along with exceptions to them. The area with the earliest flooding in the year is south-west Scotland, where flood frequencies in August-September and October-November are especially high. Moving directly east, flooding in Northumberland and at some stations in the Tweed basin is somewhat contrasting, with the months between December and March assuming greatest importance. Immediately to the north, a concentrated cluster of Group C stations indicates a much more even distribution of floods amongst the seasons, and another similar cluster of Group C stations is found in north-east Scotland. Stations with winter-dominated seasonality are found in some numbers in all parts of Scotland except the south-west, but are mostly confined to relatively large basins and inland areas.

However, these are only general trends and Figure 4.6 shows exceptions to them. Some of these appear as the result of the four groups employed merging into each other to some extent, with the effect that, in some instances, stations with relatively similar seasonalities will be shown as belonging to different groups. In other cases, however, adjacent catchments do have markedly differing seasonalities. A good example might be a cluster of three stations in the Tweed basin which each belong to a different group: 21009 Tweed @ Norham belongs to Group A, having a clearly winter-dominated flood seasonality, but a left bank tributary, the Whiteadder Water (station 21022) shows a much less pronounced seasonality and is assigned to Group C while on the opposite side of the main river, the River Till (station 21031) is assigned to Group B on account of its late winter seasonality. It would therefore seem that the determinants of flood seasonality must operate at both regional and more local scales. On the one hand, regional effects such as the general trend for flooding to occur later in the east than the west are likely to be controlled by large-scale meteorological factors, while more localised differences such as the Tweed example given above are likely to be the result of a variety of catchment-scale factors. The causes of the patterns of flood seasonality described here are discussed in Chapter 5.

4.6 Discussion

In the course of this chapter, a detailed description of the patterns of seasonality across the study area has been given. By using a number of different methods of description, many different aspects of these patterns have been identified. However, for the sake of giving a general description of these patterns, a classification analysis was employed, enabling a simple description of the spatial patterns present to be made. This analysis has allowed significant progress to be made beyond the simple mean day of flood map approach to describing seasonality which formed the basis of Hewson's work (see Chapter 2).

Though the basic trend for floods to occur later in the year in the east than in the west has been confirmed in the present investigation, representation of seasonality types through a classification analysis has shown that spatial patterns are not as simple as might be suggested by such an approach. Members of the four seasonal groups identified show distinct spatial clusters, interrupted in places by members of other groups, and these patterns are thought to represent the effects of both regional and catchment-scale controls of seasonality.

The unusual seasonality of flooding identified in the Moray-Nairn and Lothian areas by Hewson is also confirmed, not only in terms of seasonal flood frequencies, but also with reference to discharge values. This has been found in all the approaches to describing seasonality used in this chapter, but is perhaps best represented by the specification of Group C in the classification analysis whereby recognition is given to a type of seasonality in which floods occur in significant numbers at all times of the year. This type of seasonality contrasts strongly with the conventional supposition of winter dominance, and will be considered worthy of special attention in the next chapter in which seasonal patterns are explained.

Finally, in addition to noting the merits of a classification approach to describing the patterns of flood seasonality across Scotland, the value of the earlier approaches to describing seasonality should be restated. Considerable effort has been expended in standardising the data with respect to record length and discharge threshold, thereby reducing as far as possible any sources of inaccuracy. Moreover, a large number of gauging stations ensures that the results of the survey, displayed in a number of forms, can be regarded as a high quality and comprehensive description of the seasonality of flooding in Scotland. This provides a sound basis on which to attempt an explanation of the seasonal patterns present.

Chapter 5

Explanation of Seasonal Patterns

5.1 Introduction

The spatial patterns of flood seasonality across Scotland described in Chapter 4 form the starting point of this chapter, the purpose of which is to identify the factors which determine flood seasonality, and the rôle of each. The factors considered are those which originate in the hydrological theory which deals generally with the origins of floods and, more particularly, those identified in Chapter 2 which have been shown to have particular relevance to seasonality. The overall aim of this chapter is to provide as complete an explanation as possible of the seasonal patterns of flooding found in the gauging station records used in this study.

The chapter proceeds by evaluating separately each controlling factor before a final synthesis incorporating all pertinent factors is developed. Since the previous chapter concluded with a description of seasonal patterns of flooding based upon a specific classification scheme, this chapter develops directly from that classification, *ie* group (cluster) membership is explained in terms of spatial and temporal variation in the controlling variables. The chapter concludes with an application of its general findings to those areas noted in Chapter 4 for their unusual seasonalities and a discussion of how these findings compare with expectations.

5.2 Controlling factors

5.2.1 Seasonality of rainfall

In Scotland, as in most other areas of the world, storm rainfall is the primary cause of the great majority of flood events. The rôle of snowmelt in flood generation is also known and is considered later in this chapter, however this is very much a secondary factor in flood generation in Scotland. It therefore seems logical to begin this consideration of the factors influencing flood seasonality with an examination of the rôle of rainfall.

Rainfall is a key consideration in all the various approaches to flood studies, from mean annual flood estimation to the modelling of individual flood hydrographs. In seeking to explain flood seasonality, a seasonal analysis of storm rainfall occurrences is required, though the definition of the storm rainfall most relevant to flood generation will vary from one catchment to another. Irrespective of this, the basic requirement is to assess the seasonality of those rainfall events which, subject to other factors, could produce a flood event. The analysis must therefore concentrate on relatively short duration rainfalls - of hours or days rather than weeks or months - in order to assess the rôle of rainfall seasonality.

In a study of such a large number of catchments as this, data availability is obviously an important consideration. The *Flood Studies Report* (NERC 1975 I.6) presents a method of determining the critical duration of rainstorm for the flood response of a catchment. To calculate the seasonality of rainfalls of such durations for each catchment would require the availability of autographic rainfall data, giving rainfall values with, say, an hourly time resolution. Unfortunately, such data are not available since autographic rain-gauges are rather sparsely distributed over Scotland and, even for those catchments for which autographic data are available, collection of the data would be extremely costly. What does exist, however is a comprehensive network of gauges recording daily rainfall totals, and reference to this appeared to be the only means of producing an assessment of rainfall seasonality. In fact, 24-hour data appear to be quite suitable for a large majority of catchments in the study, since the equation given for storm duration d_m,

$d_m = (1.0 + \mathrm{SAAR}/1000)\ T_p$ (NERC 1975 equation 6.43)

where SAAR = standard average annual rainfall, 1941-70 (mm)
and T_p = time to peak (hours)

shows d_m to be close to or greater than 24 hours for most catchments. An investigation into the differences in seasonality between one, two and three day durations showed little sensitivity to duration.

5.2.1.1 Data Collection

To proceed with this analysis, total daily rainfall data were gathered for rain-gauges located in, or as close as possible to, all catchments satisfying the standard threshold requirement of 45 floods over the period 1979-88 or equivalent, as described in Chapter 3. These data were derived from Meteorological Office records held on the Institute of Hydrology mainframe computer and were analysed for as much of the period 1961-90 as was available for each rain-gauge. In each case, peak rainfall values were found for one-day totals which exceeded a threshold value exceeded on average ten times per year throughout the period of record used. This threshold frequency was determined somewhat arbitrarily, but as a preliminary analysis had shown that roughly half of the events in POT daily rainfall series actually caused floods exceeding a five events per year threshold value, it seemed sensible to allow approximately twice the annual average number of flood events to enter the rainfall series. Seasonality was characterised by calculation of a mean day of peak rainfall from these data series in a comparable manner to that applied to the flood series, and also an r index of clustering about the mean and two-monthly percentages of the total number of exceedances.

Rain-gauges were selected on the basis of proximity to catchment centres, while giving consideration to the length of record available where a choice existed between the use of more than one rain-gauge. For small catchments, it was felt that the use of data from a single rain-gauge was quite adequate to characterise the seasonality of storm rainfall over such basins. However, for larger basins, exceeding approximately 300 km^2 in area and where sufficient data were available, multiple gauges were used to allow for spatial variation in the seasonality of rainfall peaks. A simple arithmetic mean of daily rainfall values was calculated for analysis in such cases. Whilst acknowledging the inaccuracy of this method which makes no attempt to partition catchments into specific areas on the basis of the individual rain-gauges present, as is the case in rigorous physically-based models, and even of the simple use of single rain-gauge records which make no allowance for orographic effects (Browning and Hill 1981), it is felt that these factors do not compromise the expression of the level of variation of rainfall seasonality within catchments. A maximum of four rain-gauges were used in calculating the seasonality of peak rainfalls for the largest basins in the study. The rain-gauge records used for each catchment are detailed in Appendix F.

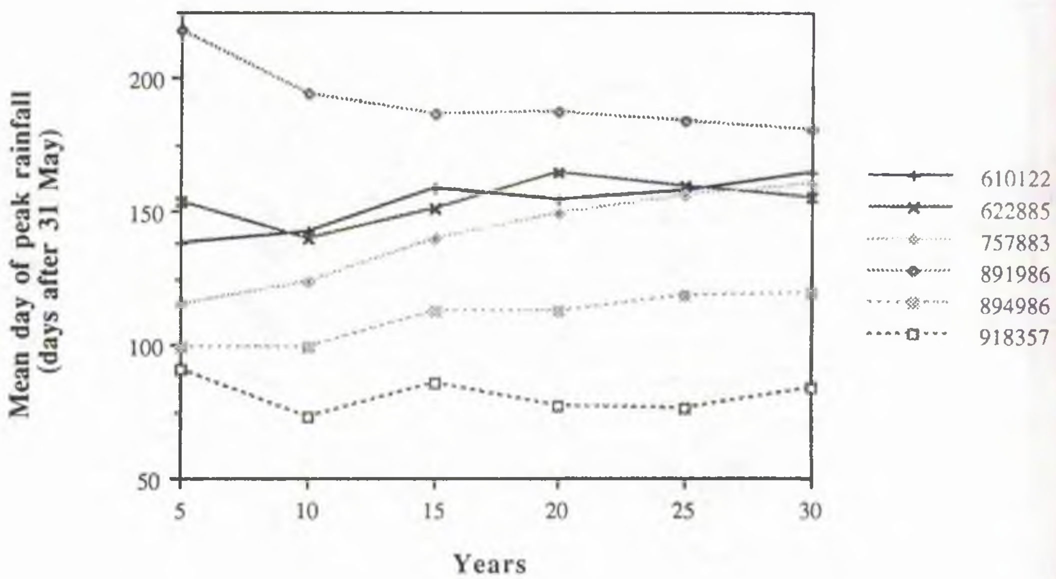
The density of the rain-gauge network varies greatly, and with it the length of daily records available at each gauge. The greatest density of available data is found in the southern part of the study area, and the least in remote, little-populated and especially upland areas. This might appear to have implications for the representativeness of these rainfall data. The great variability of period of record available means that it is impossible to use a common period of rainfall record for all catchments, and the use of short records might particularly threaten accuracy. However, examination of the effect of varying the length of record used for a random sample of rain-gauges shows (Figure 5.1) that above 15 years, mean day of peak rainfall and r are closely comparable to their longer-term (30-year) values, while with only ten years of record, differences in mean day and r relative to their 30 year values are somewhat greater. In 18 catchments, rainfall records were ten years in length or less, so these could be slightly misrepresentative of a longer-term mean seasonality, but they have been used in the absence of any alternative. Data quality was controlled, however, by using data only for years with less than ten missing daily values, as it was realised that failure to do so could introduce a seasonal bias into the results obtained. It was noticeable that data tended to be missing more frequently in winter months than in summer.

5.2.1.2 Analysis

Consideration will first be given to the mean day of peak rainfall and associated r values displayed in map form in Figures 5.2a and 5.2b. These two values will be discussed together, as r values are essential to the understanding of the mean day values shown. Values for r vary from less than 0.1 to greater than 0.6 and signify a wide range of seasonal distributions of storm rainfalls, from essentially no seasonal variation in the frequency in storm rainfalls, to quite pronounced seasonal bias. The lowest r values are generally found in the east of the study area, most especially in Morayshire and Nairnshire, East Lothian and East Northumberland. In these areas, mean day of peak rainfall values are low, but also quite meaningless as the very low r values indicate that there is no significant clustering of peak rainfalls in any season. This can be verified by examination of Figures 5.3a-5.3f which show the seasonal distribution of rainfall events in two-month periods.

Figure 5.1
Variation of peak rainfall mean day and r values with record length

a) Variation of Mean Day with record length



b) Variation of r with record length

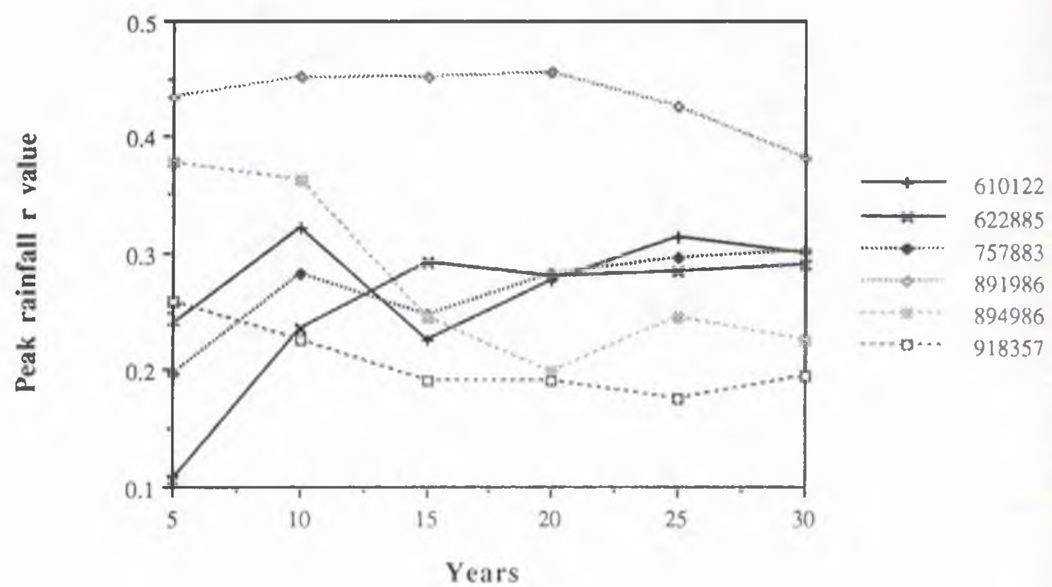


Figure 5.2a

MEAN DAY OF PEAK RAINFALL

Figures 5.2a-b
Values plotted for actual raingauge locations

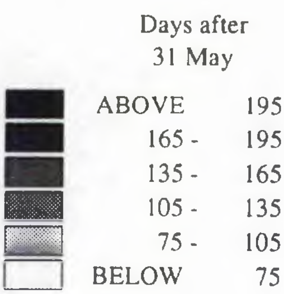


Figure 5.2b

PEAK RAINFALL r VALUE

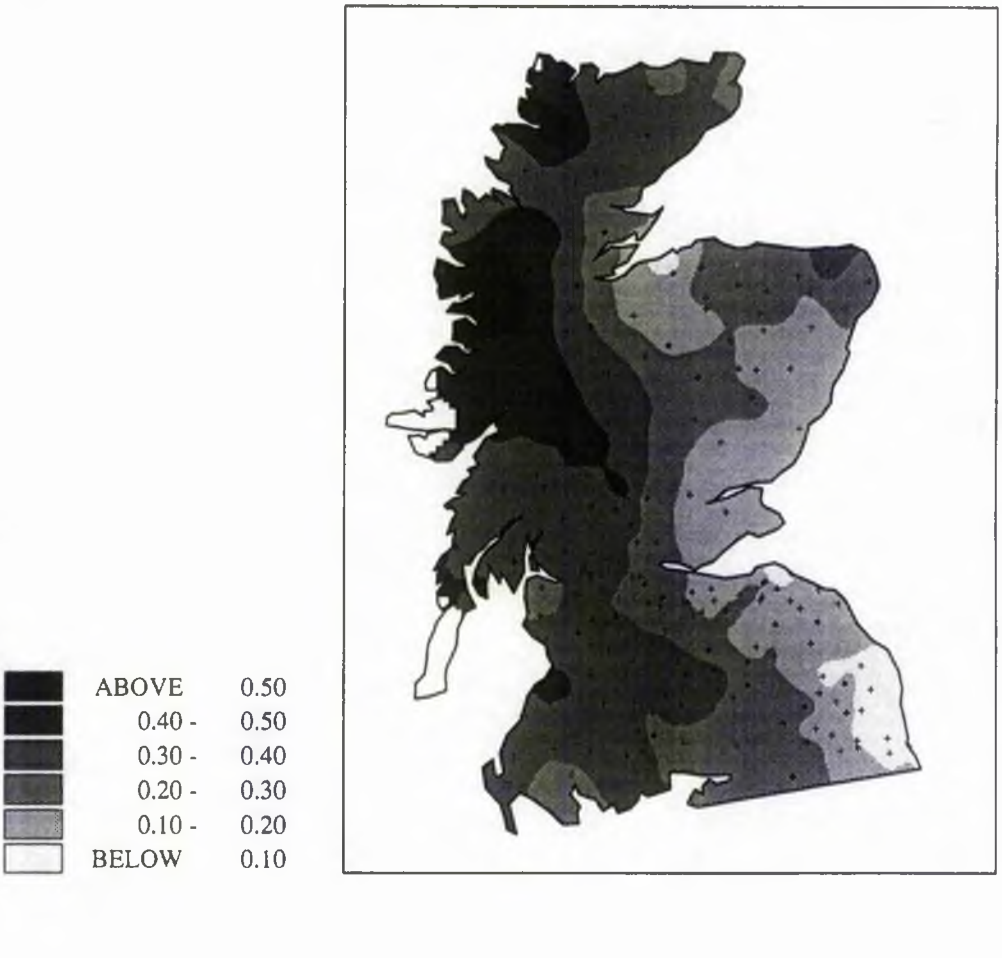


Figure 5.3a

JUNE-JULY PEAK RAINFALLS AS % OF TOTAL

Figures 5.3a-f
Values plotted for actual raingauge locations

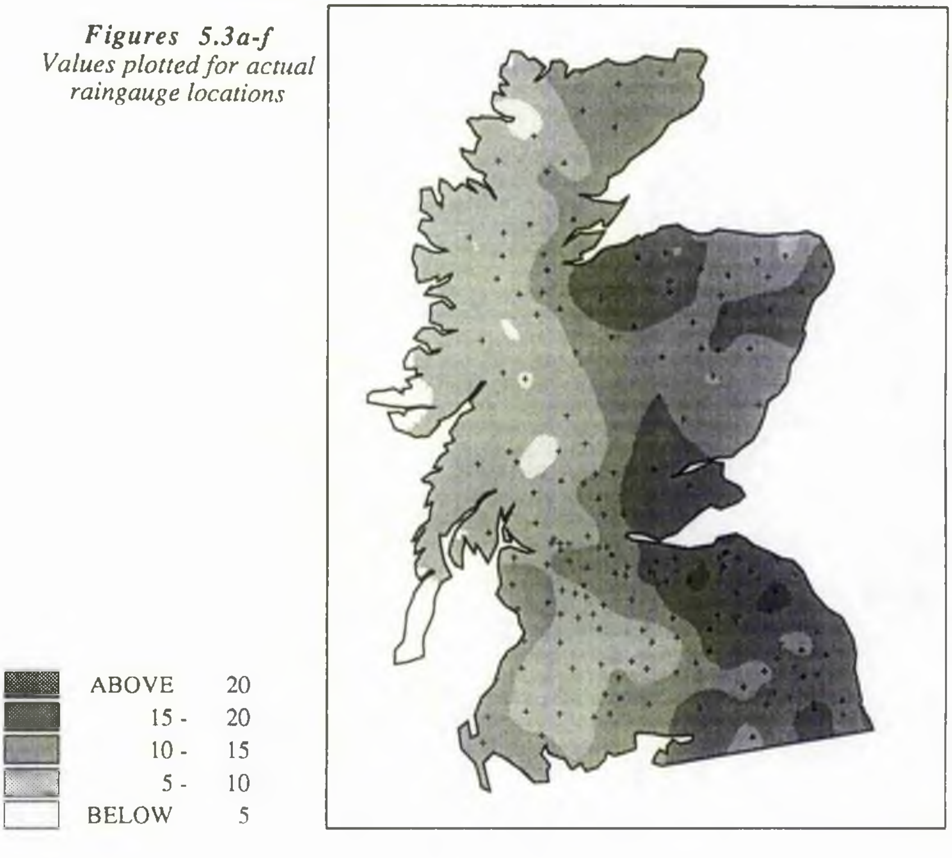


Figure 5.3b

AUGUST-SEPTEMBER PEAK RAINFALLS AS % OF TOTAL

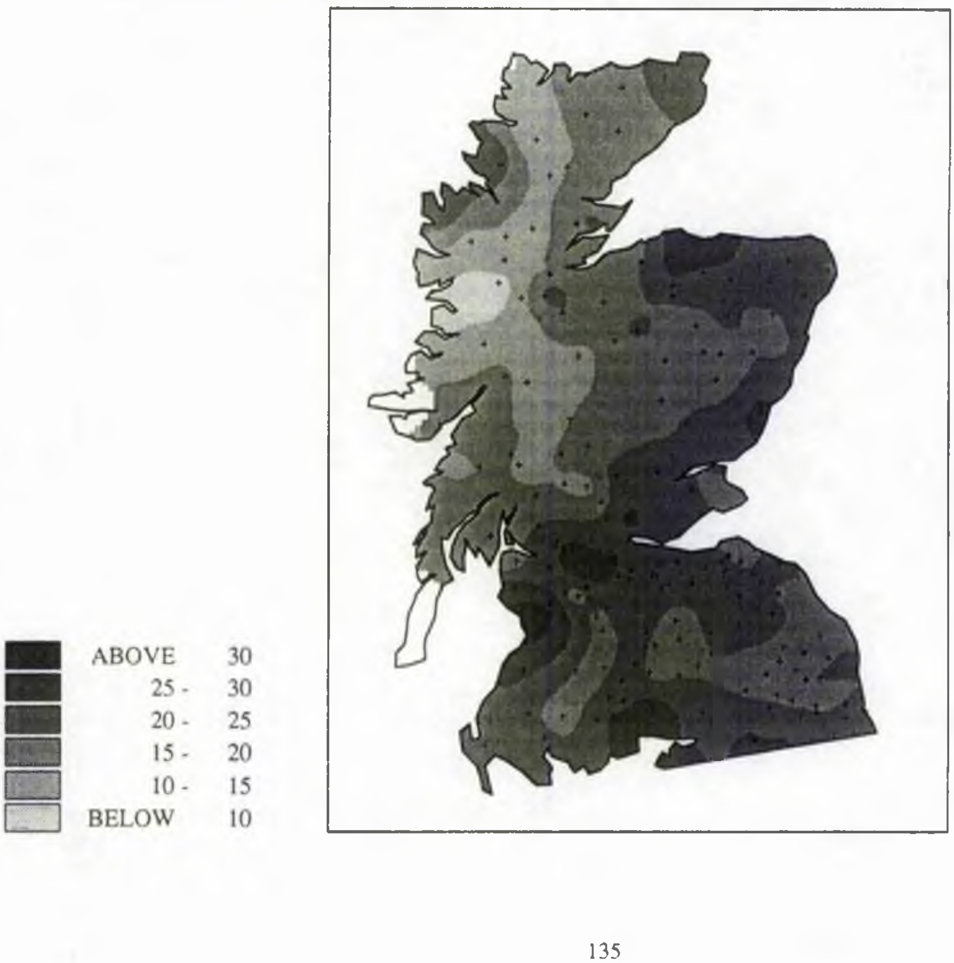


Figure 5.3c

OCTOBER-NOVEMBER PEAK RAINFALLS AS % OF TOTAL

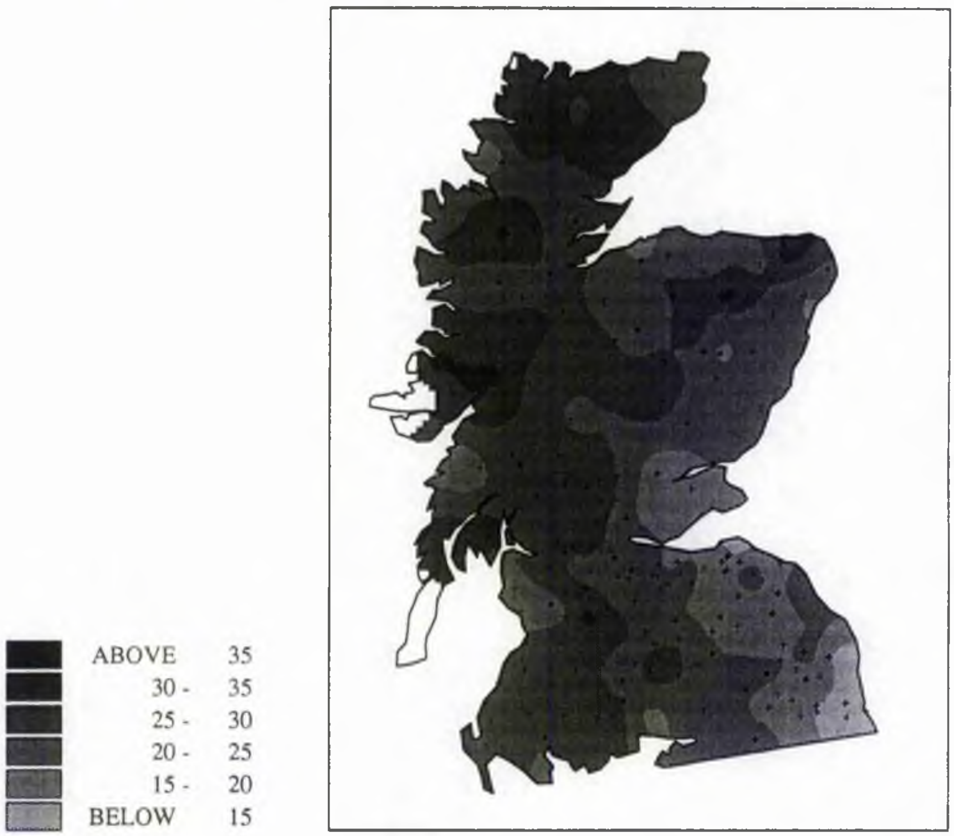


Figure 5.3d

DECEMBER-JANUARY PEAK RAINFALLS AS % OF TOTAL

Figure 5.3e

FEBRUARY-MARCH PEAK RAINFALLS AS % OF TOTAL

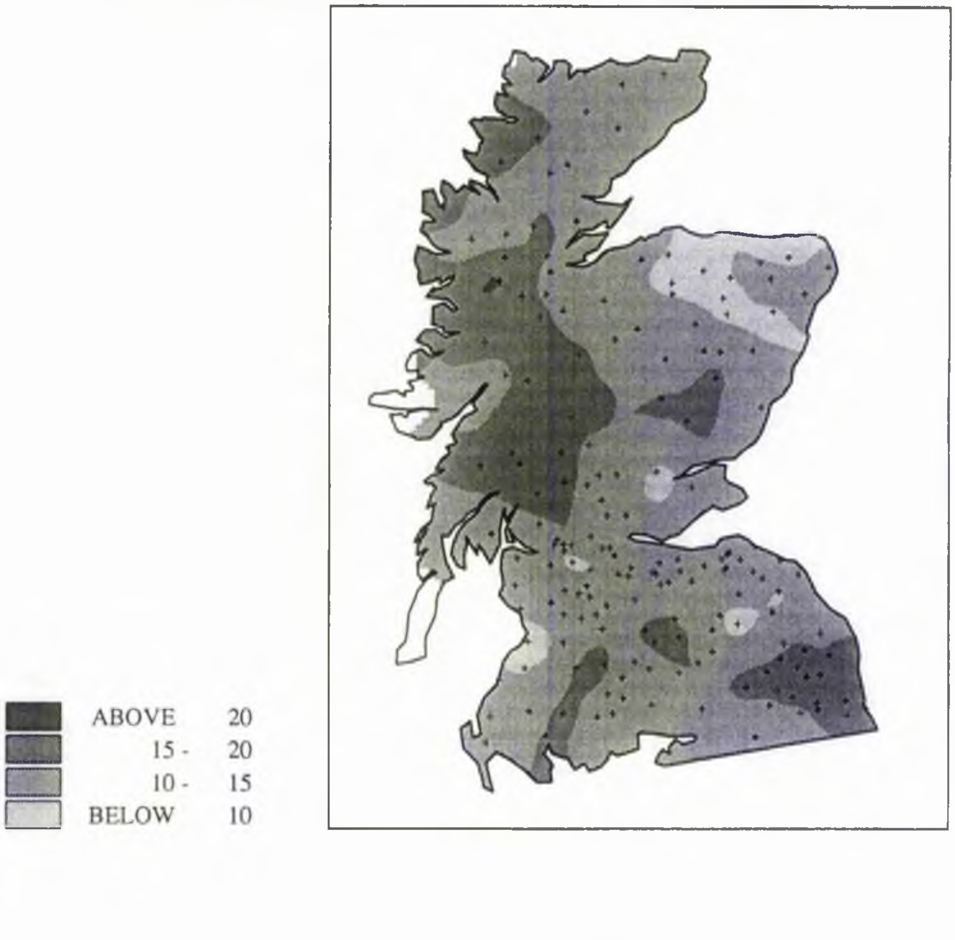
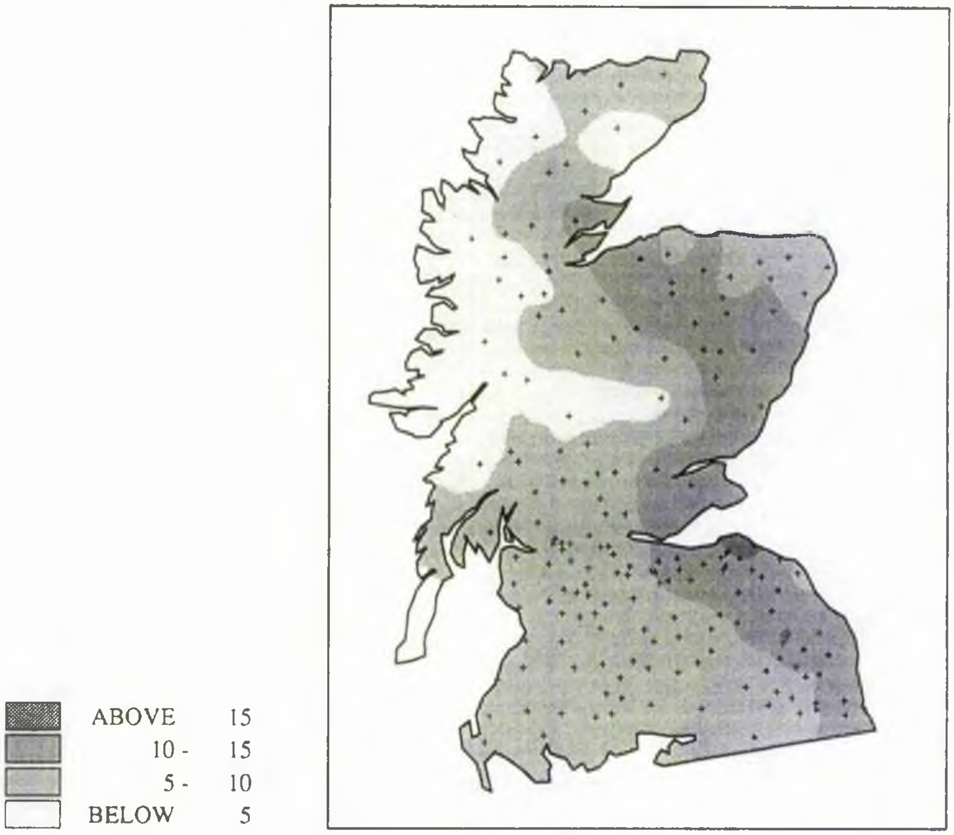


Figure 5.3f

APRIL-MAY PEAK RAINFALLS AS % OF TOTAL



However, towards the west of the map, both mean day and r values increase. Values of r exceeding 0.3 are only rarely found in eastern areas, but in the west, almost all stations record values exceeding this value. Accompanied by later mean day values, these data show that the mean time of occurrence for peak one-day rainfall totals lies between October and November in the west of Scotland. Figure 5.2a shows that mean day values increase generally across Scotland in a westerly direction, so the overall seasonal pattern shown is that storm rainfalls are quite evenly distributed among the seasons in eastern areas, but with distance to the west, the seasonal distribution becomes more pronounced with particular emphasis on autumn and early winter events. It is interesting to note at this point that the mean day map seems to show a certain altitudinal effect: high values are found over the Highlands of the west, extending over the Central Grampians to the east with the 135-day isoline, and also into the Southern Uplands and Cheviot Hills.

Examination of Figures 5.3a-5.3f shows that over the study area as a whole, the months of most frequent storm occurrence are between October and January. Distinct patterns can be observed from the six maps presented. Beginning in June and July, the Northwest Highlands are shown to be almost without storms while at stations in the east, frequencies reach and occasionally exceed 20% of the annual total. The highest values tend to be observed near coasts, there being a little evidence to support this in south-west Scotland also. In August and September, this pattern continues to some extent, with higher values, commonly exceeding 20%, occurring again near southern coasts and extending across Scotland's central belt. This coastal effect is also found along the Banff and Buchan coast, but not generally elsewhere in northern Scotland. All areas experience more than 5% of events during this period.

In October and November, all areas experience at least 10% of their annual peak one-day rainfall totals, with values increasing to maxima around 30-35% in the north-west. This general pattern is quite a clear one, and with more than 30% of events occurring in just two months at this time of year in the north-west, must play an important part in causing mean day of flood values in this area to be concentrated on autumn values. The pattern of values for December and January is less clear; high frequencies (exceeding 30%) are still found in the far north-west, and lower frequencies are found most notably in the east, particularly in the Lothians where values are less than 15% in places. This may be attributed, perhaps in large measure, to rather higher than normal values occurring here in summer months. A cluster of stations in Ayrshire shows relatively low frequencies of peak rainfalls both in this period and in the previous two months, after showing higher frequencies relative to the surrounding area in the four months from June. This might well help explain an anomalously early mean season of flooding observed in this area, though explanation of such patterns will be attempted formally at a later stage.

Figure 5.3e for February and March shows quite a small amount of variation in storm frequency, with virtually all rain-gauges recording between 10% and 20% of events in these two months. Higher frequencies, exceeding 15%, tend to be found towards the north-west and the south-east of the area, but this appears to represent rather an insignificant detail in the overall seasonality of peak rainfalls. Finally, the pattern for April and May is found to resemble closely that for June and July, with near-zero frequencies in the far north-west, tending towards higher values along the east coast, often exceeding 10% but rarely reaching 15%.

Referring again to the patterns of mean day of peak rainfall and *r* values which summarise the more detailed patterns described above, the general trend shown by the rainfall data is that in eastern areas, seasonality in the distribution of peak rainfall totals is only weakly present, but with distance to the west, this seasonal bias becomes more significant and is concentrated increasingly on the months from October to January. The implications of this for the seasonality of flooding are therefore that in the east storm rainfall is unlikely to exert any great influence on the seasonality of flooding but, in more western areas, there is a greater likelihood of floods occurring in autumn and early winter as peak rainfalls have a much greater seasonal concentration in these months.

This is a very general observation, and statistical analysis will be employed at a later stage in this chapter to investigate formally the interaction of rainfall with other factors in determining the seasonality of flooding. However, it must be noted that the map of mean day of flood for the study area (Figure 4.2a) shows a pattern nearly the reverse of that for mean day of peak rainfall, with flooding in the west clearly occurring earlier in the year than in the east. This implies a rather improbable inverse relationship between mean time of peak rainfall and mean time of flood, and reasons for this apparent contradiction between flood seasonality and one of its most important potential determinants will be addressed below.

5.2.2 Soil Moisture Deficit

On the basis of previous research, it was suggested in Chapter 2 that soil moisture status, like peak rainfall seasonality, should be of great importance in determining flood seasonality. Dry soils may yield a dramatic flashy response to rainfall in particularly intense storms (Newson 1980) but, under less extreme conditions, soil moisture deficits normally result in reduced runoff from storms as much of the rainfall infiltrates and is temporarily stored within the soil.

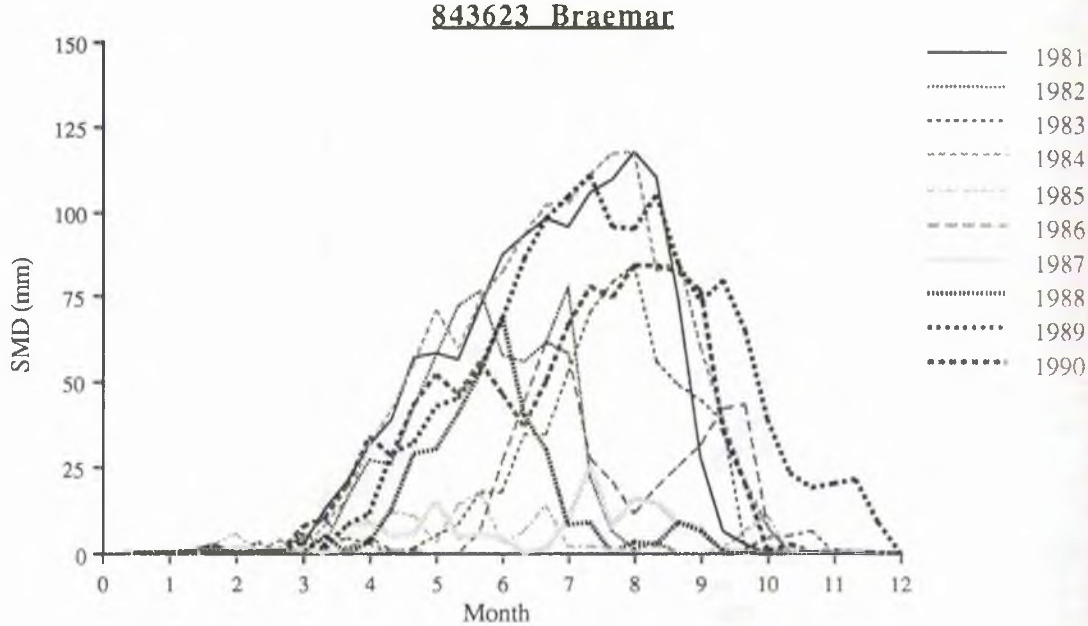
Soil moisture deficits typically build up during the summer months as a result of high evapotranspiration values coupled with lower than average rainfall over the same period. Some researchers have characterised the annual variation of SMD by use of a half sine wave, with positive values centred on summer, and zero values in the winter half of the year (Reed 1992). Figure 5.4 shows examples of the seasonality of SMD values for two stations in different areas of Scotland: the magnitude of values differs greatly but the general shape of the curves shown, *ie* the seasonal distribution of SMD values, is similar. As soil moisture levels affect flood generation processes, the seasonal distribution of SMD values must therefore be taken into account in seeking to explain flood seasonality.

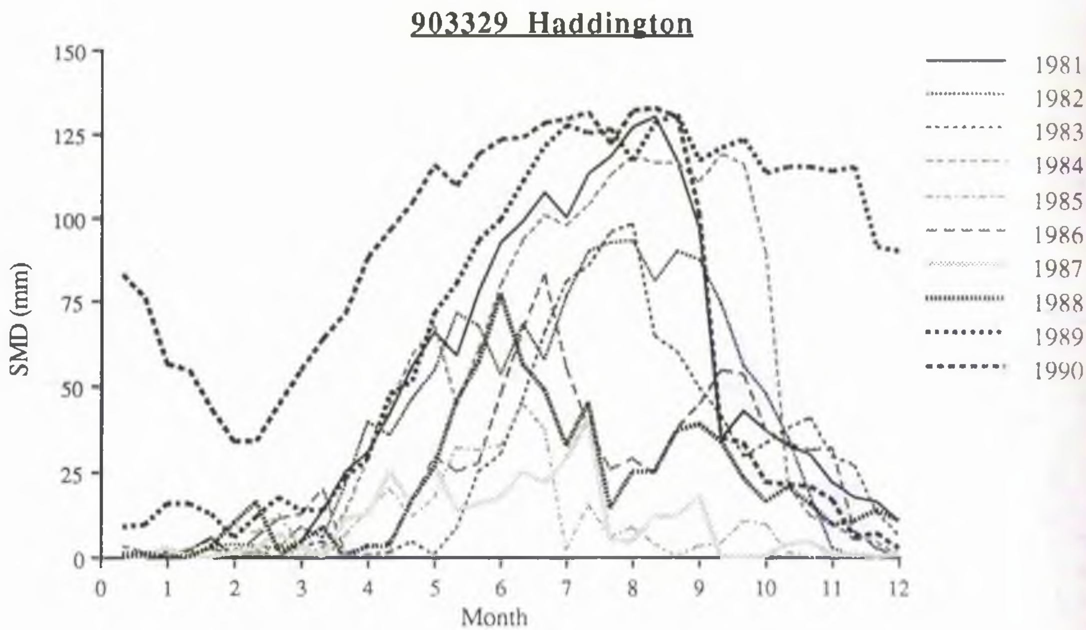
5.2.2.1 Data sources

MORECS (Meteorological Office Rainfall and Evaporation Calculation System, Thompson *et al.* 1981) data were collected as end of month mean SMD values for each of the 40 km grid squares covering the study area, for the period 1961-90. This method of data collection was chosen as it offered several advantages. The data refer to a common 30 year period, making values directly comparable between squares and representative of the long-term seasonality of SMD values. MORECS data also take account of the land use in each square and are therefore more representative of the actual soil moisture deficits found month-by-month in each square, rather than the value of potential evaporation which assumes unlimited water loss from a short green crop (Penman 1963). The data were also easily collected from the Institute of Hydrology mainframe computer (via an ORACLE™ database) rather than requiring manual collection from disparate sources such as individual SMD station records.

Such data from individual stations might conceivably be derived either from Meteorological Office designated SMD stations or from neutron probe data but in neither case does a comprehensive network of gauges exist, and individual records

Figure 5.4
Seasonal variation in soil moisture deficit at two selected stations 1981-1990





are rarely of any great length. One drawback with the MORECS data is that they relate to 40 km x 40 km squares which never correspond closely to catchment areas, and another is that values are available only at monthly intervals. However, for the reasons developed above, it is felt that these data do offer much greater accuracy and utility than any alternative and therefore evaluation of the effect of soil moisture deficits on the seasonality of flooding will be attempted using them.

5.2.2.2 Variable definition

To define the SMD 'season' in each square, it was decided to calculate the average date at which SMD rose above a threshold of 10 mm and the date at which it subsequently fell below this value after the summer maximum. The mean dates on which SMD departed from and returned to zero on either side of the summer maximum could not be found from this data set as monthly averages would always exceed zero so long as non-zero values occurred in the 30 year series of end of month SMDs. Dates based on a 10 mm threshold were therefore found by linear interpolation between the end of month values immediately above and below 10 mm. Calculation of these start and end dates for the SMD season allowed computation of two further variables: length and mid-point of the SMD season. A fifth variable, maximum end-of-month mean SMD, was also available from the data. For inclusion in an analysis of the seasonality of flooding, it was deemed desirable to choose a variable which would be physically meaningful, while also being reasonably representative of some of the other variables which could be used to describe the seasonal distribution of soil moisture deficit values. On the basis of the first of these criteria, the length of the SMD season seems to be of most use in such an analysis: under given conditions, the length of time over which SMDs might be deemed to be high would be expected to influence the seasonality of flooding by reducing the probability of flooding over that period. Table 5.1 shows that this variable is also highly correlated with all the other variables available; it was therefore decided to adopt length of SMD season to help explain the patterns of seasonality of flooding. It should be particularly noted that length of SMD season is highly correlated with the maximum end-of-month mean SMD value, such that it is not necessary to find separate variables to describe the length and extent of SMDs.

Having decided upon this method of characterising SMD data, it was necessary to relate data for MORECS squares to catchments. Where two-thirds or more of a catchment fell within a single MORECS square, the data for that square alone was used to define the length of SMD season for the catchment. In other cases, if more

	Start date	End date	Length	Mid-point	Max end-of-month mean
Start date	*	-0.936	-0.960	-0.884	-0.935
End date		*	0.997	0.992	0.925
Length			*	0.979	0.937
Mid-point				*	0.892
Max end-of-month mean					*
Mean r for correlations with other 4 variables	0.929	0.963	0.968	0.937	0.922

Table 5.1. Pearson's r correlation values for five SMD variables.
(Data: MORECS squares 1- 73)

than 20% of the catchment area was covered by any individual square beyond the primary one, then SMD season start and end dates for the catchment were calculated by finding simple averages from the values of all squares included. Length of SMD season was then derived from these dates.

5.2.2.3 Results

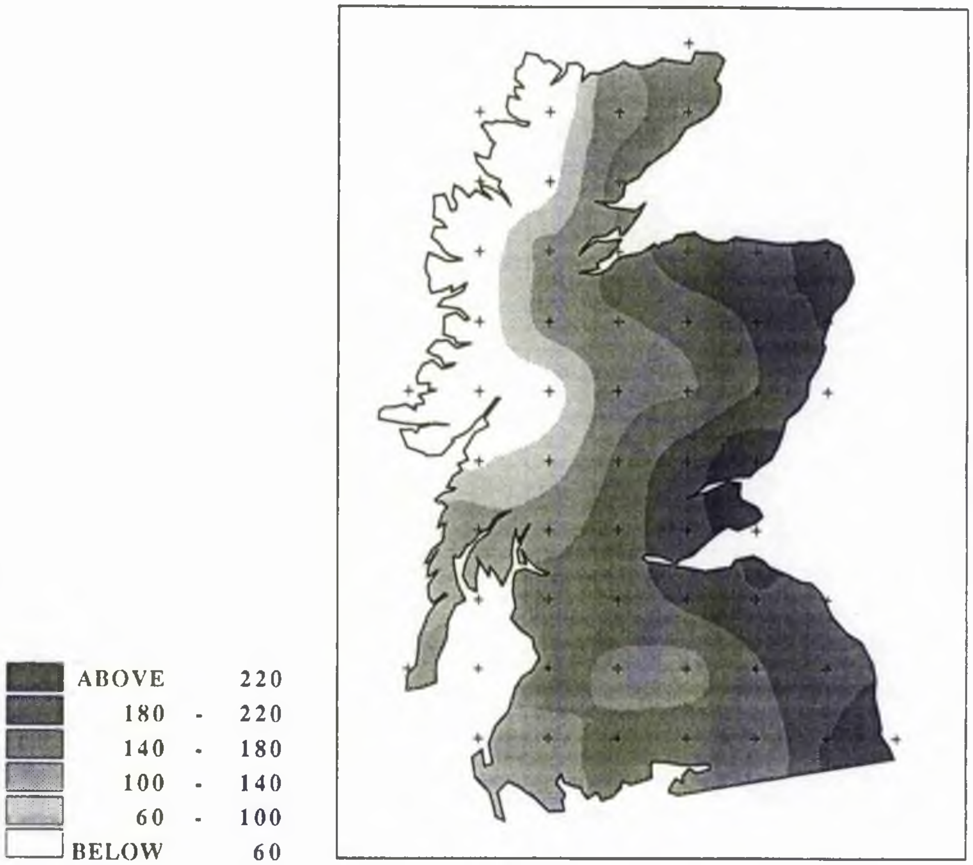
Figure 5.5 shows values of the length of SMD season index described above. The location of MORECS square centres is shown, and the choropleth map is based on interpolation of values from them. There is a great range in length values, ranging from less than 50 days in six squares in north-west Scotland to 321 days in Square 59 (Berwick-upon-Tweed) though, as the centre of this square is over coastal waters, this value does not appear on the map. It is immediately apparent that there is a strong east-west gradient in values across the map, with the lowest values in the north-west, and the highest along the east coast, with values always exceeding 180 days except in the far north. This is a particularly smooth trend in comparison with the spatial patterns of seasonality of flooding or rainfall which have previously been described. This is in part a reflection of the fact that the map is constructed from only 57 points, but despite this the 'smoothness' of the general pattern is still felt to be physically real.

The primary implication of this spatial distribution of values for seasonality of flooding is that all other factors being equal, the likelihood of flooding in the summer months must be much lower in eastern areas than in the west, particularly in the north-west. This arises because the prolonged SMD season in the east will

Figure 5.5

LENGTH OF SMD SEASON (VALUES EXCEEDING 10mm)

MORECS data



result in summer storms not generating a corresponding flood. This effect can be directly measured in terms of a lower expectation of floods in the summer months using the 2-month frequencies described in Section 4.3.2, with predictable effects on mean day of flood and *r* values. With mean day of flood values being expressed in days after 31 May, and peak rainfalls (with resultant floods) generally being concentrated on the winter months, (especially between October and January), the presence of a long period of high soil moisture deficits must lead to increased mean day of flood values. In essence, prolonged SMDs will eliminate many 'early' events from the flood record and, as a consequence, the mean day of occurrence of the remainder will be deflected to later in the year. The anticipated effect on *r* values for POT flood series will be to increase values by increasing clustering about the (winter) mean, since some of the wider scatter about the mean will have been eliminated.

At an intuitive level at least, the distribution of values for this SMD variable seems to be very helpful in explaining the spatial differences between the seasonal distributions of peak rainfall and flood events. In essence, the map of mean day of peak rainfall (Figure 5.2a) shows a greater propensity for events to occur in autumn and winter months with distance to the west, while flood events occur later in the year as one moves east across the map. Soil moisture deficits appear to offer an explanation for this: the flood-producing potential of the relatively early storm rainfalls occurring in the east is reduced or even cancelled by high soil moisture deficits (typically 35% of peak rainfalls occur in eastern areas between June and September), thus causing the remaining floods to be concentrated more in the winter months. However, in the west SMDs are not as significant in these terms as they are of much shorter duration, and therefore the seasonality of flooding more closely mirrors the average season of peak storm rainfalls. As a simple demonstration of this point, Table 5.2 compares mean values of mean day of peak rainfall (as previously defined), mean length of SMD season, and mean day of flood for all east-draining and all west-draining catchments. The data support the above contention.

	East-draining catchments	West-draining catchments	Difference (East - West)
Mean day of peak rainfall	154.3	162.0	-7.7
SMD length	163.0	135.0	28.0
Mean day of flood	196.4	173.1	23.3

Table 5.2 Combined effect of peak rainfall seasonality and soil moisture deficits for east- and west-draining catchments (hydrometric areas 2-23 and 77-97 respectively). Mean day values as days after 31 May.

5.2.3 Catchment area

In the review of literature in Chapter 2, it was shown that some degree of confusion existed over the precise rôle of catchment area in determining flood seasonality. Hewson (NDb) observed that small, upland catchments seemed more likely to exhibit unusual seasonality than most others, noting the particularly high frequency of summer flooding in these catchments. However, Archer (1981a) argued that catchment area was not an important factor in determining seasonality. While finding that small, upland catchments in his study did tend to have higher summer flood frequencies than other catchments, he argued that this was due to the higher rainfall totals and therefore lower SMDs found in the uplands, enabling the seasonality of flooding in relatively small headwater catchments to reflect the summer-dominated seasonality of peak rainfall much more closely than in catchments where greater SMDs caused summer rainstorms not to produce floods, thus increasing the proportion of events found in winter months. Following this argument, catchment area is not to be regarded as a determinant of seasonality in its own right; while there may be some variation of seasonality with area, this might be better explained simply in terms of catchment SMD.

Archer's argument clearly makes sense so far as the idea of catchment wetness affecting flood seasonality is concerned, but its extension to suggest that basin size itself exerts no influence over seasonality seems questionable. In the discussion of storm rainfall above, it was noted that critical rainstorm duration is a function of time to peak, which is in turn determined by (amongst other things) catchment area. It should therefore be expected that short duration, high intensity rainstorms will produce flood events in small catchments but not in larger ones and, as the duration and intensity of rainstorms varies seasonally (see below), then catchment area must be expected to affect seasonality in its own right. While area may well reflect a number of other catchment characteristics, it must nonetheless be included in the analysis for this reason.

To investigate the validity of this argument, flood seasonality was examined in some of both the largest and smallest catchments. As a small catchment, 80003 White Laggan @ Loch Dee presented itself as being particularly worthy of investigation since the mean day of flood for its 9-year record, 108 days after 31 May (= September 16) is the earliest value of all catchments used in the study. Furthermore, availability of autographic rainfall data, collected by the Solway RPB as part of the Loch Dee Project (Welsh and Burns 1987), enabled the rôle of storm rainfall seasonality in this small catchment to be scrutinised, though the availability of only three years of record is not ideal.

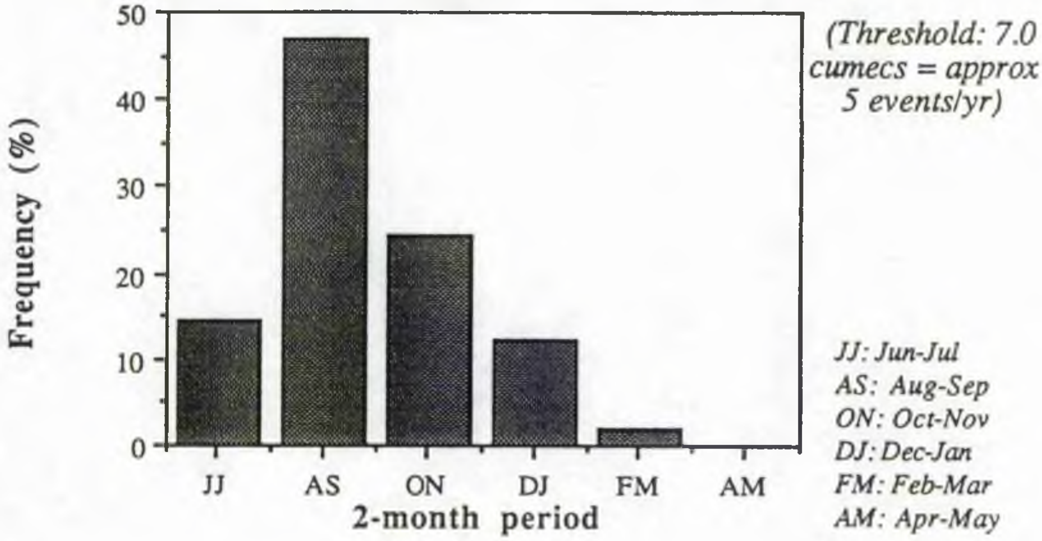
Figure 5.6a shows the seasonal distribution of floods at this station, with a remarkably high 44% of events occurring in August and September. In Figure 5.6b it can be seen that the seasonal distribution of peak 24-hour rainfall totals exceeding a ten peaks per year threshold differs significantly from that of floods. The mean day of occurrence in the rainfall series is 126 days after 31 May, slightly later than the mean day of flood, so it follows that soil moisture deficits are not responsible for the difference in seasonality between the two data sets. More significantly, the *r* value of the flood series is 0.560 while the corresponding value for the rainfall data is only 0.067; peak 24-hour rainfall occurrences exceeding the threshold set are therefore very much more evenly distributed around the year than are the discharge peaks. Indeed, with an average annual rainfall of 2232 mm, soil moisture deficits cannot be expected to exert any great influence on the seasonality of flooding and, as the catchment has no lake storage, a steep gradient and relatively impermeable soils, it would seem likely that the seasonality of flooding in this catchment is strongly determined by the seasonality of storm rainfall. It is therefore important to determine the duration of rainstorm which is responsible for producing the flood seasonality observed.

Figure 5.7a shows the variation of peak rainfall mean day and *r* values with duration, the analysis being based on the 30 largest rainfalls in the three years of record for the given durations, while Figure 5.7b shows a similar analysis based on 2-month percentage frequencies. While mean day values do not shift dramatically, it can be seen that August and September frequencies decrease steadily with duration from about 45% of all peak events of less than 5 hours duration to less than 30% at 24 hours, while December-January and February-March frequencies both increase from about 10% to 20% over the same range of durations. The result of the interaction of these values is that *r* values for short durations are high, exceeding 0.5 for 1- and 2-hour durations, with such rainfall occurrences heavily concentrated in late summer. However, *r* values fall dramatically with duration, never exceeding 0.25 for durations in excess of 12 hours, thus denoting a much wider seasonal distribution of peak rainfalls over longer durations.

In seeking to identify the critical peak rainfall duration for flood generation in this catchment, the similarity in seasonal distribution of 3-hour rainfall peaks (Figure 5.8) with that of the flood series suggests that it is the largest rainfalls of a

Figure 5.6

a) Seasonal distribution of floods 1981-89 at 80003 White Laggan Burn @ Loch Dee



b)

Seasonal distribution of peak 24-hour rainfalls 1987-89 at Upper Black Laggan rain-gauge

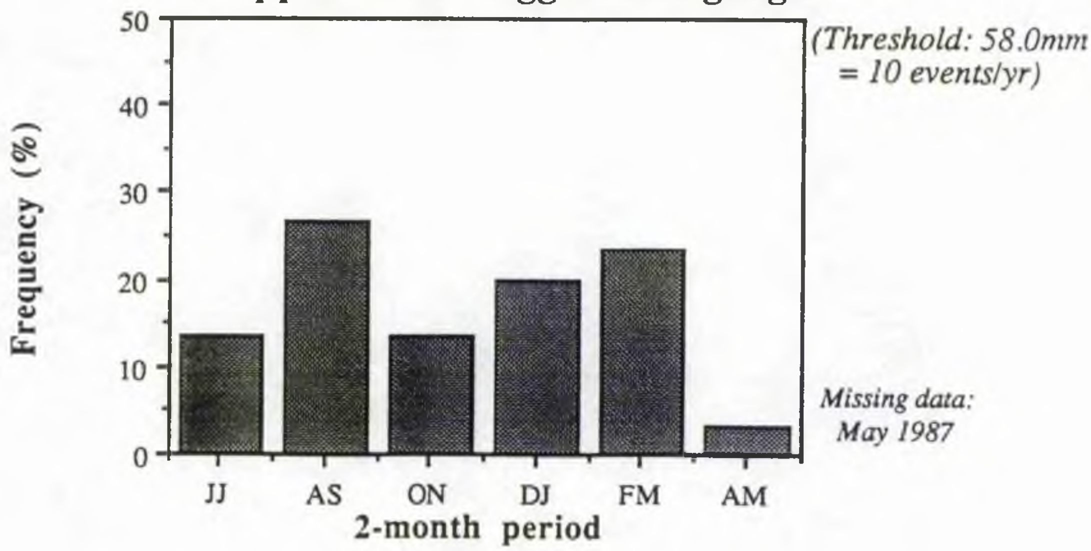
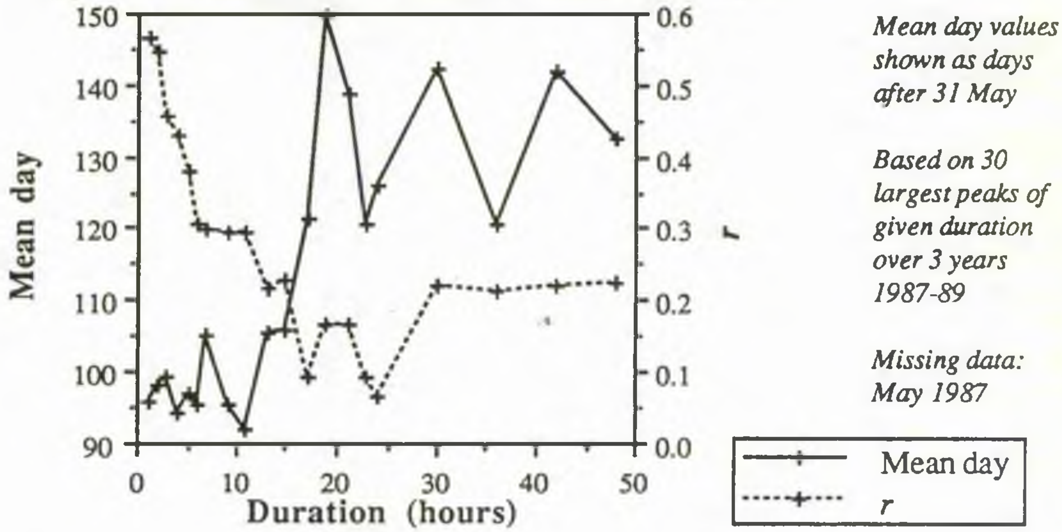


Figure 5.7

a) **Upper Black Laggan peak rainfalls: variation in mean day and r values with duration**



b) **Variation in Upper Black Laggan peak rainfall seasonality with storm duration**

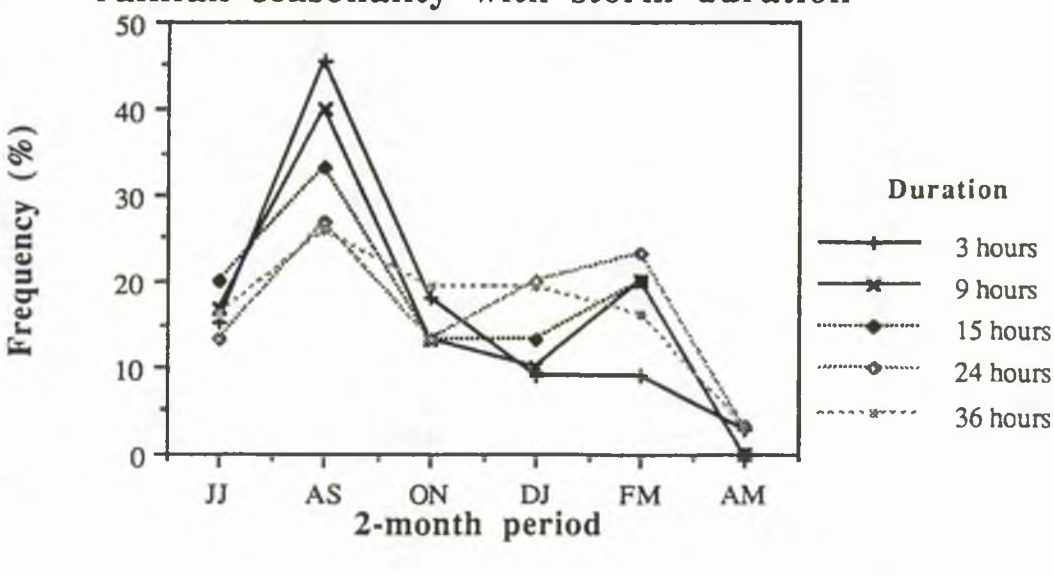
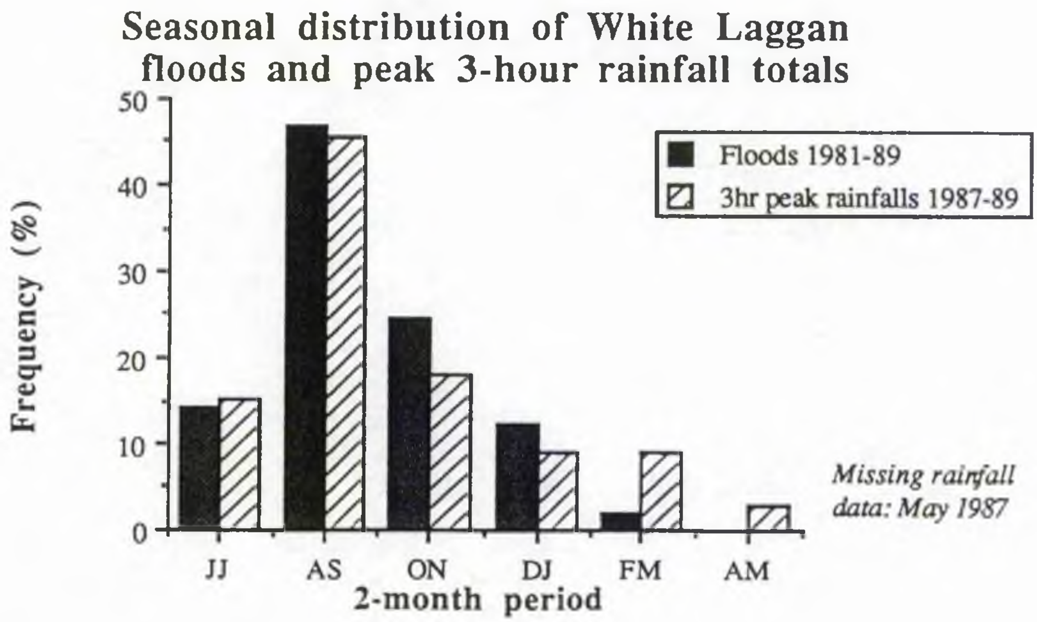


Figure 5.8


Seasonal distribution of White Laggan
floods and peak 3-hour rainfall totals
Frequency (%)
50
40
30
20
10
0
Floods 1981-89
3hr peak rainfalls 1987-89
Missing rainfall data: May 1987
JJ
AS
ON
DJ
FM
AM
2-month period

duration of this order which are responsible for producing the unusual seasonality of flooding found in this small catchment. Longer duration rainstorms, on the other hand, occur less frequently in summer and autumn and appear to be less able to explain flood seasonality here.

It is acknowledged that by using only three years of rainfall data, the identification of a 3-hour duration as the critical value for flood generation on the White Laggan may be subject to some error, but the great variation of rainfall seasonality with duration must be taken as convincing evidence that the most unusual seasonality of flooding in this catchment is essentially the result of the seasonality of peak rainfalls of a short duration. This is only the case because of its very small size.

Archer's contention that catchment area is not an important determinant of seasonality therefore seems quite invalid here. His understanding of late summer generally being the season of most frequent peak rainfalls applicable to catchments across his entire Northumbrian study area takes no account of the potential variation of critical duration rainfall seasonality with catchment area, though this may be admissible in that particular region as a result of peak 24-hour rainfalls having a similar seasonality to the rather shorter duration peak totals which are presumably responsible for generation of floods in the 11.4 km^2 Trout Beck catchment in the Pennines which he cites.

In Scotland, however, it has been shown (Figures 5.2, 5.3) that peak one-day rainfall seasonality patterns vary considerably across space, and at Loch Dee at least, that considerable variation also occurs with duration. Having shown that area is an important determinant of seasonality in this catchment, it is interesting to note that the station with the earliest 1959-88 adjusted mean day of flood value (the period of record at station 80003 is too short to allow a standard period value to be calculated) is 87801 Allt Uaine @ Loch Sloy Intake, which is also a very small (3.1 km^2) upland catchment in the west of Scotland. With other catchment characteristics similar to that of 80003, it is again suggested that the small size of this catchment is an important determinant of its flood seasonality.

Table 5.3 shows two-monthly percentage frequencies, mean day and *r* values for the six smallest catchments for which standard period frequency values were produced, and it can be seen by reference to the quartile ranges shown that these catchments have rather unusual flood seasonalities. There is a clear tendency amongst these stations for relatively low frequencies to occur in December-January and February-March and a corresponding tendency for unusually high frequencies to be found between April-May and October-November. By definition, extreme frequencies in one season must be compensated for by extremes in the opposite direction in other seasons, but the fact that 24 of the 36 two-monthly frequencies shown fall outside the quartile ranges indicates that these small catchments do indeed have rather unusual seasonalities.

Station	Area (km^2)	Jun-Jul (%)	Aug-Sep (%)	Oct-Nov (%)	Dec-Jan (%)	Feb-Mar (%)	Apr-May (%)	Mean day	r
87801	3.1	13.9+	28.9+	21.5-	24.5-	8.9-	2.4	148.7-	0.363-
91802	6.5	7.7+	11.6	41.3+	25.0-	9.7-	4.7	170.6-	0.418-
21001	23.7	3.4	12.8	49.9+	20.1-	9.1-	5.1	186.8*	0.485*
20002	26.2	6.0+	8.2-	28.5	27.0	18.6	11.7+	207.0+	0.380-
86001	30.8	1.0	28.2+	34.8+	18.6-	10.4-	6.9+	150.8-	0.443-
21026	31.0	3.2	35.8+	28.1	19.5-	13.3	0.0-	161.3-	0.459
Median		2.4	14.5	29.5	30.6	15.7	3.5	189.9	0.519
Lower quartile		1.0	10.7	26.8	26.8	12.1	1.7	176.6	0.450
Upper quartile		5.8	18.9	33.2	34.5	20.0	6.2	200.0	0.576

Table 5.3 2-monthly frequencies mean day and *r* values for six smallest catchments, with all-station median, upper and lower quartile values.
*Values greater than upper quartile value shown by +, less than lower quartile by -. All values are for 1959-88 standard period unless shown by *.*

It is interesting to note that for the six stations in the table, notably high and low frequencies occur at different times of the year; the small size of these catchments does not lead to similar seasonality being found in each. The differences shown are thought to be caused by differences in the seasonality of peak rainfalls of duration appropriate to each catchment, although the effect of soil moisture deficits may be important, especially for the August-September frequency at station 20002 for which the length of SMD season is 247 days. The data presented in the table again illustrate the importance of catchment size in producing unusual seasonal patterns, which may well arise from the response of small catchments to short duration peak rainfalls. These may have significantly different seasonalities to longer duration peak falls which are of importance for larger catchments.

When considering large drainage basins, on the other hand, rather less variation in seasonality is found. Floods between December and March are much more frequent than at the average station, while frequencies in other months are correspondingly lower. Table 5.4 compares the seasonality of flooding of the six largest catchments in the study (only the largest catchment for each river basin) with that of all stations, in the same way as in Table 5.3 for small catchments. In August and September, only one of the large catchments experiences a higher flood frequency than the all-stations median, while in December and January, all six catchments have higher frequencies than the all-station median. These results point to a slightly later overall seasonality of flooding in large catchments, as is borne out by a slightly later mean day of flood for the large catchments relative to the mean for all stations. Values of r for these large basins are highly variable: the value for the Clyde is the third highest of all the standard period-adjusted figures, but the value for the Spey is one of the lowest, while those for the Dee and the Don both fall within the lowest 40% of values.

Station	Area (km^2)	Jun-Jul (%)	Aug-Sep (%)	Oct-Nov (%)	Dec-Jan (%)	Feb-Mar (%)	Apr-May (%)	Mean day	r
21009	4390	1.7	10.9	26.2-	37.0+	21.7+	2.5	201.4+	0.535
08001	2640	6.1+	16.2	21.9-	31.4	19.4	5.0	207.9+	0.347-
84013	1903	1.0	13.4	32.3	35.6+	15.7	2.0	186.7	0.634+
12002	1844	0.0-	11.3	27.8	34.8+	18.4	7.7+	198.0	0.478
06007	1839	1.4	8.7-	25.6-	31.0	33.2+	0.0-	196.9	0.547
11001	1273	8.1+	8.2-	19.6-	36.2+	20.1+	7.6+	213.6+	0.424-
Median		2.4	14.5	29.5	30.6	15.7	3.5	189.9	0.519
Lower quartile		1.0	10.7	26.8	26.8	12.1	1.7	176.6	0.450
Upper quartile		5.8	18.9	33.2	34.5	20.0	6.2	200.0	0.576

Table 5.4 2-monthly frequencies, mean day and r values for six largest catchments, with all-station median, upper and lower quartile values.
Values greater than upper quartile value shown by +, less than lower quartile by -. All values are for 1959-88 standard period.

In seeking to explain these rather variable seasonalities, it is interesting to note that the three large rivers with low r values all drain from the mountains of north-east Scotland. The low r value for 08001 Spey @ Aberlour appears to be the result of the influence of the River Avon which joins the main Spey approximately 10 km upstream of the gauge, draining from the Cairngorm Mountains. The data in Table 5.5 suggest that the low r value for the POT series at Aberlour is caused by an unexpectedly high frequency of events in summer caused by tributary inputs from the Avon. Grantown, the first gauging station upstream of this confluence, records a much higher r value of 0.491, associated with a lower frequency of summer flooding. April - May frequencies of POT floods of 7.6% and 7.7% for the Don and Dee respectively are within the top 20% of values, but rather low r values for these rivers appear to be the result of a more generally widespread distribution of floods throughout the year, probably caused in part by spring snowmelt floods since the Cairngorms are noted for the long duration of snow lying into the spring months. However, while these three rivers have relatively high proportions of their floods in the summer months (27% of events occurring between April and September on the Spey, compared with only 10% on the Ness), these frequencies for large basins compare closely with the mean summer frequency for all stations (23%), and are much lower than the 36% or more of events in summer found in 10% of catchments. The relatively frequent incidence of summer flooding on the lower Spey seems to occur for specific local reasons relating to its Avon tributary rather than as a response to basin-wide storm precipitation.

	Jun-Jul	Aug-Sep	Oct-Nov	Dec-Jan	Feb-Mar	Apr-May	TOTAL
Number of floods at 08001 Spey @ Aberlour	9	17	15	26	20	6	93
of which corresponding peaks at 08004 Avon @ Delnashaugh	8	14	10	11	12	6	61
% of lower Spey floods with corresponding peak on Avon	89	82	67	42	60	100	66

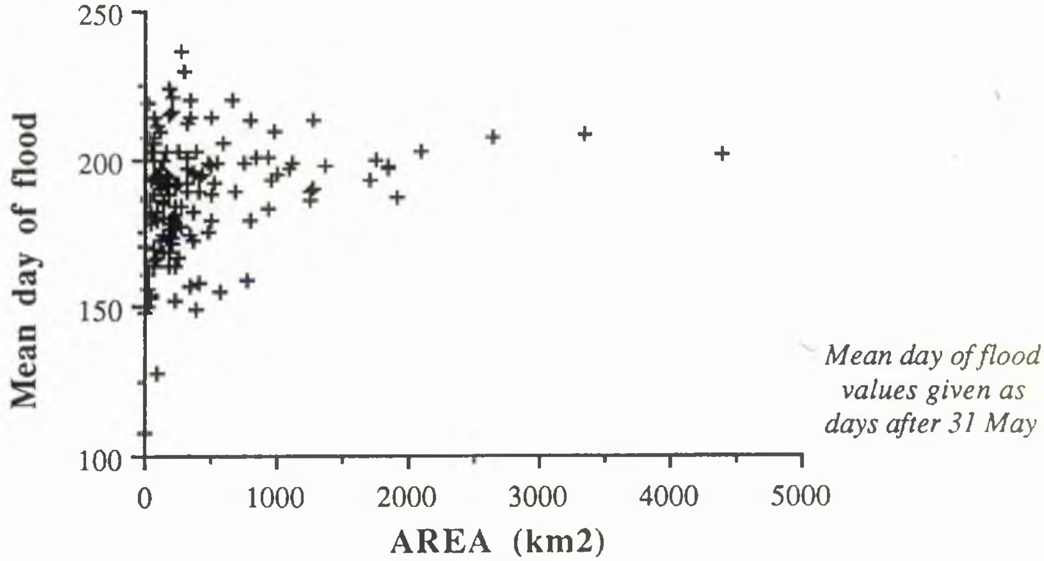
Table 5.5 Correlation between lower Spey floods (08001 Aberlour) and Avon tributary (08004 Delnashaugh), 1953-72. Contributions from the Avon to flood peaks on the lower Spey seem to be most important between the months of April and September. Correlation defined as a Delnashaugh flood occurring on the same day or the day before an Aberlour peak.

Having considered seasonality of flooding in particularly small and particularly large basins, an overall picture of the relationship between basin size and seasonality of flooding can be obtained by examining the distribution of mean day of flood and r values with catchment area, as shown in Figures 5.9a and 5.9b. It is immediately apparent that flood seasonality, as characterised by mean day values, becomes progressively less variable with increasing catchment size, though the variation in r values is rather less marked. Mean day values in larger catchments are clearly centred on dates in early December (*ie* ~190 days after 31 May), while in small catchments there is a large range from 108 to 236 in terms of mean day of flood. From this it would appear either that catchment area imposes a constraint on the seasonality of flooding which increases in proportion to basin size, or alternatively that large basins are synonymous with winter-dominated flooding while smaller basins can experience a greater variety of seasonalities because of

Figure 5.9

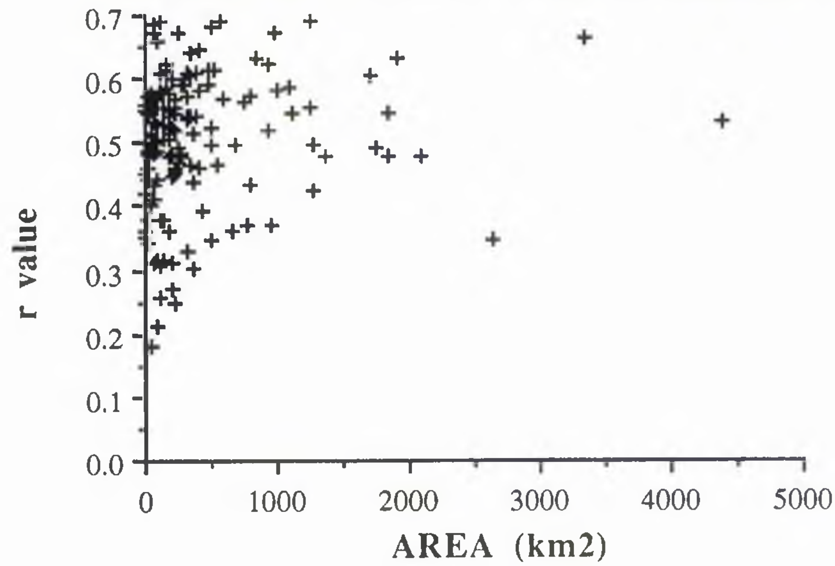
a)

Scatter of mean day of flood values with catchment area



b)

Scatter of r values with catchment area



their geographic location and their specific basin characteristics. Put another way, this latter suggestion implies that the large basins might all show a relatively similar seasonal pattern of flooding because their hydrological characteristics (especially seasonality of rainfall and SMD) might all be quite similar, while the more numerous small basins might be more diverse in their physical characteristics and therefore show a more varied seasonality of flooding.

To determine the significance of catchment area in relation to flood seasonality, both of these possibilities must be evaluated. It is felt that the former argument is valid, since it has already been shown in the Loch Dee study above that catchment area is an important determinant of seasonality for small catchments, and in large catchments which are thought to respond to peak rainfalls of at least one day's duration Table 5.6 below shows that the seasonal distribution of these peak rainfalls is indeed much less extreme than that of short duration rainfalls such as have been shown for Loch Dee. The table indicates that few catchments receive more than 28% of peak one-day rainfalls in any two-month period, and it therefore appears that catchment area is indeed an important determinant of flood seasonality through its rôle in determining the seasonality of critical duration peak rainfalls.

%	Jun-Jul	Aug-Sep	Oct-Nov	Dec-Jan	Feb-Mar	Apr-May
Maximum	22.7	30.6	37.5	45.0	22.5	17.9
U quartile	15.4	22.7	27.6	26.2	15.8	10.7
Median	10.6	20.0	24.2	22.7	13.6	7.1
L quartile	8.1	17.4	20.7	19.1	11.2	5.6
Minimum	1.2	10.0	11.4	10.0	6.8	0.0

Table 5.6 Seasonal frequency distribution of peak one-day catchment rainfall totals exceeding a 10 peaks per year frequency threshold for all stations (as calculated in Section 5.2.1)

Additionally, the second of the arguments developed above also appears to have some merit. Local factors do ensure that some large catchments exhibit rather different flood seasonalities to most other large catchments; the particular prevalence of heavy summer rainfalls over the mountains of north-east Scotland which have been shown to cause anomalous flood seasonality on the Rivers Spey, Don and Dee, and perhaps also the effect of loch storage on the River Ness are examples of this, but it is also true that many large catchments have rather similar physical characteristics. Certainly there is much less variation in the physical characteristics of large drainage basins than of small ones, simply because all the large basins in the study area cover a variety of terrains from the uplands down to coastal or near-coastal areas such that many catchment characteristics, such as stream frequency, mean annual rainfall and thus soil moisture deficit take on average values for all of them. The relative similarity of the physical characteristics of large catchments relative to those of small catchments is illustrated in Table 5.7, and it can be seen that the characteristics of small catchments are generally much more varied than for large ones, though catchment slopes (understandably) are found to be very low for large catchments relative to small ones.

	Largest 20 catchments				Smallest 20 catchments			
	S1085	STMFR	SAAR	SMD	S1085	STMFR	SAAR	SMD
Maximum	3.94	1.82	1946.0	6.70	117.73	9.82	3454.0	13.00
U quartile	3.10	1.46	1431.0	5.48	28.11	4.29	2322.0	5.00
Median	2.25	1.19	1186.0	4.95	18.09	2.13	1708.0	3.00
L quartile	1.76	0.99	1097.0	3.63	11.50	0.82	1096.0	1.90
Minimum	1.38	0.47	950.0	2.60	1.56	0.15	643.0	1.00

Table 5.7 Distribution of catchment characteristics for large and small catchments.
S1085: catchment slope (m km^{-1}); STMFR: stream frequency (junctions km^{-2}); SAAR: standard average annual rainfall 1941-70 (mm); SMD: mean effective soil moisture deficit (mm)
Data source: Acreman (1985a)

Catchment area is therefore seen to be important in influencing the seasonality of flooding both directly through determining the critical duration of peak rainfall for flood generation, and indirectly since, with increasing size, catchments become increasingly similar and flood seasonality must thus be expected to become less variable with catchment size. In the statistical analysis which follows in Section 5.3, catchment area must be included since it has been shown that it is of direct influence in determining flood seasonality. However caution must be exercised to ensure that influence is not directly attributed to it on account of its association with other catchment characteristics.

5.2.4 Loch storage

Loch storage is known to have a damping effect on flood peaks. If the volume or flashiness of flood peaks on a river varies seasonally, then it is likely from this that the presence of lochs or reservoirs in a catchment will influence the seasonality of flooding downstream. Ward (1981 p12) stresses that both the size and location of storages are important in flood peak attenuation.

5.2.4.1 Choice of variable

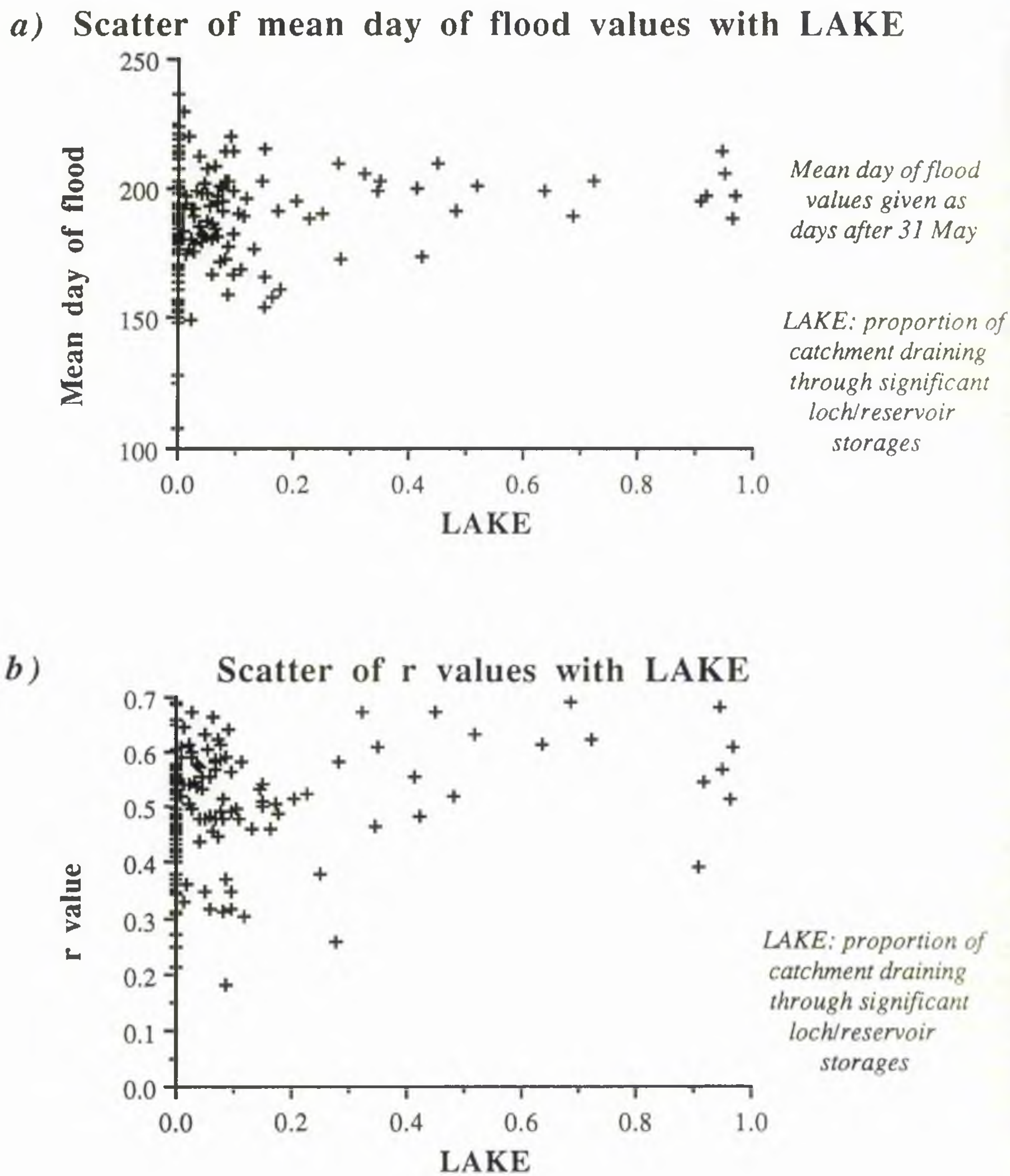
LAKE, the variable used in the *Flood Studies Report* (NERC 1975), is the proportion of a catchment draining through lakes or reservoirs, the surface area of which exceed 1% of the area draining into each individually. It therefore gives a good indication of the importance of such storage in any basin. An alternative measure to express the importance of loch storage is that used by Acreman (1985a), LOCH, being the surface area of lochs or storage reservoirs as a proportion of total basin area. However, as LAKE is calculated only for storages larger in area than 1% of their (sub-)catchment, it is felt that this goes some way to achieving the aim of the LOCH index, namely quantifying the undoubtedly important size of the storage, while in addition quantifying the proportion of the catchment which is affected by such storages. Therefore, LAKE values were chosen to represent the effect of loch storage on the seasonality of flooding.

5.2.4.2 Results

Figure 5.10 shows the distribution of mean day of flood and *r* values with LAKE values, and the scatter of points shows considerable similarity with the distribution of values against catchment area. However, this is not the result of any dependence between these two variables: the Pearson's correlation coefficient between them is only 0.079. With this possibility eliminated, it would seem that catchments which drain to a considerable extent through storages are limited in the seasonal distribution of their floods, with mean day of flood values being concentrated around 200 days after 31 May for all catchments where LAKE values are greater than 0.4. Values of *r* do not appear to be as severely constrained by LAKE values, but it does appear from Figure 5.10b that the lowest *r* values are found in catchments with zero or near-zero LAKE values.

These results therefore support the idea that loch or reservoir storage has some effect on the seasonality of flooding, and with reference to the specific values referred to above, it would seem that moderate to high LAKE values are synonymous with winter-dominated flooding. Of the 14 catchments with LAKE values in excess of 0.4, only two have *r* values of less than 0.5, so it can be said that those catchments with significant loch storage effects do experience a significant degree of clustering of floods in winter, around a mean day of flood value of 200. On the other hand, catchments with low LAKE values include those with much more unusual flood seasonalities, either through exceptionally high or low mean day of flood or *r* values, as well as including other catchments seasonally similar to those with higher LAKE values.

Figure 5.10


a) Scatter of mean day of flood values with LAKE
Mean day of flood
250
200
150
100
0.0
0.2
0.4
0.6
0.8
1.0
LAKE
Mean day of flood values given as days after 31 May
LAKE: proportion of catchment draining through significant loch/reservoir storages
b) Scatter of r values with LAKE
r value
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
1.0
LAKE
LAKE: proportion of catchment draining through significant loch/reservoir storages

These basic findings appear to be compatible with expectations. Sharply peaked floods are much more a characteristic of convectional rainstorms than other types of event, and such storms only occur in summer. Routing such floods through a loch storage is likely to result in a much greater degree of attenuation than would be the case for less steeply shaped storm hydrographs with the same peak discharge, so it follows that the effect of loch storage will be to reduce the frequency of summer peaks exceeding a discharge threshold relative to the frequency of POT events in other months. It has been seen in Chapter 4 that higher than average frequencies of summer events produce lower than average mean day of flood values, and also lower *r* values. The observation that catchments with higher than average LAKE values have a fairly limited range of mean day of flood values centred on December, and *r* values which are rarely low, therefore seems to be adequately explained by the effective filtering out of short duration, flashy, summer flood events, thereby increasing the proportion of events occurring in the winter months, and leading to much tighter clustering of events around a typically December mean day of flood occurrence.

5.3 Synthesis

The preceding paragraphs have demonstrated the effect of four separate physical factors on the seasonality of flooding, namely the seasonality of rainfall, soil moisture deficits, catchment area, and drainage through loch or reservoir storages. The first two of these can easily be thought of together: the seasonality of peak rainfalls is the primary input to determining the seasonality of peak runoff events, but is immediately tempered by the effect of soil moisture deficits which moderate catchment response to rainfall. Therefore the typical annual length of significant soil moisture deficits in any catchment will determine directly the effective mitigation of summer floods and consequently produce a corresponding shift in the seasonality of flooding. The effects of the latter two characteristics can also be summarised together: with increasing values, catchment area and the proportion of the basin draining through loch storage both result in a greater domination of winter floods relative to summer events, leading to mean times of flooding normally in December and moderate to high values of *r*, indicating a greater clustering of events around such winter means. A summary of the effects of these factors on mean day of flood and *r* values is given in Table 5.8. Having examined these influences individually, the aim is now to bring them together in order to fully explain, by reference to these physical determinants, the various patterns of flood seasonality found at the stations used in this study.

Physical factor	Effect on	
	Mean day of flood	r
Peak rainfall mean day	Later	-
Peak rainfall r	-	Higher
SMD length	Later	Higher
Catchment area	Less variable	Higher
Loch/reservoir storage	Less variable	Higher

Table 5.8 Summary of effect of physical factors on mean day of flood and r values.

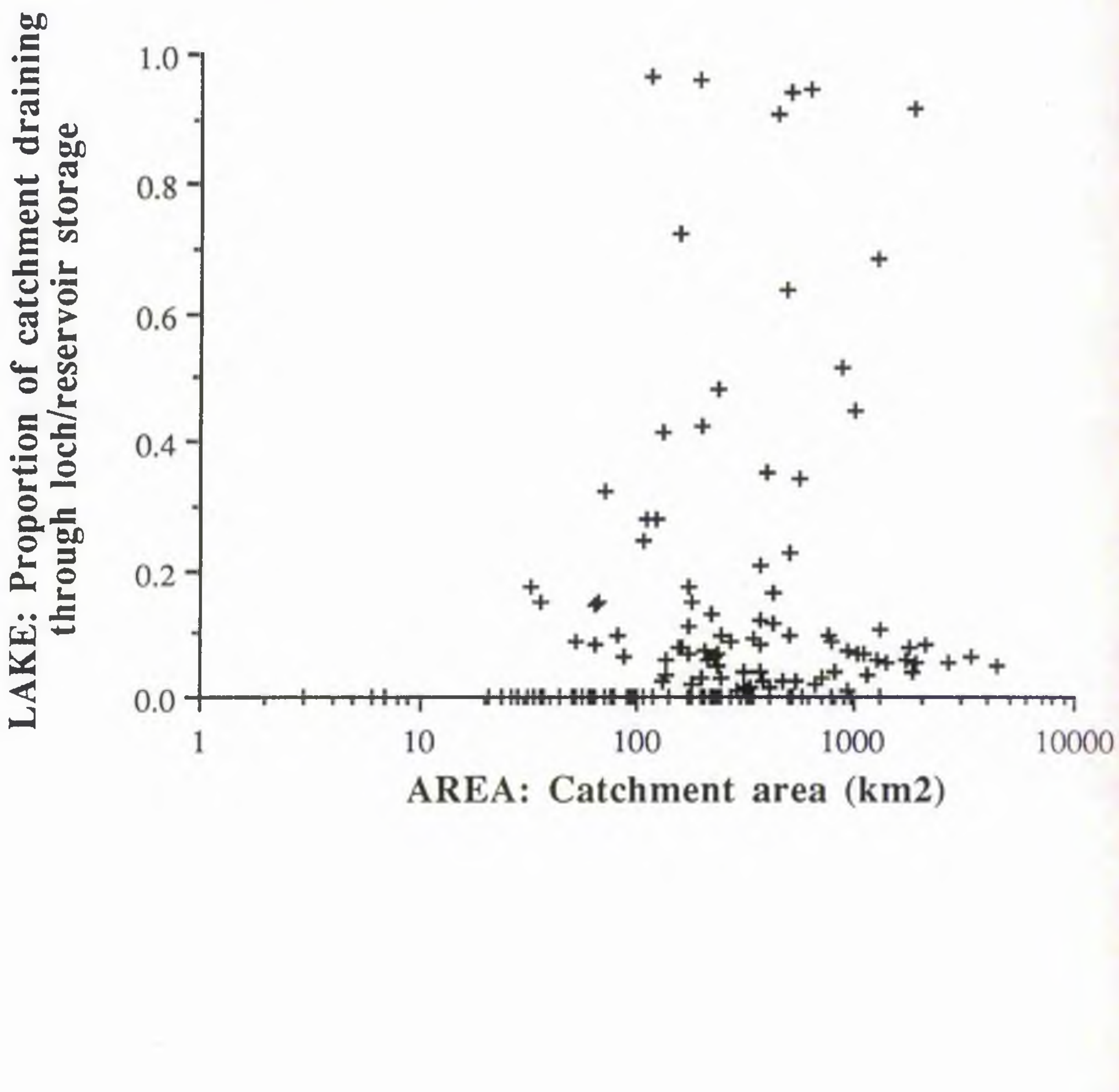
Multiple regression is one method which might be used to explain how these factors interact to produce patterns of flood seasonality. This method is frequently adopted to solve problems in hydrology, not least among the examples being the *Flood Studies Report* 'statistical approach' to estimating mean annual flood from catchment characteristics (NERC 1975 I.4). Wishing to use the physical characteristics described above to explain flood seasonality presents an obvious parallel with this, but there are two good reasons why this might actually be inappropriate.

First, the distribution of values of these catchment characteristics is problematic, both independently and in combination with each other. Independent of any relationships with other variables, both AREA and LAKE have extremely strong positively skewed distributions. While logarithmic transformation could normalise these statistical distributions to some extent, heteroscedasticity with respect to a seasonality variable such as seen above with mean day of flood may still present a problem. Moreover, when considering the distribution of values for these variables in relation to each other, it becomes apparent that significant correlations exist, and further selectivity arises in the database as a result of the physical characteristics of the sample of catchments used in the study. As an example, Figure 5.11 shows the scatter of values of AREA and LAKE: the effect of the positive-skew distribution of values for both these variables is evident, with there being no examples of very large catchments (AREA > 2000 km^2) having even modest LAKE values (>0.1). Table 5.9 gives the Pearson correlation coefficients for all the previously discussed variables with each other.

Although the r values in some cells in Table 5.9 are surprisingly low, some strong correlations do exist, particularly between SMD length and the seasonal clustering

Figure 5.11

Distribution of LAKE and AREA values



	AREA (km^2)	LAKE	SMD (days)	PEAK RAINFALL	
				Mean day	*r*
AREA	*	0.079	-0.008	0.008	-0.023
LAKE		*	-0.410	0.231	0.397
SMD			*	-0.472	-0.721
Mean day				*	0.393
r					*

Table 5.9 Correlation matrix showing Pearson's r values for flood seasonality predictor variables. *(Rainfall figures for average of 10 events/year at 1-day duration, mean day as days after 31 May. SMD is mean length of season with SMD values exceeding 10 mm.)*

of peak rainfalls, and considering also the skewed distributions and the variable representation of some combinations of variable values relative to others, it would seem that a regression method of explaining differences in flood seasonalities might not be ideal. However, a more serious problem than this exists.

Chapter 4 sought to describe the patterns of flood seasonality across the study area, and it was stressed that seasonality could not be adequately described by reference to any one variable. Mean day of flood and its associated *r* value were useful in combination, but even then did not offer an especially comprehensive characterisation, as values of these variables could mask detailed differences in the seasonal distribution of floods. Only by use of 2-monthly frequencies could greater detail be expressed, but in order to condense this information into a usable form, it was felt that a clustering analysis was necessary. It is therefore suggested that multiple regression analysis could not be employed, since the object of a regression is a single scalar variable, and none of these variables (mean day, *r*, 2-monthly frequencies) can adequately describe seasonality alone. Rather, it is felt that the results of the clustering analysis must be the target of any explanation, as cluster membership is much more meaningful than any of the statistics available. To this end, discriminant analysis is to be used to explain cluster membership.

5.3.1 Discriminant analysis

Discriminant analysis is, like linear regression, based on the general linear model; it is not therefore a radically different method to regression, but while regression methods deal exclusively with scalar variables, discriminant analysis is based on group membership and is therefore ideal for application here. The method requires the input of group membership along with values of any number of independent predictor variables (physical characteristics) for each observation (station). Linear discriminant functions are then produced for each group, as a means of predicting group membership from the physical characteristics. The analysis was undertaken using the MINITAB statistical package (MINITAB 1989) in the following manner.

Base 10 logarithms were taken of the values of AREA and LAKE in order to reduce the extreme positive skew in their distributions, and all variables were then normalised before principal components were taken to mitigate the unwanted effects of interdependence amongst the predictor variables. Five principal components were thus produced from the five original variables (peak rainfall mean day, peak rainfall *r*, SMD length, AREA, LAKE). Discriminant analysis was then performed for the four-group classification described in Chapter 4 using these five components, and resulted in 59.4% of catchments being assigned to their correct groups. Taking logarithms of those variables not already transformed before calculating principal component scores resulted in a slight improvement to 62.2% successful assignment.

This represents a modest degree of success, but with 37.8% of stations assigned to groups other than their own it is apparent that the method used falls some way short of being able to offer a wholly satisfactory explanation of cluster membership by reference to these physical factors. It was noticeable that at 35 (64.8%) of the misclassified stations, the discriminant analysis showed the true cluster to be the second most probable of the four, and this raises questions regarding the suitability of the classification method used. This seems especially important in view of the fact that the clusters do not have distinct boundaries: examination of Figure 4.5a shows that some stations could easily be allocated to another group. Therefore a variety of other similarity measures were used, and it was found that by using a shape measure which measures distance "as the variance of the differences between variable values of two cases or cluster centres" in all dimensions (Wishart 1987 p 197) and a discriminant analysis based on principal components of just four variables (mean day of peak rainfall was excluded as it resulted in a reduction in performance), 74.1% of stations' cluster membership could be explained by reference to the four principal components described above. Figures 5.12a and 5.12b show the seasonal distribution of floods for the members of the four groups produced by this new classification which again seems physically reasonable, and their geographical distribution is shown in Figure 5.13. The distribution of misclassified catchments between groups can be seen in Table 5.10 and also in Figure 5.13.

Figure 5.12a

Seasonal distribution of floods for members of clusters produced using shape similarity measure

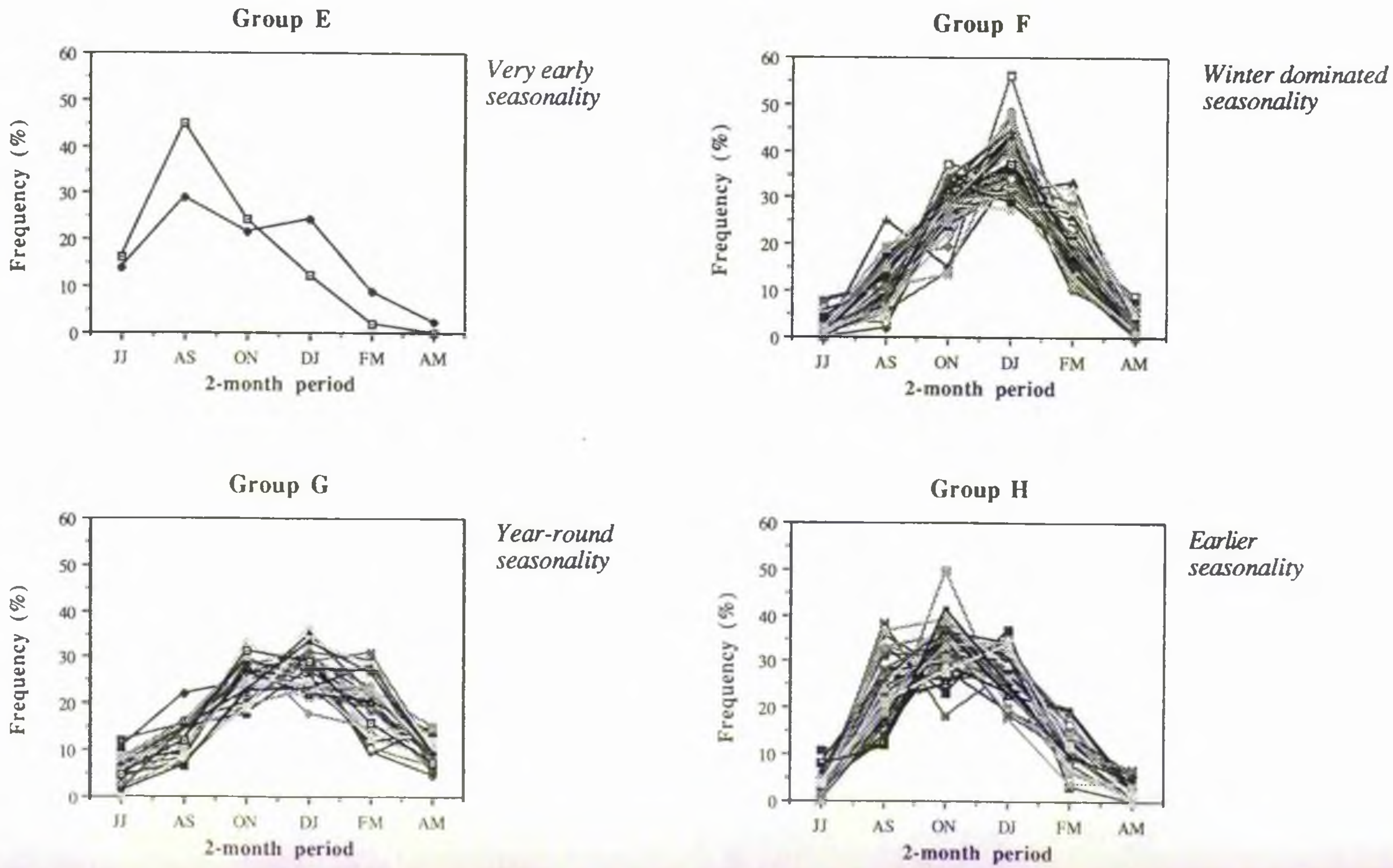
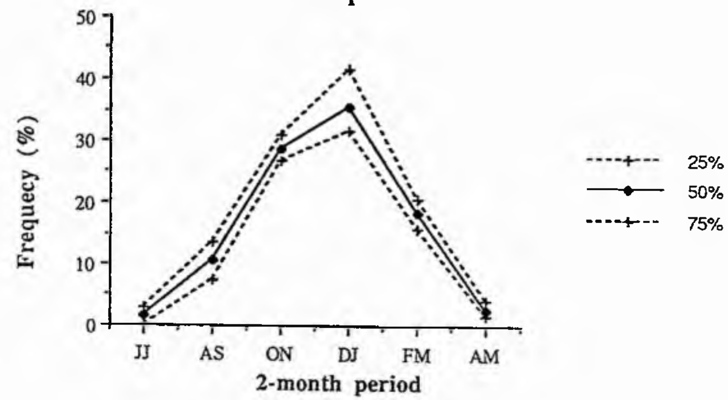


Figure 5.12b

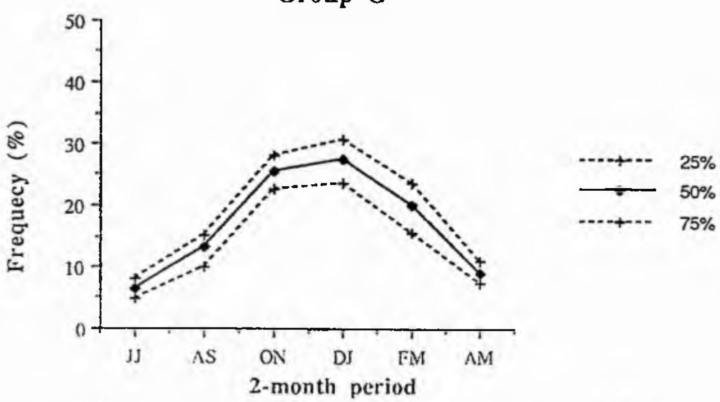
2-month frequency median and quartile ranges for groups classified using shape similarity measure

Group E:
Values not calculated as only 2 members in group

Group F



Group G



Group H

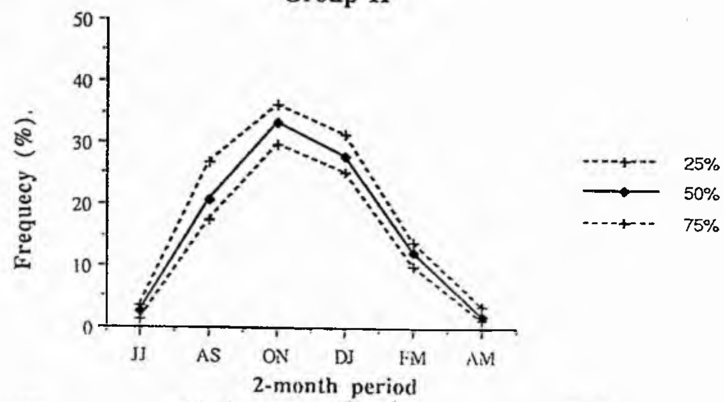
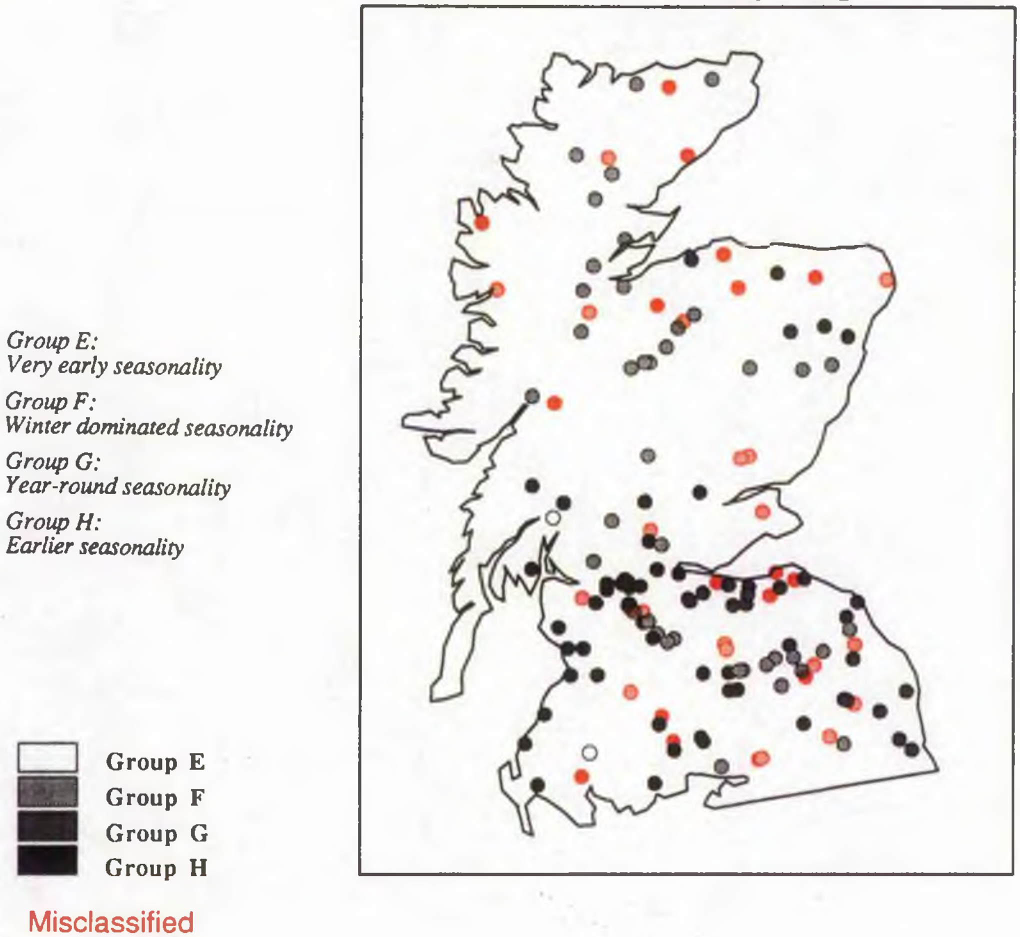


Figure 5.13

4-fold classification using shape similarity



Put into group	True group			
	E	F	G	H
E	0	13	4	39
F	0	7	24	2
G	0	41	4	5
H	2	0	1	1
Total number	2	61	33	47
Number correct	2	41	24	39
% correct	100.0	67.2	72.7	83.0

Table 5.10 Results of final discriminant analysis

This rather higher level of successful explanation clearly indicates that the physical characteristics used here are important determinants of seasonality, and considering the limitations of the data used (*ie* rainfall seasonality based on one-day peak totals irrespective of critical storm duration of catchments, and the relatively small number of physical factors used), this represents a much more satisfactory level of success in attempting to account for the observed patterns of seasonality. However, the failure of the method to explain cluster membership for the remaining 26% of stations must be considered, and two particular aspects of this are now addressed.

The first of these is the continuing dependence of the chosen method upon the results of the classification method employed. The specification of the correct classification for use in an analysis such as this is a matter of conjecture, and while the use of a shape similarity measure has resulted in an increase in the proportion of stations correctly assigned by the discriminant analysis, the problem of stations being classified into one group while they might relatively easily be classified into another remains, and total success of the discriminant analysis is therefore most unlikely. Of the 37 stations misclassified in the final analysis, 23 (59.0%) of these actually belonged to the group identified as second most probable by the discriminant analysis.

The second important aspect of the misclassification concerns the proportion of individual groups' members which are misclassified. It is surprising that the group with most members, Group F (winter-dominated flooding) with 61 members, also has the greatest proportion (32.8%) of its members misclassified (see Table 5.10). 13 of these 20 stations are misallocated to Group H (earlier seasonality) while the other seven are misallocated to Group G (year-round seasonality). A logical reason for a discriminant analysis based on the catchment characteristics used here to predict less flooding in the winter months than actually occurs is the failure to take account of the contribution of snowmelt to flood generation in the winter months. Most Group F stations are found in inland areas, and as winter snow accumulations will be relatively high in such areas, this does seem physically sensible, although such an explanation probably does not account for all the misclassified members of this group. One example might be station 14001 Eden @ Kemback draining a lowland catchment in Fife. Although snowmelt is sure to contribute to some floods at this station (as indeed at all stations used in this study), a more important factor for this particular station may be its high base-flow index of 0.60: owing to the slope and soil characteristics of its catchment, a high proportion of total flow here is in the form of base-flow, so its flood seasonality may be more dominated by long duration rainfalls in winter than other factors might suggest. The identification of snowmelt as a likely important determinant of seasonality fits well with theoretical expectations, and makes the lack of appropriate data especially unfortunate. Snowmelt is also likely to affect flooding indirectly by supplementing soil moisture levels.

5.4 Discussion

From the review of literature and a more intuitive consideration of the likely determinants of seasonality presented in Chapter 2, a number of factors were identified which were thought worthy of investigation in seeking to explain the patterns of seasonality described in detail in the previous chapter. These were the seasonality of peak rainfalls, soil moisture deficits, catchment area, loch or reservoir storage and snowmelt. The first two of these had been clearly identified in the literature as significant determinants of flood seasonality; some confusion appeared to exist concerning the rôle of the third, and the latter two factors were suggested as logical additions to the list of relevant factors without there being any specific evidence in the literature to support their consideration.

The evidence presented in the preceding sections of this chapter suggests that all five of these factors are important determinants of seasonality. Taking each of them in turn, peak rainfall seasonality has been seen to be important both on a regional scale, particularly in south-west Scotland where relatively frequent peak rainfalls in autumn contribute to more frequent flooding at that time of year than elsewhere, and also at the catchment scale where the seasonality of peak short duration rainfalls have been seen to affect flood seasonality in a small catchment.

Soil moisture deficits have been shown to exert a major control on flood seasonality by directly affecting the translation of summer rainfalls into runoff. It is thought that the spatial distribution of soil moisture deficit lengths plays a large part in the determination of the pattern of mean day of flood values, since SMDs are much longer in the east of the study area than in the west, so peak summer rainfalls in eastern areas (which account for a large proportion of the total) are only rarely translated into peak flows which exceed the threshold values set at individual stations. As a result, mean day of flood values show a clear trend to increase with distance east. SMD is an important barrier to flood generation which has an important effect on the observed patterns of seasonality.

The suggestion that catchment area is not an important determinant of flood seasonality has been refuted by showing that despite an important correlation between small, upland catchments and generally high catchment wetness values, catchment size is also important in determining the critical duration of rainstorm to which individual catchments respond. By affecting this duration, basin size affects flood seasonality since it has been seen that rainstorm seasonality varies with duration. However, it is acknowledged that in a study such as this, correlation between catchment size and other basin characteristics does exist, so care in interpretation is necessary. It is therefore acknowledged that the similarity in flood seasonality amongst very large catchments (AREA > 1000 km^2) is likely to be the result of all such catchments having broadly similar characteristics: all drain a range of land areas, from steep, wet headwater catchments down to rather flatter, drier lowland areas with soils and other characteristics accordingly showing a range of types.

The effect of loch or reservoir storage appears to be as expected, again leading to a concentration of winter flooding with increasing LAKE values. To check that this apparent constraint on seasonality with increasing values is not connected with the effects of large catchment areas, the seasonality of small catchments with high LAKE values was investigated. It was found that all six catchments with LAKE values greater than 0.4 and areas smaller than 250 km^2 belonged to Group F, indicating that winter dominated flooding could be produced by storage without any effect of catchment area. All of these catchments (04003, 08008, 18008, 21011,21020, 21034 (the latter three all below the same storages)) have relatively short SMD lengths (no more than 125 days), so the effect of storage does seem to be important here since short SMDs would ordinarily lead to relatively early flood seasonality, *ie* Group H membership. However, most catchments do not have any significant storages, so the effect of this factor on flood seasonality is restricted to relatively few catchments.

Finally, snow was identified from the wider literature on flooding as an important factor in flood generation, and while a lack of suitable data prevented its specific inclusion in this analysis, the results of the discriminant analysis described in the preceding section indicate that this is very important in increasing the number of winter floods found in inland catchments. The fact that the discriminant analysis was least successful in predicting membership of Group F (winter dominated seasonality) despite this being the largest group, and also the geographical distribution of these misclassified catchments suggests that snowmelt definitely has an important rôle in determining the seasonality of flooding in the area studied.

All these factors combine to produce the patterns of seasonality found, and a brief explanation of the patterns, as described by group membership, is now presented. Only two stations were assigned to Group E which is characterised by a very early flood seasonality. August-September is the period of highest flood frequency, with June-July also experiencing relatively high flood frequencies at these two stations. This most unusual seasonality is explained by the very small size of the catchments (3.1 km^2 and 5.7 km^2) in combination with the seasonality of short duration peak rainfalls. It may be surprising that a group of only two members has been identified by the classification procedure, but this is thought to be justified by the most unusual seasonality found at these two stations. Other catchments with similar flood seasonalities are sure to exist, but owing to the gauging strategy of hydrometric authorities, are not gauged and therefore cannot be represented in the data set used in this study.

Membership of Group F indicates a winter dominated flood seasonality and this group is the largest of the four identified in the final classification procedure, having 61 members. Most of these stations drain catchments which lie well inland, and are generally larger than those of other groups: 61% of Group F stations drain areas exceeding 250 km^2 whereas for all other stations, the corresponding proportion is only 30%. It is therefore suggested that basin size is important in producing winter-dominated flooding at many of these stations, as discussed in Section 5.2.3. This is supported by the finding that smaller catchments are more likely to have relatively early or late flood seasonalities rather than being dominated by winter events.

Another factor which is also thought to be important here is loch or reservoir storage. Of the 14 stations with LAKE values exceeding 0.4, 13 were assigned to Group F on the basis of their flood seasonalities (the only exception, 94001 Ewe @ Poolewe, was assigned to Group G because of the unusually high proportion of events occurring there in February-March). As it was shown in Section 5.2.4 that such storages result in a greater concentration of events in the winter months, this effect, along with that of catchment area, also appears to be important in producing the flood seasonalities found at stations in this group.

In addition, results of the discriminant analysis described above suggest that snowmelt is important in explaining the seasonality of flooding found at these stations. It has been already noted that these rivers mainly drain inland catchments, which are therefore more likely than others to be affected by snow, so this can be taken as a third factor in determining the overall seasonality of flooding at these stations.

The 33 stations of Group G are characterised by a relatively even distribution of floods around the year, and are found in two quite distinct spatial clusters: one in north-east Scotland extending from the River Findhorn to the Don, and the other in south-east Scotland, extending from the south side of the Firth of Forth south along the coast and into Northumberland. In the former cluster, high flood frequencies (relative to other stations) are recorded in June-July and August-September while in the latter, April-May and June-July are similarly significant. In both cases, the effect is to reduce flood frequencies found in winter months which would otherwise lead to more concentrated flood seasonalities as found at Group F stations. Flooding in both these areas is also characterised by low r values, again emphasising the relatively even distribution of floods around the year.

Much of the explanation for the seasonality of flooding found at these stations appears to lie in the seasonality of peak rainfalls in these two areas. Examination of Figures 5.2 and 5.3 shows that mean day of peak rainfall and peak rainfall r values are generally low, with June-July and August-September having unusually high peak rainfall frequencies in the Moray-Nairn area and April-May and June-July being more important in south-east Scotland and Northumberland. Some of the greatest SMD lengths are associated with stations in the more southerly of the two clusters, and this can be taken to explain the fact that the frequency of peak rainfalls in the summer months in this area exceeds flood frequencies in the corresponding two-month periods. The same applies, though to a lesser extent, to the cluster of stations in the Moray-Nairn area.

In Northumberland, SMD season lengths are especially long, and coupled with a very even seasonal distribution of peak rainfalls (very low rainfall r values) results in very late mean day of flood values, but the generally even seasonal distribution of peak rainfalls ensures that these stations are assigned to Group G. The three River Don stations classified into this group do not experience summer rainfalls as frequently as other stations in this group; their assignment to it is due to the relatively high proportion of events experienced in February-March which is thought to result, as at station 94001, from the effects of snowmelt. These stations are precluded from Group F membership on account of their comparatively low December-January flood frequencies and relatively high frequencies in April-May and June-July. However, the main reason for producing Group G seasonality can be seen to be the somewhat unusual seasonality of peak rainfalls found in the two main areas identified above, tempered by the effect of soil moisture deficits.

Finally, the relatively early seasonality of flooding found at the 47 stations of Group H can also be explained by reference to peak rainfall seasonality. These stations are clearly concentrated in south-west Scotland, and Figures 5.3b and 5.3c show that the proportion of peak rainfalls occurring in this area between August and November is high relative to other parts of the study area. This translates into the distinctly early seasonality of flooding shown for this group in Figure 5.12. The rôle of SMD values in this area is much less important than for, say, the southern members of Group G since western SMD values are much lower than those in the east.

Specific mention must now be made of some of the areas found in Chapter 4 to have particularly unusual flood seasonalities. The area of most strikingly unusual flood seasonality described in this study must surely be the Moray-Nairn area. The above analysis suggests that two factors are of key importance in producing the spatial variations in flood seasonality observed here. The first is peak rainfall seasonality, with there being many more peak rainfalls in the summer months in coastal areas than further inland: this results in more frequent summer flooding in these areas. The second factor is snowmelt: the River Spey rises to the west of the Monadhliath Mountains and also drains the western and northern flanks of the Cairngorm Mountains before eventually reaching the Moray Firth. Snowmelt must therefore be an important factor in flood flows in its upper reaches, but will be less important in its lower course where snowmelt inputs are lower and summer rainstorms assume a greater importance (especially from the River Avon, see Table 5.5). Furthermore, Figure 5.2 shows that peak rainfalls over the upper Spey basin are much more heavily concentrated in winter than is the case along the Moray-Nairn coast. A combination of rainfall seasonality and the influence of snowmelt therefore explain the seasonal anomaly found in this area.

Similarly anomalous seasonality has been described for the Lothian area. This also appears to be related to summer peak rainfall occurrences, and flooding might be more frequent in summer except for the effect of soil moisture deficits. While Figure 4.4b shows the modal month of flood for the largest 20 recorded floods at stations in the Moray-Nairn area to be August or September, in the Lothians it is generally October or November. Even though peak rainfalls in this area are less frequent in these two months than in August - September, the large event modal month is in the later period as a result of soil moisture deficits assuming a greater importance earlier in the year. Hewson's (1983b) suggestion that the unusual flooding in the Moray-Nairn area may be partly caused by its having a north facing coast may equally be applied to the Lothians. Hewson finds that the Moray-Nairn area is unique as an upland area of Britain which receives its two year return period rainfall in the summer months, and again the rainfall characteristics of this area, as depicted in Figures 5.2 and 5.3, appear to be somewhat analogous to it.

A number of stations in the area around Ayr have also been described as having unusually early flood seasonality, and this too can be explained by reference to rainfall seasonality. Figure 5.3b shows a very clear positive anomaly in August-September peak rainfall frequencies centred on this area, and corresponds with high flood frequencies in these months at stations in hydrometric areas 82 and 83. Extremely high August-September flood frequencies at stations 80003 White Laggan @ Loch Dee and 87801 Allt Uaine @ Loch Sloy Intake have also been referred to on many occasions. These are explained not only by reference to rainfall seasonality, but also to their especially small catchment areas which are thought to make their flooding regimes responsive to peak rainfalls of a very short duration and which differ in their seasonal distribution from those of longer duration. Finally, stations 06007 Ness @ Ness-side and 94001 Ewe @ Poolewe are mentioned as stations with notably high late winter flood frequencies and low early summer frequencies, this seasonality being the result of both of these catchments draining through very large loch storages.

In conclusion, the analysis outlined in this chapter has allowed the rôle of individual physical factors to be identified through the use of a large and diverse set of catchments from across Scotland and northernmost England. Through such a comprehensive analysis, it has allowed the importance of peak rainfall seasonality, soil moisture deficits, catchment area, loch or reservoir storage and snowmelt to be identified in a way not possible in studies based on only single or small groups of catchments, and the success of the discriminant analysis in being able to explain 74% of seasonal group membership by reference to four catchment characteristics excluding snowmelt represents a high level of accomplishment. While it has been recognised that a high degree of interdependence exists between some physical characteristics of drainage basins, use of the statistical methods outlined has overcome this and enabled a high degree of explanation to be offered for the patterns of flood seasonality reported in Chapter 4. Any future method of accurately assessing the contribution of snowmelt to flooding is confidently expected to further increase the success of such a method.

Chapter 6

Implications for flood frequency analysis based upon POT series

6.1 Introduction

In the previous two chapters, the patterns of flood seasonality in Scotland have been described, and the factors responsible for producing them identified. The purpose of this penultimate chapter of the dissertation is to consider the significance of flood seasonality in a number of ways, and in doing so to lead towards the ultimate conclusions of the study, which will be presented in the final chapter.

Each of the areas of significance to be examined is considered to be important in its own right, but in some cases there is also interdependence between them. First, the importance of seasonality is examined in relation to the accuracy of index flood (mean annual flood) estimation, using a very simple method. Evidence is presented which suggests that the accuracy with which the index flood can be estimated by one method relative to another at a given site is related to the seasonality of flooding. This provides a useful starting point in considering the significance of seasonality, as design flood estimation arguably lies at the very centre of flood hydrology, and implications of seasonality here must be seen as having great importance.

A second area of significance is the seasonal variation of flood risk at a station. A number of long records are examined in this respect, and seasonal variations compared. Exponential distributions are fitted to the data in order to allow an assessment of the variation of peak discharge with return period in each season. It is found that, at some stations there is little seasonal variation in flood risk while, at others, there are considerable seasonal differences. This is a matter of some direct interest for the engineer concerned with temporary works, but may also have wider implications for the identification of the optimal parent distribution to characterise flood frequency at a site.

The investigation is further developed into an examination of the synoptic conditions responsible for flood generation. It is found that the largest floods in neighbouring catchments can be caused by distinctly different meteorological situations, and this leads to the suggestion that in terms of the generation of high return period events, catchments respond to somewhat different generating mechanisms. On this basis, an examination of the rôle of distinct generating mechanisms on the overall frequency distribution of floods is undertaken, revealing that in some catchments, different genetic groups of events interact in such a way as to prevent the exponential model from accurately describing the magnitude-frequency relationship. The chapter considers each of these themes in turn, and concludes with a general discussion bringing together all the themes considered.

6.2 Index flood estimation in relation to seasonality

One of the reasons for undertaking this study was to investigate the possibility that seasonality of flooding might in some way affect the frequency distribution of floods at a given station. The distinction must be made, however, between identifying a causal link and a simple association with unproven cause. To firmly establish a cause would require a considerable amount of complex mathematical modelling work, which lies beyond the scope of this thesis. Nonetheless, as an initial step in this chapter, an examination of index flood estimation in relation to seasonality is presented.

Work by Archer (1981a) in north-east England has suggested that there is a definite link between flood seasonality and the agreement between mean annual flood estimates using different methods. Specifically, he found that in catchments where there were relatively few summer floods in the POT series, the *Flood Studies Report* catchment characteristic approach (NERC 1975 I.4.3) overestimated the mean annual flood relative to estimates based on the arithmetic mean of the annual series (AMAF). In this study, the opportunity arises to examine more closely the relationship between seasonality and mean annual flood estimates. If distinct differences are found in mean annual flood estimates between seasonal groups of stations, then this suggests that the method employed is more suitable to one type of flood seasonality than another. Put another way, such differences would strongly suggest that seasonality actually affects the frequency distribution of floods, as consistent differences between AMAF and its statistical estimate must imply that the method of estimation is unreliable.

6.2.1 Method

Rather than using a catchment characteristic method to estimate the mean annual flood, it was felt to be rather more useful to consider the way in which an estimate of $\overline{Q}$ based on the POT model compared with AMAF, since this study has been exclusively concerned with POT data series thus far. In this way, the suitability of the exponential model recommended for POT data could be evaluated.

To undertake this analysis, all stations with 20 years record or more were selected, numbering 78 in all. The average number of peaks per year of record varied greatly amongst these stations, from 2.63 at 20003 Tyne @ Spilmersford to 9.38 at 84016 Luggie Water @ Condorrat. For the purposes of this and further work outlined later in this chapter, the two stations with fewest peaks per year were excluded from analysis, namely 20003 Tyne @ Spilmersford and 18001 Allan Water @ Kinbuck. This ensured that all remaining stations had an average of at least 3.4 peaks per year. One further station, 08007 Spey @ Invertruim, was excluded, on the basis that the 44% of its catchment lying above Spey Dam might detract unacceptably from its usefulness in this analysis. For each of the remaining 75 stations, AMAF was calculated from the annual maximum series, and the POT model outlined in Section I.2.7.9 of the *Flood Studies Report* (NERC 1975) was used to calculate the mean annual flood using the partial duration series data. Data from the Surface Water Archive at the Institute of Hydrology were used to supply annual maxima for years where the POT record contained no peak above the threshold.

Mean annual flood estimates PT1MAF, PT2MAF and PT3MAF (NERC 1975 I.2.7.9) were each calculated for an average of 1, 2 and 3 peaks per year using the POT data, and in each case expressed as a ratio of AMAF. It was found that

PT2MAF and PT3MAF values were consistently very similar (within 1% of each other) while PT1MAF values could differ significantly from these. As the erratic PT1MAF values were thought to be the result of using small data sets (as few as 20 values), PT3MAF was chosen as the POT-based estimate of mean annual flood. The POT method does assume that flood frequencies are exponentially distributed and that the magnitudes of individual events follow an EV1 extreme value distribution.

In order to assess the rôle of seasonality, cluster membership resulting from the final four-fold seasonal classification described in Chapter 5 was used. For each group, the distribution of mean annual flood ratios (POT method estimate expressed as a fraction of AMAF) was plotted, and these then compared between groups. A statistical test was then conducted to ascertain whether differences between the distributions of ratios were significant.

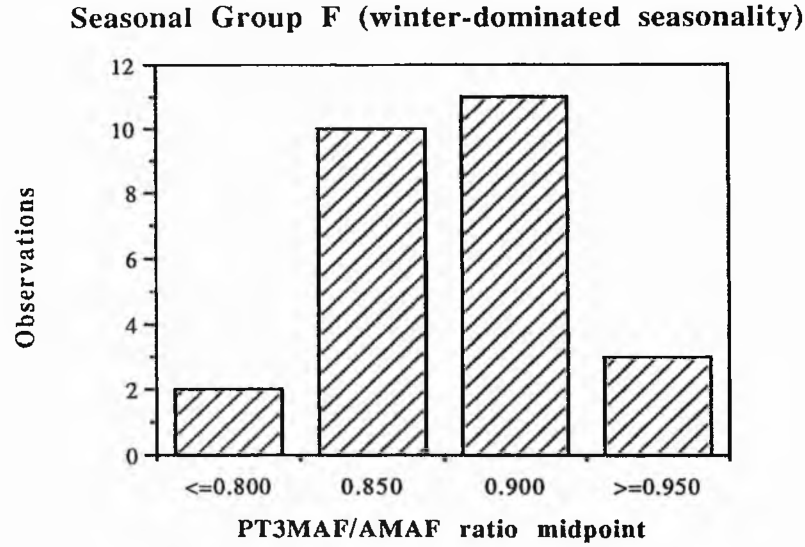
6.2.2 Results

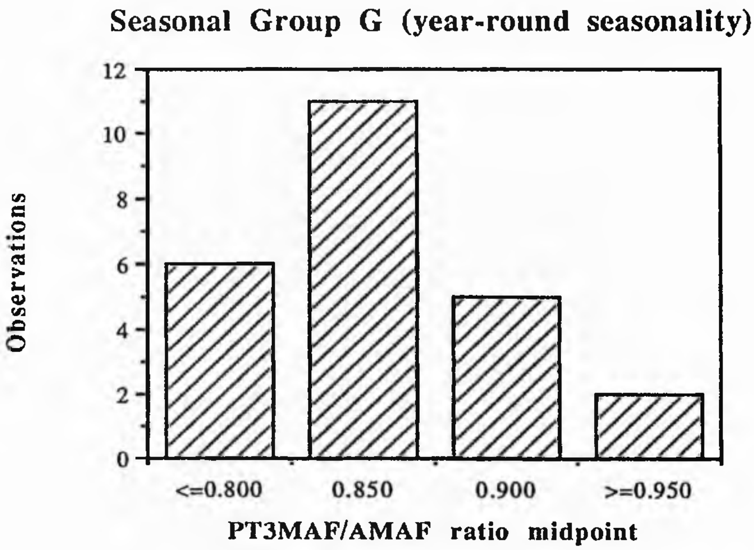
The distribution of PT3MAF:AMAF ratios for 3 of the 4 seasonal groups identified in Chapter 5 are shown in Figure 6.1. As only one of the 75 stations belongs to Group E, information is not shown for this group.

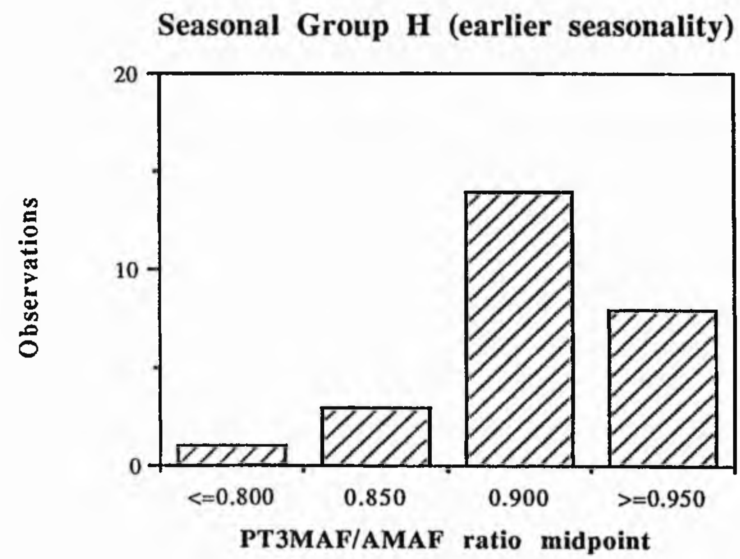
It can be seen that the distribution of values differs between each of the three groups. The most striking feature common to all three groups is that ratios are almost all below 1: at only 3 of the 75 stations did PT3MAF exceed AMAF (and then only by no more than 5%), the opposite situation to that found by Archer (1981b) for stations in north-east England. Differences between groups are quite distinct too however, Group G stations tending to have the lowest ratios, and Group H stations having the highest ratios. A χ^2 test shows that the distribution of values does differ significantly between the three seasonal groups (even at the 0.1% significance level), although owing to the small sample sizes this had to be based on a division of values into just two categories, above and below 0.875.

Reasons to account for these differences are difficult to arrive at with any certainty. However, one possibility is that the POT model used to produce the PT3MAF values implicitly assumes that the flood series are composed of a specific seasonal mix. The seasonality group with the best POT estimates of AMAF, *ie* highest ratios, is Group H, characterised by a generally earlier flood seasonality than other

Figure 6.1
PT3MAF/AMAF ratios for seasonal groups F-H







stations, while Groups F and G with winter-dominated and less pronounced seasonalities respectively have lower PT3MAF:AMAF ratios. Group F stations have an uncharacteristically high proportion of events occurring in the winter months, while Group G stations are characterised by especially frequent summer floods in relative terms. It can therefore be hypothesized that these extremes of seasonality are in some way responsible for the greatest observed discrepancies between mean annual flood estimates.

6.2.3 Interpretation

If AMAF is considered to be an accurate estimate of the mean annual flood, and the use of at least 20 years data at each station makes this a reasonable assumption, then this analysis certainly shows that the ability of the exponential model to estimate $\overline{Q}$ varies significantly with the seasonality of flooding. It cannot be taken to prove that the suitability of the model is dependent on seasonality, as some other unaddressed influence may be responsible for the apparent relationship between PT3MAF/AMAF and seasonality. However, the findings presented above may be taken as one contributory factor to suggest that flood seasonality does have a significant effect on the real flood frequency at a station.

This brief analysis has investigated how well a POT method estimates the value of the mean annual flood, said to have a return period of 2.33 years under the assumption of an EV1 model (see NERC 1975). The disagreements between the estimates found could be the result of either the unsuitability of the exponential distribution, or the assumptions inherent in its use. The value of the analysis is also dependent on mean annual flood actually being a sensible concept worth using in this context. Whether or not this is considered to be the case, by demonstrating that the performance of the POT model in determining $\overline{Q}$ varies according to the seasonality pattern inherent within the data, it does call into question the ability of one model to properly represent the variation of flood magnitude with return period. If estimates of $\overline{Q}$ vary so widely between stations with different flood seasonalities, the possibility must be contemplated that the distribution of flood peaks across a range of return periods might vary with seasonality. The following sections of this chapter consider further aspects of this same issue.

6.3 Seasonal variation in flood risk

In Chapter 4, the patterns of seasonality at stations used in this study were described, mostly in terms of the proportion of events occurring in each season at each station. Some information was also presented concerning the seasonality of the largest floods in each record, but in this section, the opportunity is taken to consider the relationship between flood magnitude and return period in each season. While much has already been said about the relative frequencies with which flows exceed the established thresholds between seasons at each station, this analysis explores the rates at which peak flows can be expected to increase with return period in each season.

This is a matter of considerable practical interest to engineers. In addition to directing a focus on the magnitude of rare flood events for the design of structures, there is also a need to estimate the magnitude of less rare events, especially when temporary works in or near rivers are involved. In some cases, this will involve the assessment of risk of a flood of a given magnitude over the period of just a few months. Clearly, if flood risk is thought to vary seasonally, then a seasonal analysis will be justified in assessing flood risk in such a situation. If an engineering project is to be carried out over just a few months, then this type of approach should be able to suggest when such work should be carried out to minimise the risk of flooding of a given magnitude.

Beyond the immediate practical benefits of such an investigation, it is also thought that an understanding of the magnitude-frequency relationships within the flood populations of individual seasons might also contribute to a better understanding of the overall magnitude-frequency relationships within complete flood series. It has been previously observed (Chapter 4) that at some stations, the largest floods on record have a rather different seasonality to the flood series as a whole. This seasonal mix may be responsible for the actual distribution of points when subject to a theoretical distribution. This idea is addressed more fully later in this chapter; the present section concentrates more explicitly on frequency distributions for individual seasons themselves. The following paragraphs outline the methods used in this analysis, the results obtained, and what meaning might be derived from them, specifically addressing the importance of seasonality in relation to flood frequency analysis in general.

6.3.1 Methods of analysis

To examine seasonal differences in flood frequency distributions, the year was split into six seasons, using the same pairs of months as previously (Chapter 4), June-July through to April-May. The aim of this analysis was to examine the frequency distribution of floods in each season, and a model was therefore required from which the plotting positions (return periods) of events could be derived. The *Flood Studies Report* (NERC 1975 I.2.7) recommends the exponential model for use with partial duration series data; it was therefore selected for use and applied in the following manner.

The 75 long-record stations identified in Section 6.2 were again selected for use. As described above, a common threshold giving an average of 3.4 peaks per year was set for all these stations, offering a compromise between maximising the number of stations available for analysis and the number of peaks available in each record.

At each station, peaks above the new threshold were assigned to their respective seasons, and for each season with a minimum of ten events, a frequency distribution was fitted. For each season, the exceedance rate λ was calculated as

$$\lambda = \frac{M}{N}$$

where M is the number of peaks exceeding the new threshold in the specified season over the period of N years. Adapting the POT model to this seasonal use, the two parameters of the model are then calculated as

$$\beta = \frac{M(\overline{q} - q_{min})}{M-1}$$

and

$$q_0 = q_{min} - \frac{\beta}{M}$$

where $\overline{q} = \frac{\sum_{i=1}^{M} q_i}{M}$ and

q_{min} is the smallest q value exceeding the new threshold in any season.

The magnitude of a T year flood could then be estimated from the parameters of the model thus:

$$Q_T = q_0 + \beta \ln\lambda + \beta \ln T$$

and enabled the model to be fitted for each season. Plotting positions (reduced variate values), y_i, were calculated according to:

$$y_i = \sum_{j=1}^{i} \frac{1}{N+1-j}\ .$$

This, when combined with a linear scale for discharge, resulted in the exponential model for the T-year flood plotting as a straight line. Full plots for each station are given in Appendix H.

An index flood was required, as a reference against which longer return period floods could be measured, and growth factors determined. As this study is based mainly around POT methods, the EV1 assumption of the mean annual flood having a 2.33 year return period was rejected in favour of simply using a 2 year event as an index flood. This and the 20 year flood were calculated in each season, by the above equation, for each of the stations used. Their ratio was tabulated for as many seasons as were available at each station, and the results are given in Table 6.1. Consideration of the variation of the growth factors given by these ratios forms the basis of the remainder of this section.

Table 6.1 Q_{20}/Q_2 **growth factors for all stations used in analysis**

Station	Jun-Jul	Aug-Sep	Oct-Nov	Dec-Jan	Feb-Mar	Apr-May
07001		2.20	1.59	1.78	1.87	
07002	3.12	3.48	1.89	1.60	3.88	
07003	3.97	4.09	2.13	1.89	1.82	
08001	3.67	2.79	1.60	1.71	1.49	
08002		2.02	1.64	1.79	1.99	
08004	4.52	2.43	2.11	1.72	1.83	2.12
08005		1.69	1.50	1.77	1.95	
08006	7.61	2.66	1.69	1.61	1.54	
08008		4.82	1.81	1.96	2.06	
08009		2.81	1.69	1.68	2.07	
08010		2.23	1.49	1.62	1.68	
08903			1.53	1.57	2.34	
09001		2.45	1.84	1.67	1.58	2.02
09002		3.07	1.96	1.71	1.55	
09003		2.49	1.75	1.86	1.98	
10001			1.94	1.60	1.60	
11001			2.53	1.80	1.78	
12001		3.18	2.07	1.86	1.78	2.36
14001			1.63	1.64	2.30	

Table 6.1 (cont'd) Q_{20}/Q_2 growth factors for all stations used in analysis

Station	Jun-Jul	Aug-Sep	Oct-Nov	Dec-Jan	Feb-Mar	Apr-May
15008			1.77	1.55	1.58	
16003		2.19	1.76	1.75	1.67	
17001		2.83	1.99	2.01	2.15	
19001		2.14	1.97	1.71	1.55	
19002		2.01	1.86	1.85	1.88	
19004		2.92	2.09	1.72	1.73	
19006			2.05	1.80	1.47	
19007		3.56	2.26	2.16	1.75	
19008		5.36	3.00	2.10	2.19	
19011		4.21	2.25	1.78	1.85	
19005			1.88	1.72		
20001		4.37	2.03	1.72	1.80	
20002			2.18	2.24	2.19	2.84
20005		4.61	2.13	2.30	1.95	
21003		1.93	1.79	1.86	1.65	
21005		1.73	1.78	1.68	1.76	
21007		1.90	1.80	1.89	1.95	
21008		2.26	1.73	1.64	1.81	
21009		2.54	1.72	1.68	1.75	
21012			1.71	1.67	1.58	
21015			3.07	1.85	1.88	
21016			2.54	2.00	2.24	2.83
21022			3.40	2.28	2.26	3.23
21006		1.79	1.82	1.92	1.91	
21010		2.46	1.82	1.66	1.90	
21031		3.56	2.02	1.69	2.04	
21032		3.90	2.59	1.95	2.12	
22001			2.11	1.70	2.12	
22006			2.34	2.35	2.29	
22007			3.21	2.12	2.42	
77002		2.46	1.80	1.85	1.78	
78003			1.54	1.49	1.41	
78004		1.58	1.68	1.51	1.68	
79002		1.72	1.60	1.63	1.85	
79003		1.57	1.59	1.58	1.86	
79004		1.71	1.65	1.61	1.66	
79005		1.40	1.78	1.73	1.70	
79006		1.66	1.65	1.59		
80001		1.97	1.68	1.65	1.61	
81002		1.90	1.71	1.61		
81003		2.05	1.57	1.52	1.82	
83802	1.48	1.56	1.59	1.52	1.33	
84003		1.70	1.68	1.54	1.60	
84005		2.03	1.75	1.49	1.53	
84012		2.07	1.43	1.67	1.64	
84013			1.70	1.51	1.47	
84014		3.44	1.76	1.83	1.98	
84015		1.42	1.35	1.35	1.40	
84016		2.38	1.98	1.98	1.73	
84020		1.72	1.68	1.56		
84001		1.57	1.45	1.51	1.75	
84004		1.99	1.63	1.63	1.61	
84006		1.75	1.64	1.60	1.55	
86001		1.78	1.62	1.98		
87801		1.49	1.42	1.36		
91802		1.56	1.53	1.63	1.83	

6.3.2 Results

Considerable variation exists between stations in terms of the ratio of their 2 year and 20 year floods in the six seasons used, these differences being illustrated by reference to six contrasting stations. At each, the frequency distributions for each season are presented graphically, and the seasonal variation of discharge values for given return periods, their associated growth factors, and return periods for given flood magnitudes discussed.

08004 Avon @ Delnashaugh

In terms of seasonality, this is undoubtedly one of the most unusual stations considered in this study. All nine events exceeding 300 m^3s^{-1} in the 37 years of record occurred in the summer months between June and October, and this unusual seasonality is reflected strongly in the seasonal differences between frequency distributions (Figure 6.2). The points lie reasonably close to the line in each case, but it can be seen that there is a wide variety of slopes between seasons. In each of the figures, the fitted line shows the magnitude of flood for return periods between 2 and 200 years, and seasonal differences in these values of Q_T as well as the slope of line (growth rate) between them will be considered.

There is considerable diversity amongst seasons in the value of the 2-year flood, from 75.29 m^3s^{-1} in June-July to 165.02 m^3s^{-1} in August-September, a fact made more remarkable when considering that these two seasons occur in direct succession. In actual fact, the value of the 2-year flood decreases very steadily with season from August-September through to June-July (see Table 6.2). At high return periods, however, the pattern is somewhat different. The year appears to be split into two distinct halves, with the seasons between June-July and October-November having Q_{200} values greatly in excess of those in the other half of the year. The growth factors in these six seasons therefore vary greatly, the Q_{20}/Q_2 ratio ranging from a mere 1.72 in December-January to 4.52 in June-July. In practical terms, this means that small spring/early summer storms are much rarer than late summer/autumn/winter events of similar magnitude, but at high discharges, say 400 m^3s^{-1}, summer return periods become progressively smaller in relation to winter ones, *ie* winter/spring events of this magnitude are extremely rare, but those in summer are much less so. Table 6.3 illustrates the seasonal variation of return period for 100, 250 and 400 m^3s^{-1} floods.

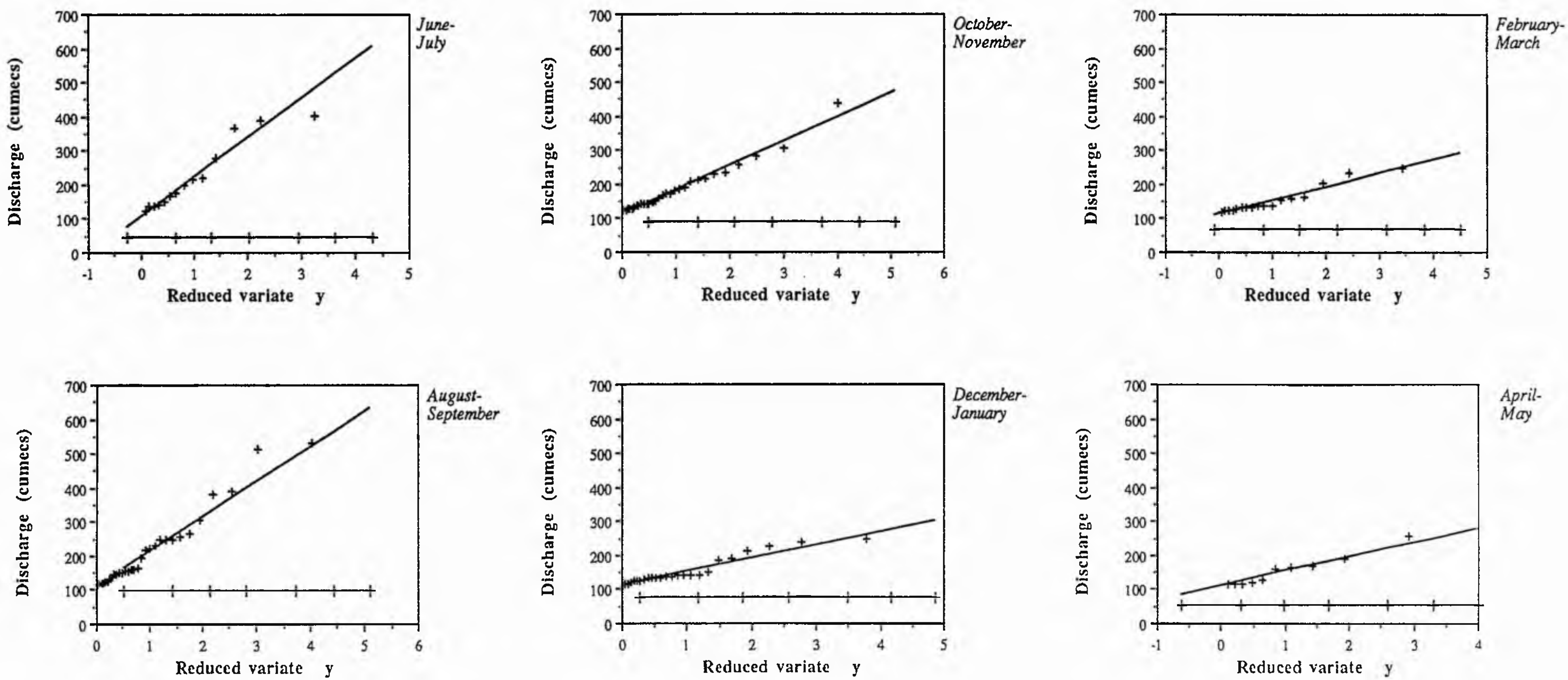
Chapter 6

FREQUENCY DISTRIBUTION PLOTS

(Figures 6.2 - 6.7, 6.9 - 6.17)

Upper horizontal axis shows return period for values of 2, 5, 10, 20, 50, 100 and 200 years

Figure 6.2
Seasonal frequency distributions for station 08004 Avon @ Delnashaugh



Season	Q_2	Q_{20}	Growth factor Q_{20}/Q_2	Q_{200}
Jun-Jul	75.3	340.3	4.52	605.4
Aug-Sep	165.0	400.2	2.43	635.3
Oct-Nov	147.5	311.0	2.11	474.5
Dec-Jan	124.1	213.3	1.72	302.5
Feb-Mar	109.9	201.0	1.83	292.0
Apr-May	85.7	181.8	2.12	277.9

Table 6.2 Station 08004: Discharge of 2, 20 and 200 year events (m^3s^{-1})

Season	T=100 m^3s^{-1}	T=250 m^3s^{-1}	T=400 m^3s^{-1}
Jun-Jul	2.47	9.08	33.44
Aug-Sep	1.06	4.59	19.93
Oct-Nov	1.03	8.48	70.12
Dec-Jan	1.07	10.45	86.40
Feb-Mar	1.55	69.22	3086.39
Apr-May	2.82	102.83	3752.57

Table 6.3 Station 08004: Return period of 100, 250 and 400 m^3s^{-1} events (years)

Bringing together the information in the tables, it can be seen that at the low return period of 2 years, floods are much smaller in spring/early summer than in late summer, but growth factors in spring/summer, especially in June-July, are such that the distribution of higher return period flood values between seasons is somewhat different, with the largest events occurring between June-July and October-November.

An example shows how this can be translated into useful information for an engineer interested in short-term flood risk on the river. Suppose a small, 2-month construction project were to be carried out on the banks of the Avon at Delnashaugh, and would be damaged by any flood exceeding 250 m^3s^{-1}. Analysis of the full POT series yields a return period of 2.11 years for the 250 m^3s^{-1} event, and if the project were to take only 2 months, then the risk of any flood exceeding that level during the period is 1 in (6 x 2.11) = 1 in 12.68. However, if the engineer has complete freedom in the timing of the work, Table 6.3 shows that he would be well advised to plan the project to take place in April and May when there is only a 1 in 102.8 chance of that flood value being exceeded while on the other hand, he should be at pains to avoid the months of August and September, when there is a 1 in 4.6 chance of such an exceedance. Should the planned works be intended to last for a period longer than 2 months, the analysis could be performed using a more suitable division of the year.

08005 Spey @ Boat of Garten

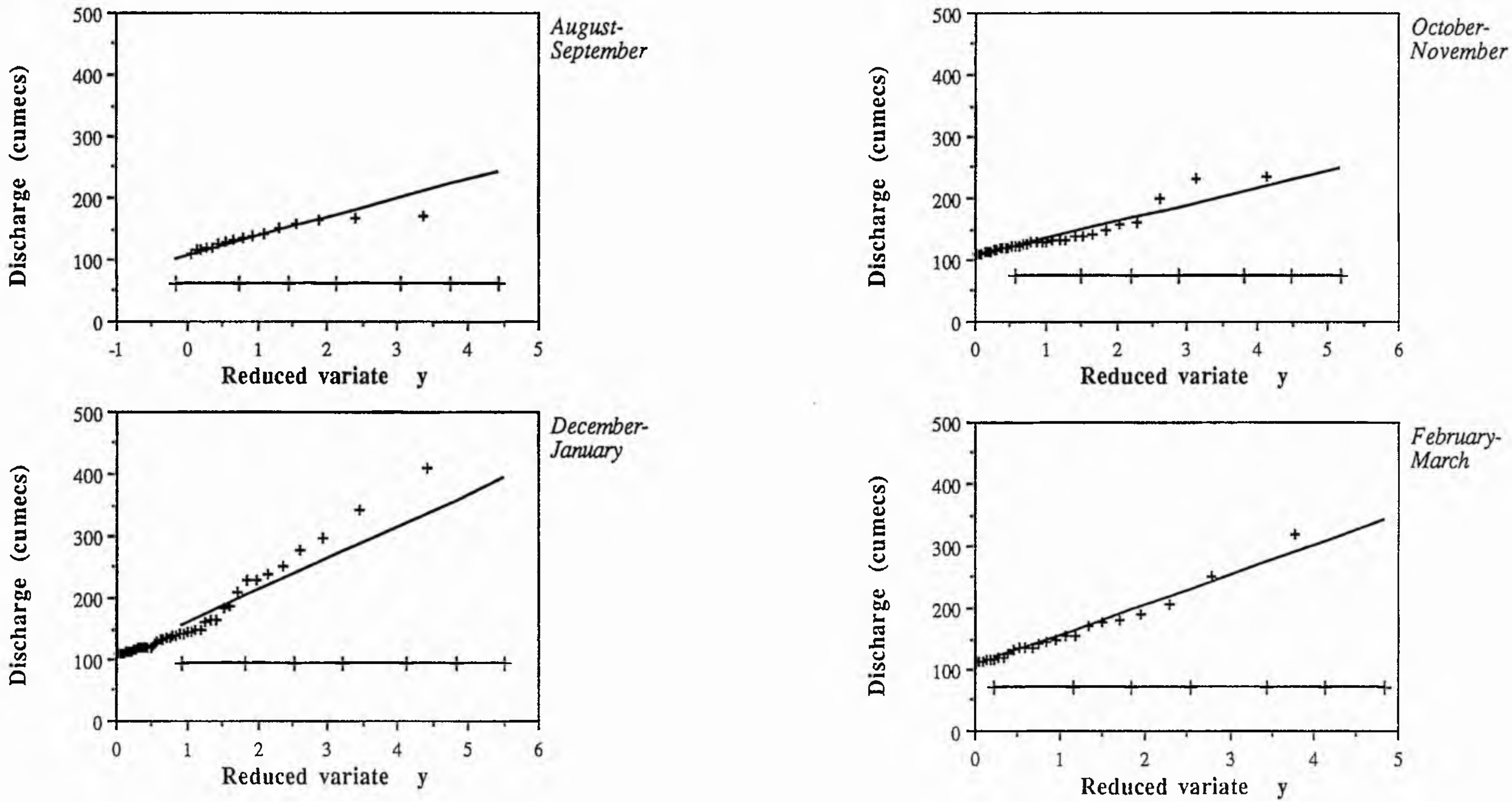
At this station, distributions have been fitted to the data of only four seasons (Figure 6.3), as less than 10 events occurred in both April-May and June-July. As at Delnashaugh, the highest value of Q_2 occurs in winter, with the December-January value of 154.3 m^3s^{-1} exceeding the August-September value by 52% (Table 6.4). The ratio may be found to be higher again if it were possible to derive values for the two missing summer seasons. However, unlike Delnashaugh, this seasonal pattern is maintained at higher return periods, December-January again having the greatest magnitude and August-September the smallest. The ratios of highest to lowest discharges at any return period seem slightly lower than those on the Avon (even accounting for missing seasons at Boat of Garten), and since the seasonal differences in distributions are much less than on the Avon, there is a very small range in growth factors at Boat of Garten compared with Delnashaugh.

Season	Q_2	Q_{20}	Growth factor Q_{20}/Q_2	Q_{200}
Aug-Sep	101.5	171.8	1.69	242.1
Oct-Nov	123.5	185.3	1.50	247.1
Dec-Jan	154.3	273.2	1.77	392.0
Feb-Mar	118.0	229.7	1.95	341.3

Table 6.4 Station 08005: Discharge of 2, 20 and 200 year events (m^3s^{-1})

Estimates of a T-year flood at this station do still vary with season, but in a much less spectacular manner compared with those for the Avon. The broadly similar growth factors shown in Table 6.4 indicate a much more homogeneous frequency distribution within the whole flood series at this station. The omitted data for June-September seem unlikely to affect this as only 6 of the largest 100 events at this station fell in these four months, and the largest of them, at 192 m^3s^{-1} (30/7/1956) is less than half the magnitude of the largest recorded event at 410.3 m^3s^{-1} (18/12/1966).

Figure 6.3
Seasonal frequency distributions for station 08005 Spey @ Boat of Garten



Season	T=100 m^3s^{-1}	T=250 m^3s^{-1}	T=400 m^3s^{-1}
Aug-Sep	1.9	260.5	35618.3
Oct-Nov	0.8	225.6	60826.9
Dec-Jan	0.7	12.7	233.1
Feb-Mar	1.4	30.5	671.5

Table 6.5 Station 08005: Return period of 100, 250 and 400 m^3s^{-1} events (years)

However, Table 6.5 shows that there are still significant seasonal variations in flood risk; while differences appear to be relatively modest at the 100 m^3s^{-1} level, by 250 m^3s^{-1} these are quite pronounced, and if extension of this model to 400 m^3s^{-1} could be accepted as reasonable at this station, it would appear that such floods in August-September and October-November are most improbable indeed!

12001 Dee @ Woodend (Figure 6.4)

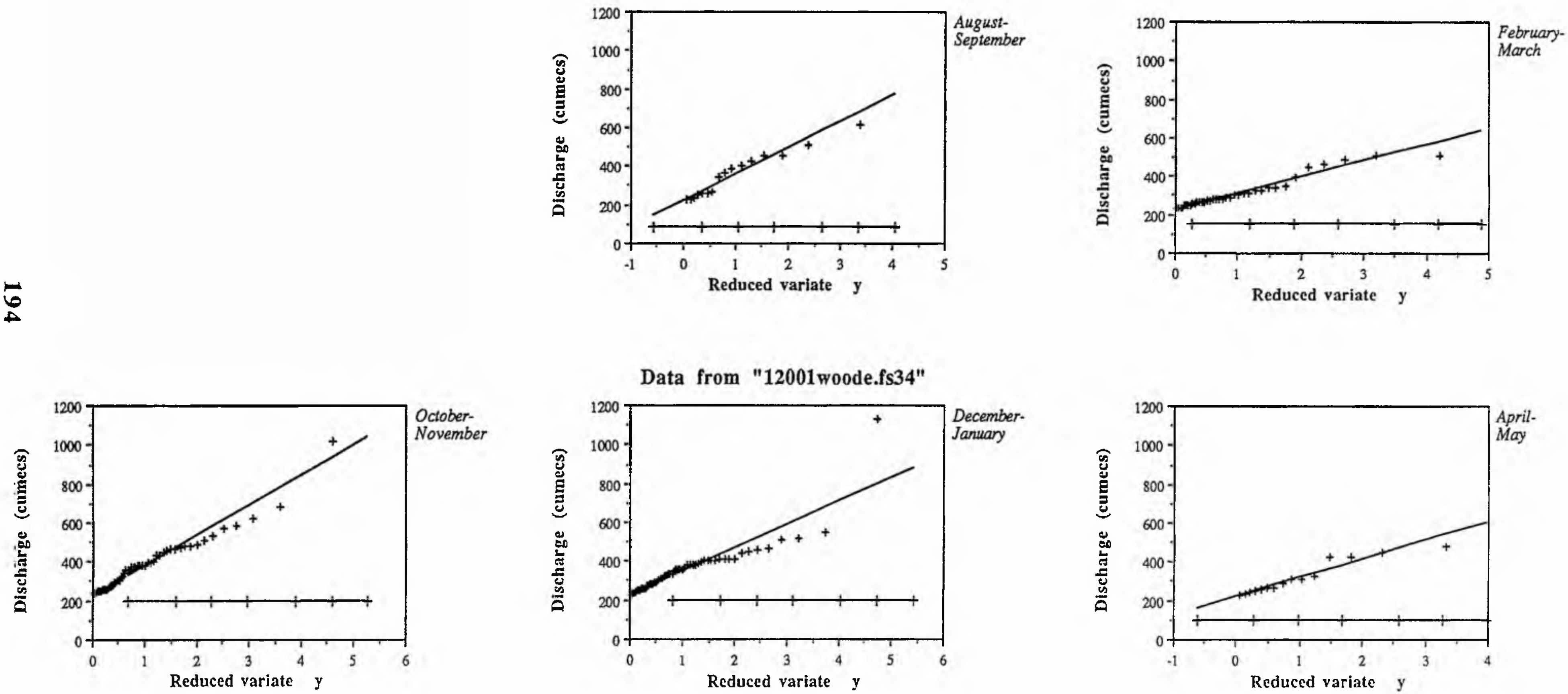
The seasonal variation of Q_2 values at this station is somewhat similar to that at Delnashaugh though, at this station, there were insufficient data to produce a frequency distribution for June-July. At most stations, Q_2 values are highest in the winter months, most commonly reaching a maximum in December-January, and are lowest in the summer. However, at Delnashaugh the highest Q_2 value is unusually early in August-September, and at this station the maximum of 329.6 m^3s^{-1} is also quite early in October-November. At both this station and Delnashaugh, the minimum Q_2 value occurs in the season immediately preceding that of the maximum (see Table 6.6).

Season	Q_2	Q_{20}	Growth factor Q_{20}/Q_2	Q_{200}
Aug-Sep	143.9	457.5	3.18	771.1
Oct-Nov	329.6	683.8	2.07	1038.0
Dec-Jan	324.6	602.6	1.86	880.6
Feb-Mar	249.9	444.4	1.78	639.0
Apr-May	162.4	383.0	2.36	603.5

Table 6.6 Station 12001: Discharge of 2, 20 and 200 year events (m^3s^{-1})

October-November retains the maximum value of all seasons at the high return periods shown, but as on the Avon, August-September shows a high Q_{20}/Q_2 growth factor, and a moderately high Q_{200} value of 771.1 m^3s^{-1}. The winter

Figure 6.4
Seasonal frequency distributions for station 12001 Dee @ Woodend



seasons of December-January and February-March are again characterised by relatively low growth factors, although the values at this station as a whole are quite high.

20002 West Peffer Burn @ Luffness (Figure 6.5)

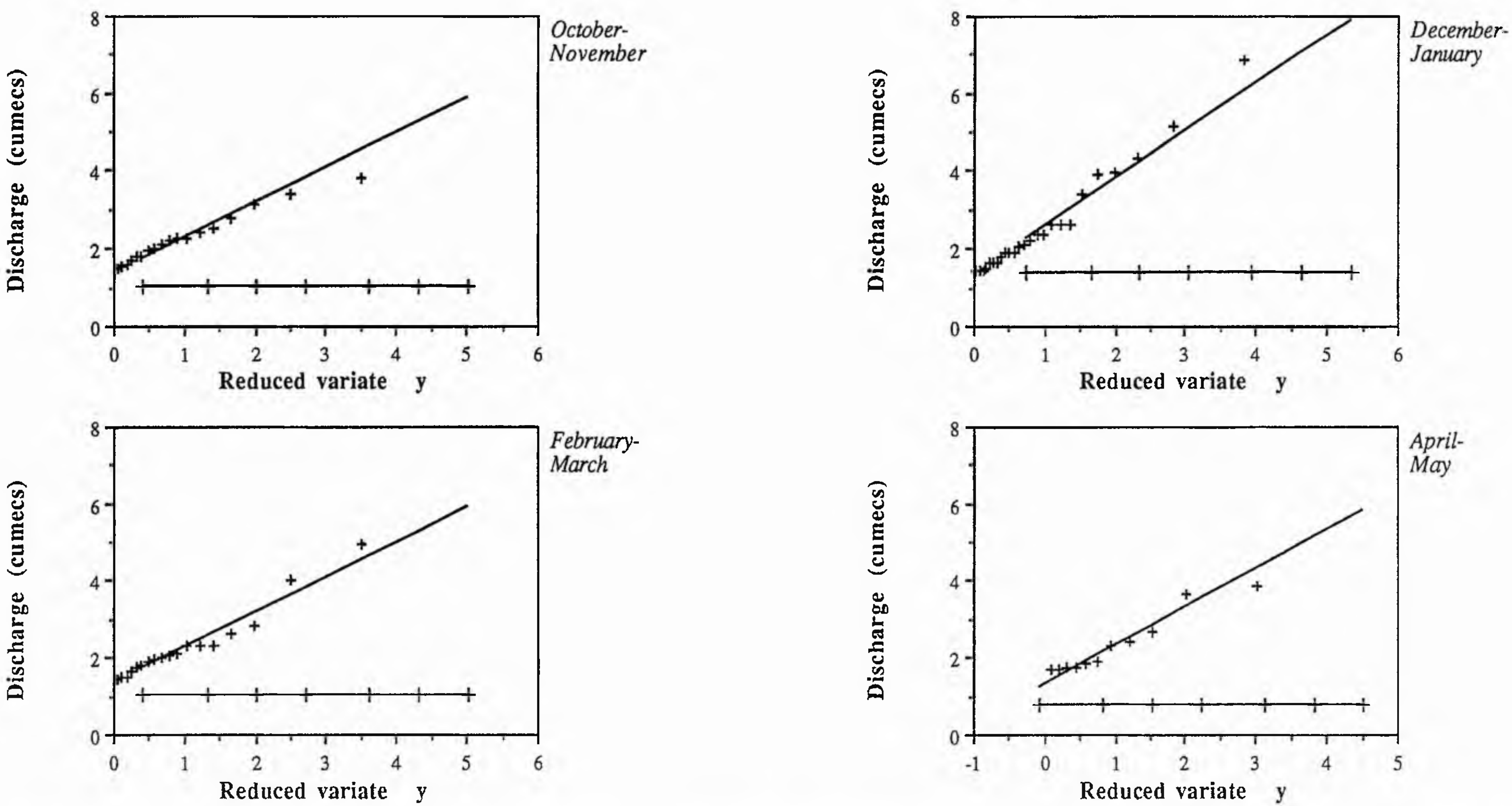
The data for this small East Lothian catchment show a large amount of variation in Q_2 values between seasons (Table 6.7), the December-January value being 82% greater than that for April-May. However, the growth rates for the three seasons October-November to February-March are almost identical, and are high in comparison with most stations in all seasons. Once again, December-January has the highest Q_2 value and the growth factors shown ensure that this season has the highest values at higher return periods also. Not unusually, the highest growth factor again occurs in a spring/summer season, April-May. However, it is unusual that lack of events prevented plots being produced for both June-July and August-September, the latter, in particular, reflecting the unusual overall seasonality of flooding at this station. A record of sufficient length to provide an adequate number of events and therefore allow production of plots for these missing seasons might produce interesting results: while only 3 of the 30 largest events on record occurred in these 4 summer months, they include the second largest event, 5.4 m^3s^{-1} on 22/9/1985 and also the 9th largest, 3.9 m^3s^{-1} on 1/6/1983, indicating that while events are rare at this time of year, they may be more important at high return periods than their missing status would suggest. Alternatively, it could be argued that both these events occur near to the end and beginning of their respective seasons, and therefore that these seasons as a whole are of little importance in flood frequency terms.

Season	Q_2	Q_{20}	Growth factor Q_{20}/Q_2	Q_{200}
Oct-Nov	1.7	3.8	2.18	5.9
Dec-Jan	2.3	5.1	2.24	7.9
Feb-Mar	1.7	3.8	2.19	5.9
Apr-May	1.3	3.5	2.84	5.8

Table 6.7 Station 20002: Discharge of 2, 20 and 200 year events (m^3s^{-1})

Figure 6.5

Seasonal frequency distributions for station 20002 West Peffer Burn @ Luffness Mains



83802 Irvine @ Kilmarnock (Figure 6.6)

Data from this Ayrshire station with the longest of all POT records in the study are presented to exemplify a station with a significant range of Q_2 values between seasons, but with relatively little variation in the growth factors for each season (Table 6.8).

Season	Q_2	Q_{20}	Growth factor Q_{20}/Q_2	Q_{200}
Jun-Jul	48.2	71.4	1.48	94.6
Aug-Sep	64.8	101.2	1.56	137.6
Oct-Nov	67.5	107.5	1.59	147.5
Dec-Jan	66.4	101.3	1.52	136.1
Feb-Mar	56.1	74.6	1.33	93.0

Table 6.8 Station 83802: Discharge of 2, 20 and 200 year events (m^3s^{-1})

As a result, the seasonal differences observed in Q_{20} and Q_{200} values are essentially a reflection of the variation of Q_2 values, multiplied by very similar growth factors. The highest discharge values are found in the autumn/winter seasons across the range of return periods shown. With such similar growth factors, the flood series for this station might be described as essentially homogeneous. Differences in Q_T between seasons can be simply ascribed to differences in flood frequency between seasons, those with lower Q_T values having lower frequencies than others.

84015 Kelvin @ Dryfield (Figure 6.7)

Finally, this station is considered, as most unusually it shows almost identical growth rates between seasons, and only a minimal amount of variation in Q_T estimates (Table 6.9). Despite the small margin, December-January again has the highest Q_2 value, but the subtle differences in growth factors between seasons result in the highest seasonal Q_{20} and Q_{200} values occurring in August-September. On the basis of the information presented, this station has the smallest seasonal differences in flood frequency distributions. It should be noted that the points in all 4 graphs of Figure 6.7 fall below the fitted line above a return period of approximately 5-10 years. Intuitively, it might be expected that a record with such consistency in terms of growth factors and minimal seasonal discrepancies in Q_T estimates might fit such a model well, yet the same pattern is found when the full (annual) data set is used. This point will be addressed in Section 6.5.

Figure 6.6
Seasonal frequency distributions for station 83802 Irvine @ Glenfield

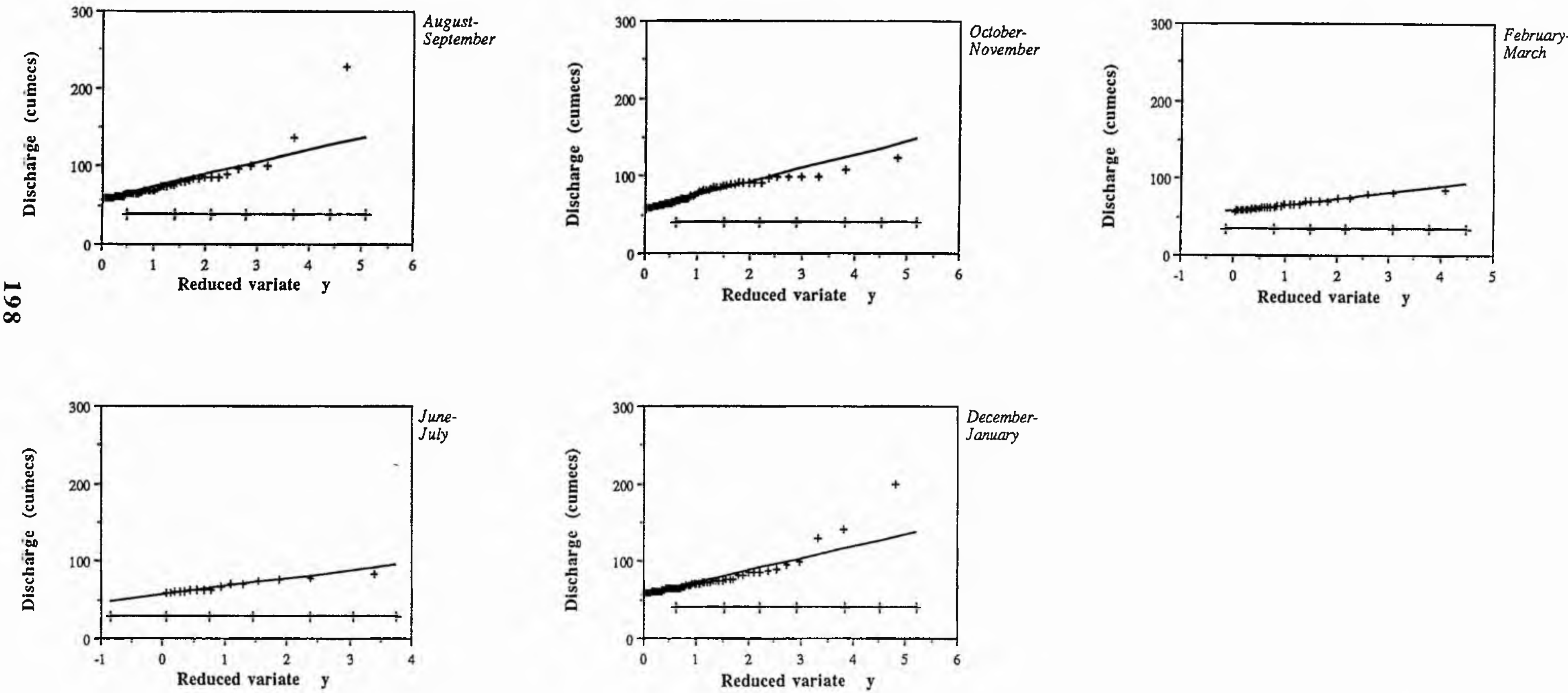
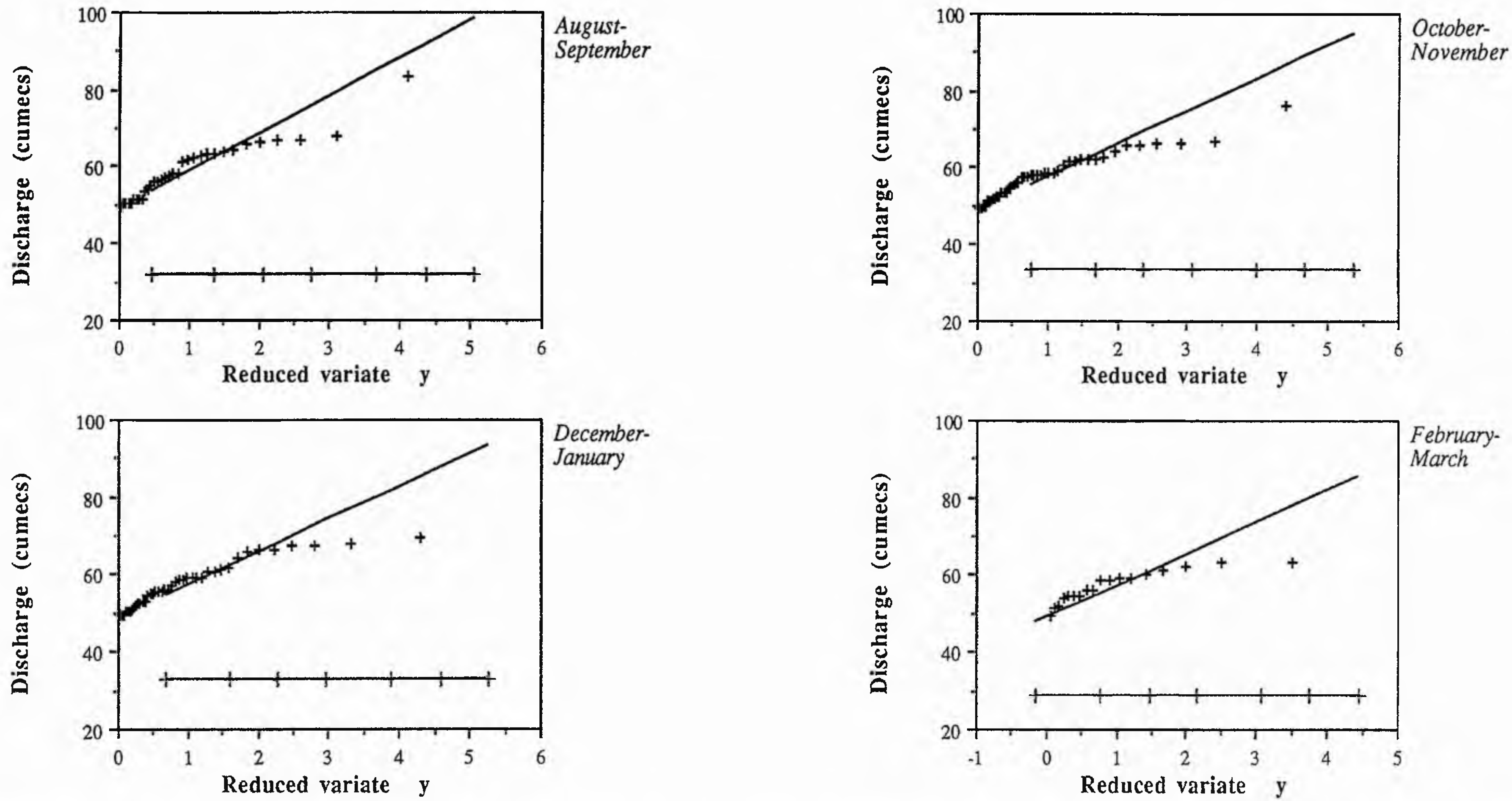


Figure 6.7

Seasonal frequency distributions for station 84015 Kelvin @ Dryfield



Season	Q_2	Q_{20}	Growth factor Q_{20}/Q_2	Q_{200}
Aug-Sep	53.3	75.9	1.42	98.3
Oct-Nov	55.7	75.3	1.35	94.8
Dec-Jan	54.8	74.0	1.35	93.2
Feb-Mar	47.6	66.6	1.40	85.6

Table 6.9 Station 84015: Discharge of 2, 20 and 200 year events (m^3s^{-1})

The presentation of results above has been of necessity selective, deliberately focusing on a small number of stations with contrasting seasonal variations in frequency distributions. Table 6.1 and Figure 6.8 give Q_{20}/Q_2 growth factors for all seasons at each of the stations used in this section of the analysis. It will be seen that there is a considerable range in values, and also a variety of inter-relationships between the values of one season and another. Examples of the main types of seasonal distribution have been described in the paragraphs above.

It is particularly noticeable from Figure 6.8 that some geographical areas are characterised by much higher growth rates in summer months than are other areas. This seems especially true in hydrometric areas 7 and 8, though many of the events at stations 8001/4/6 are common to each other. However, more generally it is clear that east-draining catchments are much more likely to have high summer growth rates than are west-draining ones. Another interesting feature is that stations in south-east Scotland and Northumberland (areas 17-22) appear to have much higher growth factors in October-November than those elsewhere. Station 79005 appears most unusual by its very low August-September growth rate, both absolutely and relative to other seasons.

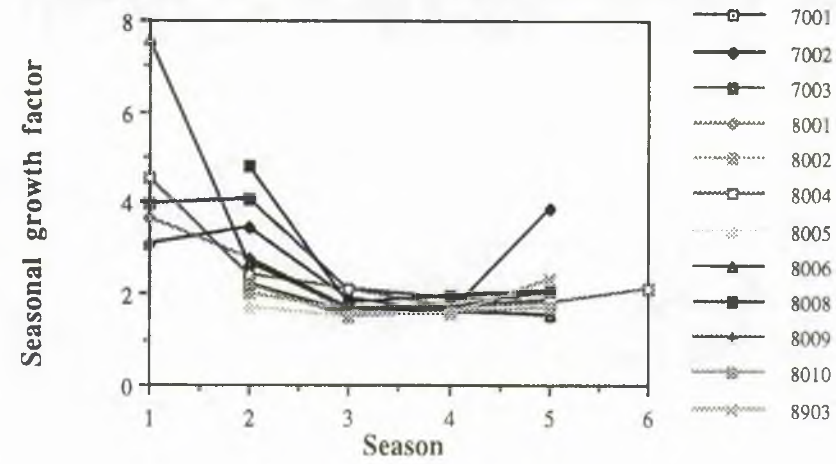
6.3.3 Interpretation

The results presented in this section are valuable in three respects. In the first instance, they are of intuitive interest, as considerable attention has been directed in this thesis towards identifying the seasonality of flooding across Scotland. While work in Chapter 4 has demonstrated the variation in overall flood frequency between seasons at a station, this chapter has demonstrated clearly the importance of each season with respect to the occurrence of higher return period floods. At

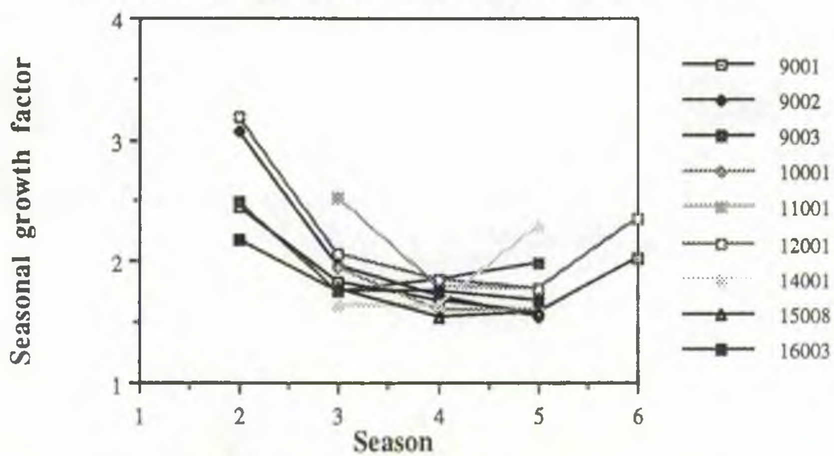
Figure 6.8
Seasonal variation in Q20/Q2 growth factors

NB Season 1=June-July; 2=August-September; 3=October-November; 4=December-January; 5=February-March; 6=April-May

Seasonal growth factors: Hydrometric areas 7 - 8



Seasonal growth factors: Hydrometric areas 9 - 16



Seasonal growth factors: Hydrometric areas 17 - 21

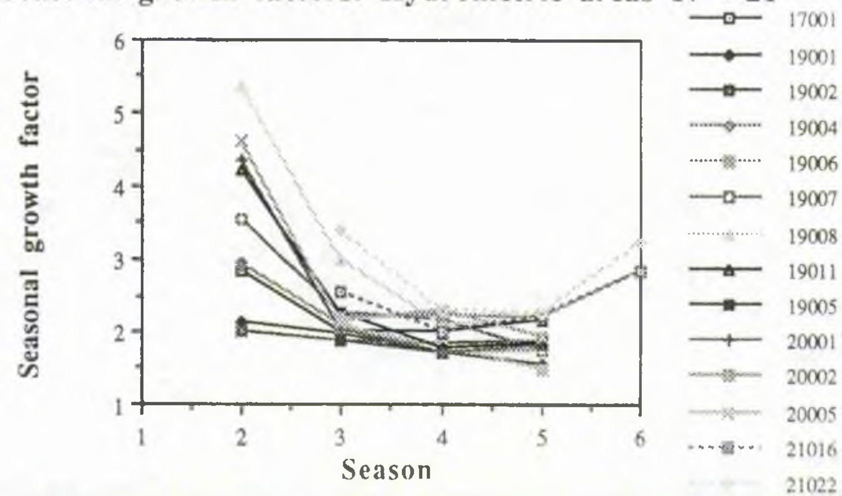
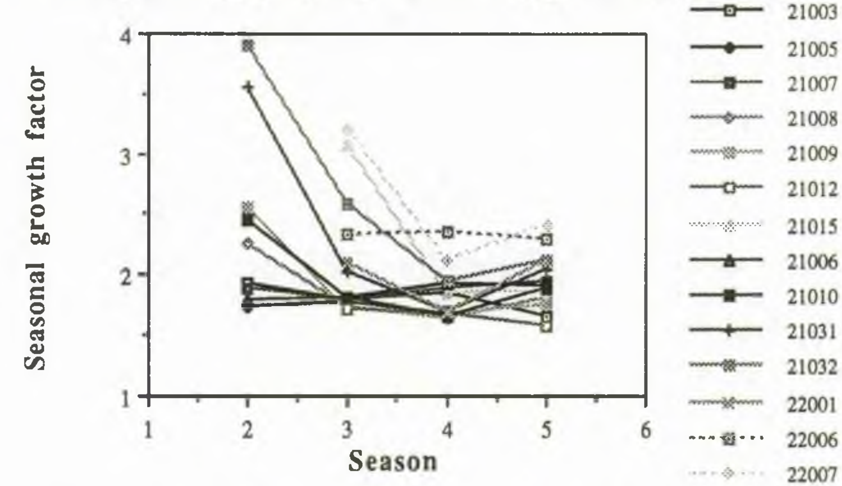
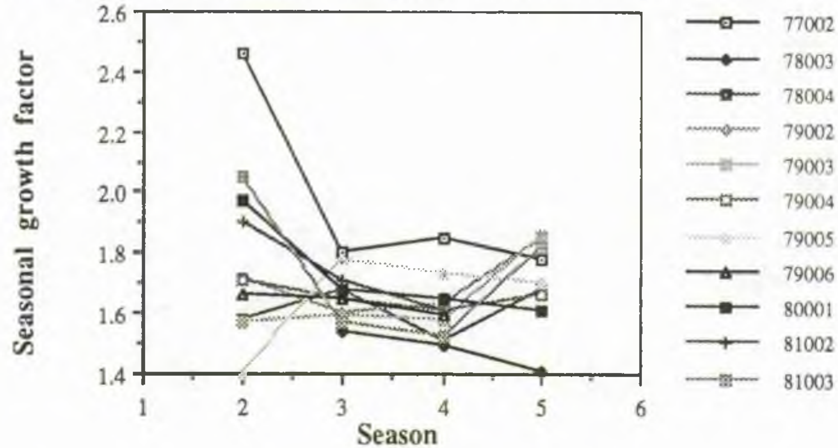


Figure 6.8 (cont'd)

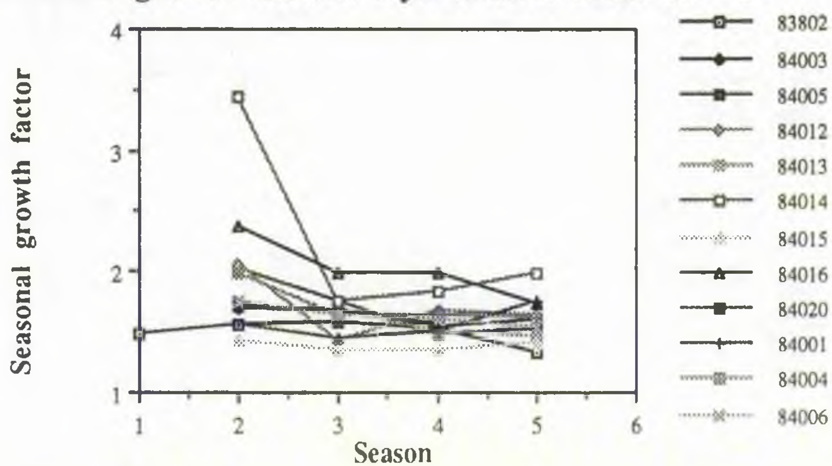
Seasonal growth factors: Hydrometric areas 21 - 22



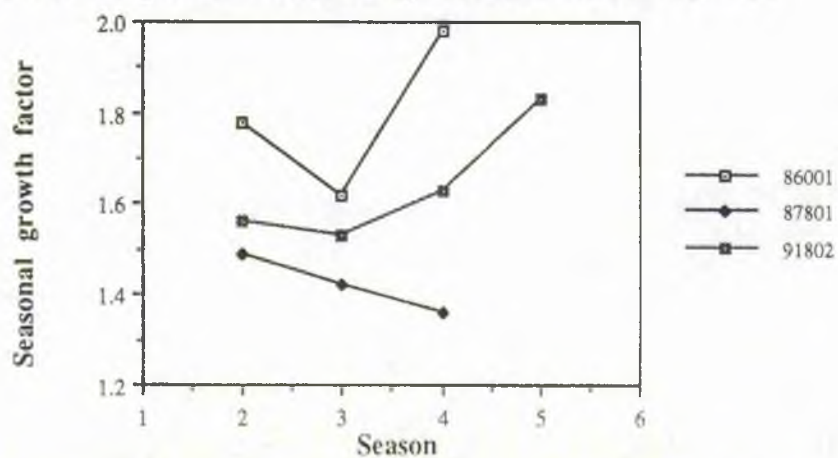
Seasonal growth factors: Hydrometric areas 77 - 81



Seasonal growth factors: Hydrometric areas 83 - 84



Seasonal growth factors: Hydrometric areas 86 - 91



some stations, winter events (dominant in overall frequency terms) are entirely dominant at higher return periods, while elsewhere, events in other seasons assume a greater importance.

Secondly, it has been demonstrated with specific reference to stations 08004 and 08005 that these seasonal differences in growth factors (or the seasonal distribution of discharge values of a given return period) have practical importance for the engineer. For projects of just a few months' duration, it has been shown that certain times of the year are much more favourable than others in terms of minimising flood risk. The use of such a seasonal analysis is therefore strongly recommended in order to assess flood risk at various times of year, rather than relying on a conventional non-seasonal approach.

Finally, it is argued that the differing contribution of seasonal sub-populations to overall flood series has implications for the suitability of specific models in fitting theoretical distributions to full annual POT series. As has been demonstrated the high magnitude end of some stations' overall frequency distributions is heavily (or occasionally totally) dominated by summer events, while more commonly the largest events, as well as most of the smaller floods, occur in winter months. Where summer events seem to be responsible for extending the frequency distribution to larger discharges than would otherwise be the case, it is argued that this must be the result of a distinct generating process, which must render inappropriate the simple fitting of an exponential distribution function. Certainly, this appears to be the conclusion of other investigations (Waylen and Woo 1982, Fiorentino *et al.* 1985): a suitable theoretical model has been arrived at only by addressing separate frequency distributions from different generating mechanisms as distinct entities, rather than simply assuming them to be members of a homogeneous population. The next two sections of this chapter therefore consider firstly the possibility that differences in seasonal flood frequencies are indicative of the rôle of different flood generating mechanisms and secondly full annual flood frequencies themselves.

However, one important cautionary point must be raised in terms of the results above. The station showing least variation in seasonal growth factors and Q_T estimates across a range of return periods was 84015 Kelvin @ Dryfield. If, as is suggested above, contrasts in the flood frequencies of different seasons indicate a diversity of generating processes causing floods to be more frequent in one season than in another, then the corollary is that limited variation indicates uniformity in the processes producing floods, and, it is therefore assumed, a good model fit should be expected. The impression given by previous research is that it is only when extraneous, additional generating processes contribute significantly to the flood series that the data fail to fit a standard model, and instead a new model must be devised (Waylen and Woo 1982, Fiorentino *et al.* 1985). However, application of an exponential frequency distribution to the data for station 84015 seems distinctly unsuccessful. From this it might be implied that the exponential model assumes a certain seasonality in flood series, both in terms of the frequency distribution between seasons of events above the threshold, and the growth factors within their separate sub-populations. However, it is suspected that there may be an alternative cause for the frequency distribution found at 84015, which is discussed below.

6.4 Synoptic variations in flood generation

To investigate whether differences in seasonal frequency distributions are the result of different generating mechanisms, two approaches are used. First, results of previous studies are consulted, giving an indication of the differing rôles of specific synoptic conditions. Second, using synoptic situation to indicate flood generating mechanism, existing POT records are divided into synoptic groups. Frequency distributions are produced for each of these, and comparison of the results for a number of stations shows that generating mechanisms can have distinctly different distributions which, when combined, may have significant implications for the overall distribution of floods at a station.

6.4.1 Literature

In the published literature, a useful account is given by Smithson (1969) who considers the synoptic origin of rainfall across Scotland by reference to eight autographic rain-gauges. His study classifies rainfall events into one of nine distinct categories, and considers the rainfall amount and duration for each type at the eight gauges used. He shows that rainfall amounts and intensities do vary spatially for different synoptic storm types. In particular, the proximity and direction of coasts and mountain areas relative to a rain-gauge were shown to be important in determining the rainfall it received in particular synoptic situations. The general point can therefore be taken that the rôle played by individual storm types in generating peak rainfalls varies spatially, and consequently the synoptic origin of floods must also vary between catchments. He further discusses the seasonal aspects of these synoptic situations, as well as the seasonal variation in rainfall characteristics of certain types. These findings suggest that the assumption made in the previous section, namely that flood generating processes vary between catchments, is valid.

By reference to accounts of some of Scotland's largest known floods, the published literature can also provide information on the synoptic conditions surrounding certain individual great floods which pre-date instrumental flow recording, thus extending greatly the amount of available information on rare floods. A comprehensive record of great floods in any one area is difficult to construct by systematic searching of the literature, without the expenditure of a great amount of effort. Fortunately, however, such a study has been undertaken by McEwen for three of Scotland's largest rivers, the Spey, Dee and Tweed, over a timescale far outreaching that of the instrumental record (McEwen 1986). Reference to this study allows a consideration of the generating mechanisms responsible for many of the largest floods on these three important rivers.

To assess the generating mechanism of floods described in McEwen's work, reference was made to the Lamb catalogue of daily weather types (Lamb 1972, Jones and Kelly 1982, Briffa *et al.* 1990). The catalogue describes, for every day since 1 January 1861, the synoptic situation over the British Isles by a single index, indicating whether the country was dominated by a cyclone, anticyclone, a dominant airflow from one of eight compass directions, or some combination of these. Characterising synoptic situation by a single index provides a most useful means of describing the generating mechanism of floods which are known to have occurred.

Lamb weather types were found for every specifically dated flood after 1861 listed by McEwen for the three rivers mentioned. Cyclonic and westerly types were the most common situations on the dates of these floods, but it became apparent that there were certain difficulties with this type of analysis. Floods on each of the rivers were not defined in relation to any specific place but could instead have occurred at any point on the rivers, nor did they specifically exceed any magnitude threshold other than being deemed worthy of record in newspapers, journals or private accounts. Considering the large size of the three rivers in question, it seems quite conceivable that the generating mechanisms of major floods in their upper courses may differ from those responsible further downstream, so this further complicates interpretation of the information. However, some general differences in the synoptic origin of floods on the three rivers do seem apparent from the information presented in Table 6.10.

Weather type	Spey	Dee	Tweed
A			
ANE/AE		1 (4)	
ASE/AS		1 (4)	
ASW/AW		1 (4)	
ANW/AN			
NE/E		1 (4)	
SE/S	1 (7)	2 (8)	
SW/W	3 (21)	4 (16)	7 (33)
NW/N	3 (21)	1 (4)	2 (10)
C	5 (36)	11 (44)	9 (43)
CNE/CE			
CSE/CS			1 (5)
CSW/CW	1 (7)	2 (8)	2 (10)
CNW/CN			
Indeterminate	1 (7)	1 (4)	
Total	14	25	21

Table 6.10 Frequency of Lamb weather types for floods detailed in McEwen (1986) for Rivers Spey, Dee and Tweed (Column percentages in parentheses).
Lamb weather type codes: A - anticyclone; C - cyclone; N,E,S,W - directions.

The Table shows that more events occur under pure cyclonic conditions than under any other single weather type on all three rivers. Westerly/south-westerly conditions are also of great significance on the River Tweed (33% of the total), but on the other two rivers, no other category in the table accounts for any more than 21% of events. It is noticeable that only the Dee has any floods generated under anticyclonic conditions, accounting for 12% of all events since 1861 recorded in McEwen's chronology. North-westerly and northerly types also appear to be more common on the Spey than on the other two rivers, though with such a small sample of events, this cannot be said with any great certainty. For the reasons outlined above, interpretation of these data will not be carried any further, but the differences in flood generating situations described here should be taken as a broad illustration of the variable nature of flood generation between rivers. More precise examination of the differing rôles of individual weather types, symptomatic of different flood generating mechanisms, can be made in the second part of this analysis.

6.4.2 POT records

An extension of this examination of the rôles of distinct generating mechanisms can be made using the POT series collated in this study, with a comparison being made between the frequency distribution of floods generated under different synoptic situations. Again, the Lamb catalogue of daily weather types was used, with the exponential model being fitted to data from these groups in the same way as previously described for seasonal sub-groups (Section 6.3).

It was found that pure cyclonic, westerly, southwesterly and southerly types were responsible for most events at the majority of the 75 gauging stations for which there were 20 years or more data. As the three directional types were somewhat similar, each representing weather dominated by neither a cyclone nor an anticyclone centred over the British Isles, and with an airflow from a contiguous, restricted range of directions, it was decided to treat these three Lamb types as one group. Frequency distributions were produced both for this group, to be referred to as south-westerly situations, and also for pure cyclonic situations; the distributions for both groups at each of the 75 stations are shown in Appendix I. Following the analysis of seasonal frequency distributions in the preceding section, the results of fitting exponential distributions to synoptic groups of events at the same six stations are presented here. The proportion of events occurring under each synoptic situation was also calculated for each station - for the whole POT series and also for just the largest 10% of events - the results being given in Table 6.11.

08004 Avon @ Delnashaugh

The frequency distributions of the two synoptic groups at this station are strikingly different (Figure 6.9). The points lie quite close to the line in both cases, but the slope of the line fitted to the cyclonic group of events is much steeper than that for the south-westerly group. Table 6.11a shows cyclonic situations to be the most frequent situation under which POT events occur at this station, while at a higher return period, this situation is quite dominant (Table 6.11b). As a result, the significant difference between discharge values of 130.7 and 229.1 m^3s^{-1} for the 2 year flood, under south-westerly and cyclonic conditions respectively, increases

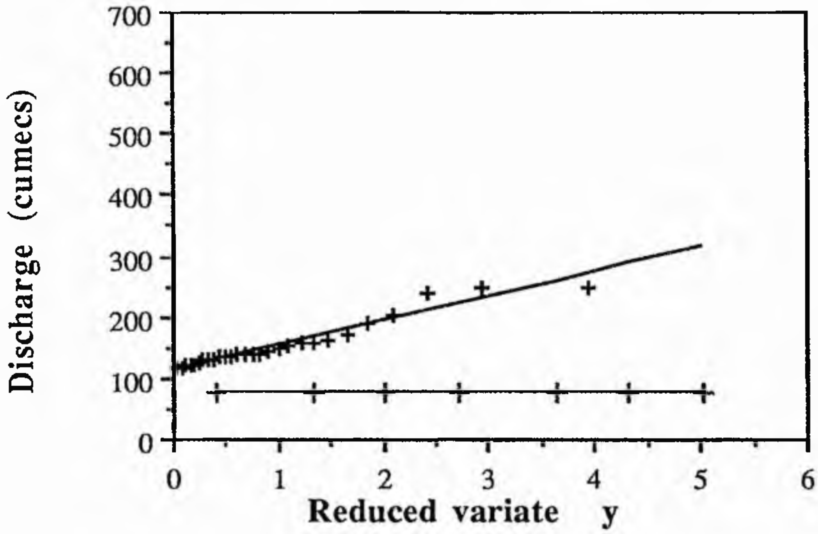
Weather type	08004	08005	12001	20002	83802	84015
AW	4.6	4.1	2.9		5.3	5.5
S	3.1	4.1	14.9	6.8	4.1	3.3
SW	7.7	13.2	11.1	5.5	2.9	9.9
W	9.2	28.1	22.1	1.4	50.0	35.2
NW	2.3	6.6	1.4		0.6	
N	6.9	5.8	1.9	2.7		
C	35.4	19.8	24.5	54.8	23.5	31.9
CS	5.4	0.8	5.8		0.6	
CW	3.1	8.3	5.3	1.4	7.1	2.2
CN	7.7	2.5	1.0	5.5	0.6	1.1
Indeterminate	1.5	0.8	0.5	11.0	1.8	4.4
Others	13.1	5.8	8.7	11.0	3.5	6.6
Sample size	130	121	208	73	170	91

Table 6.11a Percentage of flood events occurring under individual Lamb weather types at six selected stations - all POT events

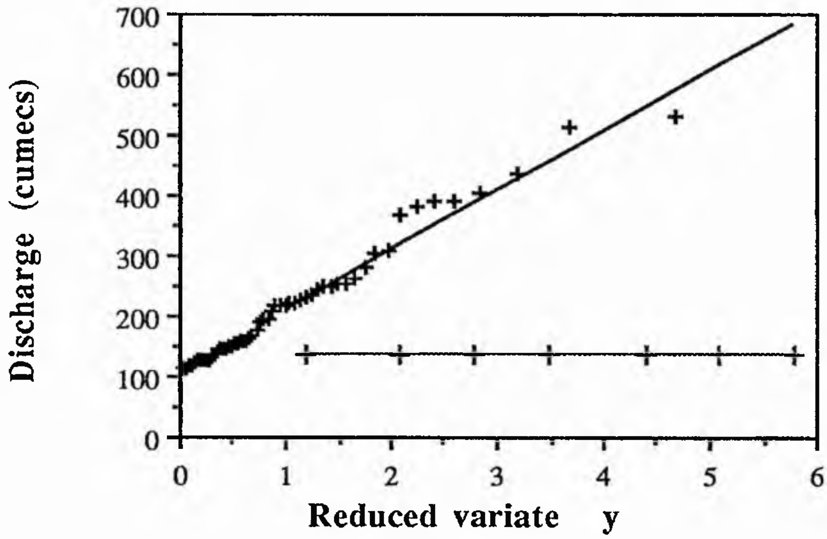
Weather type	08004	08005	12001	20002	83802	84015
A					5.9	
ASW						11.1
AW		8.3			5.9	
S			14.3			11.1
SW		8.3	19.0		5.9	
W		58.3	14.3		35.3	44.4
NW						
N	7.7		4.8			
C	26.9		28.6	71.4	29.4	22.2
CS			14.3			
CSW		8.3				
CW	7.7	8.3			11.8	11.1
CN	7.7	8.3		14.3		
Indeterminate	7.7		4.8	14.3	5.9	
Sample size	13	12	21	7	17	9

Table 6.11b Percentage of flood events occurring under individual Lamb weather types at six selected stations - largest 10% of POT events

Figure 6.9
Synoptic type frequency distributions for station 08004 Avon @ Delnashaugh



South-westerly weather type



Cyclonic weather type

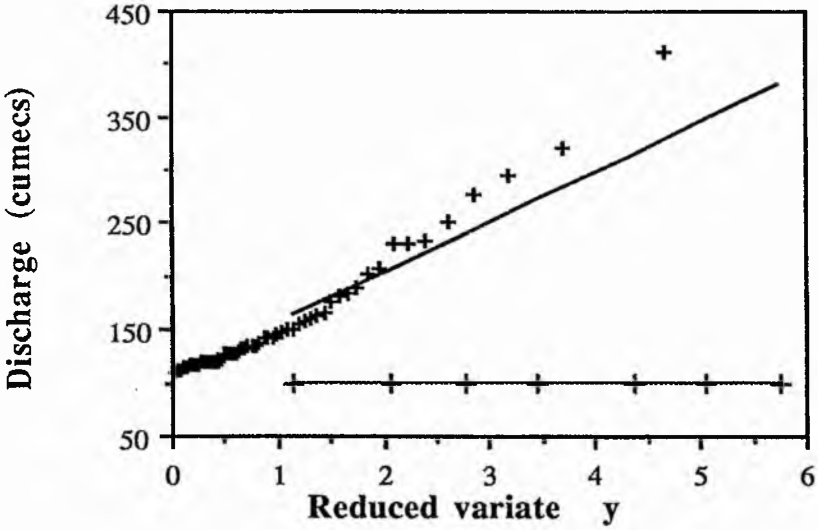
more than proportionately to 314.9 and 679.6 m^3s^{-1} for estimates of Q_{200}. The difference between the two groups can alternatively be illustrated by graphical estimation of the return period of an event of given discharge for each group, a quite striking difference showing at, for example, the 300 m^3s^{-1} level.

In the previous section, it was noted that summer events were responsible for all the largest events on record at this station; this analysis now shows that the majority of these events were produced under cyclonic conditions. Indeed, the largest fifteen events in 37 years of record here all occurred under either pure cyclonic or cyclonic-directional conditions with only one exception, an indeterminate case. It would therefore seem reasonable to suggest that in attempting to model the frequency of large floods for this site, the frequency distribution of cyclonic events is likely to be of greatest importance. Considering also that the largest Lamb-classified event of non-cyclonic origin occurred with a magnitude of 249.8 m^3s^{-1}, slightly less than half the cyclonic maximum, these events are unlikely to be of any great importance in the generation of large floods.

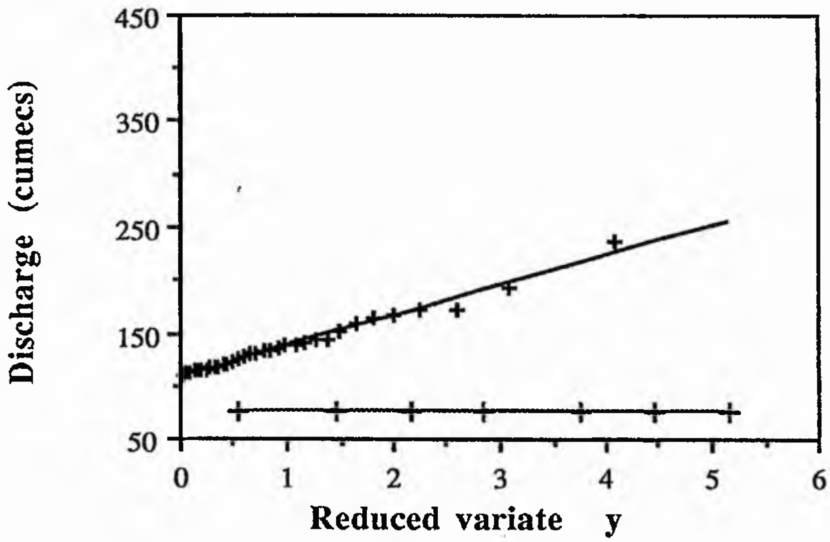
08005 Spey @ Boat of Garten

As at Delnashaugh, a striking difference in the frequency distribution of the two synoptic flood groups is also found at this station (Figure 6.10), though the difference is in the opposite sense to that at the previous station. Table 6.11 shows that at a low threshold, floods with a westerly synoptic origin are more numerous than those of purely cyclonic origin (28.1% *vs* 19.8% respectively), and south-westerly situations also account for a significant number of smaller flood events (13.2%). However, the south-westerly category accounts for two-thirds of the largest 10% of POT events, while cyclonic events are absent above this threshold. Accordingly, the frequency distribution for the south-westerly group shows a much steeper increase in flood peak with return period than does the corresponding cyclonic distribution. A south-westerly generated 200 m^3s^{-1} flood would be expected to recur with approximately a 5 year return period, while the return period for a similar cyclonic event would be about 100 years. If the fitted lines were drawn by a graphical method rather than based upon the exponential model, this difference would be accentuated further. These distributions therefore show that the frequency distribution for larger floods at this site is essentially driven by the incidence of south-westerly events (most especially westerly events), which have been found to occur dominantly in the winter months.

Figure 6.10
Synoptic type frequency distributions for station 08005 Spey @ Boat of Garten



South-westerly weather type



Cyclonic weather type

12001 Dee @ Woodend

At this station, the frequency distribution of floods does not differ greatly between the two synoptic groups (Figure 6.11). South-westerly situations are associated with more POT events than are cyclonic ones (Table 6.11a) so that Q_2 in the former group exceeds that in the latter (357.8 *vs* 324.3 m^3s^{-1} respectively), but at the higher threshold it can be seen (Table 6.11b) that the cyclonic group, though still less common (28.6%) than the south-westerly group (47.6%), increases in frequency more rapidly than the south-westerly group and accordingly the growth rate for the cyclonic-generated events is the higher of the two.

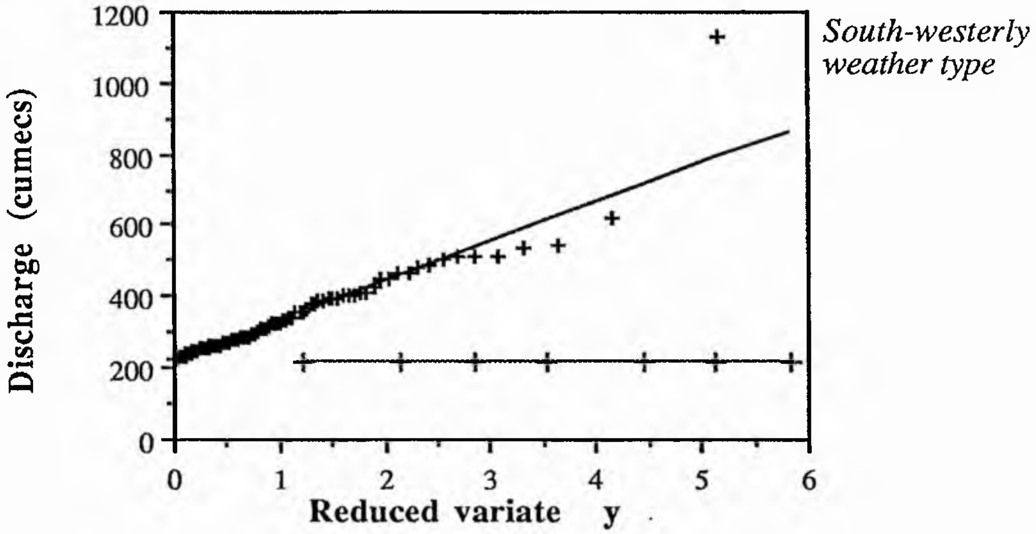
Figure 6.11 shows that two exceptionally large floods have been recorded at this station, both exceeding 1000 m^3s^{-1}, with the next largest on record being only 685 m^3s^{-1}. One of these was of southerly origin while the other occurred under cyclonic conditions. Furthermore, it can be seen that events belonging to both groups contribute significantly to the production of the next few largest floods, so whereas at the previous two stations only one group seems to be important in generating the largest floods on record, at Woodend both major groups seem to be important.

20002 West Peffer Burn @ Luffness Mains

Both Figure 6.12 and Table 6.11 show cyclonic-generated events to be very important at this station, with south-westerly events accounting for only 6.8% of all POT events and none of the largest 10%. Accordingly, the Q_2 value of 3.13 m^3s^{-1} for the former group far exceeds the corresponding 1.20 m^3s^{-1} of the latter. However, it can be seen that while Q_T estimates for cyclonic events still exceed those of south-westerly group at high return periods, the growth rate of the latter exceeds that of the former group. Q_{20}/Q_2 growth rates are 2.92 for south-westerly types, but only 1.81 for the cyclonic group.

This observation might have implications for the form of the overall flood frequency distribution at this station, were it not for the fact that the largest south-westerly generated event is only 3.9 m^3s^{-1}, compared with a cyclonic maximum of 6.9 m^3s^{-1}. If a much longer period of record were available at this station, the slope of these curves suggests that very rare, large south-westerly events may occur, leading to the suggestion that at extremely high return periods (>500 years), the two types might be of approximately equal importance in flood generation. For

Figure 6.11
Synoptic type frequency distributions for station 12001 Dee @ Woodend



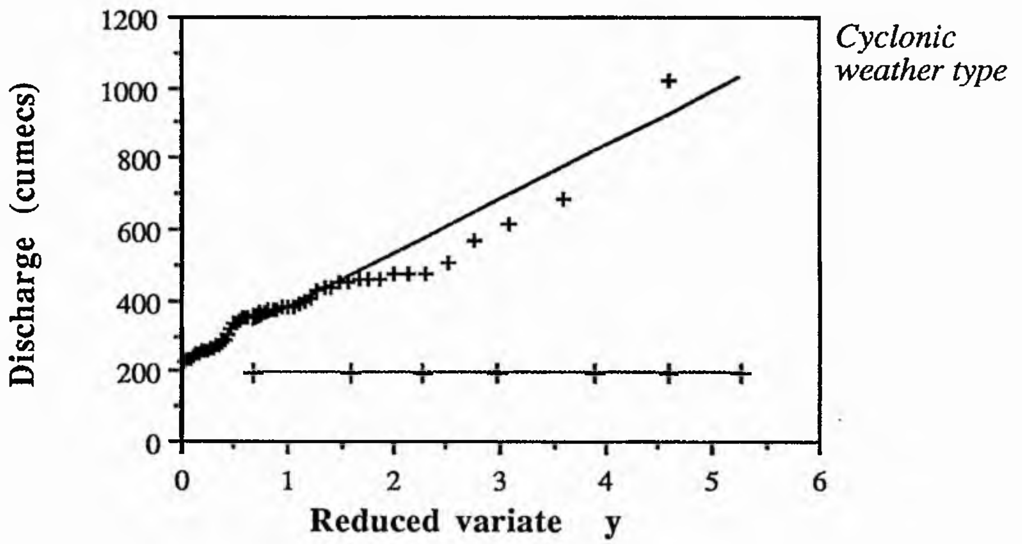
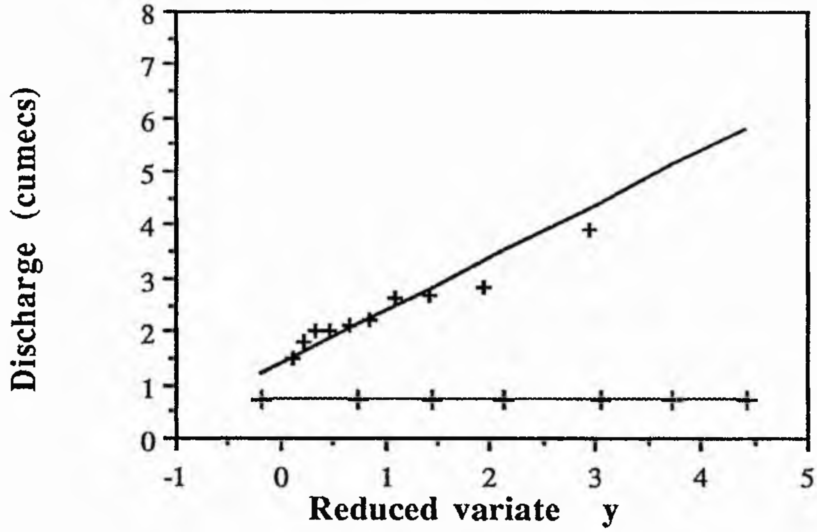
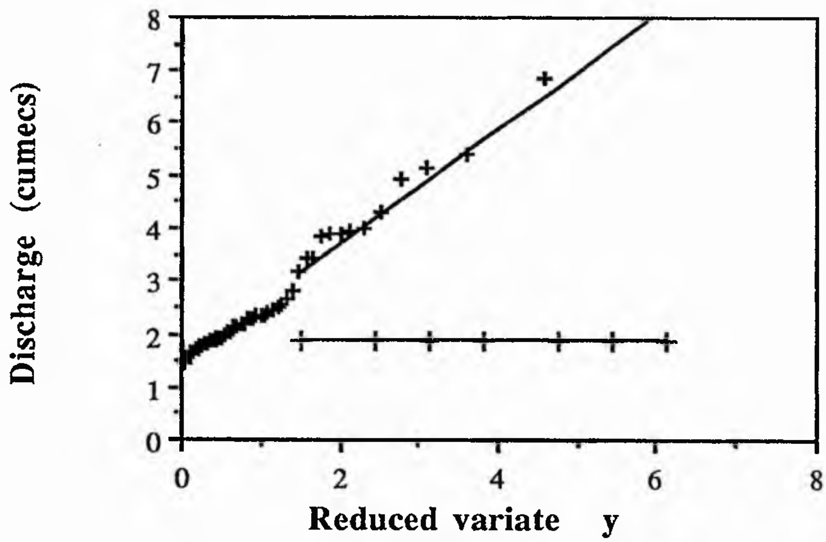


Figure 6.12
Synoptic type frequency distributions for station 20002 West Peffer Burn @ Luffness Mains



South-westerly weather type



Cyclonic weather type

shorter return period events, however, it certainly seems that cyclonic events are of primary importance in determining the overall flood frequency distribution.

83802 Irvine @ Kilmarnock

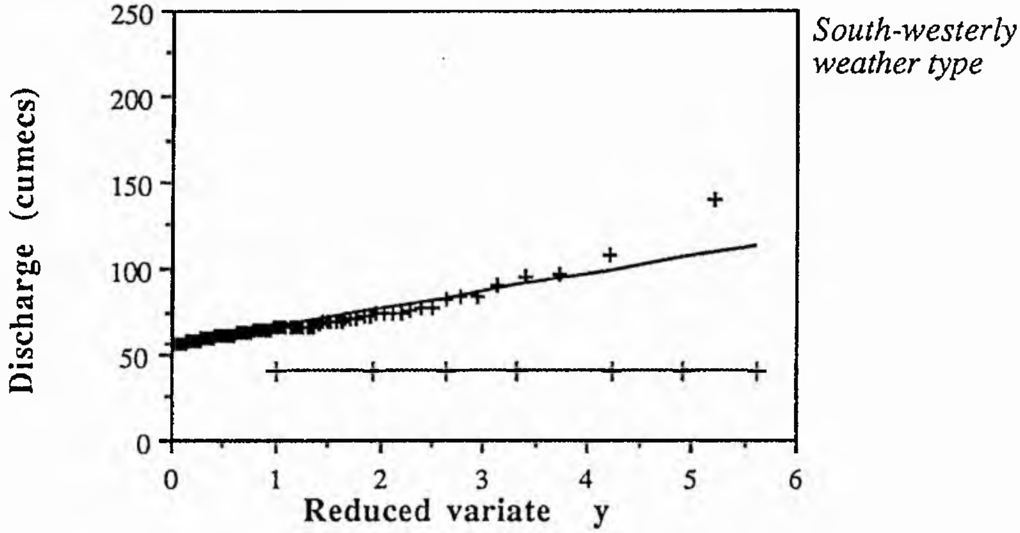
The frequency distribution of south-westerly and cyclonic floods at this station again differ only slightly (Figure 6.13). Q_2 for the former group is 66.1 m^3s^{-1}, exceeding slightly the 56.4 m^3s^{-1} for the latter group. However, by the Q_{20} level, the situation is reversed, with flood estimates being 89.7 and 94.0 m^3s^{-1} respectively. The cyclonic group therefore has a slightly higher growth rate than the south-westerly group.

It is interesting to note that in this, the longest record used in this study, there is a significant mismatch between the fitted line and the distribution of points in the south-westerly group, with the seven largest events following what would appear to be a steeper, upper limb to a curve which could be graphically fitted to the points. 91 events occurred in this group and, with such a high number, it would be expected that random effects would be minimised in favour of a good model fit. That this is not the case raises questions of the suitability of the model to describe the frequency distribution of these events. On the other hand, all but one of the points lie very close to the line in the cyclonic group. The exception is the largest event, 227 m^3s^{-1} on 8 August 1961 which occurs as a very large outlier on the graph, and probably has a return period well in excess of the 135 years suggested by the model. The suitability of the exponential model for these data will be discussed more fully later in this chapter, but in the present examination of synoptic groups' frequency distributions, it is sufficient to conclude that the difference between the two groups at this station is relatively minor.

84015 Kelvin @ Dryfield

At this final station, two frequency distributions are found which are almost identical (Figure 6.14). Return periods for Q_2 and Q_{200} differ by less than 5% between the two synoptic groups. It is also striking that the points appear to follow a second, upper curve with lower slope than for low return periods above a 65 m^3s^{-1} threshold. Table 6.11 shows that south-westerly origin events are more common than pure cyclonic ones, especially at a higher return period, but the graph shows that despite this, the fitted distributions for the two groups are quite similar. In the previous section, this station was selected because of the small differences in frequency distribution amongst its seasonal sub-groups; this analysis shows the same to be true for sub-groups defined on a synoptic basis.

Figure 6.13
Synoptic type frequency distributions for station 83802 Irvine @ Kilmarnock



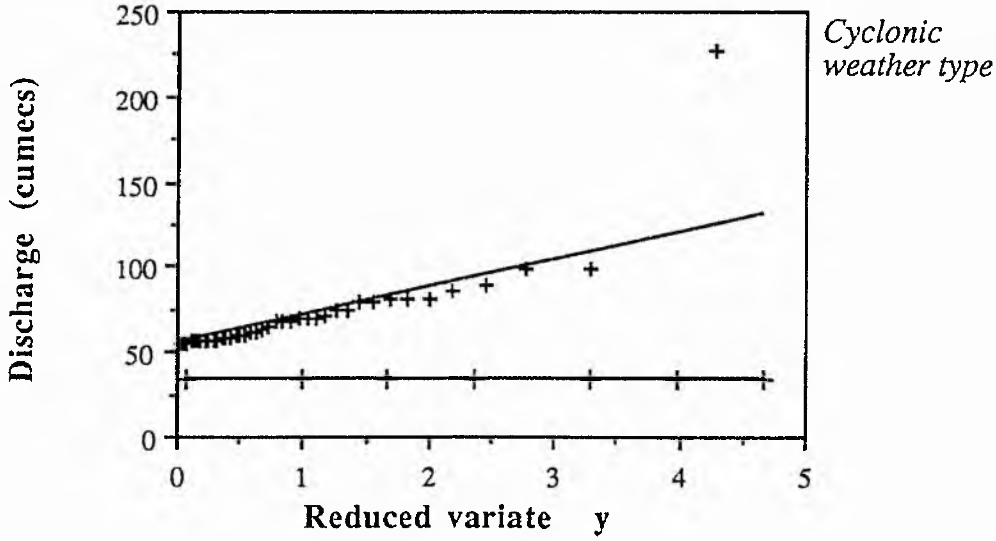
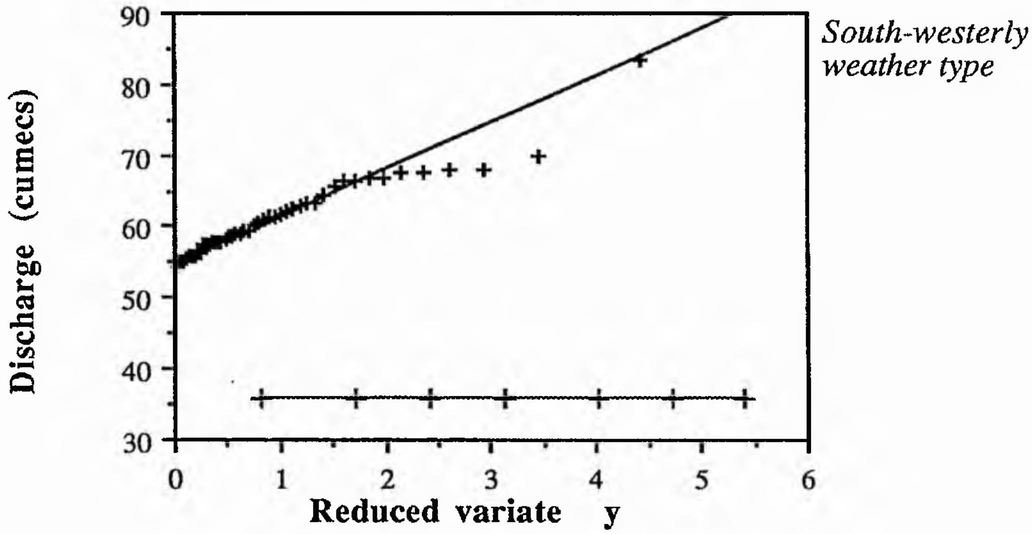
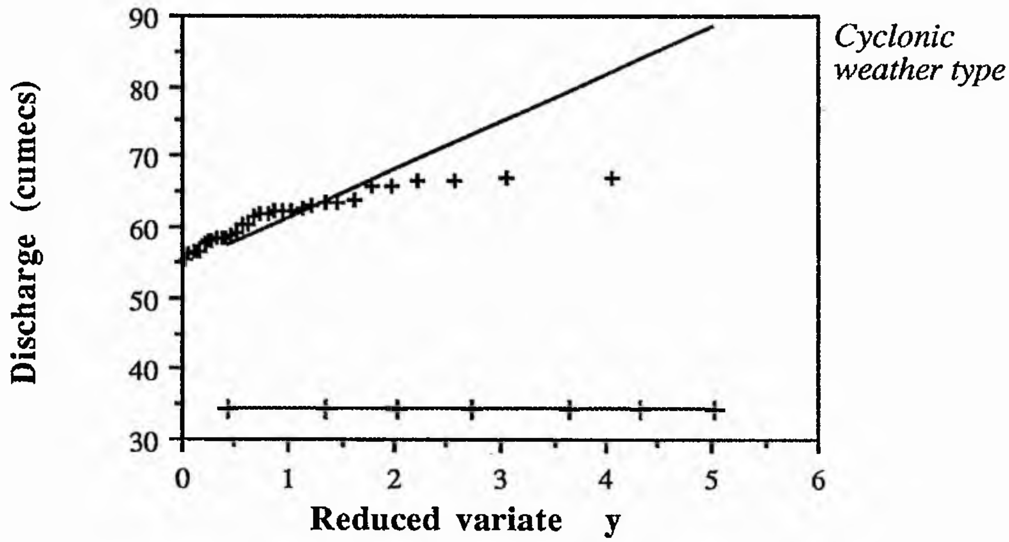


Figure 6.14
Synoptic type frequency distributions for station 84015 Kelvin @ Dryfield





6.4.3 Interpretation

The six stations studied here show that as with seasonal sub-groups of events, there are substantial differences between the frequency distribution of events of synoptic groups. This difference is also found in the specification of the exponential models fitted to the data from the synoptic groups. The two Spey basin stations show the greatest differences, both between the two synoptic groups at each station, and between each other. Station 08004 Avon @ Delnashaugh shows cyclonic events of any given return period to be much larger than corresponding south-westerly floods, the difference increasing with return period such that the overall frequency distribution of events above about 300 m^3s^{-1} will be determined entirely by the cyclonic group. At 08005 Spey @ Boat of Garten, the opposite situation is apparent, with south-westerly events being much more frequent than cyclonic ones throughout the range of return periods considered, and therefore being solely responsible for the generation of high return period events. At both 12001 Dee @ Woodend and 83802 Irvine @ Kilmarnock, the two synoptic groups' frequency distribution curves cross, with discharge rising more rapidly with return period for the cyclonic group than the south-westerly group in both cases. For 20002 West Peffer Burn @ Luffness Mains, the lines depicting the fit of the respective exponential models are essentially parallel with higher flood values being found for the cyclonic group, while at 84015 Kelvin @ Dryfield, the two synoptic groups' distributions are almost identical.

So, to return to the question posed in the previous section as to whether seasonal differences in flood frequency distribution arise from the operation of different generating mechanisms with their own particular flood frequency distributions, it would appear from both this investigation and examination of the literature that different synoptic groups do indeed have their own, though sometimes greatly differing, frequency distributions. It is therefore suggested that the seasonal differences observed arise from seasonal variation in the frequency of occurrence of each of these generating mechanisms. That the synoptic mix of floods varies seasonally can be verified from Table 6.12. It can be seen that the proportion of events generated under each of the two synoptic groups varies seasonally at all stations, *eg* at station 08005 in December and January, 35 events occurred under south-westerly conditions while only 3 occurred under cyclonic conditions, whereas in June and July, all the six recorded events occurred under cyclonic conditions. There are also noticeable differences in the seasonal patterns between stations, *eg* at station 20002, cyclonic events are the more common type throughout the year, while at station 83802, south-westerly events are the more common in four of the six seasons shown.

	08004		08005		12001		20002		83802		84015	
Season	**SW**	**C**	**SW**	**C**	**SW**	**C**	**SW**	**C**	**SW**	**C**	**SW**	**C**
Jun-Jul	0	12	0	6	1	4	0	4	4	4	0	3
Aug-Sep	2	27	2	14	4	14	0	5	15	14	7	13
Oct-Nov	5	13	20	10	20	29	1	16	34	9	14	8
Dec-Jan	13	5	35	3	51	11	6	13	34	11	18	8
Feb-Mar	10	1	13	2	33	2	4	10	21	2	9	1
Apr-May	6	6	1	1	8	5	1	7	5	2	0	0

Table 6.12 Seasonal distribution of flood events of each synoptic group
Key: SW = southerly/south-westerly/westerly; C = cyclonic

Each Lamb weather type can be seen to have its own seasonal distribution, and it is the combination of the events of various generating mechanisms that produces the observed patterns of seasonality and overall frequency distributions. In the next section of this chapter, the rôle of these individual generating mechanisms is considered in detail, in relation to the frequency distribution of whole POT flood series.

6.5 The rôle of generating mechanisms in flood frequency distributions

In flood hydrology, much attention is focused on the correct specification of models to describe the frequency distribution of flood peaks. This is of paramount importance in the estimation of design floods: numerous models are available for use with annual maximum or partial duration series data. Cunane (1989) gives a comprehensive guide to the main methods available for use, and much debate centres on model choice, *eg* Ahmad, Sinclair and Spurr (1988). Throughout this chapter, the exponential model has been used, as recommended in the *Flood Studies Report*, for partial duration series data which thus far have all been sub-populations of whole POT series, identified either on the basis of season or generating mechanism.

In this section, the model is finally applied to whole POT records, and the rôle of individual generating mechanisms assessed in relation to the overall frequency distribution of flood peaks. As has been suggested above, it is felt that there are many stations where the frequency distribution of floods of individual synoptic groups differs in such a way that it would seem impossible for the combined flood series to fit the exponential model. The purpose of this section is therefore to examine the effect of combining these elements in the analysis of whole series frequency distributions of flood peaks. It is hoped that by such an examination, brought about by the realisation that frequency distributions differed widely between seasons, it may be possible to identify instances where the fitting of the recommended exponential model cannot be satisfactory, and to recommend what approach might provide a more suitable alternative.

The exponential model was fitted to the full POT records from the 75 stations previously referred to. A common frequency threshold giving 3.4 peaks per year was again used, and the resulting plots are presented in Appendix G. The fitted line is shown for values of Q_T from 2 to 200 years. It can be seen that at all stations, the points lie close to the fitted line at low values of Q_T. However, at higher return periods variations occur: the points in some of the plots deviate upwards from the fitted line; in other cases they deviate downwards relative to it (though of course discharge still increases with return period); and others become generally more scattered about the line without having any significant departure from the line in their overall trend, occasionally following it closely throughout the entire distribution. The means by which the floods of individual synoptic groups interact to produce these different types will now be considered.

It is argued that it is the mix of events, and how this mix varies with magnitude, that determines the distribution of points relative to the fitted line produced by the exponential model. Description of the distribution of points relative to the line is difficult, since any deviation of the points from it is often erratic in nature, sometimes involving the very highest points being on one side of the line but the next few largest on the opposite side. Quantitative description of the deviation of points from the line has not been attempted because of this.

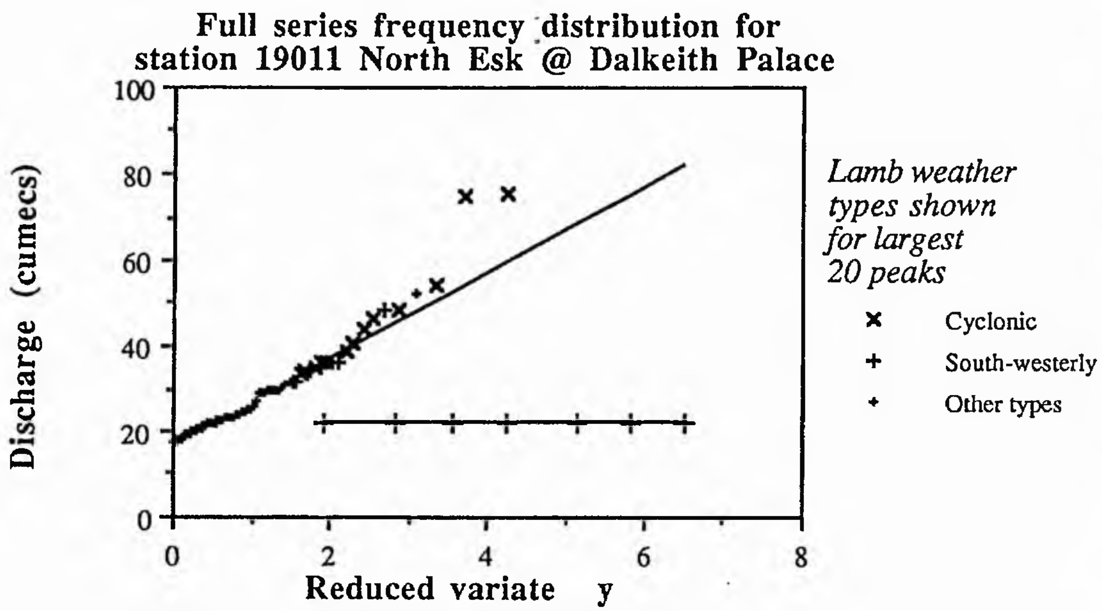
However, one relevant observation is that in about half of the 75 stations studied, the largest few points in the flood series plot significantly above the line, while in only about 10% of cases do they appear significantly below it. Explanation of these upward deviations is therefore attempted first; in fact, two possibilities are offered to account for this situation.

6.5.1 Upward deviations

The first suggested explanation for such upward deviations is that where two synoptic groups exist with greatly differing growth rates, the lower part of the overall distribution will be dominated by the group with more events exceeding a low return period threshold (say ≤2 years). This type also determines the slope of the fitted line to a large extent, while the other group (with a higher frequency of events exceeding a higher threshold, say 20 years) will contribute all or most of the largest events in the overall distribution, and because of the higher growth rate of this group, the points will deviate away from the fitted line in an upward direction. This upward deviation should still be expected in cases where the dominant group at high return periods is also the more common at low return periods. What is of fundamental importance is the change with return period in the ratio of frequencies of the two groups. If, say, south-westerly generated floods are slightly more common at a relatively low flood level than cyclonic ones, but above a higher discharge cyclonic generated events are not found such that south-westerly events dominate the top of the overall distribution, the south-westerly group would be expected to cause an upward deviation of points from the fitted line at high return periods. This will be demonstrated by reference to an example.

Some of the best instances of such behaviour are found in the Spey basin, but lest the reader should think that interesting phenomena in this study are confined only to the Spey, the example chosen comes from another area, station 19011 North Esk @ Dalkeith Palace. Cyclonic generated floods are the dominant type at any flood value throughout the range of return periods 2 - 200 years at this station, but the importance of this group relative to the south-westerly group varies with discharge. Overall, 51% of events exceeding the 3.4 peaks/year threshold occurred on days with cyclonic weather conditions, compared with only 29% of events with south-westerly conditions. However, of the largest 10% of these events (nine events), only one (11%) was associated with south-westerly conditions while the other eight (89%) occurred under cyclonic conditions (see Figure 6.15). This causes the cyclonic group to have a much greater growth rate than the south-westerly group, and in combining the two elements, along with events which fall into neither category, the cyclonic influence causes the largest events in the record to lie

Figure 6.15


Full series frequency distribution for
station 19011 North Esk @ Dalkeith Palace
Discharge (cumecs)
100
80
60
40
20
0
0
2
4
6
8
Reduced variate y
Lamb weather
types shown
for largest
20 peaks
Cyclonic
South-westerly
Other types

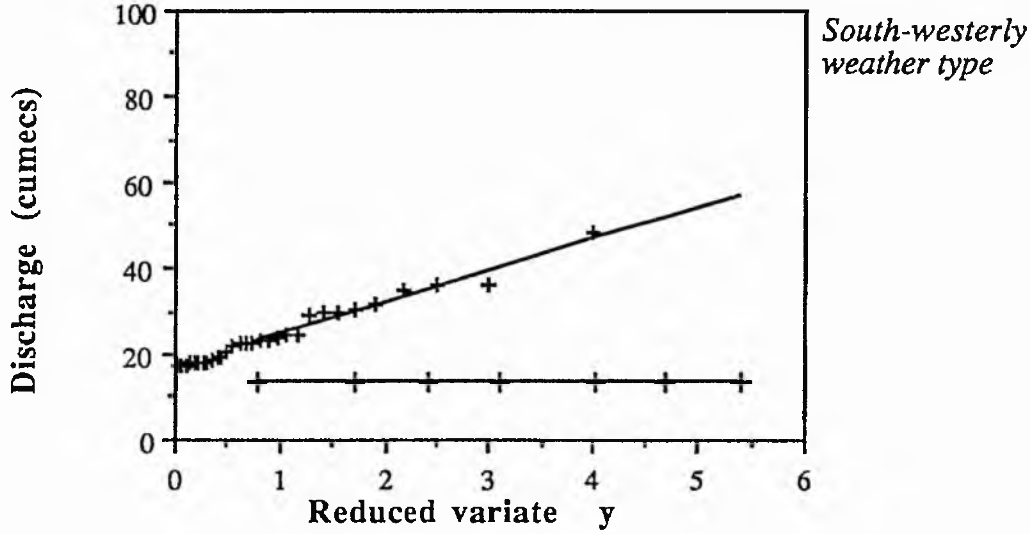
progressively higher above the fitted line as return period increases. It can be seen in Figure 6.15 that the eight largest events in the distribution plot significantly above the line; all but the sixth-largest of these are of cyclonic origin. Examination of the separate plots for the two synoptic groups (Figure 6.16) shows the gradient of the curve fitted to the cyclonic group to be much greater than that for the south-westerly group. Because of the high frequency of occurrence of events of both groups at low discharges, both are important in determining the gradient of the overall fitted line. However, above a higher discharge (say 35 m^3s^{-1}), the actual growth rate of events belonging to the cyclonic group is much greater than that of the fitted line, and as a result the largest discharge values plot significantly above the line. The significant difference in growth rate between the two groups manifests itself in an upward deviation of the points away from the fitted line at high return periods.

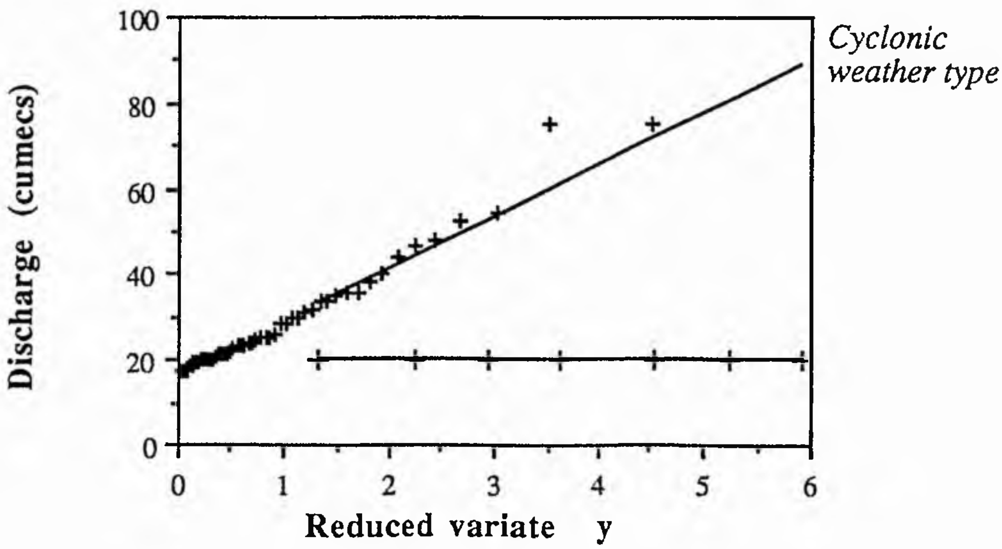
Such clear upward departures from the exponential model are not always seen, even when the flood frequency distributions from separate synoptic groups differ significantly. The overall pattern depends on the occurrence or otherwise of a few large events and, as the incidence of floods is generally modelled as a stochastic process, it is inevitable in a consideration of 75 flood records that some stations will lack the few rare events which might be expected within a certain level of probability, given their length of record, while others will have an over-abundance of them (Benson (1960) gives an illustration of the variability of short records drawn from a longer parent record). This introduces the second explanation for flood frequency distributions in which the largest points deviate upward away from the fitted exponential model. In some instances, the frequency distributions of the two main synoptic groups are not dissimilar, and yet the largest few points in the overall distribution lie well above the line. These outliers may be derived from either of the two main synoptic groups, or indeed from another generating mechanism, since even the group with the lowest growth factor may be capable, under sufficiently rare conditions, of producing a truly large flood. Put simply, upward deviations may result simply from the random nature of the flood generating process, as indeed may downward ones in exactly the same way.

One apparent example of this type of distribution is 21003 Tweed @ Peebles, where the largest three events in the overall distribution depart radically upward from the fitted line. These three events all belong to the south-westerly group and, rather than representing the upper extreme of a well-fitted distribution, lie conspicuously far above the line for that group also. It is, of course, possible that

Figure 6.16

Synoptic type frequency distributions for station 19011 North Esk @ Dalkeith Palace





these three events should actually be assigned to another group rather than this one - they could for example be snowmelt events (a suggestion not incompatible with their dates) which might arguably warrant separate classification - and that the positive anomaly presented by them actually represents a similar result of mixing generating types to that described above for Dalkeith Palace. However, insufficient information has been gathered to substantiate such a claim and, even if it were found to be true for this station, this explanation for such upward deviations must apply to others. In such situations, it follows that although the plotted points lie well above the fitted line, it is only the plotting positions (y values) of the few floods in question which are in error. The slope of the line is still essentially accurate and valid for use in estimating the magnitude of floods of some given recurrence interval, *ie* such large events are outliers which do not belong to the underlying model. It is noticeable that in the example given, south-westerly events account for 41% of the total population and 36% of the largest 10% of events, with the proportions for cyclonic events being 35% and 36% respectively: the ratio of frequencies between the two groups changes very little between the two threshold levels. Other stations with conspicuous outliers creating similarly large positive deviations include 21031 Till @ Etal, 84014 Avon Water @ Fairholm, and 07002 Findhorn @ Forres with Britain's largest recorded flood of 2410 m^3s^{-1} on 17 August 1970, although at this station the strong cyclonic element in the flood series is responsible for an upward deviation, albeit on a smaller scale, in any case.

Because of the random nature of flood series, it is suggested that examination of the scatter of points in the full distribution might not be a reliable guide to the cause of any such upward deviation of points. Even so it is worth determining their cause, since by doing so it can be established whether the exponential model can be considered to describe accurately the frequency distribution of floods at a station and thus be suitable for design flood estimation. The first explanation for these upward deviations outlined above can be taken as an indication of the inapplicability of this model to the full series, being characterised by markedly different frequency distributions for individual generating processes. The second, however, results from the occurrence of rare outliers which, as well as failing to follow the fitted distribution of the overall distribution, also occur as outliers in the distribution of their own particular synoptic group. In this situation, it follows that the exponential model remains valid for use. It therefore follows that if there appear to be two distinct elements to the overall flood population, with significantly differing frequency distributions and a good fit of points to each, then an upward deviation of points relative to the fitted line is indicative of a fundamental reason for not accepting a single exponential model for the whole flood series. Estimation of higher return period design floods would then be better undertaken with reference solely to the generating process which produces the largest floods at that station. Thus by an assessment of goodness of fit for each of the synoptic groups making up the flood population as a whole, the most appropriate method of estimating a moderate or rare design flood can be determined. Low return period floods would still best be estimated using the whole flood series.

Methods could be developed which, in a systematic manner, could suggest which of these two cases apply when a positive departure of points from the exponentially-fitted line is found. This could amount to a major exercise in its own right, and thus falls considerably beyond the purpose of this chapter. It is nonetheless hoped that the account given thus far will be considered instructive in illustrating the value of separating out flood series into distinct groups, and could perhaps form the basis of further work. In particular, the practical implementation of this approach would require the identification or development of methods for the objective assessment of differences in frequency distribution between distinct groups, and for the assessment of the goodness of fit of points in each.

6.5.2 Downward deviations

Having considered fully the case of upward deviation of points from the fitted line, attention is now directed towards departures in the opposite direction. As stated earlier, such cases are considerably rarer than upward deviations, and this point will be returned to at a later stage. First, however, the cause of these downward departures will be considered. Examination of the frequency distribution of floods belonging to separate synoptic groups reveals a common feature amongst all the eight stations considered to show a clear downward tendency (15008, 19001, 84006/12/15/16/20, 87801; see Appendix G), namely that the largest points in the whole flood series also plot below the line in their individual synoptic groups. Furthermore, in all eight cases, the frequency distributions of the two synoptic groups differ only slightly in comparison with the great differences found at those stations where upward deviations are thought to result from differences between generating processes. As a number of other stations have similar frequency distributions for individual synoptic groups and a good overall fit, it is therefore suggested that downward deviation of the points from overall fitted lines results not from the interaction of different synoptic groups' frequency distributions, but rather from a simple lack of particularly large floods at the top of one or more individual groups' distributions. This could arise from one or both of two reasons.

The first is the corollary of the second reason given for upward deviations: just as the random nature of flood generation can produce an unexpectedly large number of especially large floods, so can it result in a lack of them. When this happens, the largest floods in the whole series are not as large as might be expected for a record of given length, and consequently they plot below the fitted line with return period values which are too high.

The second reason is that the magnitude of the largest floods in a series may actually be subject to physical constraint in the form of floodplain storage upstream of the gauging location. The rôle of storage in any catchment is difficult to evaluate without considerable detailed local knowledge, though for example "significant local depressions and boggy areas", cited in the *Hydrometric Register and Statistics* (IH/BGS 1988) for station 84016 Luggie Water @ Condorrat may be important in this respect. A fieldwork visit to the White Cart Water while in flood also showed significant areas to be under water above station 84012 (Plate 6.1), and it is noticeable in the frequency distributions for both these stations that at higher discharges, the points lie below the fitted line. Archer (1989) has demonstrated the importance of floodplain storage in affecting flood frequency distributions through flood wave attenuation in a study on the River Tees, with further work by Mason (1992) showing this to be primarily controlled by floodplain area and roughness. However, despite large volumes of water being held in floodplain storage when the River Spey floods, most stations on this river still show an upward deviation of points from their fitted lines (see Appendix G).

Where a random effect is suspected, the exponential model is still considered to describe well the true frequency distribution of events at a station. However, if storage is thought to be important, the magnitude of a large flood of given return period will be less than that suggested by the fitted line. The occurrence of a break of slope at the same discharge value in the distribution of points in each synoptic group should be taken as good evidence of this, and it is suggested that the clear breaks of slope at 155 m^3s^{-1} at station 19001 (Figure 6.17) and 65 m^3s^{-1} at 84015 (Figure 6.18) are good examples of this, also of course occurring at the same value in the full series frequency distributions. It is interesting to note that no similar feature is found at station 19005 Almond @ Almondell, some 10 km upstream of 19001: with two-thirds of the period of record used at 19001 overlapping with

Figure 6.17
Full series frequency distribution for 19001 Almond @ Craigiehall

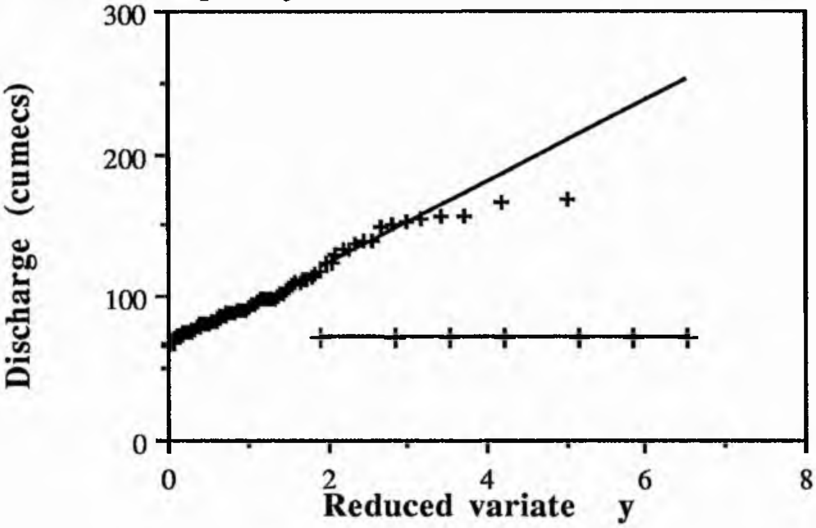


Figure 6.18
Full series frequency distribution for station 84015 Kelvin @ Dryfield

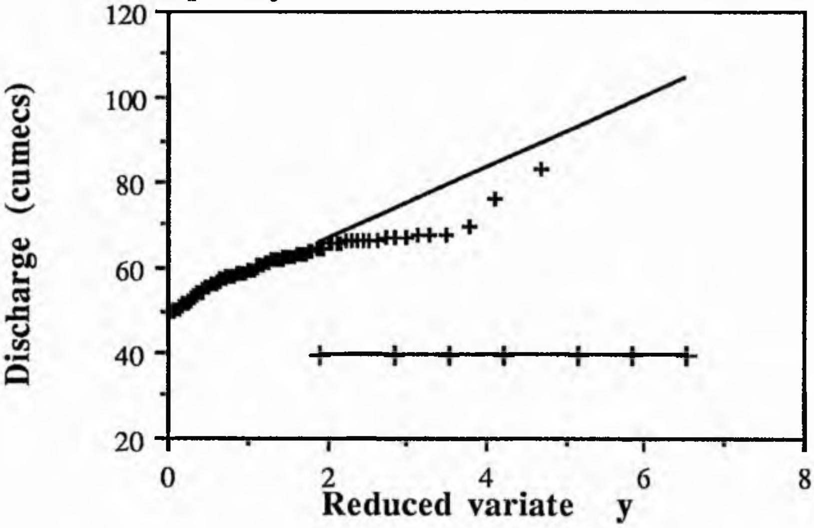


Plate 6.1 Out-of-bank flooding on the White Cart Water near Hawkhead, 1 April 1992
Storage of floodwaters on the floodplain causes attenuation of peaks further downstream.

station 19005, and 62% of its area, it seems that there must be some significant storage between these two sites. This seems plausible on the basis of reference to small-scale maps.

Considering downward deviations therefore to be either a random feature (due to a lack of especially large events), the result of storage, or both of these, rather than a product of the interaction of different generating processes, the fact that downward deviations are rather less common than upward ones becomes understandable. While storage does not induce upward deviations, and random effects should act equally in both these directions, it is the fact that the interaction of greatly differing generating processes results only in upward deviations that accounts for this type of departure from the fitted line occurring more frequently than downward deviations. That differences in synoptic groups' frequency distributions do not produce downward deviations in the distribution of points relative to the line fitted to whole series is surprising, for it does not seem impossible that this should be the case. However, it is thought to be a reflection of the range of relationships between individual groups' relationships which actually occur.

6.5.3 Minor deviations

By graphical inspection of the distribution of points relative to the fitted exponential models, two further types of distribution were identified, warranting only very brief mention. One was a general scatter of points about the line but with a general trend closely resembling that of the line, and can be thought of as either a random effect, or possibly the result of a storage effect, or a combination of both. The other was a close fit of points to the theoretical distribution from the smallest to the largest. This too should be thought of as a random effect rather than a result which should always be expected unless brought about by other factors. However, the fact that about 40% of all the distributions examined conformed to one of these two types is a reassuring indication of the applicability of the exponential model.

6.5.4 Applicability of the exponential model

The only cases where it is suggested that the exponential model is not suitable are firstly those where one or more generating processes produce a frequency distribution at high flood values greatly different to that which would be arrived at using the whole flood series, and secondly those where storage is known to significantly reduce flood peaks above a threshold. Having considered the rôle of distinct generating mechanisms in the distribution of points relative to theoretical model fits, it can be seen that flood series are by no means homogeneous populations of events. The earlier section on seasonal variations in frequency distributions showed that considerable seasonal variations exist, and was followed by an analysis based on synoptic types. At some stations in particular, it was found that seasonal variations actually result from the operation of quite different generating mechanisms operating differently on a seasonal basis, and exhibit differing frequency distributions accordingly. The present section has examined the interaction of the frequency distributions of these distinct flood groups, and produces the important conclusion that at some stations, the differences between the groups are such that use of full POT series could be dangerously misleading in a frequency analysis. For the estimation of high return period design floods, reference should be made instead only to the frequency distribution of the group responsible for the largest floods in the series. Differences first detected in a seasonal analysis have therefore proved to be useful in raising awareness of the fundamental nature of flood series, and have shown their worth in suggesting an improved method for the estimation of design floods.

6.6 Discussion

The preceding pages of this chapter have shown this investigation to have been of considerable practical benefit. Flood frequency analysis on the basis of a seasonal division of flood series has shown frequency distributions to vary markedly between seasons and, for the engineer concerned with short-term projects within reach of a flooding river, it has further been shown that such an analysis can yield useful results. It is hoped that such an approach might be developed further in practical application.

Beyond such practical implications, the investigation had also been useful in increasing our understanding of flood series in a more fundamental sense. It has shown the diversity which exists in the composition of flood series, how growth factors vary seasonally, and how the different generating mechanisms producing these also vary in their frequency distributions. Having uncovered such diversity, it is perhaps inevitable that it should be found that index flood estimation varies with seasonality, though the specific mechanisms involved here remain to be discovered.

The ideas discussed in this chapter also pose a fundamental question. It has been shown that flood populations can be, though are not necessarily, quite heterogeneous in their composition, and it has been suggested that as an aid to understanding and modelling their overall frequency distributions, it is advantageous to separate out the individual populations which make up the whole series. The question then arises as to the basis on which these components should be identified. In this chapter, disaggregation had been carried out both on the basis of season and using synoptic situation as a surrogate for flood generating mechanism. In both cases, such disaggregation has proved instructive in gaining an understanding of the overall seasonality and frequency distribution of floods at a site, though it is difficult to argue that either one of the two approaches should be used in preference to the other; rather it is suggested that to gain a full understanding of the structure of the flood series at any site, both methods of investigation should ideally be employed.

It should be acknowledged that both methods of disaggregation have their attendant problems. A seasonal analysis requires the use of arbitrarily defined seasons, and it may be sensible to use more than one set of seasons to reduce the risk of masking interesting patterns. An analysis by generating mechanism, on the other hand, is dependent on the use of weather type data as a surrogate for generating mechanism. This also employs arbitrary divisions and is subject to some inaccuracy due to the large-scale classification of synoptic situation for floods generated in rather smaller river basins. It is also unable to accommodate the undoubtedly important rôle of melting snow in flood production.

Yet despite these weaknesses, it has been shown clearly that the heterogeneity of flood series at some stations, whether defined in terms of seasonality or generating mechanism (and it has further been shown that these two are interdependent), is responsible for flood frequency distributions which differ radically from theoretically-based expectations; the effect of combining different generating mechanism groups' frequency distributions on overall flood frequency could equally be explained in terms of seasonal groups. Since the incidence of Lamb daily weather types varies seasonally, seasonality must be said to be the driving force behind the diversity found amongst the components of individual flood series.

The general conclusion to be drawn from this is that even though flood series in Scotland do not divide themselves so obviously or easily into discrete groups as is the case elsewhere, the general principle of modelling flood frequency distributions by explicitly addressing the existence of such discrete groups is no less valid in this country than in Italy or Canada where such methods have been successfully applied. Indeed it may only be by the adoption of such methods - at least in some catchments - that flood frequency analyses can be undertaken satisfactorily. To arrive at this conclusion is to have moved on considerably from a purely exploratory investigation of the seasonality of flooding in Scotland, and serves as an excellent justification for this whole study.

Chapter 7

Summary and conclusions

This chapter sets out to summarise the findings of the study in relation to the aims originally defined; to assess its value while noting limitations where appropriate; and also to suggest directions for further research on the basis of the findings made. Three aims were defined in Chapter 1: to describe the patterns of flood seasonality across Scotland; to reach an understanding of how these are produced; and to consider the wider implications of the variations in flood seasonality found. Each of these will be discussed in turn in the following paragraphs.

7.1 Patterns of seasonality

The investigation of the patterns of flood seasonality (Chapter 4) found a great diversity amongst the flood records of the 143 stations used in the main part of the analysis. While some records were found to be heavily dominated by winter flood events and many others showed floods in other seasons to have only minor importance, a few stations showed radically different seasonalities with late summer assuming a dominant rôle in some instances. A broad trend for floods to occur later on average in the east than in the west was found, confirming the results of some previous research, but the more detailed nature of this study allowed important exceptions to this broad trend to be identified.

A number of methods of characterising flood seasonality were employed since it became apparent that no single index of seasonality could convey all the information of interest held within the database. Mean day of flood, and *r* values indicating the degree of clustering around the mean day, were found useful in illustrating general trends, while a more detailed break-down into six two-month seasons allowed more specific information on the patterns of seasonality to be obtained, *eg* the notably high frequency of flooding in south-west Scotland in late summer, and the general tendency towards relatively high flood frequencies throughout the summer in east coast areas.

Unusual patterns of seasonality in the Moray-Nairn and Lothian areas were further highlighted by an analysis of just the largest peak flows in individual records. This showed that late summer flood frequencies which were relatively high in comparison with other stations assumed an even greater importance at high discharge values, and at one station in particular (08004 River Avon @ Delnashaugh) late summer completely dominates the seasonality of floods exceeding a discharge threshold approximately equivalent to a 3-year return period.

Small catchments in different parts of the study area were also found to have especially unusual patterns of seasonality; while some examples showed strikingly early flood seasonalities, *eg* 80003 White Laggan @ Loch Dee, others experienced a very late mean season of flood occurrence, *eg* 22003 Usway Burn @ Shillmoor. The great wealth of information uncovered was finally condensed using a classification analysis which assigned each station to one of four seasonally similar groups. In this way, the spatial distribution of seasonal types could be readily comprehended.

The findings of this part of the project provided a comprehensive and accurate picture of the patterns of flood seasonality across Scotland, with an extension of the study area into Northumberland initially justified on the basis of Hewson's work (*eg* Hewson 1982a) providing a valuable addition to the database through some records showing very late seasonalities. Threshold standardisation and compensation for the effects of the periods of record sampled have added to the quality of the patterns described, though it is recognised that these are dependent on the frequency definition of a flood which has been used. The patterns identified do much to dispel any presuppositions that flooding in Scotland is essentially a winter phenomenon, and should be of value in other studies where the timing of peak flows is of importance; these might include studies of biological, chemical and sedimentological processes.

In the process of this part of the work, a high quality POT flood database was produced, extending records collected for the *Flood Studies Report* (NERC 1975) and later by Acreman (1985a). The 3458 station-years of record amassed have served as the foundation for this study, but also constitute a resource of great potential for other future research projects.

7.2 Explanation of seasonal patterns

In describing the seasonal patterns, it was found that adjacent drainage basins could exhibit strikingly different flood seasonalities, and that such occurrences tended to be associated with differences in the physical characteristics of drainage basins. Considering that broad spatial trends were also seen, it appeared that the factors influencing flood seasonality operate at a range of spatial scales, and investigation of the likely factors has lent support to this idea (Chapter 5).

Five physical factors were investigated, and each found to have its own specific effect on flood seasonality. The seasonal distribution of peak rainfalls was found to have a direct correlation with flood seasonality, though the critical duration of flood-generating rainfalls does appear to vary between catchments, catchment area being considered to have a key rôle in this. The effect of soil moisture was considered in direct connection with that of peak rainfall seasonality, since this was found to exercise clear control over the translation of peak rainfalls into runoff events. Values of a SMD season length were found to show a very clear trend towards greater values in the east, and this is taken to account for the similarly clear trend for mean day of flood values also to be later in the east.

The observed effects of these two factors agree well with those predicted for them in the literature. The effects of other factors, however, appear to be rather less clearly understood in the limited literature on seasonality, and the findings of this study regarding them are now also summarised. As well as affecting the critical duration of storm rainfalls which affect flood seasonality, catchment area has also been found to affect flood seasonality indirectly. Large catchments have all shown a certain degree of similarity in their physical characteristics while the small catchments used have been much more diverse in character, and flood seasonality has reflected this. Large catchments were found to show mainly winter-dominated flood seasonalities, while as mentioned above, small catchments were found to show seasonalities which ranged from extremely early to extremely late.

By causing flood peak attenuation, loch or reservoir storages were found to promote a winter dominated flood seasonality in a manner similar to the effect of large catchment areas. This is interpreted as a reflection of the fact that most prolonged periods of heavy rain occur in the winter months. However, because only a relatively small proportion of Scotland's main rivers drain through large loch storages, the effects of this factor are only quite rarely seen.

Finally, the effect of snowmelt in adding to winter or spring flood peaks is also thought to be important in an overall analysis of flood seasonality. Though no appropriate data were available, the results of a discriminant analysis point convincingly to a missing factor in the physical characteristics data set, which contributes to winter flood occurrence especially in inland areas. Snowmelt appears to fit this description well, and it is suggested that this factor is especially deserving of further study if a means can be found of addressing the problem of data availability (see below).

7.3 Implications of seasonality variations

By highlighting the range of physical factors which affect the seasonal distribution of peak flows, it is felt that this study has already made a significant contribution towards the understanding of the flooding behaviour of rivers. In addition, the findings outlined in Chapter 6 show some implications arising from the study which are considered to have direct practical benefit for design flood estimation. Two themes have been pursued; first the seasonal variation in flood risk (a topic previously addressed by other authors) and second, the suitability of the exponential model in areas where flood series appear to be composed of different populations.

On the first of these themes, a method was developed to show the seasonal variation in flood risk by splitting the year into six seasons and fitting a statistical distribution to each. It was found that considerable variation existed amongst stations in the relationships between individual seasons' frequency curves. While at most, the rate of increase in peak discharge with return period was slower in summer than in winter months, notable exceptions were found. These differences are significant for engineers when planning temporary works in or near river channels since the time of year chosen for such works may seriously affect the risk of flooding; while the summer months may be relatively safe in one catchment the same may not be true of another. The method used allows the time of year of lowest flood risk for a given number of months to be estimated, subject to instrumental records being available. By recognising the seasonal variation in flood frequency distributions, the method must offer the best possible means of assessing seasonal flood risk for any given recurrence interval or discharge value.

POT records were also disaggregated on the basis of synoptic situation as a surrogate for flood generating mechanism, and again considerable differences in frequency distribution were found between groups. The implications of flood record heterogeneity were considered and evidence was found which suggested that the mix of flood types within an individual station's record, whether these were defined in terms of seasons or generating types, was important in affecting the frequency distribution of the entire flood series at that station. While the analyses presented rely exclusively upon POT methods, the exploratory use of an annual maximum method has also been found to support this idea. In essence, the findings suggest that where flood series are composed of a number of distinct groups, an exponential model may be an inappropriate representation of the magnitude-frequency relationship for floods at that site. Such findings must be taken to have considerable significance for design flood estimation methods.

7.4 Recommendations for further work

Because of the great practical potential of these findings, it is strongly recommended that further work be carried out to investigate more fully the precise effects of flood record heterogeneity on magnitude-frequency relationships. In fitting exponential frequency distributions to the data used in Chapter 6, it was found that great differences in frequency distribution between either seasonal or synoptic groups were generally associated with higher return period floods exceeding the magnitude predicted for them from the fitted model by a considerable margin. If such heterogeneity is accepted to be responsible for causing such departures from model behaviour, continued use of standard methods will result in the serious under-estimation of design floods in some cases, so further investigation of this matter must clearly be seen as a matter of priority.

Much of the analysis presented in Chapter 6 has relied upon the disaggregation of flood series. If future work considers disaggregation of flood records to be essential to a better understanding of magnitude-frequency relationships, then a further important area of research will be the means by which flood series should best be separated into distinct groups. It has been seen that there is much interdependence between season and flood generating mechanism, the two criteria upon which disaggregation of the flood series has been based, so a definite challenge exists in finding the most useful method of separating flood series into groups which should ideally be capable of displaying statistically significant differences.

A third recommendation for future studies is that the effect of snowmelt on flood seasonality should be investigated further. In seeking an explanation of the patterns observed in Chapter 4, snowmelt has been an important missing factor as no suitable data were available to describe its effect. It is possible that remote sensing methods could be developed to estimate the temporal variation of snow storage in individual catchments; changes in storage due to the passage of rain-bearing weather systems would be of particular interest in quantifying the snowmelt contribution to flood flows. An alternative approach to this issue might be to use altitude data, perhaps a hypsometric curve for each catchment, as a surrogate for snow storage since this is known to be strongly correlated with altitude. However, regional effects are also likely to be important and such studies would still need to address the change of storage associated with flood events. Whatever method might be used, a detailed analysis of the contribution of snowmelt to flood generation would provide a valuable advance in the overall understanding of flood seasonality which might in turn be of benefit in the development of flood frequency analyses. The findings of this study make it quite conceivable that snowmelt plays an important rôle in the determination of flood magnitude-frequency relationships on some rivers.

A final suggestion is that efforts should be made to increase the diversity of catchments from which instrumental flow records are collected. It is an inescapable fact that the patterns of flood seasonality observed are entirely dependent on the data which are available, and it is significant that the few very small catchments from which records were available have yielded most unusual and interesting information in terms of their flood seasonalities. All that has followed in this study, in terms of explaining the patterns of seasonality and considering their implications, is again dependent on the data available and it is strongly felt that more information from other small catchments would be of great value. It is therefore recommended that gauging authorities or other interested bodies should consider the installation of instruments on watercourses draining small catchments in a range of environments, since the data which these could collect are vital to a wider understanding of flood seasonality and may have considerable practical benefit.

7.5 Final conclusions

Through considering flooding in Scotland from a previously neglected perspective this study has been of considerable value; much new information on the seasonality of flooding on Scotland's main rivers has been presented, the rôle of each of the key factors determining the observed patterns has been identified, and significant implications arising from these findings have been proposed. The great diversity of seasonality which has been found effectively challenges the conventional supposition that floods in Scotland essentially occur only in the winter months, and where this is clearly not the case, the findings must be taken to alter what might be dangerous assumptions about flood behaviour.

For analyses of short period flood risk, specific reference to seasonality has been seen to be essential, and it has further been demonstrated that where unusual seasonality does exist, the accepted exponential frequency model is often seriously in error. Through an investigation of flood seasonality, a fundamental question has been placed over the conventional approach to flood frequency analysis. The rôle of distinct populations within flood series has been highlighted, casting presently accepted methods of modelling flood series as homogeneous units into considerable doubt. It is therefore recommended that further research should be undertaken which, by specifically addressing the heterogeneity which this study of seasonality has shown to exist within flood series, might usefully improve upon methods of design flood estimation.

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Seasonality of flooding in Scottish rivers

A thesis submitted as fulfilment of the requirements for the degree of Doctor of Philosophy in the University of St Andrews

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VOLUME II: APPENDICES

St Leonard's College October 1992

APPENDIX A

POT record details

No.	Station Name	Grid Ref.	Thresh	Record from - to	Yrs	Area	Q_{max}
2001	Helmsdale @ Kilphedir	NC997181	97.0	1: 1:1975 29:12:1988	14	551.0	311.9
3002	Carron @ Sgodachail	NH490920	106.0	1: 1:1974 31:12:1988	15	241.0	353.5
3003	Oykel @ Easter Turnaig	NC403001	210.0	1: 1:1978 31:12:1988	11	331.0	847.5
3801	Cassley @ Duchally	NC387168	42.0	1: 1:1951 31:12:1958	7	72.0	96.8
3901	Shin @ Lairg	NC581062	22.0	1: 1:1951 31:12:1956	6	495.0	92.6
3803	Tirry @ Rhian Bridge	NC553167	32.0	1: 1:1951 31:12:1957	7	64.0	110.9
4003	Alness @ Alness	NH654695	30.0	1: 1:1974 26:12:1988	15	201.0	196.3
4001	Conon @ Moy Bridge	NH483547	191.0	1: 1:1948 31:12:1956	9	971.0	474.8
5901	Beauly @ Erchless	NH426406	180.0	1: 1:1950 31:12:1962	13	850.0	599.7
6007	Ness @ Ness-side	NH645427	190.0	1: 1:1973 27:12:1988	16	1839.0	504.3
6008	Enrick @ Mill of Tore	NH450300	14.6	1: 1:1980 1: 1:1989	9	105.9	58.4
6903	Moriston @ Invermoriston	NH416169	164.0	1: 1:1931 31:12:1943	13	391.0	557.5
7001	Findhorn @ Shenachie	NH828339	107.0	1: 1:1961 4: 1:1989	28	417.0	577.7
7002	Findhorn @ Forres	NJ018583	131.0	1: 1:1959 31:12:1988	30	782.0	2410.0
7003	Lossie @ Sherriff Mills	NJ198626	17.0	1: 1:1959 3: 1:1990	31	216.0	91.8
8001	Spey @ Aberlour	NJ278439	242.0	1: 1:1939 31:12:1974	26	2654.7	1241.8
8002	Spey @ Kinrara	NH881082	75.0	1: 1:1953 3: 1:1990	33	387.8	325.2
8004	Avon @ Delnashaugh	NJ184352	109.0	1: 1:1953 31:12:1989	37	544.0	532.0
8005	Spey @ Boat of Garten	NH946191	82.0	1: 1:1952 30:12:1989	38	1270.0	410.3
8006	Spey @ Boat o' Brig	NJ318518	275.0	1: 1:1953 3: 1:1990	37	2850.0	1594.7
8007	Spey @ Invertruim	NN688964	39.0	1: 1:1953 3: 1:1990	37	401.0	256.9
8008	Tromie @ Tromie Bridge	NN788995	21.0	1: 1:1953 24:12:1989	23	130.0	155.0
8009	Dulnain @ Balnaan Bridge	NH976247	49.0	1: 1:1953 3: 1:1990	37	272.0	201.8
8010	Spey @ Grantown	NJ034268	120.9	1: 1:1952 2: 1:1990	38	1750.0	487.5
8903	Spey @ Ruthven Bridge	NN759996	58.0	1: 1:1952 31:12:1973	22	534.0	223.3
9001	Deveron @ Avochie	NJ532464	68.0	1: 1:1960 3: 1:1990	30	442.0	237.4
9002	Deveron @ Muiresk	NJ705498	92.0	1: 1:1961 3: 1:1990	29	956.0	520.9
9003	Isla @ Grange	NJ493506	24.0	1: 1:1960 31:12:1989	30	176.0	80.4
10001	Ythan @ Ardlethen	NJ924308	28.0	1: 1:1940 31:12:1984	43	488.0	104.0
10002	Ugie @ Inverugie	NK101485	19.0	1: 1:1972 7: 1:1990	18	325.0	91.0
11001	Don @ Parkhill	NJ887141	71.0	1: 1:1970 4: 1:1990	20	1273.0	285.6
11002	Don @ Haughton	NJ756201	57.6	1: 1:1972 31:12:1989	18	787.0	189.1
11003	Don @ Alford	NJ566170	41.0	1: 1:1974 3: 1:1990	16	507.0	188.5
12001	Dee @ Woodend	NO635956	195.0	1: 1:1934 4: 1:1990	56	1370.0	1134.0
12002	Dee @ Park Bridge	NO798983	234.0	1: 1:1973 16: 1:1990	17	1844.0	839.8
12003	Dee @ Polhollick	NO343965	140.0	1: 1:1976 4: 1:1990	14	690.0	397.0
14001	Eden @ Kemback	NO415158	18.5	1: 1:1968 3: 1:1990	22	307.0	71.2
15008	Dean Water @ Cookston	NO340479	15.0	1: 1:1954 4: 1:1990	36	177.1	42.0
15010	Isla @ Wester Cardean	NO295466	53.0	1: 1:1972 4: 1:1990	18	367.0	151.0
15013	Almond @ Almondbank	NO068258	46.0	1: 1:1974 31:12:1988	15	175.0	157.8
15016	Tay @ Kenmore	NN782467	100.0	1: 1:1975 3: 1:1990	15	601.0	252.0
16003	Ruchill Water @ Cultybraggan	NN764204	70.0	1: 1:1960 3: 1:1990	29	99.5	283.3
17001	Carron @ Headswood	NS832820	33.0	1: 1:1969 5: 1:1990	20	122.3	222.0
17005	Avon @ Polmonthill	NS952797	30.0	1: 1:1971 3: 1:1990	19	195.3	85.2
18005	Allan Water @ Bridge of Allan	NS786980	58.0	1: 1:1972 9: 1:1990	18	209.5	127.3
18008	Leny @ Anie	NN585096	48.0	1: 1:1974 9: 1:1990	16	190.0	115.7
18001	Allan Water @ Kinbuck	NN792053	47.0	1: 1:1958 31:12:1982	25	161.0	99.0
18002	Devon @ Glenochil	NS858960	23.0	1: 1:1957 31:12:1970	14	181.0	57.0
19001	Almond @ Craigiehall	NT165752	55.0	1: 1:1957 3: 1:1990	33	369.0	167.9
19002	Almond @ Almond Weir	NT004652	9.0	1: 1:1962 3: 1:1990	28	43.8	32.6
19004	North Esk @ Dalmore Weir	NT252616	9.5	1: 1:1962 2: 1:1990	28	81.6	39.5
19006	Water Of Leith @ Murrayfield	NT228732	12.0	1: 1:1963 2: 1:1990	27	107.0	44.0
19007	Esk @ Musselburgh	NT339723	28.0	1: 1:1962 2: 1:1990	28	362.0	180.8
19008	South Esk @ Prestonholm	NT325623	9.0	1: 1:1964 2: 1:1990	26	112.0	78.1
19011	North Esk @ Dalkeith Palace	NT333678	14.0	1: 1:1963 2: 1:1990	27	137.0	75.6
19003	Breich Water @ Breich Weir	NT014639	14.0	1: 1:1962 31:12:1979	18	51.8	46.0
19005	Almond @ Almondell	NT086686	43.0	1: 1:1963 31:12:1983	21	229.0	165.8
20001	Tyne @ East Linton	NT591768	23.0	1: 1:1959 2: 1:1990	31	307.0	113.0
20002	Peffer West @ Luffness Mains	NT489811	1.1	1: 1:1966 2: 1:1990	24	26.2	6.9
20003	Tyne @ Spilmersford	NT456698	16.0	1: 1:1963 2: 1:1990	27	161.0	131.5
20005	Birns Water @ Saltoun Hall	NT457678	7.6	1: 1:1963 2: 1:1990	27	93.0	59.2
20006	Biel Water @ Belton House	NT645768	3.6	1: 1:1972 2: 1:1990	18	51.8	30.6

No.: Institute of Hydrology Gauging Station Number
Grid ref.: National Grid Reference
Thresh: Threshold discharge for POT series ($m^3 s^{-1}$)

Yrs: Length of record in years, accounting for gaps
Area: Catchment area (km^2)
Q_{max}: Maximum discharge in record ($m^3 s^{-1}$)

No.	Station Name	Grid Ref.	Thresh	Record from	- to	Yrs	Area	Q_{max}
20007	Gifford Water @ Lennoxlove	NT511717	3.2	1: 1:1973	2: 1:1990	17	64.0	60.2
21003	Tweed @ Peebles	NT257400	100.0	1: 1:1949	8: 1:1990	41	694.0	1079.0
21005	Tweed @ Lyne Ford	NT206397	60.0	1: 1:1962	31:12:1989	28	373.0	232.1
21007	Ettrick @ Lindean	NT486315	96.0	1: 1:1962	31:12:1989	28	499.0	564.5
21008	Teviot @ Ormiston Mill	NT702280	150.0	1: 1:1961	3: 1:1990	29	1110.0	582.5
21009	Tweed @ Norham	NT898477	449.0	1: 1:1960	2: 1:1990	30	4390.0	1555.7
21012	Teviot @ Hawick	NT522159	91.0	1: 1:1964	3: 1:1990	26	323.0	269.5
21015	Leader Water @ Earlston	NT565388	30.0	1: 1:1967	1: 1:1990	23	239.0	238.3
21016	Eye Water @ Eyemouth Mill	NT942635	13.0	1: 1:1968	7: 1:1990	22	119.0	67.5
21022	Whiteadder Water @ Hutton Castle	NT881550	50.0	1: 1:1970	3: 1:1990	20	503.0	279.8
21024	Jed Water @ Jedburgh	NT655214	20.0	1: 1:1972	3: 1:1990	18	139.0	161.9
21025	Ale Water @ Ancrum	NT634244	19.0	1: 1:1973	3: 1:1990	17	174.0	80.4
21026	Tima Water @ Deephope	NT278138	25.0	1: 1:1974	2: 1:1990	16	31.0	71.8
21001	Fruid Water @ Fruid	NT088228	10.0	1: 1:1948	31:12:1961	14	23.7	24.7
21002	Whiteadder Water @ Hungry Snout	NT663633	11.0	1: 1:1958	31:12:1967	10	45.6	63.1
21006	Tweed @ Boleside	NT498334	228.0	1: 1:1962	31:12:1982	21	1500.0	1153.1
21010	Tweed @ Dryburgh	NT588320	253.0	1: 1:1950	31:12:1982	33	2080.0	1174.1
21011	Yarrow Water @ Philiphaugh	NT439277	31.0	1: 1:1963	31:12:1981	19	233.0	270.1
21013	Gala Water @ Galashiels	NT479374	25.0	1: 1:1964	31:12:1982	19	207.0	80.1
21017	Ettrick Water @ Brockhoperig	NT234132	23.0	1: 1:1966	31:12:1982	17	37.5	141.3
21018	Lyne Water @ Lyne Station	NT209401	13.0	1: 1:1969	31:12:1982	14	175.0	50.1
21019	Manor Water @ Cademuir	NT217369	11.0	1: 1:1969	31:12:1982	14	61.6	33.4
21020	Yarrow Water @ Gordon Arms	NT309247	22.0	1: 1:1968	31:12:1981	14	155.0	155.9
21021	Tweed @ Sprouston	NT752354	382.0	1: 1:1970	31:12:1982	13	3330.0	1411.3
21027	Blackadder Water @ Mouth Bridge	NT826530	16.0	1: 1:1974	31:12:1982	9	159.0	69.4
21030	Megget Water @ Henderland	NT231232	21.0	1: 1:1969	31:12:1981	13	56.2	126.9
21031	Till @ Etal	NT927396	43.2	1: 1:1956	31:12:1978	23	648.0	299.6
21032	Glen @ Kirknewton	NT919310	17.8	1: 1:1962	31:12:1982	21	198.9	105.0
21034	Yarrow Water @ Craig Douglas	NT288244	15.0	1: 1:1969	31:12:1981	13	116.0	113.3
22001	Coquet @ Morwick	NU234044	78.0	1: 1:1964	31:12:1985	22	569.8	289.7
22002	Coquet @ Bygate	NT870083	11.0	1: 1:1967	31:12:1980	14	59.5	34.0
22003	Usway Burn @ Shillmoor	NT886077	7.0	1: 1:1967	31:12:1979	13	21.4	55.3
22004	Aln @ Hawkhill	NU211129	28.0	1: 1:1961	31:12:1979	19	205.0	150.0
22006	Blyth @ Hartford Bridge	NZ243800	19.2	1: 1:1961	31:12:1985	25	269.4	150.2
22007	Wansbeck @ Mitford	NZ175858	35.7	1: 1:1964	31:12:1985	22	287.3	312.9
22008	Alwin @ Clennell	NT925063	4.0	1: 1:1972	31:12:1978	7	27.7	9.4
22009	Coquet @ Rothbury	NU067016	40.0	1: 1:1973	31:12:1985	13	346.0	211.7
23008	Rede @ Rede Bridge	NY868832	70.0	1: 1:1969	31:12:1985	17	343.8	266.8
23010	Tarset Burn @ Greenhaugh	NY789879	22.0	1: 1:1971	31:12:1979	9	96.0	105.6
23011	Kielder Burn @ Kielder	NY644946	27.0	1: 1:1971	31:12:1985	15	58.8	106.7
77002	Esk @ Canonbie	NY397751	199.0	1: 1:1963	7: 1:1990	26	495.0	636.6
77003	Liddel @ Rowanburnfoot	NY415759	138.0	1: 1:1974	3: 1:1986	12	269.4	389.7
78003	Annan @ Brydekirk	NY191704	179.0	1: 1:1968	2: 1:1990	22	925.0	473.4
78004	Kinnel @ Redhall	NY077868	37.0	1: 1:1967	3: 1:1990	23	76.1	112.7
78005	Kinnel @ Bridgemuir	NY091845	72.0	1: 1:1979	3: 1:1990	11	229.0	155.1
79002	Nith @ Friar's Carse	NX923851	280.0	1: 1:1958	3: 1:1990	32	799.0	986.2
79003	Nith @ Hall Bridge	NS684129	44.0	1: 1:1960	3: 1:1990	30	155.0	223.1
79004	Scar @ Capenoch	NX845940	82.0	1: 1:1964	5: 1:1990	26	142.0	255.3
79005	Cluden @ Fiddler's Ford	NX928795	65.9	1: 1:1964	3: 1:1990	26	238.0	271.0
79006	Nith @ Drumlanrig	NX858994	164.0	1: 1:1968	10: 1:1990	22	471.0	429.6
80001	Urr @ Dalbeattie	NX822610	55.0	1: 1:1964	4: 1:1990	26	199.0	159.4
80003	White Laggan @ Loch Dee	NX468781	7.0	1: 1:1981	4: 1:1990	9	5.7	9.5
81002	Cree @ Newton Stewart	NX412653	115.0	1: 1:1964	3: 1:1990	26	368.0	350.6
81003	Luce @ Airyhemming	NX180599	77.0	1: 1:1967	3: 1:1990	23	171.0	283.6
82003	Stinchar @ Balnowlart	NX108832	102.0	1: 1:1975	31:12:1987	10	341.0	271.0
82001	Girvan @ Robstone	NX217997	56.0	1: 1:1964	31:12:1982	19	246.0	116.2
83004	Lugar Water @ Langholm	NS508217	63.0	1: 1:1973	31:12:1987	15	181.0	270.3
83002	Garnock @ Dalry	NS293488	36.6	1: 1:1960	31:12:1969	10	88.8	82.7
83005	Irvine @ Shewalton	NS345369	90.0	1: 1:1973	31:12:1981	9	380.6	375.5
83006	Ayr @ Mainholm	NS361216	170.0	1: 1:1976	31:12:1982	7	574.0	365.8
83802	Irvine @ Glenfield	NS430369	48.0	1: 1:1914	31:12:1988	75	218.0	227.0
84003	Clyde @ Hazelbank	NS835452	140.0	1: 1:1956	27:12:1988	33	1090.0	514.8
84005	Clyde @ Blairston	NS704579	221.0	1: 1:1956	27:12:1988	33	1710.0	669.7
84012	White Cart Water @ Hawkhead	NS499629	63.0	1: 1:1964	31:12:1988	25	234.9	187.1
84013	Clyde @ Daldowie	NS672616	210.0	1: 1:1964	27:12:1988	24	1903.0	755.2
84014	Avon Water @ Fairholm	NS755518	90.0	1: 1:1965	27:12:1988	24	266.0	410.0

No.: Institute of Hydrology Gauging Station Number
Grid ref.: National Grid Reference
Thresh: Threshold discharge for POT series (m^3s^{-1})

Yrs: Length of record in years, accounting for gaps
Area: Catchment area (km^2)
Q_{max}: Maximum discharge in record ($m^3 s^{-1}$)

No.	Station Name	Grid Ref.	Thresh	Record from - to		Yrs	Area	Q_{max}
84015	Kelvin @ Dryfield	NS638739	37.0	1: 1:1947	28:12:1988	42	235.0	83.5
84016	Luggie Water @ Condorrat	NS739725	6.0	29:12:1968	28:12:1988	20	33.9	34.7
84020	Glazert Water @ Milton of Campsie	NS656763	26.0	1: 1:1969	28:12:1988	20	51.8	76.2
84026	Allander @ Milngavie	NS558738	11.0	1: 1:1974	28:12:1988	15	32.8	64.6
84001	Kelvin @ Killermont	NS558705	51.0	1: 1:1949	31:12:1982	34	334.0	159.4
84004	Clyde @ Sills of Clyde	NS927424	108.0	1: 1:1956	31:12:1982	27	742.0	410.8
84006	Kelvin @ Bridgend	NS672749	9.0	1: 1:1957	31:12:1982	26	63.7	23.4
84806	Clyde @ Cambusnethan	NS786522	171.0	1: 1:1956	31:12:1963	8	1261.0	479.9
84007	South Calder Water @ Forgewood	NS751585	9.0	1: 1:1967	31:12:1982	15	93.0	39.5
84008	Rotten Calder @ Redlees	NS679604	16.5	1: 1:1967	31:12:1982	16	51.3	51.5
84009	Nethan @ Kirkmuirhill	NS810429	22.0	1: 1:1967	31:12:1982	16	66.0	80.5
84011	Gryfe @ Craigend	NS415664	34.0	1: 1:1964	31:12:1982	19	71.0	98.3
84018	Clyde @ Tulliford Mill	NS891404	130.0	1: 1:1969	31:12:1982	14	932.6	467.8
84019	North Calder Water @ Calderpark	NS681625	13.0	1: 1:1964	31:12:1982	19	130.0	65.6
84023	Bothlin Burn @ Auchengeich	NS680717	5.0	1: 1:1974	31:12:1982	9	35.6	13.5
84025	Luggie Water @ Oxgang	NS666734	16.0	1: 1:1974	31:12:1982	9	87.6	51.7
85003	Falloch @ Glen Falloch	NN321197	104.0	1: 1:1971	31:12:1987	17	80.3	185.2
85002	Endrick Water @ Gaidrew	NS485866	75.0	1: 1:1964	31:12:1982	19	220.0	149.9
86001	Little Eachaig @ Dalinlongart	NS143821	26.0	1: 1:1968	31:12:1987	20	30.8	112.8
87801	Allt Uaine @ Loch Sloy Intake	NN263113	5.9	1: 1:1951	31:12:1971	21	3.1	11.3
89804	Strae @ Duiletter	NN146294	28.4	4: 1:1978	5: 1:1989	11	36.2	67.5
91002	Lochy @ Camisky	NN145805	323.5	1: 1:1980	30:12:1988	9	1252.0	1195.3
91802	Allt Leachdach @ Intake	NN261781	4.2	1: 1:1939	31:12:1974	34	6.5	13.3
93001	Carron @ New Kelso	NG942429	87.5	1: 1:1979	5: 1:1989	10	137.8	286.8
94001	Ewe @ Poolewe	NG859803	47.0	1: 1:1970	29:12:1988	19	441.0	185.9
96001	Halladale @ Halladale	NC891561	56.0	1: 1:1975	30:12:1988	14	205.0	230.8
96002	Naver @ Apigill	NC713568	64.0	1: 1:1978	2: 1:1989	11	477.0	291.4
97002	Thurso @ Halkirk	ND131595	51.0	1: 1:1972	26:12:1988	17	413.0	181.2

No.: Institute of Hydrology Gauging Station Number
Grid ref.: National Grid Reference
Thresh: Threshold discharge for POT series (m^3s^{-1})

Yrs: Length of record in years, accounting for gaps
Area: Catchment area (km^2)
Q_{max}: Maximum discharge in record ($m^3 s^{-1}$)

APPENDIX B

Threshold adjustment

The following list shows the threshold discharge values originally used in the collection of the POT series, and those subsequently applied before calculation of mean day of flood, *r* and two-monthly percentage values. The new threshold value is based on a frequency of 45 events during the period 1979-88 or equivalent. Missing new threshold values indicate insufficient peaks in original record to meet this requirement.
Units: m^3s^{-1}.

GSN	STATION NAME	THRESHOLD OLD	THRESHOLD NEW
.2001	HELMSDALE @ KILPHEDIR	97.0	107.6
3002	CARRON @ SGODACHAIL	106.0	107.7
3003	OYKEL @ EASTER TURNAIG	210.0	
3801	CASSLEY @ DUCHALLY	42.0	57.9
3803	TIRRY @ RHIAN BRIDGE	32.0	34.0
3901	SHIN @ LAIRG	22.0	34.8
4001	CONON @ MOY BRIDGE	191.0	234.4
4003	ALNESS @ ALNESS	30.0	34.0
5901	BEAULY @ ERCHLESS	180.0	200.1
6007	NESS @ NESS-SIDE	190.0	217.2
6008	ENRICK @ MILL OF TORE	14.6	
6903	MORISTON @ INVERMORISTON	164.0	176.2
7001	FINDHORN @ SHENACHIE	107.0	156.0
7002	FINDHORN @ FORRES	131.0	170.9
7003	LOSSIE @ SHERRIFF MILLS	17.0	18.2
8001	SPEY @ ABERLOUR	242.0	
8002	SPEY @ KINRARA	75.0	
8004	AVON @ DELNASHAUGH	109.0	
8005	SPEY @ BOAT OF GARTEN	82.0	109.6
8006	SPEY @ BOAT O' BRIG	275.0	
8007	SPEY @ INVERTRUIM	39.0	55.2
8008	TROMIE @ TROMIE BRIDGE	21.0	
8009	DULNAIN @ BALNAAN BRIDGE	49.0	62.6
8010	SPEY @ GRANTOWN	120.9	165.1
8903	SPEY @ RUTHVEN BRIDGE	58.0	73.6
9001	DEVERON @ AVOCHIE	68.0	
9002	DEVERON @ MUIRESK	92.0	113.8
9003	ISLA @ GRANGE	24.0	25.9
10001	YTHAN @ ARDLETHEN	28.0	
10002	UGIE @ INVERUGIE	19.0	25.1
11001	DON @ PARKHILL	71.0	72.7
11002	DON @ HAUGHTON	57.6	61.8
11003	DON @ ALFORD	41.0	48.4
12001	DEE @ WOODEND	195.0	217.4
12002	DEE @ PARK BRIDGE	234.0	253.5
12003	DEE @ POLHOLLICK	140.0	153.0
14001	EDEN @ KEMBACK	18.5	23.6
15008	DEAN WATER @ COOKSTON	15.0	17.9
15010	ISLA @ WESTER CARDEAN	53.0	54.3
15013	ALMOND @ ALMONDBANK	46.0	58.1
15016	TAY @ KENMORE	100.0	110.1

GSN	STATION NAME	THRESHOLD OLD	NEW
16003	RUCHILL WATER @ CULTYBRAGGAN	70.0	93.6
17001	CARRON @ HEADSWOOD	33.0	53.6
17005	AVON @ POLMONTHILL	30.0	39.2
18001	ALLAN WATER @ KINBUCK	47.0	55.0
18002	DEVON @ GLENOCHIL	23.0	31.5
18005	ALLAN WATER @ BRIDGE OF ALLAN	58.0	67.9
18008	LENY @ ANIE	48.0	53.4
19001	ALMOND @ CRAIGIEHALL	55.0	68.1
19002	ALMOND @ ALMOND WEIR	9.0	10.0
19003	BREICH WATER @ BREICH WEIR	14.0	15.6
19004	NORTH ESK @ DALMORE WEIR	9.5	11.2
19005	ALMOND @ ALMONDELL	43.0	47.5
19006	WATER OF LEITH @ MURRAYFIELD	12.0	15.3
19007	ESK @ MUSSELBURGH	28.0	35.7
19008	SOUTH ESK @ PRESTONHOLM	9.0	
19011	NORTH ESK @ DALKEITH PALACE	14.0	17.0
20001	TYNE @ EAST LINTON	23.0	26.3
20002	PEFFER WEST @ LUFFNESS MAINS	1.1	1.5
20003	TYNE @ SPILMERSFORD	16.0	
20005	BIRNS WATER @ SALTOUN HALL	7.6	11.0
20006	BIEL WATER @ BELTON HOUSE	3.6	5.4
20007	GIFFORD WATER @ LENNOXLOVE	3.2	6.8
21001	FRUID WATER @ FRUID	10.0	11.6
21002	WHITEADDER WATER @ HUNGRY SNOUT	11.0	
21003	TWEED @ PEEBLES	100.0	
21005	TWEED @ LYNE FORD	60.0	
21006	TWEED @ BOLESIDE	228.0	
21007	ETTRICK @ LINDEAN	96.0	127.1
21008	TEVIOT @ ORMISTON MILL	150.0	197.1
21009	TWEED @ NORHAM	449.0	451.7
21010	TWEED @ DRYBURGH	253.0	273.5
21011	YARROW WATER @ PHILIPHAUGH	31.0	
21012	TEVIOT @ HAWICK	91.0	109.0
21013	GALA WATER @ GALASHIELS	25.0	
21015	LEADER WATER @ EARLSTON	30.0	31.3
21016	EYE WATER @ EYEMOUTH MILL	13.0	18.0
21017	ETTRICK WATER @ BROCKHOPERIG	23.0	
21018	LYNE WATER @ LYNE STATION	13.0	
21019	MANOR WATER @ CADEMUIR	11.0	13.9
21020	YARROW WATER @ GORDON ARMS	22.0	
21021	TWEED @ SPROUSTON	382.0	
21022	WHITEADDER WR @ HUTTON CASTLE	50.0	54.0
21024	JED WATER @ JEDBURGH	20.0	32.9
21025	ALE WATER @ ANCRUM	19.0	25.4
21026	TIMA WATER @ DEEPHOPE	25.0	33.9
21027	BLACKADDER WATER @ MOUTH BRIDGE	16.0	
21030	MEGGET WATER @ HENDERLAND	21.0	
21031	TILL @ ETAL	43.2	47.4
21032	GLEN @ KIRKNEWTON	17.8	20.4
21034	YARROW WATER @ CRAIG DOUGLAS	15.0	22.4
22001	COQUET @ MORWICK	78.0	
22002	COQUET @ BYGATE	11.0	14.9
22003	USWAY BURN @ SHILLMOOR	7.0	9.4
22004	ALN @ HAWKHILL	28.0	34.7
22006	BLYTH @ HARTFORD BRIDGE	19.2	21.3

GSN	STATION NAME	THRESHOLD OLD	THRESHOLD NEW
22007	WANSBECK @ MITFORD	35.7	37.8
22008	ALWIN @ CLENNELL	4.0	4.3
22009	COQUET @ ROTHBURY	40.0	46.9
23008	REDE @ REDE BRIDGE	70.0	88.4
23010	TARSET BURN @ GREENHAUGH	22.0	43.8
23011	KIELDER BURN @ KIELDER	27.0	34.3
77002	ESK @ CANONBIE	199.0	202.8
77003	LIDDEL @ ROWANBURNFOOT	138.0	
78003	ANNAN @ BRYDEKIRK	179.0	208.6
78004	KINNEL @ REDHALL	37.0	47.3
78005	KINNEL @ BRIDGEMUIR	72.0	77.8
79002	NITH @ FRIAR'S CARSE	280.0	
79003	NITH @ HALL BRIDGE	44.0	48.2
79004	SCAR @ CAPENOCH	82.0	91.3
79005	CLUDEN @ FIDDLER'S FORD	65.9	74.4
79006	NITH @ DRUMLANRIG	164.0	193.0
80001	URR @ DALBEATTIE	55.0	63.8
80003	WHITE LAGGAN @ LOCH DEE	7.0	
81002	CREE @ NEWTON STEWART	115.0	154.1
81003	LUCE @ AIRYHEMMING	77.0	97.0
82001	GIRVAN @ ROBSTONE	56.0	62.4
82003	STINCHAR @ BALNOWLART	102.0	
83002	GARNOCK @ DALRY	36.6	42.8
83004	LUGAR WATER @ LANGHOLM	63.0	
83005	IRVINE @ SHEWALTON	90.0	157.4
83006	AYR @ MAINHOLM	170.0	202.7
83802	IRVINE @ GLENFIELD	48.0	55.8
84001	KELVIN @ KILLERMONT	51.0	
84003	CLYDE @ HAZELBANK	140.0	170.5
84004	CLYDE @ SILLS OF CLYDE	108.0	130.6
84005	CLYDE @ BLAIRSTON	221.0	251.4
84006	KELVIN @ BRIDGEND	9.0	15.5
84007	SOUTH CALDER WATER @ FORGEWOOD	9.0	11.8
84008	ROTTEN CALDER @ REDLEES	16.5	19.4
84009	NETHAN @ KIRKMUIRHILL	22.0	25.0
84011	GRYFE @ CRAIGEND	34.0	
84012	WHITE CART WATER @ HAWKHEAD	63.0	94.7
84013	CLYDE @ DALDOWIE	210.0	274.2
84014	AVON WATER @ FAIRHOLM	90.0	101.5
84015	KELVIN @ DRYFIELD	37.0	54.5
84016	LUGGIE WATER @ CONDORRAT	6.0	14.2
84018	CLYDE @ TULLIFORD MILL	130.0	160.5
84019	NORTH CALDER WATER @ CALDERPARK	13.0	
84020	GLAZERT WR @ MILTON OF CAMPSIE	26.0	38.0
84023	BOTHLIN BURN @ AUCHENGEICH	5.0	6.0
84025	LUGGIE WATER @ OXGANG	16.0	17.8
84026	ALLANDER @ MILNGAVIE	11.0	19.9
84806	CLYDE @ CAMBUSNETHAN	171.0	188.8
85002	ENDRICK WATER @ GAIDREW	75.0	82.7
85003	FALLOCH @ GLEN FALLOCH	104.0	113.8
86001	LITTLE EACHAIG @ DALINLONGART	26.0	31.1
87801	ALLT UAINE @ LOCH SLOY INTAKE	5.9	6.3
89804	STRAE @ DUILETTER	28.4	39.6
91002	LOCHY @ CAMISKY	323.5	373.2
91802	ALLT LEACHDACH @ INTAKE	4.2	4.5
93001	CARRON @ NEW KELSO	87.5	93.9
94001	EWE @ POOLEWE	47.0	54.1
96001	HALLADALE @ HALLADALE	56.0	70.3
96002	NAVER @ APIGILL	64.0	75.6
97002	THURSO @ HALKIRK	51.0	58.1

APPENDIX C
Rose Diagrams

The following graphs ('rose diagrams') show the magnitude (discharge) and season of occurrence of all events above the revised thresholds listed in Appendix B. Season is represented by angle around the circumference of the circle, starting from 31 May shown at the eastern end of the horizontal axis, and progressing anti-clockwise in accordance with statistical convention. Month labels shown outside the circle represent mid-points of each month. Event discharge is represented by distance from the centre of the circle, and values in m^3s^{-1} are shown on the horizontal axis. The threshold value is represented by a dotted inner circle.

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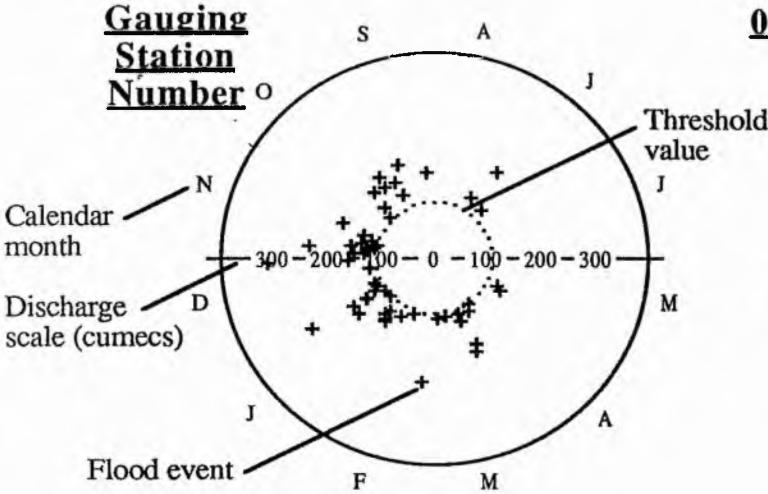

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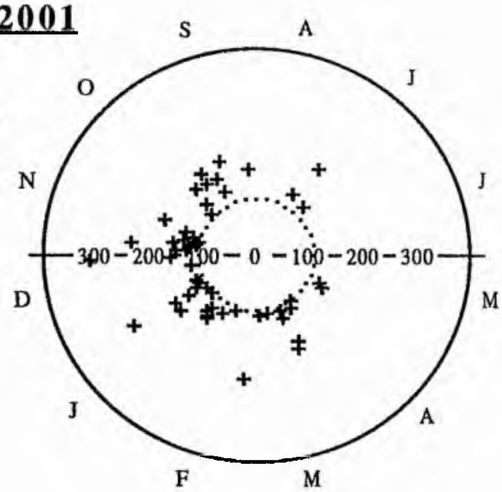

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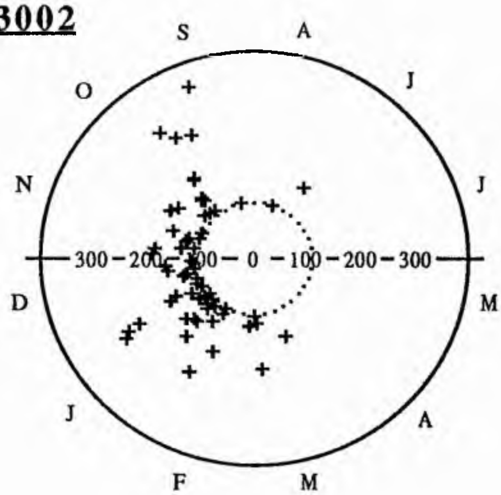

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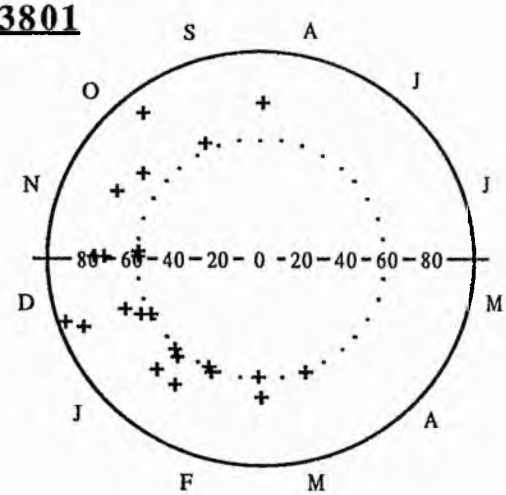

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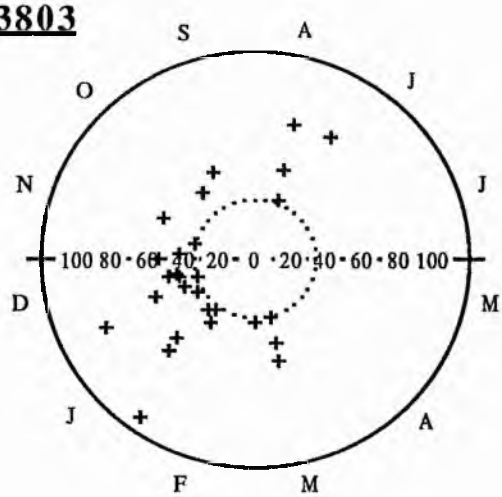

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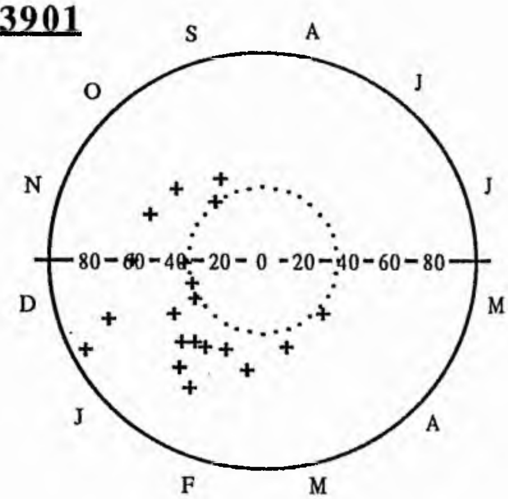

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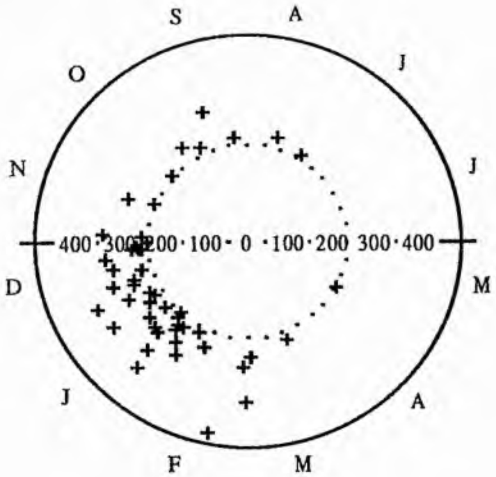

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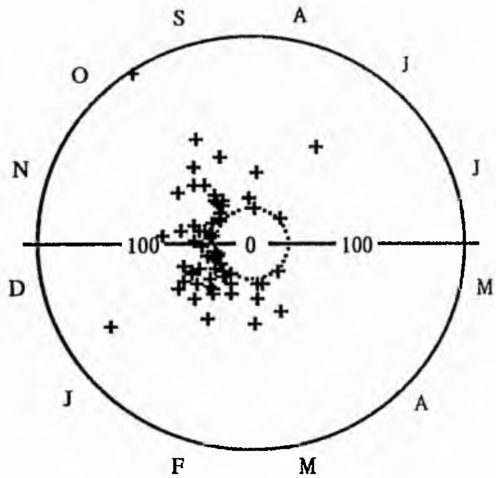

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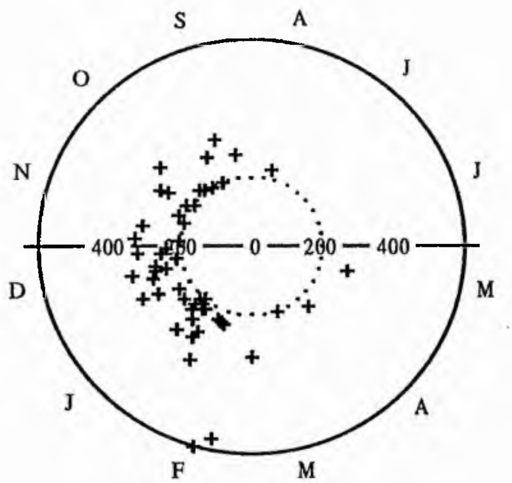

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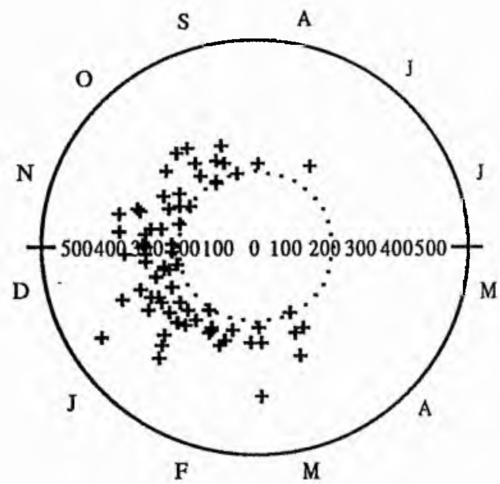

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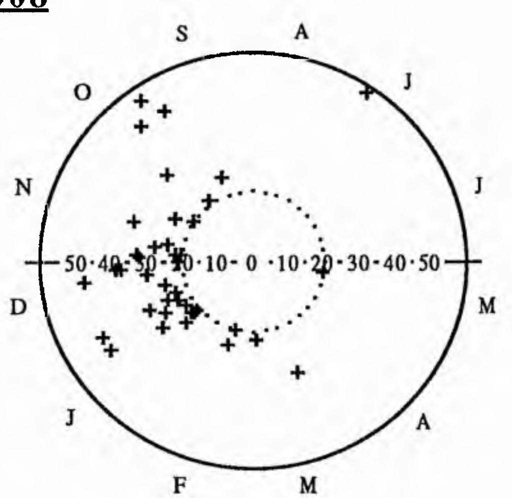

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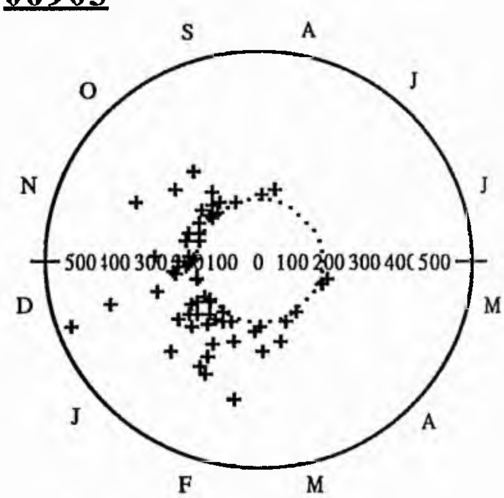

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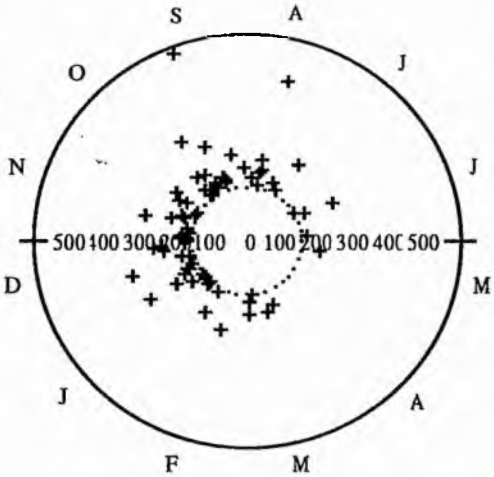

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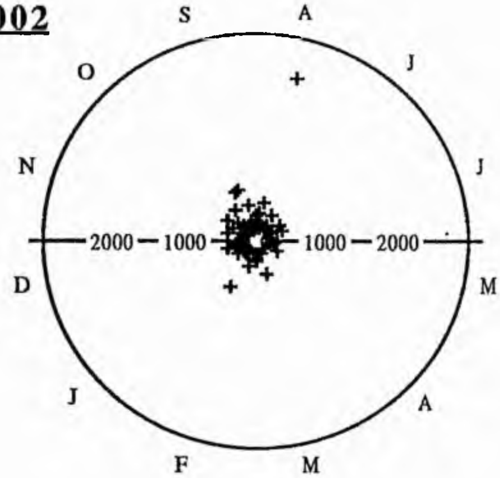

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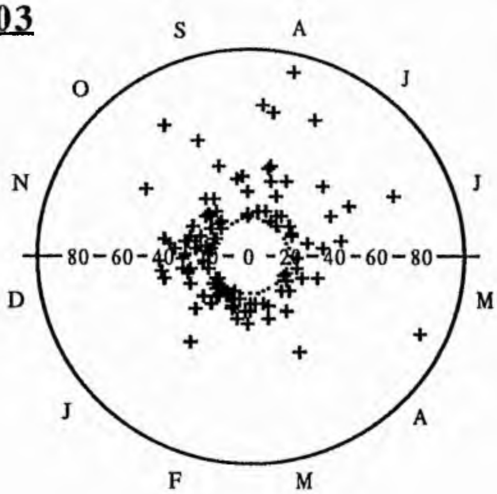

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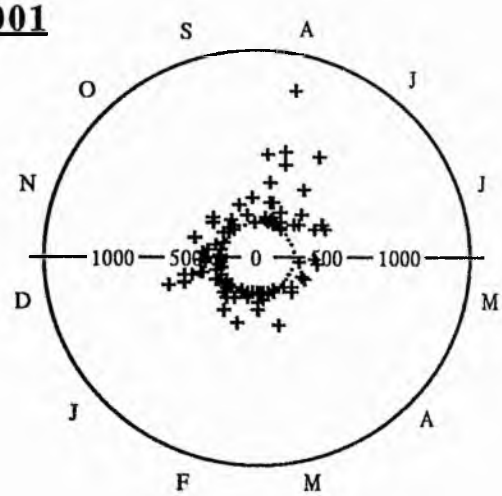

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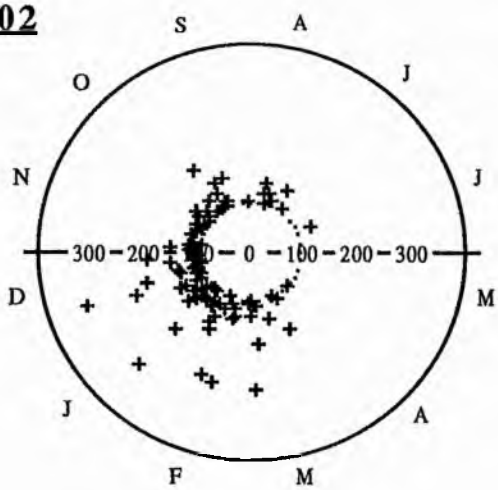

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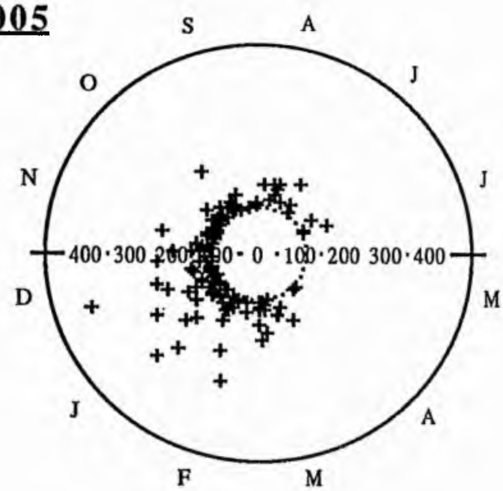

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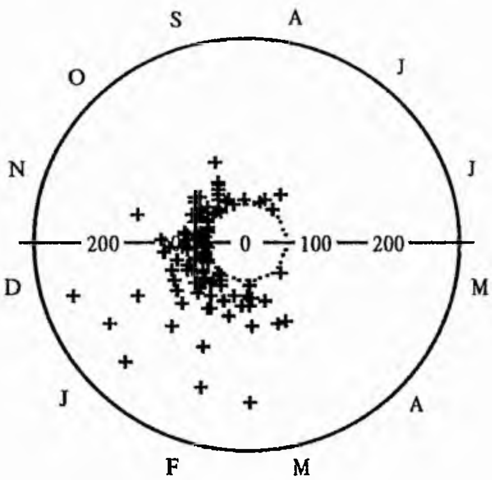

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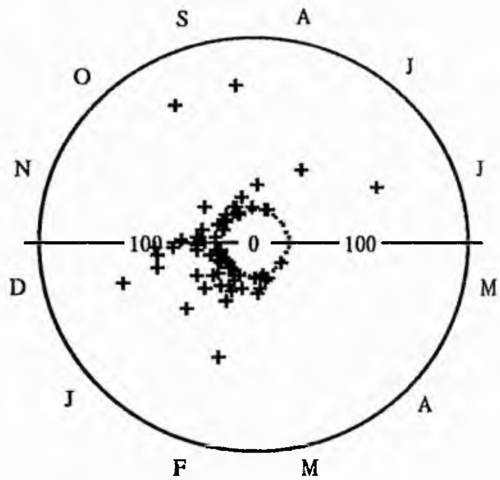

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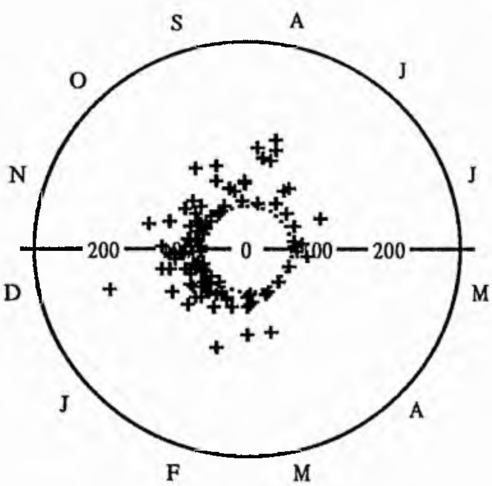

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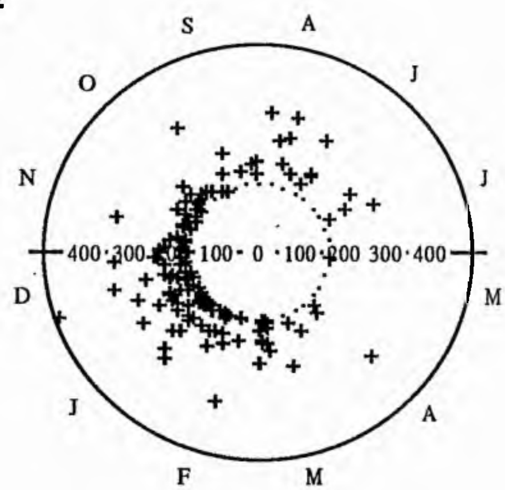

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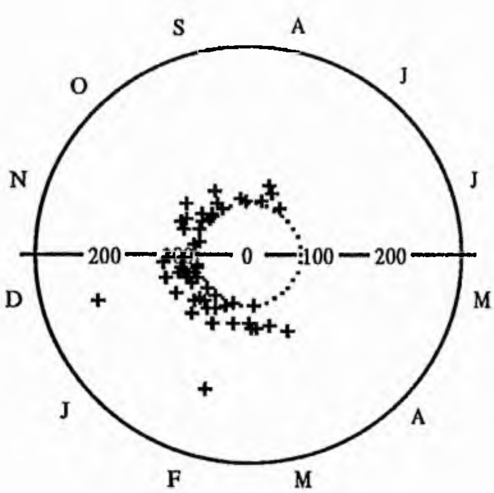

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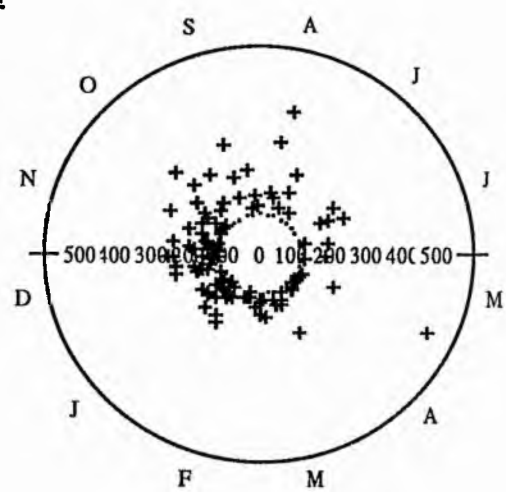

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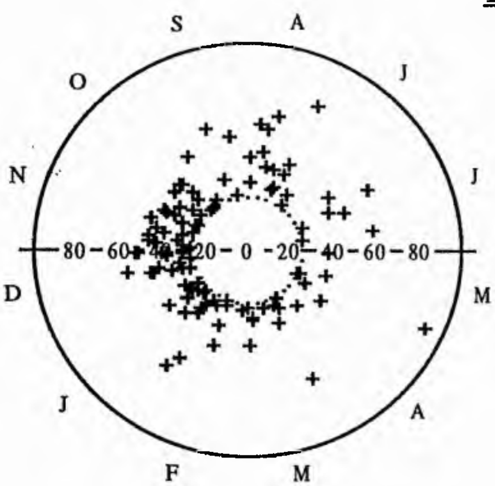

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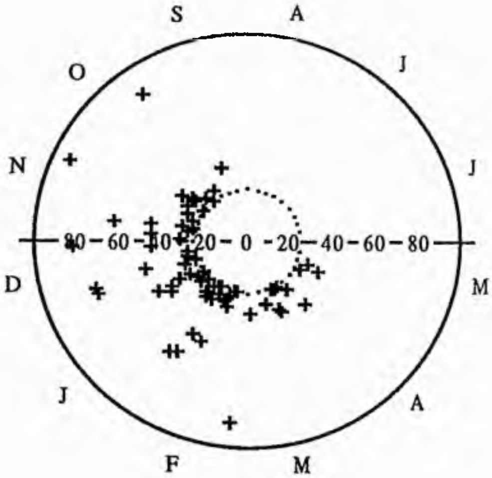

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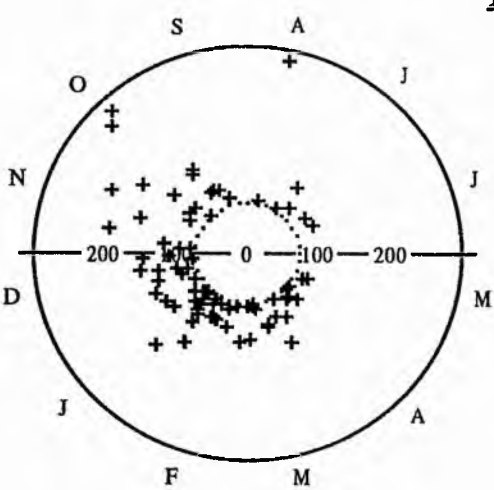

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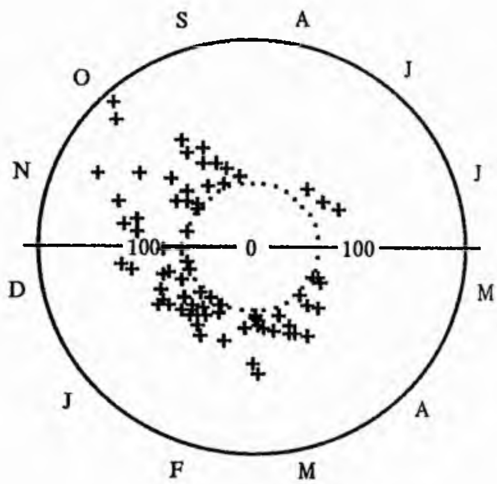

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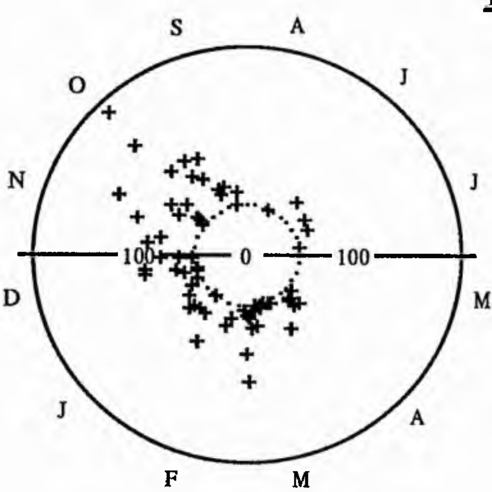

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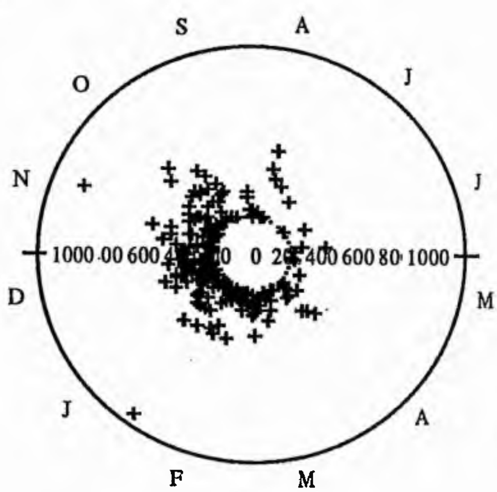

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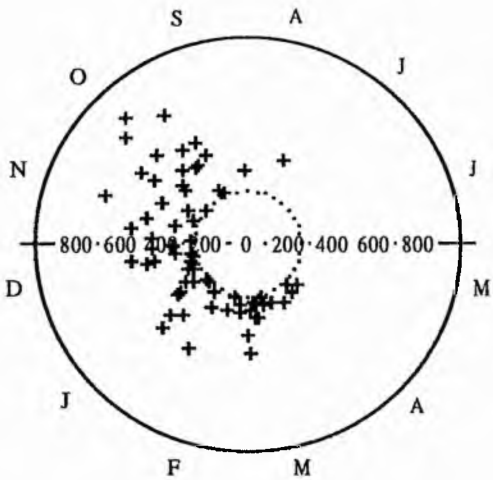

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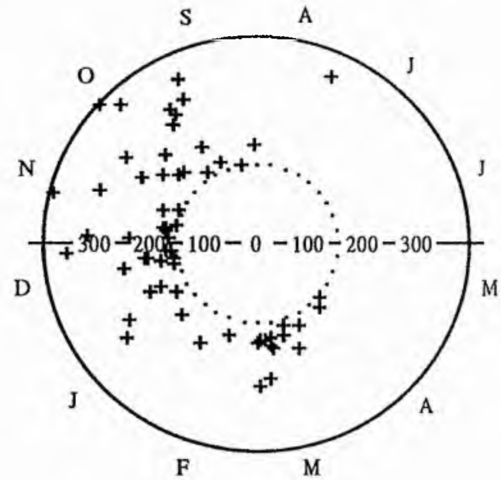

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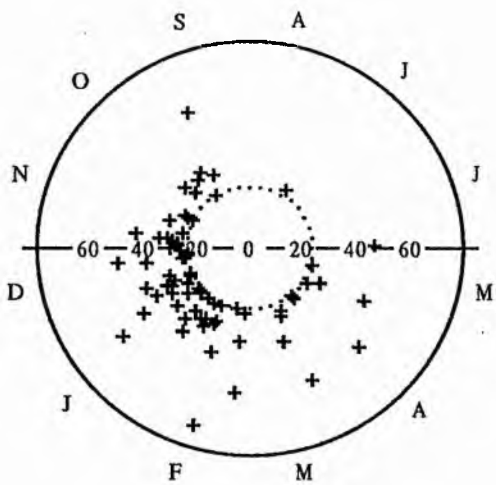

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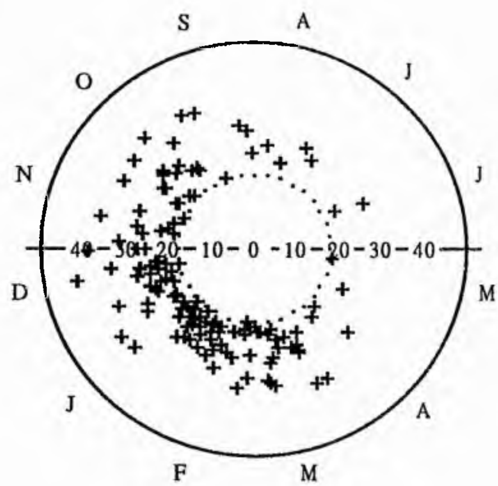

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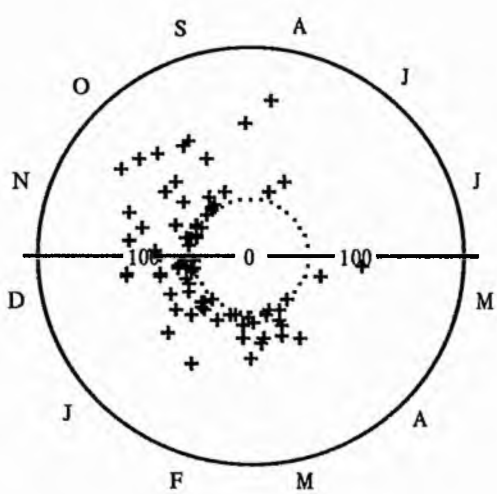

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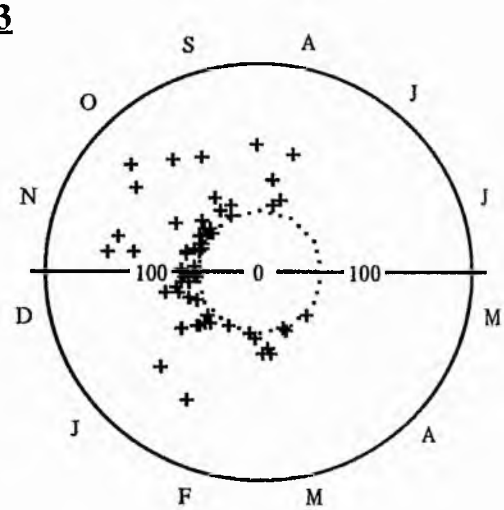

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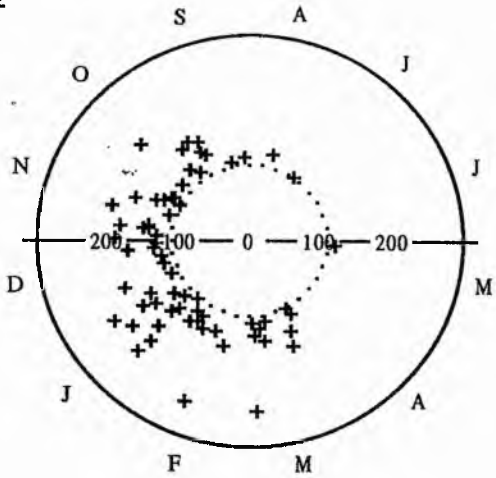

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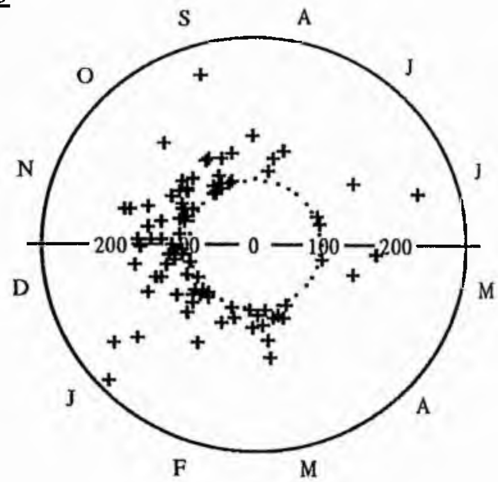

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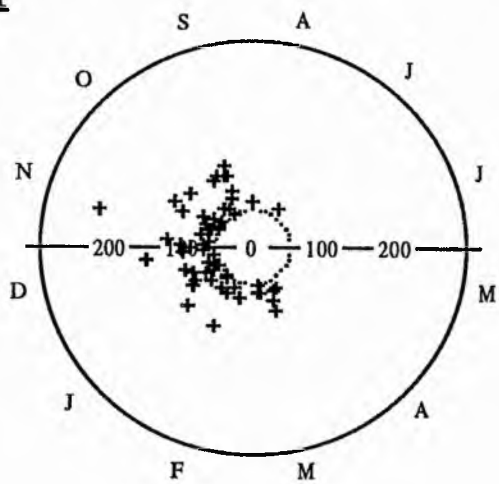

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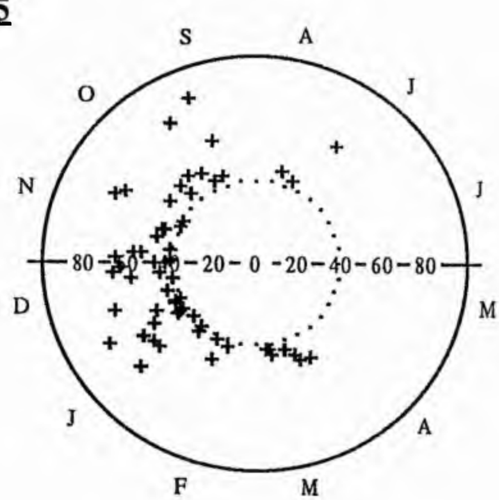

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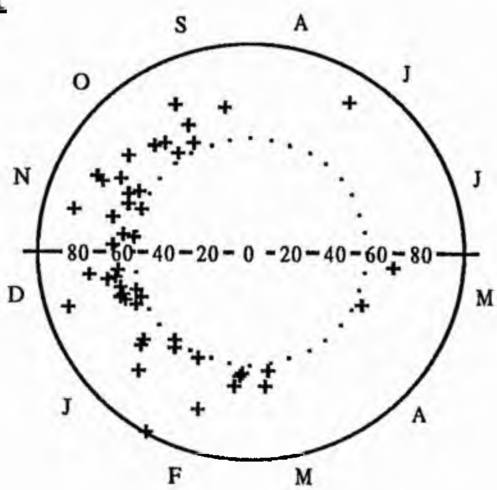

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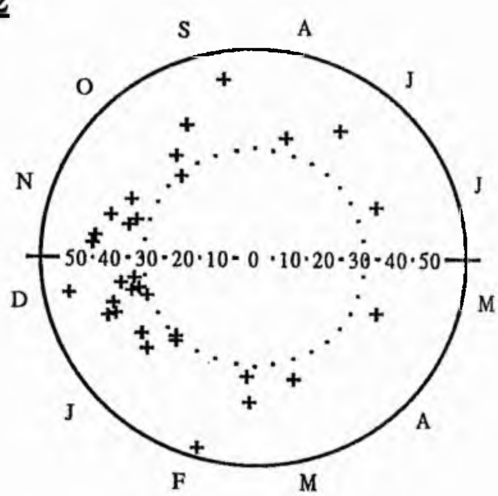

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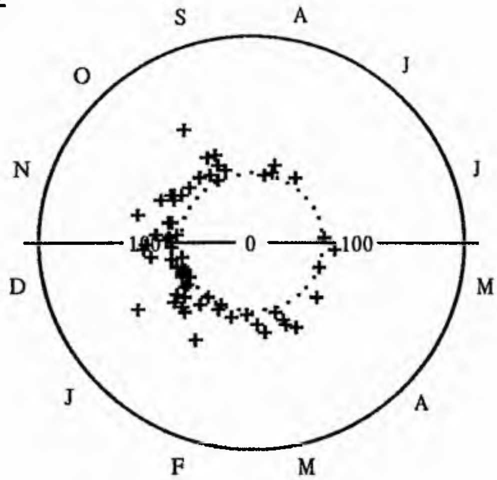

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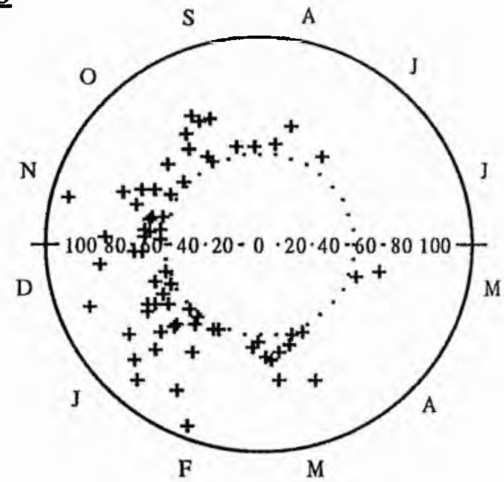

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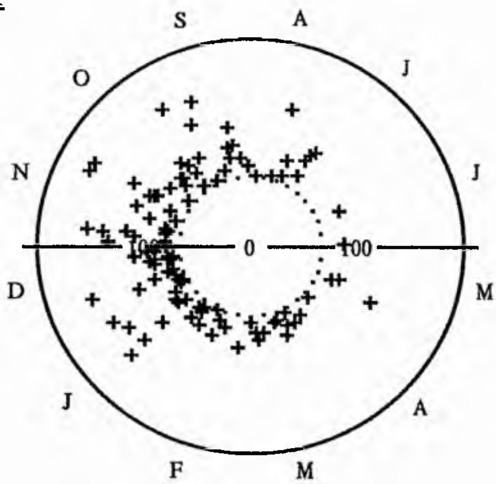

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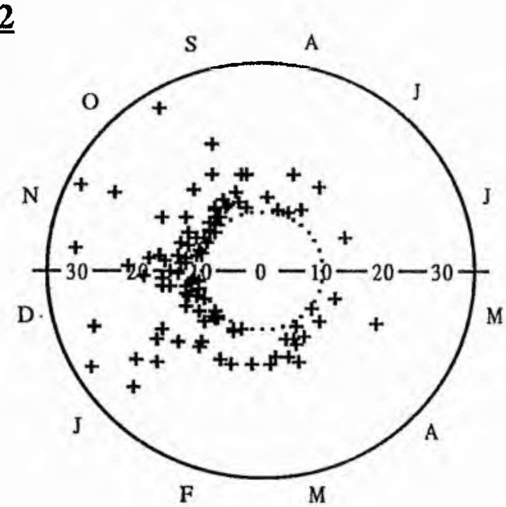

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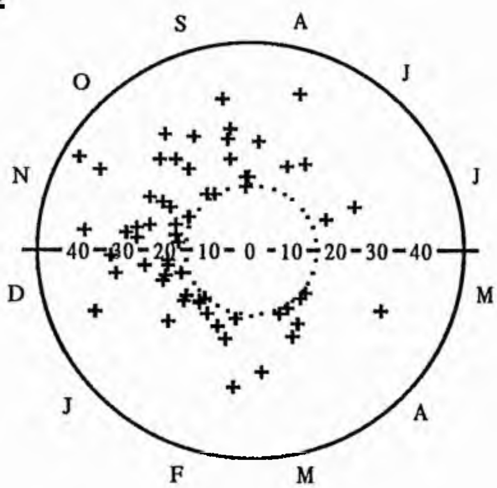

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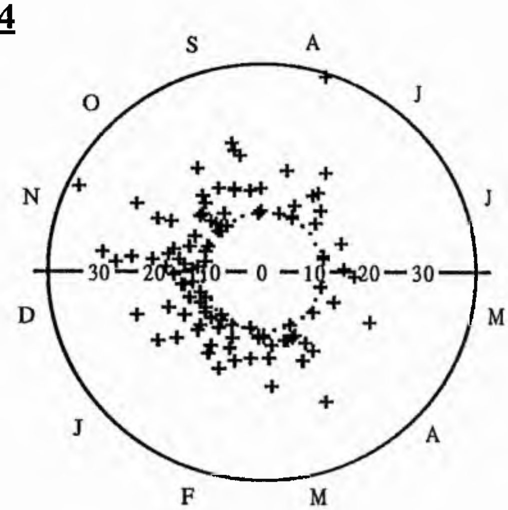

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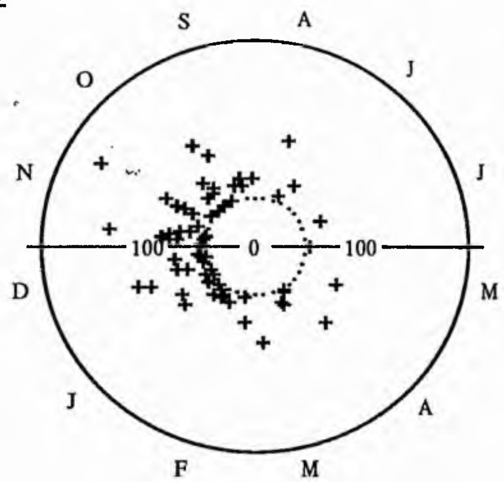

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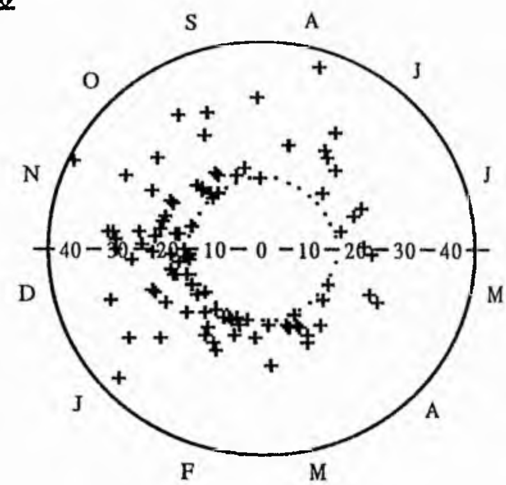

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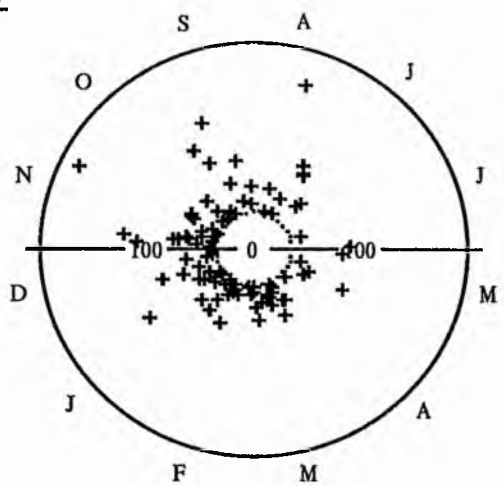

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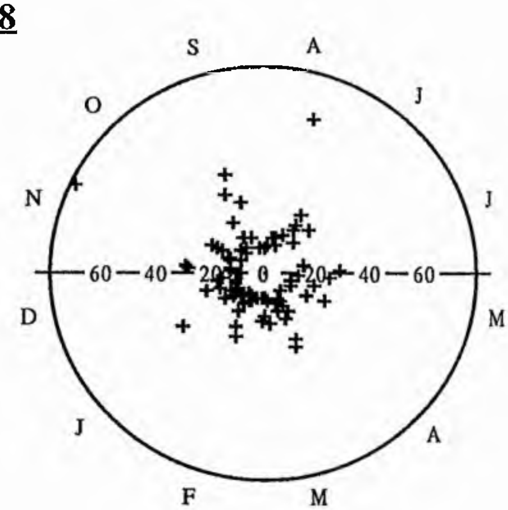

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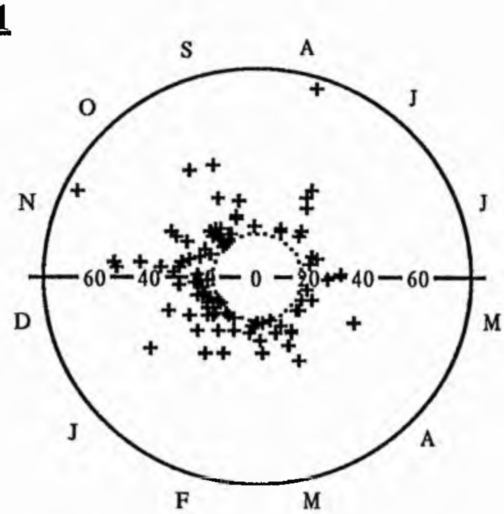

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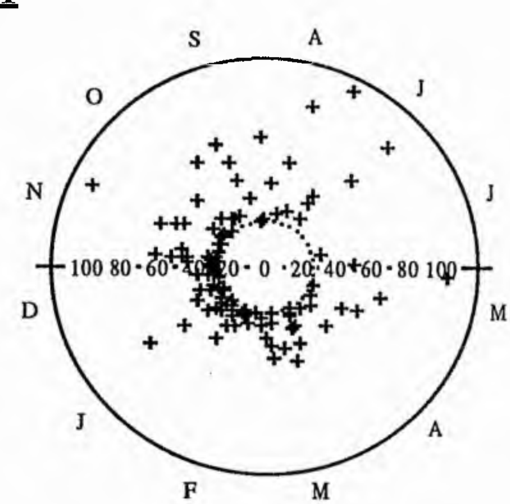

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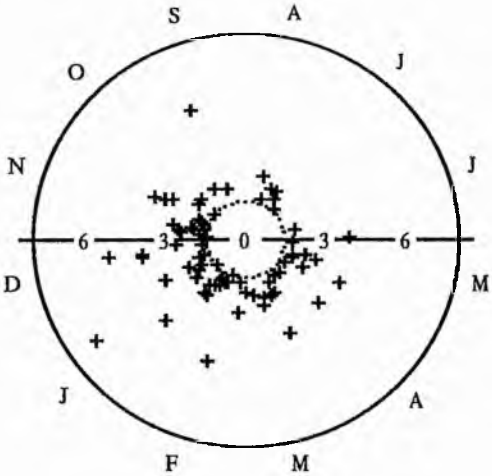

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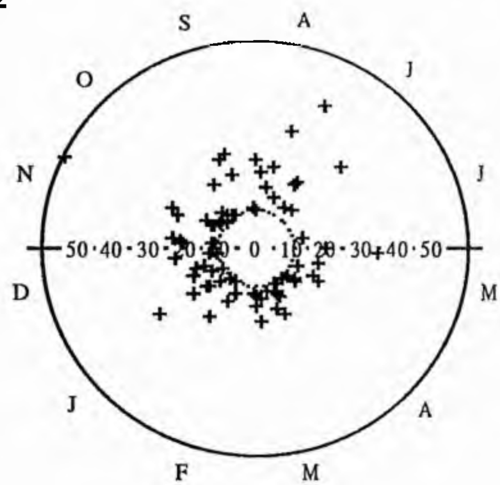

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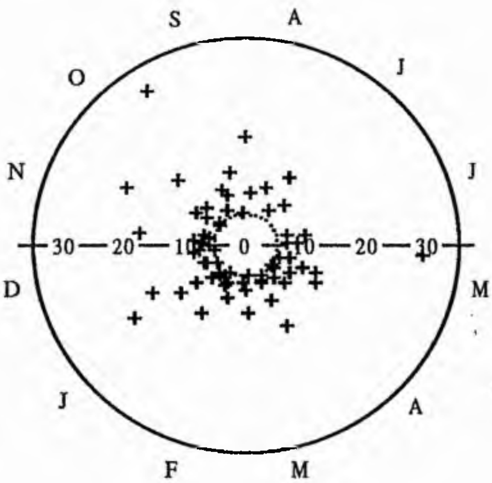

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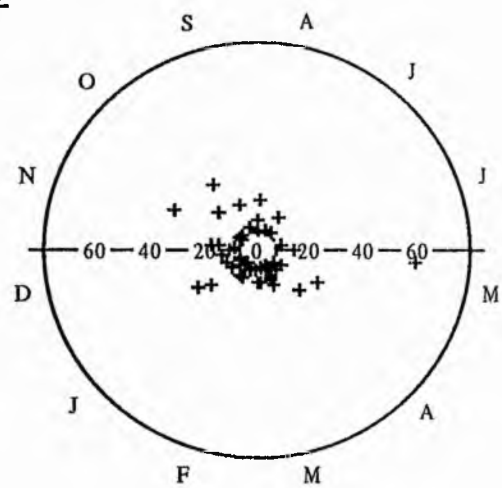

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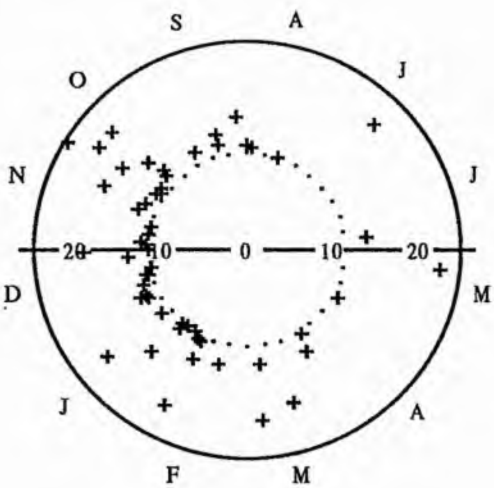

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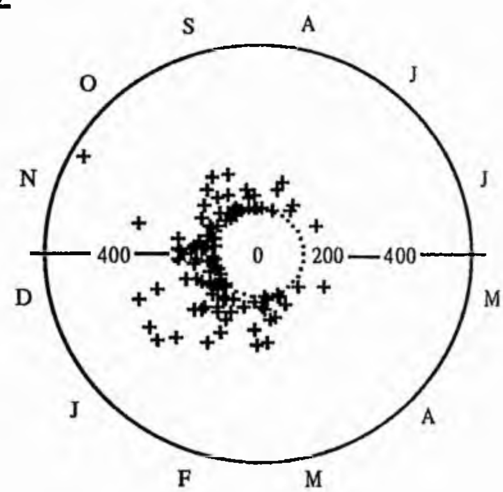

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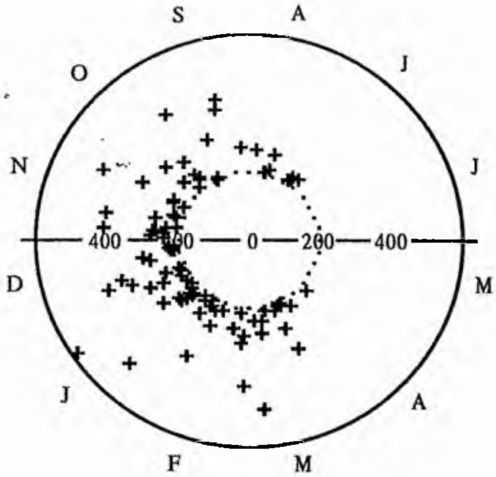

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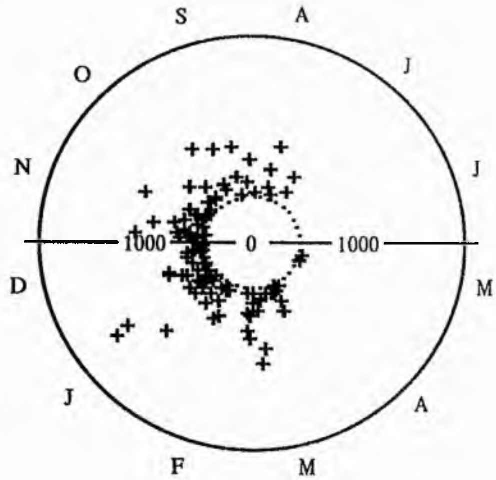

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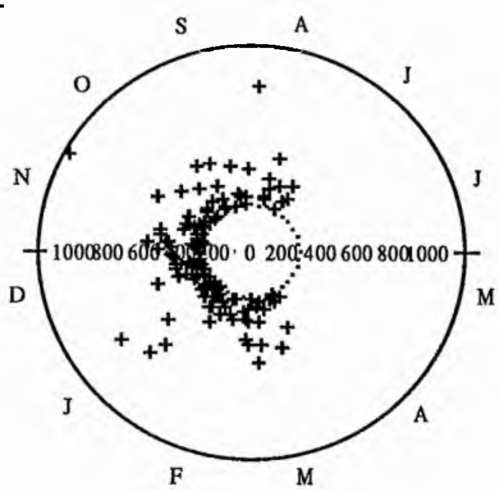

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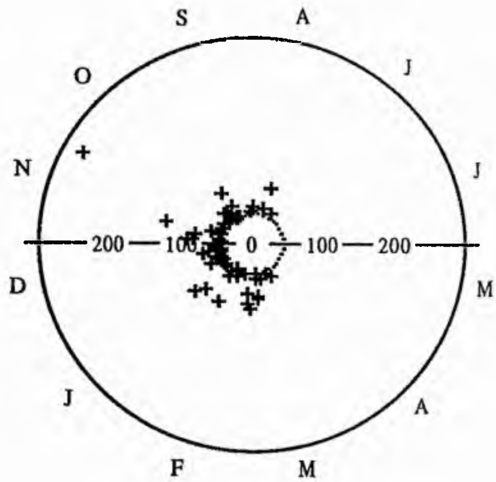

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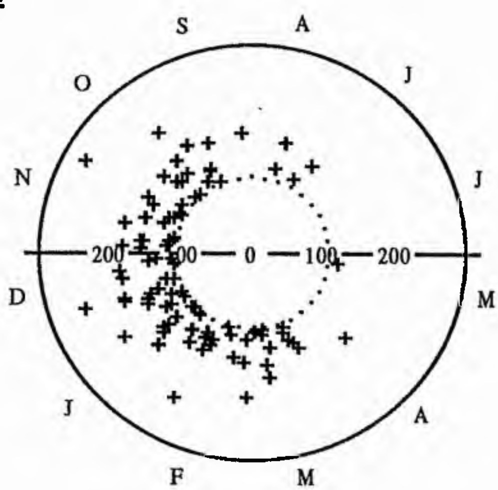

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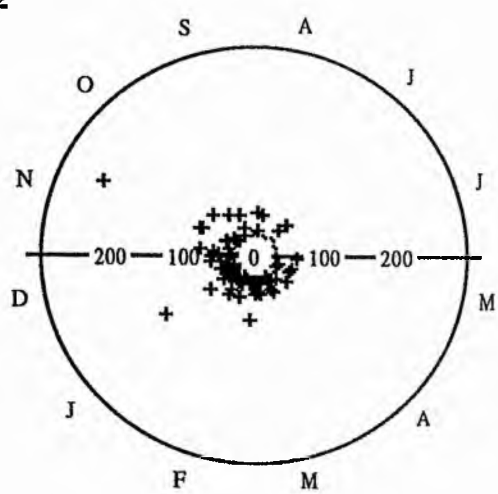

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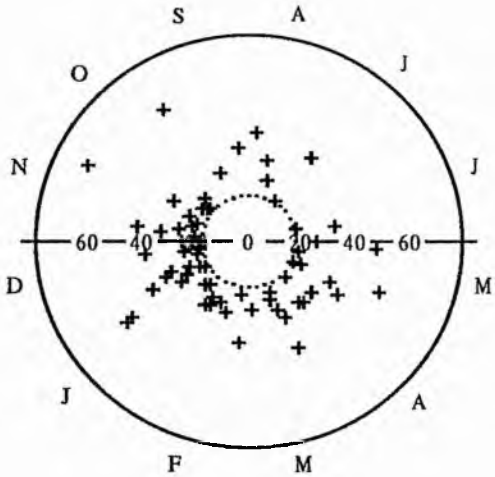

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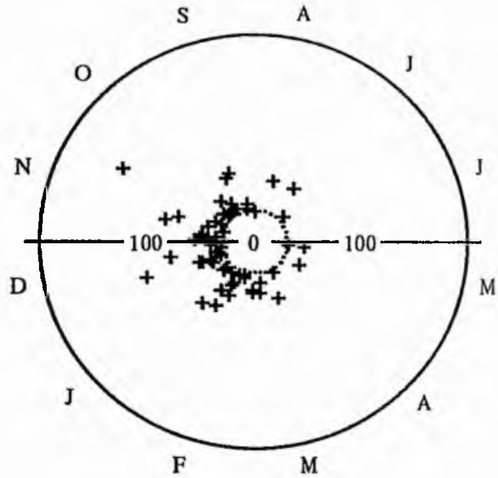

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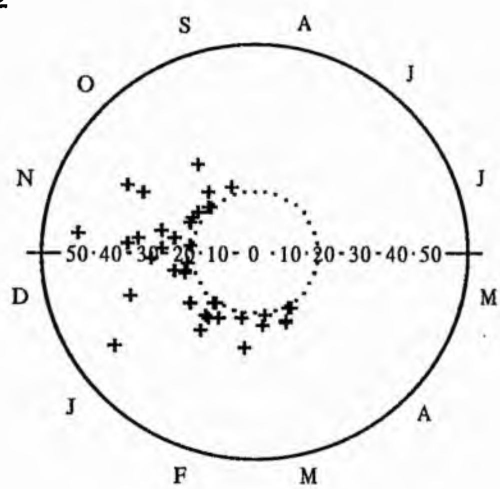

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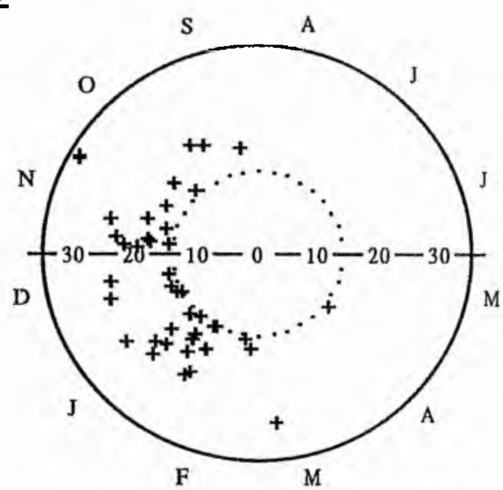

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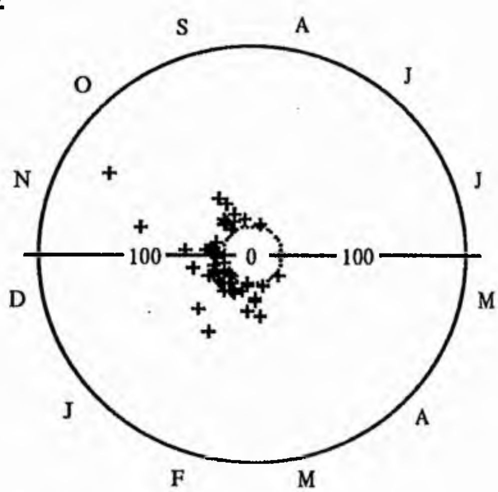

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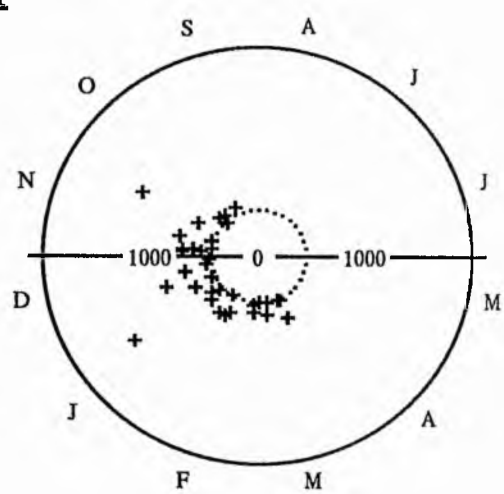

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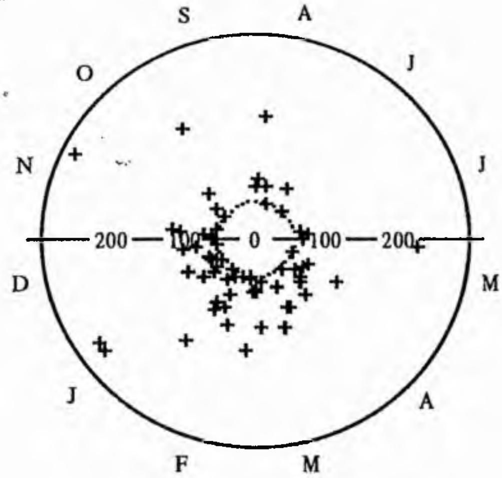

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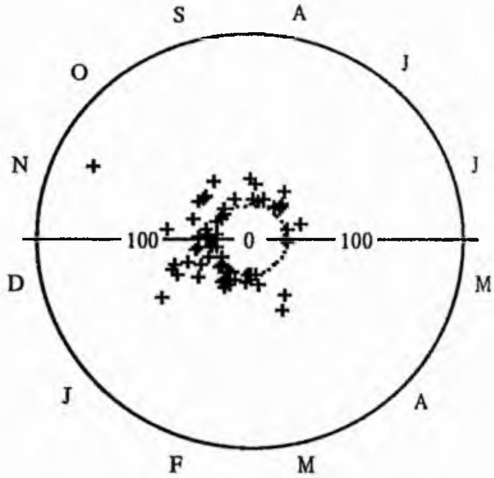

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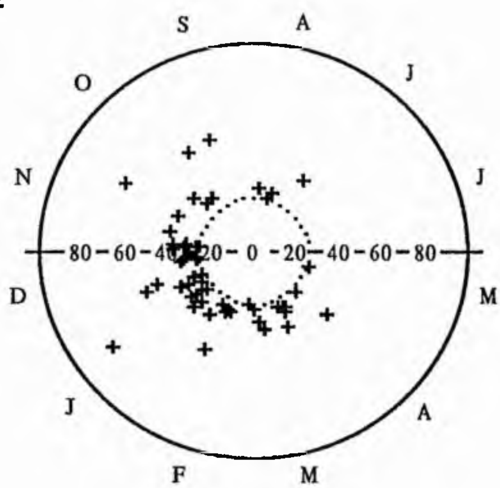

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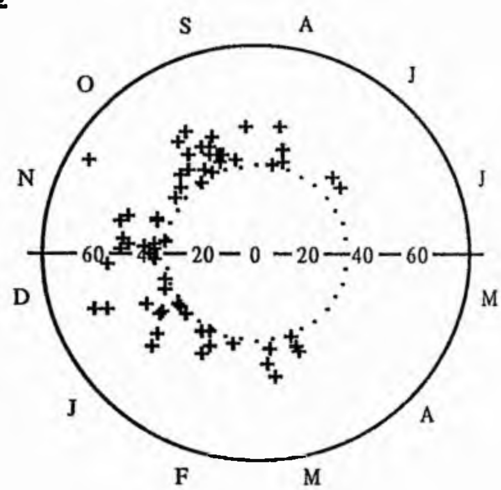

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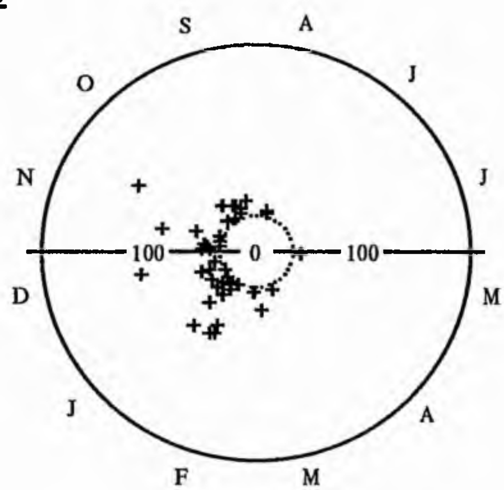

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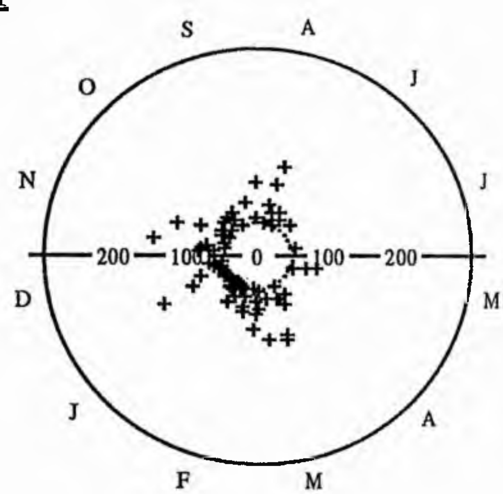

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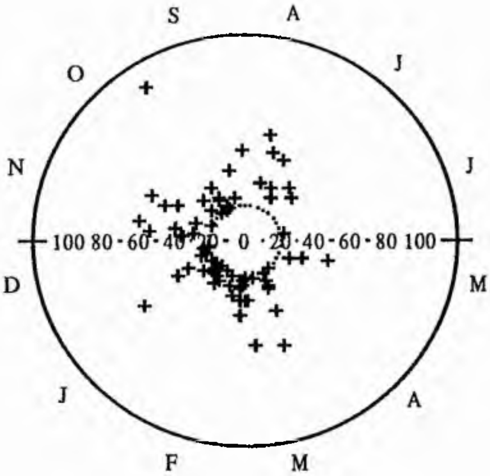

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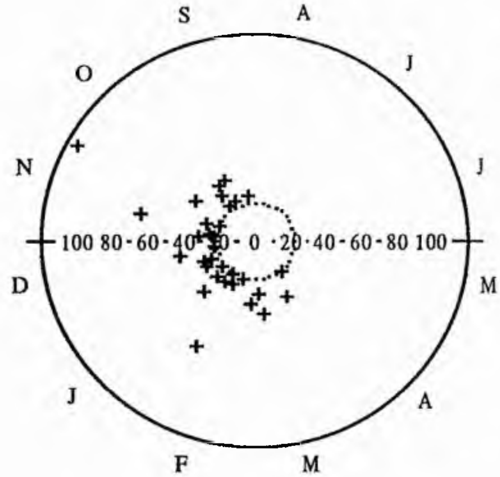

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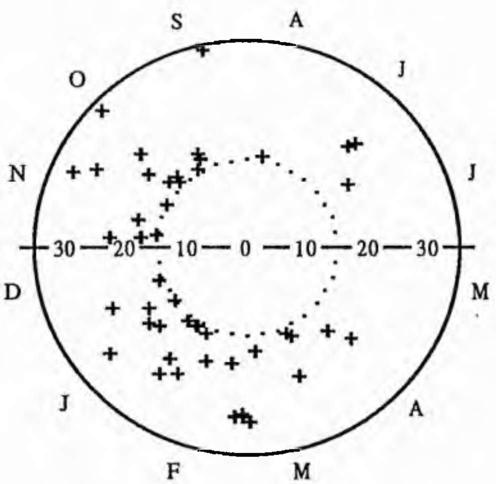

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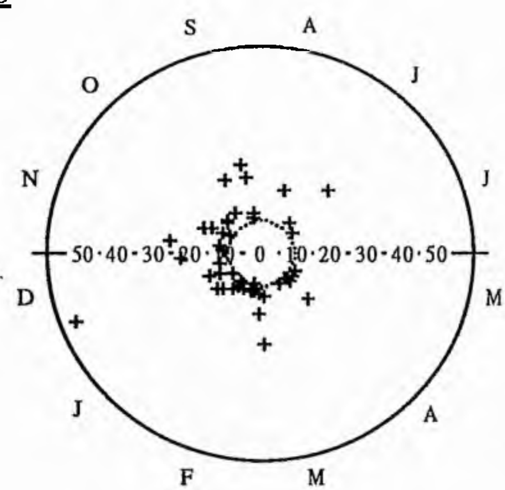

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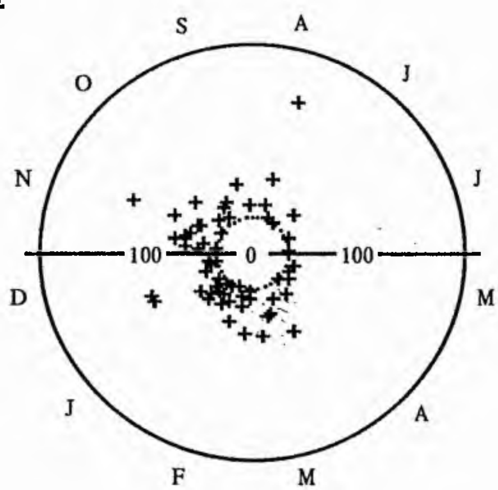

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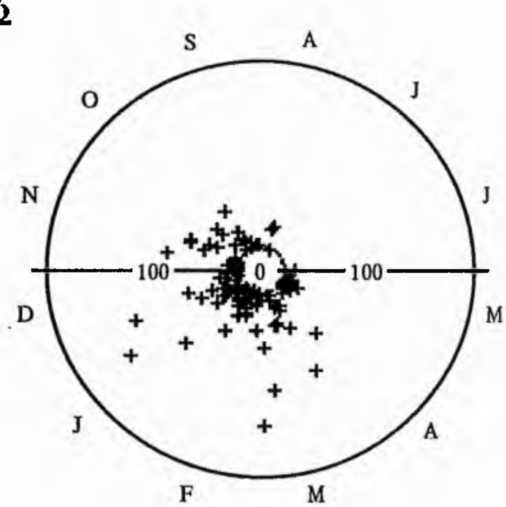

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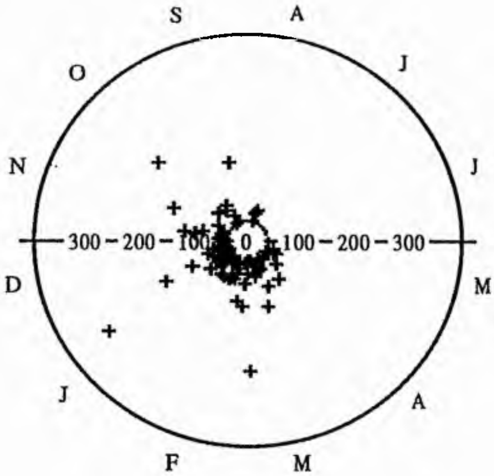

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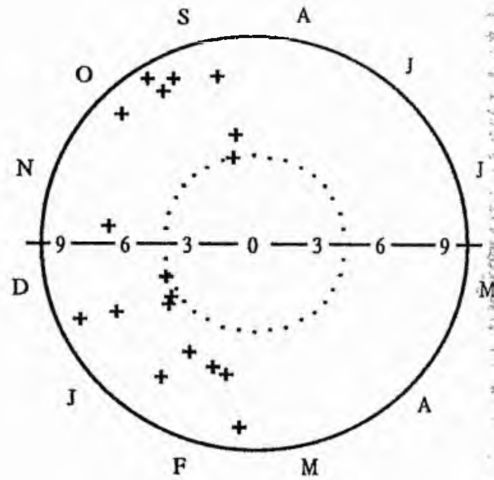

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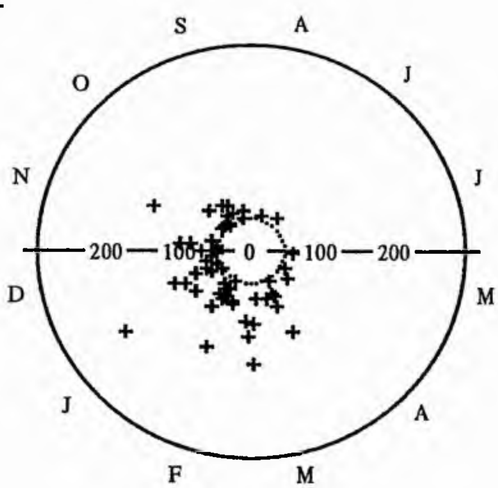

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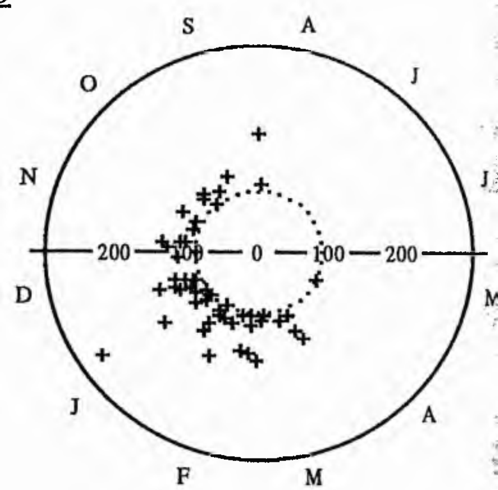

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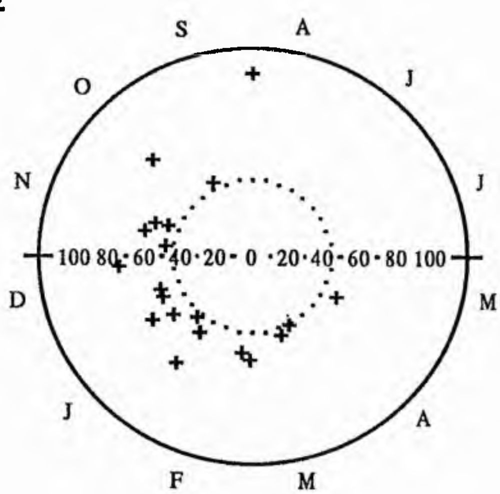

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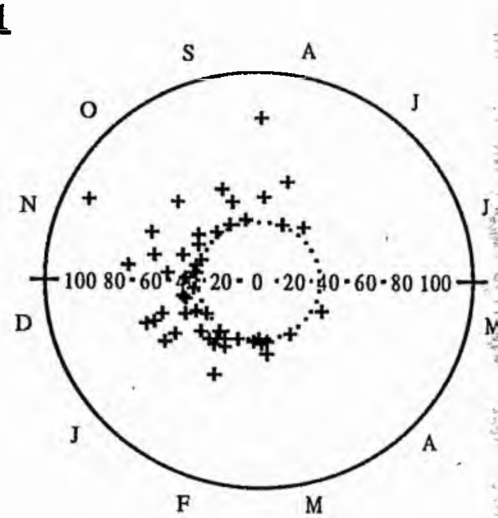

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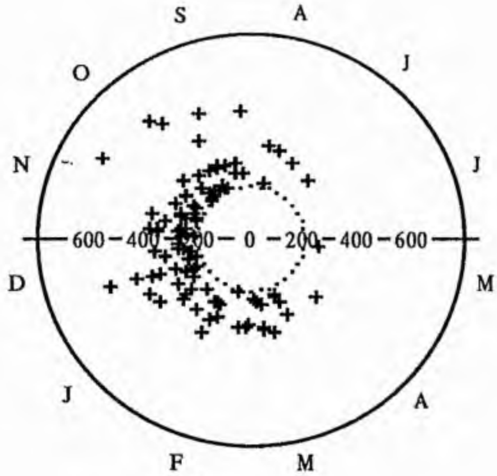

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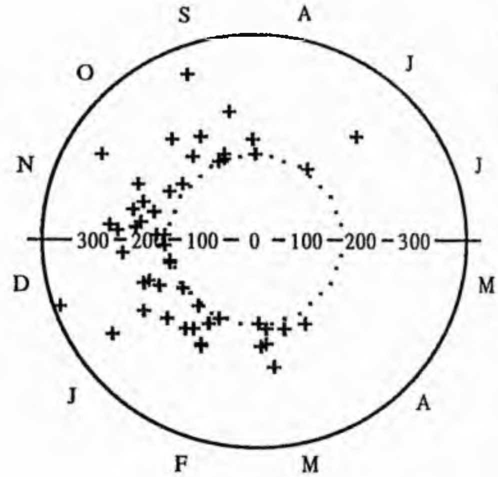

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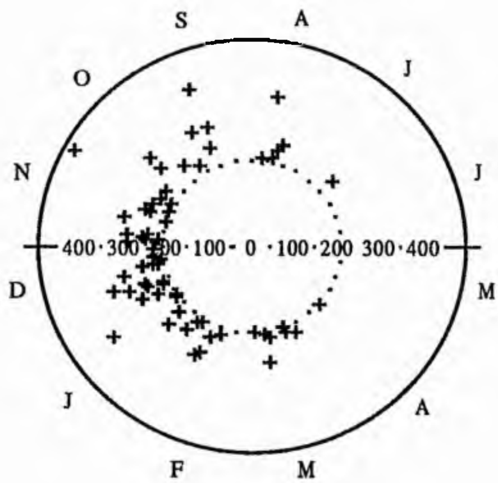

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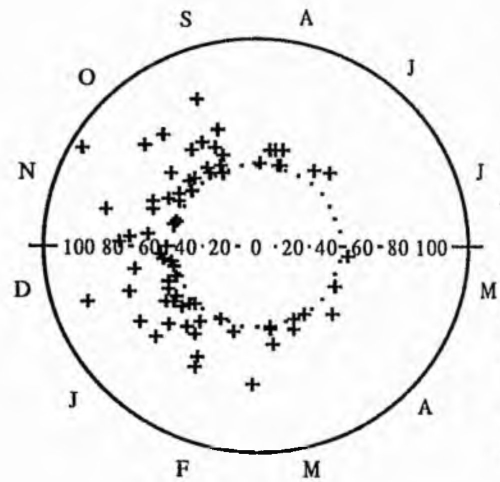

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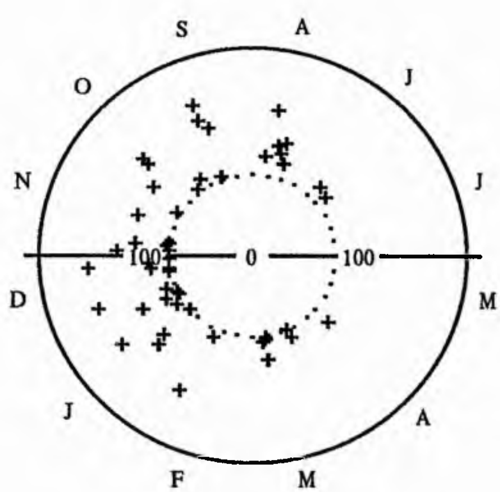

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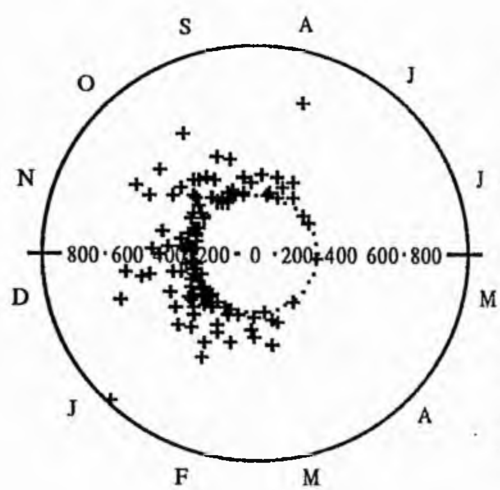

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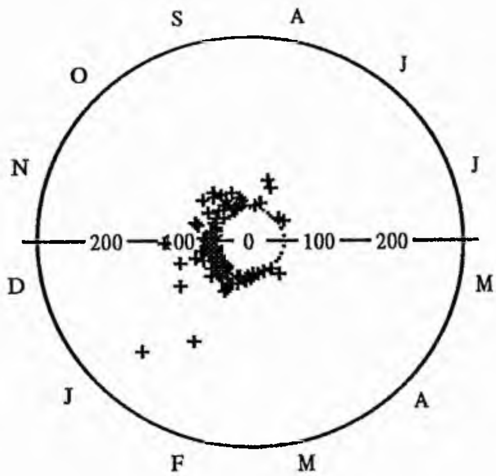

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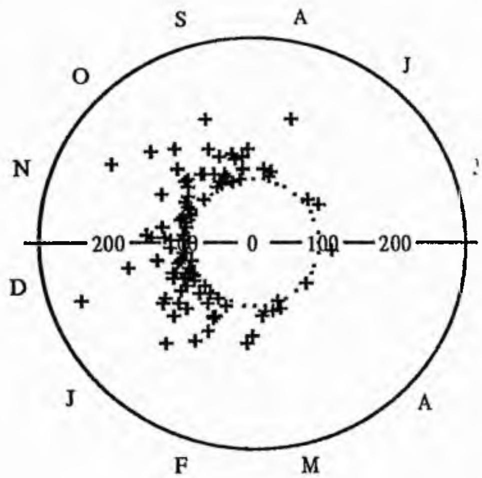

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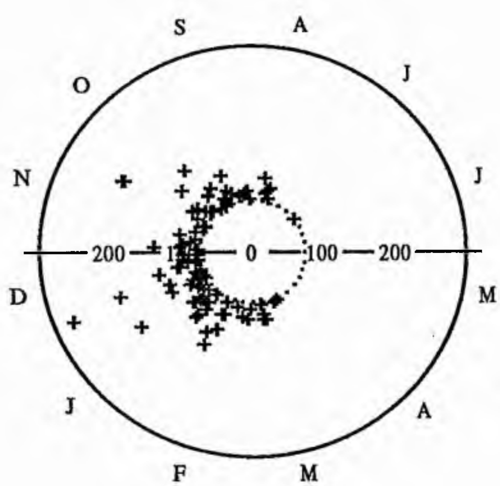

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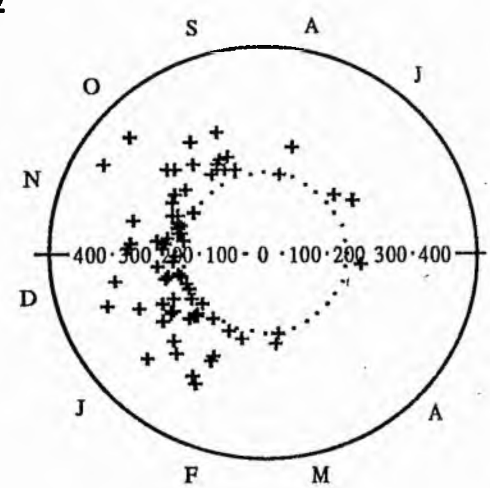

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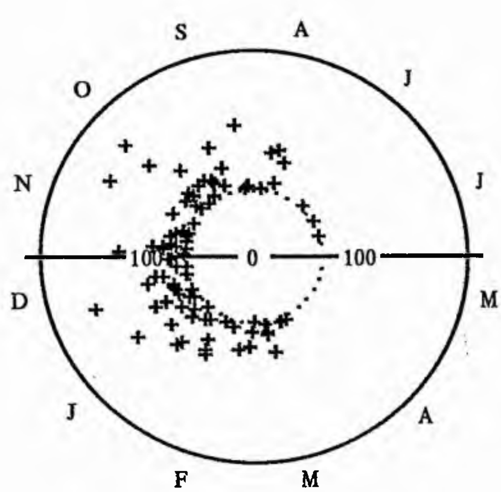

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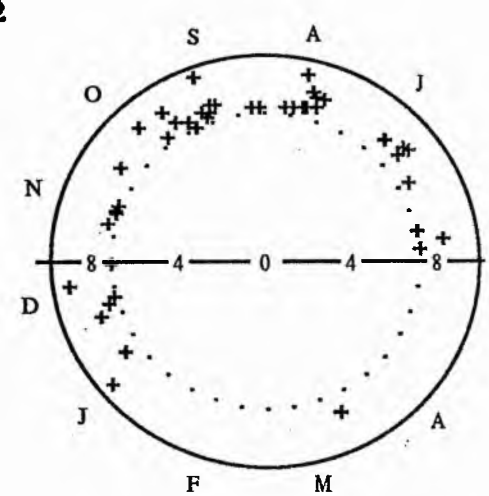

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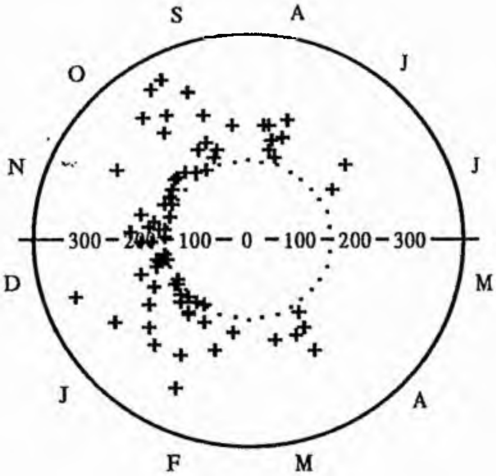

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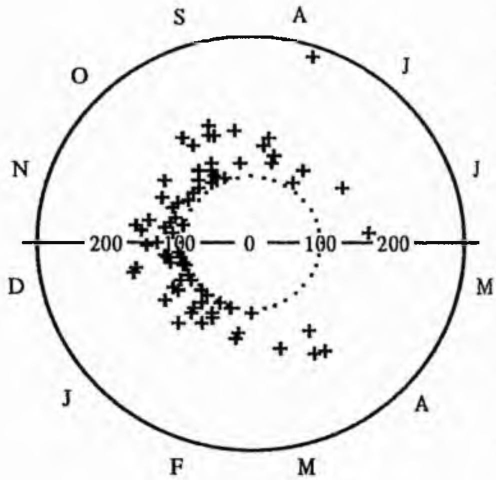

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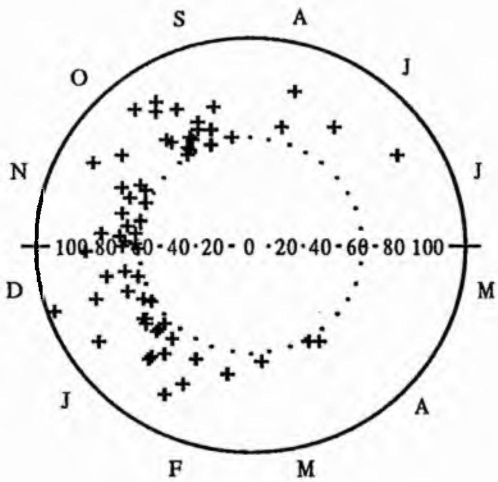

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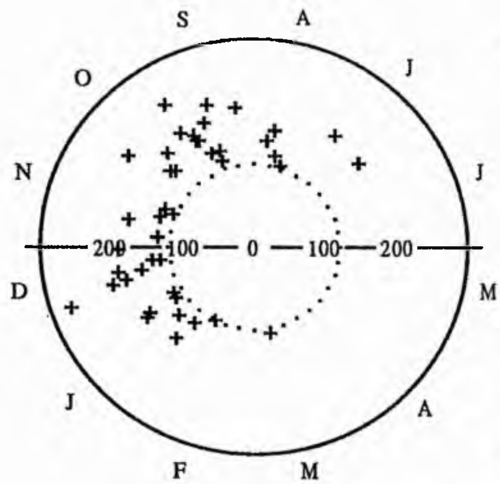

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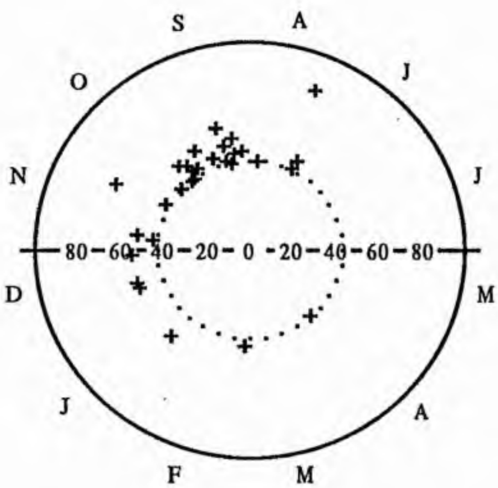

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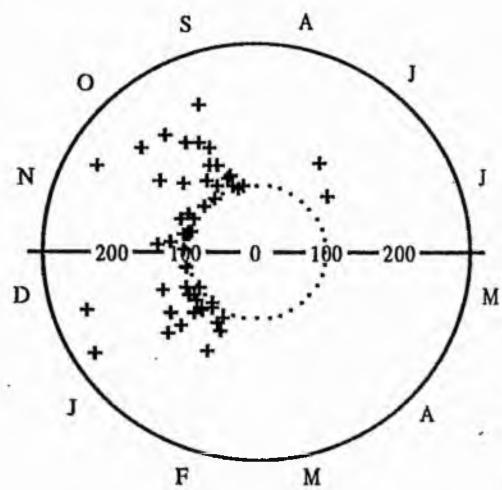

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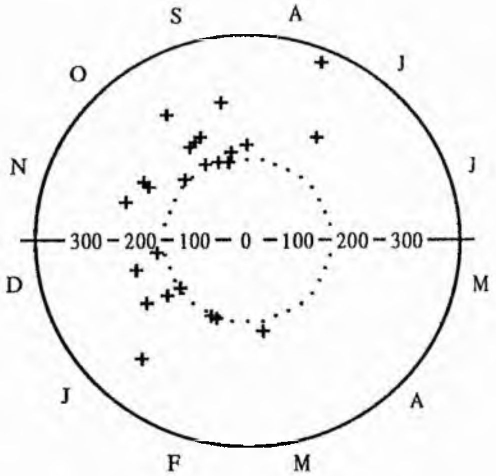

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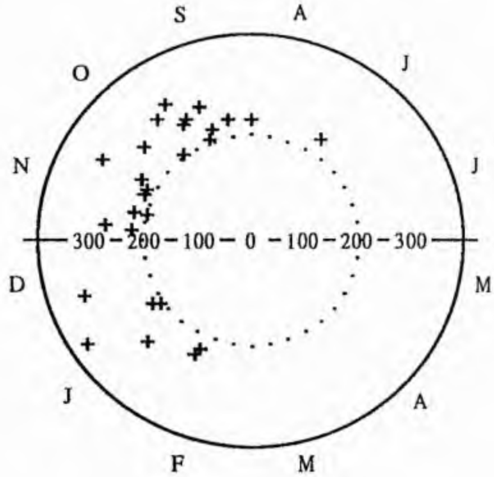

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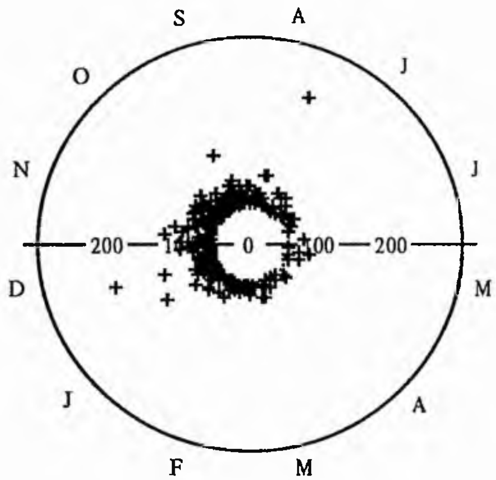

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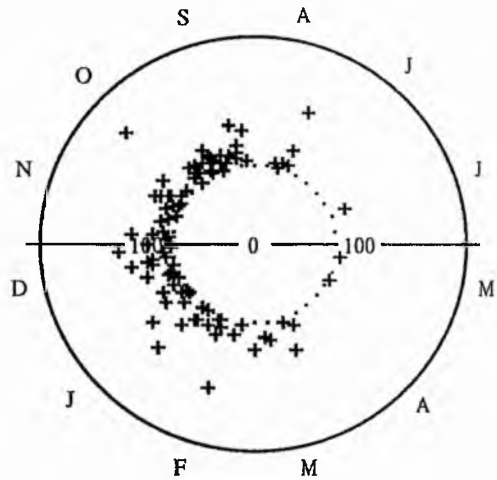

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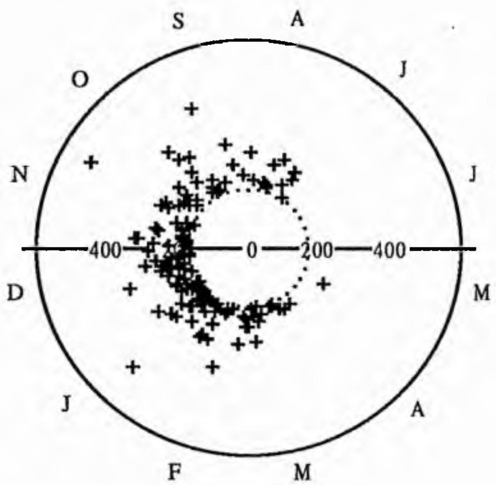

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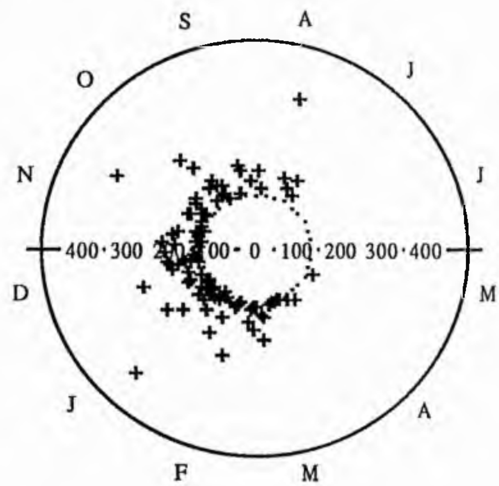

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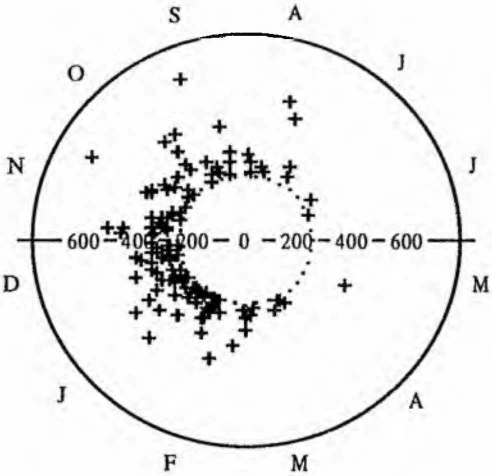

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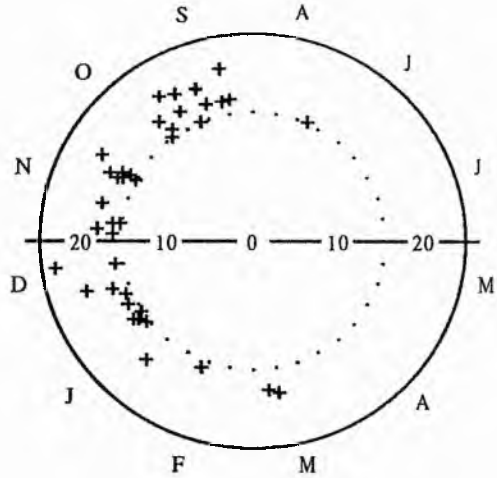

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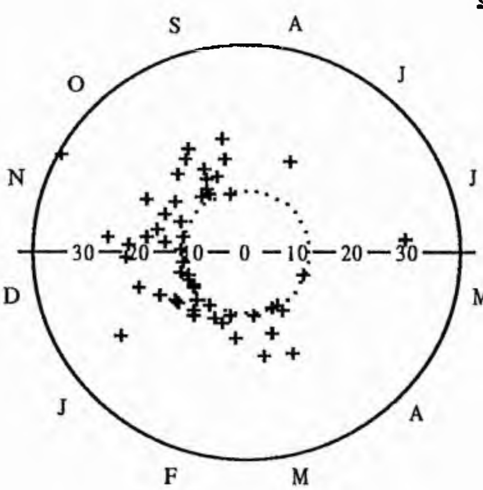

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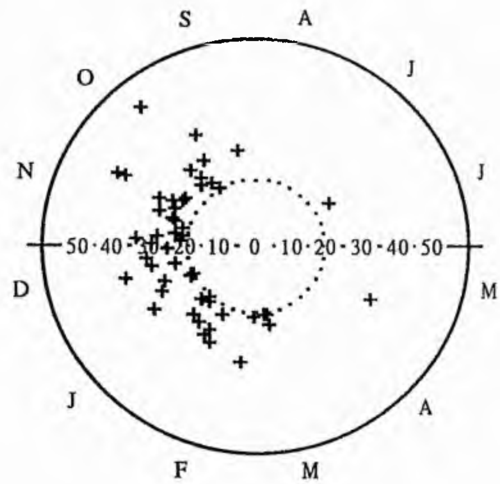

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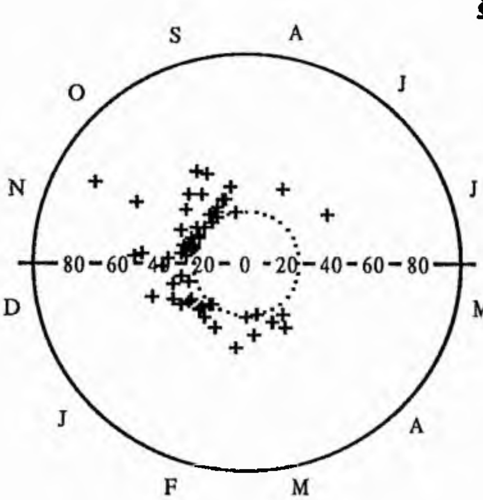

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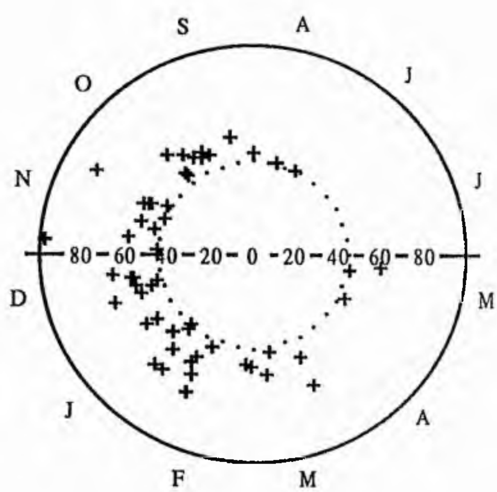

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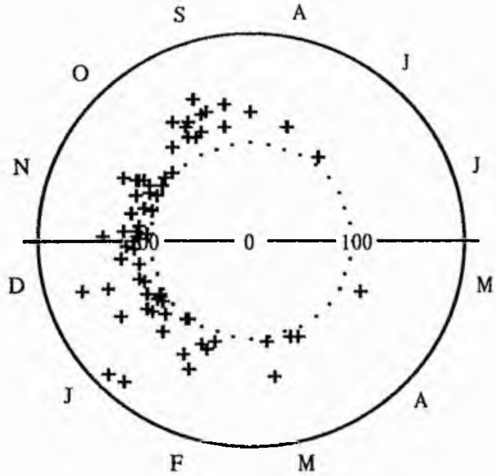

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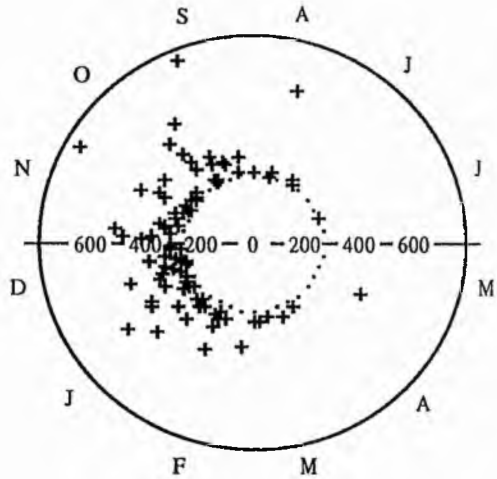

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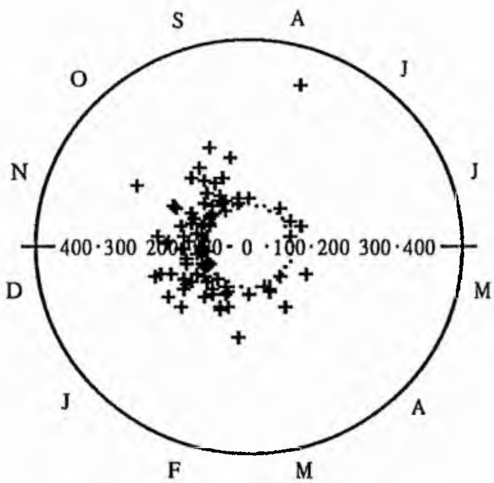

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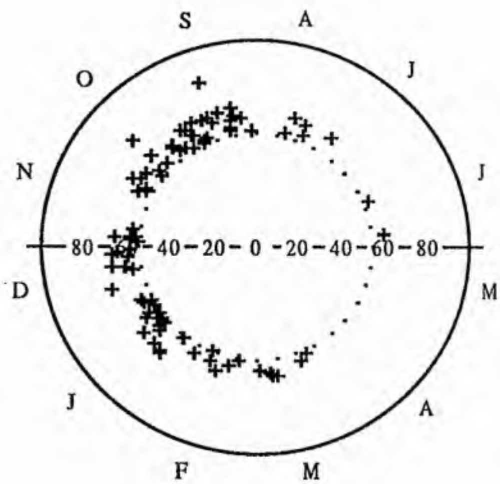

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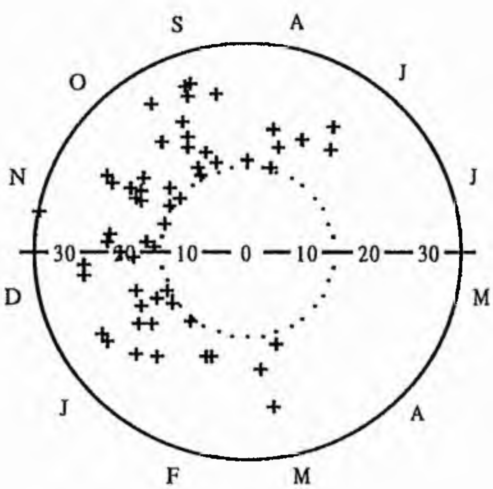

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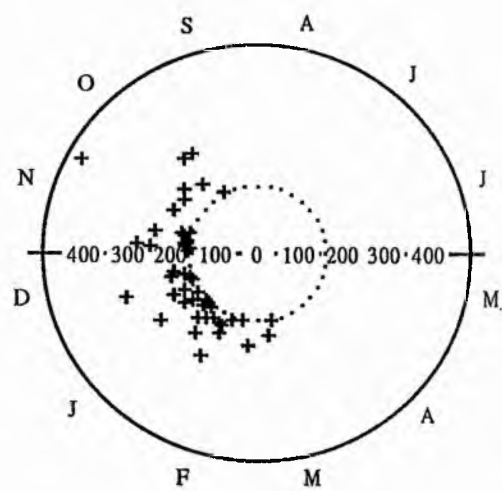

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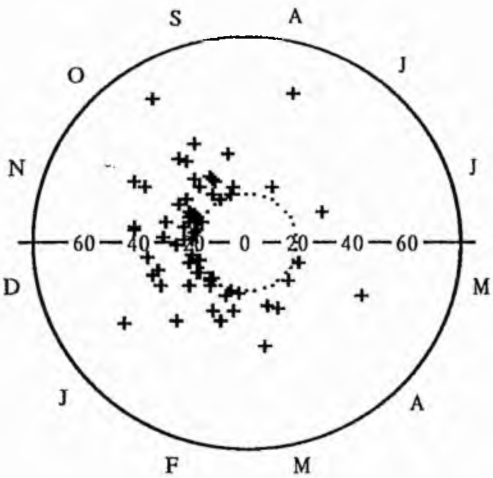

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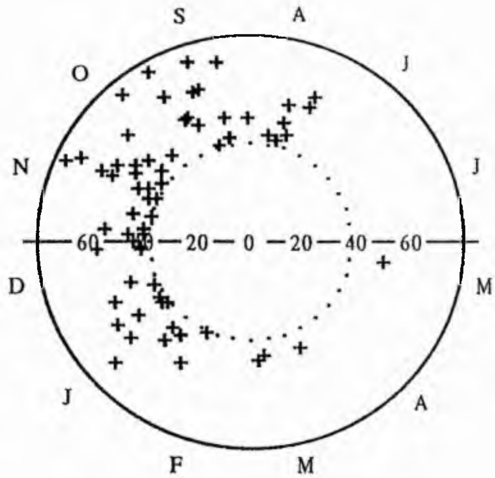

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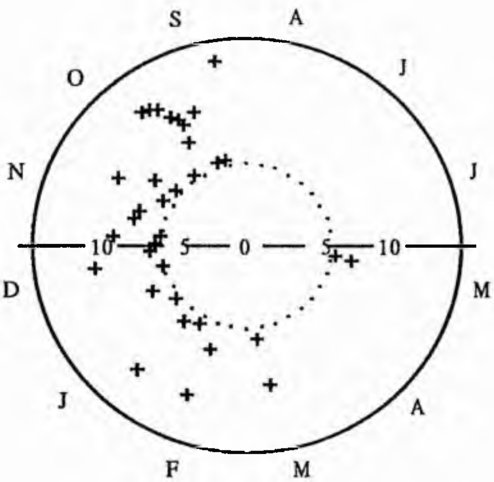

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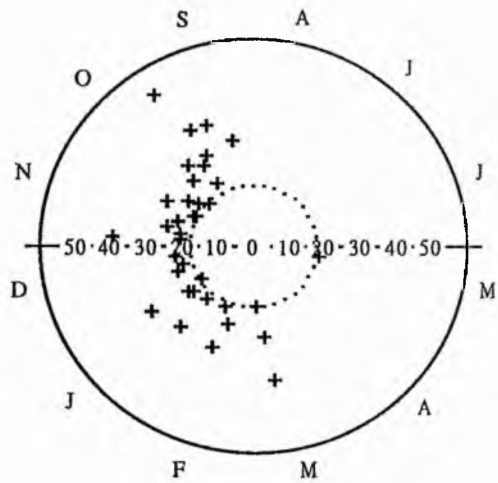

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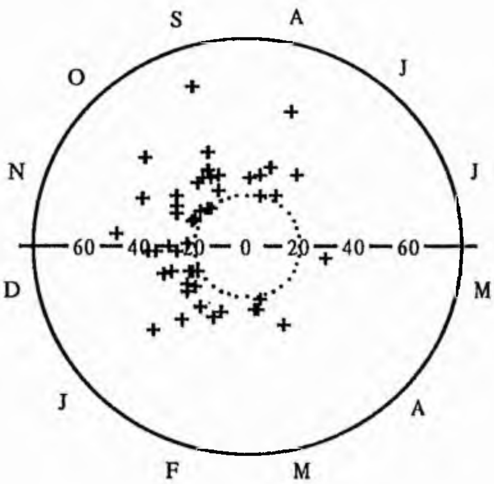

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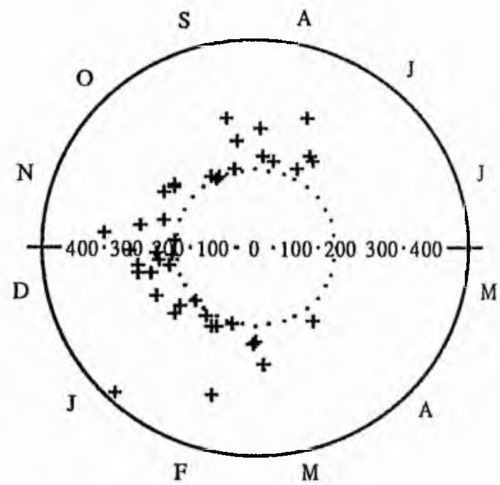

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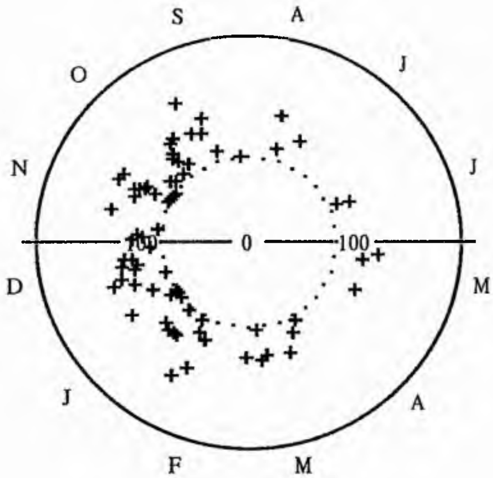

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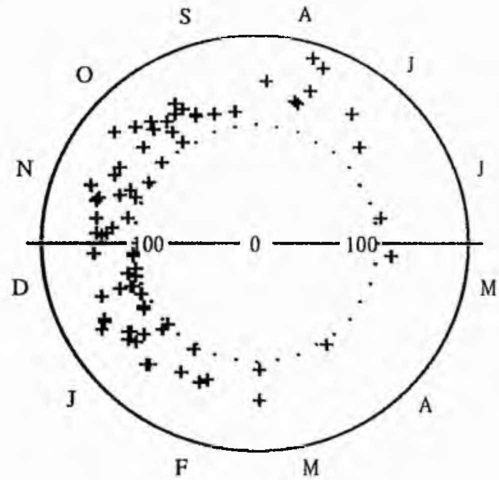

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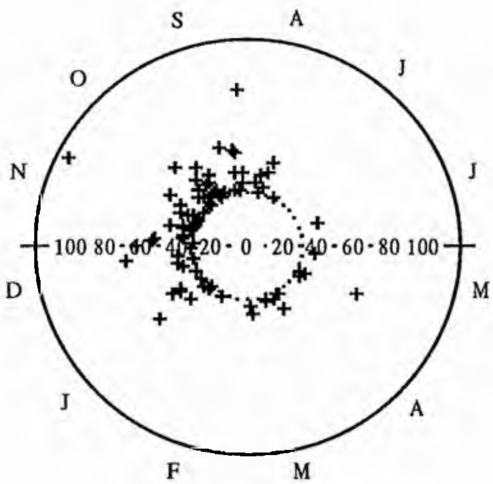

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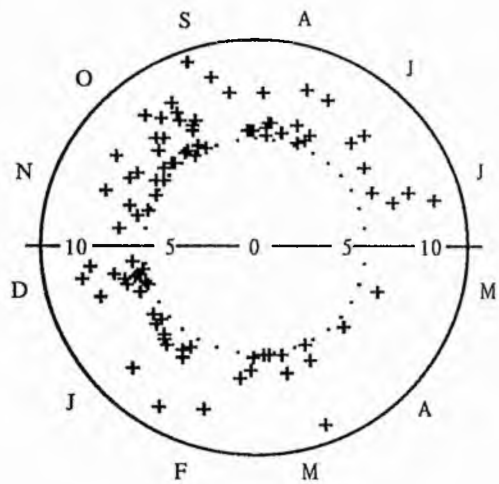

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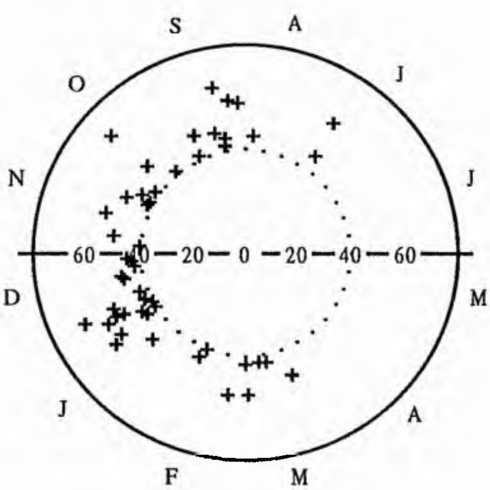

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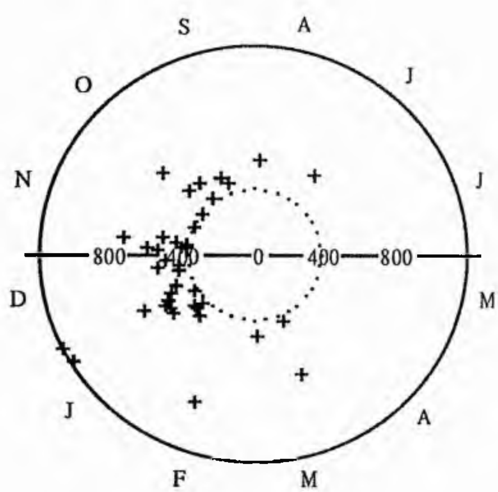

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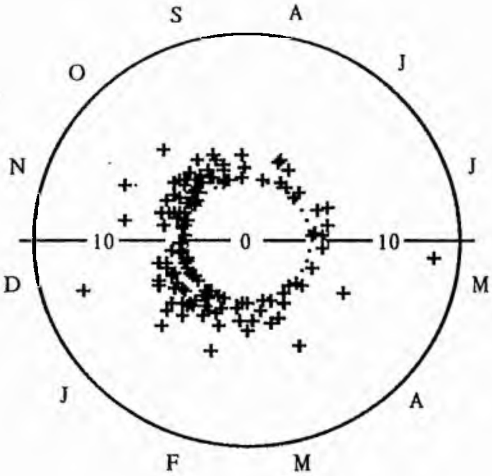

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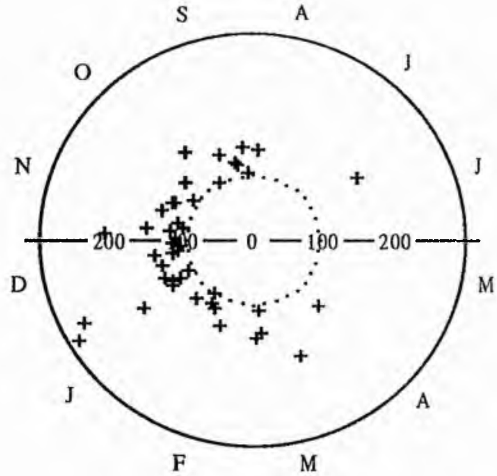

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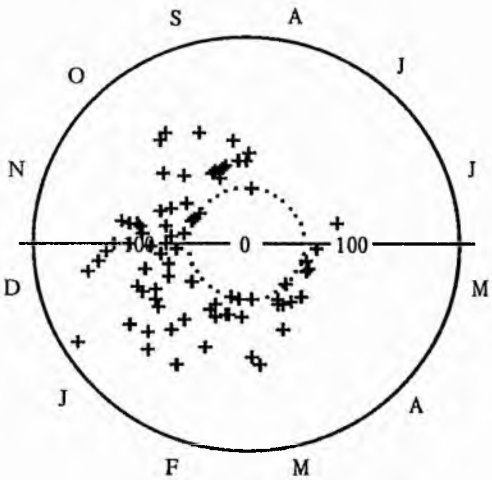

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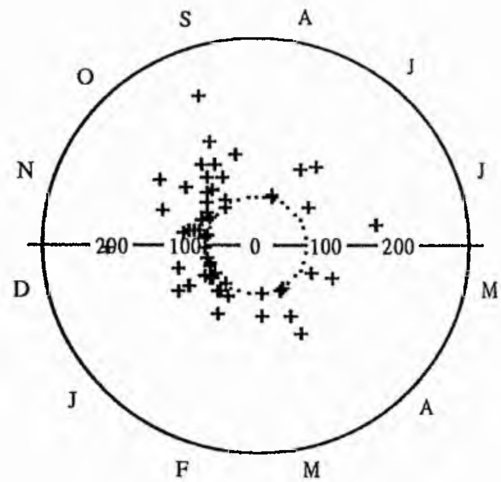

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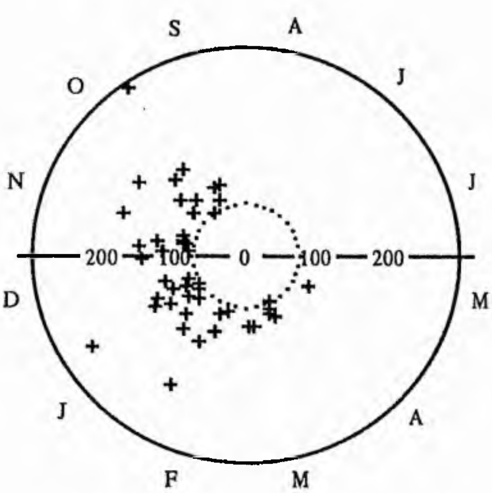

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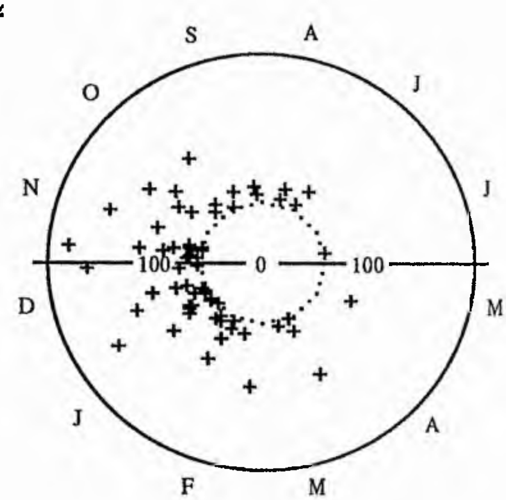


APPENDIX D

Mean day of flood and *r* values before and after adjustment to standard period (1959 - 88)

No.	Gauging Station Name	Original		1959 - 88 Adjusted	
		Mean Day	*r*	Mean Day	*r*
2001	HELMSDALE @ KILPHEDIR	198.8	0.467		
3002	CARRON @ SGODACHAIL	191.7	0.675		
3801	CASSLEY @ DUCHALLY	205.3	0.673		
3901	SHIN @ LAIRG	214.0	0.683		
3803	TIRRY @ RHIAN BRIDGE	202.5	0.532		
4003	ALNESS @ ALNESS	188.0	0.598	173.8	0.485
4001	CONON @ MOY BRIDGE	209.1	0.675		
5901	BEAULY @ ERCHLESS	200.3	0.631		
6007	NESS @ NESS-SIDE	195.7	0.635	196.9	0.547
6008	ENRICK @ MILL OF TORE	190.4	0.689		
6903	MORISTON @ INVERMORISTON	202.7	0.608		
7001	FINDHORN @ SHENACHIE	159.2	0.463	158.0	0.459
7002	FINDHORN @ FORRES	159.1	0.370	159.1	0.370
7003	LOSSIE @ SHERRIFF MILLS	180.5	0.235	176.0	0.248
8001	SPEY @ ABERLOUR	191.9	0.220	207.9	0.347
8002	SPEY @ KINRARA	199.5	0.563	194.8	0.584
8005	SPEY @ BOAT OF GARTEN	193.3	0.494	190.3	0.499
8007	SPEY @ INVERTRUIM	194.7	0.656	193.4	0.648
8008	TROMIE @ TROMIE BRIDGE	199.7	0.557		
8009	DULNAIN @ BALNAAN BRIDGE	186.6	0.463	184.0	0.477
8010	SPEY @ GRANTOWN	199.4	0.510	199.4	0.491
8903	SPEY @ RUTHVEN BRIDGE	194.4	0.578	192.2	0.612
9002	DEVERON @ MUIRESK	195.2	0.339	192.5	0.371
9003	ISLA @ GRANGE	181.6	0.329	176.6	0.361
10002	UGIE @ INVERUGIE	215.7	0.598	200.4	0.572
11001	DON @ PARKHILL	222.4	0.417	213.6	0.424
11002	DON @ HAUGHTON	213.5	0.435		
11003	DON @ ALFORD	216.4	0.336	197.6	0.347
12001	DEE @ WOODEND	202.0	0.484	198.1	0.478
12002	DEE @ PARK BRIDGE	199.3	0.530	198.0	0.478
12003	DEE @ POLHOLLICK	186.6	0.523	189.3	0.499
14001	EDEN @ KEMBACK	217.3	0.570	211.9	0.538
15008	DEAN WATER @ COOKSTON	218.3	0.529	224.0	0.551
15010	ISLA @ WESTER CARDEAN	193.4	0.531	194.4	0.513
15013	ALMOND @ ALMONDBANK	176.9	0.602	174.5	0.578
15016	TAY @ KENMORE	201.0	0.559	205.3	0.570
16003	RUCHILL WATER @ CULTYBRAGGAN	181.9	0.486	179.3	0.488
17001	CARRON @ HEADSWOOD	185.3	0.587	172.2	0.584
17005	AVON @ POLMONTHILL	191.7	0.620	178.4	0.600
18005	ALLAN WATER @ BRIDGE OF ALLAN	194.6	0.492	180.2	0.481
18008	LENY @ ANIE	200.2	0.534	187.9	0.516
18001	ALLAN WATER @ KINBUCK	190.2	0.609	194.6	0.586
18002	DEVON @ GLENOCHIL	190.6	0.542	214.9	0.541
19001	ALMOND @ CRAIGIEHALL	183.6	0.438	182.1	0.436

Mean day of flood values expressed as days after 31 May.
Missing adjusted values due to excessive interpolation requirements.

No.	Gauging Station Name	Original		1959 - 88 Adjusted	
		Mean Day	r	Mean Day	r
19002	ALMOND @ ALMOND WEIR	183.3	0.521	182.2	0.513
19004	NORTH ESK @ DALMORE WEIR	182.7	0.317	182.5	0.317
19006	WATER OF LEITH @ MURRAYFIELD	193.0	0.384	189.9	0.378
19007	ESK @ MUSSELBURGH	196.4	0.300	196.2	0.303
19008	SOUTH ESK @ PRESTONHOLM	215.4	0.238	208.9	0.259
19011	NORTH ESK @ DALKEITH PALACE	188.5	0.307	185.9	0.316
19003	BREICH WATER @ BREICH WEIR	172.4	0.416	178.2	0.400
19005	ALMOND @ ALMONDELL	181.3	0.509	184.3	0.458
20001	TYNE @ EAST LINTON	197.1	0.328	197.1	0.328
20002	PEFFER WEST @ LUFFNESS MAINS	223.1	0.345	207.0	0.380
20005	BIRNS WATER @ SALTOUN HALL	195.7	0.196	193.4	0.212
20006	BIEL WATER @ BELTON HOUSE	229.9	0.192	202.4	0.182
20007	GIFFORD WATER @ LENNOXLOVE	238.0	0.317	213.9	0.310
21007	ETTRICK @ LINDEAN	188.6	0.520	188.0	0.523
21008	TEVIOT @ ORMISTON MILL	198.5	0.523	198.4	0.545
21009	TWEED @ NORHAM	201.6	0.533	201.4	0.535
21012	TEVIOT @ HAWICK	198.9	0.555	192.2	0.608
21015	LEADER WATER @ EARLSTON	223.7	0.465	202.9	0.469
21016	EYE WATER @ EYEMOUTH MILL	216.2	0.308	193.0	0.308
21022	WHITEADDER WR @ HUTTON CASTLE	238.9	0.363	214.1	0.349
21024	JED WATER @ JEDBURGH	185.7	0.412	168.6	0.380
21025	ALE WATER @ ANCRUM	211.2	0.532	191.4	0.507
21026	TIMA WATER @ DEEPHOPE	167.7	0.525	161.3	0.459
21001	FRUID WATER @ FRUID	186.8	0.485		
21010	TWEED @ DRYBURGH	191.9	0.540	202.6	0.477
21011	YARROW WATER @ PHILIPHAUGH	188.5	0.567	190.6	0.519
21017	ETTRICK WATER @ BROCKHOPERIG	183.1	0.500	181.1	0.487
21018	LYNE WATER @ LYNE STATION	197.6	0.628	193.6	0.477
21019	MANOR WATER @ CADEMUIR	202.6	0.721	200.0	0.555
21020	YARROW WATER @ GORDON ARMS	202.8	0.622		
21021	TWEED @ SPROUSTON	208.7	0.666		
21030	MEGGET WATER @ HENDERLAND	192.5	0.580		
21031	TILL @ ETAL	207.5	0.362	220.2	0.363
21032	GLEN @ KIRKNEWTON	209.9	0.304	220.9	0.273
21034	YARROW WATER @ CRAIG DOUGLAS	196.3	0.608		
22002	COQUET @ BYGATE	207.9	0.413		
22003	USWAY BURN @ SHILLMOOR	219.0	0.343		
22004	ALN @ HAWKHILL	209.3	0.337	215.7	0.310
22006	BLYTH @ HARTFORD BRIDGE	230.5	0.469	236.4	0.482
22007	WANSBECK @ MITFORD	230.1	0.508	229.8	0.591
22008	ALWIN @ CLENNELL	185.9	0.546		
22009	COQUET @ ROTHBURY	214.5	0.465		
23008	REDE @ REDE BRIDGE	219.9	0.643		
23010	TARSET BURN @ GREENHAUGH	211.4	0.568		
23011	KIELDER BURN @ KIELDER	193.5	0.534		
77002	ESK @ CANONBIE	183.8	0.518	179.2	0.496
77003	LIDDEL @ ROWANBURNFOOT	188.9	0.544		
78003	ANNAN @ BRYDEKIRK	190.3	0.575	183.0	0.519
78004	KINNEL @ REDHALL	178.4	0.465	169.7	0.484

Mean day of flood values expressed as days after 31 May.
Missing adjusted values due to excessive interpolation requirements.

No.	Gauging Station Name	Original		1959 - 88 Adjusted	
		Mean Day	r	Mean Day	r
78005	KINNEL @ BRIDGEMUIR	179.4	0.458		
79002	NITH @ FRIAR'S CARSE	179.2	0.565	178.9	0.574
79003	NITH @ HALL BRIDGE	193.7	0.610	191.4	0.613
79004	SCAR @ CAPENOCH	179.1	0.561	174.1	0.528
79005	CLUDEN @ FIDDLER'S FORD	186.1	0.594	180.9	0.554
79006	NITH @ DRUMLANRIG	182.0	0.657	175.1	0.590
80001	URR @ DALBEATTIE	183.0	0.555	178.2	0.524
80003	WHITE LAGGAN @ LOCH DEE	108.0	0.560		
81002	CREE @ NEWTON STEWART	176.1	0.536	172.1	0.514
81003	LUCE @ AIRYHEMMING	173.1	0.498	168.7	0.477
82003	STINCHAR @ BALNOWLART	157.1	0.603		
82001	GIRVAN @ ROBSTONE	173.6	0.603	166.4	0.491
83004	LUGAR WATER @ LANGHOLM	170.2	0.647	164.0	0.554
83002	GARNOCK @ DALRY	128.5	0.660		
83005	IRVINE @ SHEWALTON	149.3	0.544		
83006	AYR @ MAINHOLM	155.0	0.690		
83802	IRVINE @ GLENFIELD	165.3	0.452	152.4	0.450
84003	CLYDE @ HAZELBANK	195.2	0.562	196.9	0.585
84005	CLYDE @ BLAIRSTON	191.1	0.577	192.5	0.607
84012	WHITE CART WATER @ HAWKHEAD	181.0	0.616	180.9	0.568
84013	CLYDE @ DALDOWIE	180.6	0.601	186.7	0.634
84014	AVON WATER @ FAIRHOLM	179.2	0.569	177.9	0.593
84015	KELVIN @ DRYFIELD	167.0	0.541	163.4	0.547
84016	LUGGIE WATER @ CONDORRAT	161.3	0.599	156.2	0.572
84020	GLAZERT WR @ MILTON OF CAMPSIE	157.9	0.596	153.7	0.573
84026	ALLANDER @ MILNGAVIE	163.5	0.514	160.7	0.488
84001	KELVIN @ KILLERMONT	174.4	0.525	174.1	0.542
84004	CLYDE @ SILLS OF CLYDE	196.8	0.534	199.1	0.566
84006	KELVIN @ BRIDGEND	163.6	0.682	163.8	0.685
84806	CLYDE @ CAMBUSNETHAN	176.7	0.464	185.8	0.557
84007	SOUTH CALDER WATER @ FORGEWOOD	190.6	0.487	192.2	0.443
84008	ROTTEN CALDER @ REDLEES	186.8	0.637	180.7	0.551
84009	NETHAN @ KIRKMUIRHILL	172.1	0.604	165.9	0.501
84011	GRYFE @ CRAIGEND	192.1	0.503	188.3	0.433
84018	CLYDE @ TULLIFORD MILL	200.4	0.770	200.2	0.622
84019	NORTH CALDER WATER @ CALDERPARK	177.4	0.560	180.5	0.507
84023	BOTHLIN BURN @ AUCHENGEICH	165.1	0.547	154.5	0.510
84025	LUGGIE WATER @ OXGANG	178.0	0.596	166.6	0.555
85003	FALLOCH @ GLEN FALLOCH	172.8	0.568	166.5	0.527
85002	ENDRICK WATER @ GAIDREW	181.3	0.499	176.6	0.460
86001	LITTLE EACHAIG @ DALINLONGART	154.1	0.482	150.8	0.443
87801	ALLT UAINE @ LOCH SLOY INTAKE	152.0	0.377	148.7	0.363
89804	STRAE @ DUILETTER	182.0	0.559		
91002	LOCHY @ CAMISKY	189.4	0.692		
91802	ALLT LEACHDACH @ INTAKE	185.0	0.396	170.6	0.418
93001	CARRON @ NEW KELSO	185.2	0.576		
94001	EWE @ POOLEWE	199.4	0.451	195.1	0.394
96001	HALLADALE @ HALLADALE	172.0	0.447		
96002	NAVER @ APIGILL	198.6	0.613		
97002	THURSO @ HALKIRK	189.5	0.582		

Mean day of flood values expressed as days after 31 May.
Missing adjusted values due to excessive interpolation requirements.

APPENDIX E
Percentage of total station floods occurring in 2-month periods (1959-88 adjusted)

No.	Gauging Station Name	2-monthly percentage					
		JUN-JUL	AUG-SEP	OCT-NOV	DEC-JAN	FEB-MAR	APR-MAY
2001	HELMSDALE @ KILPHEDIR	8.9	8.8	28.2	28.2	20.2	5.8
3002	CARRON @ SGODACHAIL	2.6	7.4	31.7	46.0	12.3	0.0
3801	CASSLEY @ DUCHALLY						
3901	SHIN @ LAIRG						
3803	TIRRY @ RHIAN BRIDGE						
4003	ALNESS @ ALNESS	5.7	8.2	34.9	33.3	15.5	2.4
4001	CONON @ MOY BRIDGE						
5901	BEAULY @ ERCHLESS	0.0	5.3	33.2	45.6	11.4	4.4
6007	NESS @ NESS-SIDE	1.4	8.7	25.6	31.0	33.2	0.0
6008	ENRICK @ MILL OF TORE						
6903	MORISTON @ INVERMORISTON						
7001	FINDHORN @ SHENACHIE	8.0	26.2	26.8	28.2	9.4	1.4
7002	FINDHORN @ FORRES	10.5	21.9	24.8	28.6	9.5	4.8
7003	LOSSIE @ SHERRIFF MILLS	11.9	15.3	27.1	23.7	13.6	8.5
8001	SPEY @ ABERLOUR	6.1	16.2	21.9	31.4	19.4	5.0
8002	SPEY @ KINRARA						
8005	SPEY @ BOAT OF GARTEN	4.9	12.7	29.4	35.3	15.7	2.0
8007	SPEY @ INVERTRUIM	2.0	9.2	31.6	42.9	13.3	1.0
8008	TROMIE @ TROMIE BRIDGE						
8009	DULNAIN @ BALNAAN BRIDGE	8.0	11.4	29.5	37.5	10.2	3.4
8010	SPEY @ GRANTOWN	5.8	9.7	25.2	37.9	17.5	3.9
8903	SPEY @ RUTHVEN BRIDGE	1.6	11.6	29.1	43.2	14.4	0.0
9002	DEVERON @ MUIRESK	6.2	12.6	27.8	32.1	12.5	8.8
9003	ISLA @ GRANGE	8.0	16.0	28.4	30.6	10.3	6.7
10002	UGIE @ INVERUGIE	0.0	2.1	27.9	42.7	19.5	7.9
11001	DON @ PARKHILL	8.1	8.2	19.6	36.2	20.1	7.6
11002	DON @ HAUGHTON						
11003	DON @ ALFORD	6.6	15.9	20.3	30.3	21.5	5.5
12001	DEE @ WOODEND	0.0	11.3	32.0	30.9	19.6	6.2
12002	DEE @ PARK BRIDGE	0.0	11.3	27.8	34.8	18.4	7.7
12003	DEE @ POLHOLLICK	0.0	13.7	31.2	33.2	17.7	4.3
14001	EDEN @ KEMBACK	3.0	3.2	27.3	38.0	19.6	9.0
15008	DEAN WATER @ COOKSTON	0.9	5.6	22.4	34.6	31.8	4.7
15010	ISLA @ WESTER CARDEAN	0.0	7.1	34.7	33.7	16.6	7.8
15013	ALMOND @ ALMONDBANK	0.0	16.7	38.6	29.8	12.8	2.1
15016	TAY @ KENMORE	1.2	8.0	28.6	39.7	21.1	1.5
16003	RUCHILL WATER @ CULTYBRAGGAN	4.3	13.9	34.0	31.0	13.8	3.2
17001	CARRON @ HEADSWOOD	2.1	18.5	37.6	27.8	14.0	0.0
17005	AVON @ POLMONTHILL	1.8	15.9	33.3	34.5	14.4	0.0
18005	ALLAN WATER @ BRIDGE OF ALLAN	3.6	20.0	25.2	35.0	12.1	4.2
18008	LENY @ ANIE	1.7	16.4	30.4	30.7	18.2	2.6
18001	ALLAN WATER @ KINBUCK	3.3	7.6	30.4	39.6	14.4	4.7
18002	DEVON @ GLENOCHIL	4.6	7.1	24.0	46.5	14.5	3.3
19001	ALMOND @ CRAIGIEHALL	5.1	15.3	29.6	29.6	15.3	5.1

Missing values due to excessive interpolation requirements.

No.	Gauging Station Name	2-monthly percentage					
		JUN-JUL	AUG-SEP	OCT-NOV	DEC-JAN	FEB-MAR	APR-MAY
19002	ALMOND @ ALMOND WEIR	2.8	14.1	32.2	32.3	13.0	5.5
19004	NORTH ESK @ DALMORE WEIR	8.0	14.9	30.3	21.8	18.9	6.2
19006	WATER OF LEITH @ MURRAYFIELD	8.6	11.4	27.3	27.4	18.4	6.9
19007	ESK @ MUSSELBURGH	7.0	14.5	26.3	22.7	21.4	8.1
19008	SOUTH ESK @ PRESTONHOLM	6.5	15.7	22.4	23.2	22.5	9.6
19011	NORTH ESK @ DALKEITH PALACE	8.7	12.0	28.1	27.2	15.2	8.9
19003	BREICH WATER @ BREICH WEIR	4.8	14.5	29.4	25.6	11.6	14.1
19005	ALMOND @ ALMONDELL	4.1	14.6	26.5	30.7	8.9	15.2
20001	TYNE @ EAST LINTON	6.5	13.1	27.1	25.2	19.6	8.4
20002	PEFFER WEST @ LUFFNESS MAINS	6.0	8.2	28.5	27.0	18.6	11.7
20005	BIRNS WATER @ SALTOUN HALL	7.9	15.8	24.0	22.6	18.9	10.9
20006	BIEL WATER @ BELTON HOUSE	8.1	15.3	30.3	17.7	14.9	13.6
20007	GIFFORD WATER @ LENNOXLOVE	5.8	14.9	24.3	21.4	22.8	10.8
21007	ETTRICK @ LINDEAN	3.0	14.9	30.9	31.6	17.9	1.7
21008	TEVIOT @ ORMISTON MILL	4.0	10.0	27.8	35.9	20.4	2.0
21009	TWEED @ NORHAM	1.7	10.9	26.2	37.0	21.7	2.5
21012	TEVIOT @ HAWICK	0.8	9.2	34.8	30.2	22.6	2.4
21015	LEADER WATER @ EARLSTON	2.4	10.8	25.6	29.8	23.6	7.7
21016	EYE WATER @ EYEMOUTH MILL	6.6	10.1	33.3	24.6	12.7	12.7
21022	WHITEADDER WR @ HUTTON CASTLE	6.8	9.8	26.9	21.9	20.5	14.1
21024	JED WATER @ JEDBURGH	11.0	11.9	36.1	24.0	14.2	2.8
21025	ALE WATER @ ANCRUM	1.6	11.0	30.0	30.5	22.1	4.9
21026	TIMA WATER @ DEEPHOPE	3.2	35.8	28.1	19.5	13.3	0.0
21001	FRUID WATER @ FRUID	3.4	12.8	49.4	20.1	9.1	5.1
21010	TWEED @ DRYBURGH	1.1	14.4	25.9	35.2	22.0	1.3
21011	YARROW WATER @ PHILIPHAUGH	1.7	15.0	28.5	35.4	19.4	0.0
21017	ETTRICK WATER @ BROCKHOPERIG	3.1	18.7	30.2	26.8	14.9	6.2
21018	LYNE WATER @ LYNE STATION	0.0	6.1	35.8	33.4	22.2	2.6
21019	MANOR WATER @ CADEMUIR	0.0	11.7	27.0	48.1	10.7	2.5
21020	YARROW WATER @ GORDON ARMS	0.0	17.2	27.1	30.6	25.0	0.0
21021	TWEED @ SPROUSTON	0.0	4.7	36.4	31.6	27.3	0.0
21030	MEGGET WATER @ HENDERLAND	0.0	38.5	18.3	27.7	13.3	2.2
21031	TILL @ ETAL	4.0	9.5	24.0	31.6	26.2	4.8
21032	GLEN @ KIRKNEWTON	6.6	14.7	17.9	27.3	27.2	6.4
21034	YARROW WATER @ CRAIG DOUGLAS	0.0	17.9	26.8	30.5	20.9	3.9
22002	COQUET @ BYGATE						
22003	USWAY BURN @ SHILLMOOR						
22004	ALN @ HAWKHILL	8.0	9.9	25.1	24.0	23.6	9.4
22006	BLYTH @ HARTFORD BRIDGE	2.1	7.3	19.9	28.9	31.1	10.6
22007	WANSBECK @ MITFORD	0.0	8.4	18.8	33.7	28.2	10.9
22008	ALWIN @ CLENNELL						
22009	COQUET @ ROTHBURY						
23008	REDE @ REDE BRIDGE	0.0	7.9	26.8	34.5	28.8	2.0
23010	TARSET BURN @ GREENHAUGH						
23011	KIELDER BURN @ KIELDER	1.5	21.1	32.1	26.8	14.8	3.6
77002	ESK @ CANONBIE	0.8	18.9	33.4	24.2	19.6	3.0
77003	LIDDEL @ ROWANBURNFOOT						
78003	ANNAN @ BRYDEKIRK	1.1	19.2	28.7	31.2	18.1	1.7
78004	KINNEL @ REDHALL	1.1	28.8	28.0	27.4	12.7	1.9
78005	KINNEL @ BRIDGEMUIR						

Missing values due to excessive interpolation requirements.

No.	Gauging Station Name	2-monthly percentage					
		JUN-JUL	AUG-SEP	OCT-NOV	DEC-JAN	FEB-MAR	APR-MAY
79002	NITH @ FRIAR'S CARSE	1.7	18.3	33.3	32.5	12.5	1.7
79003	NITH @ HALL BRIDGE	1.7	13.4	27.8	41.2	14.3	1.7
79004	SCAR @ CAPENOCH	1.6	23.4	31.2	28.8	12.1	2.9
79005	CLUDEN @ FIDDLER'S FORD	0.8	20.1	29.8	31.2	18.0	0.0
79006	NITH @ DRUMLANRIG	2.0	19.1	34.8	32.0	10.6	1.6
80001	URR @ DALBEATTIE	2.6	17.9	34.1	28.8	16.7	0.0
80003	WHITE LAGGAN @ LOCH DEE						
81002	CREE @ NEWTON STEWART	2.1	23.3	30.0	31.2	9.8	3.6
81003	LUCE @ AIRYHEMMING	3.8	27.0	26.0	27.5	12.6	3.1
82003	STINCHAR @ BALNOWLART	3.7	33.3	23.4	36.6	3.0	0.0
82001	GIRVAN @ ROBSTONE	4.1	17.8	37.4	25.2	11.8	3.8
83004	LUGAR WATER @ LANGHOLM	1.8	33.4	29.5	25.1	10.2	0.0
83002	GARNOCK @ DALRY	0.0	36.3	39.1	18.0	3.7	3.0
83005	IRVINE @ SHEWALTON						
83006	AYR @ MAINHOLM						
83802	IRVINE @ GLENFIELD	6.3	28.0	29.4	23.1	10.5	2.8
84003	CLYDE @ HAZELBANK	0.8	11.5	30.0	36.2	19.2	2.3
84005	CLYDE @ BLAIRSTON	1.7	11.9	29.7	37.3	17.8	1.7
84012	WHITE CART WATER @ HAWKHEAD	0.9	15.9	35.0	31.0	12.9	4.3
84013	CLYDE @ DALDOWIE	1.0	13.4	32.3	35.6	15.7	2.0
84014	AVON WATER @ FAIRHOLM	3.4	12.9	36.3	33.9	11.6	1.8
84015	KELVIN @ DRYFIELD	3.0	24.2	31.3	30.3	10.1	1.0
84016	LUGGIE WATER @ CONDORRAT	3.9	31.2	31.4	25.3	8.3	0.0
84020	GLAZERT WR @ MILTON OF CAMPSIE	0.0	32.9	35.7	24.3	6.0	1.2
84026	ALLANDER @ MILNGAVIE	2.2	26.5	30.5	27.1	12.1	1.6
84001	KELVIN @ KILLERMONT	3.4	20.5	28.9	34.9	10.4	2.0
84004	CLYDE @ SILLS OF CLYDE	0.7	11.3	30.7	33.9	20.7	2.6
84006	KELVIN @ BRIDGEND	0.0	24.5	39.0	29.2	7.2	0.0
84806	CLYDE @ CAMBUSNETHAN	1.2	15.5	28.2	33.7	18.8	2.5
84007	SOUTH CALDER WATER @ FORGEWOOD	1.9	19.2	24.6	31.0	20.0	3.4
84008	ROTTEN CALDER @ REDLEES	2.0	7.5	37.3	34.0	18.3	0.9
84009	NETHAN @ KIRKMUIRHILL	1.6	17.0	36.9	22.9	19.5	2.0
84011	GRYFE @ CRAIGEND	0.0	12.3	28.2	27.6	27.3	4.6
84018	CLYDE @ TULLIFORD MILL	0.0	6.5	31.9	42.5	19.1	0.0
84019	NORTH CALDER WATER @ CALDERPARK	2.6	14.1	36.0	27.4	13.8	6.1
84023	BOTHLIN BURN @ AUCHENGEICH	0.0	25.9	37.7	24.3	9.7	2.4
84025	LUGGIE WATER @ OXGANG	0.0	18.9	39.3	26.5	14.2	1.2
85003	FALLOCH @ GLEN FALLOCH	3.8	19.9	33.1	34.2	6.3	2.7
85002	ENDRICK WATER @ GAIDREW	4.3	12.7	32.8	29.0	18.1	3.1
86001	LITTLE EACHAIG @ DALINLONGART	1.0	28.2	34.8	18.6	10.4	6.9
87801	ALLT UAINE @ LOCH SLOY INTAKE	13.9	28.9	21.5	24.5	8.9	2.4
89804	STRAE @ DUILETTER						
91002	LOCHY @ CAMISKY						
91802	ALLT LEACHDACH @ INTAKE	7.7	11.6	41.3	25.0	9.7	4.7
93001	CARRON @ NEW KELSO						
94001	EWE @ POOLEWE	1.3	14.7	22.8	23.1	28.3	9.8
96001	HALLADALE @ HALLADALE						
96002	NAVER @ APIGILL						
97002	THURSO @ HALKIRK	7.7	10.7	29.8	30.6	18.5	2.7

Missing values due to excessive interpolation requirements.

Appendix F Daily rainfall record details

Part 1 Rainfall records used for flow stations

Flow station	Raingauge records used (see parts 2 and 3)			
02001	773652			
03002	791188			
03801	781338			
03901	782882	781338		
03803	782882	781338		
04003	787077			
04001	789962	791188	789210	792393
05901	796632	795076		
06007	797415	803321	799028	
06008	804431	795076		
06903	802245			
07001	803321	816916		
07002	810891			
07003	811847			
08001	814042	822712	817539	
08002	816916	814042		
08005	817539	814042		
08007	814042			
08008	814042	816916		
08009	817539			
08010	814042	817539		
08903	814042			
09002	827555	827441	829495	
09003	827555			
10002	833151			
11001	839564	838080		
11002	839564	838080		
11003	838080	836996		
12001	846334	843623		
12002	847422	846334	843623	
12003	843623			
14001	884481			
15008	874259			
15010	873322			
15013	879168	881185		
15016	861812	861125	859814	
16003	880486			
17001	896059			
17005	898119	897038		
18005	893956	894223		
18008	891684			
18001	893956			
18002	894986			
19001	898326	898753	899283	
19002	898119			
19004	900315			
19006	899577	899806		
19007	900662	900959		
19008	900959			

Flow station	Raingauge records used		
19011	900662	900315	
19003	898326		
19005	898119	898326	898753
20001	902783	902952	
20002	903308		
20005	902783		
20006	903637		
20007	903146	903797	
21007	914002	909975	910529
21008	914180	920561	
21009	918357	914180	912526
21012	914180	914002	
21015	912526		
21016	904278	904751	
21022	922829		
21024	914180	920561	
21025	914180	912964	
21026	610122		
21001	905228		
21010	910529	912526	907264
21011	910529	909975	
21017	610122		
21018	906424	907264	
21019	907264		
21020	909975		
21021	914180	912526	907264
21030	909975	905228	
21031	919808	920561	
21032	918357	920561	
21034	909975		
22002	920561		
22003	920561		
22004	001910		
22006	007863	005785	
22007	006734	005785	
22008	919190		
22009	003552		
23008	010659	011706	
23010 .	008887	010064	
23011	008887	010659	
77002	611820	610122	
77003	008887	611820	
78003	617949	615794	
78004	617949	615794	
78005	621983	615794	617949
79002	622885	621335	
79003	620168		
79004	621335	623619	
79005	623954	623619	
79006	621335		
80001	625486		
80003	627371	632320	
81002	633631	632320	
81003	638546	636400	

Flow station	Raingauge records used			
82003	641540	636400		
82001	641540	641169		
83004	644415			
83002	647948			
83005	646062			
83006	645445	644415		
83802	646062			
84003	652954	652672	651763	
84005	656475	655036	652672	651763
84012	660468			
84013	656475	655036	652672	651763
84014	655036	655838		
84015	896059	658904	896457	
84016	658904	896457		
84020	663787			
84026	658765	658669		
84001	658765	658904	896457	
84004	652672	651763	650085	
84006	896457	663787		
84806	654466	652672	651763	
84007	656041	656475		
84008	657086			
84009	654466	654310		
84011	659724			
84018	652954	652672	651763	
84019	657000			
84023	658904	657000		
84025	658904	896457	657000	
85003	891986	859814		
85002	663787	662984	896059	
86001	666484			
87801	891986			
89804	686357			
91002	696749	695547		
91802	696749	695547		
93001	708615	713571		
94001	713571	714597		
96001	754770			
96002	752600	750583		
97002	757883	773652		

Part 2 Rainfall station details

Number	NGR	Station
001910	NU109130	Broome Park
003552	NY974996	Swindon
005785	NZ035843	Wallington Hall
006734	NZ201856	Morpeth
007036	NZ038805	Capheaton
007863	NZ212771	Blagdon Hall
008232	NZ320812	Blyth, Ridley Park
008887	NY632935	Kielder Castle
010064	NY808909	High Green Manor
010311	NY761832	Chirdon
010659	NT749031	Catcleugh Nursery
011706	NY897872	West Woodburn
012594	NY942781	Colt Crag Res
014554	NY681640	Haltwhistle
610122	NT235026	Eskdalemuir Observatory
611820	NY374806	Irvine House
615794	NT061049	Moffat, Auchen Castle
617949	NY074827	Lochmaten Hospital
620168	NS630050	Afton Filters No 4
621335	NS797074	Eliock
621983	NX901995	Kettleton Filters
622885	NX907870	Blackwood
623619	NX820896	Maxwelton House
623954	NX849776	Glenkiln Res
625486	NX758755	Corsock
627371	NX554780	Clatteringshaws
632320	NX361789	Bargrennan
633631	NX452646	Palnure
636400	NX139759	Lagafater Lodge
638546	NX112609	Castle Kennedy
641169	NS334047	Kirkbride House
641540	NX184979	Girvan
644415	NS558204	Cumnock, Holmhead
645445	NS348211	Ayr Cemetery
646062	NS560374	Darvel
646827	NS484443	Amlaird Filters No 2
647948	NS275549	Camphill Resr
648612	NS309407	Ravenspark Hosp
650085	NS976092	Garls Craig
651763	NT036276	Coulter Resr
652672	NS974464	Carnwath
652954	NS787285	Monksfoot
654310	NS748372	Dunside Resr
654466	NS809429	Burnfoot
655036	NS663351	Glengavel Resr
655838	NS709478	Glassford Filters
656041	NS880613	Shotts Res
656475	NS694546	Townhill Filters
657000	NS712643	Coatbridge
657086	NS643497	Leaburn
657926	NS605794	Campsie, Glenmill
658669	NS501793	Burncrooks Filters
658765	NS558755	Mugdock Resr

Number	NGR	Station
658904	NS608686	Glasgow, Springburn
659724	NS287711	Gryfe Resr
660285	NS480667	Abbotsinch Met Office
660468	NS567516	Picketlaw Resr No 1
662984	NS415918	Arrochymore
663787	NS555796	Blanefield
663840	NS518820	Quinloch Farm
666484	NS141857	Younger Botanic Garden
686357	NN256342	Airidh Castulaich
687182	NN079268	Cruachan Power Sta
695547	NN351782	Fersit
696749	NN218816	Spean Bridge
708615	NG802332	Plockton
713571	NH025629	Kinlochewe
714597	NG861818	Poolewe
741962	NC187087	Knockanrock
750583	NC677617	Torrisdale
752600	NC680386	Dalharrold
754770	NC894543	Croick
757883	ND137607	Hoy Power Sta
773652	NC872285	Kinbrace, The Hatchery
780686	NC469022	Rosehall
781338	NC369232	Cassley Power Sta
782882	NC576071	Lairg Dam
787077	NH629738	Ardross, Glensax
789210	NH219660	Fannich Lodge
789962	NH216519	Scardroy Lodge
791188	NH374710	Blackbridge
792393	NH455528	Fairburn House
795076	NH314288	Fasnakyle
796632	NH184381	Misgeach Intake
797415	NH475435	Aigas Dam
799028	NH102014	Kingie Camp
802245	NH417170	Invermoriston
803321	NH552201	Aberchalder
804431	NH447302	Balnain
809027	NH790264	Kyllachy
810891	NJ006507	Logie House
811847	NJ165539	Kellas House
814042	NN647942	Cluny Castle
816916	NH856038	Lagganlia
817539	NH986095	Glenmore Lodge
822712	NJ185369	Ballindalloch
827441	NJ535403	Huntly Sewage Works
827555	NJ372441	Drummuir Castle
829495	NJ704496	Muiresk House
832359	NJ865526	Fedderate Res No 1
833151	NK094462	Forehill Water Wks No 3
836996	NJ328123	Edinglassie House
838080	NJ516185	Littlewood Park
839564	NJ779204	Inverurie Sewage Wks
843623	NO152914	Braemar
846334	NO474958	Glen Tanar House
847422	NO666964	Invercannie Water Wks No 2
859814	NN301285	Cononish

Number	NGR	Station
861125	NN546350	Lochay Power Sta
861812	NN702394	Ardtalnaig
873322	NO275540	Lintrathen
874259	NO388486	Glamis Castle
875211	NO131674	Dalhenzean Lodge
879168	NO101239	Perth
880213	NN696157	Auchinner No 1
880486	NN765215	The Ross
881185	NN867223	Strathearn Hydro
884481	NO306144	Letham
891684	NN561167	Strathyre
891986	NN401103	Stronachlachar
893956	NN780059	Cromlix House
894223	NS812972	Parkhead, Stirling University
894986	NS925970	Tillicoutry Cemetery
896059	NS717839	Craigannet No 2
896457	NS782772	Cumbernauld, Dunns Wood Sewage Works
896522	NS827773	Tippetcraig
897038	NS858726	Balquhatstone House
898119	NS950655	Whitburn Sewage Works
898326	NS940603	Fauldhouse Sewage Works
898753	NT076631	Morton
899283	NT121683	Linburn
899577	NT101616	Harperrig
899806	NT226699	Colinton, Firhill Tank
900315	NT175566	Newhall House
900662	NT245663	Bush House
900959	NT308570	Rosebery
902783	NT498638	Stobshiel Filters
902952	NT486711	Samuelston
903146	NT512657	Skedsbush
903308	NT513736	Haddington
903329	NT532744	Haddington Sewage Works
903637	NT594700	Nunraw Abbey
903797	NT672971	Dunbar
904278	NT822699	Redheugh
904751	NT929615	Ayton Castle
905228	NT089205	Fruid Dam
906424	NT126554	Baddingsgill Resr
907264	NT210351	Hallmanor House
909975	NT239232	Cappercleugh
910529	NT428278	Bowhill
912526	NT585495	Blythe
912964	NT581317	Newton St Boswells Sewage Wks
914002	NT349082	Craick
914180	NT428151	Roberton Filters
918357	NT776389	Lochton
919190	NT963160	Linhope
919808	NU052262	Chillingham Barns
920561	NT845202	Sourhope
922829	NT721589	Whitchester

Part 3 Rainfall records used: years with less than 10 missing days

TOT = total years record

	1960s										1970s										1980s									1990	TOT
Station	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	
001910										*	*	*	*	*	*	*	*			*		*	*	*			*	*			14
003552										*	*	*	*	*	*	*	*		*	*	*										11
005785										*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	21
006734											*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	19
007036											*	*		*	*					*	*	*		*	*	*	*	*	*	*	14
007863											*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		19
008232							*	*	*	*		*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*			20
008887	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*			*	*	*	27
010064												*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	18
010311													*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		17
010659				*						*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	21
011706												*	*	*	*	*	*	*	*	*	*	*			*	*	*	*	*	*	17
012594			*			*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		24
014554				*	*	*	*	*		*	*	*		*	*		*			*	*	*	*		*	*	*		*		19
610122	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	30
611820	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	29
615794											*	*		*							*	*	*	*	*	*	*	*	*		12
617949				*	*	*		*	*	*			*		*	*	*	*	*	*		*	*	*	*		*	*	*	*	21
620168	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*		*	*	*									20
621335				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		26
621983				*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*		24
622885	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	30
623619								*	*	*	*	*	*	*	*	*	*	*	*	*				*	*		*	*	*		18
623954			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		27
625486					*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	25
627371			*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		26
632320			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		27
633631				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*							21
636400			*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		26
638546			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*		*		25
641169				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*						22
641540			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	28
644415	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*				*		*	*	*		*				21
645445	*	*	*			*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*					23
646062																			*	*	*	*	*	*	*	*	*	*	*	*	12
646827																				*	*	*	*	*	*	*	*	*	*	*	11
647948											*		*	*	*	*	*	*		*	*	*		*		*	*	*	*	*	16
648612	*	*		*			*						*	*	*	*	*	*	*	*			*	*	*	*	*	*			18
650085				*	*	*	*	*	*		*	*	*	*	*					*	*	*	*		*	*	*	*			19
651763											*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		19
652672											*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		19
652954	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*		*	*	*		27
654310	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	29
654466							*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	24
655036			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				*	*			23
655838	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*			*	*		26
656041	*	*		*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				25
656475			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*		*	*	*	*	*				22
657000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*						25
657086													*		*	*				*		*	*	*		*		*		*	10
657926																								*	*	*	*	*	*		6
658669					*	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	*		*	*	*	*	*		22

	1960s										1970s										1980s									1990	TOT
Station	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	
658765			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		27
658904											*	*	*	*	*	*	*	*	*	*	*	*									12
659724	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*				*			*				*	*			19
660285							*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	24
660468		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	28
662984											*	*	*	*	*		*	*	*		*	*	*	*	*	*	*	*			16
663787							*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		22
663840														*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	16
666484			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		27
686357	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*				*									17
687182												*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	18
695547	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*		27
696749								*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*		*	*	*		20
708615			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	28
713571											*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*			17
714597			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	28
741962							*					*	*	*	*			*	*	*	*	*	*	*	*	*	*	*	*		17
750583																*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	15
752600																		*	*	*	*	*	*	*	*		*	*	*	*	12
754770						*	*	*	*	*	*	*	*	*	*			*	*	*	*	*	*								16
757883	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	30
773652																				*	*	*	*	*	*	*	*	*	*	*	11
780686			*		*	*	*	*	*	*					*		*		*	*		*	*								13
781338			*	*		*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		25
782882					*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				*	*	*		22
787077				*	*	*	*	*	*	*	*	*	*	*	*							*							*		14
789210			*	*	*	*			*	*	*	*	*		*		*	*		*	*	*	*	*	*	*	*	*			21
789962												*	*	*	*	*	*	*	*		*	*	*	*		*	*	*	*		16
791188			*	*							*	*	*	*		*	*	*	*	*	*	*	*	*				*	*		17
792393			*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		26
795076	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*		*		*	*	*	*	*	*	*	*	*	*	*	27
796632																	*	*	*	*	*	*	*			*		*	*		10
797415												*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	18
799028	*	*	*	*		*	*	*	*	*	*	*	*	*	*				*	*	*		*								18
802245										*	*	*			*	*	*	*	*	*											9
803321	*	*	*	*	*	*				*		*	*	*	*	*	*	*		*	*	*	*							*	19
804431						*	*	*	*	*										*	*		*					*			9
809027										*	*	*	*	*	*																6
810891													*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	18
811847	*	*	*	*			*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*								20
814042	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*					*	*	*	*		*		24
816916											*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*					16
817539	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*												18
822712		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				*	*	*	*								19
827441														*	*	*			*	*	*	*	*	*	*	*	*	*	*	*	15
827555		*	*	*	*	*	*	*	*	*				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	26
829495	*	*														*	*	*		*	*	*	*	*	*	*		*	*	*	15
832359	*	*		*	*	*	*			*		*	*	*																	10
833151																		*	*	*	*	*	*	*	*	*	*	*	*	*	13
836996							*		*	*	*	*				*	*	*		*	*	*	*	*	*		*	*	*	*	18
838080	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*											19
839564						*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	25
843623	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*		*	*	*	*	*	*	*	*	*	*	28
846334	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*					*	*	*	*	*	*		*	*	*	*	25
847422			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	28
859814	*	*	*	*	*	*	*		*	*		*							*												11
861125		*		*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*			24
861812	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	29
873322	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*		*	*	*		27

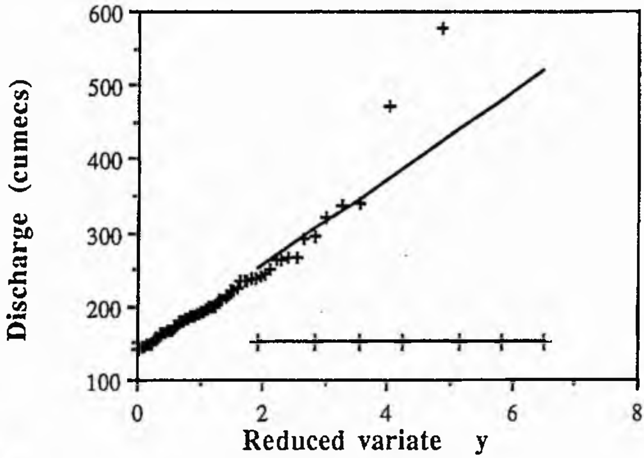
	1960s										1970s										1980s										1990	TOT
Station	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	
874259			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*		26
875211																								*	*	*	*	*	*	*	7
879168	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*													18
880213					*			*	*	*	*	*	*																		7
880486									*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*					18
881185	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	29
884481							*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	24
891684	*	*	*	*	*	*	*	*												*	*	*	*	*							13
891986	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	30
893956										*	*	*	*	*	*	*	*	*	*												10
894223											*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	20
894986	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	30
896059								*			*	*	*		*		*	*		*	*	*	*	*	*	*	*	*			16
896457												*	*	*	*	*	*			*	*	*	*	*	*	*	*	*	*	*	17
896522													*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	17
897038											*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	18
898119						*	*	*	*	*		*	*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	22
898326							*				*	*	*	*	*	*		*				*	*	*	*	*	*	*	*		16
898753				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	*	*	*	*	*	*		24
899283							*		*	*	*	*	*	*	*		*	*		*	*	*	*	*	*	*	*	*	*		20
899577						*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*		23
899806						*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		24
900315				*	*		*	*		*	*	*	*	*	*	*									*	*					13
900662			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		27
900959			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*		26
902783	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	29
902952			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	27
903146	*	*		*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*		*	*	*	*	25
903308	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*											19
903329																					*	*	*	*		*		*			6
903637												*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	19
903797	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	*	28
904278										*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	20
904751													*	*	*	*	*		*	*	*			*	*						10
905228				*	*	*	*	*		*	*	*	*	*	*	*	*			*	*	*	*	*	*	*	*		*	*	23
906424	*			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	28
907264								*	*	*	*	*	*	*	*	*	*			*	*	*	*	*	*	*	*	*		*	20
909975									*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	22
910529	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	29
912526						*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	25
912964													*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	18
914002									*	*	*	*	*	*	*	*	*	*		*		*	*		*	*		*			16
914180				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	27
918357	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	30
919190	*	*		*	*	*	*	*	*	*	*	*																			11
919808	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	28
920561										*	*	*	*		*	*	*						*	*	*	*		*	*	*	14
922829	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			28

Appendix G

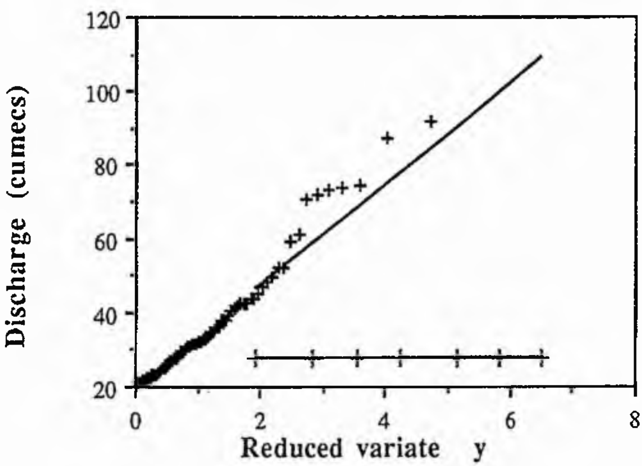
Frequency distributions for full POT series

Upper horizontal axis indicates return periods of 2, 5, 10, 20, 50, 100 and 200 years.

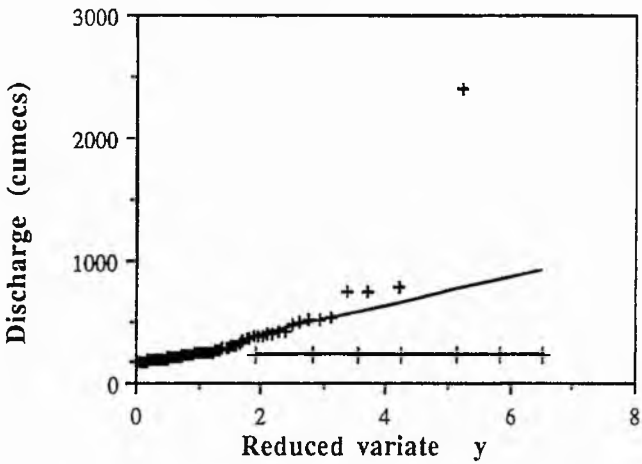
07001 Findhorn @ Shenachie



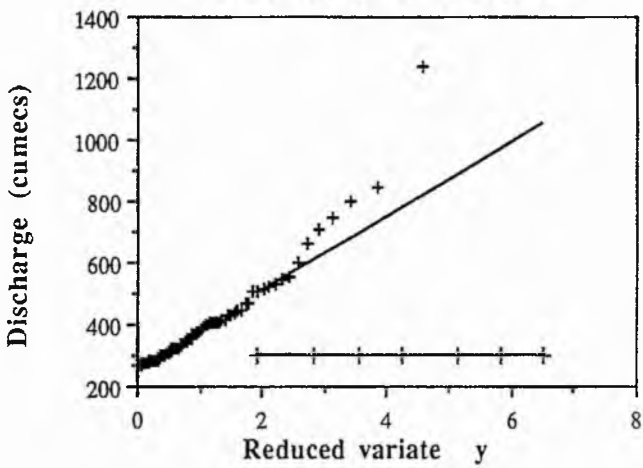
07003 Lossie @ Sherriff Mills



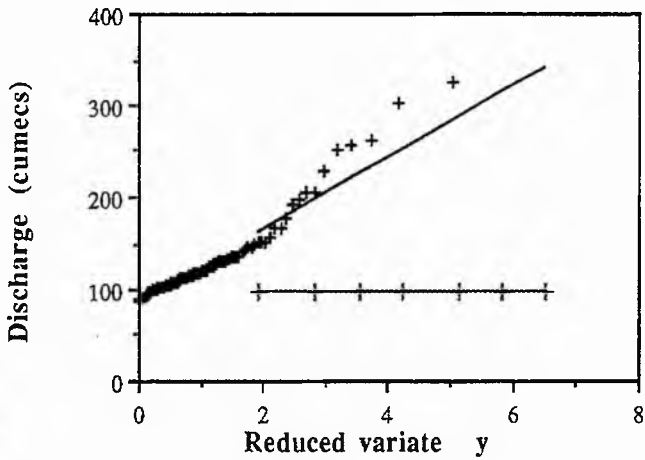
07002 Findhorn @ Forres



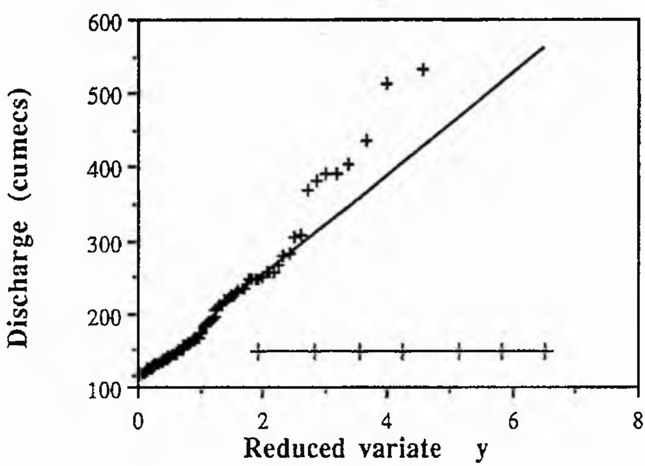
08001 Spey @ Aberlour

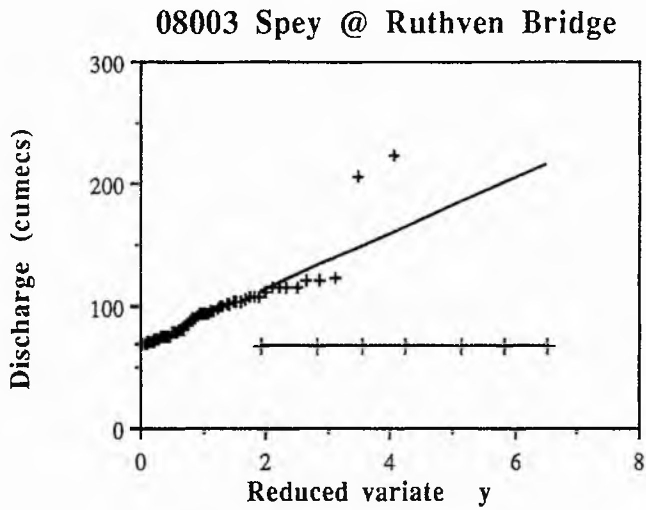


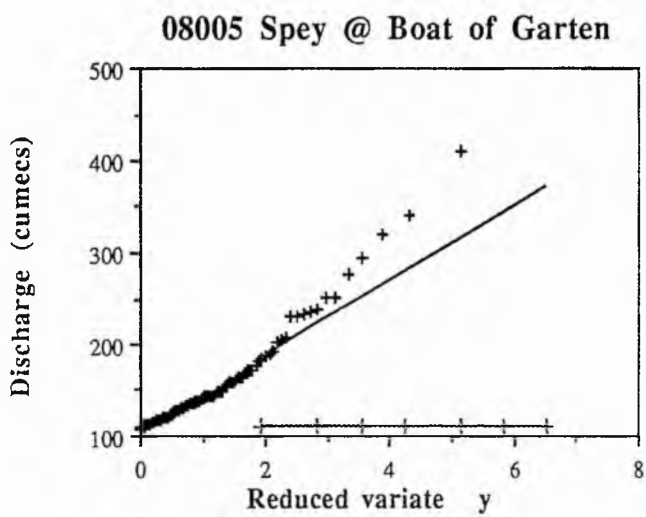
08002 Spey @ Kinrara



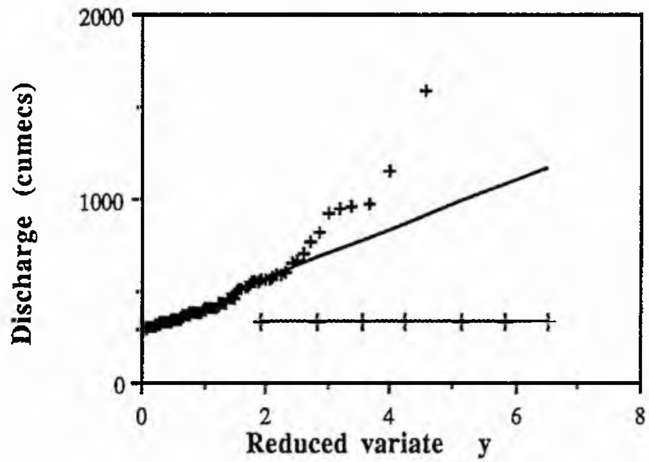
08004 Avon @ Delnashaugh



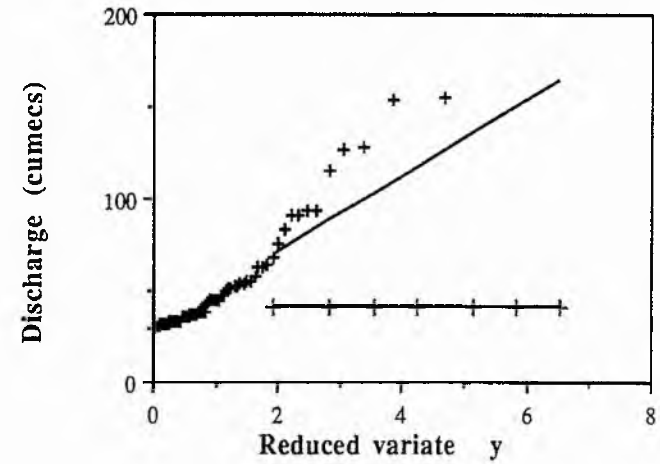

08003 Spey @ Ruthven Bridge
Discharge (cumecs)
300
200
100
0
0
2
4
6
8
Reduced variate y


08005 Spey @ Boat of Garten
Discharge (cumecs)
500
400
300
200
100
0
2
4
6
8
Reduced variate y

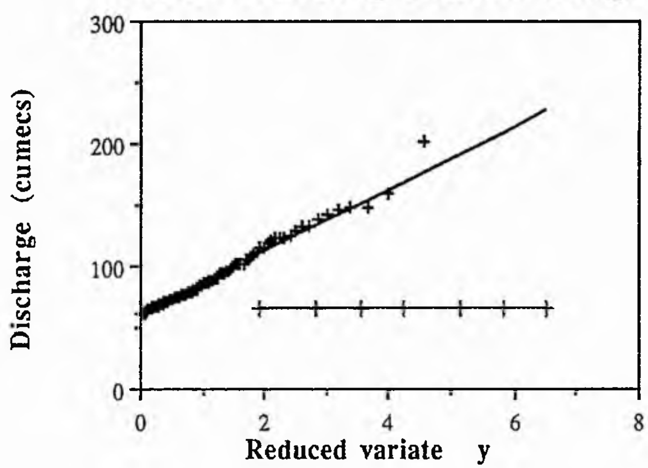
08006 Spey @ Boat o' Brig



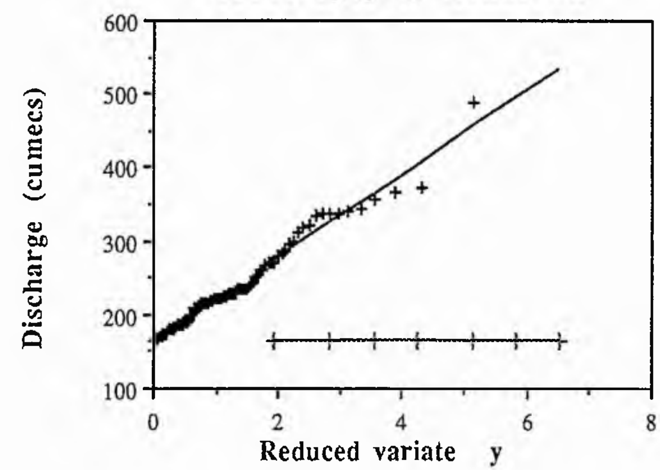
08008 Tromie @ Tromie Bridge



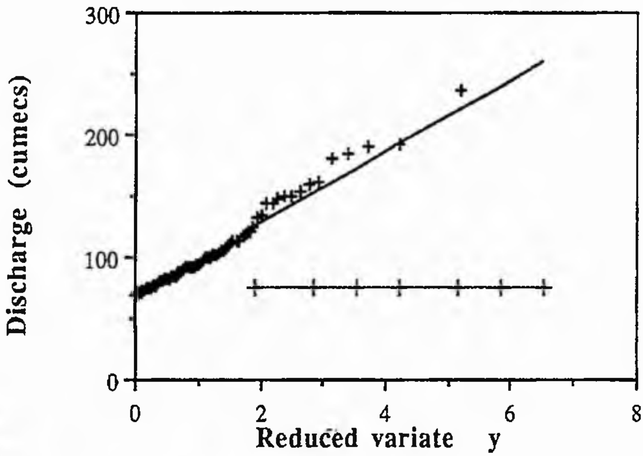
08009 Dulnain @ Balnaan Bridge



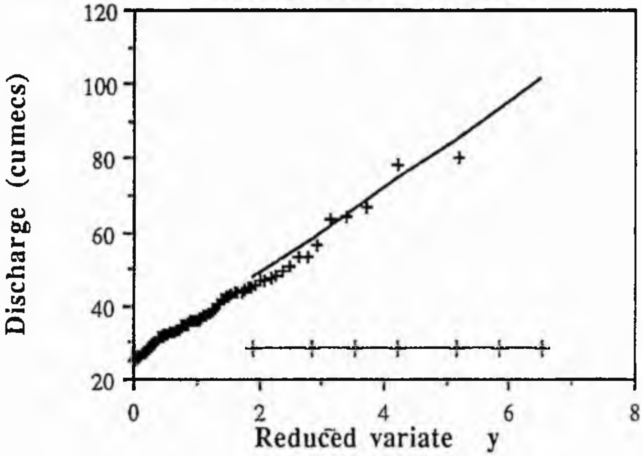
08010 Spey @ Grantown

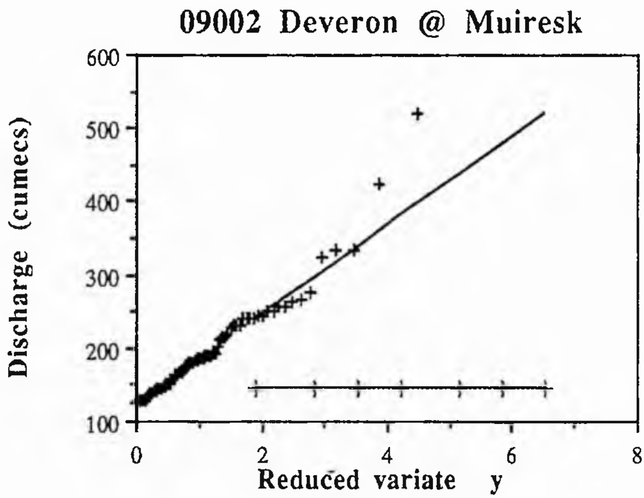


09001 Deveron @ Avochie

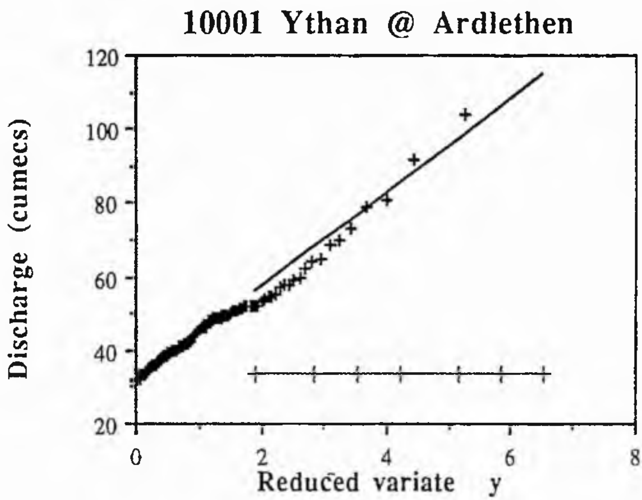


09003 Isla @ Grange



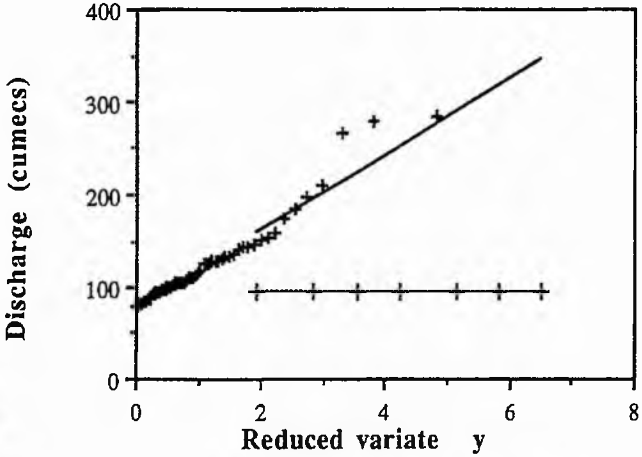


09002 Deveron @ Muiresk
Discharge (cumecs)
600
500
400
300
200
100
0
2
4
6
8
Reduced variate y

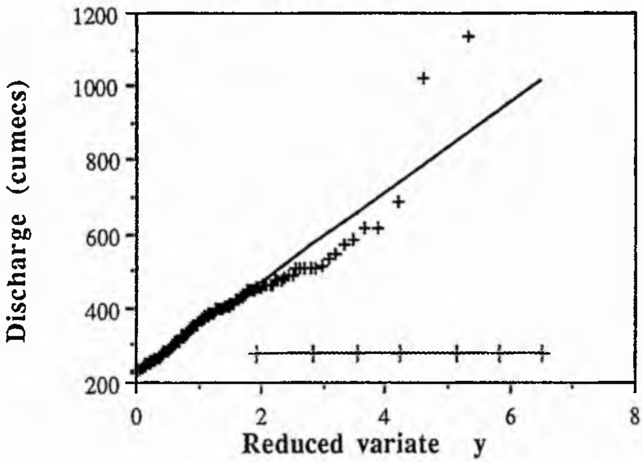


10001 Ythan @ Ardlethen
Discharge (cumecs)
120
100
80
60
40
20
0
2
4
6
8
Reduced variate y

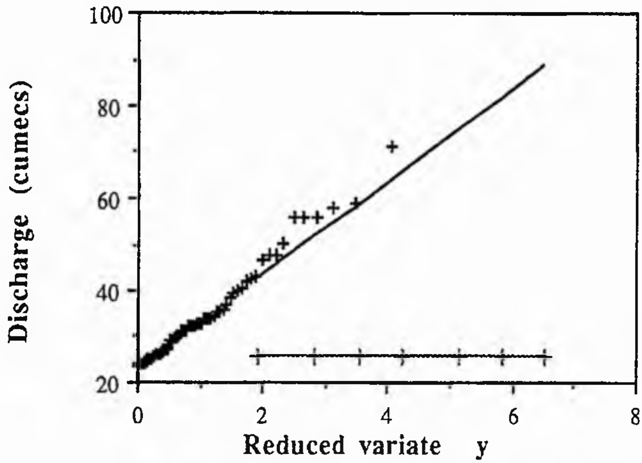
11001 Don @ Parkhill



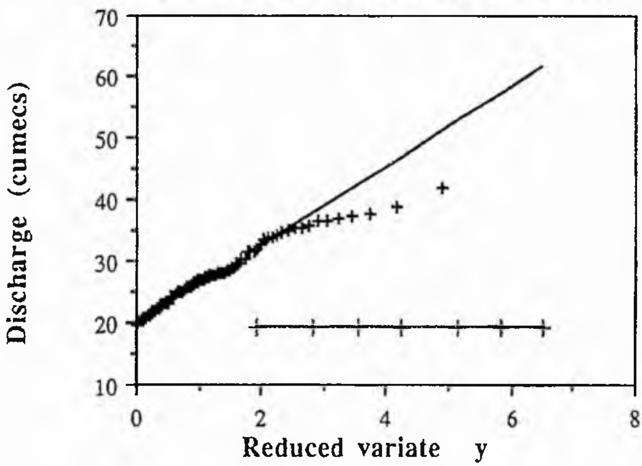
12001 Dee @ Woodend



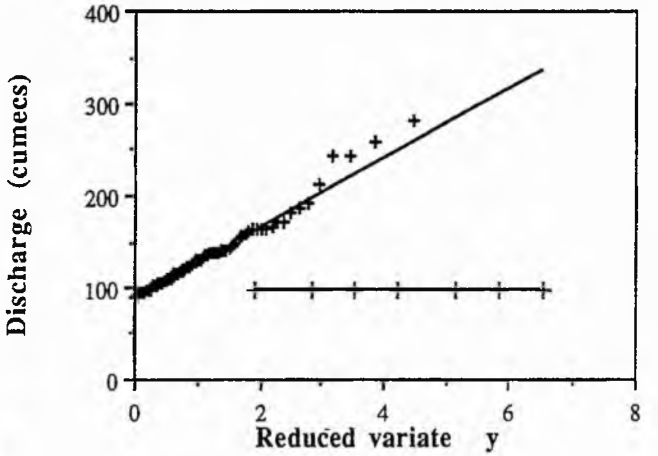
14001 Eden @ Kemback



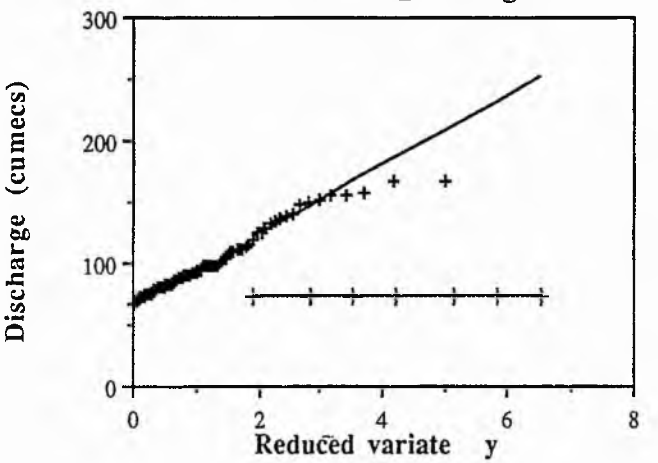
15008 Dean Water @ Cookston

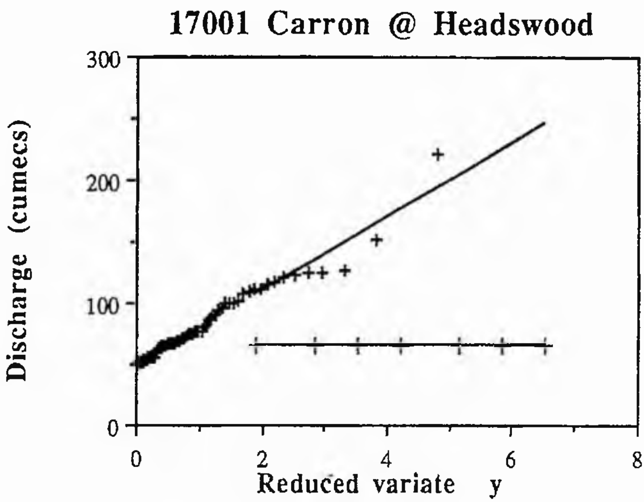


16003 Ruchill Water @ Cultybraggan

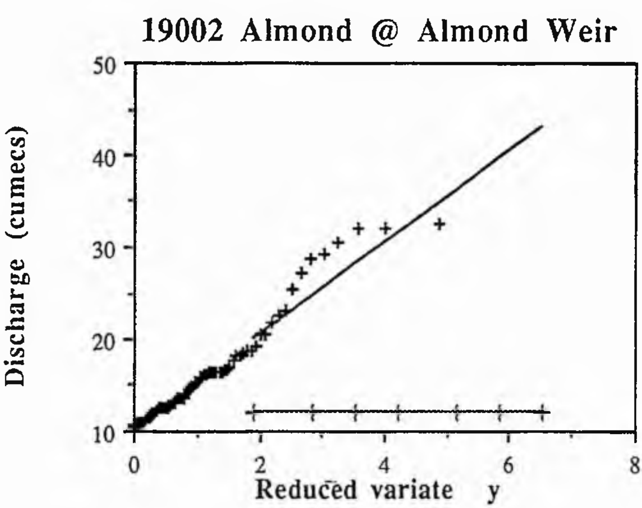


19001 Almond @ Craigiehall



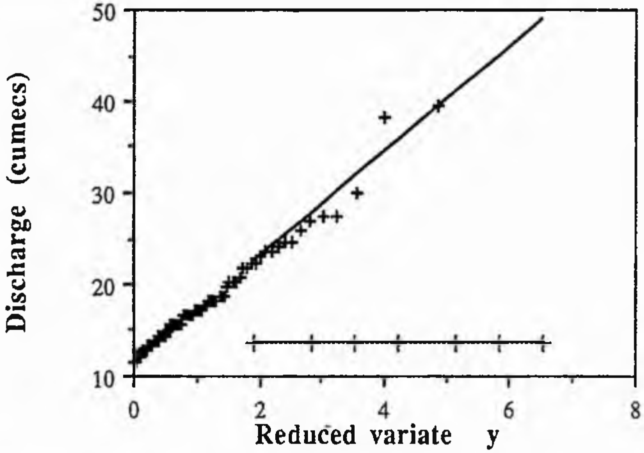


17001 Carron @ Headswood
Discharge (cumecs)
300
200
100
0
0
2
4
6
8
Reduced variate y

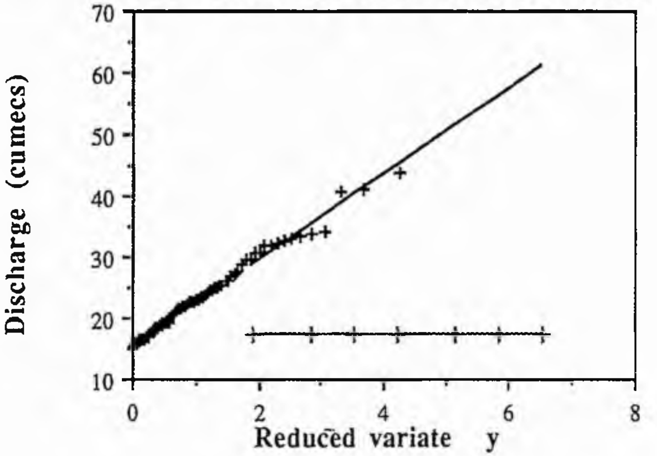


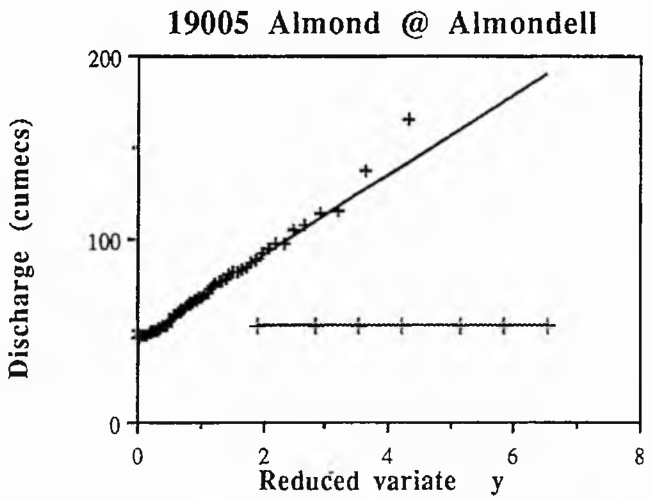
19002 Almond @ Almond Weir
Discharge (cumecs)
50
40
30
20
10
0
2
4
6
8
Reduced variate y

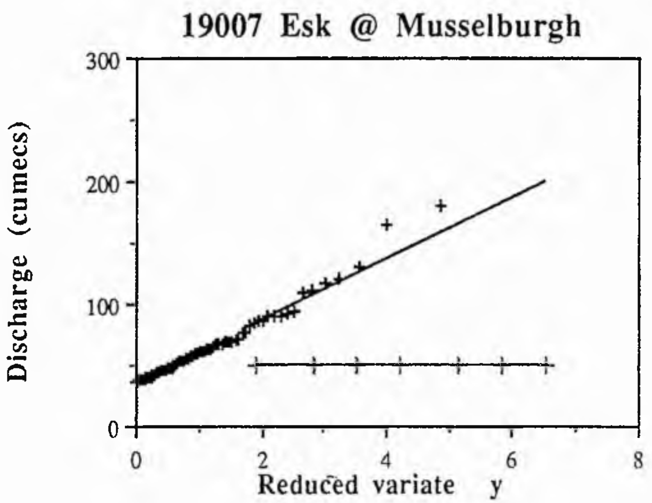
19004 North Esk @ Dalmore Weir



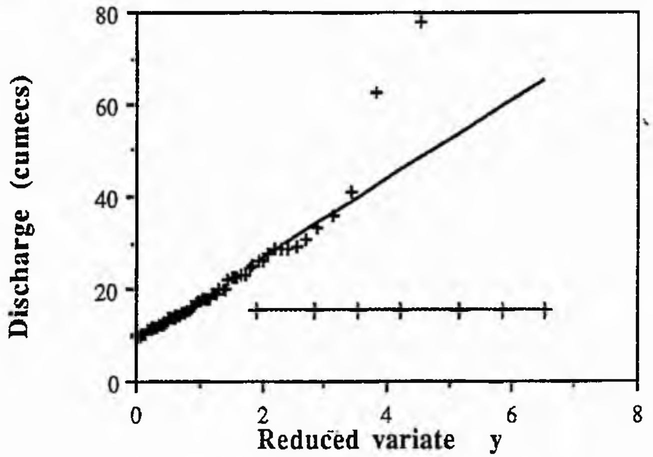
19006 Water of Leith @ Murrayfield



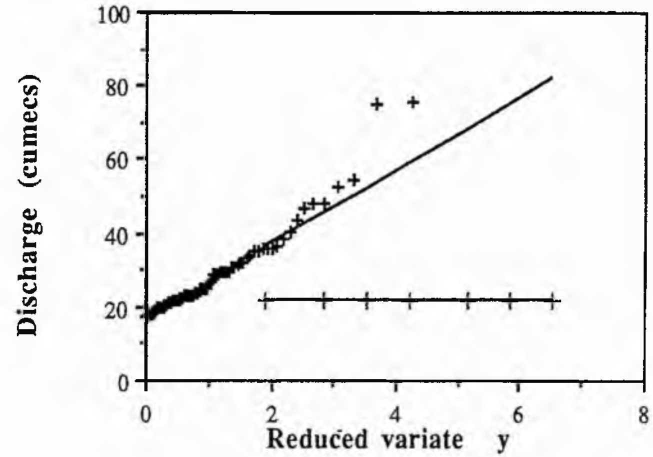

19005 Almond @ Almondell
Discharge (cumecs)
200
100
0
0
2
4
6
8
Reduced variate y


19007 Esk @ Musselburgh
Discharge (cumecs)
300
200
100
0
0
2
4
6
8
Reduced variate y

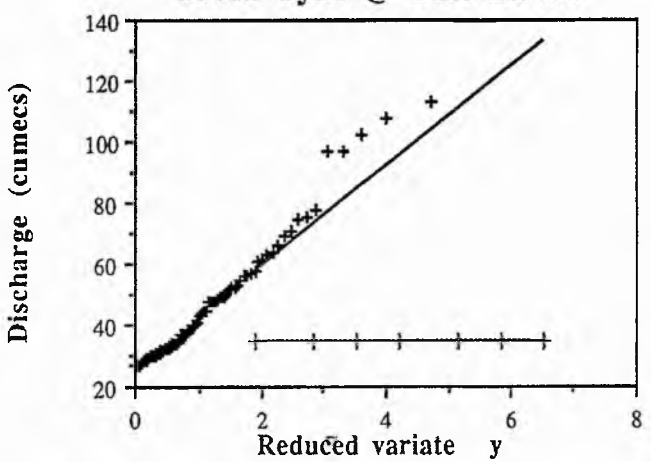
19008 South Esk @ Prestonholm



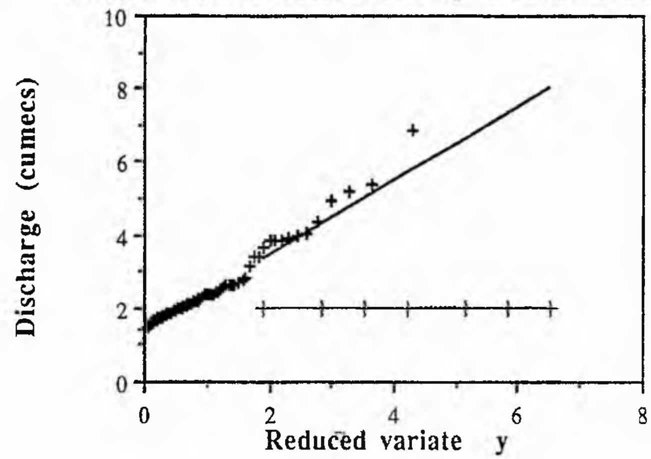
19011 North Esk @ Dalkeith Palace



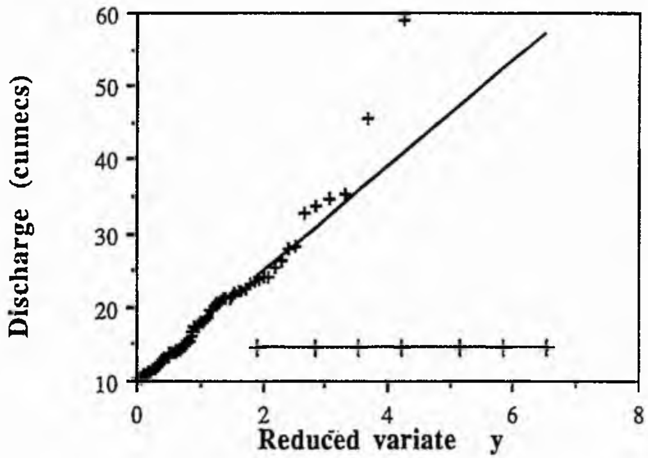
20001 Tyne @ East Linton



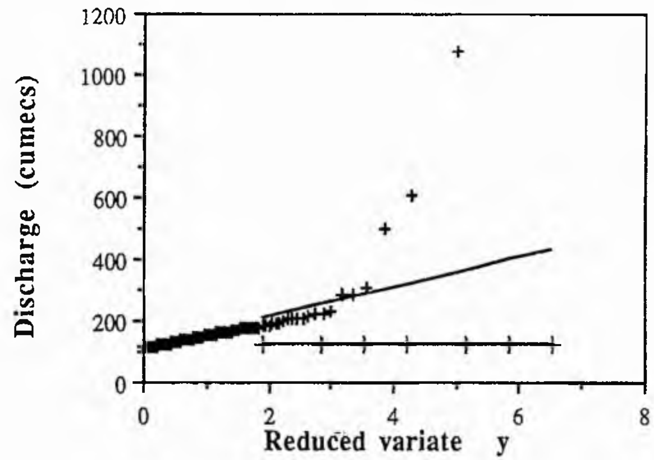
20002 West Peffer Burn @ Luffness Mains



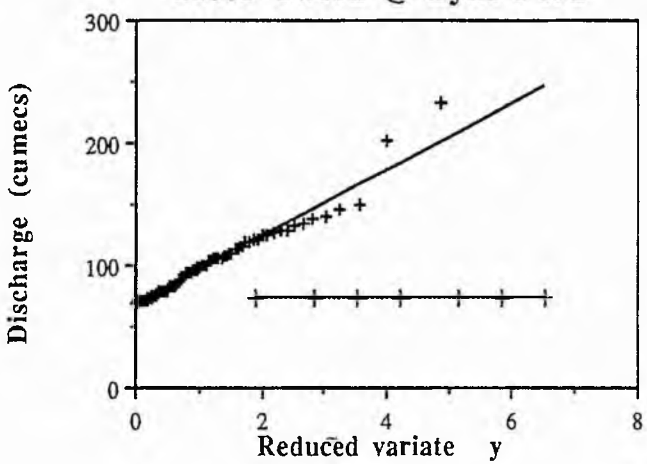
20005 Birns Water @ Saltoun Hall



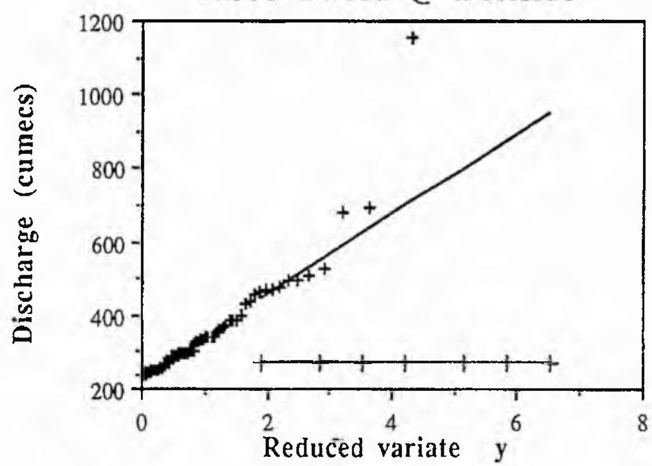
21003 Tweed @ Peebles



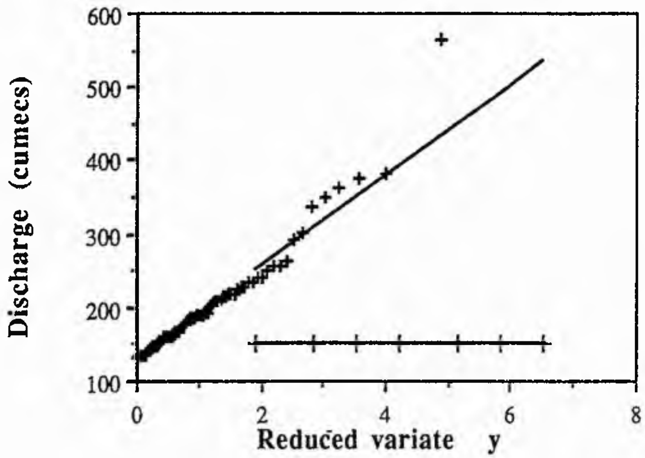
21005 Tweed @ Lyne Ford



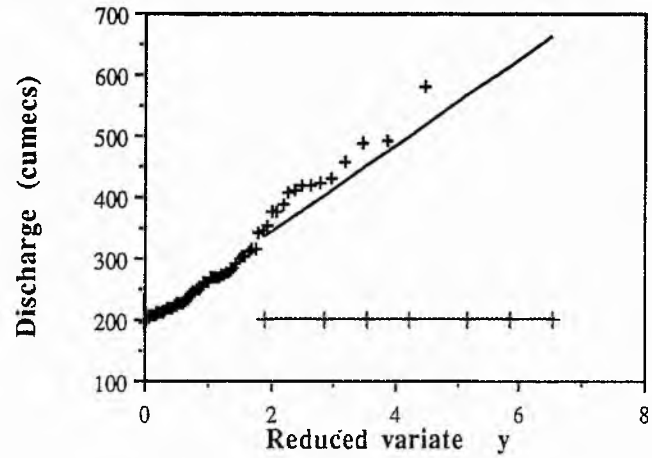
21006 Tweed @ Boleside



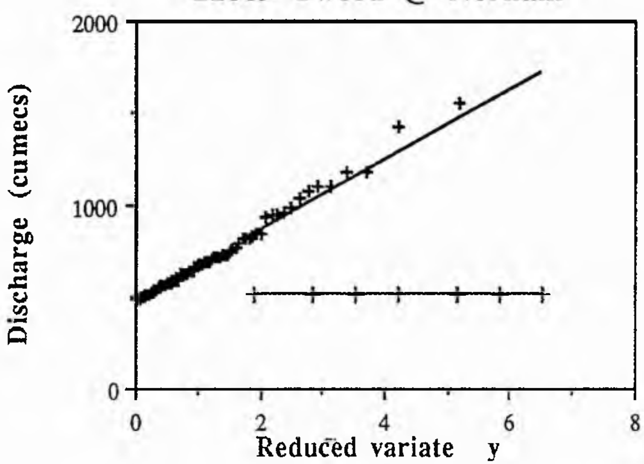
21007 Ettrick @ Lindean



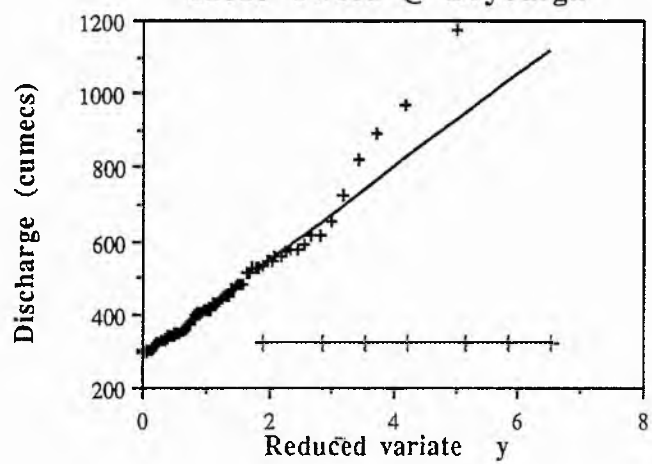
21008 Teviot @ Ormiston Mill



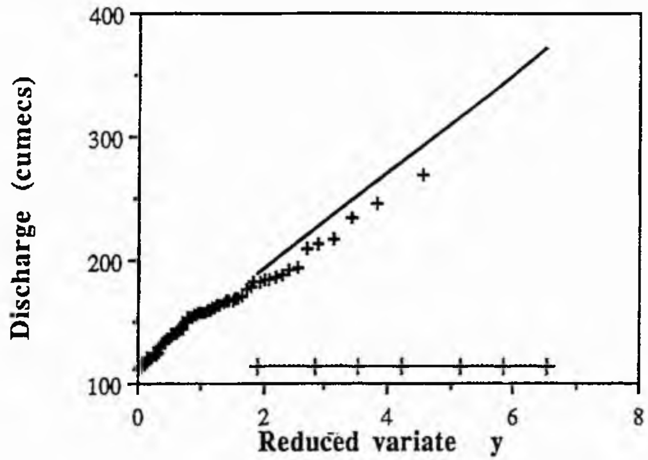
21009 Tweed @ Norham



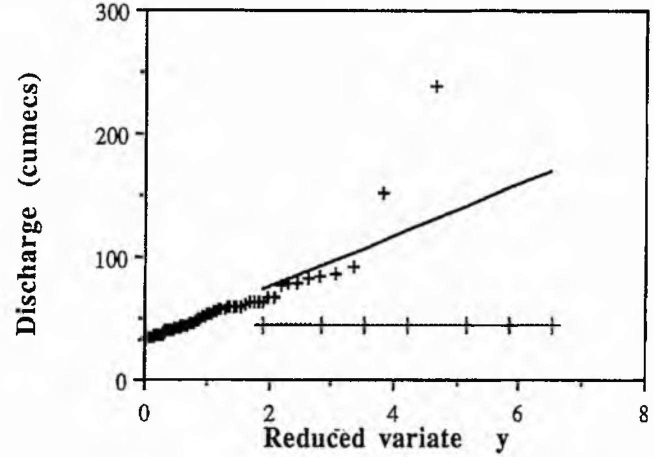
21010 Tweed @ Dryburgh



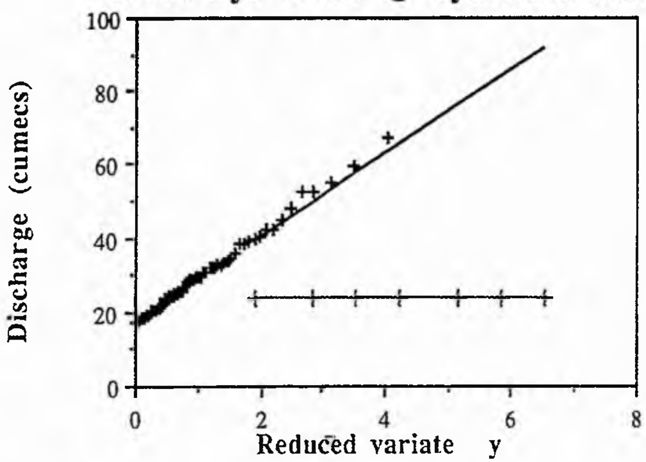
21012 Teviot @ Hawick



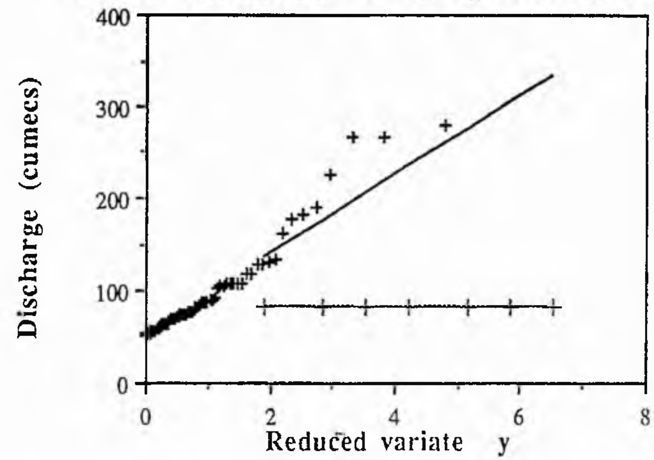
21015 Leader Water @ Earlston



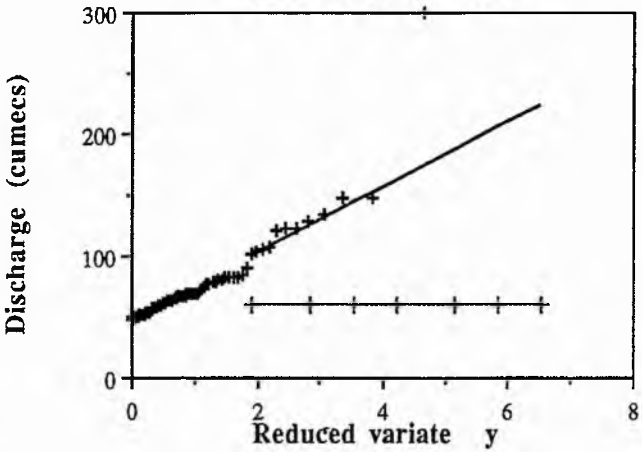
21016 Eye Water @ Eyemouth Mill



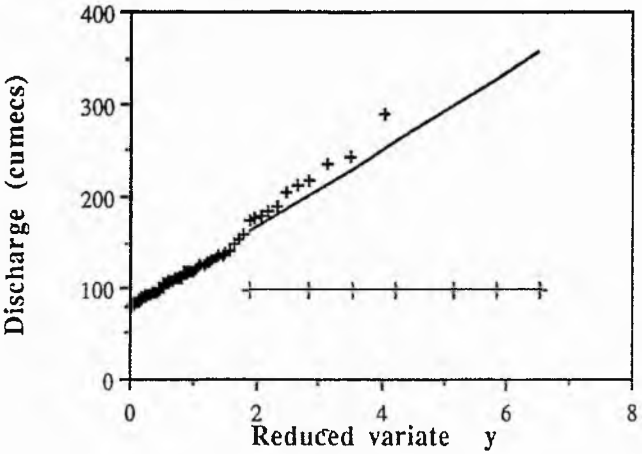
21022 Whiteadder Water @ Hutton Castle



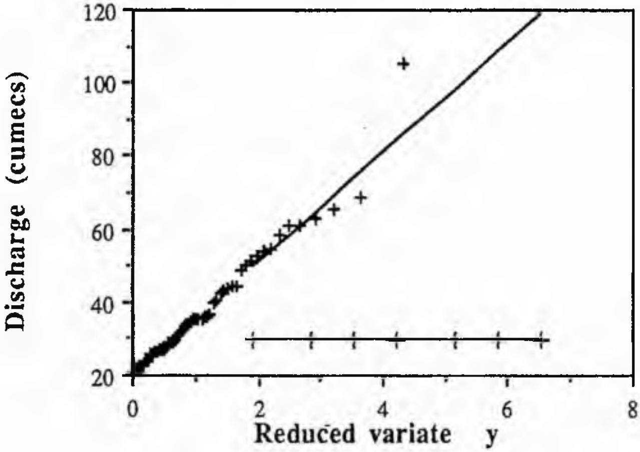
21031 Till @ Etal



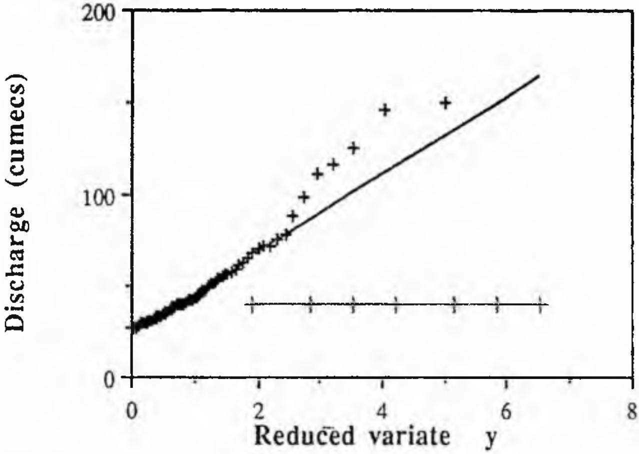
22001 Coquet @ Morwick



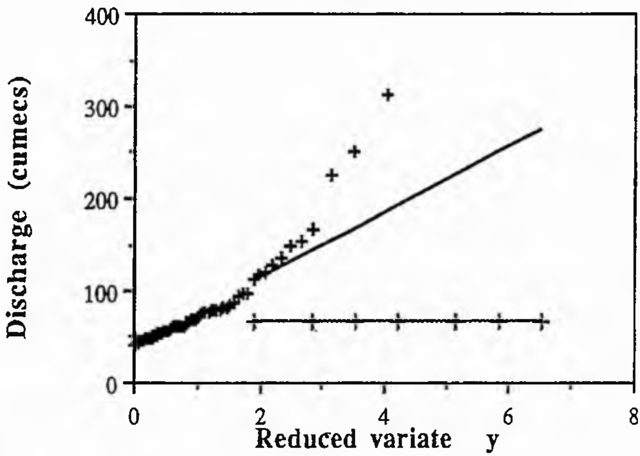
21032 Glen @ Kirknewton



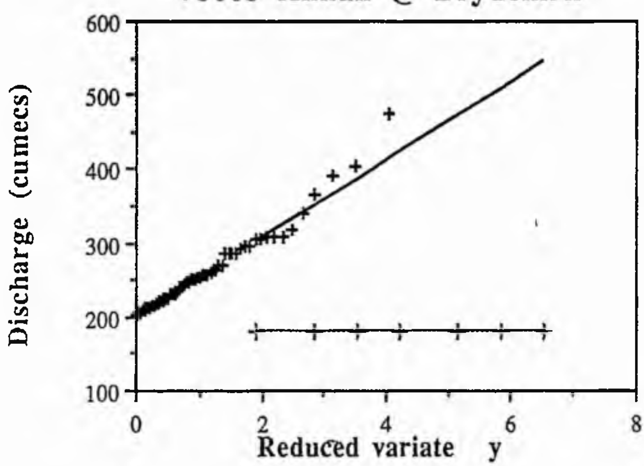
22006 Blyth @ Hartford Bridge

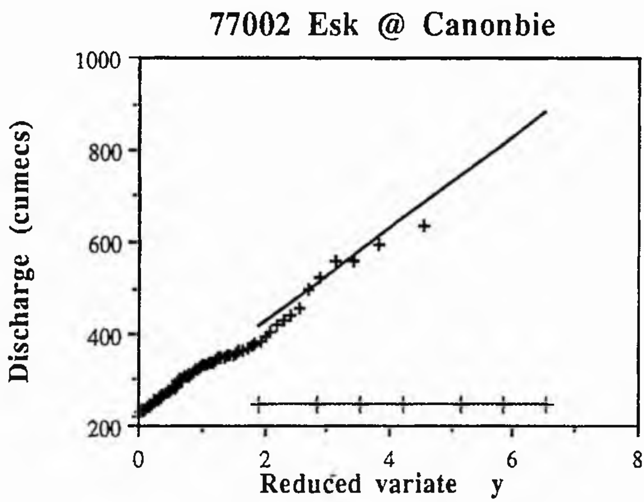


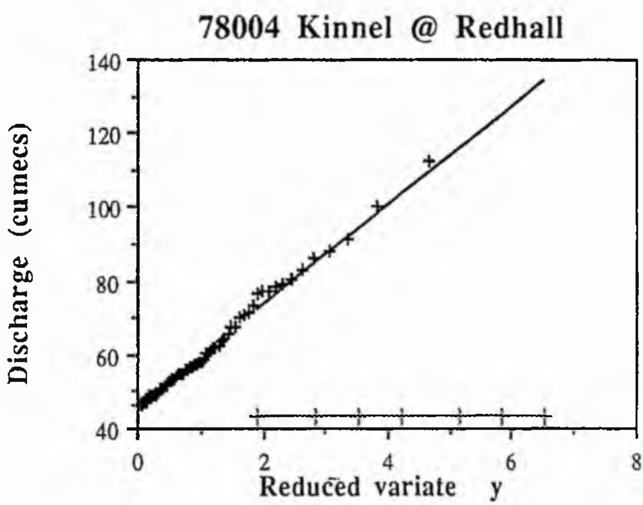
22007 Wansbeck @ Mitford



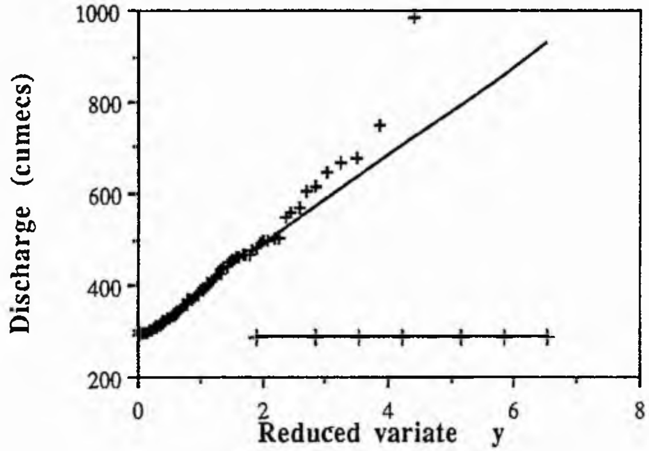
78003 Annan @ Brydekirk



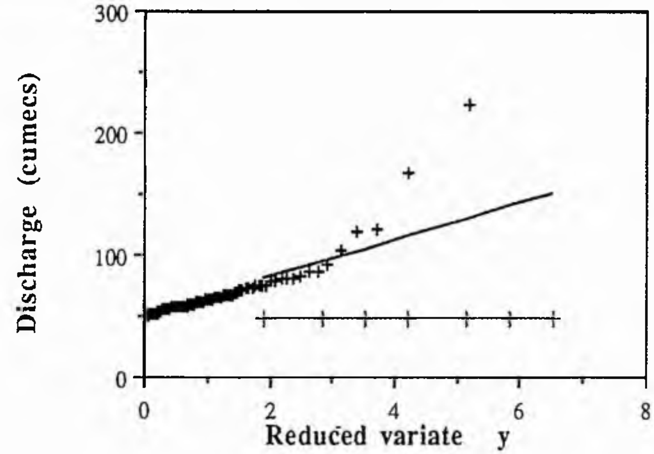

77002 Esk @ Canonbie
Discharge (cumecs)
1000
800
600
400
200
0
2
4
6
8
Reduced variate y


78004 Kinnel @ Redhall
Discharge (cumecs)
140
120
100
80
60
40
0
2
4
6
8
Reduced variate y

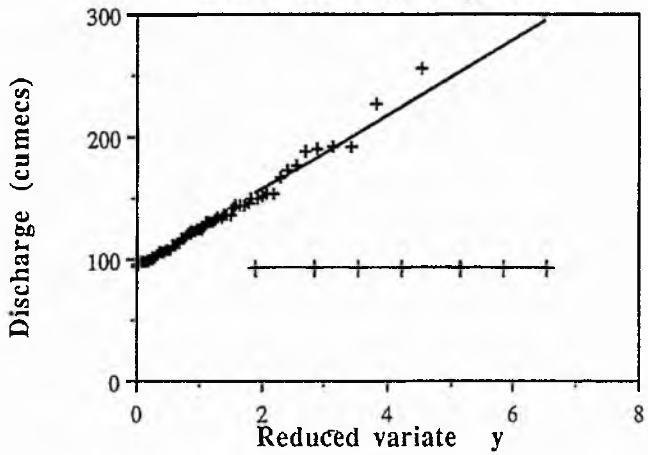
79002 Nith @ Friar's Carse



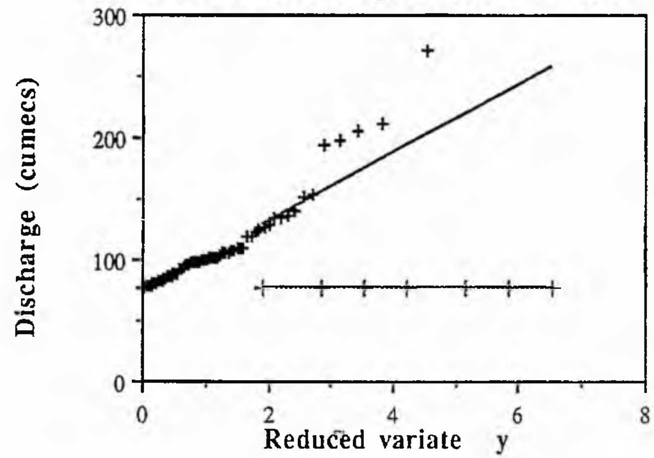
79003 Nith @ Hall Bridge



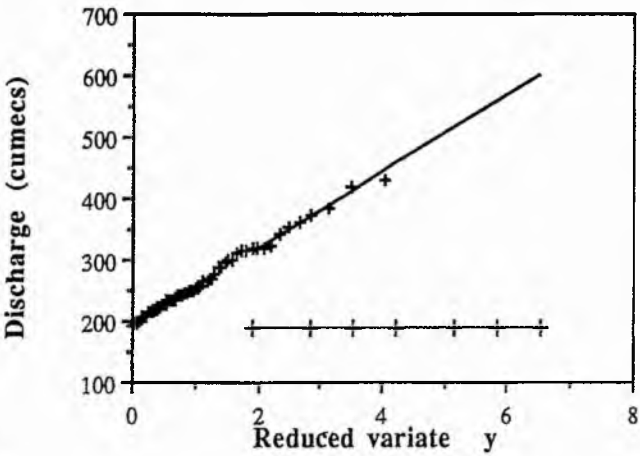
79004 Scar @ Capenoch



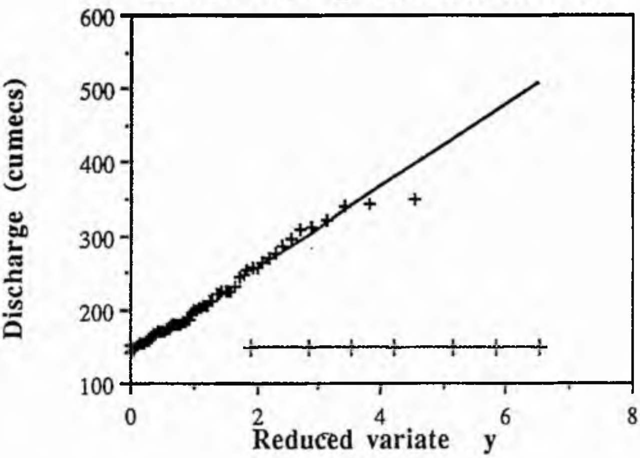
79005 Cluden @ Fiddler's Ford



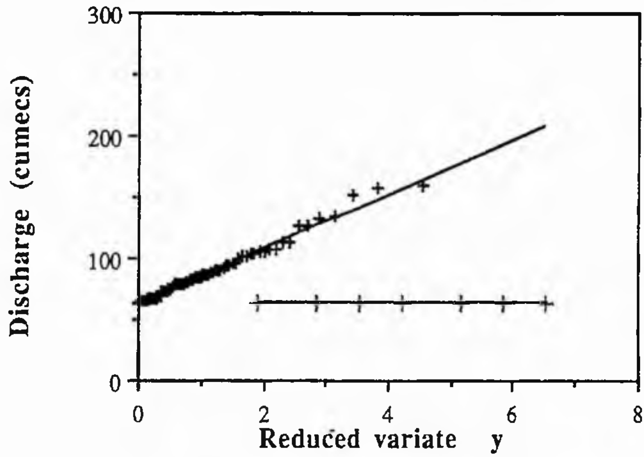
79006 Nith @ Drumlanrig



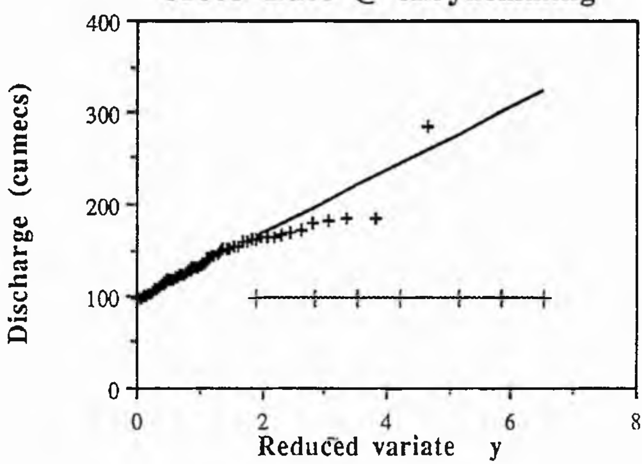
81002 Cree @ Newton Stewart



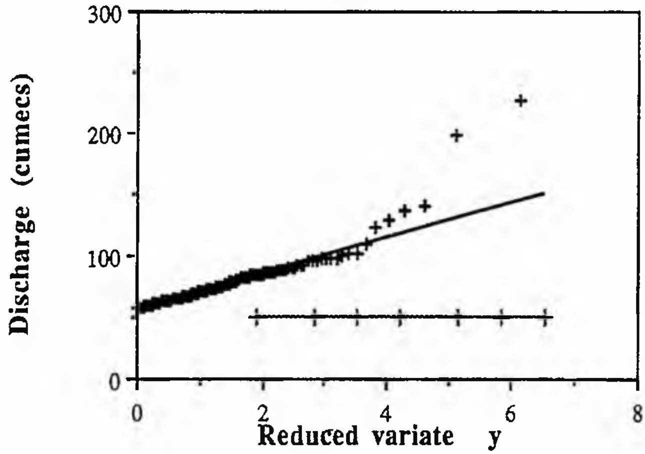
80001 Urr @ Dalbeattie



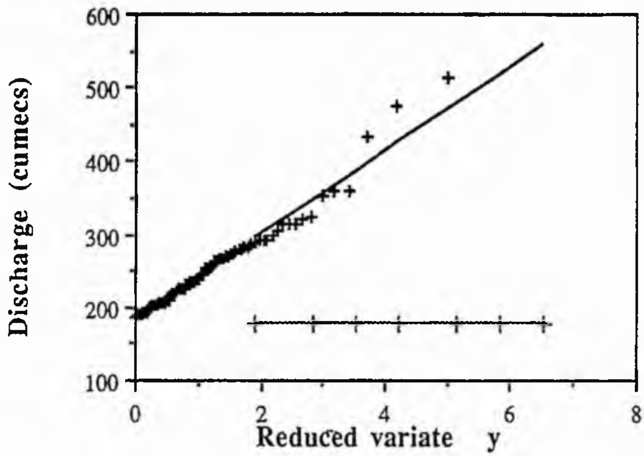
81003 Luce @ Airyhemming

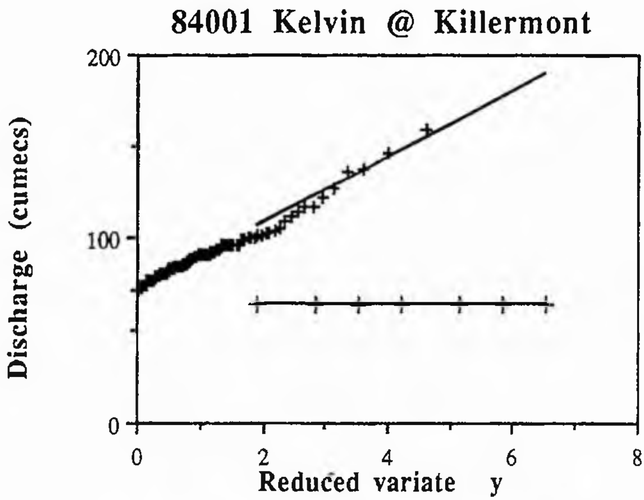


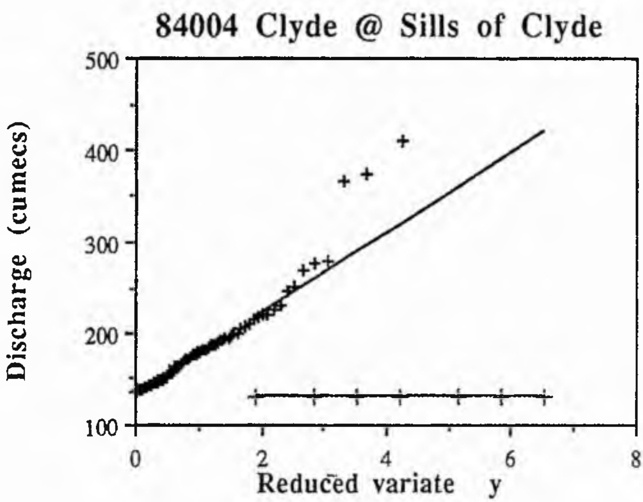
83802 Irvine @ Glenfield



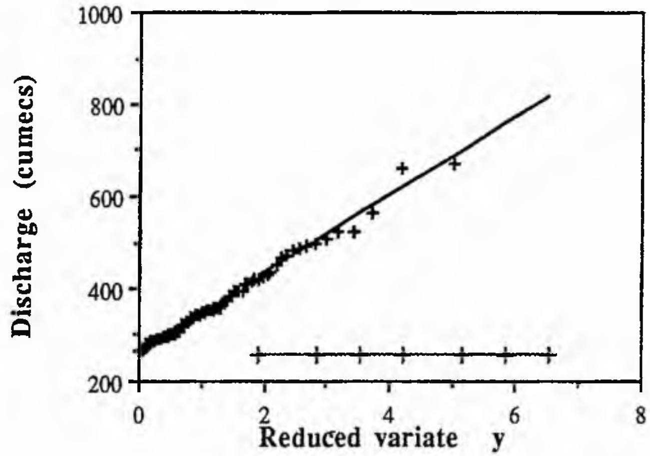
84003 Clyde @ Hazelbank



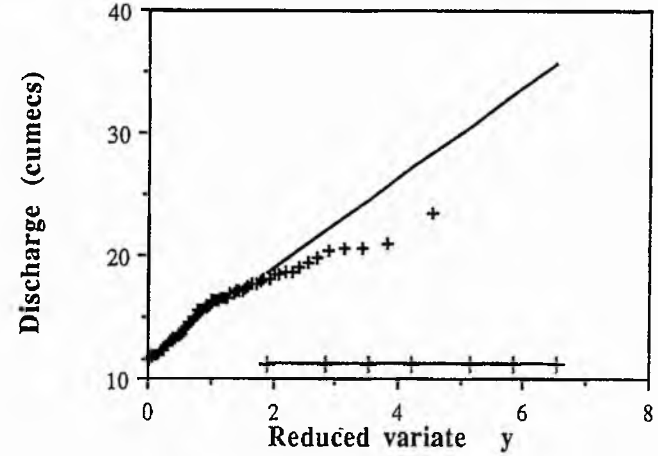

84001 Kelvin @ Killermont
Discharge (cumecs)
200
100
0
0
2
4
6
8
Reduced variate y


84004 Clyde @ Sills of Clyde
Discharge (cumecs)
500
400
300
200
100
0
2
4
6
8
Reduced variate y

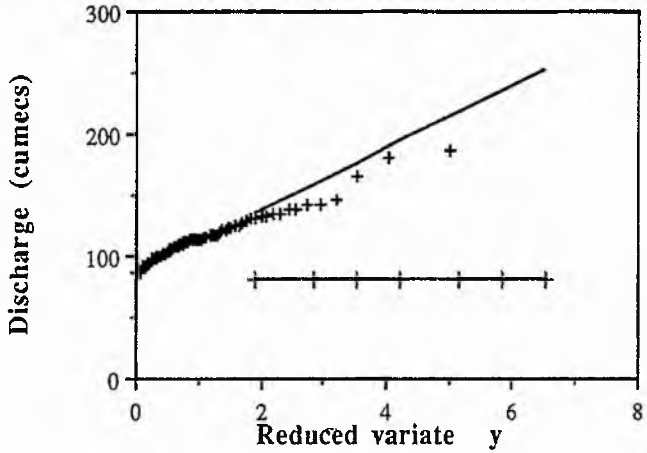
84005 Clyde @ Blairston



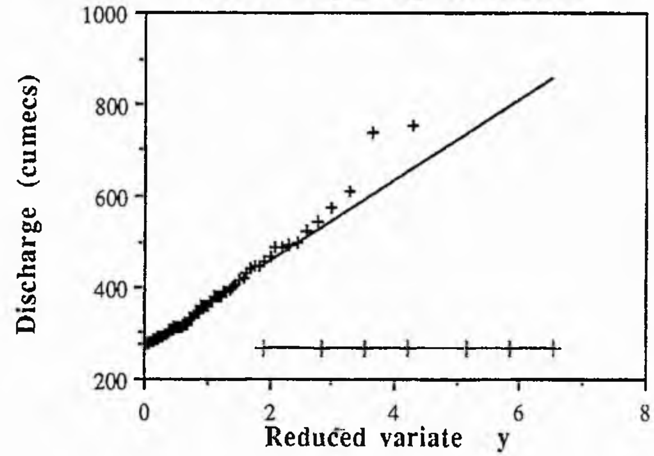
84006 Kelvin @ Bridgend



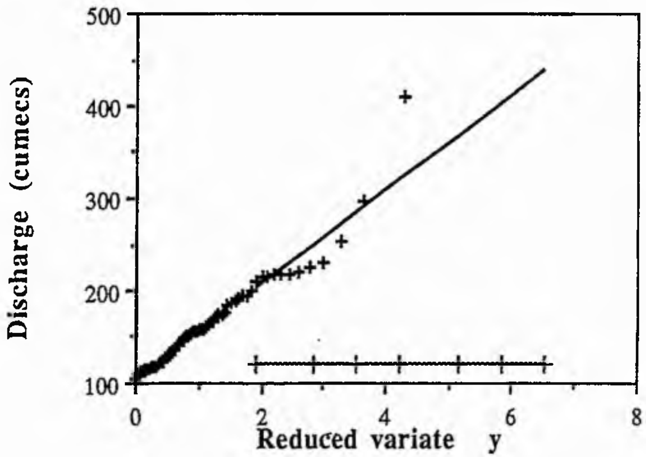
84012 White Cart Water @ Hawkhead



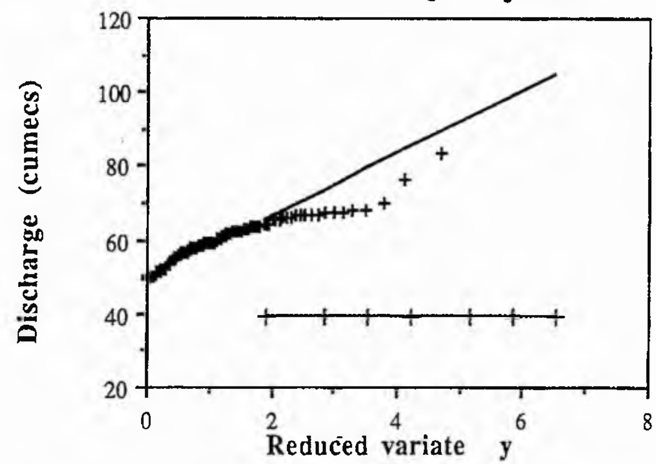
84013 Clyde @ Daldowie



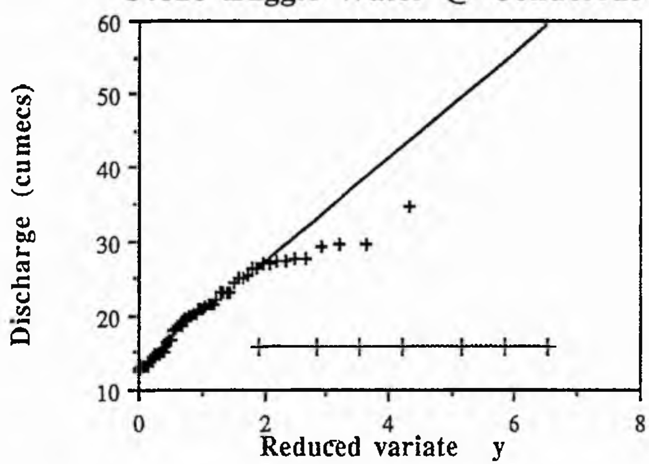
84014 Avon Water @ Fairholm



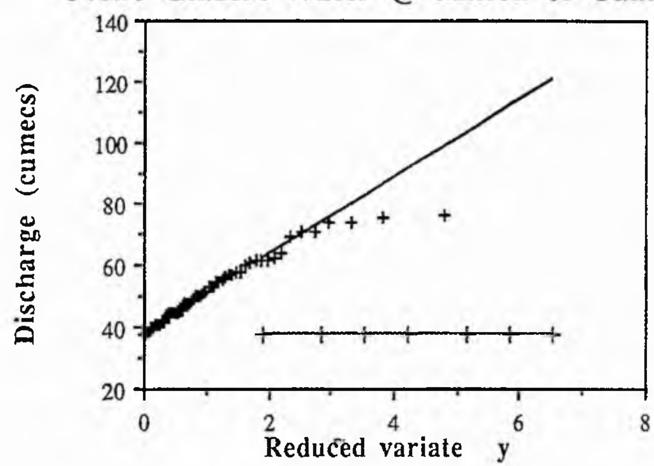
84015 Kelvin @ Dryfield



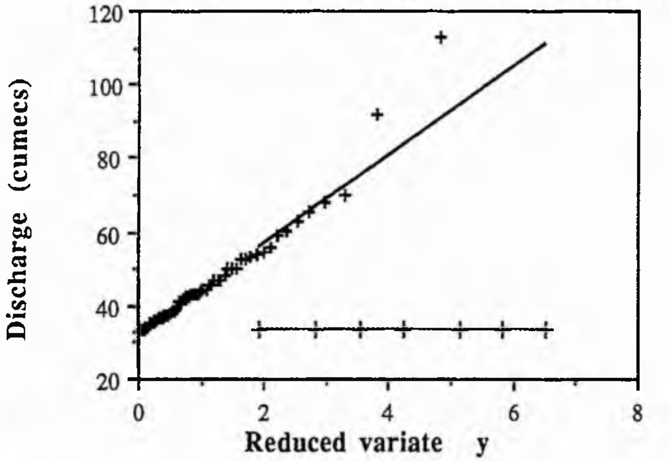
84016 Luggie Water @ Condorrat



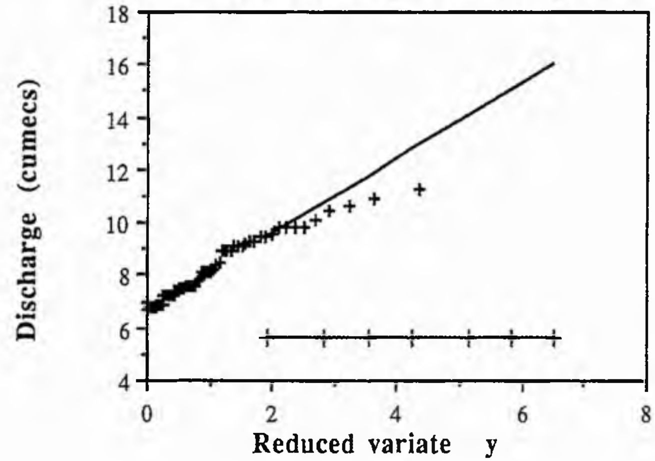
84020 Glazert Water @ Milton of Campsie



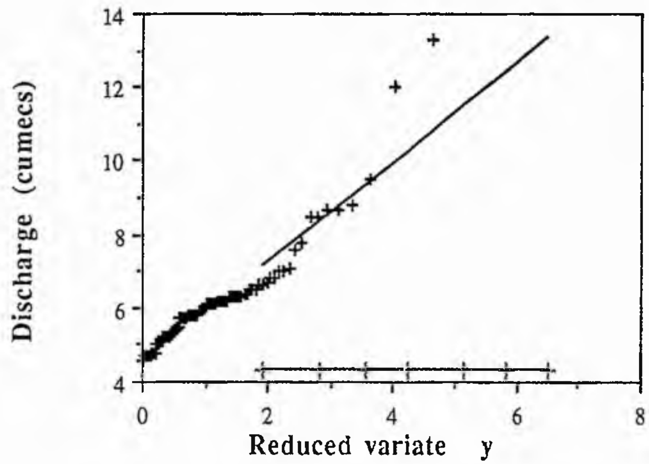
86001 Little Eachaig @ Dalinlongart



87801 Allt Uaine @ Loch Sloy Intake



91802 Allt Leachdach @ Intake



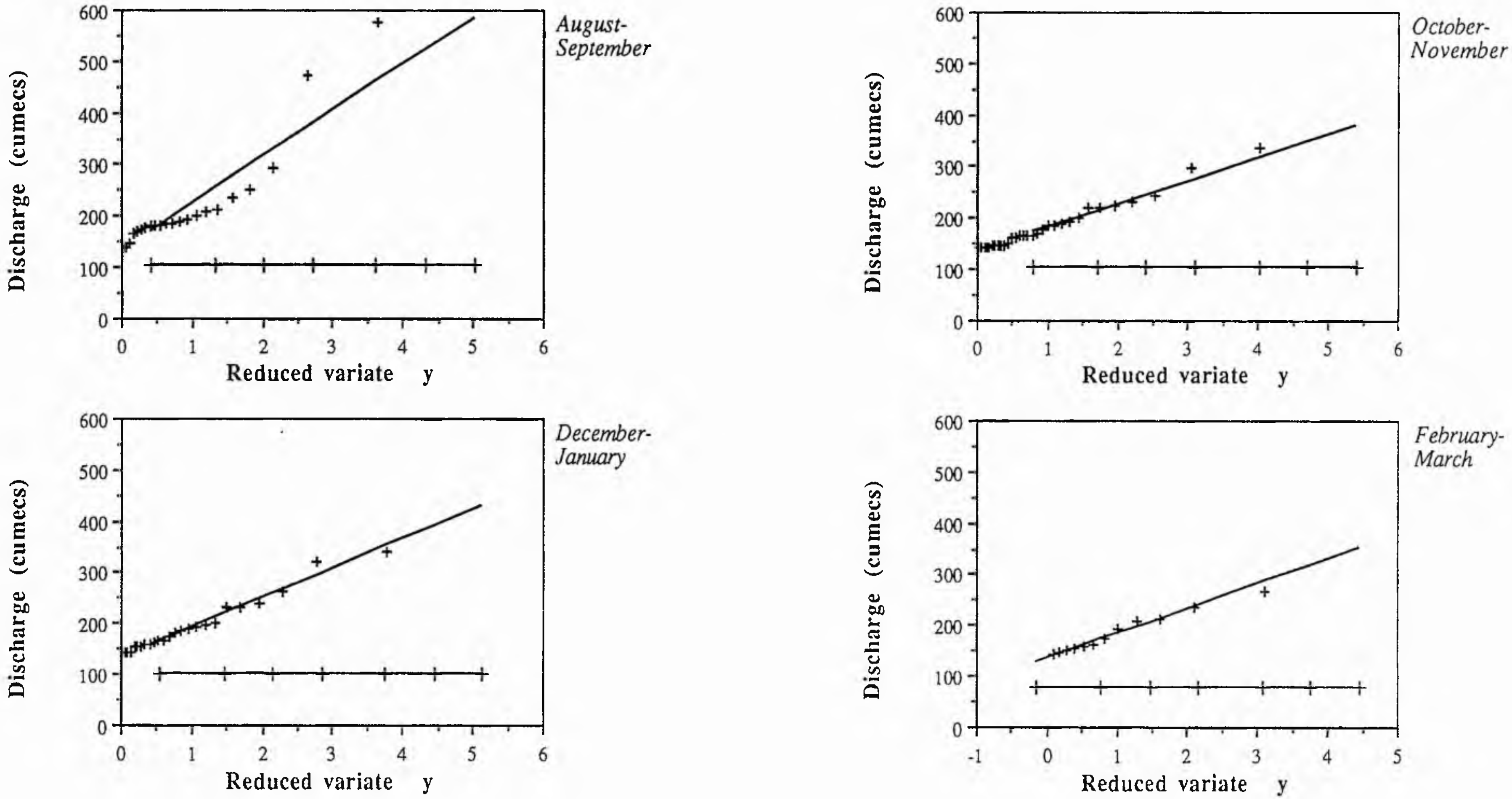
Appendix H

Frequency distributions for seasonal groups

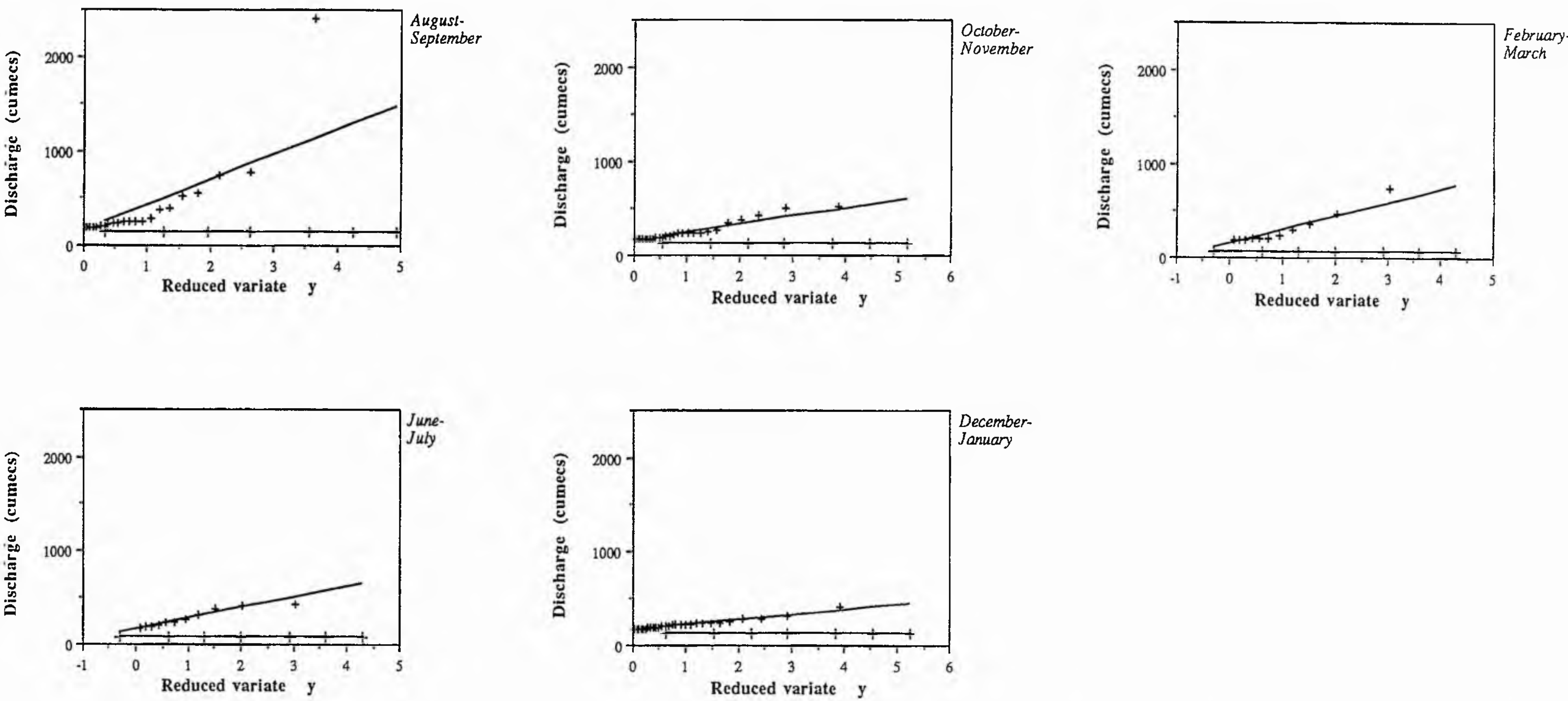
Graphs are produced for every 2-month season in which 10 or more peaks exceeding the revised threshold are present in the record available.

Upper horizontal axis indicates return periods of 2, 5, 10, 20, 50, 100 and 200 years.

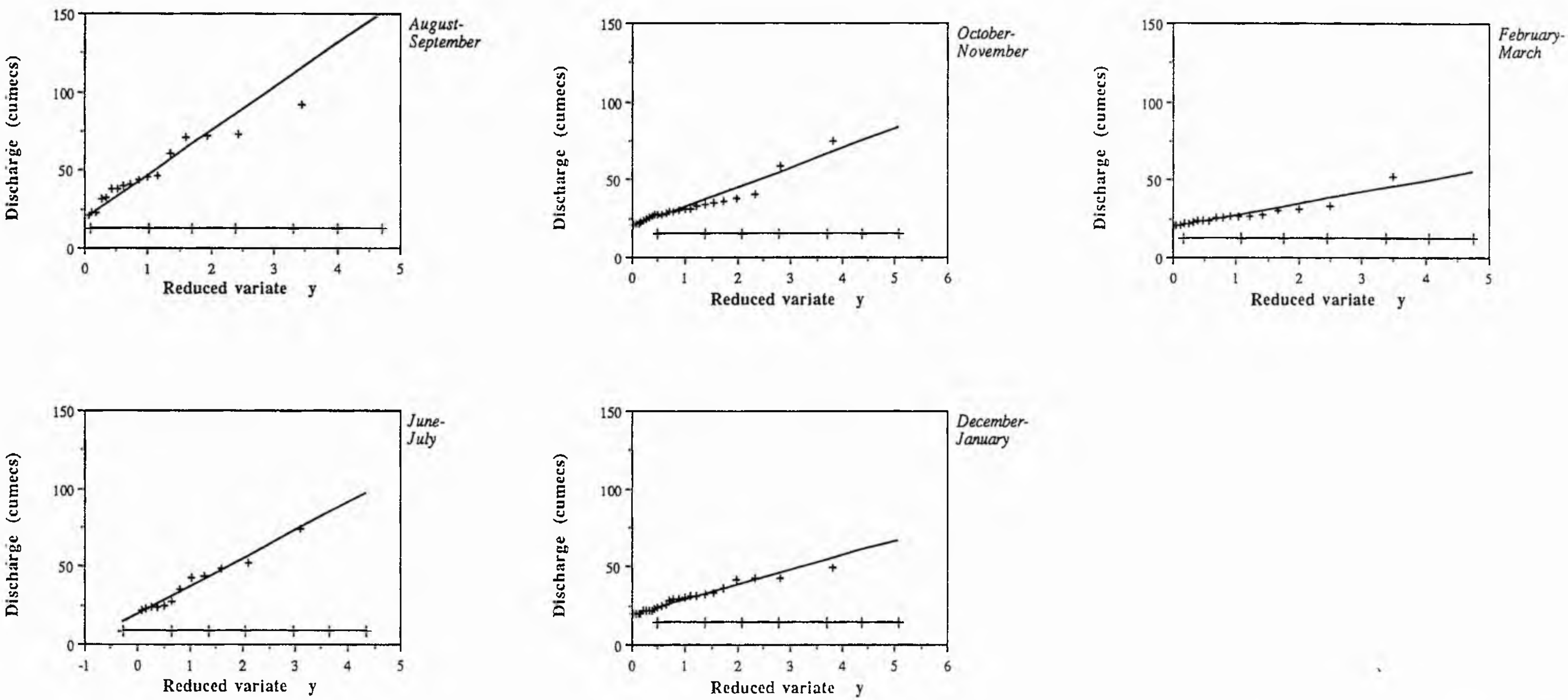
Seasonal frequency distributions for station 07001 Findhorn @ Shenachie



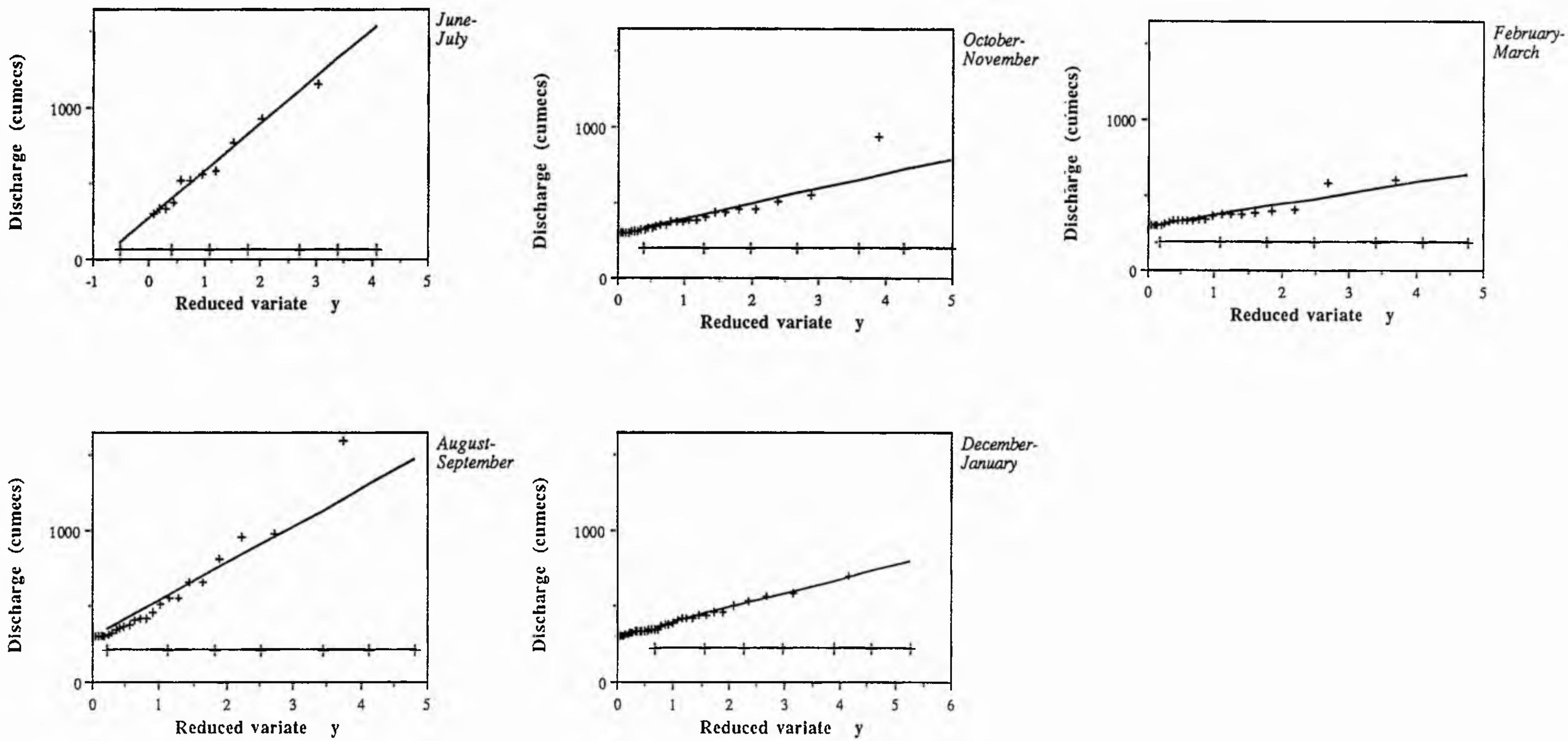
Seasonal frequency distributions for station 07002 Findhorn @ Forres



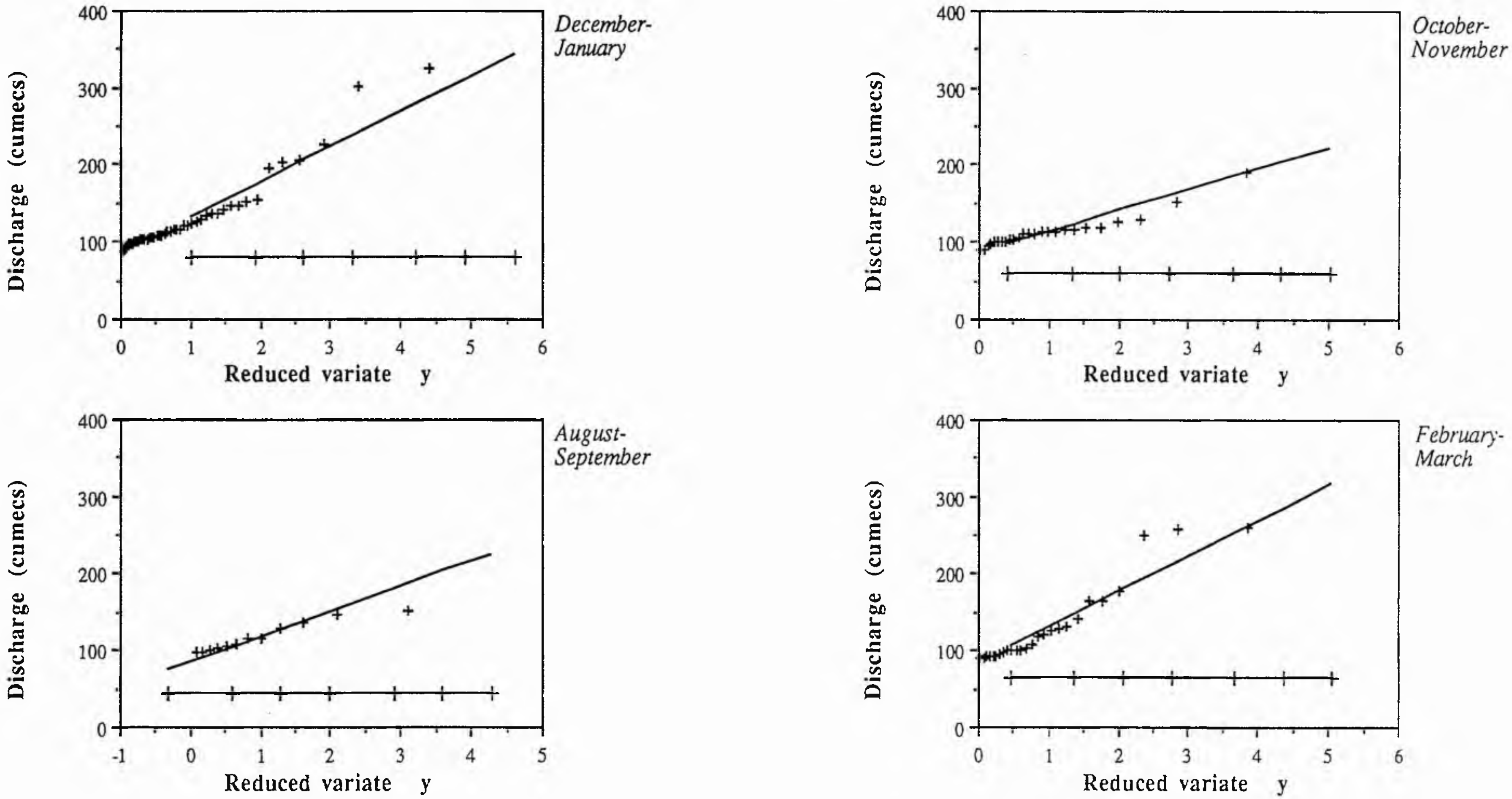
Seasonal frequency distributions for station 07003 Lossie @ Sherriff Mills



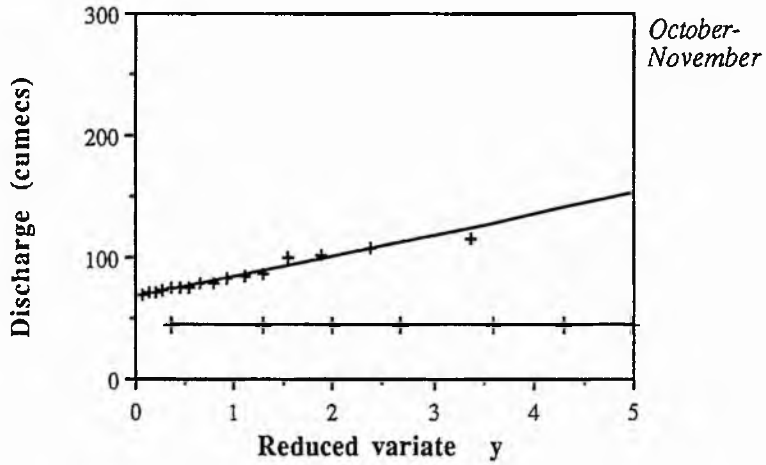
Seasonal frequency distributions for station
08001 Spey @ Aberlour

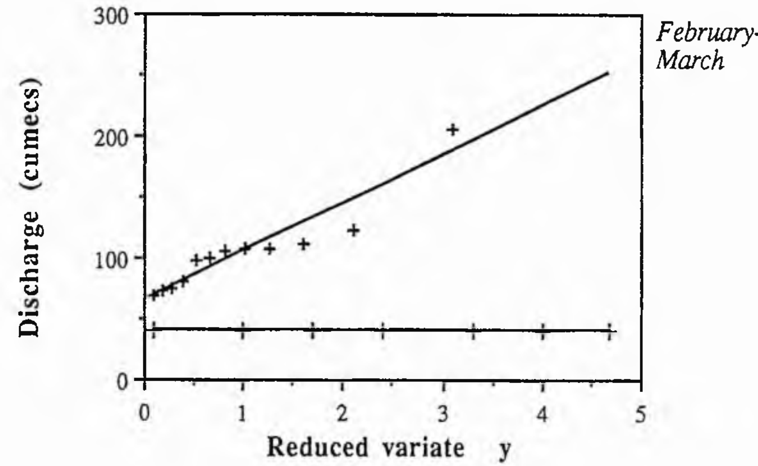


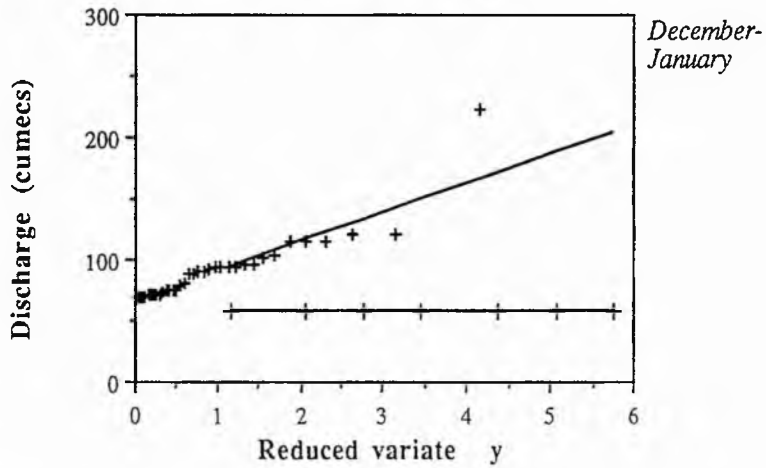
Seasonal frequency distributions for station 08002 Spey @ Kinrara



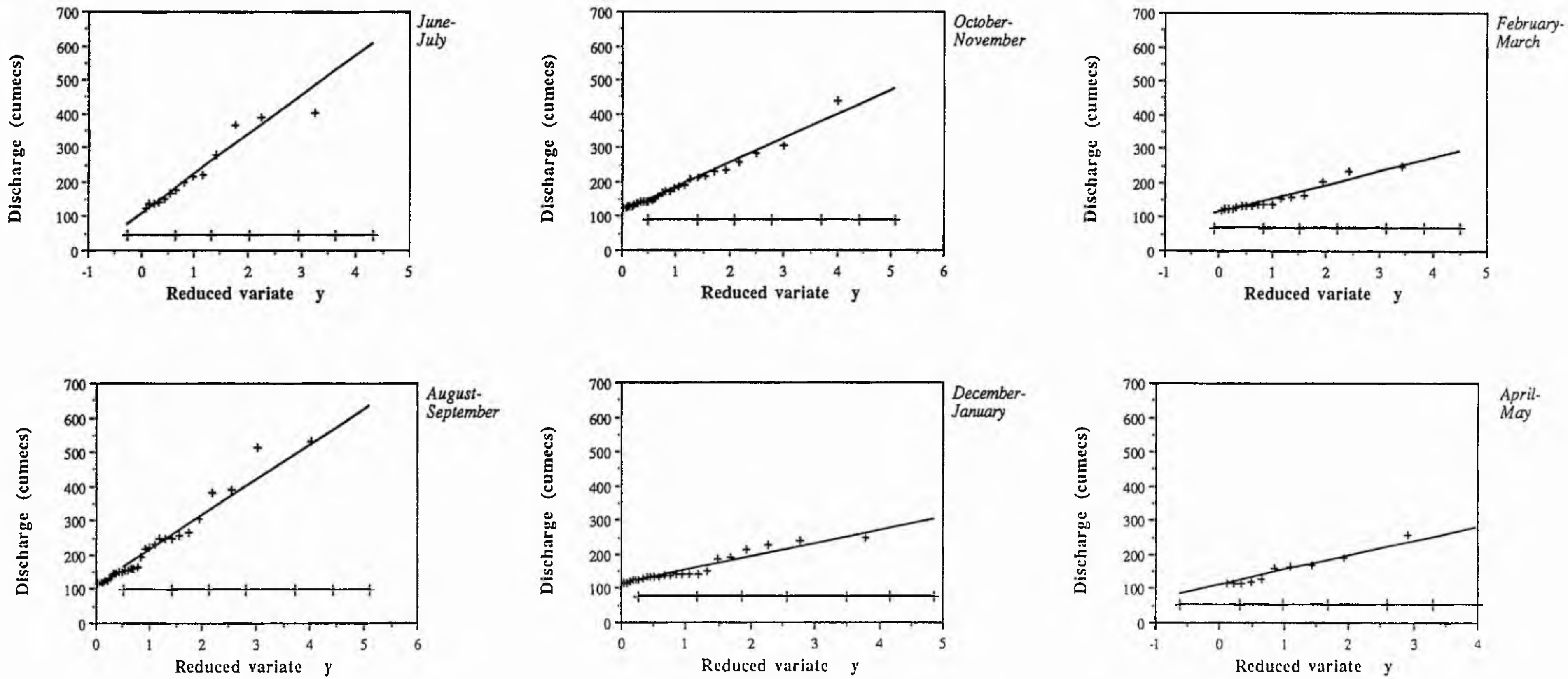
Seasonal frequency distributions for station
08003 Spey @ Ruthven Bridge



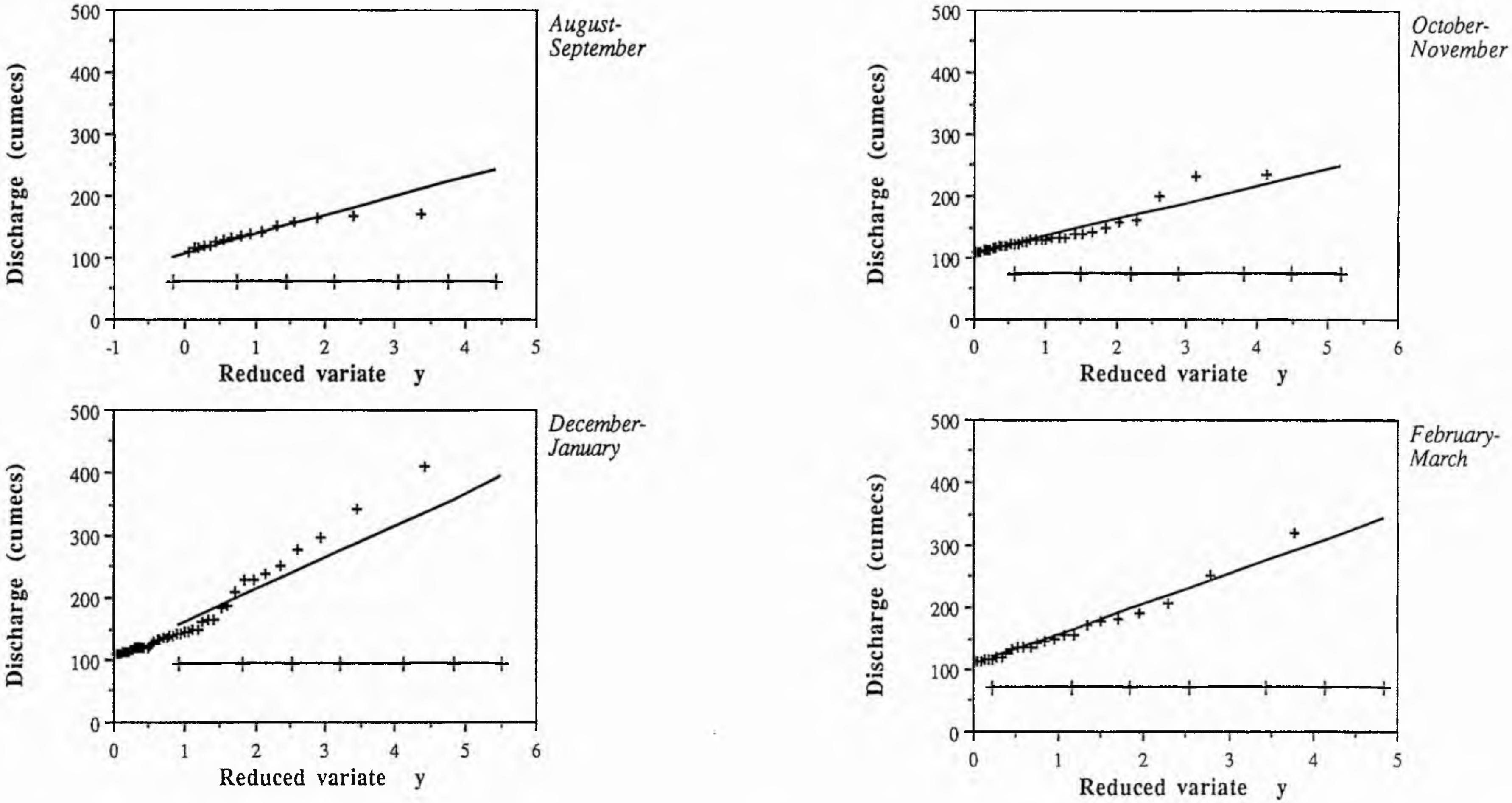




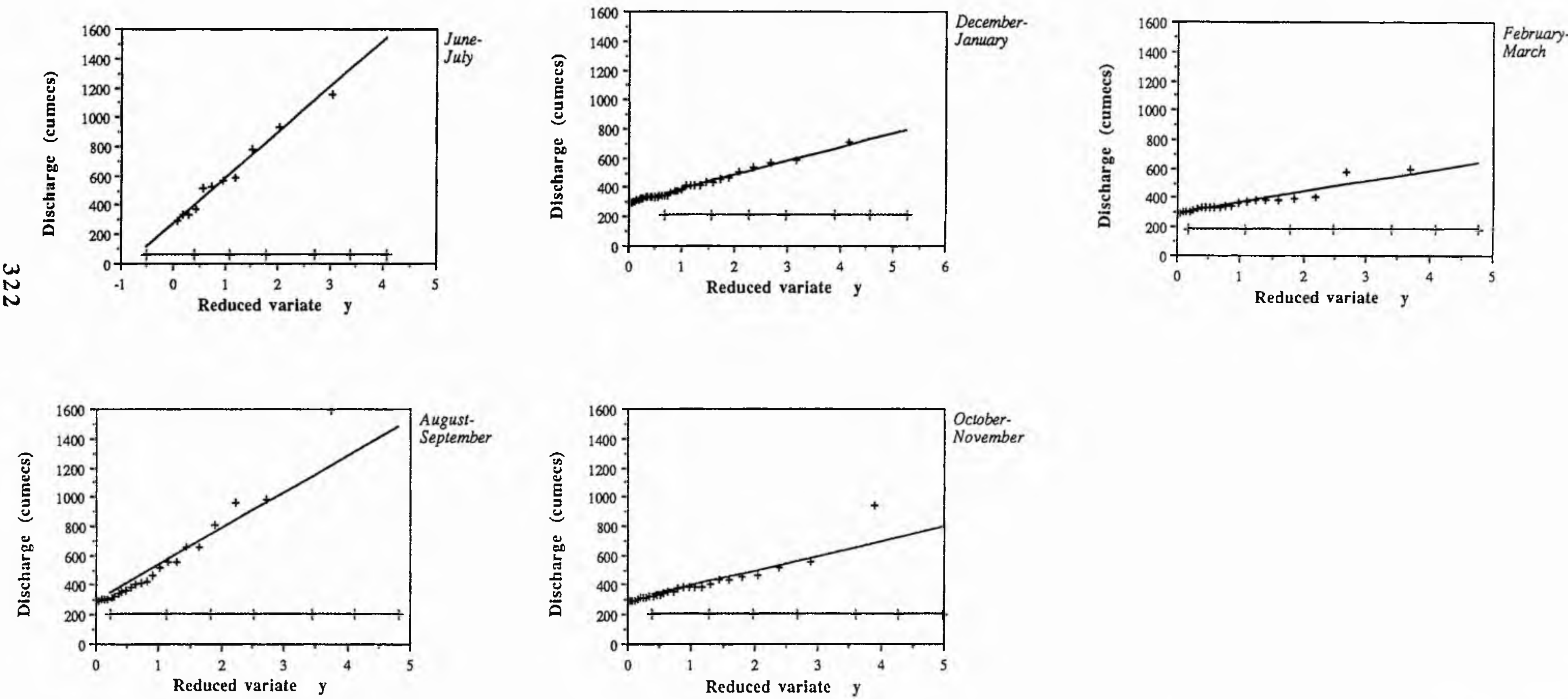
Seasonal frequency distributions for station 08004 Avon @ Delnashaugh



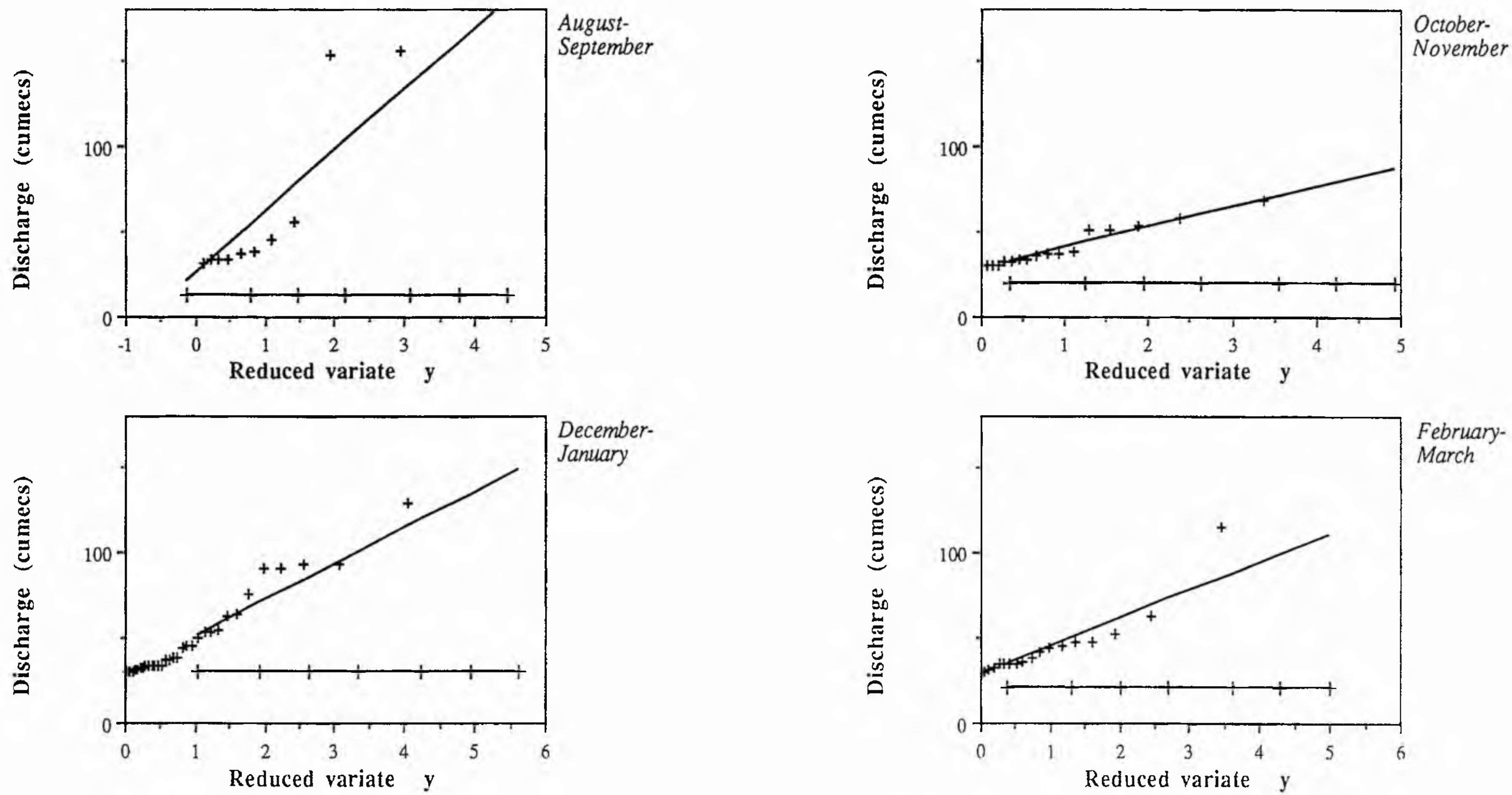
Seasonal frequency distributions for station 08005 Spey @ Boat of Garten



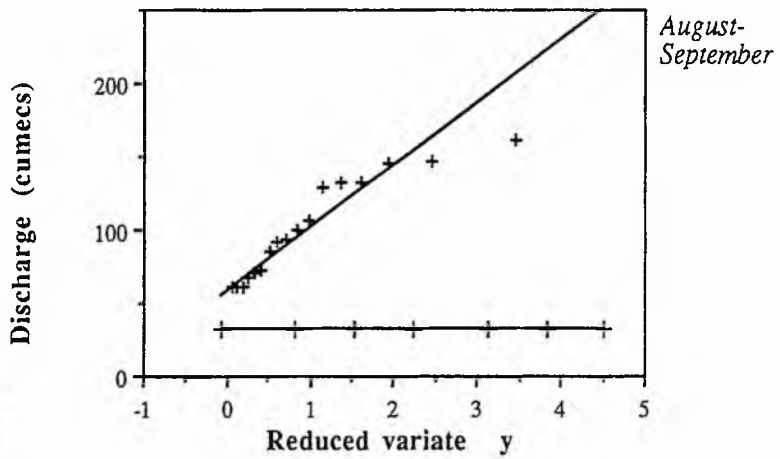
Seasonal frequency distributions for station 08006 Spey @ Boat o' Brig

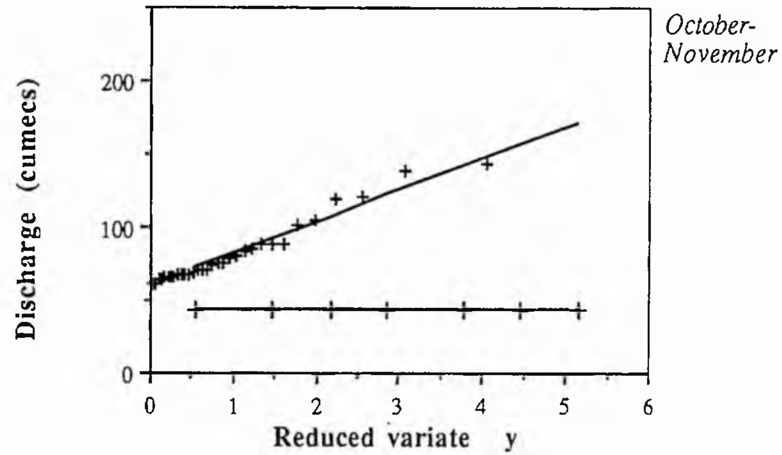


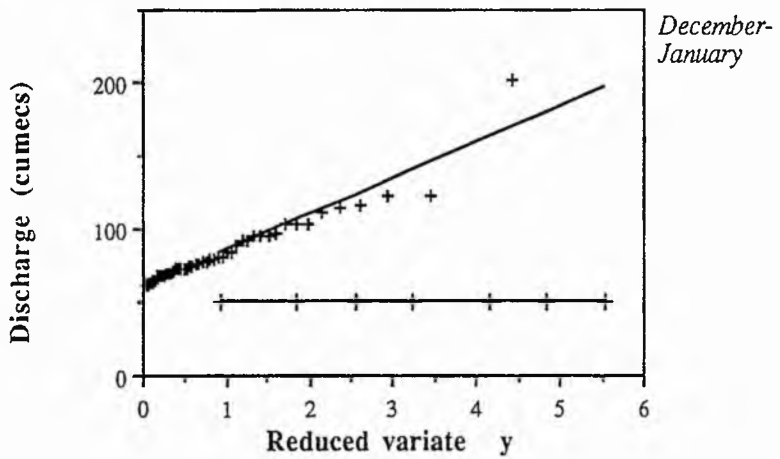
Seasonal frequency distributions for station 08008 Tromie @ Tromie Bridge

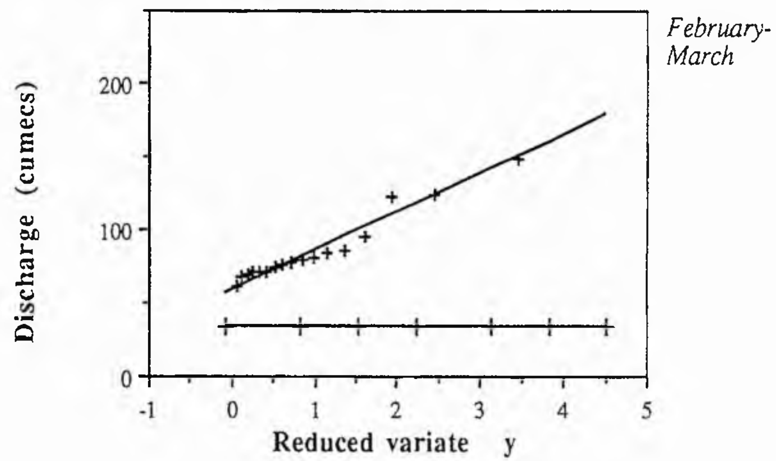


Seasonal frequency distributions for station 08009 Dulnain @ Balnaan Bridge

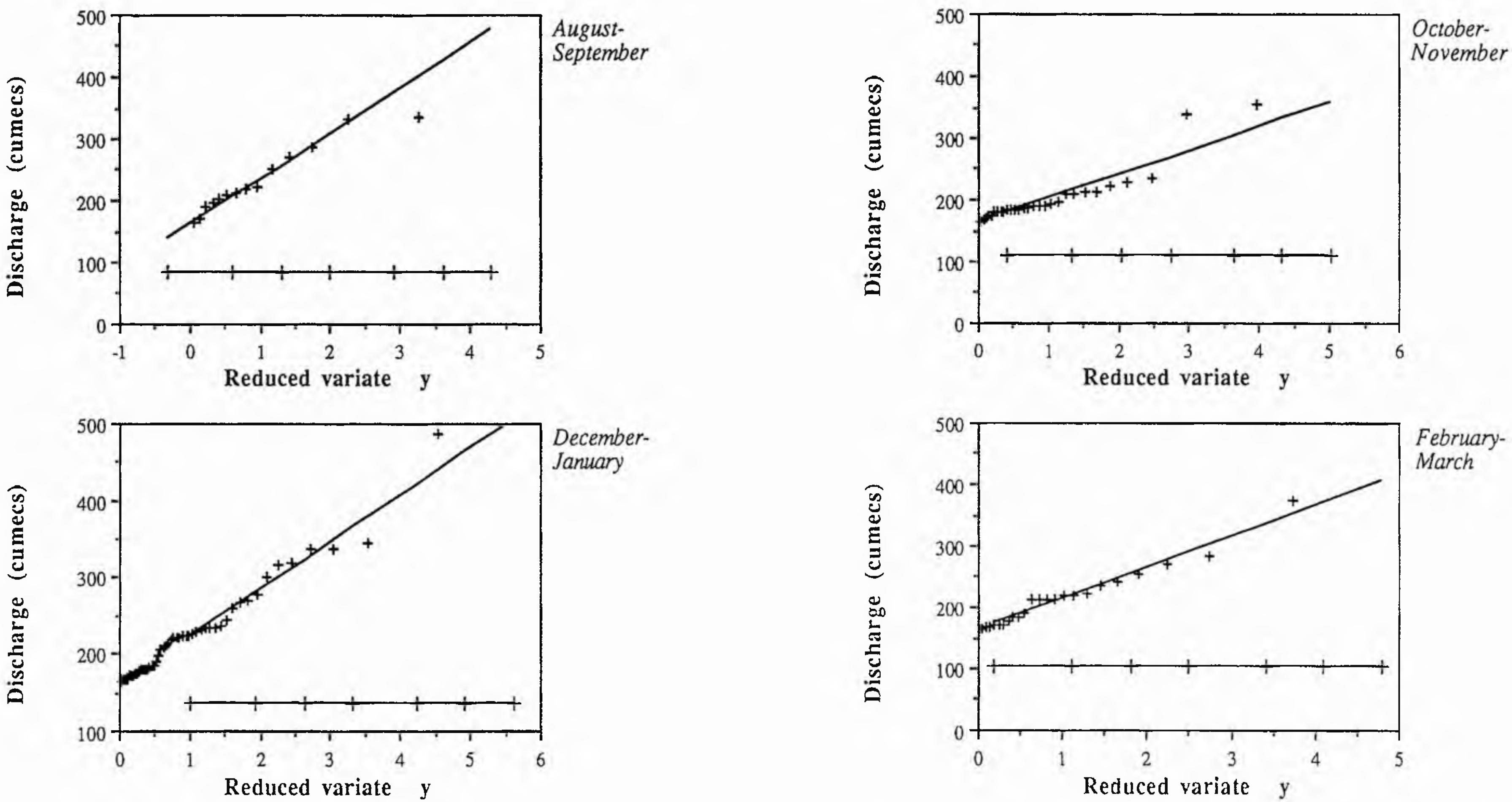




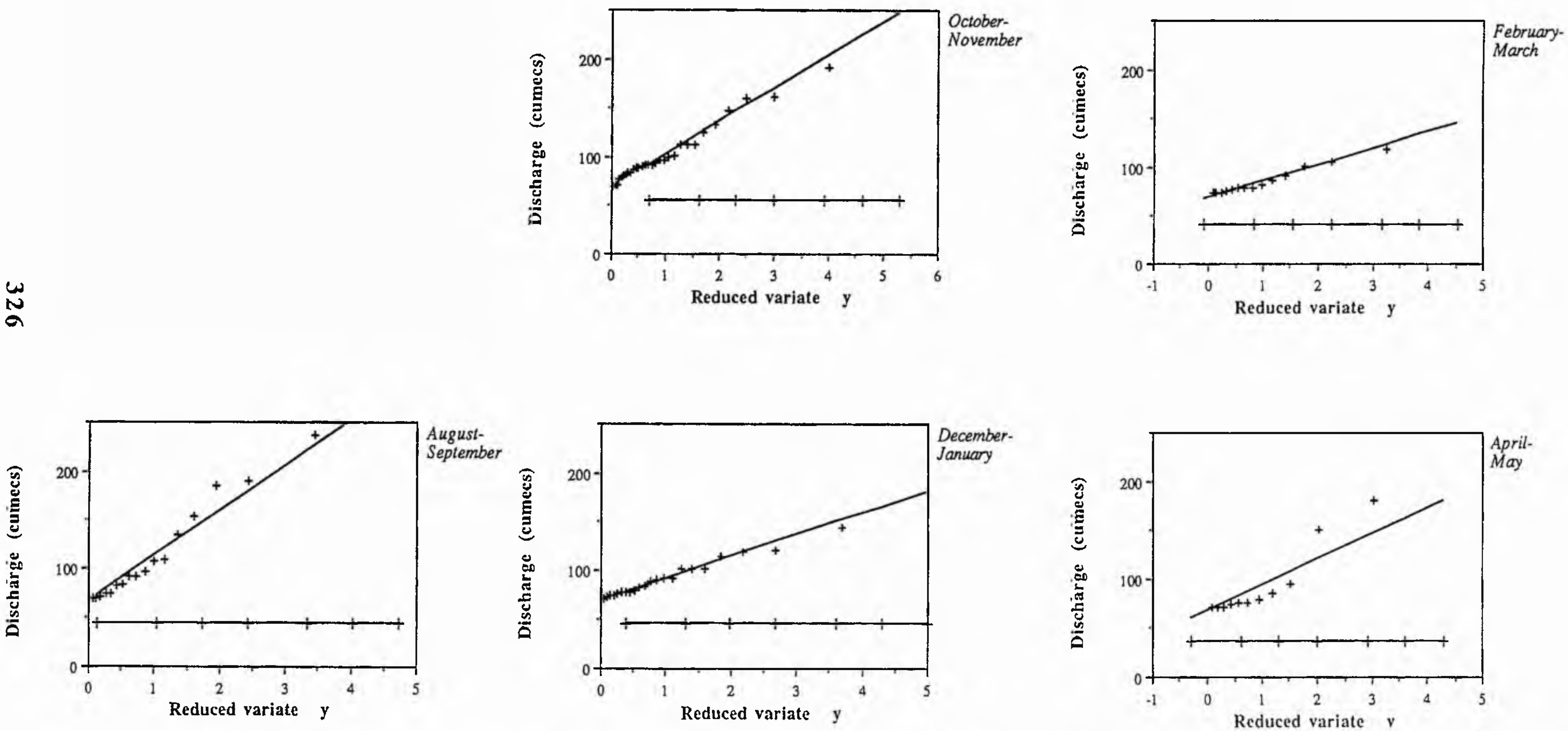




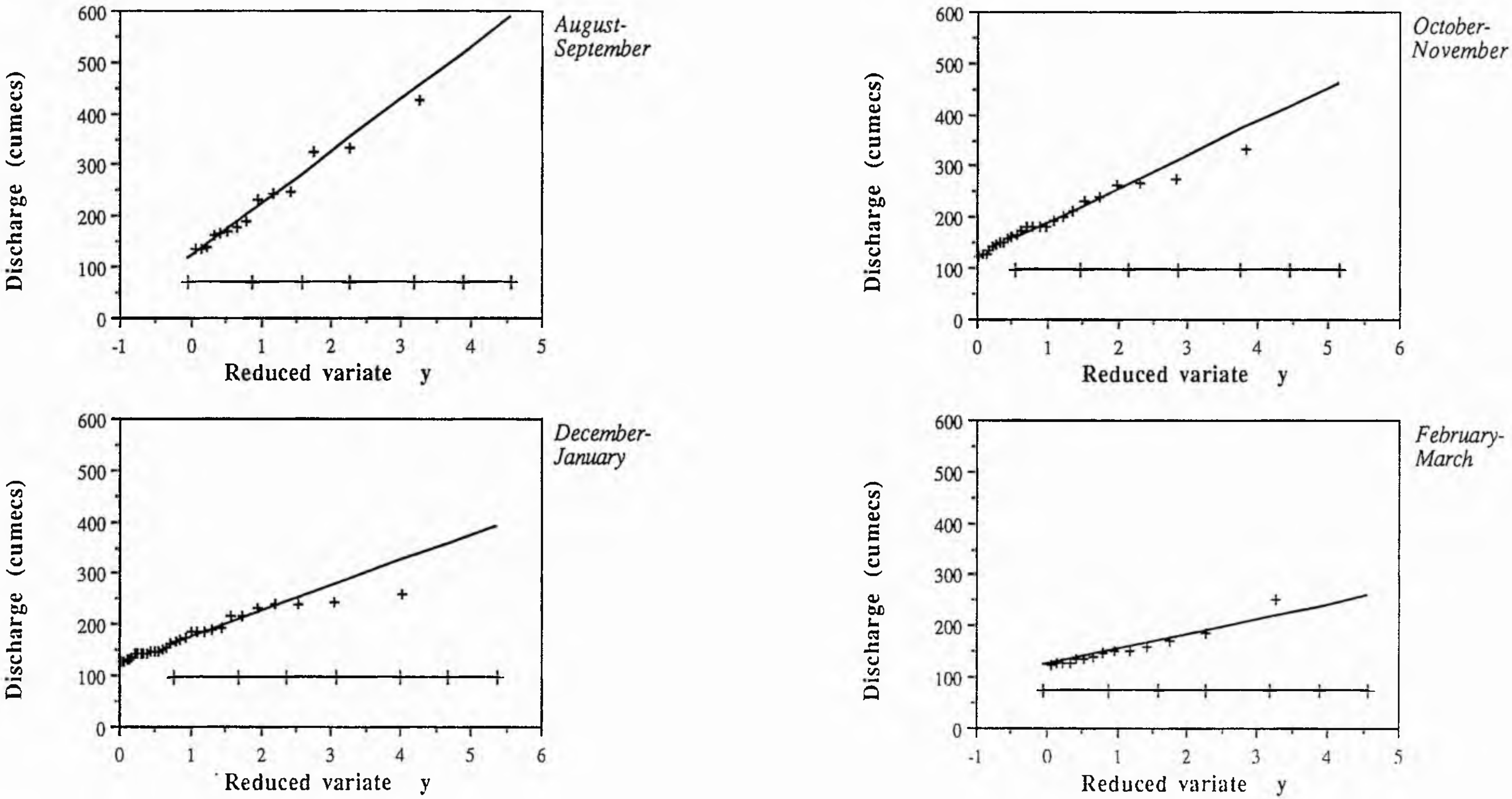
Seasonal frequency distributions for station 08010 Spey @ Grantown



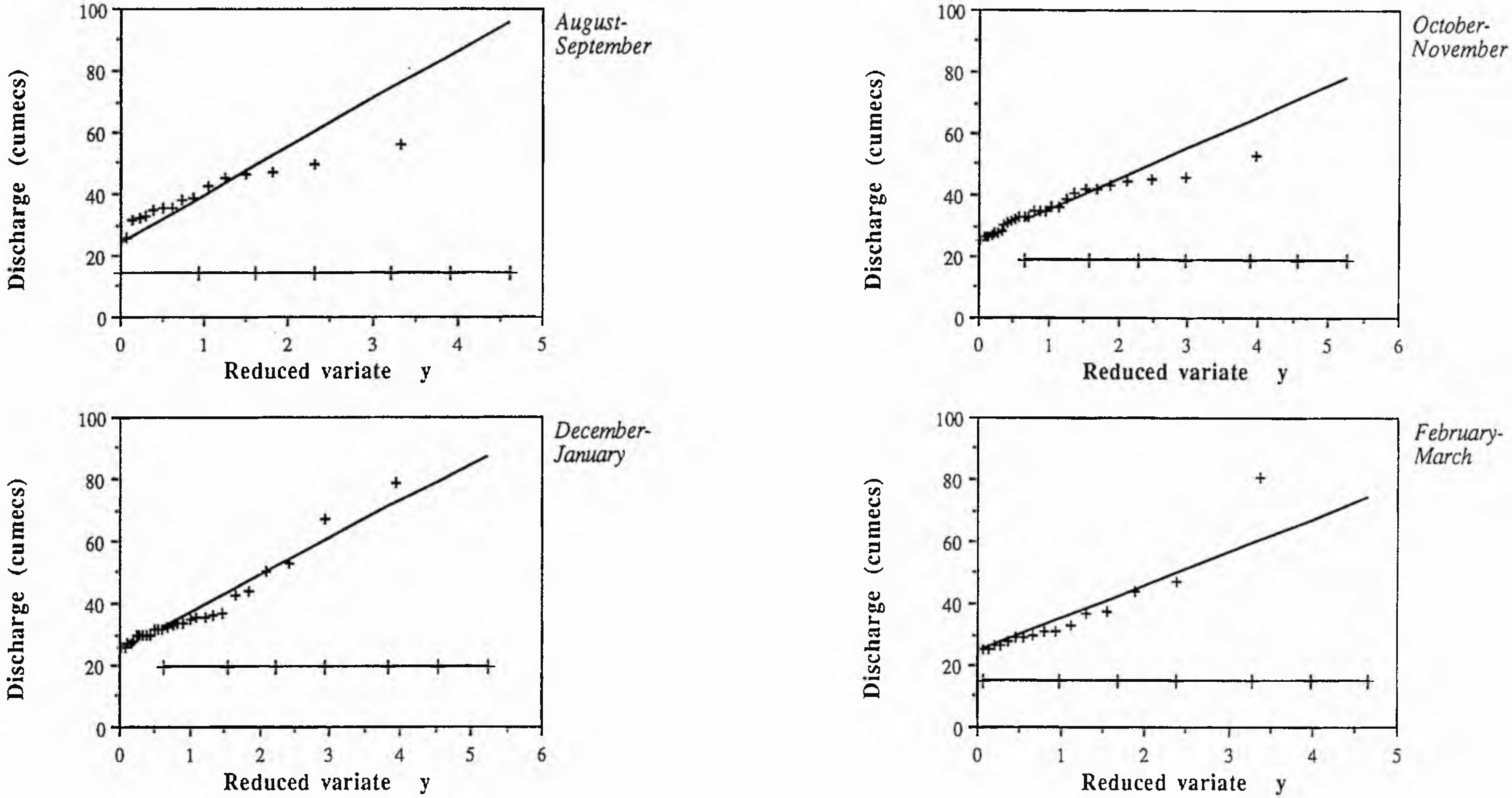
Seasonal frequency distributions for station 09001 Deveron @ Avochie



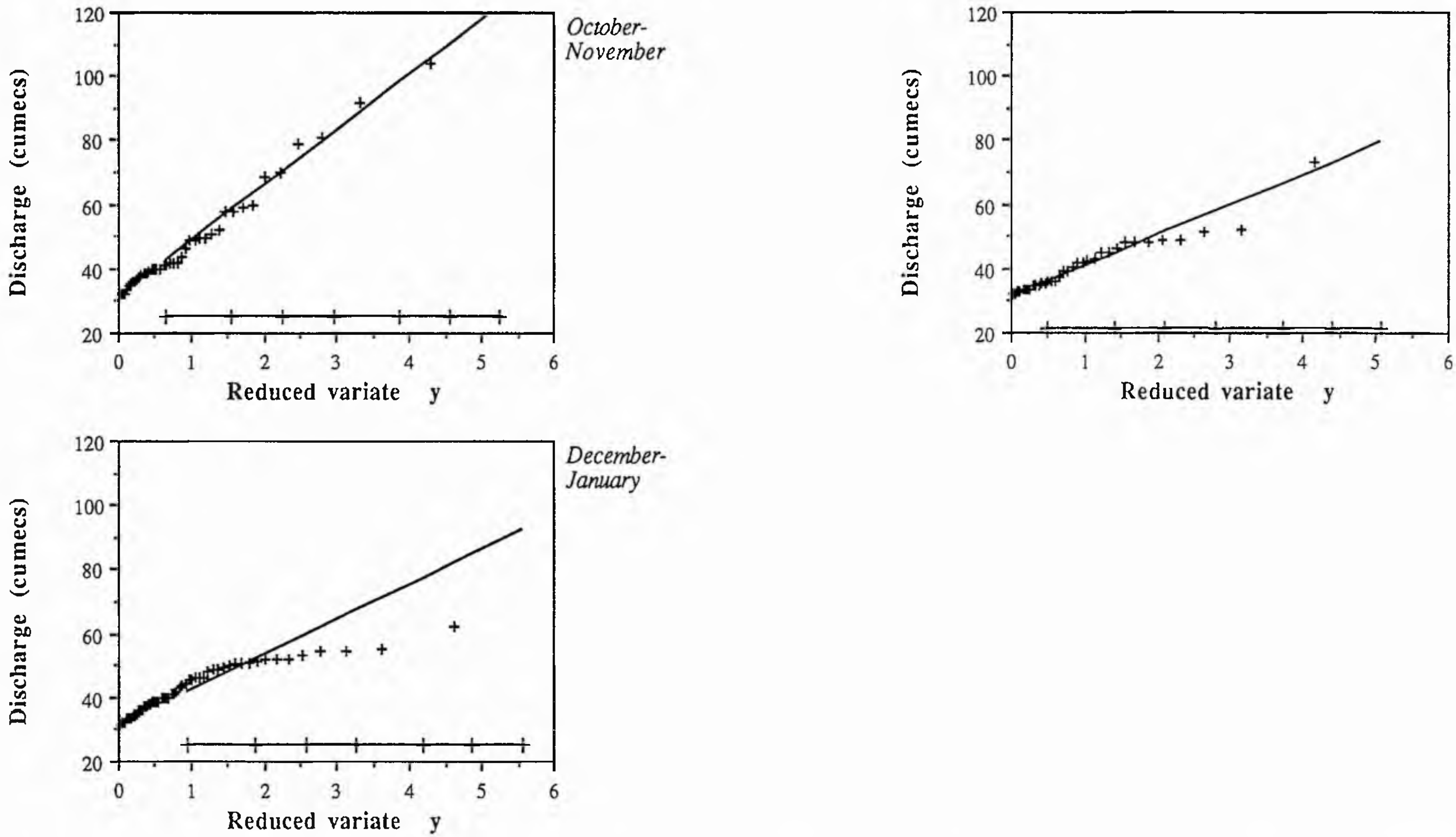
Seasonal frequency distributions for station 09002 Deveron @ Muiresk



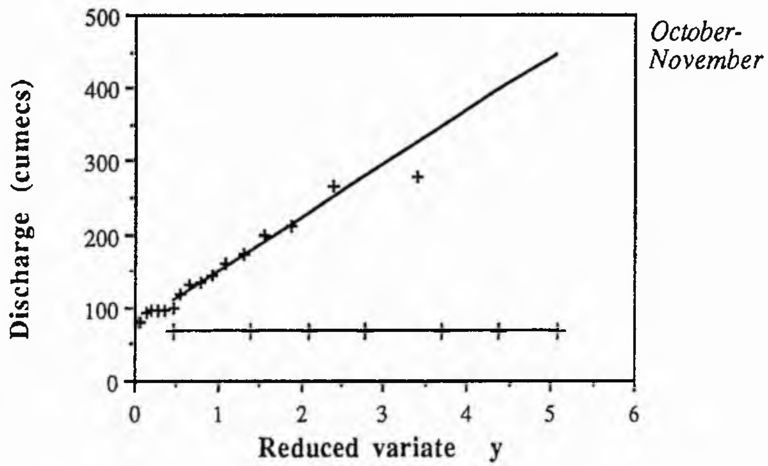
Seasonal frequency distributions for station 09003 Isla @ Grange

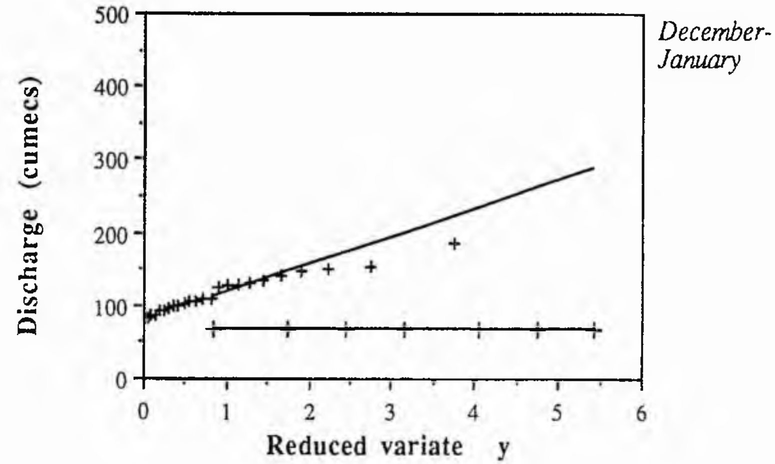


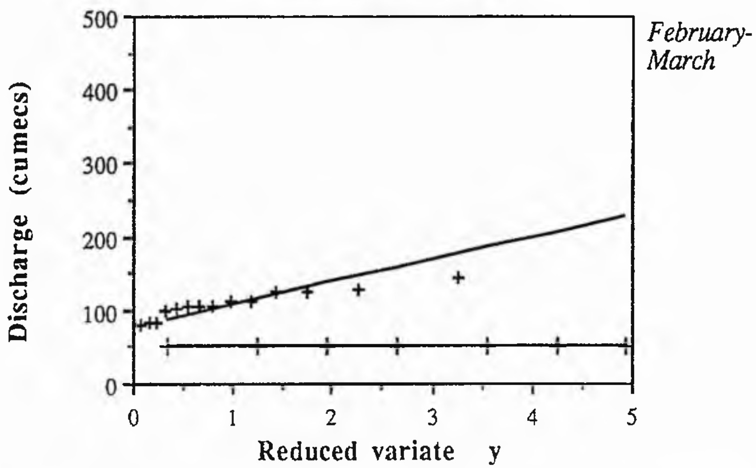
Seasonal frequency distributions for station 10001 Ythan @ Ardlethen



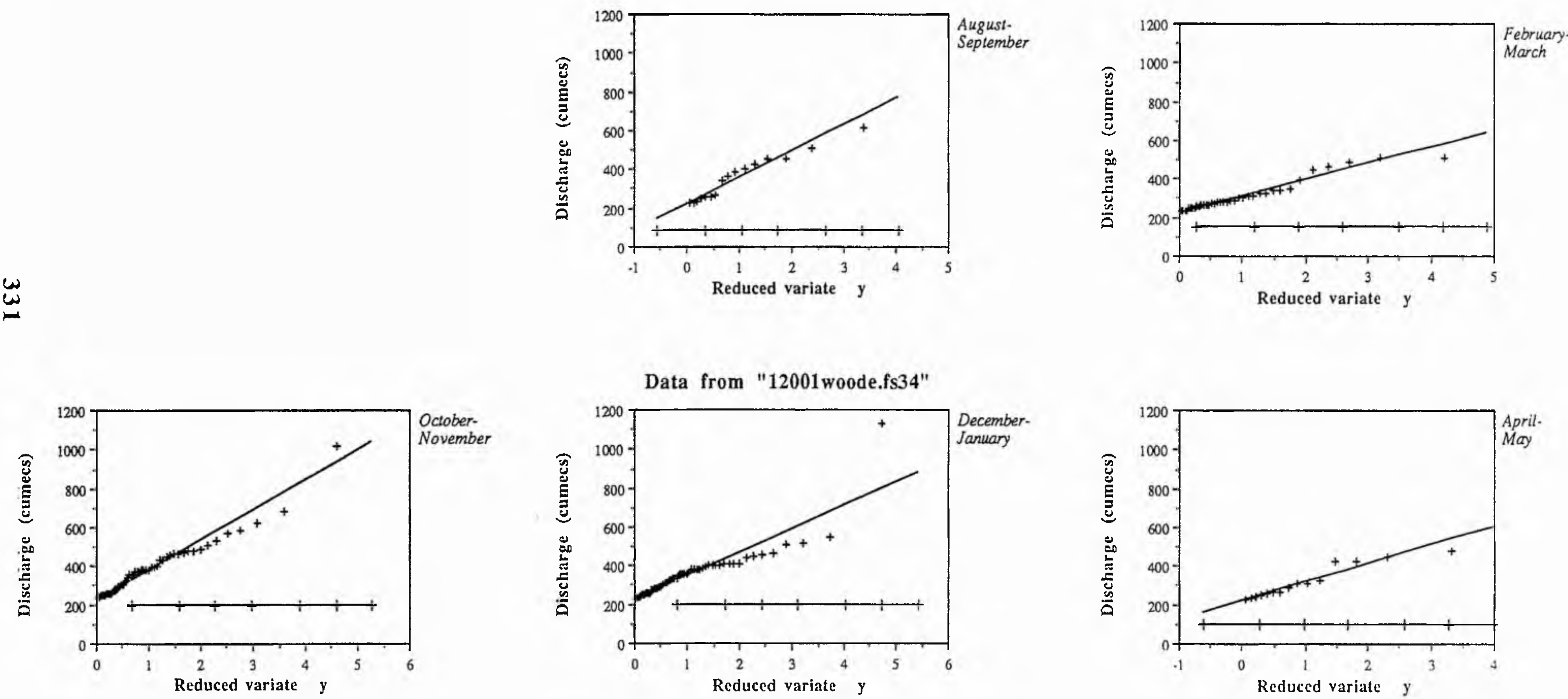
Seasonal frequency distributions for station
11001 Don @ Parkhill



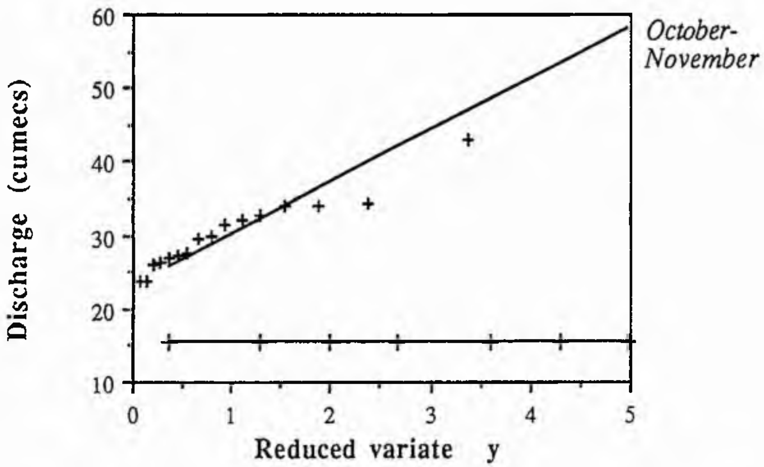


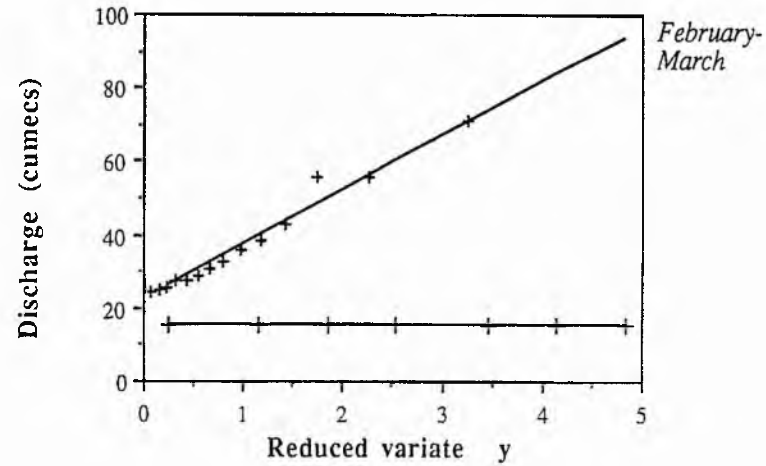


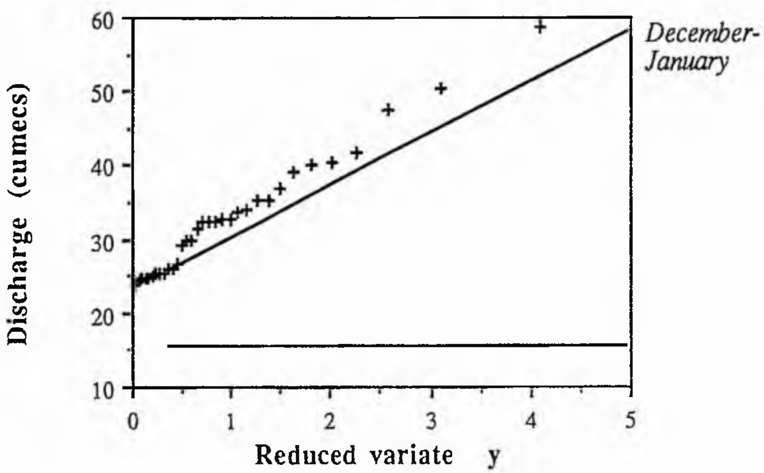
Seasonal frequency distributions for station 12001 Dee @ Woodend



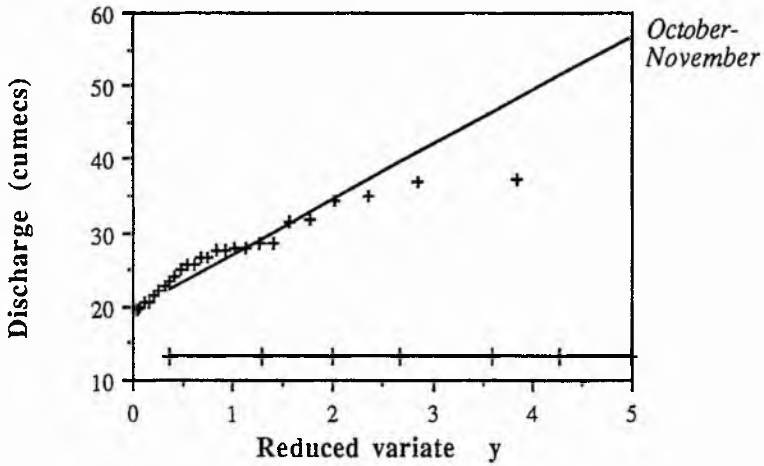
Seasonal frequency distributions for station 14001 Eden @ Kemback

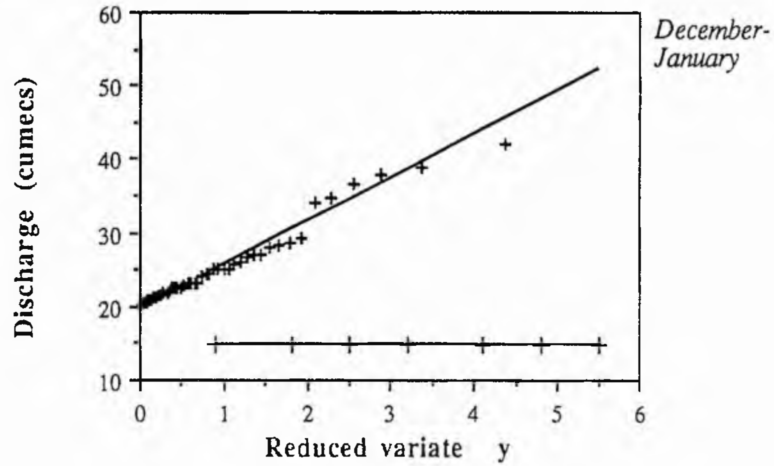


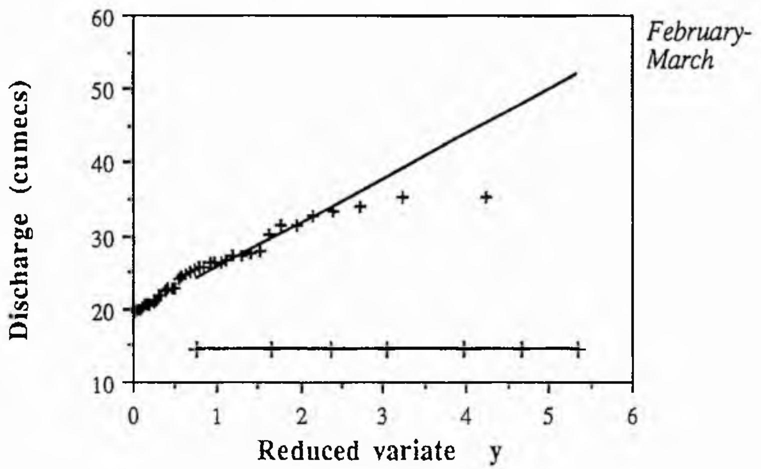




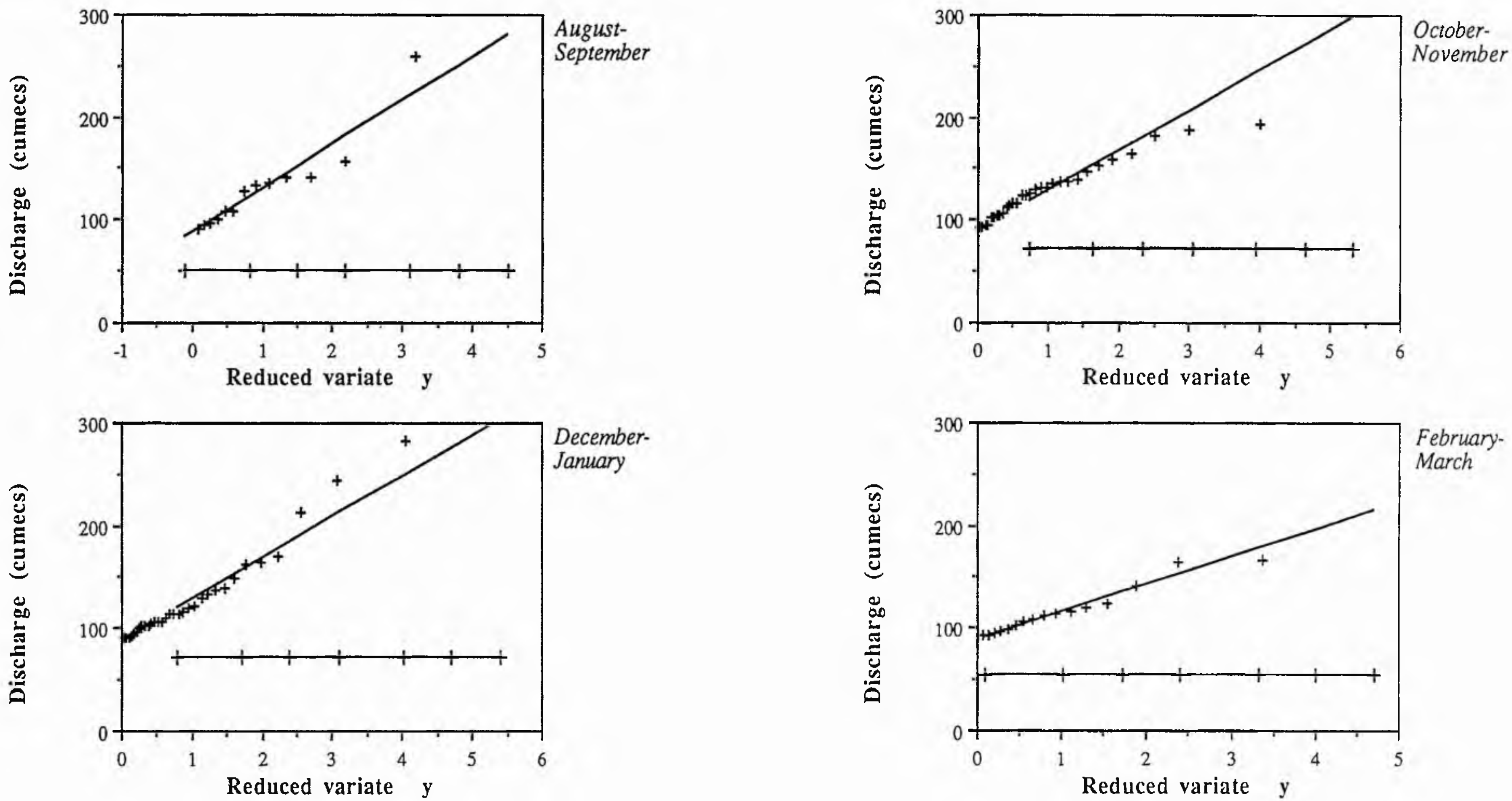
Seasonal frequency distributions for station 15008 Dean Water @ Cookston



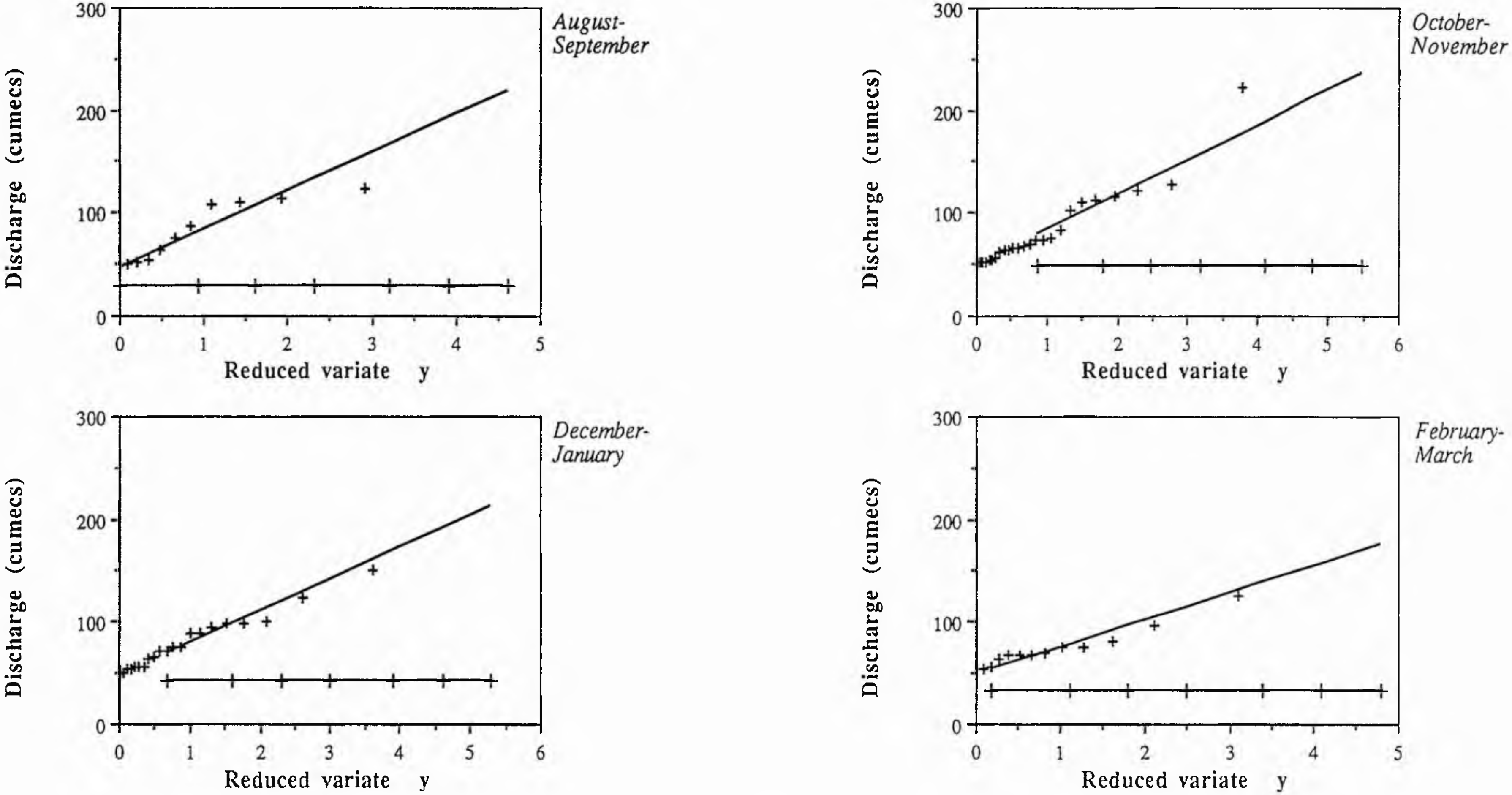




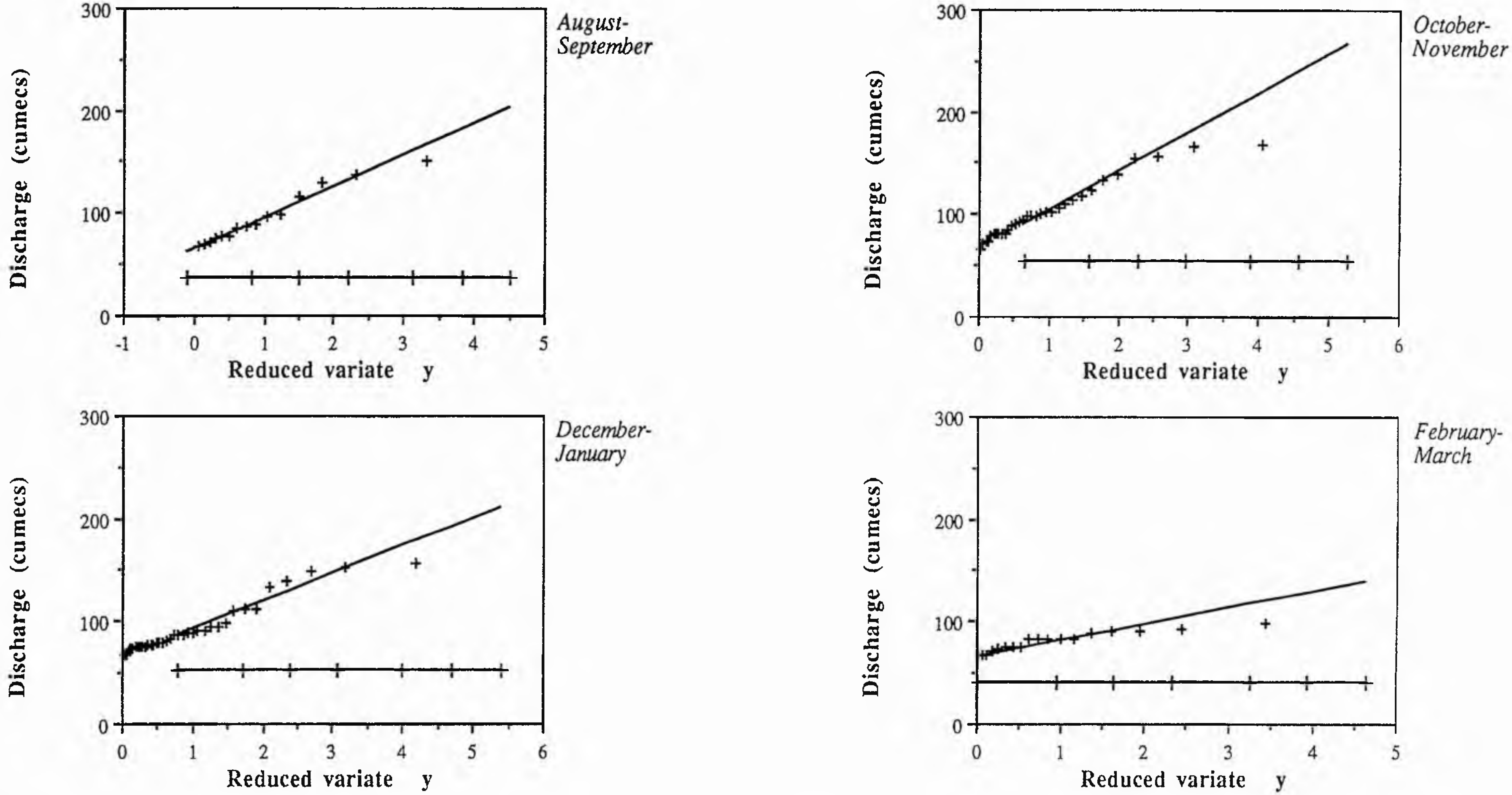
Seasonal frequency distributions for station 16003 Ruchill Water @ Cultybraggan



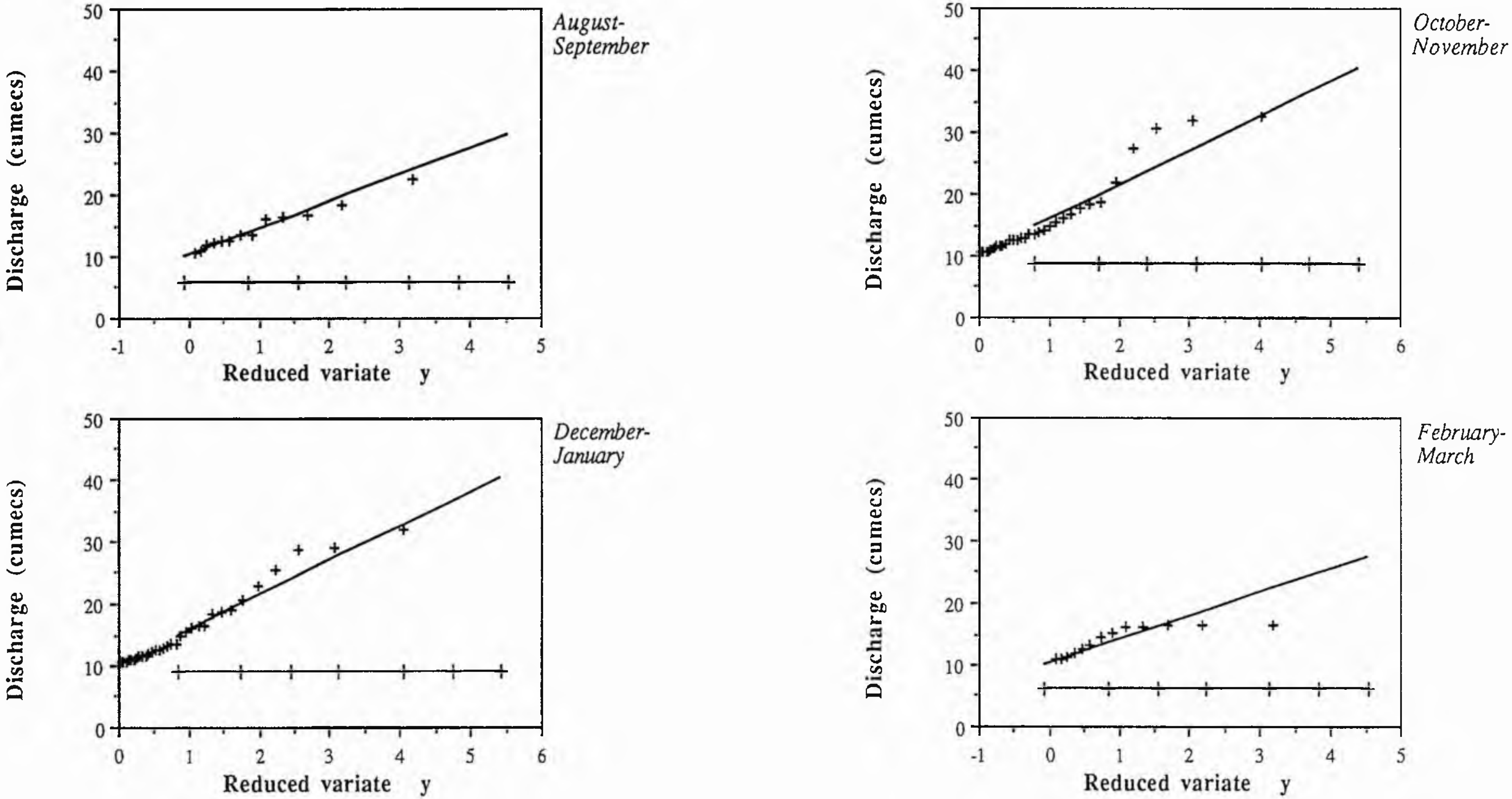
Seasonal frequency distributions for station 17001 Carron @ Headswood



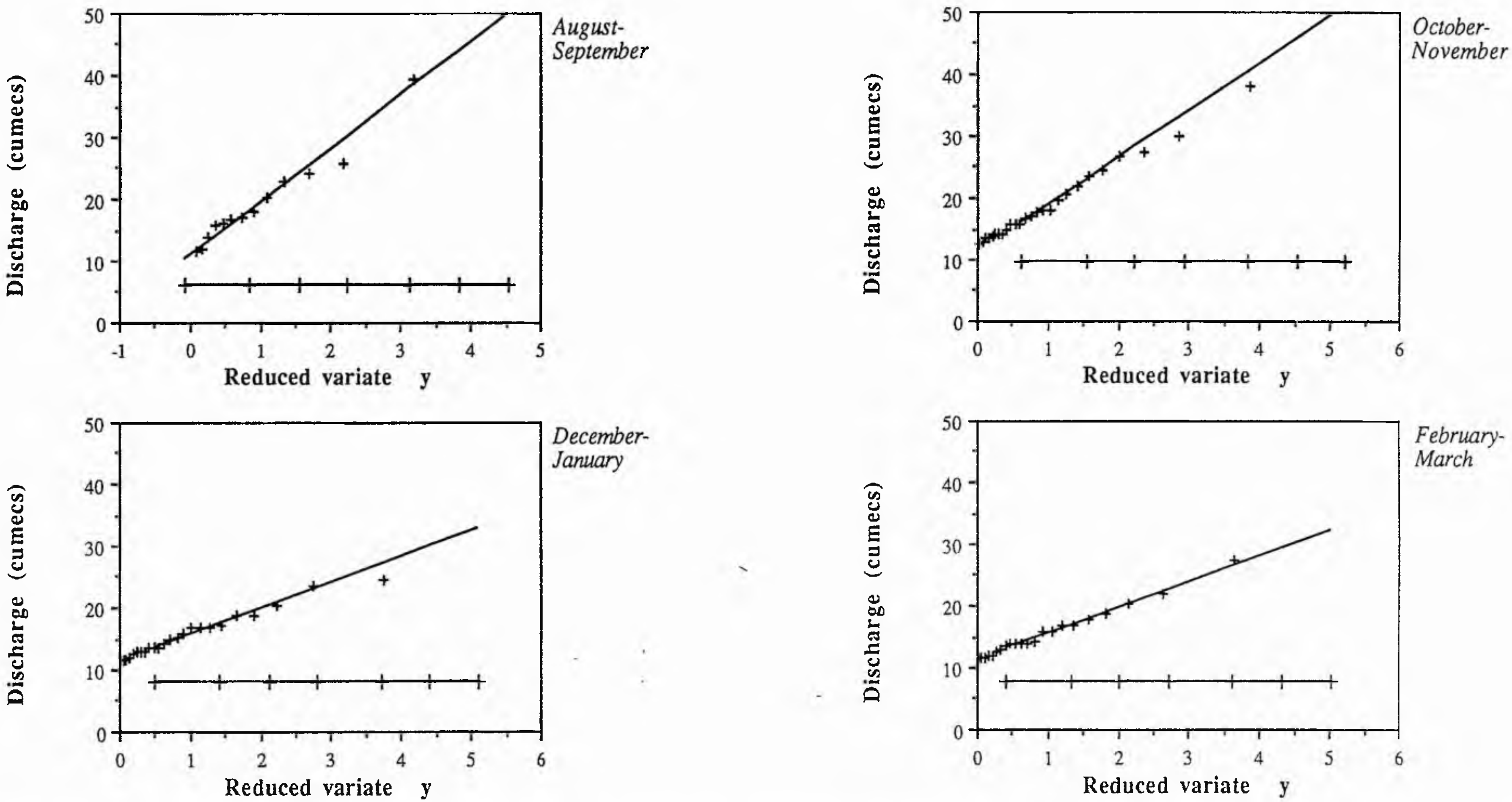
Seasonal frequency distributions for station 19001 Almond @ Craigiehall



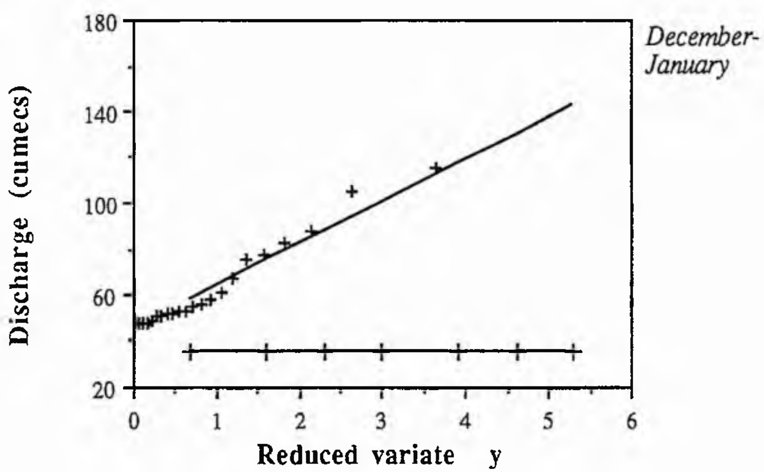
Seasonal frequency distributions for station 19002 Almond @ Almond Weir

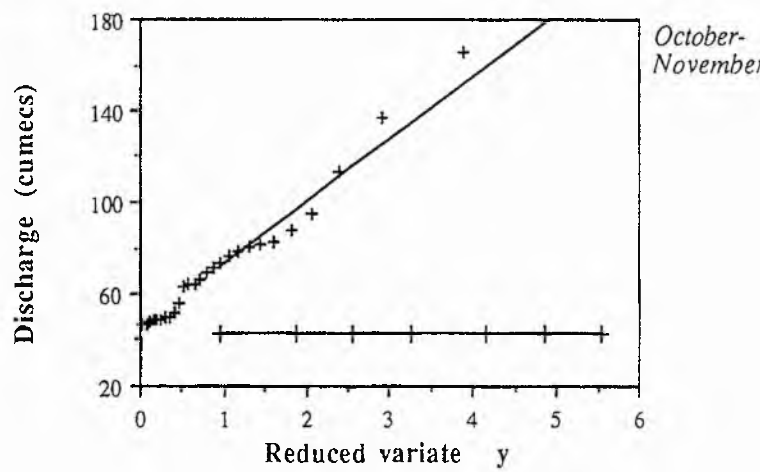


Seasonal frequency distributions for station 19004 North Esk @ Dalmore Weir

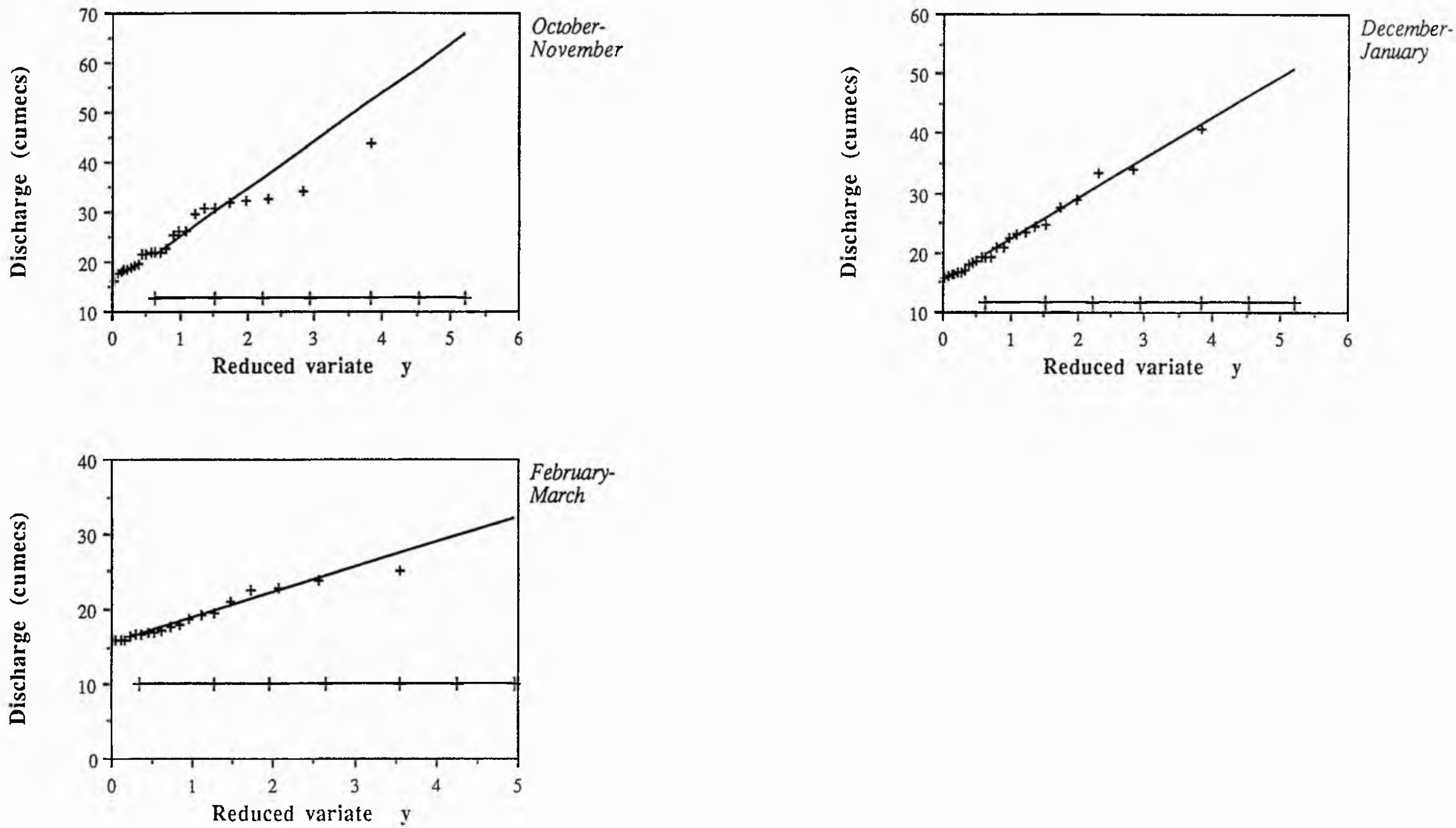


Seasonal frequency distributions for station 19005 Almond @ Almondell

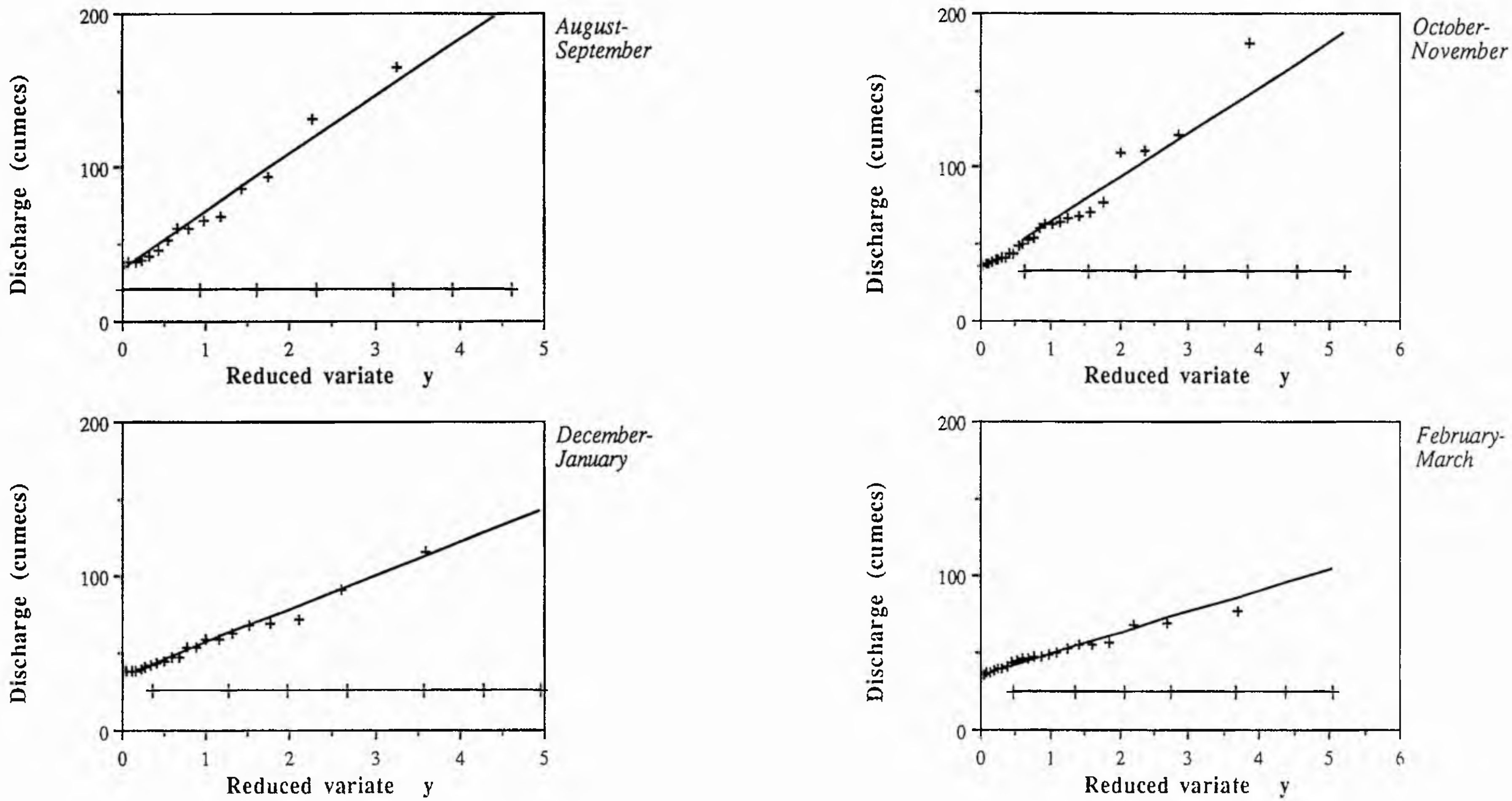




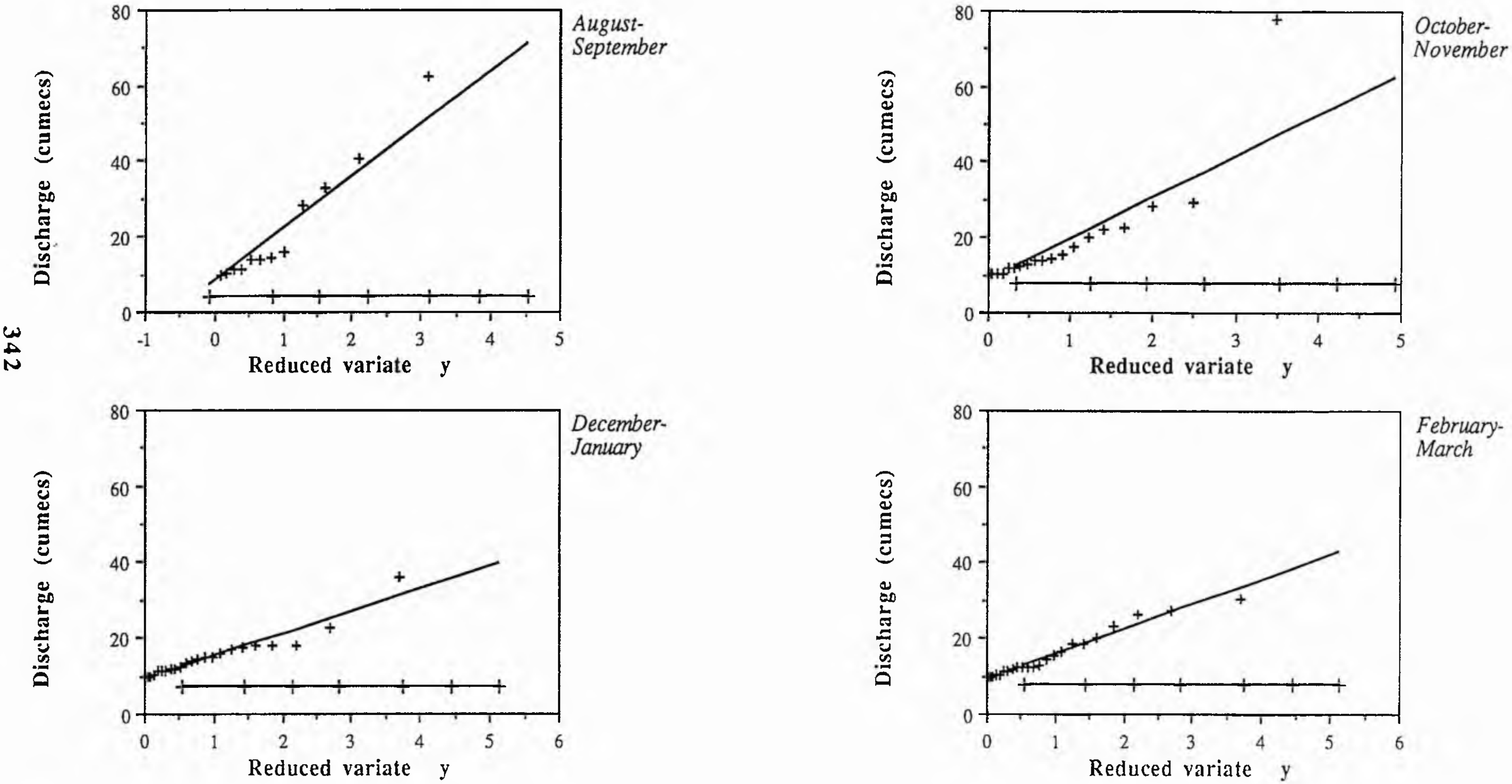
Seasonal frequency distributions for station 19006 Water of Leith @ Murrayfield



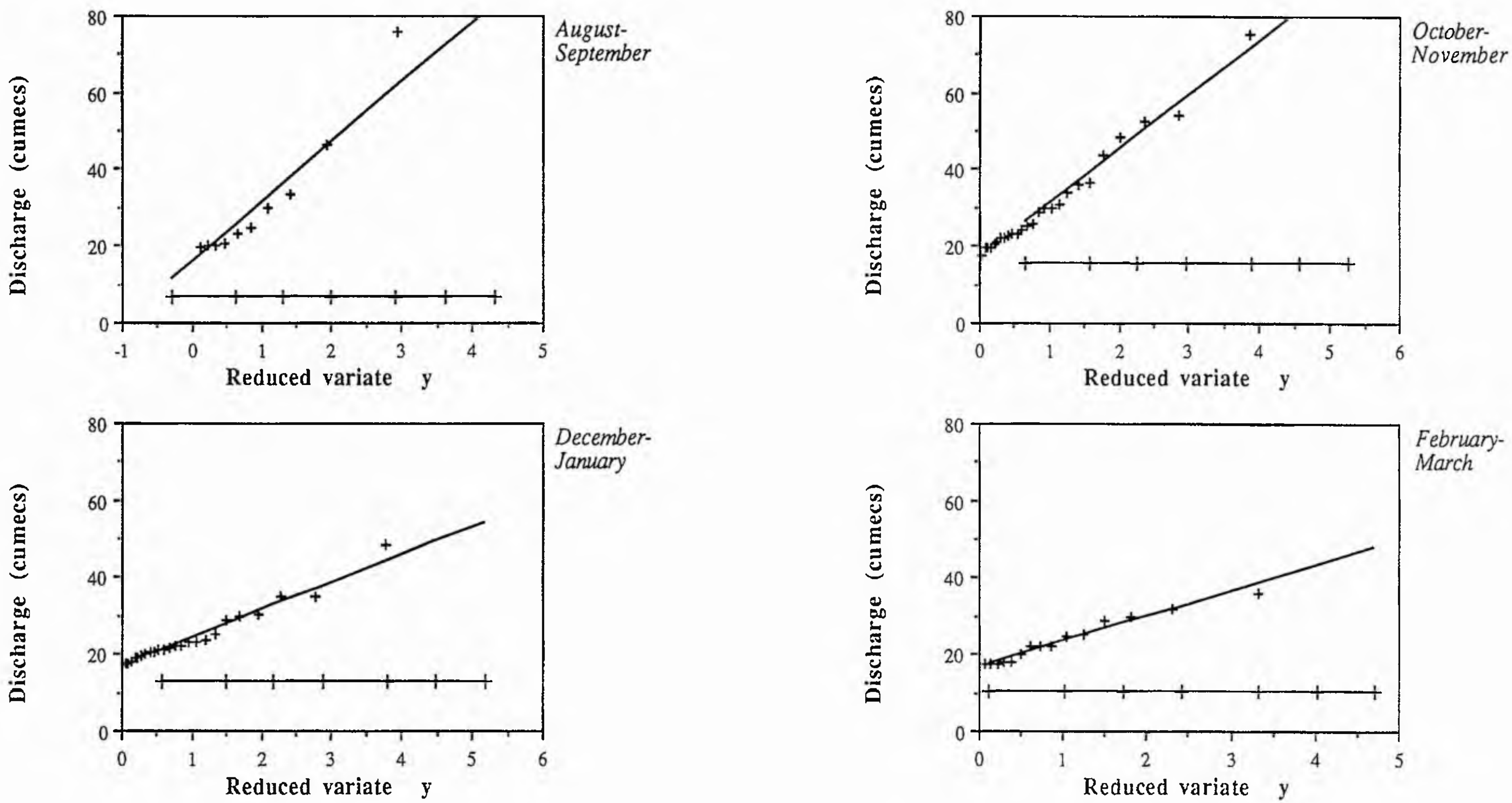
Seasonal frequency distributions for station 19007 Esk @ Musselburgh



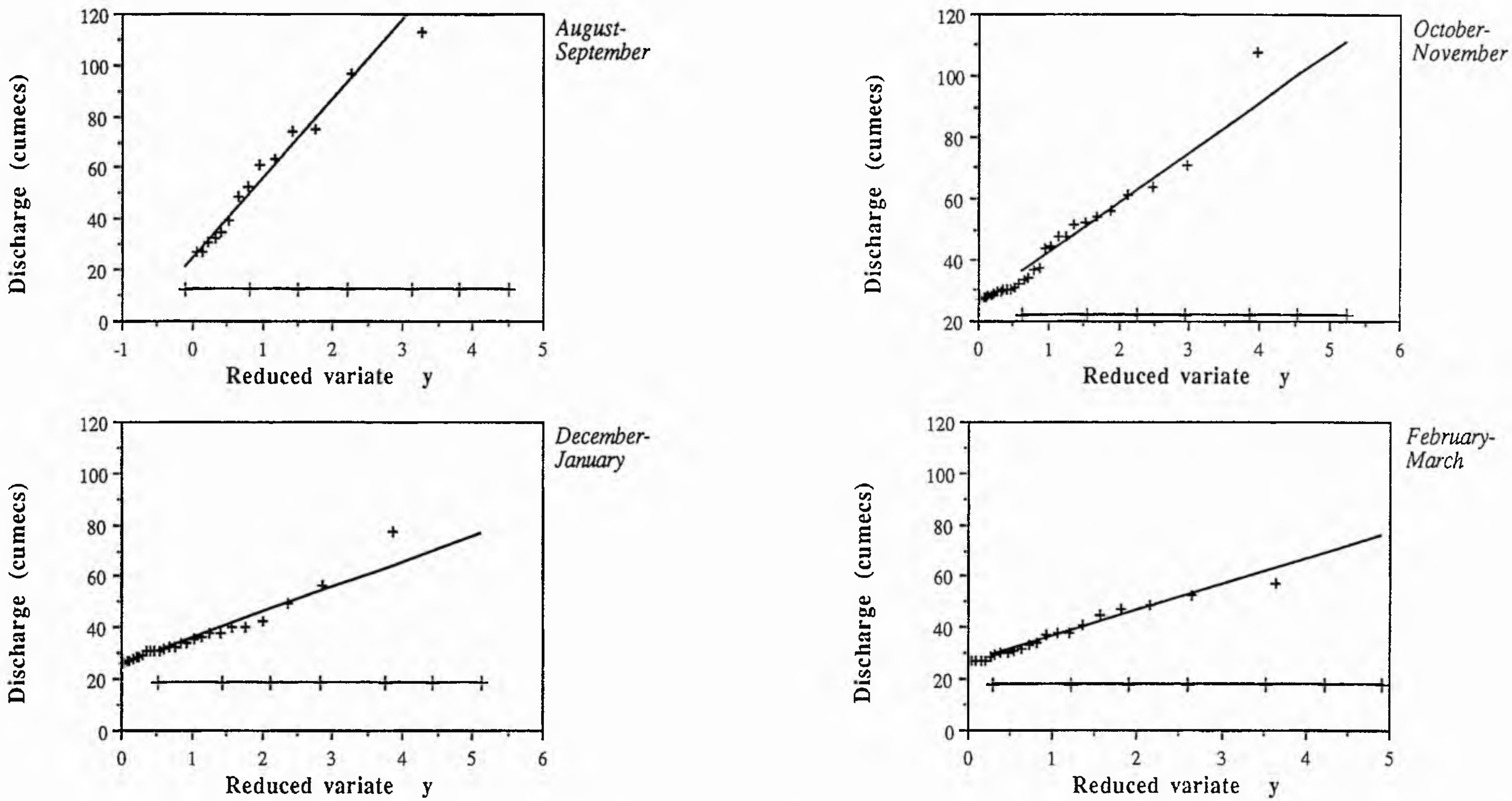
Seasonal frequency distributions for station 19008 South Esk @ Prestonholm



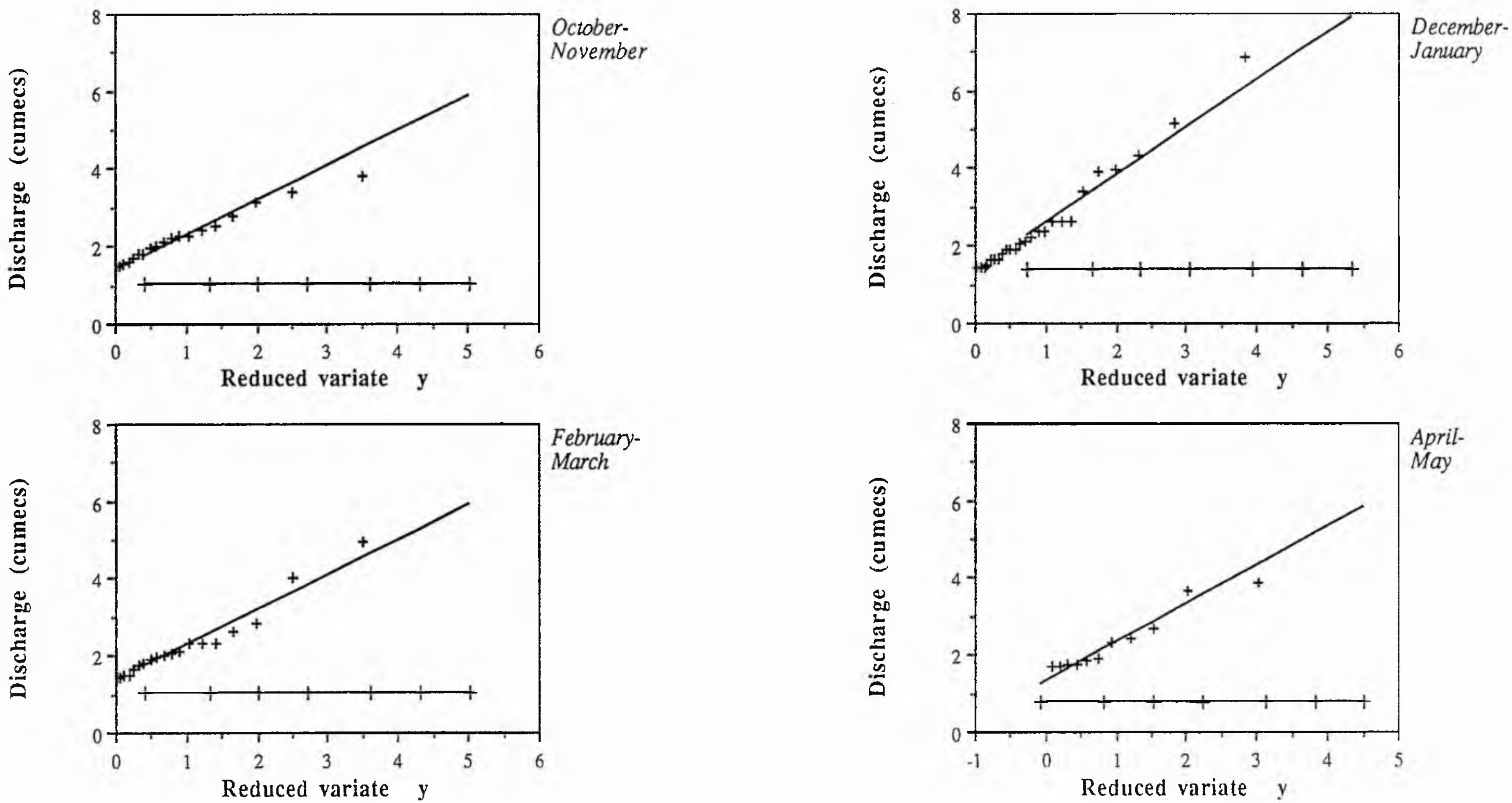
Seasonal frequency distributions for station 19011 North Esk @ Dalkeith Palace



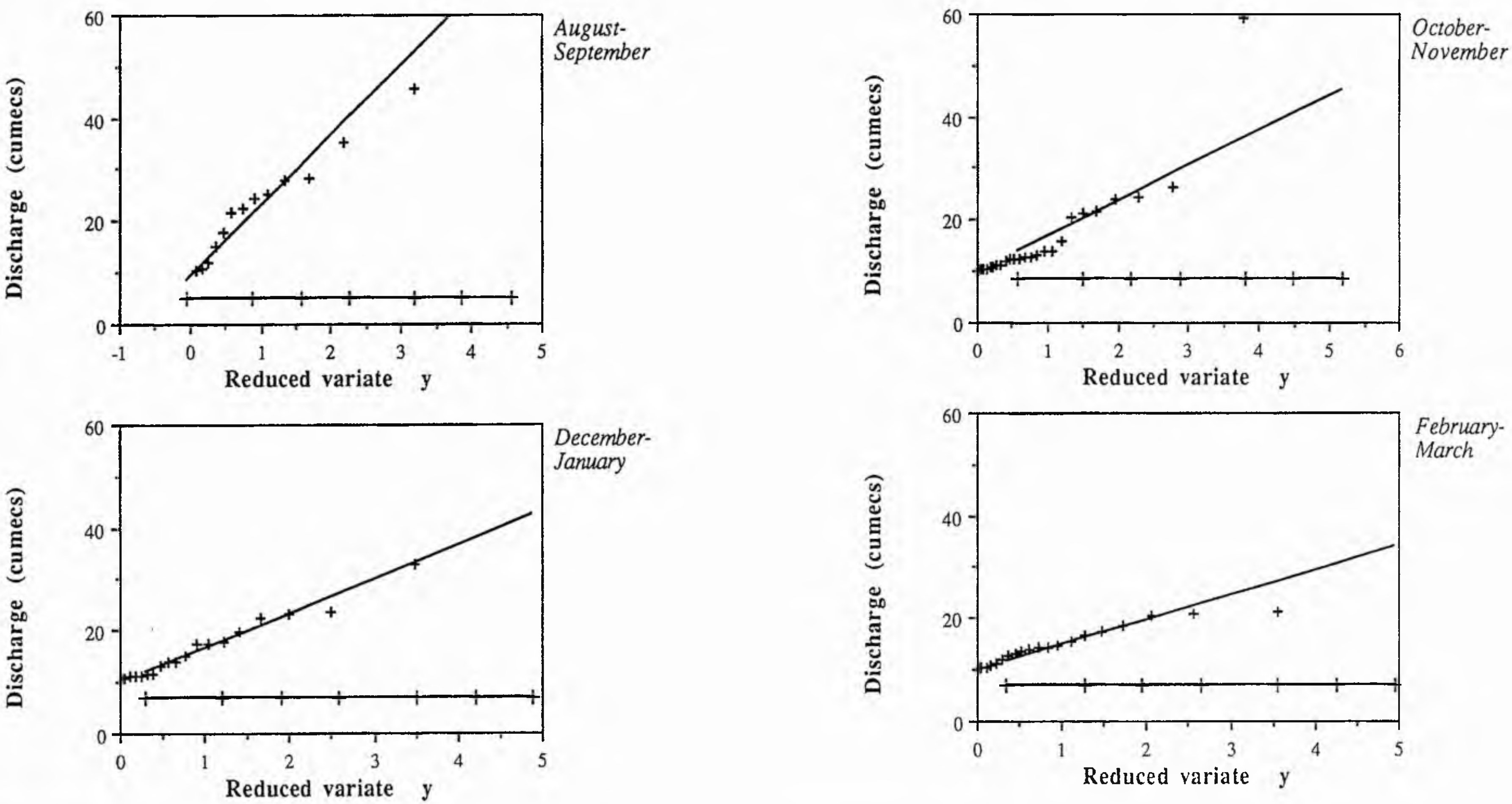
Seasonal frequency distributions for station 20001 Tyne @ East Linton



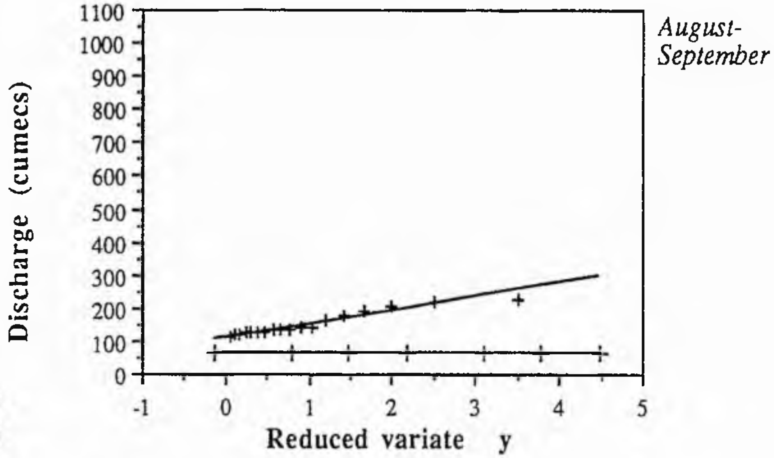
Seasonal frequency distributions for station 20002 West Peffer Burn @ Luffness Mains

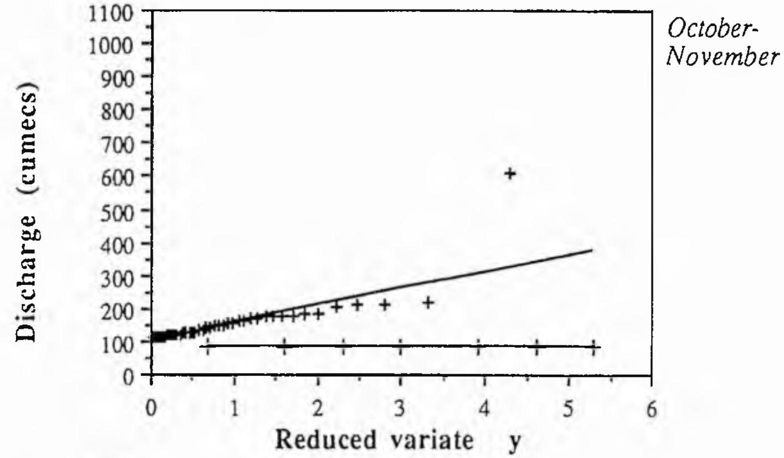


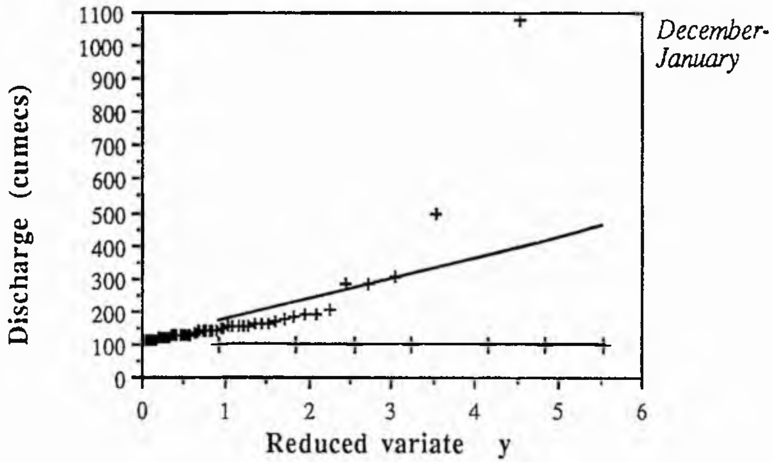
Seasonal frequency distributions for station 20005 Birns Water @ Saltoun Hall

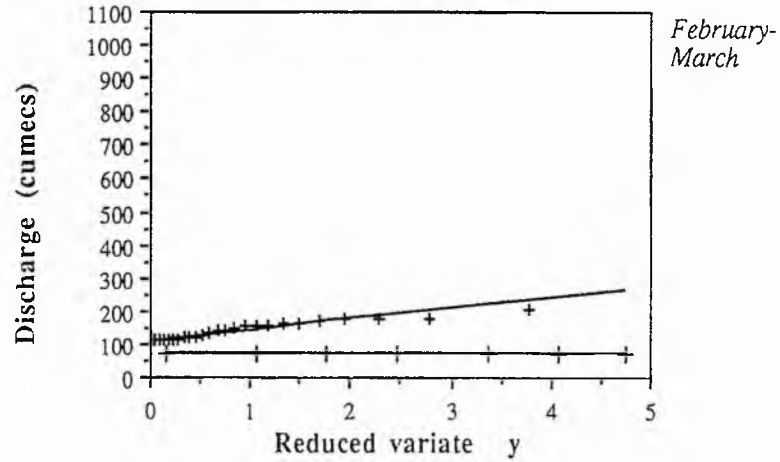


Seasonal frequency distributions for station
21003 Tweed @ Peebles

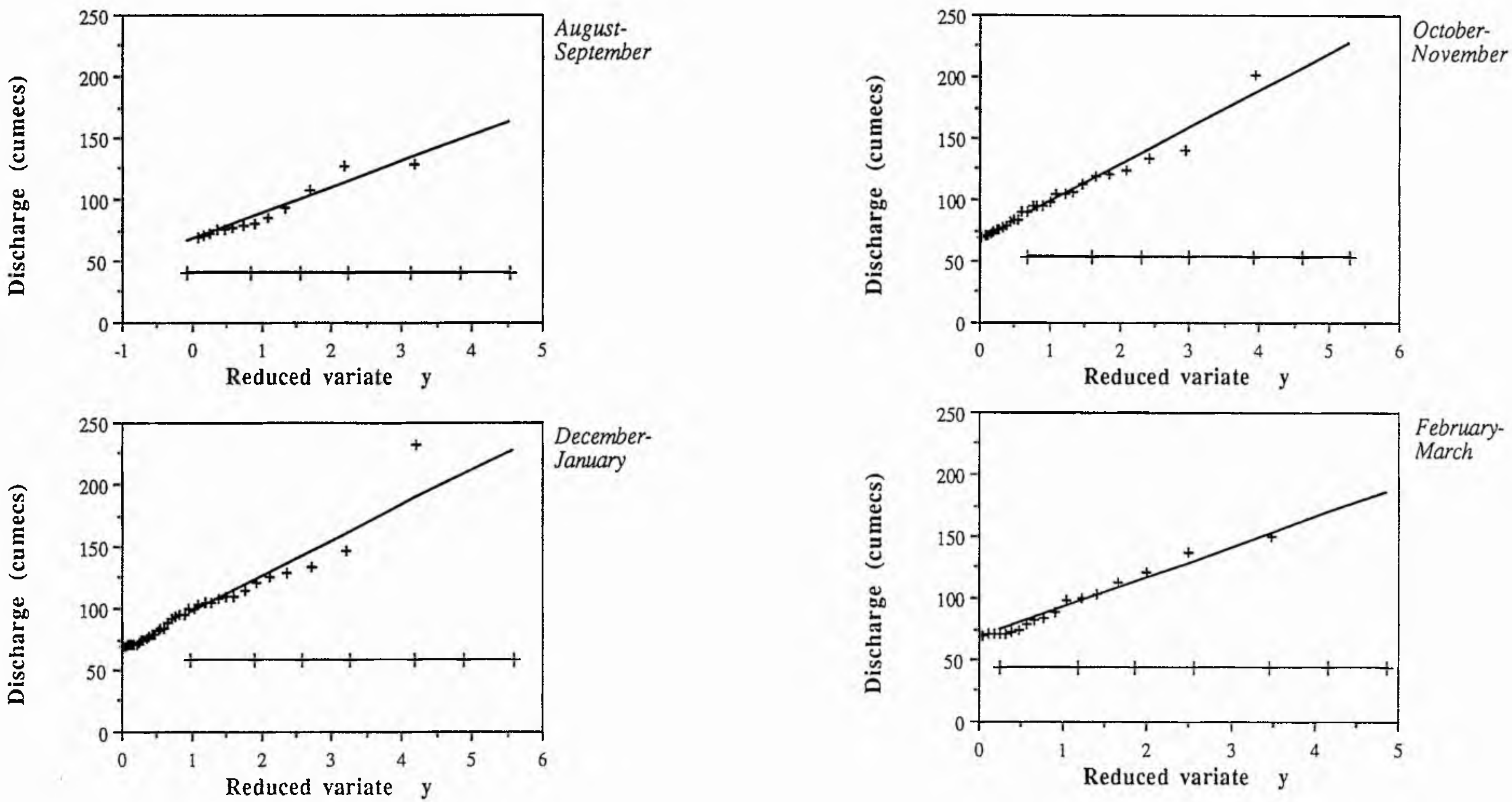




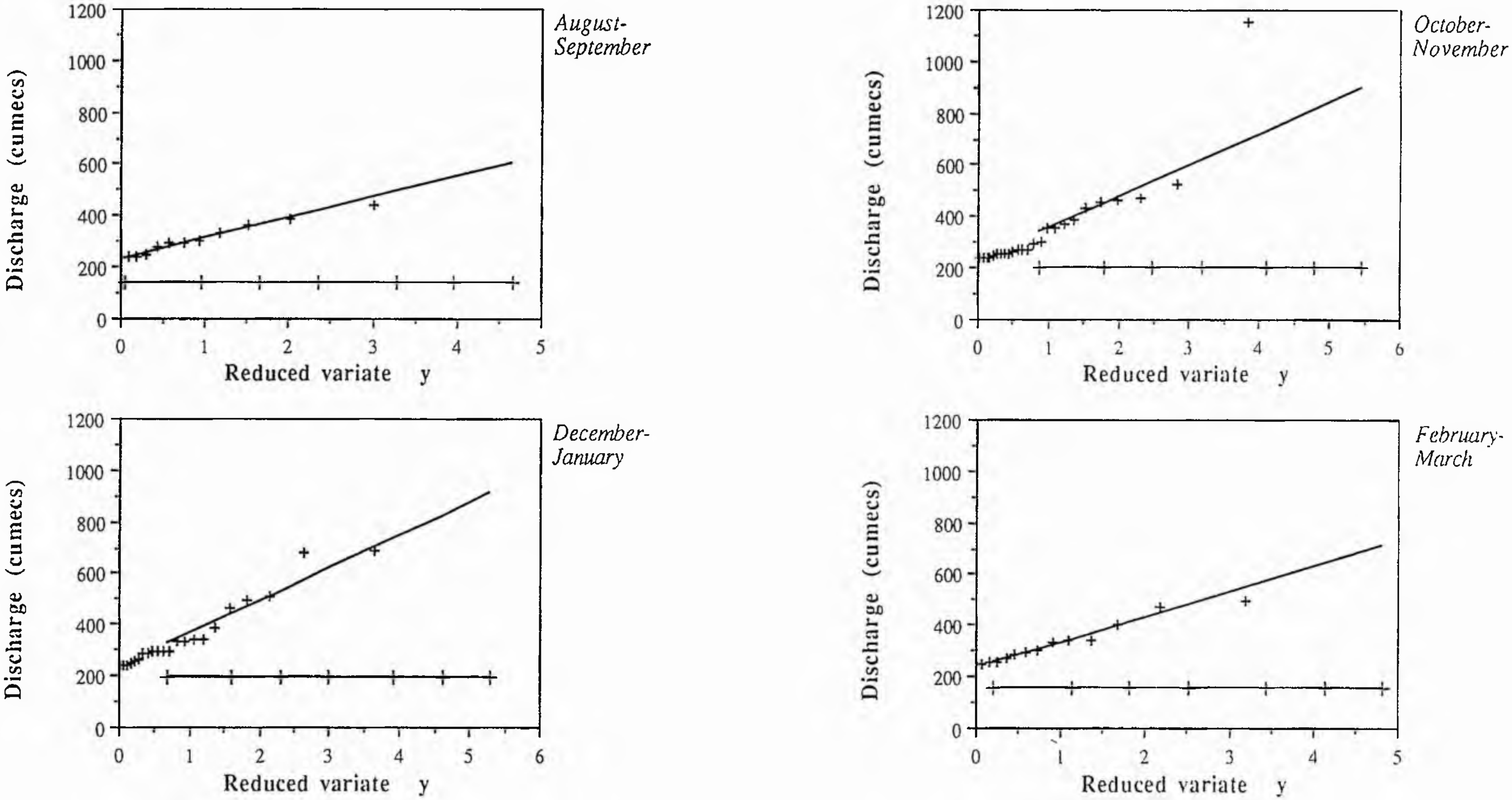




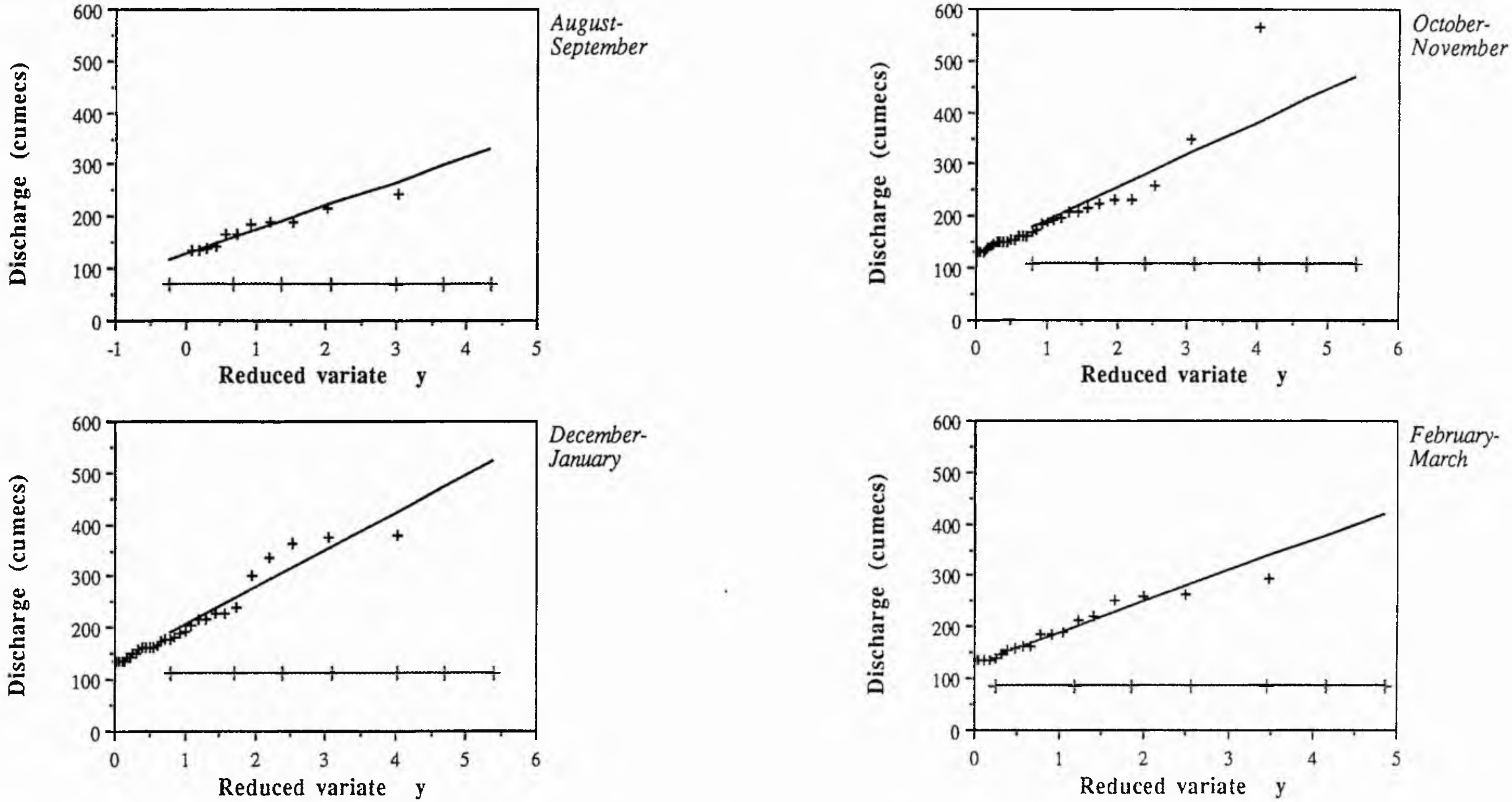
Seasonal frequency distributions for station
21005 Tweed @ Lyne Ford



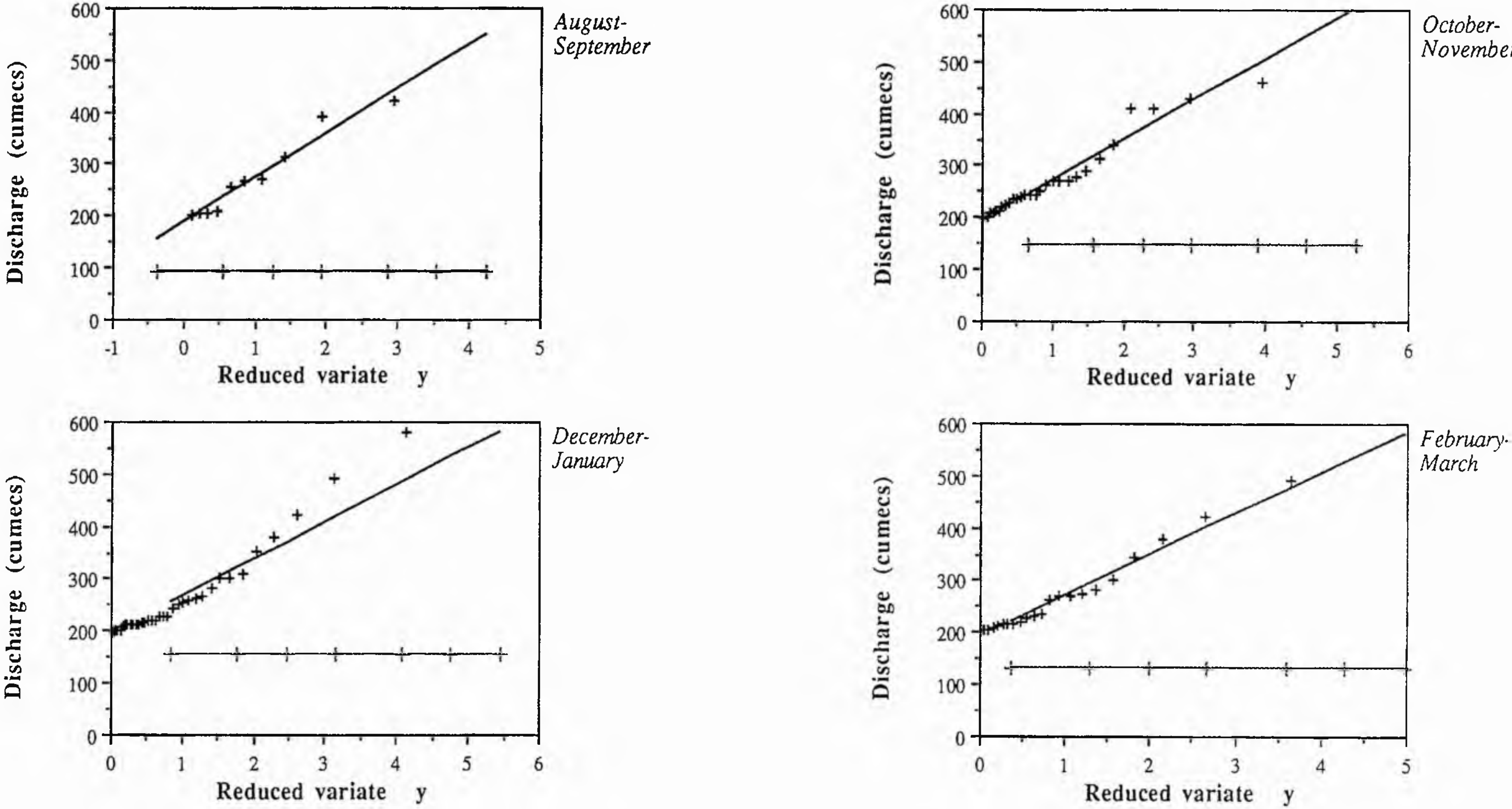
Seasonal frequency distributions for station 21006 Tweed @ Boleside



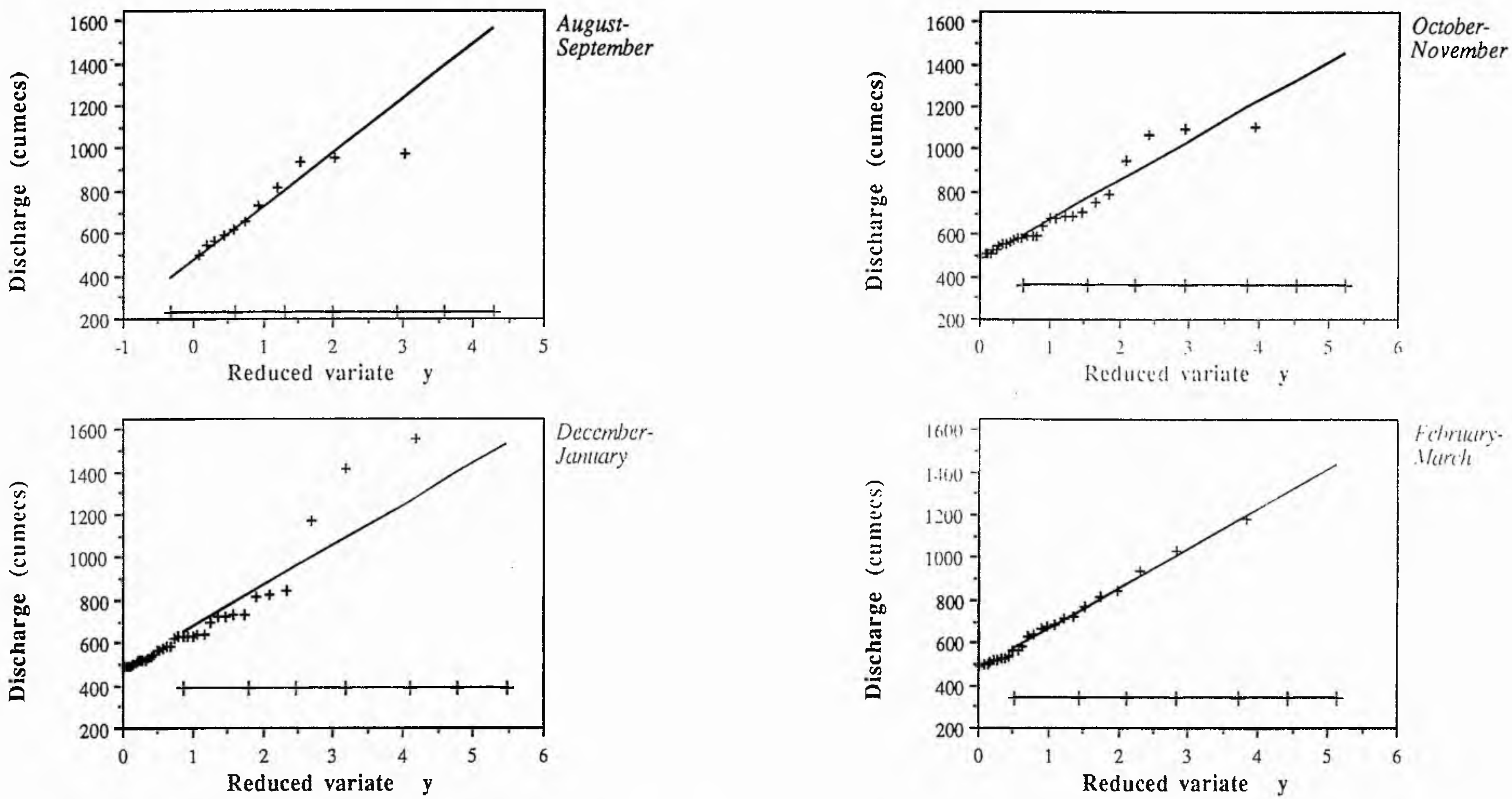
Seasonal frequency distributions for station 21007 Ettrick @ Lindean



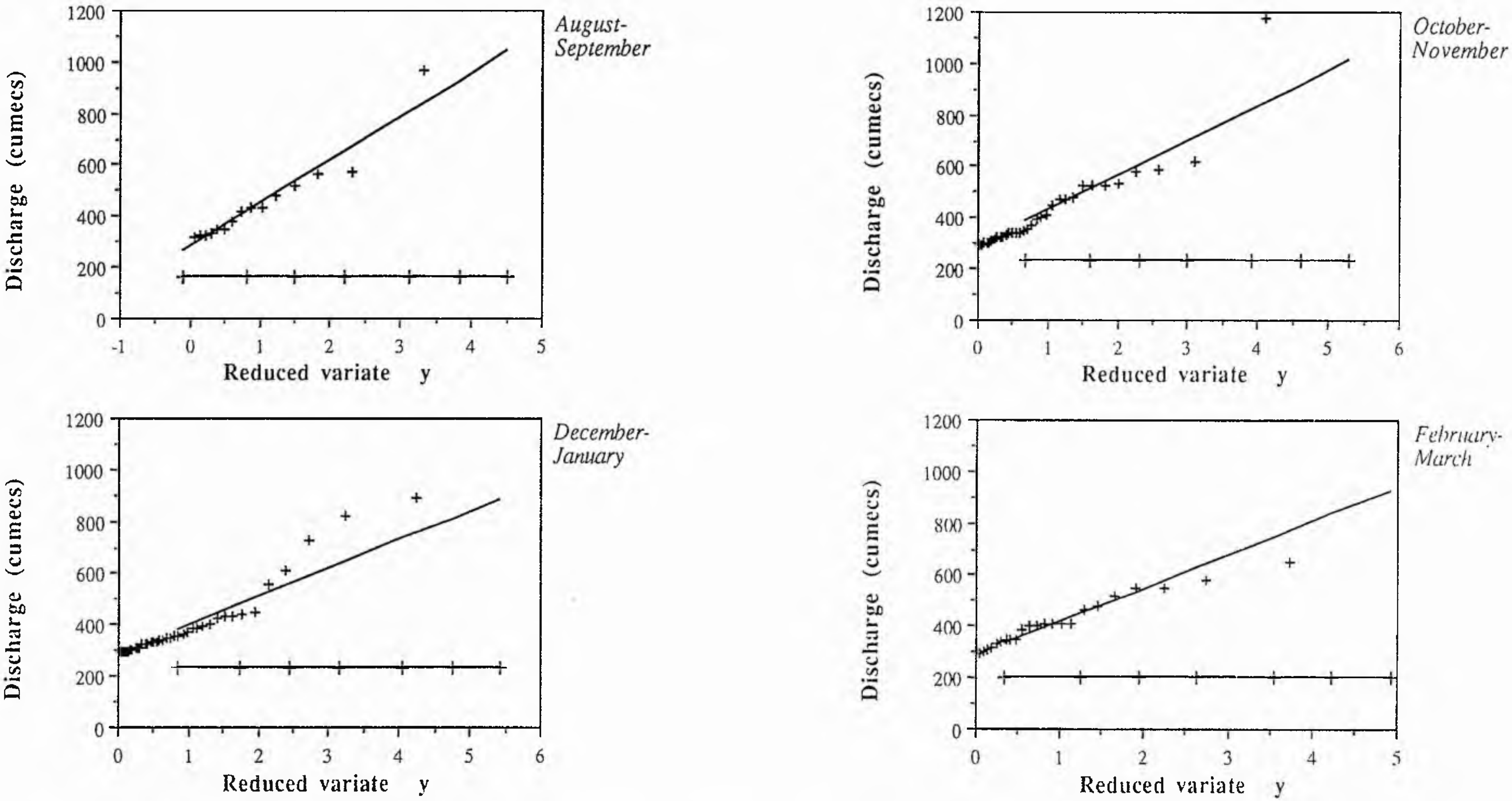
Seasonal frequency distributions for station 21008 Teviot @ Ormiston Mill



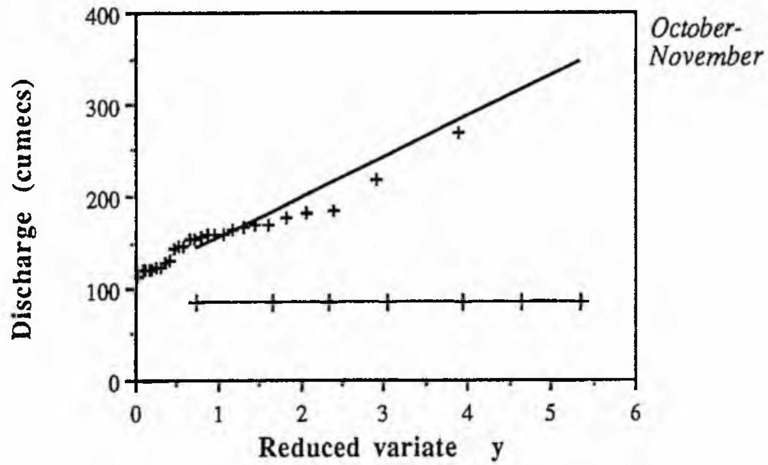
Seasonal frequency distributions for station 21009 Tweed @ Norham

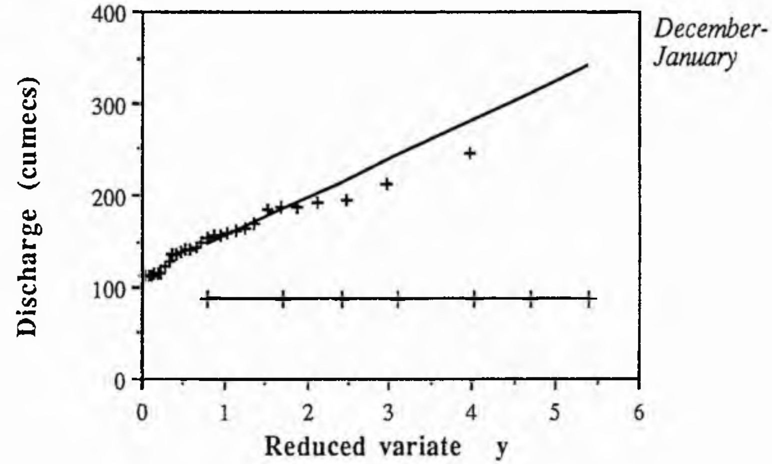


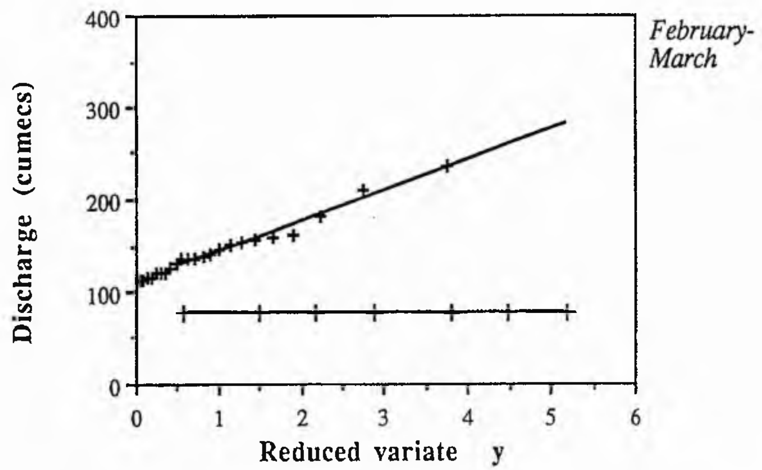
Seasonal frequency distributions for station 21010 Tweed @ Dryburgh



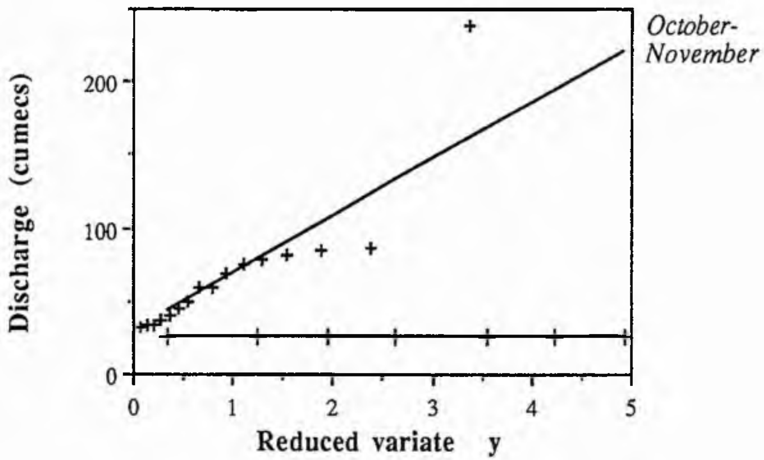
Seasonal frequency distributions for station 21012 Teviot @ Hawick

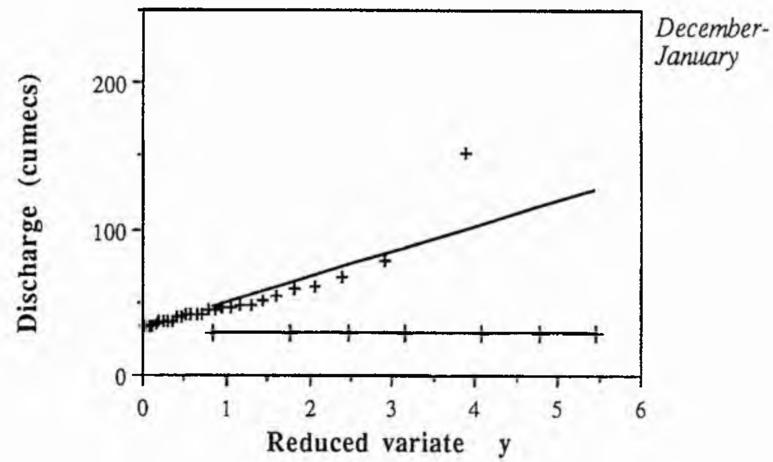


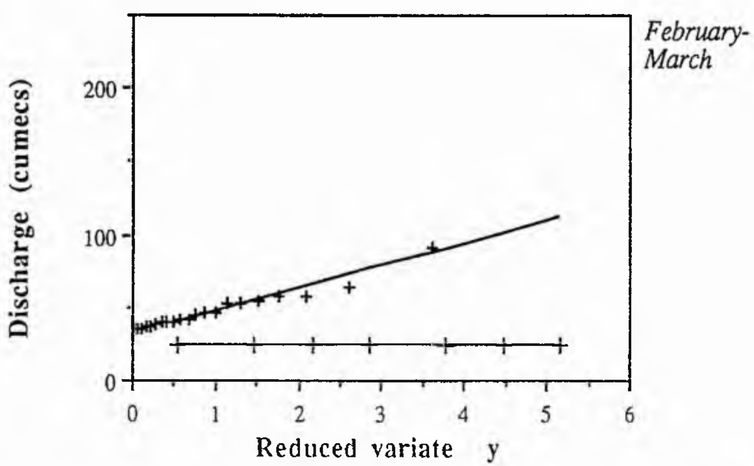




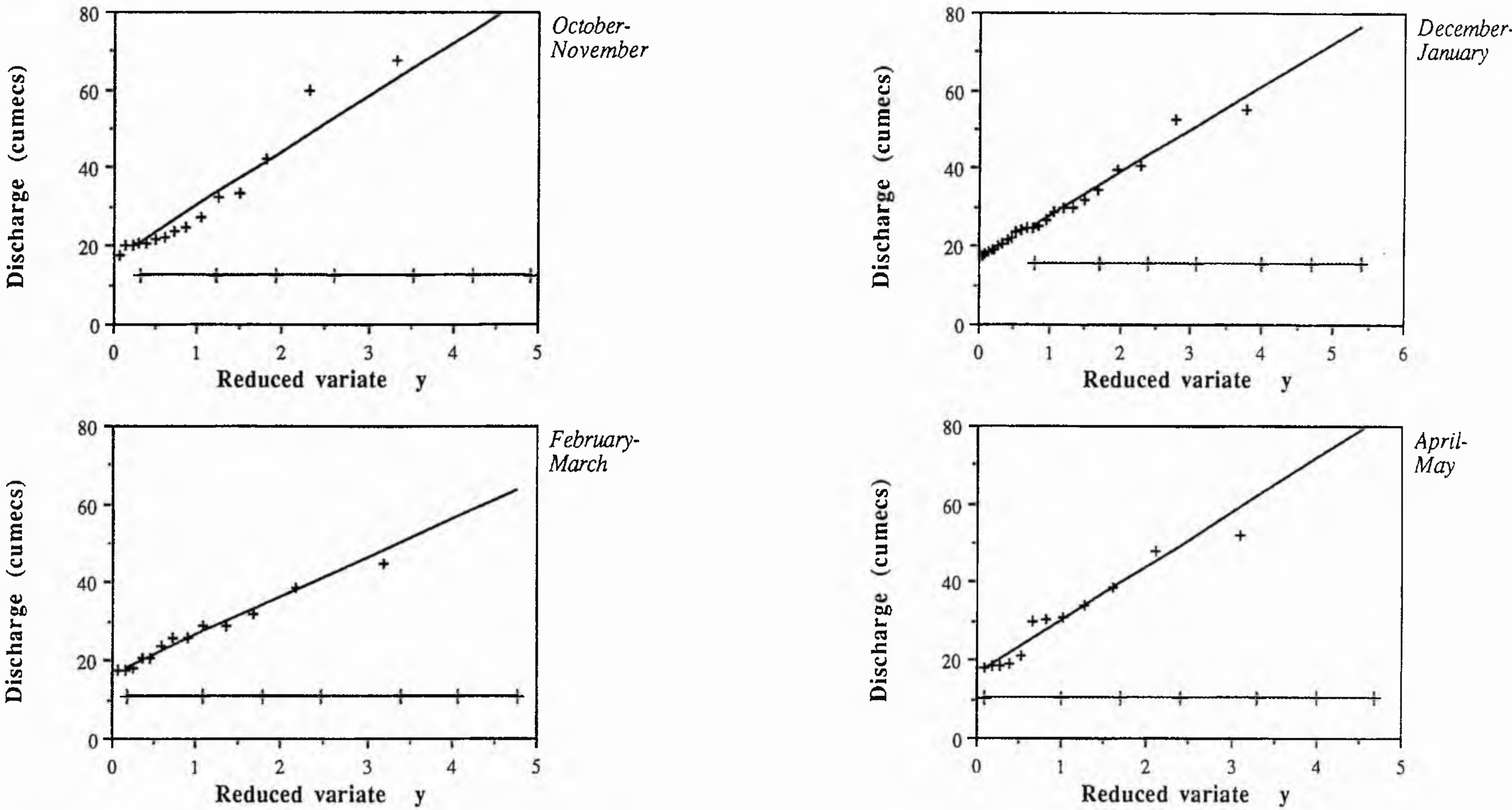
Seasonal frequency distributions for station 21015 Leader Water @ Earlston



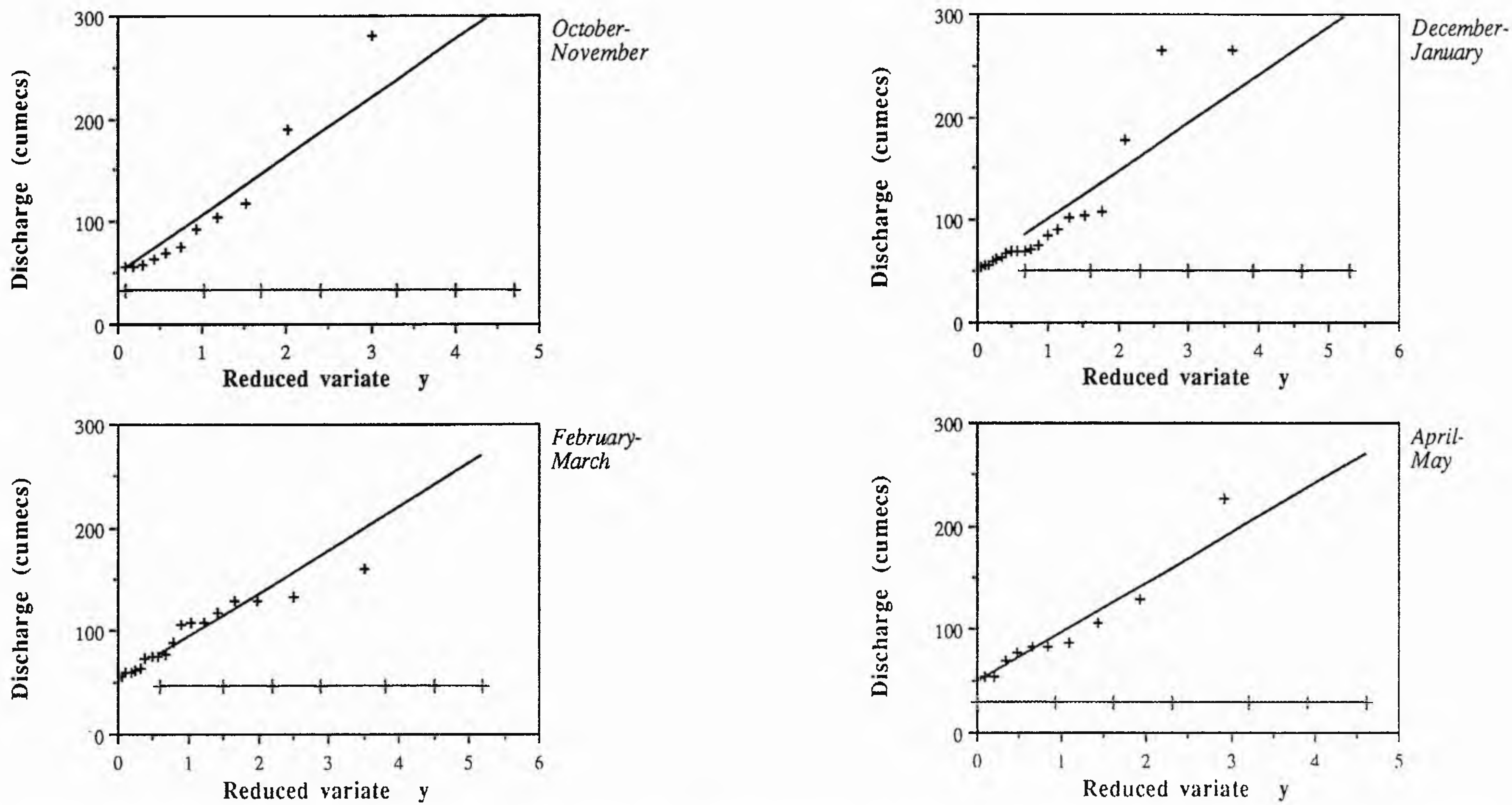




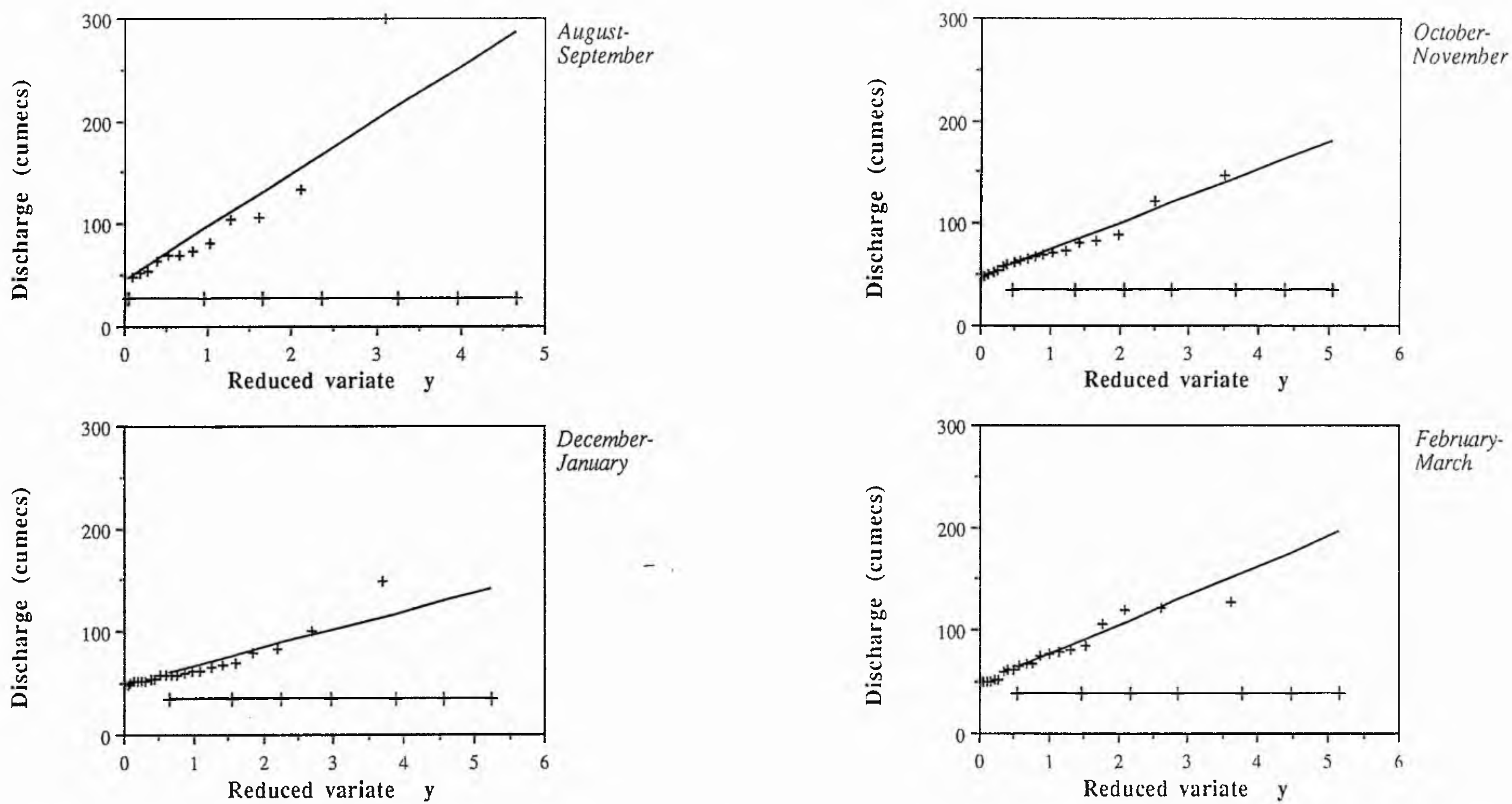
Seasonal frequency distributions for station 21016 Eye Water @ Eyemouth Mill



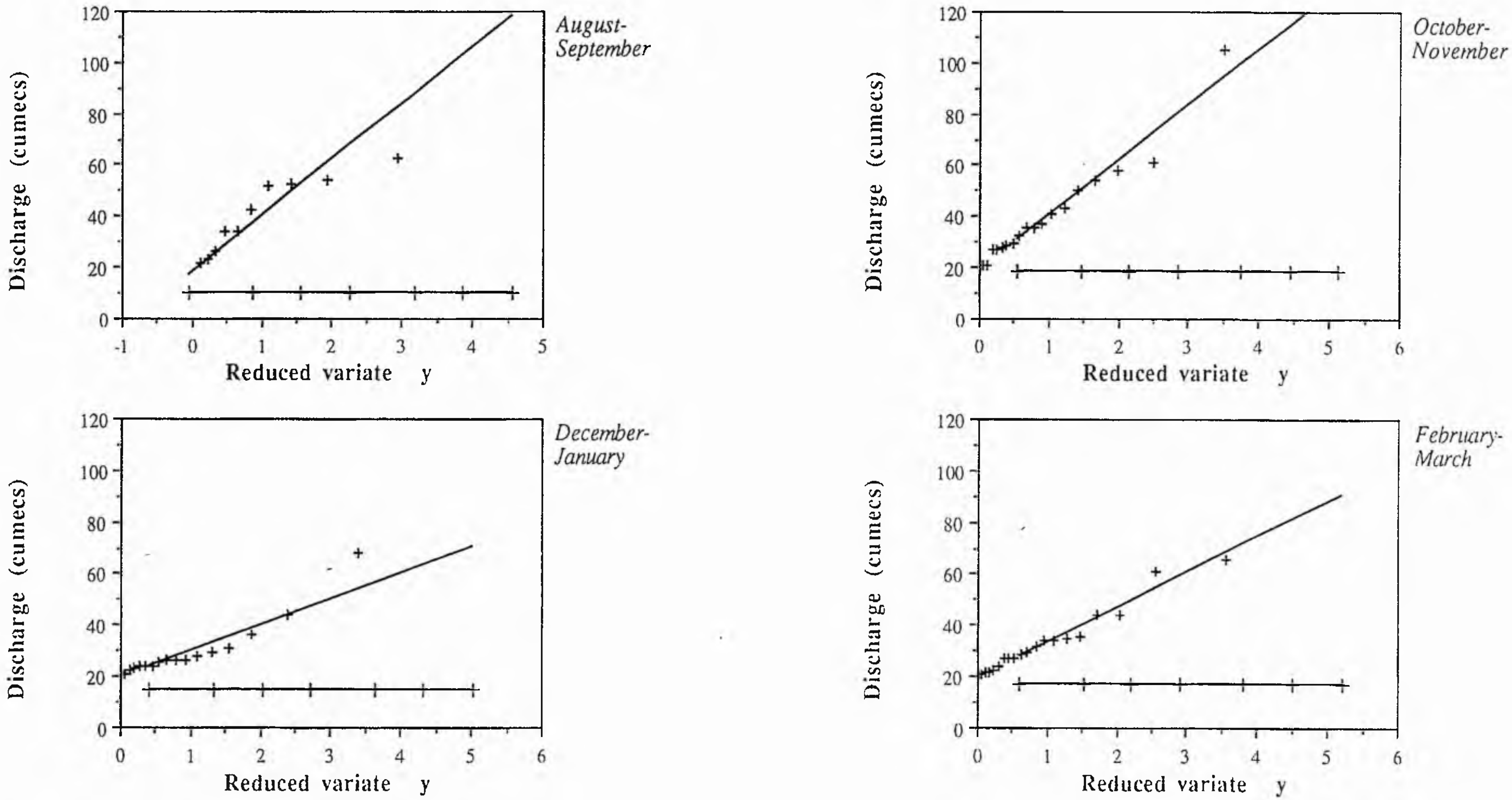
Seasonal frequency distributions for station 21022 Whiteadder Water @ Hutton Castle



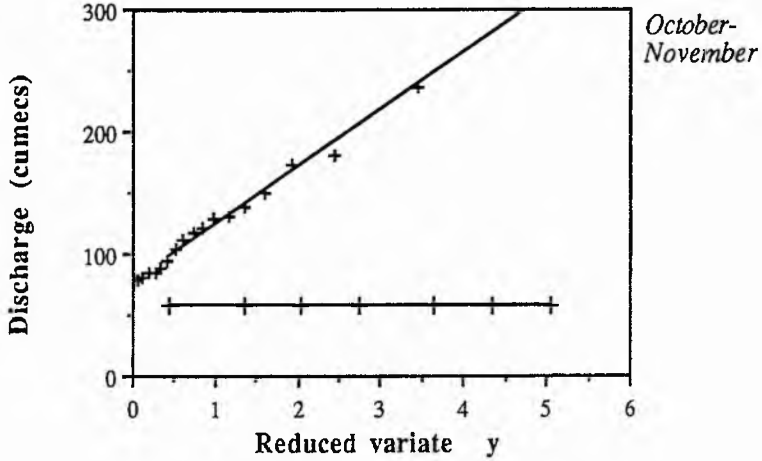
Seasonal frequency distributions for station 21031 Till @ Etal

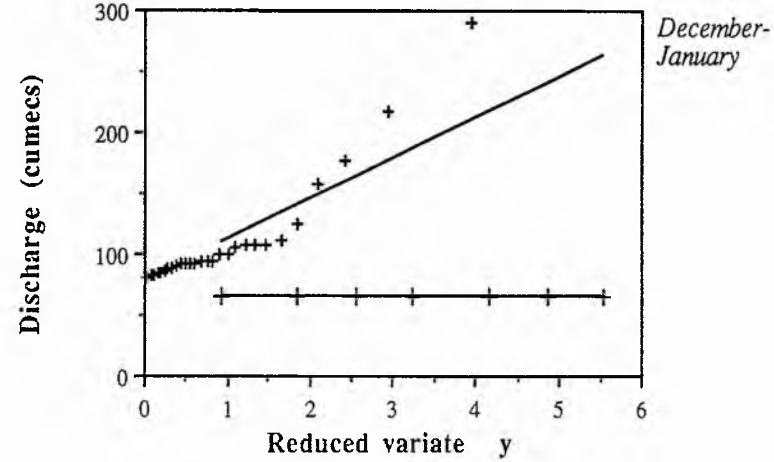


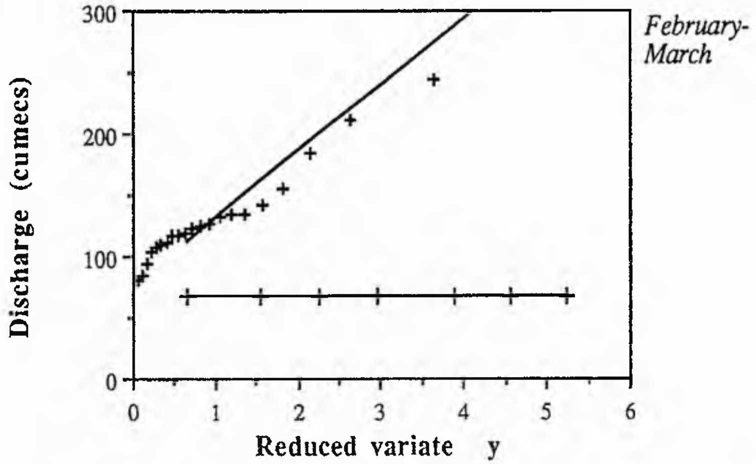
Seasonal frequency distributions for station 21032 Glen @ Kirknewton



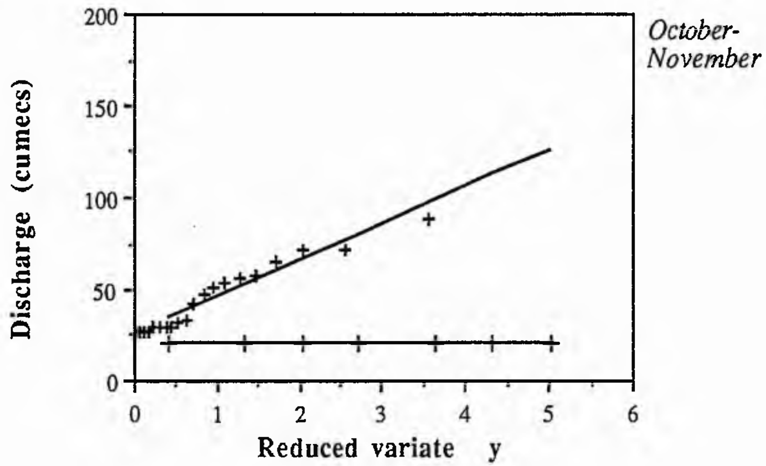
Seasonal frequency distributions for station 22001 Coquet @ Morwick

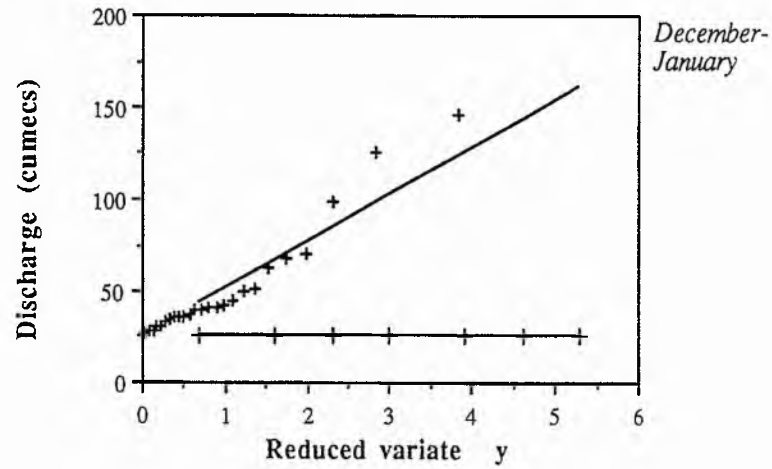


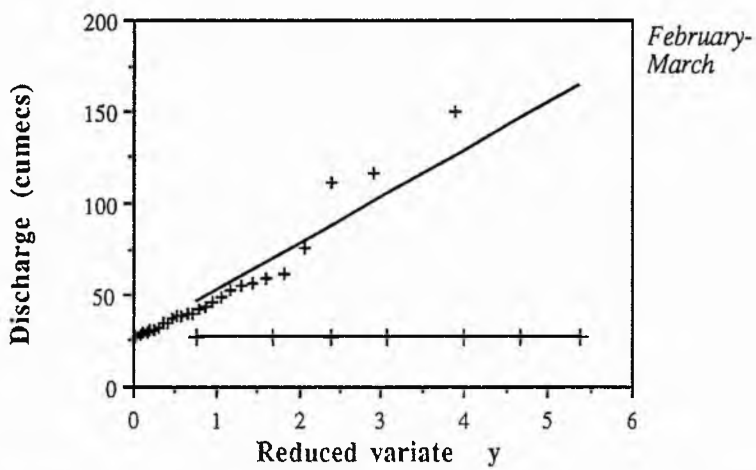




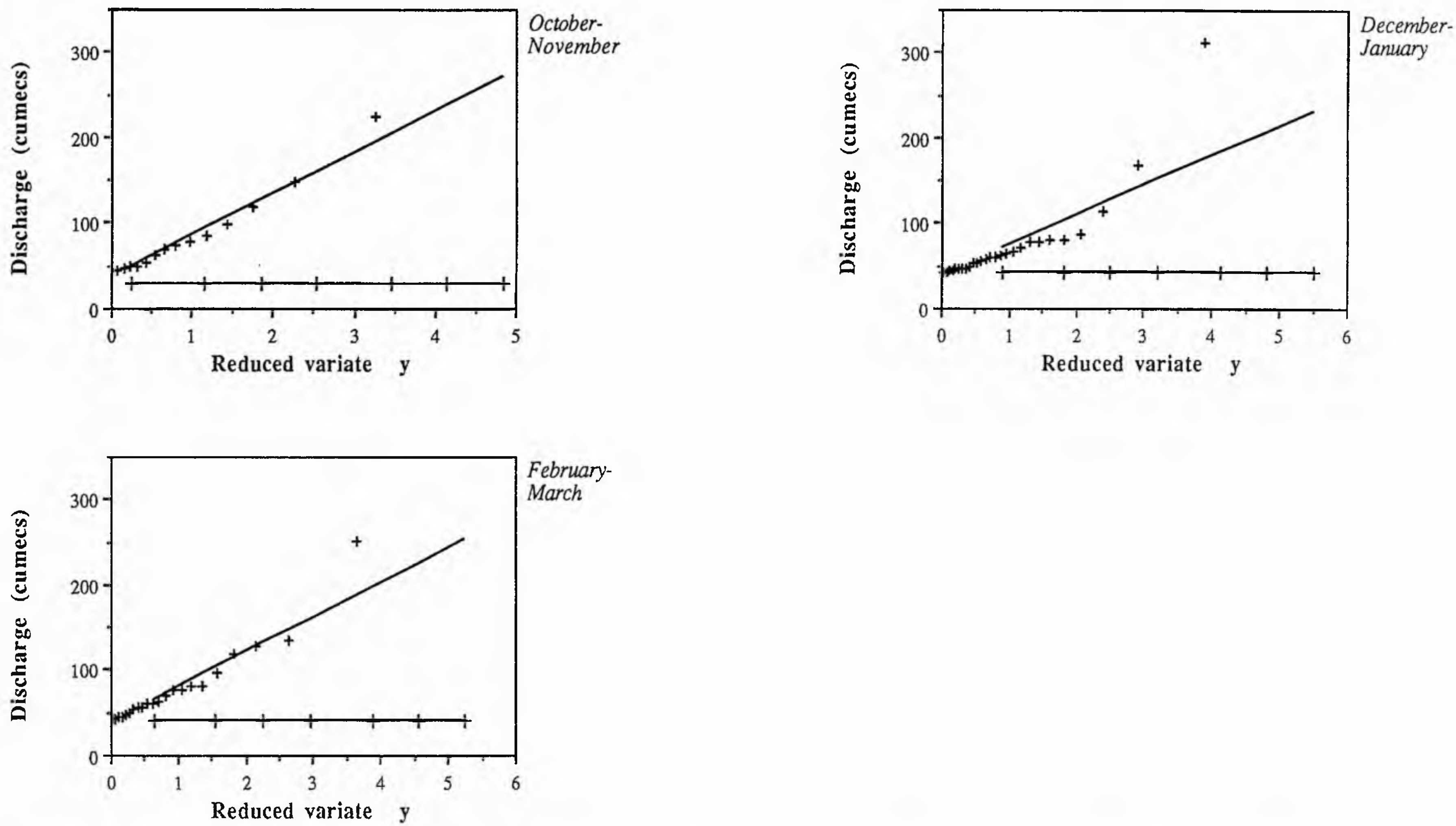
Seasonal frequency distributions for station 22006 Blyth @ Hartford Bridge



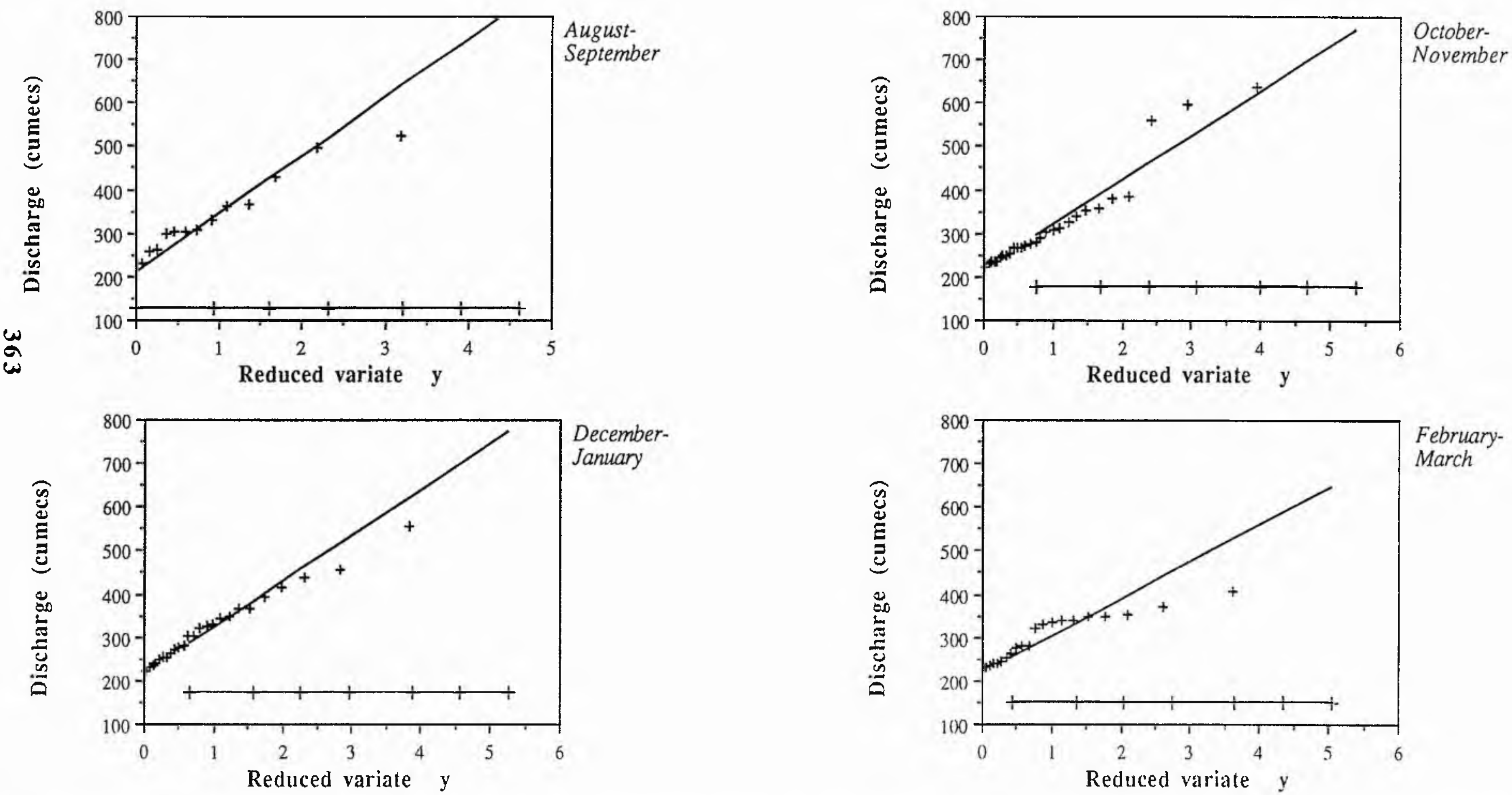




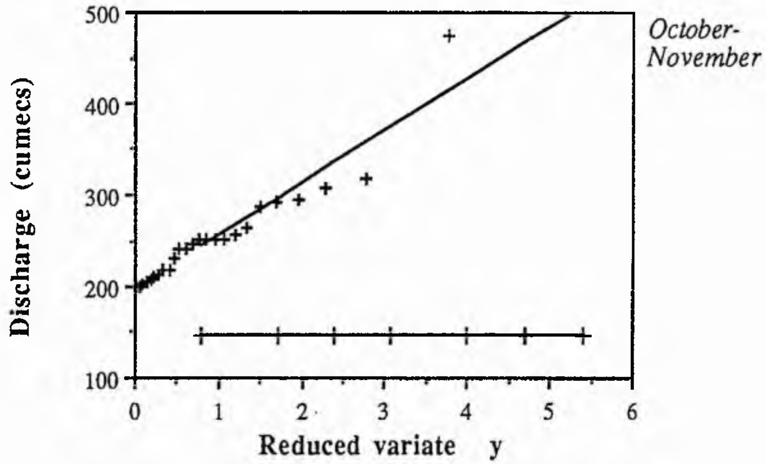
Seasonal frequency distributions for station 22007 Wansbeck @ Mitford

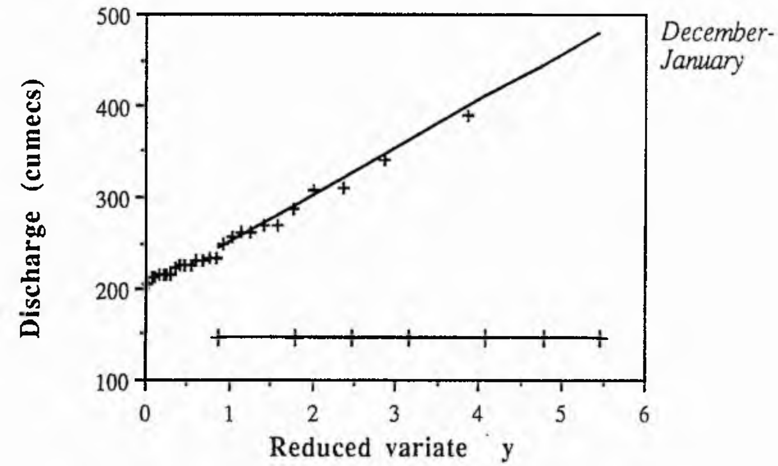


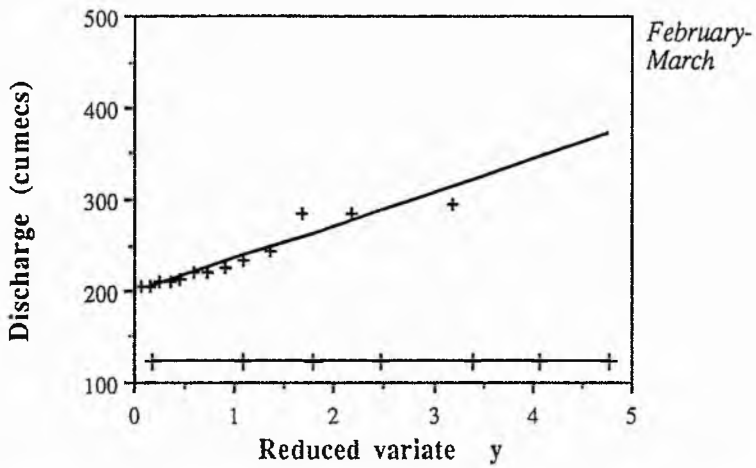
Seasonal frequency distributions for station 77002 Esk @ Canonbie



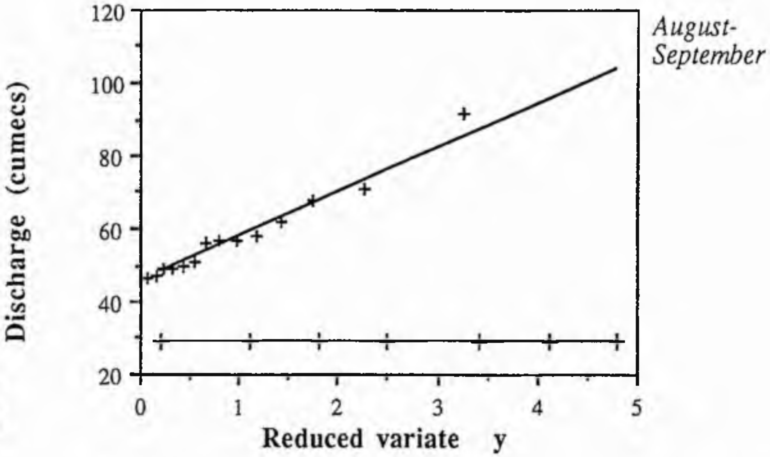
Seasonal frequency distributions for station 78003 Annan @ Brydekirk

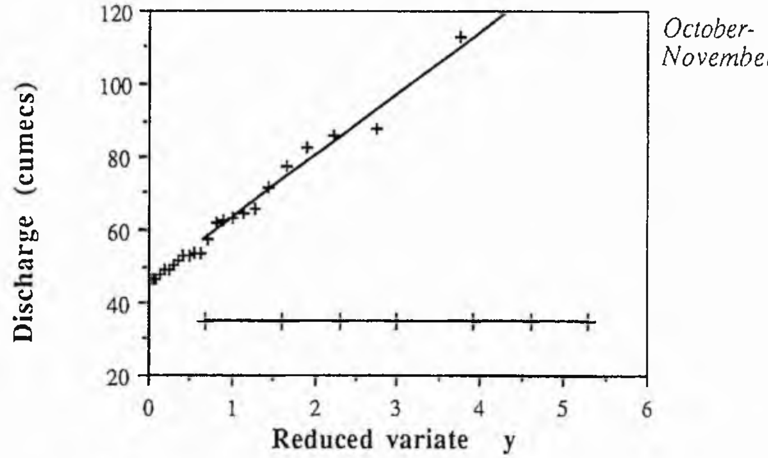


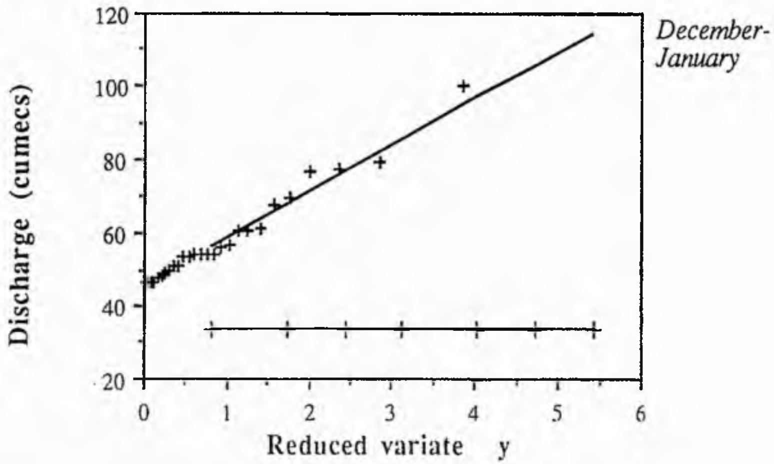


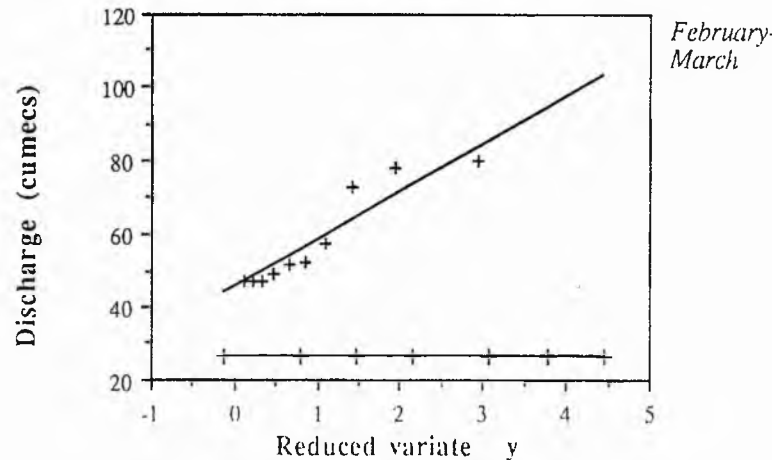


Seasonal frequency distributions for station 78004 Kinnel @ Redhall

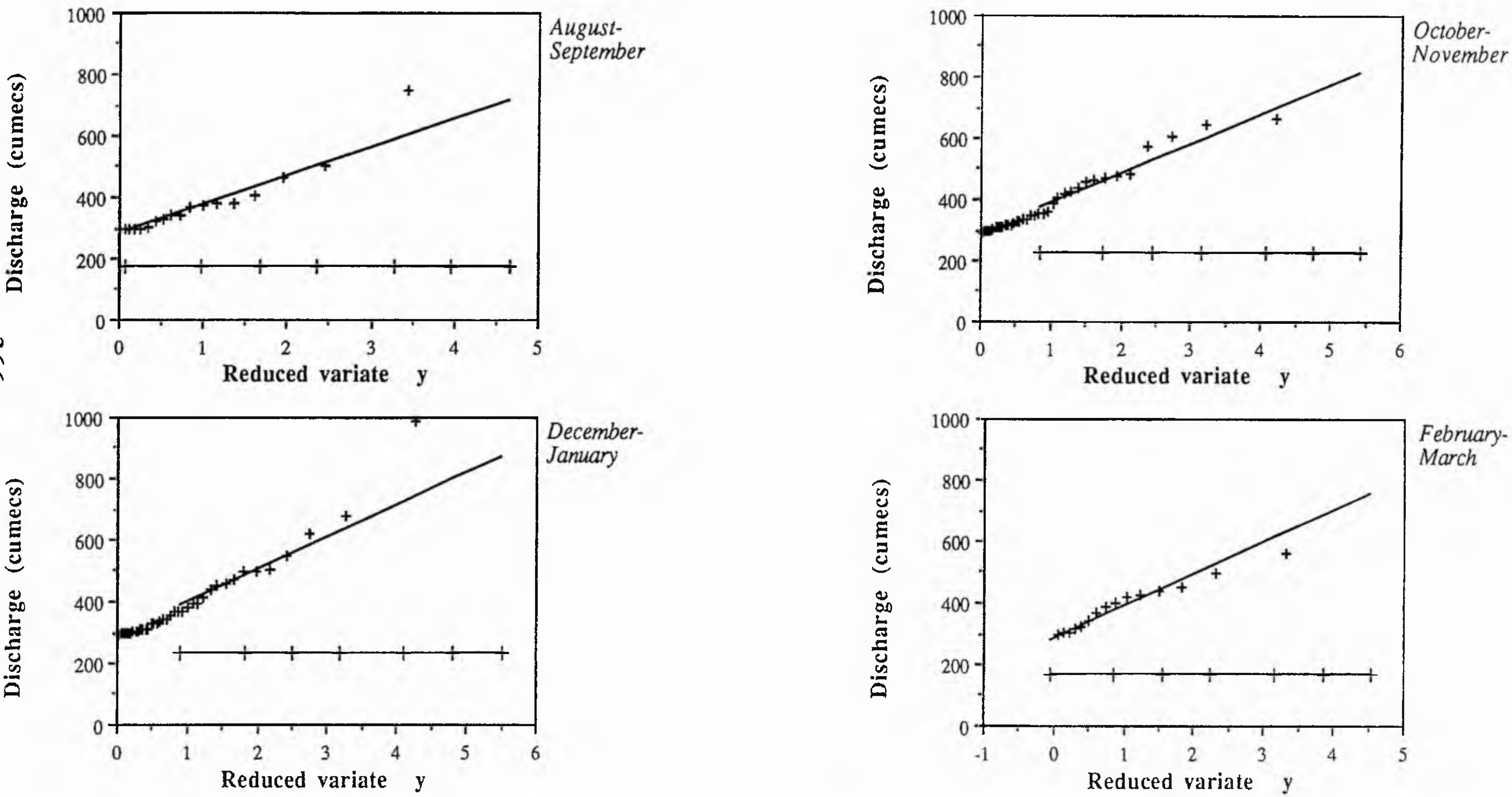




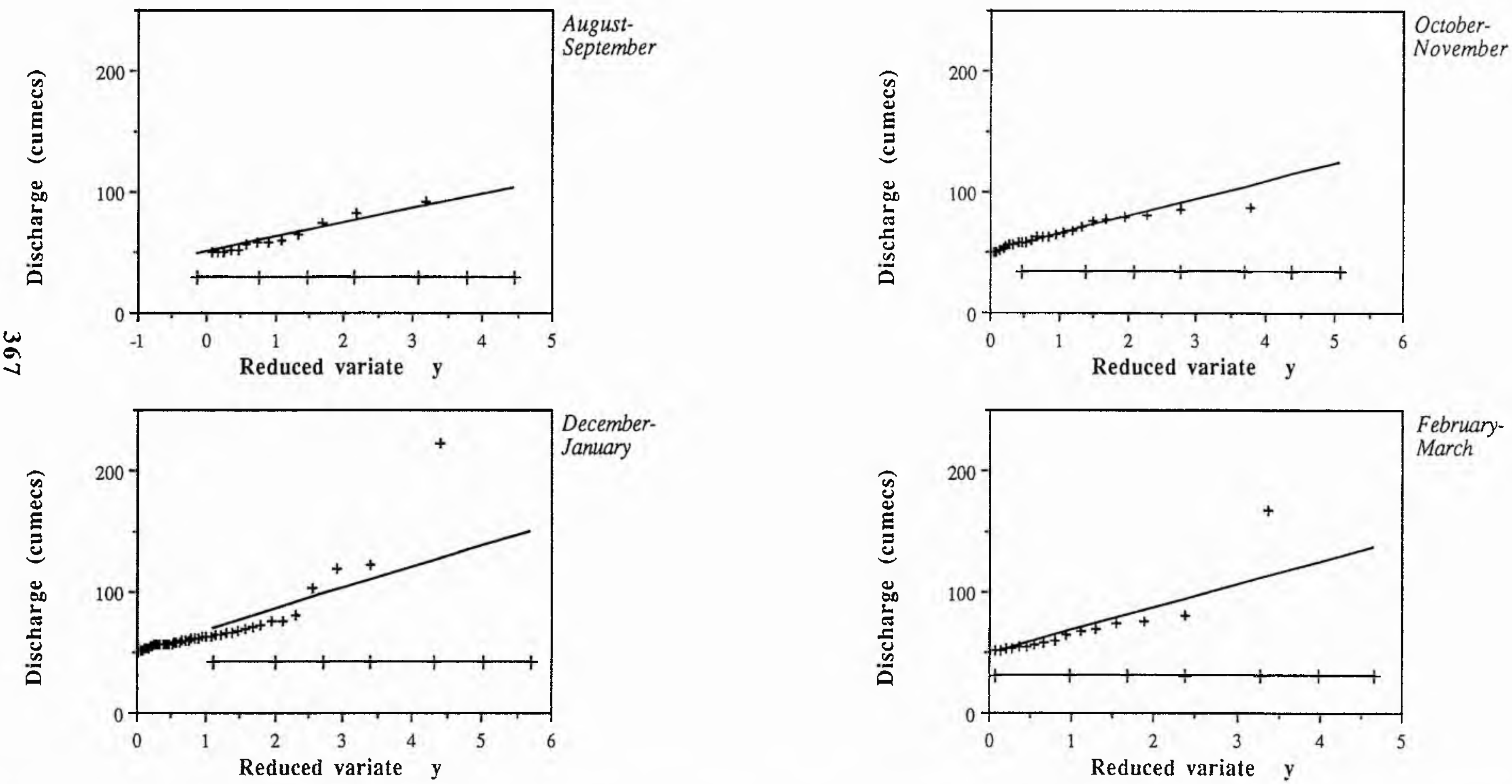




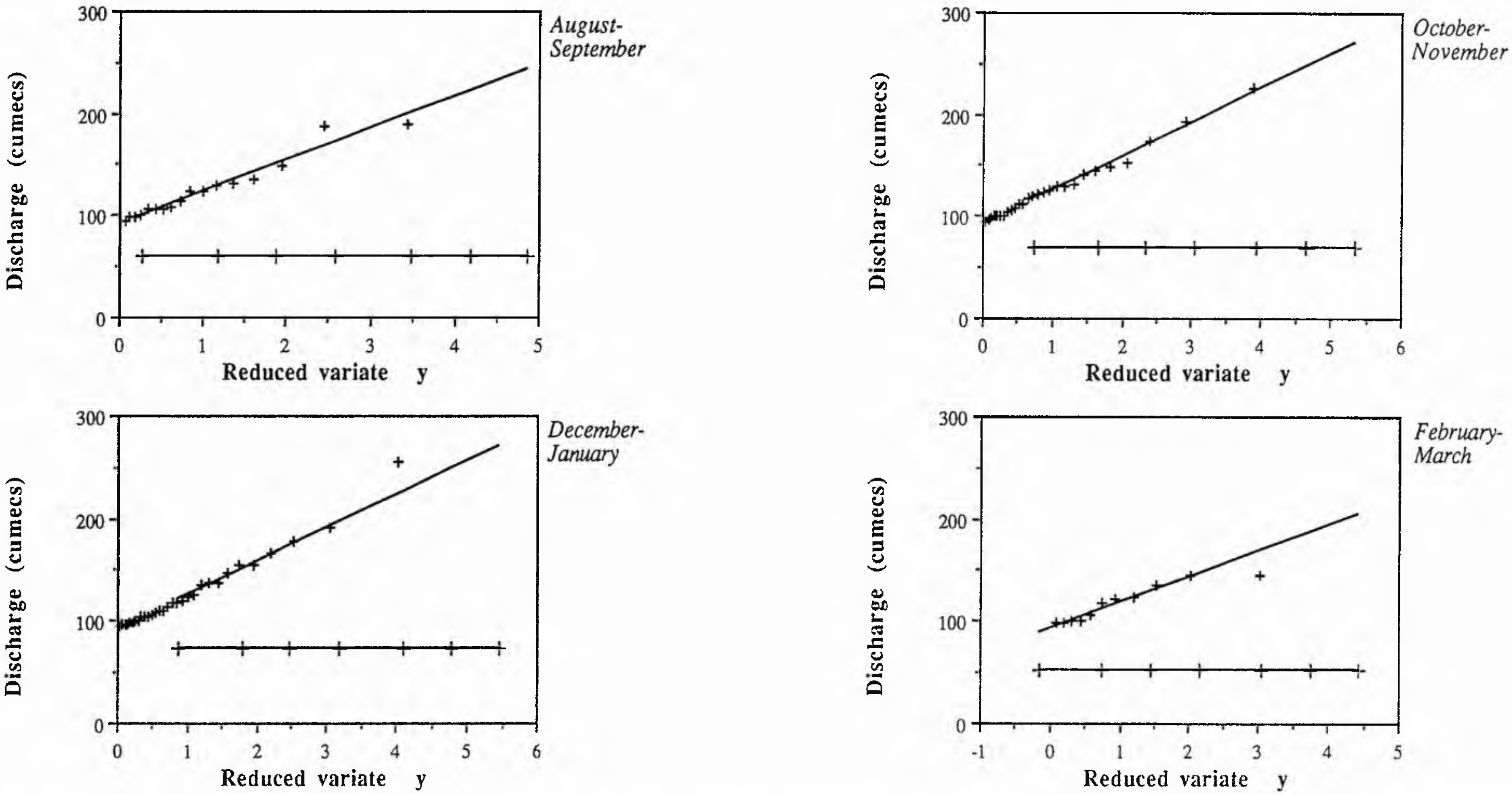
Seasonal frequency distributions for station 79002 Nith @ Friar's Carse



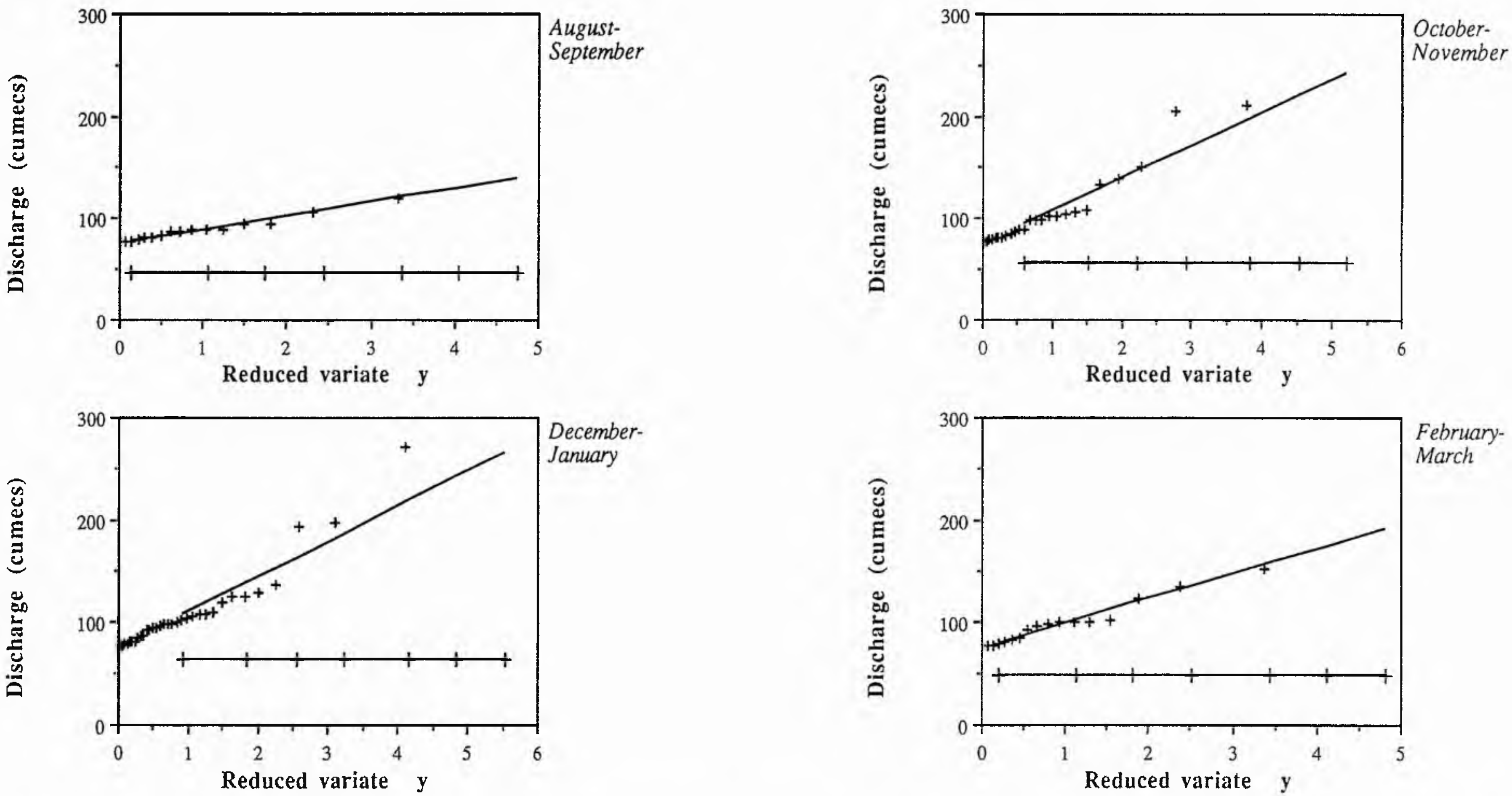
Seasonal frequency distributions for station 79003 Nith @ Hall Bridge



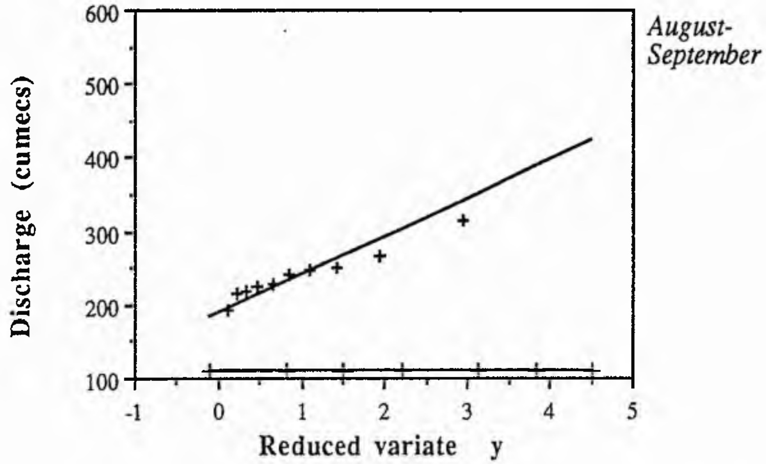
Seasonal frequency distributions for station 79004 Scar @ Capenoch

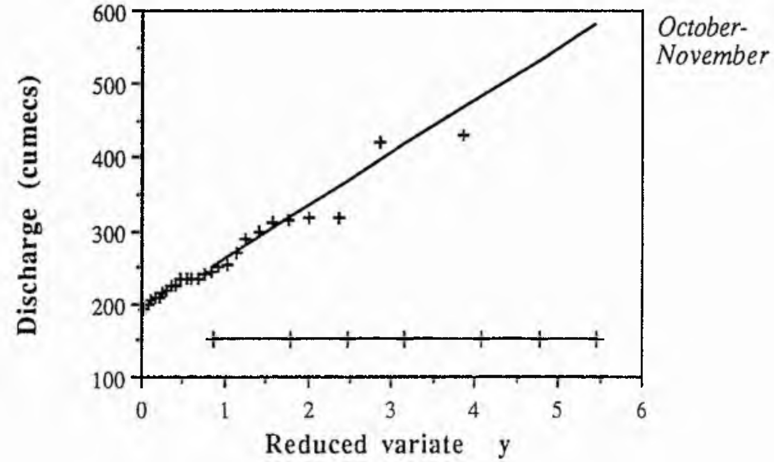


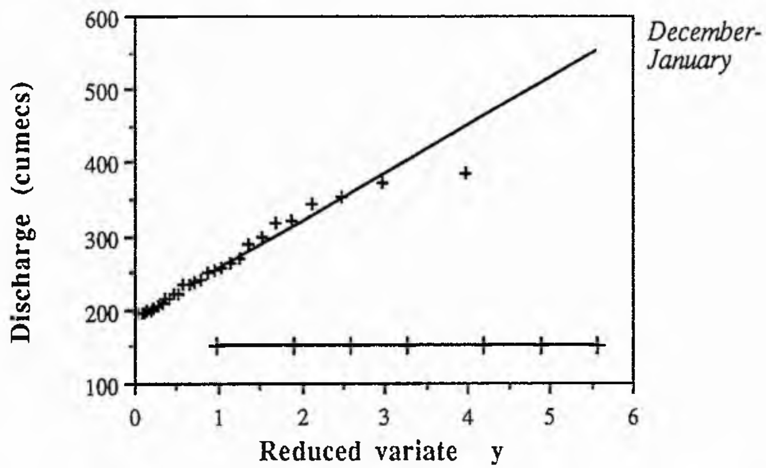
Seasonal frequency distributions for station 79005 Cluden @ Fiddler's Ford



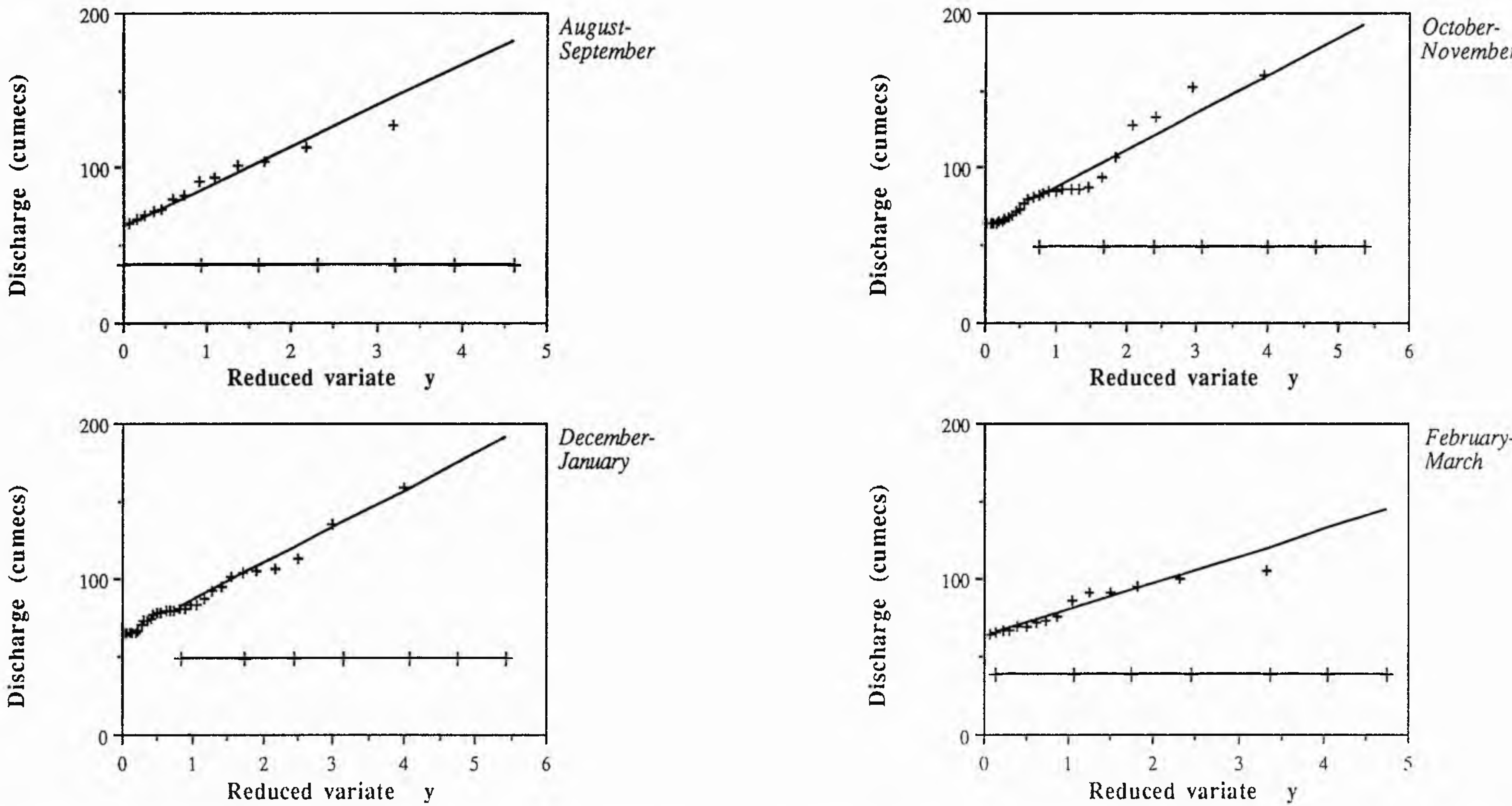
Seasonal frequency distributions for station 79006 Nith @ Drumlanrig



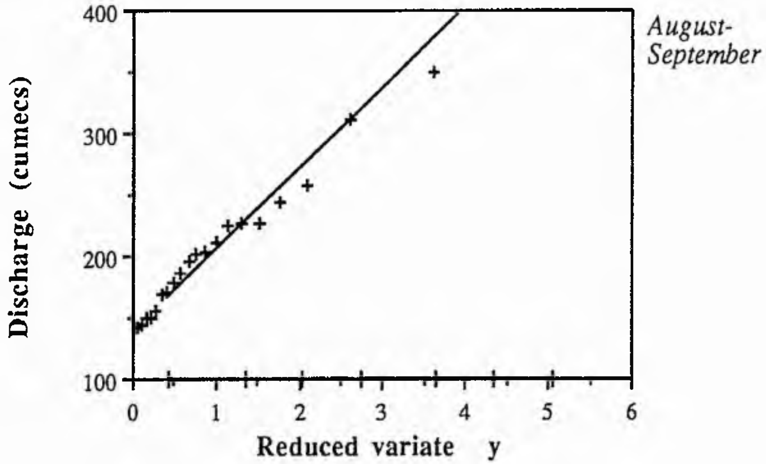


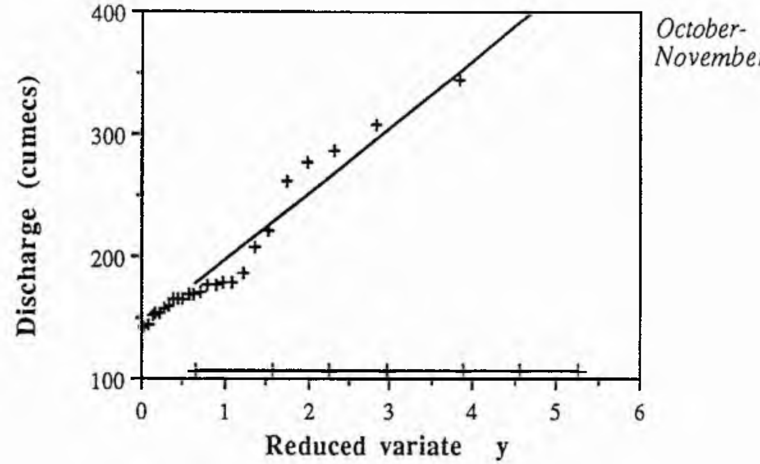


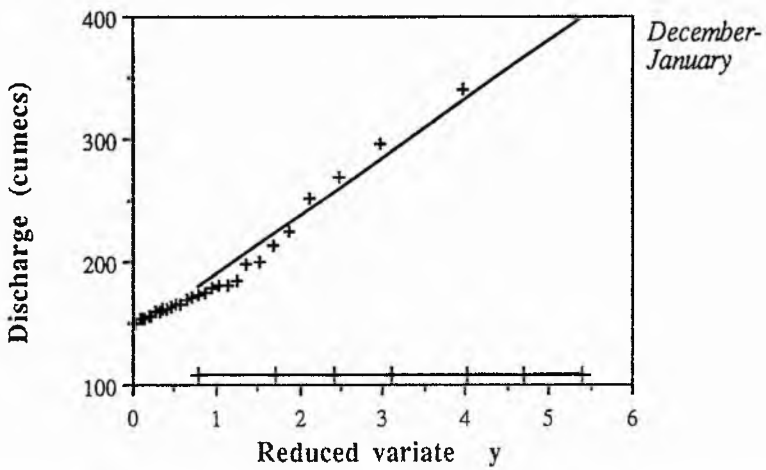
Seasonal frequency distributions for station 80001 Urr @ Dalbeattie



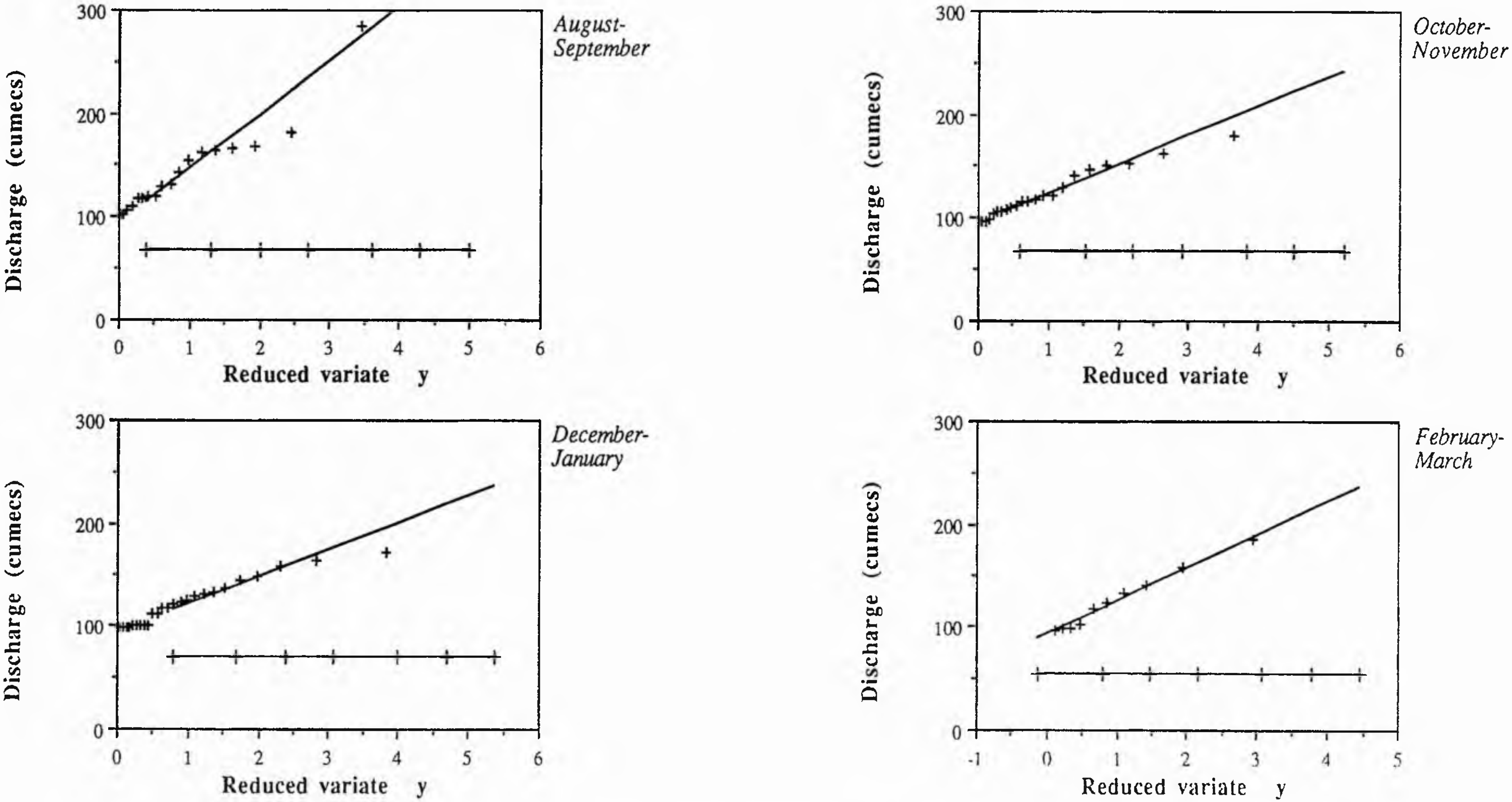
Seasonal frequency distributions for station 81002 Cree @ Newton Stewart



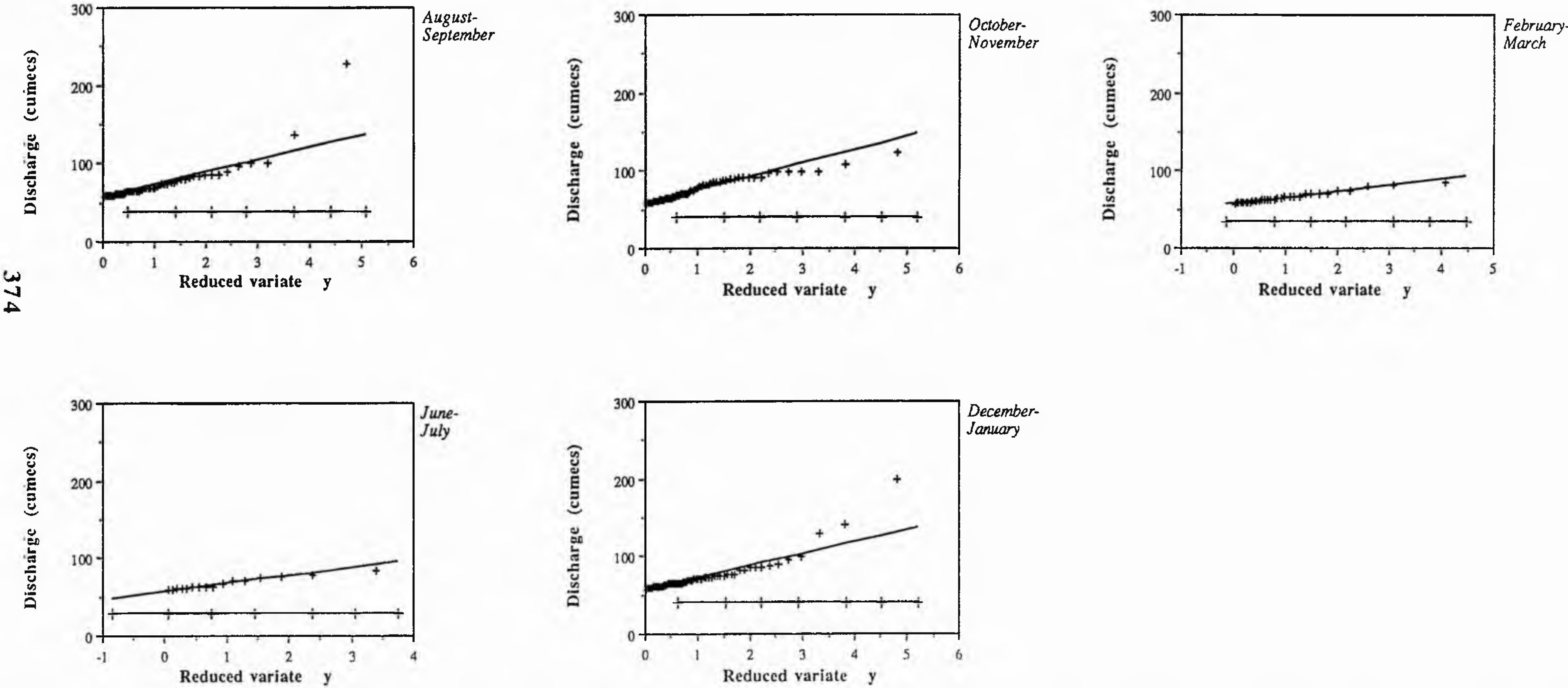




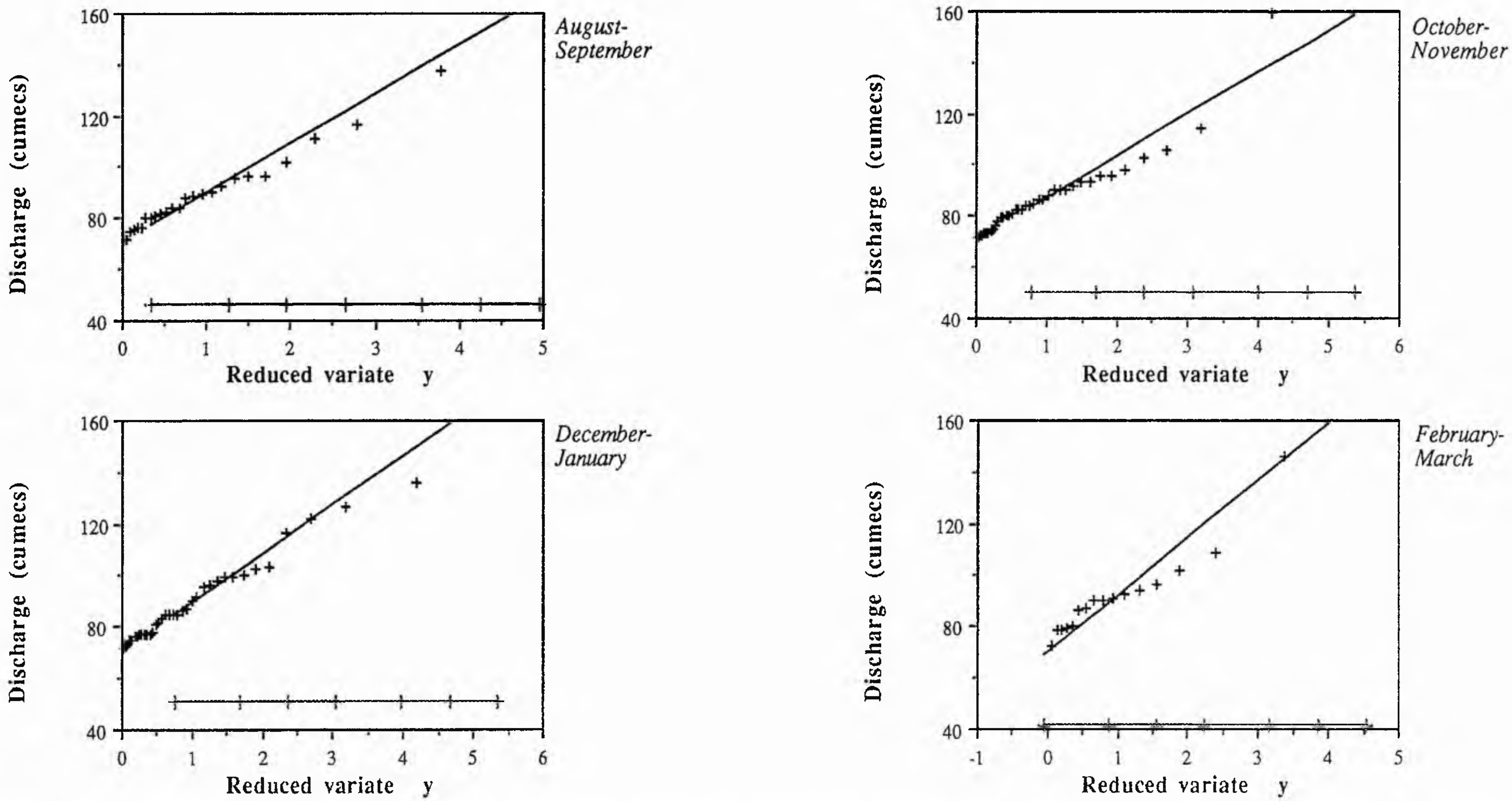
Seasonal frequency distributions for station 81003 Luce @ Airyhemming



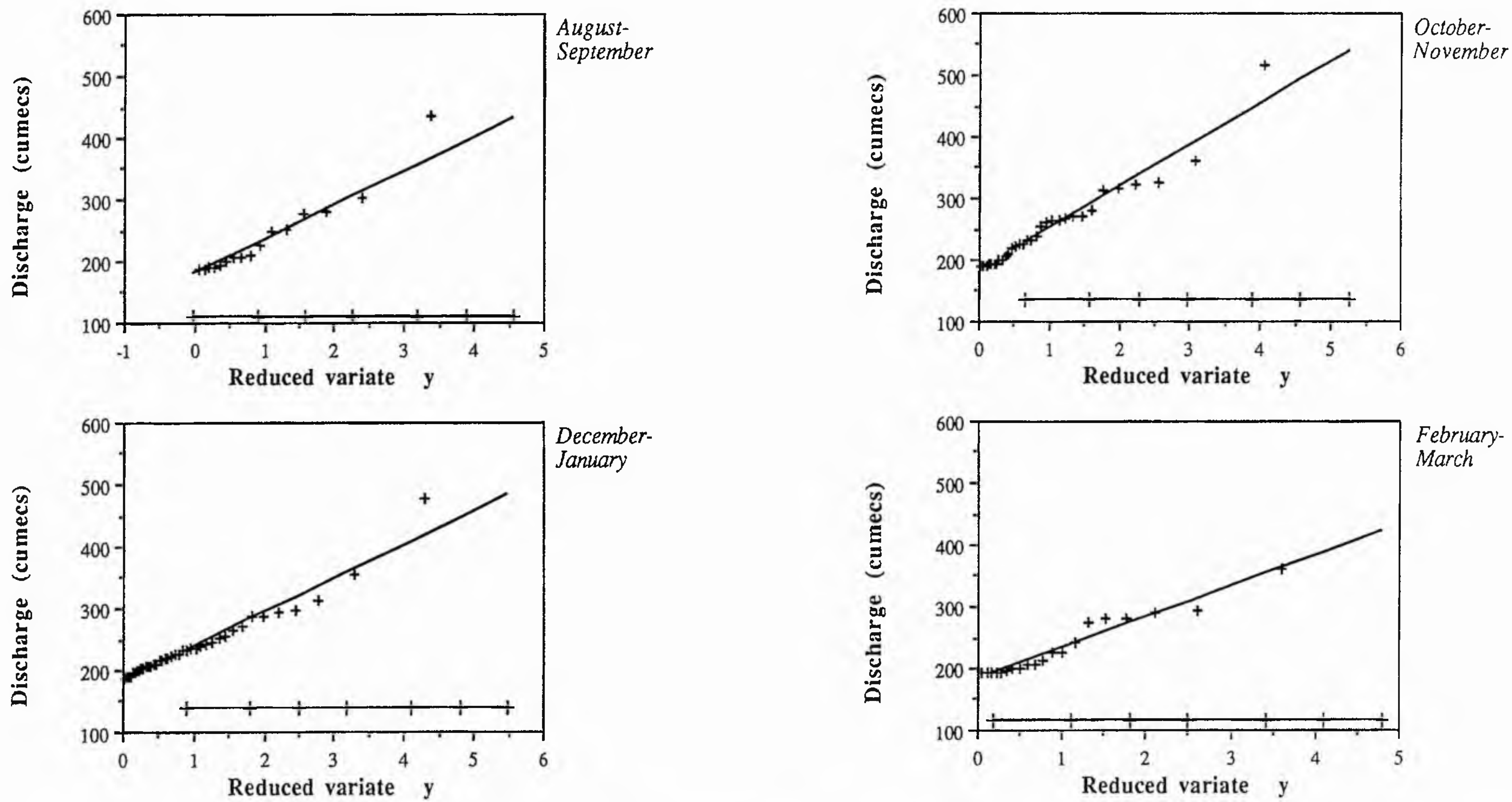
Seasonal frequency distributions for station
83802 Irvine @ Glenfield



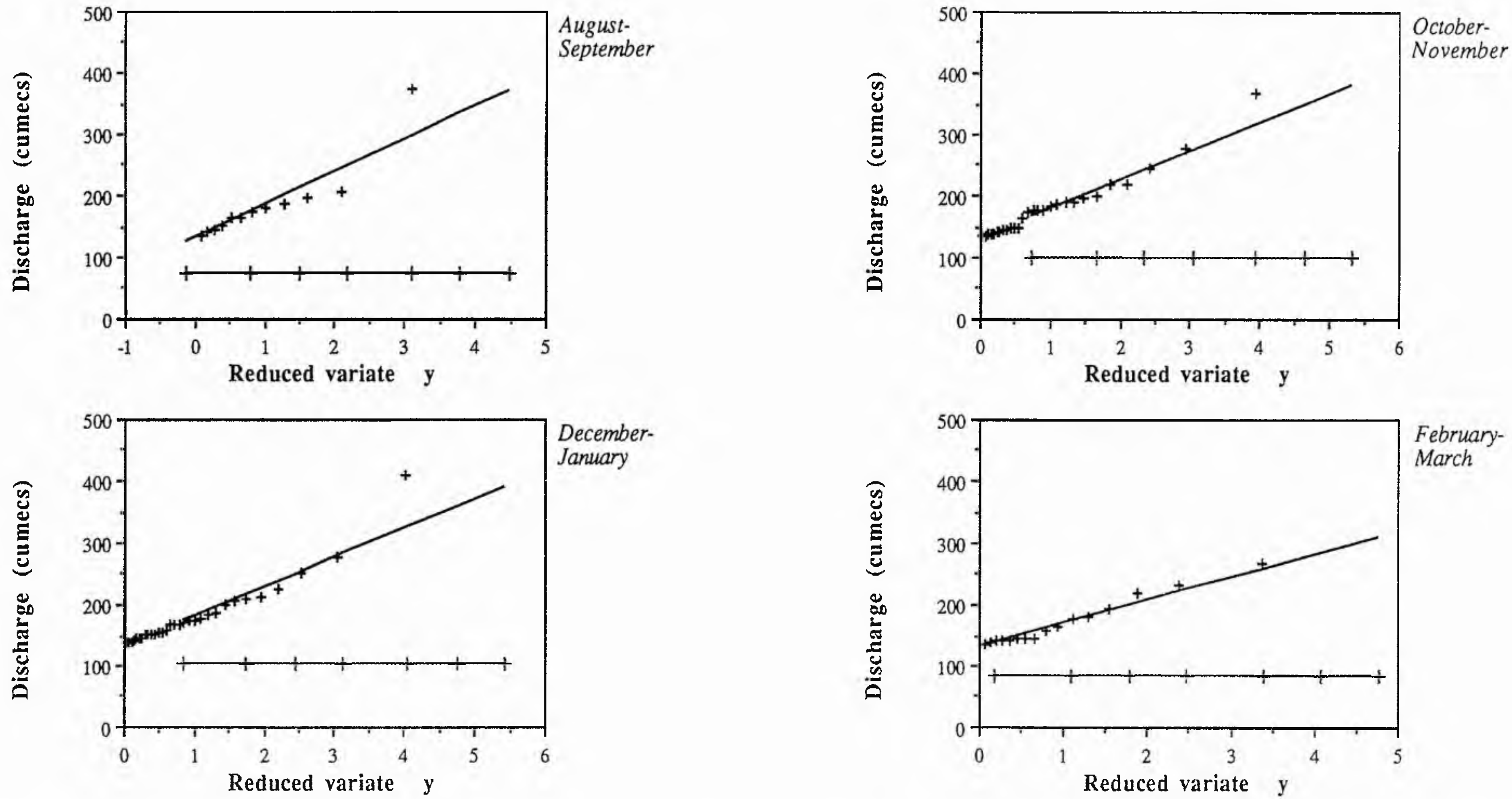
Seasonal frequency distributions for station 84001 Kelvin @ Killermont



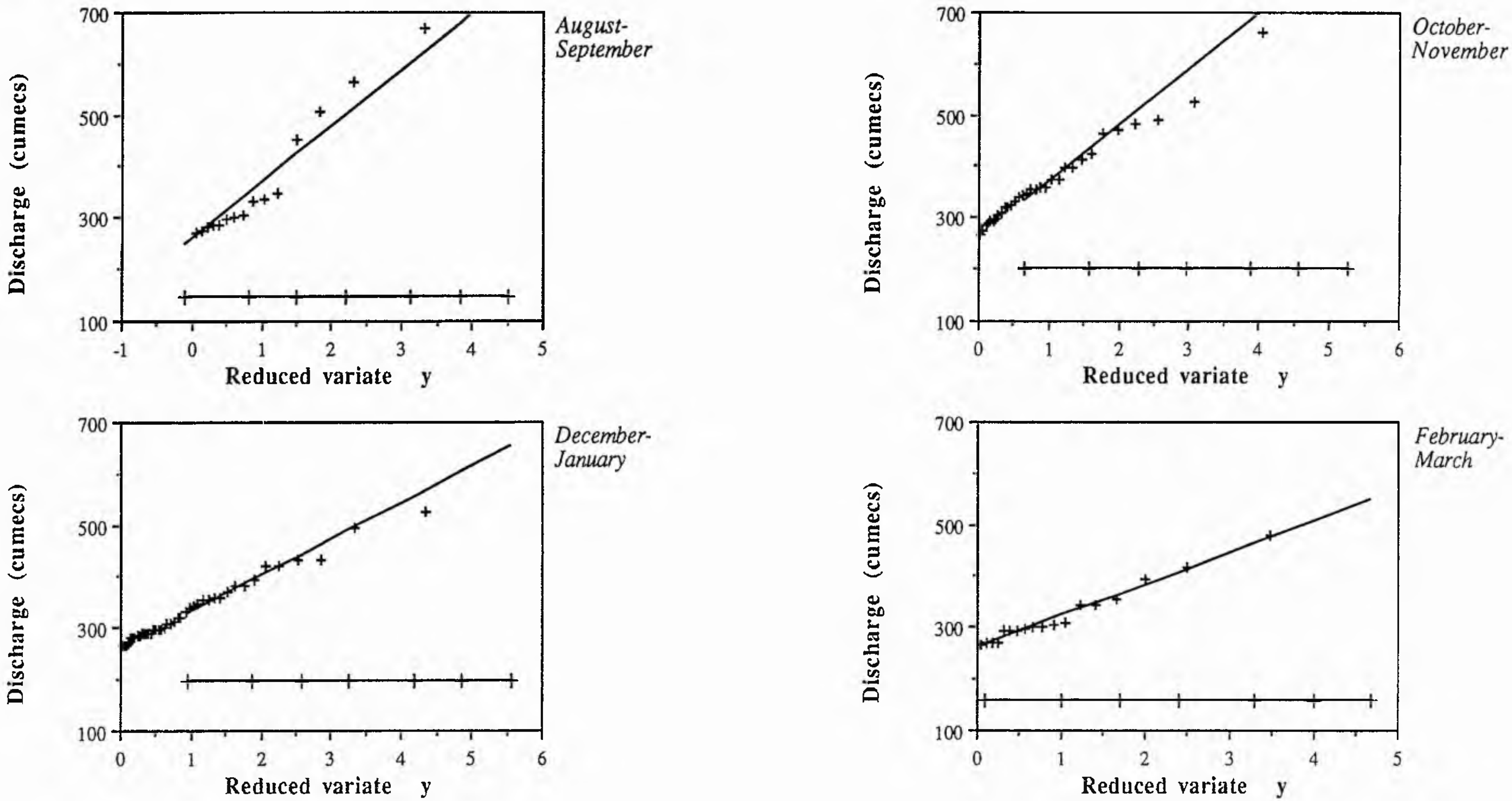
Seasonal frequency distributions for station 84003 Clyde @ Hazelbank



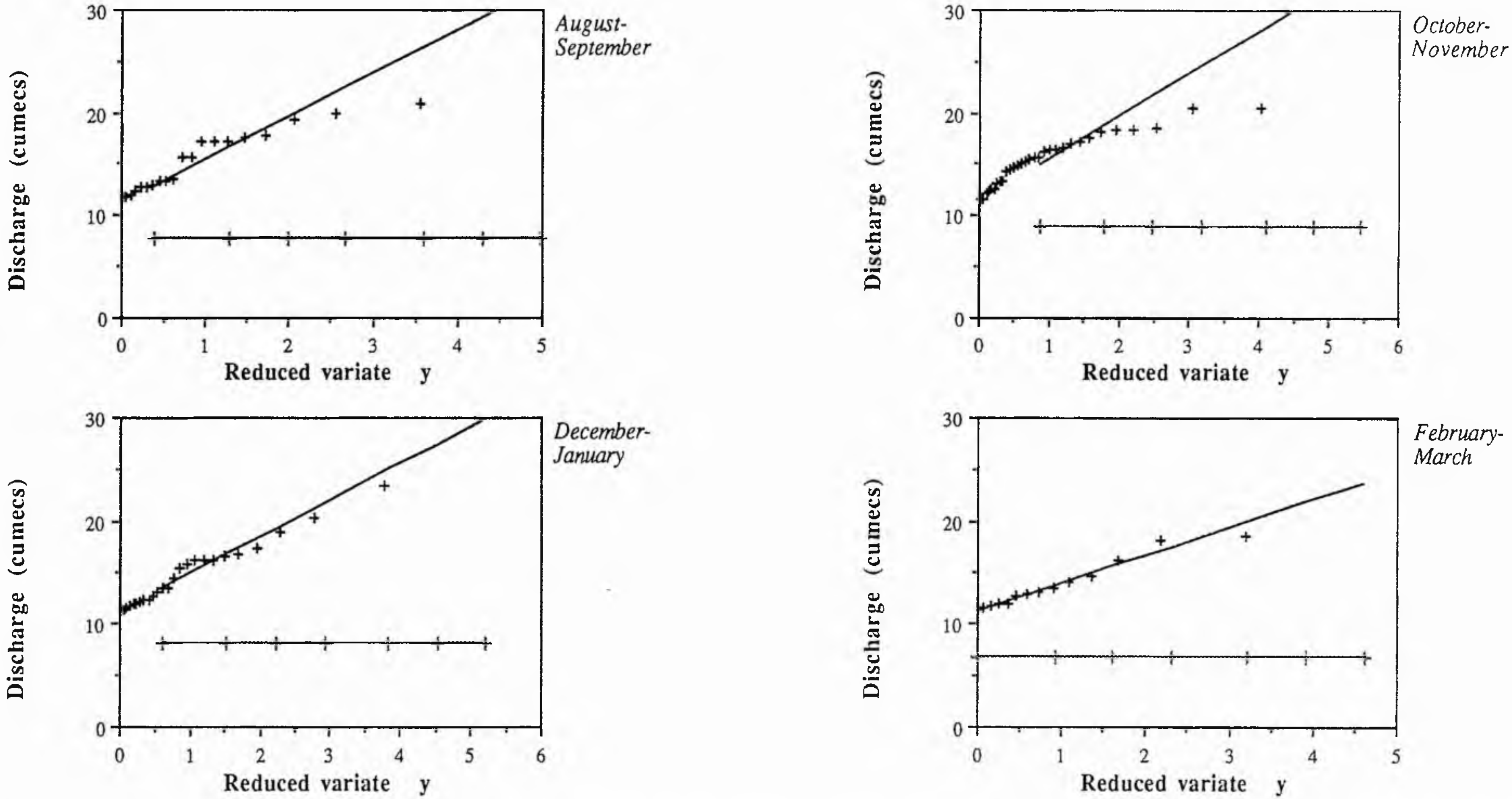
Seasonal frequency distributions for station 84004 Clyde @ Sills of Clyde



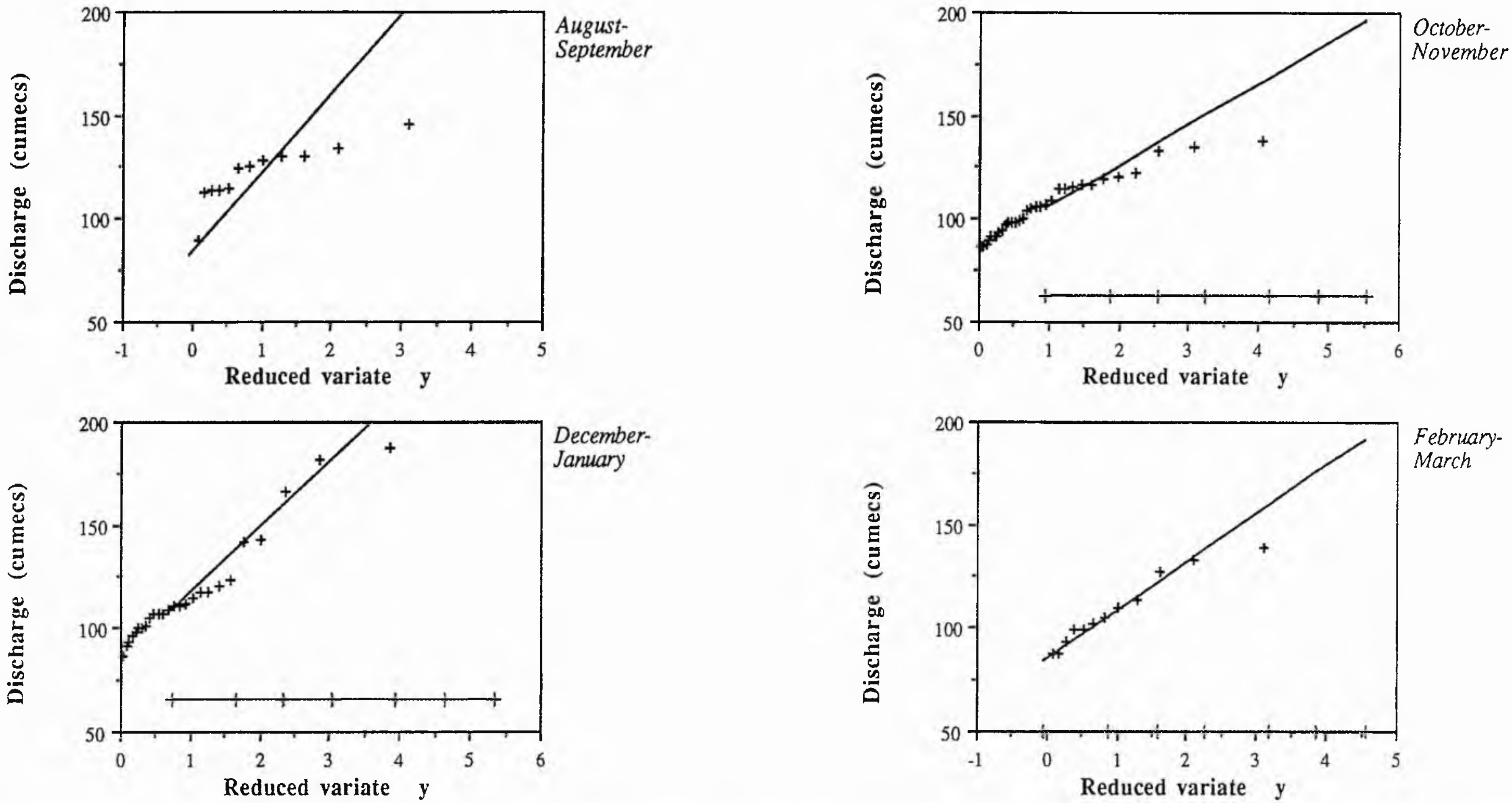
Seasonal frequency distributions for station 84005 Clyde @ Blairston



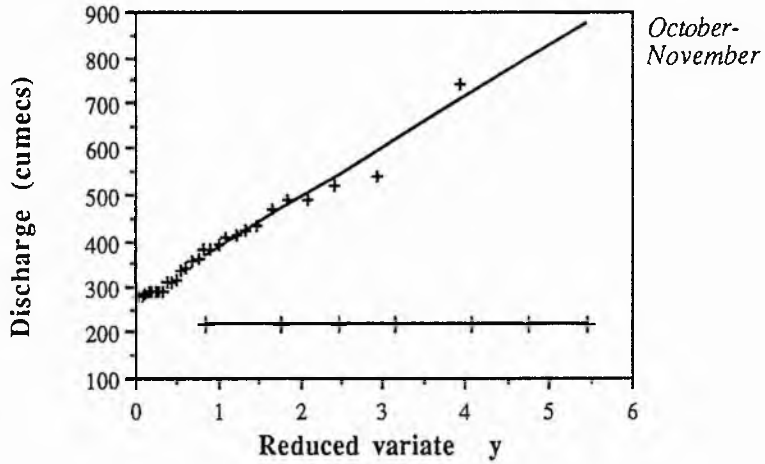
Seasonal frequency distributions for station 84006 Kelvin @ Bridgend

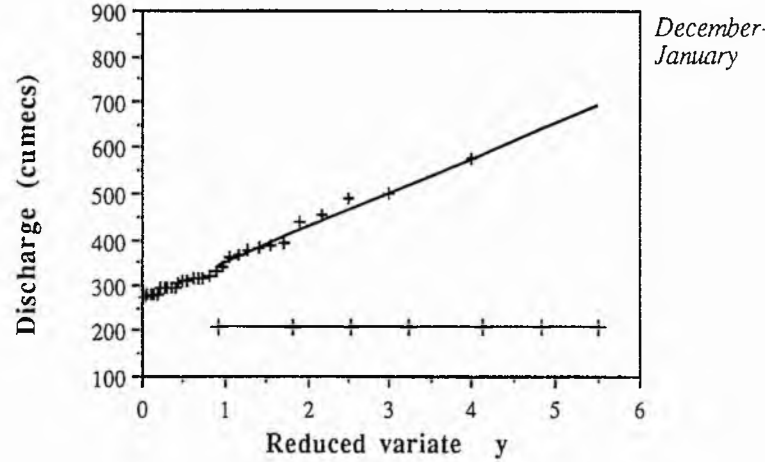


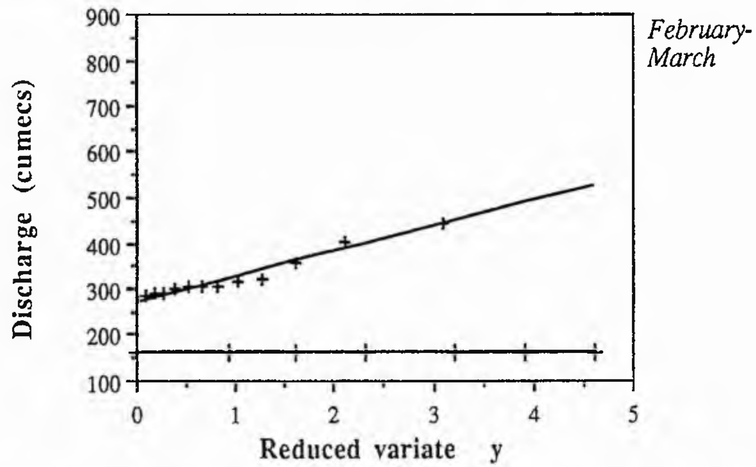
Seasonal frequency distributions for station 84012 White Cart Water @ Hawkhead



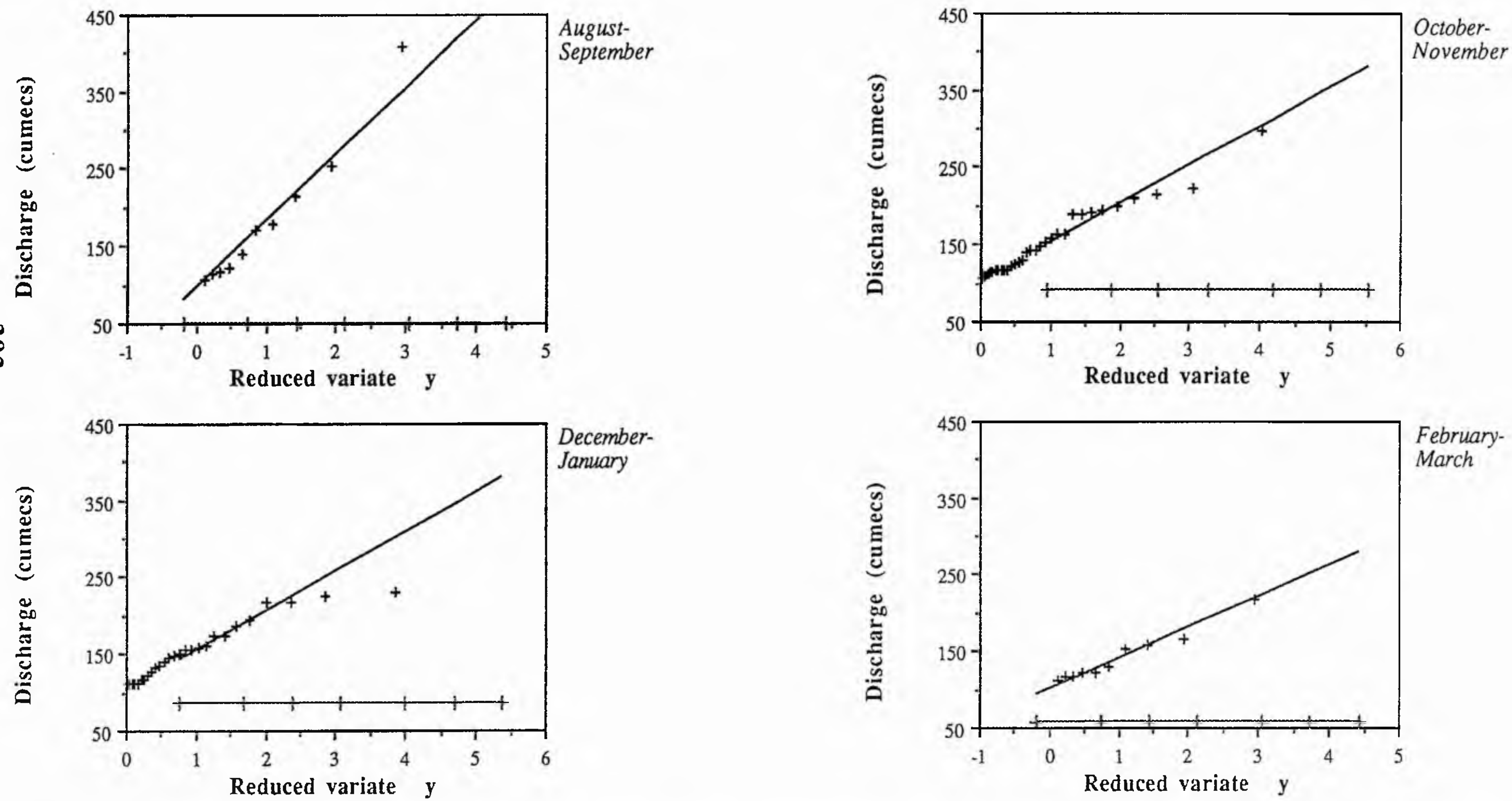
Seasonal frequency distributions for station
84013 Clyde @ Daldowie



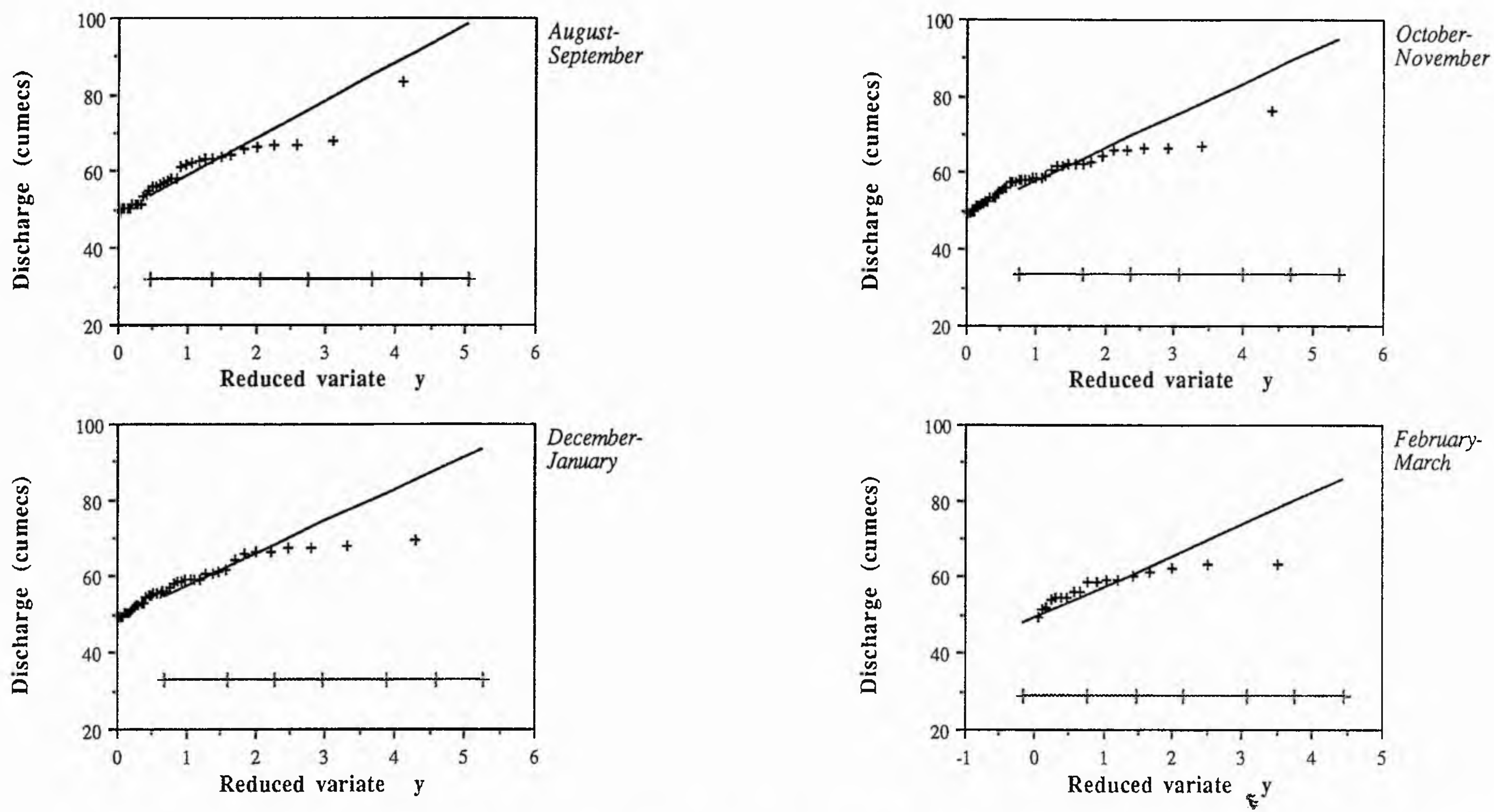




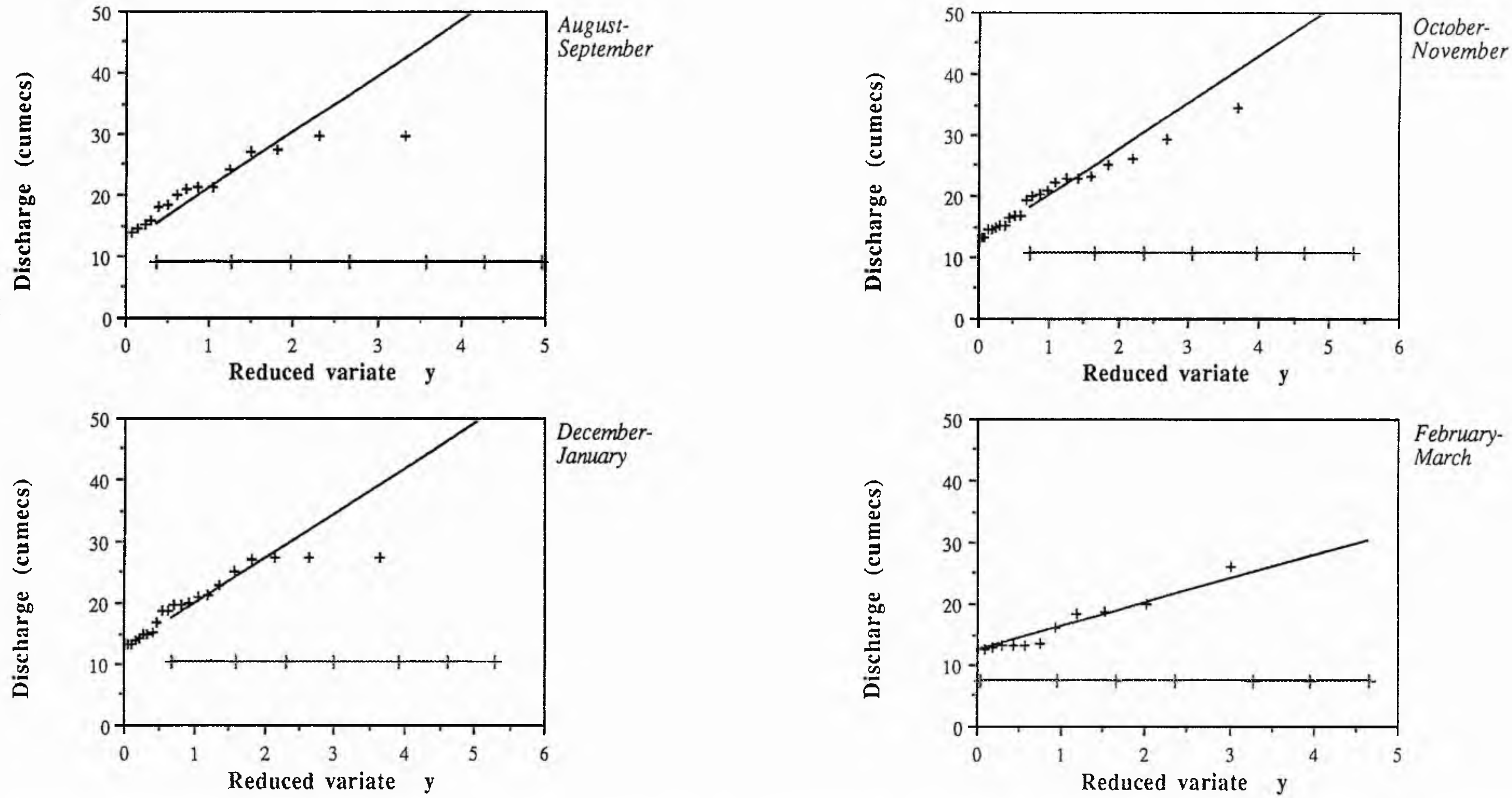
Seasonal frequency distributions for station 84014 Avon Water @ Fairholm



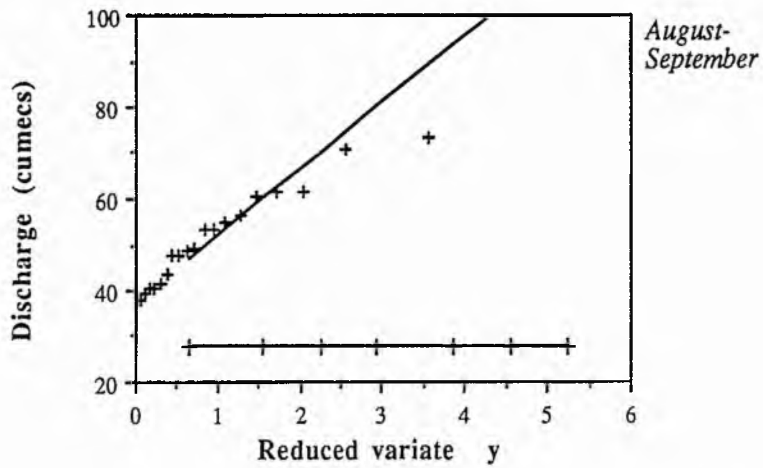
Seasonal frequency distributions for station 84015 Kelvin @ Dryfield

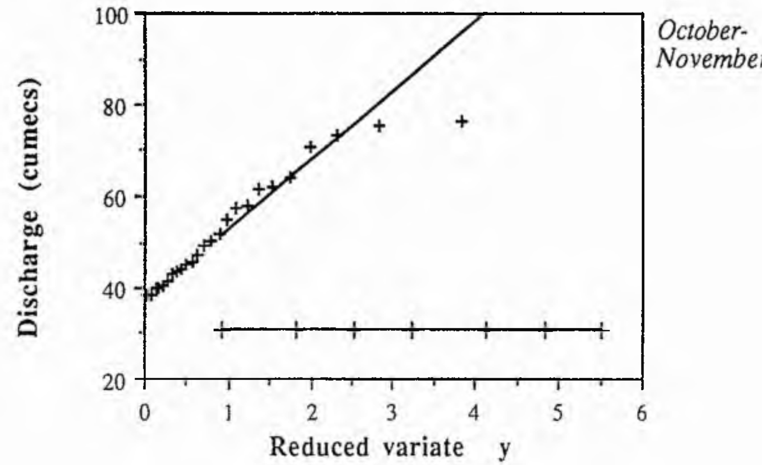


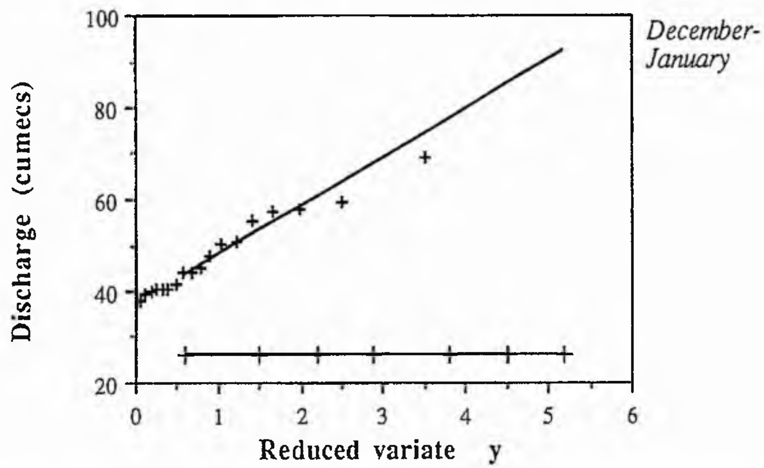
Seasonal frequency distributions for station 84016 Luggie Water @ Condorrat



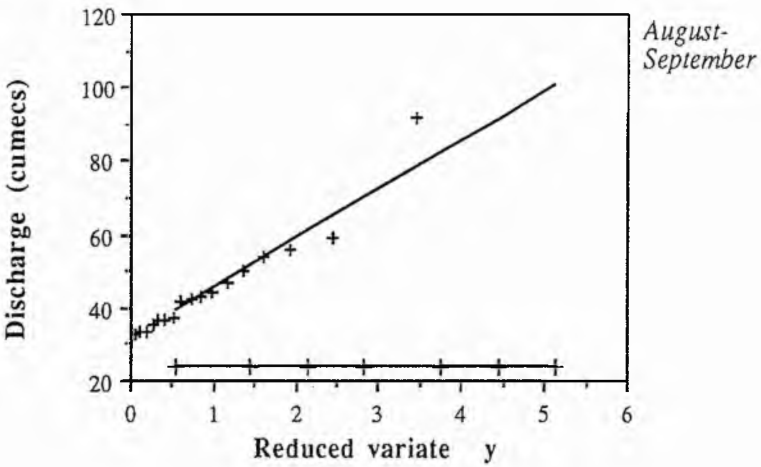
Seasonal frequency distributions for station 84020 Glazert Water @ Milton of Campsie

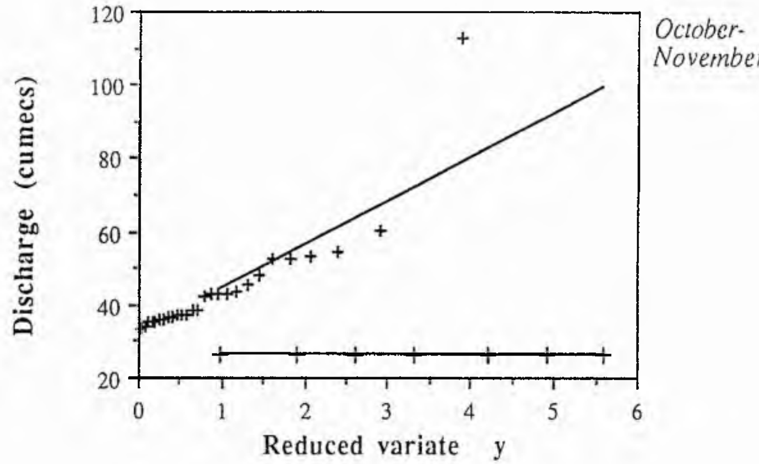


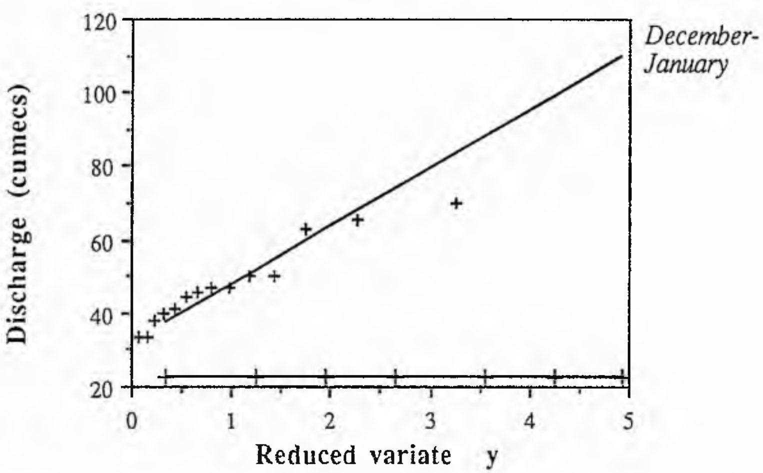




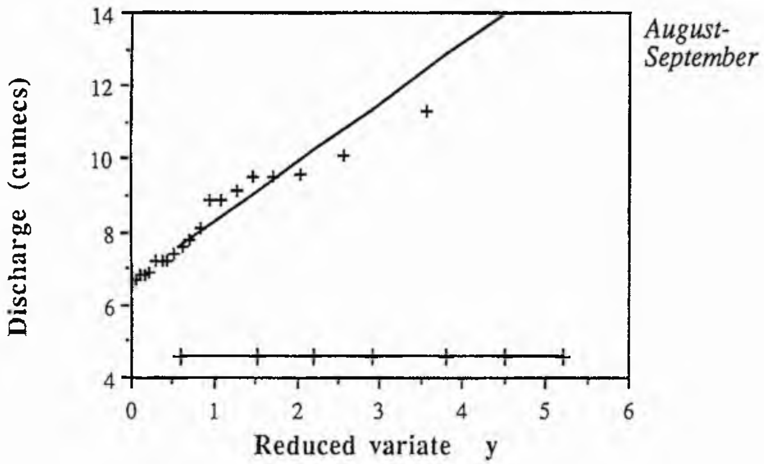
Seasonal frequency distributions for station 86001 Little Eachaig @ Dalinlongart

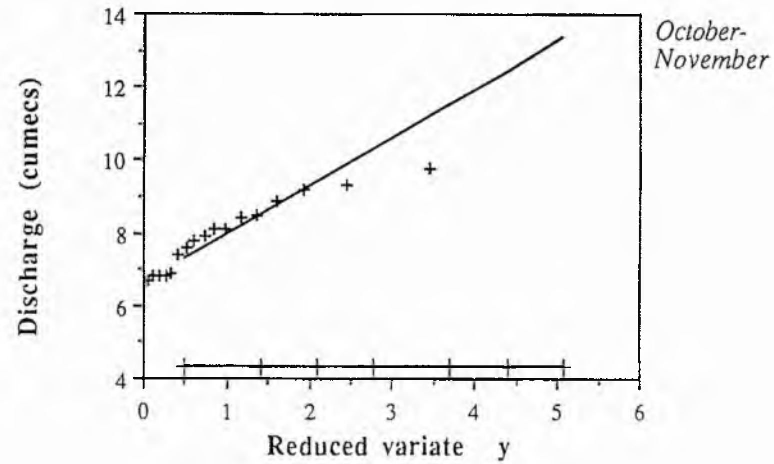


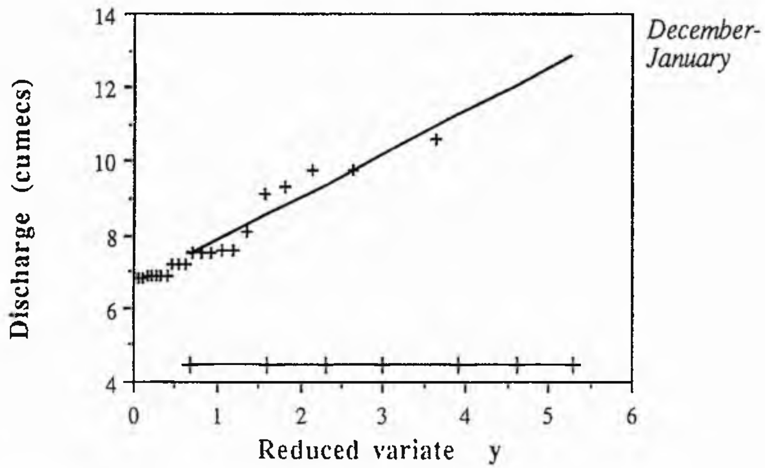




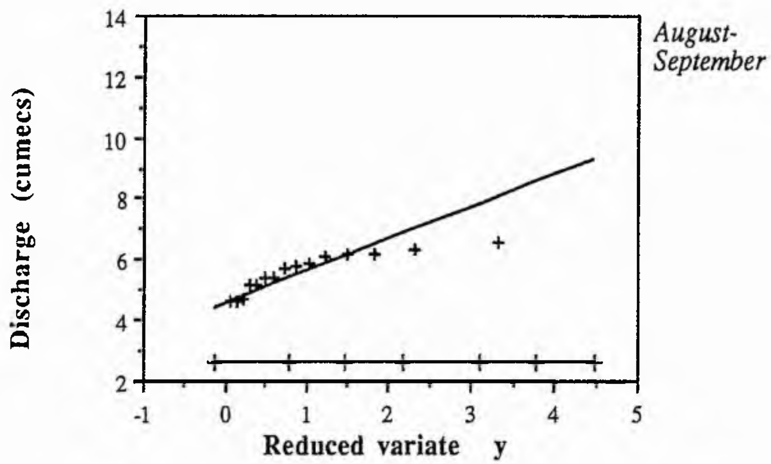
Seasonal frequency distributions for station 87801 Allt Uaine @ Loch Sloy Intake

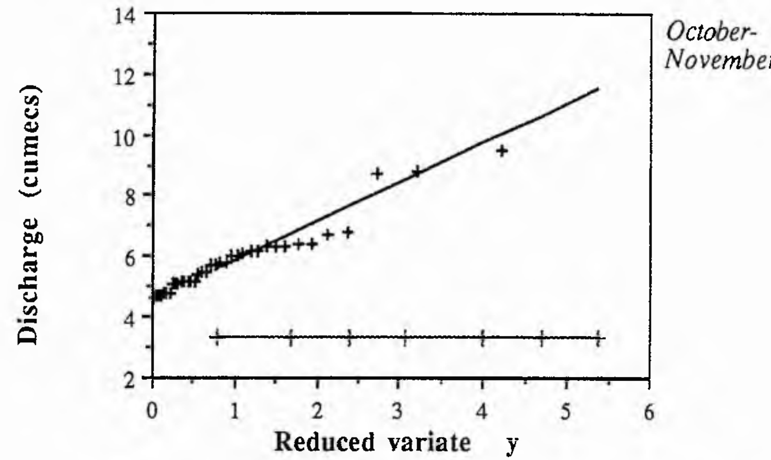


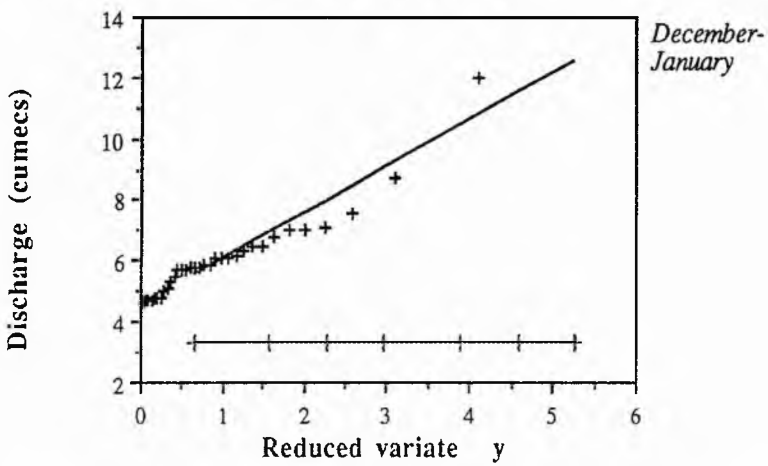


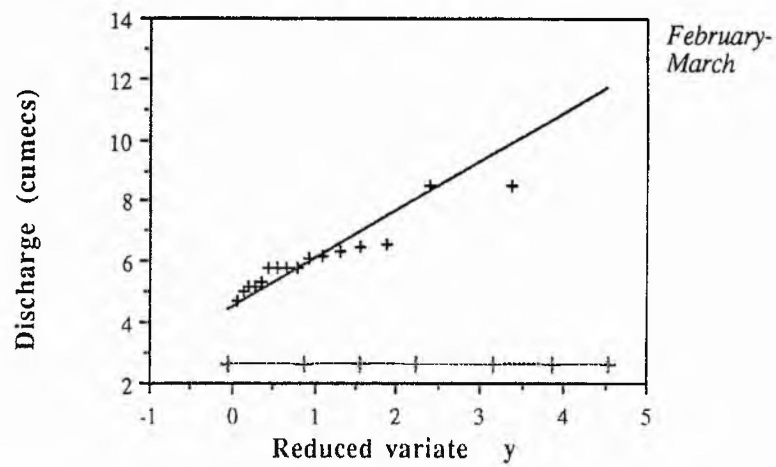


Seasonal frequency distributions for station 91802 Allt Leachdach @ Intake









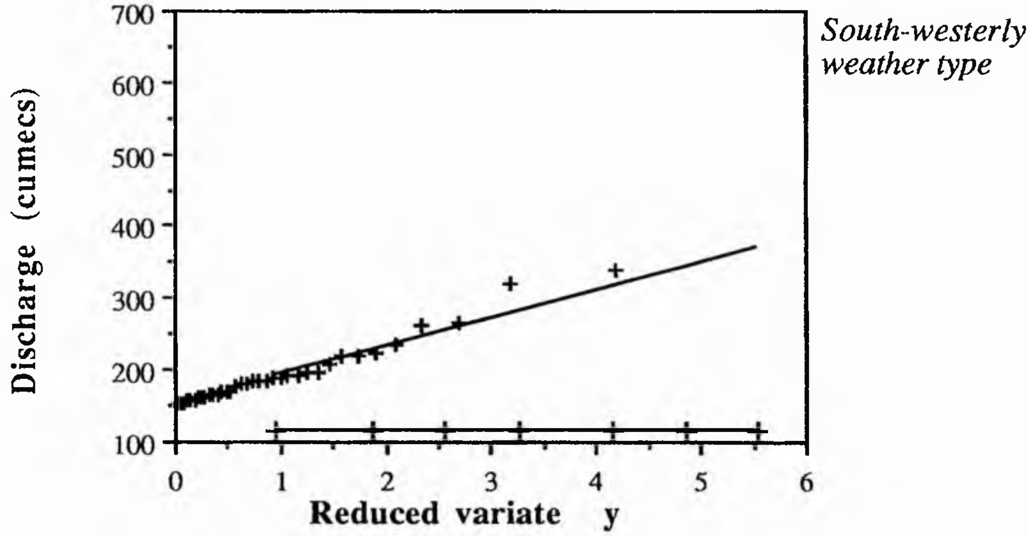
Appendix I

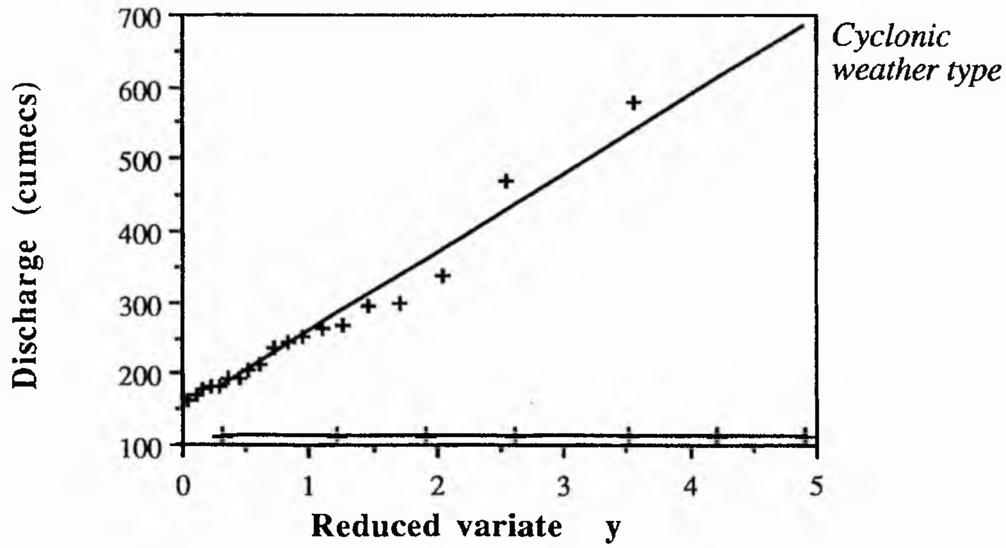
Frequency distributions for synoptic groups

South-westerly weather types include southerly, south-westerly and westerly types; cyclonic indicates pure cyclonic weather type only.

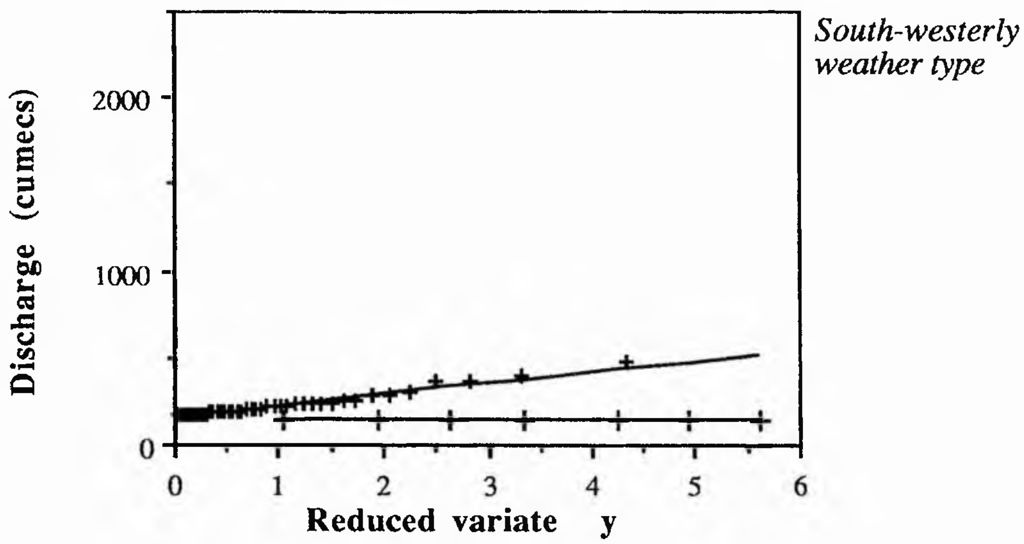
Upper horizontal axis indicates return periods of 2, 5, 10, 20, 50, 100 and 200 years.

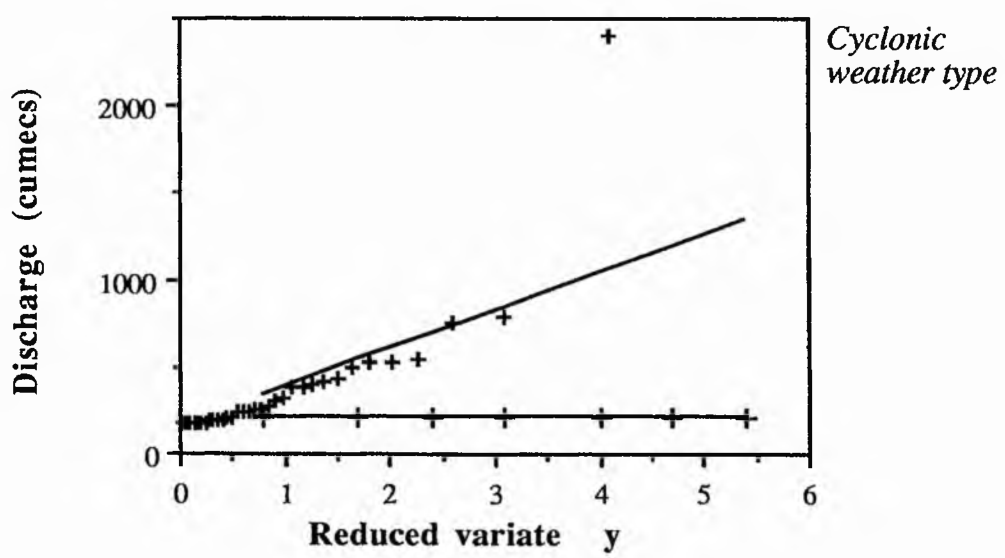
07001 Findhorn @ Shenachie



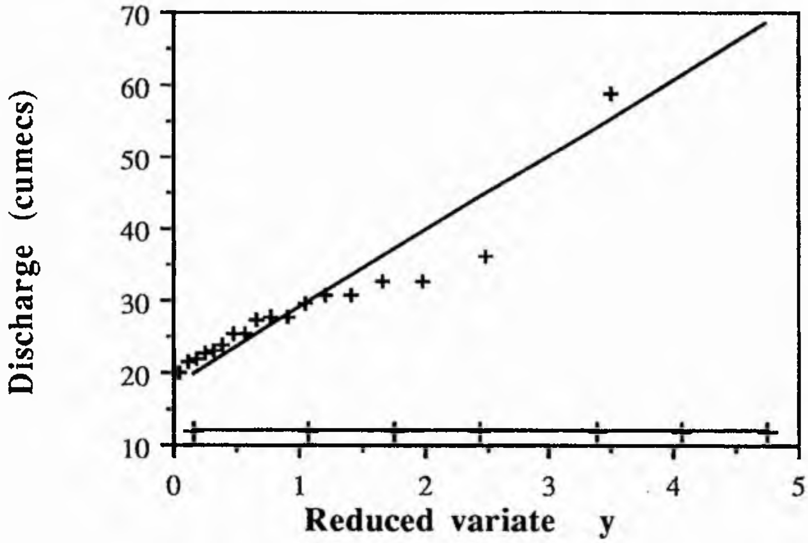


07002 Findhorn @ Forres

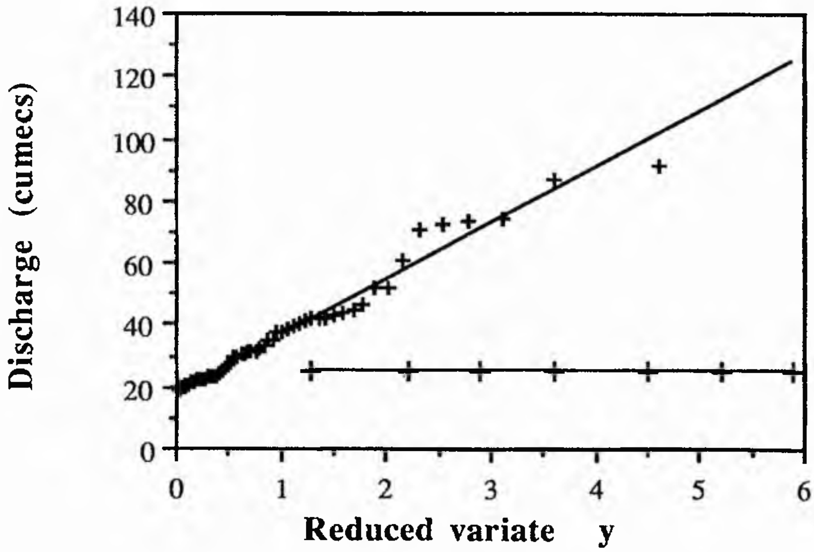




07003 Lossie @ Sherriff Mills

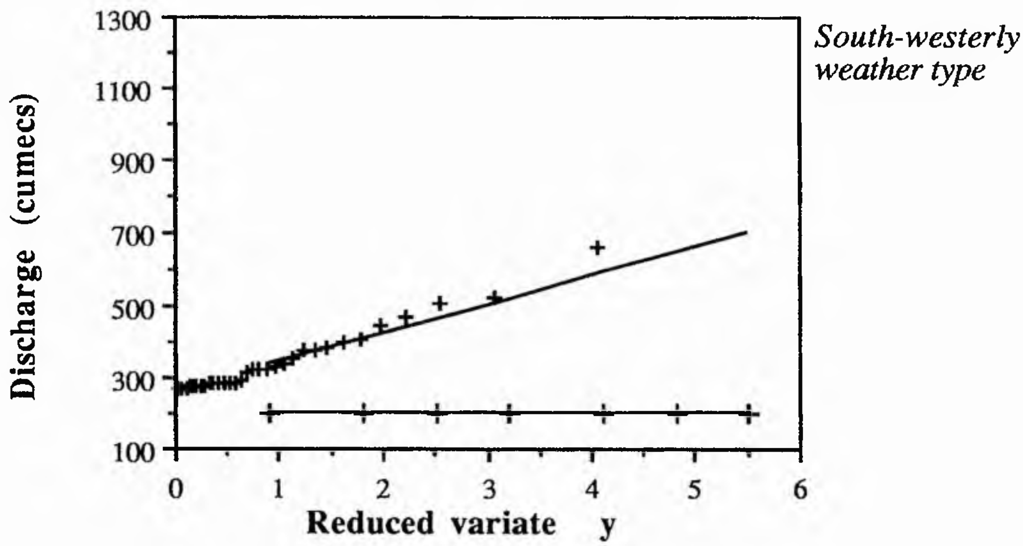


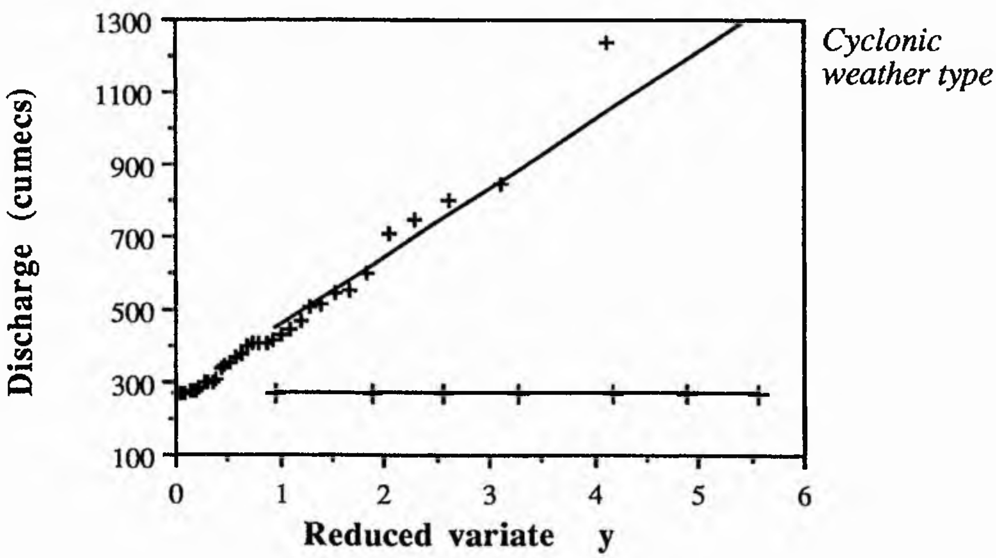
South-westerly weather type



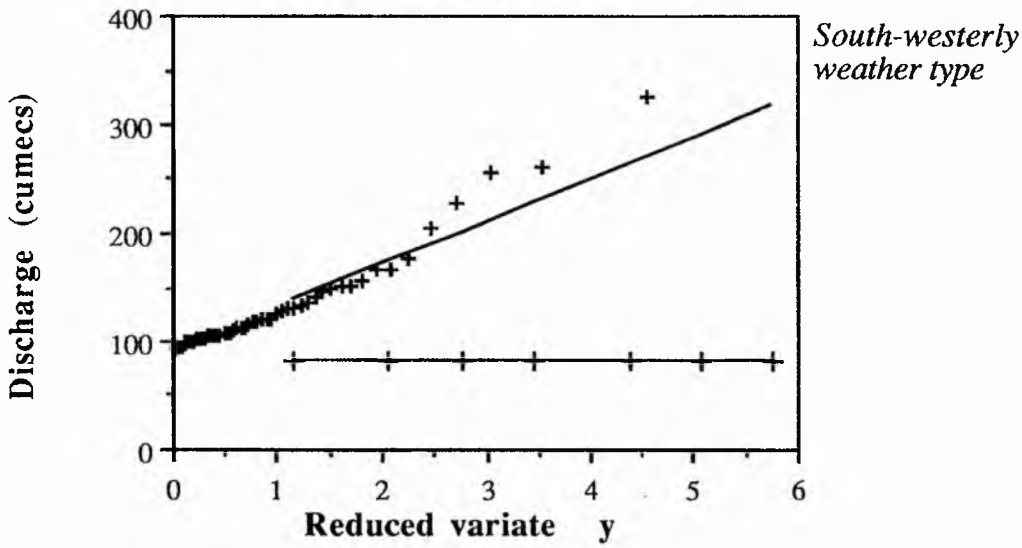
Cyclonic weather type

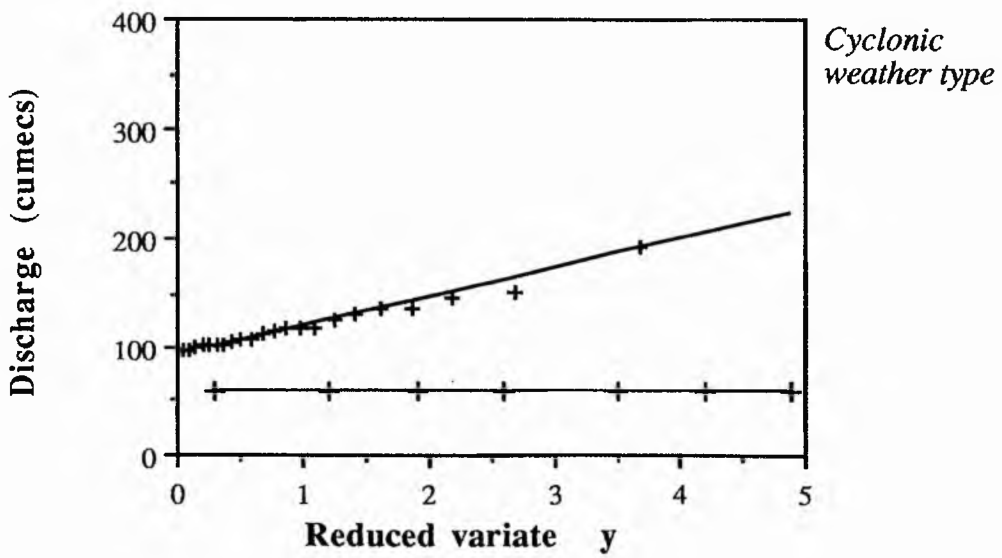
08001 Spey @ Aberlour

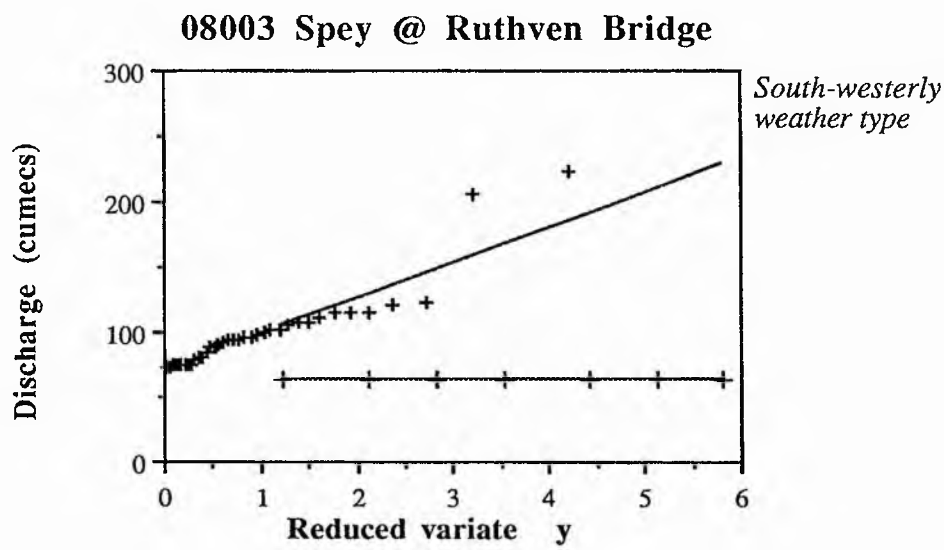




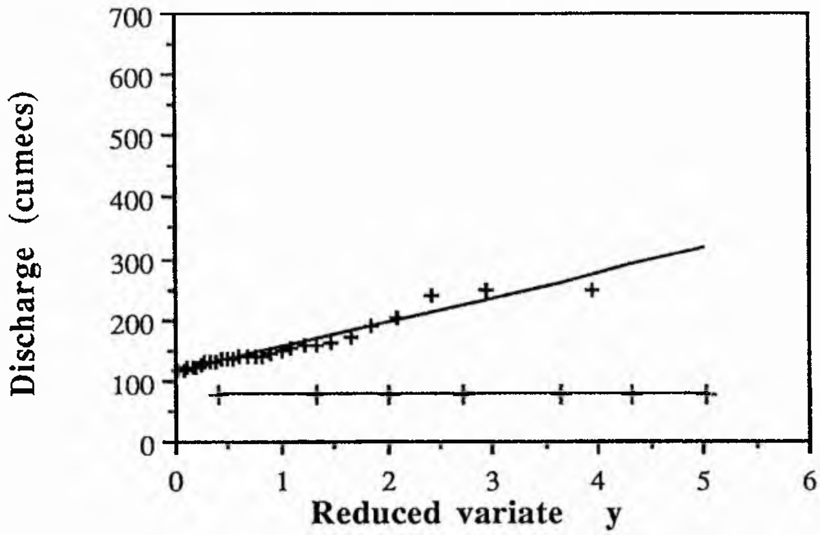
08002 Spey @ Kinrara



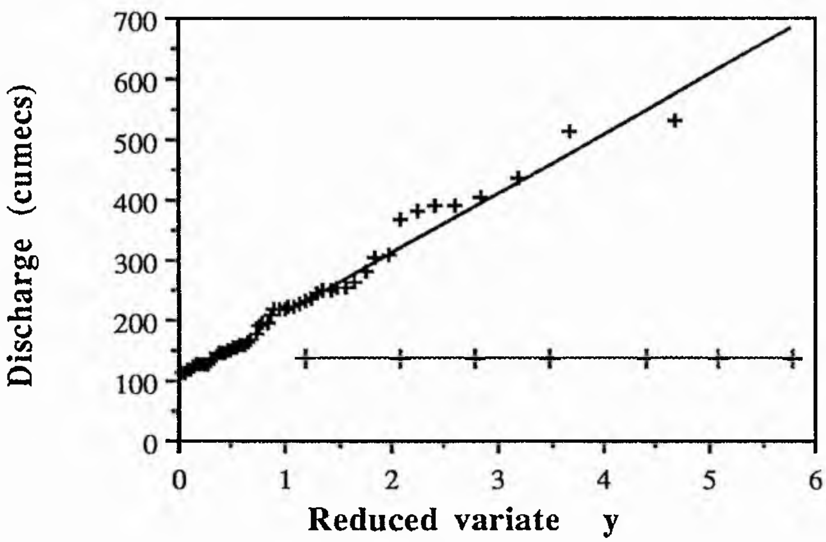



08003 Spey @ Ruthven Bridge
South-westerly
weather type
Discharge (cumecs)
300
200
100
0
0
1
2
3
4
5
6
Reduced variate y

08004 Avon @ Delnashaugh

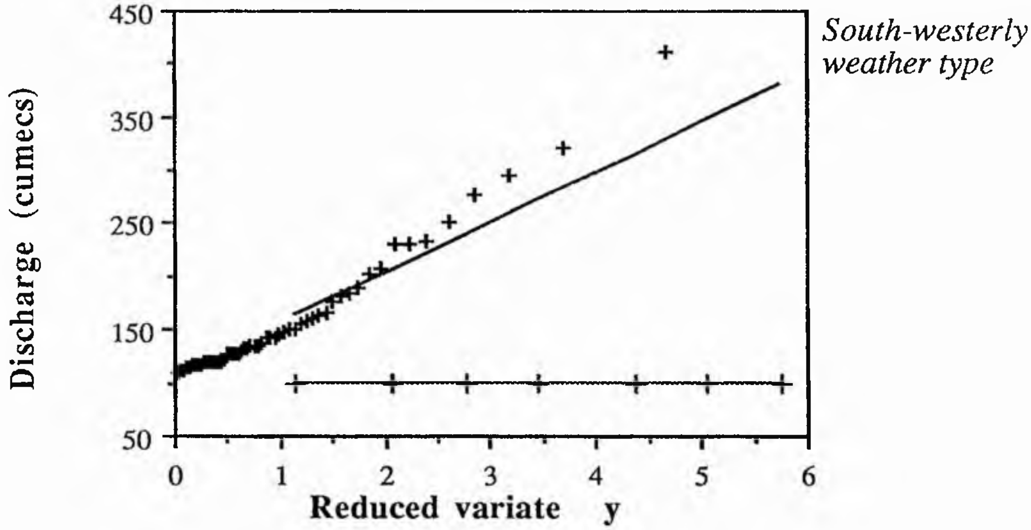


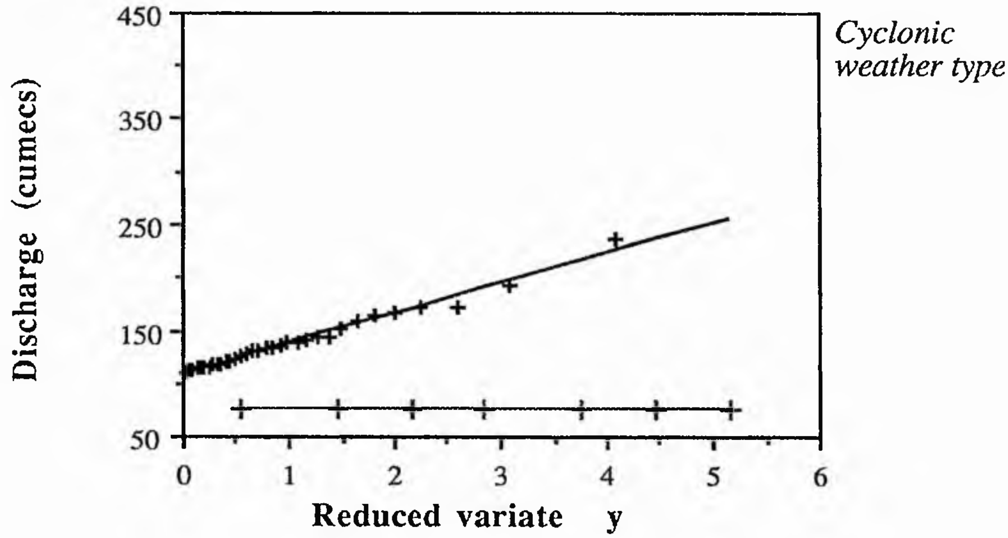
South-westerly weather type



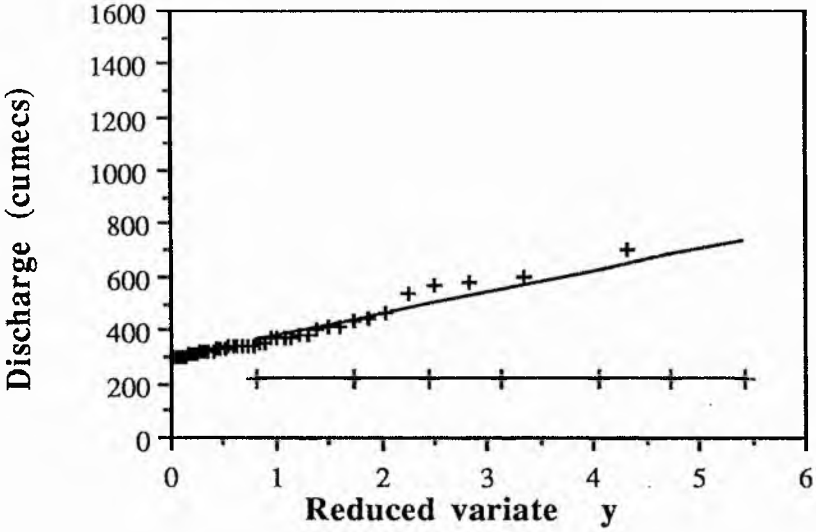
Cyclonic weather type

08005 Spey @ Boat of Garten

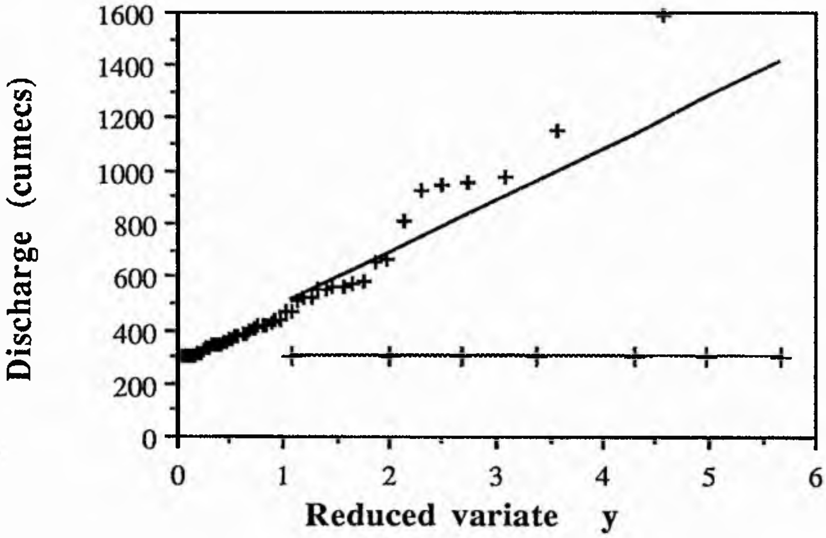




08006 Spey @ Boat o' Brig

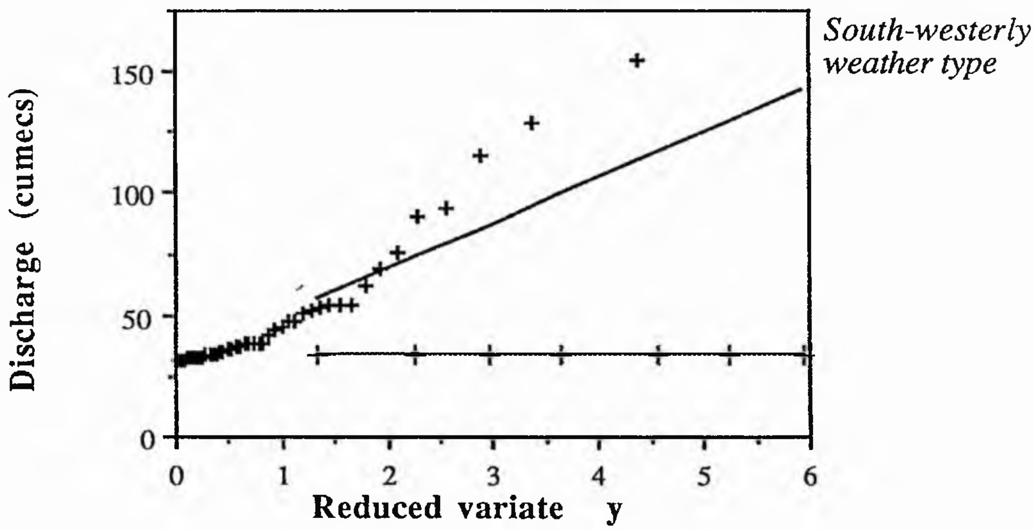


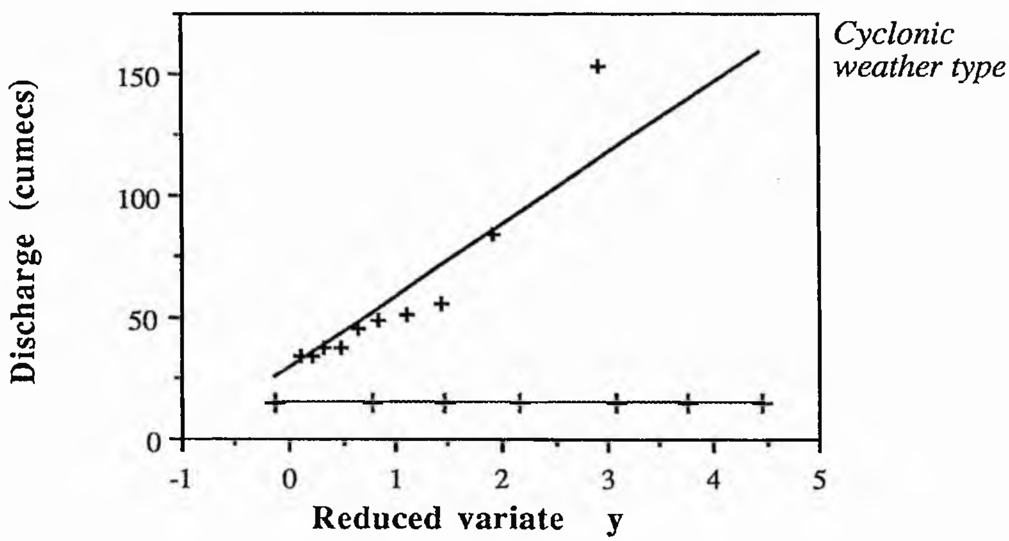
South-westerly weather type



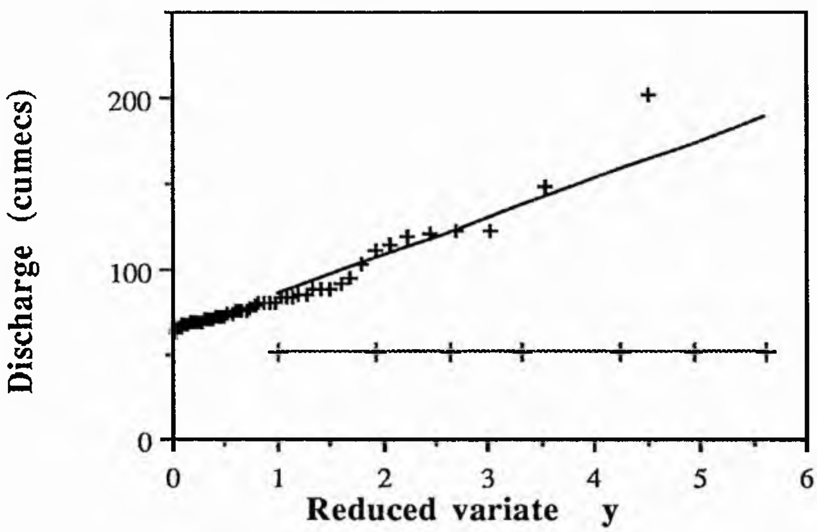
Cyclonic weather type

08008 Tromie @ Tromie Bridge

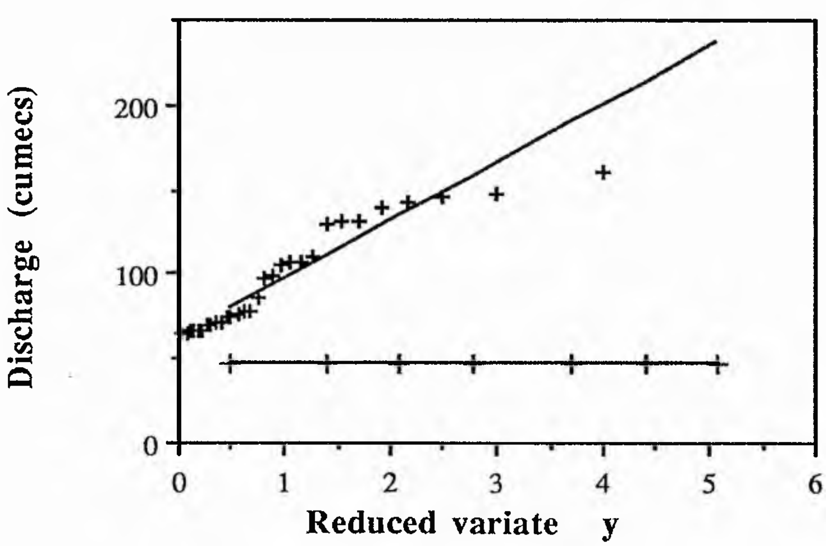




08009 Dulnain @ Balnaan Bridge

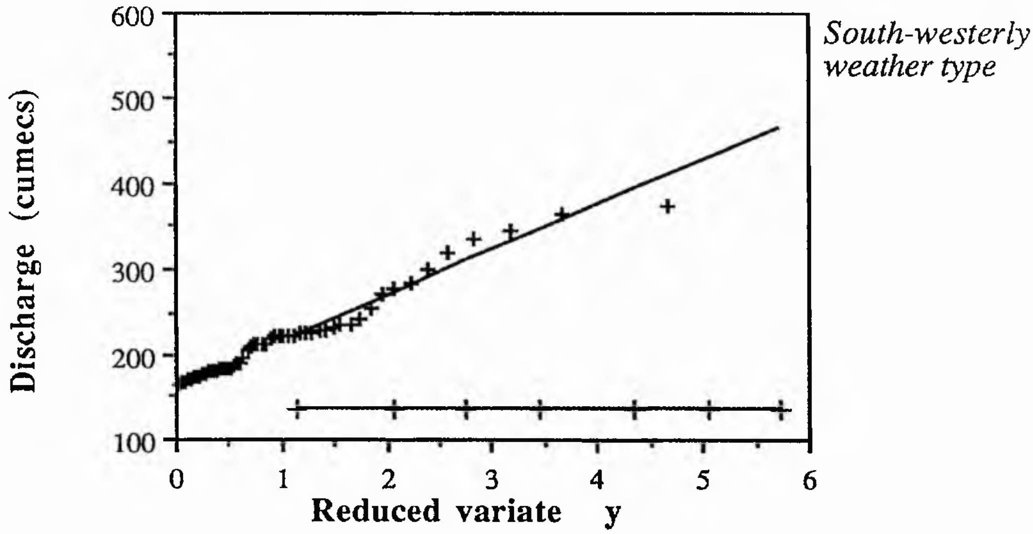


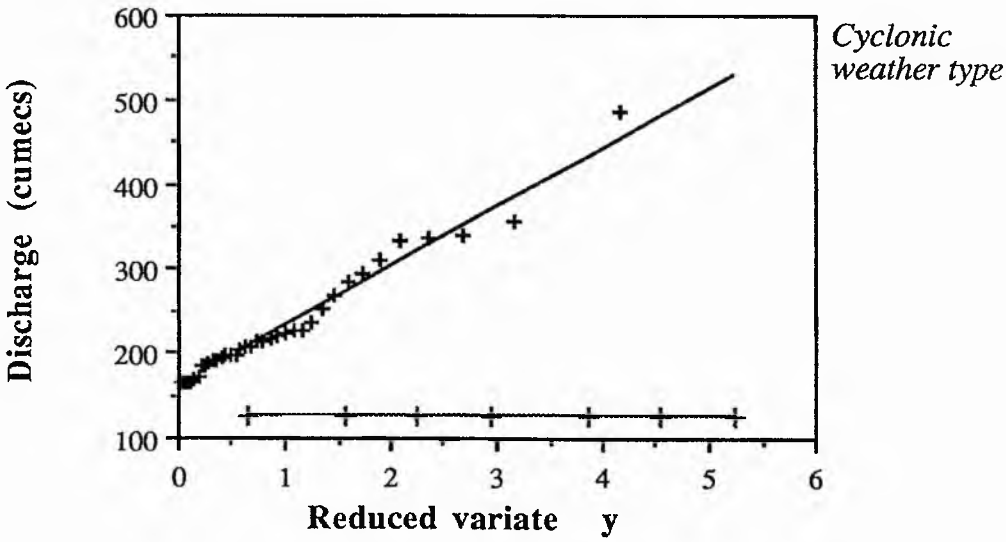
South-westerly weather type



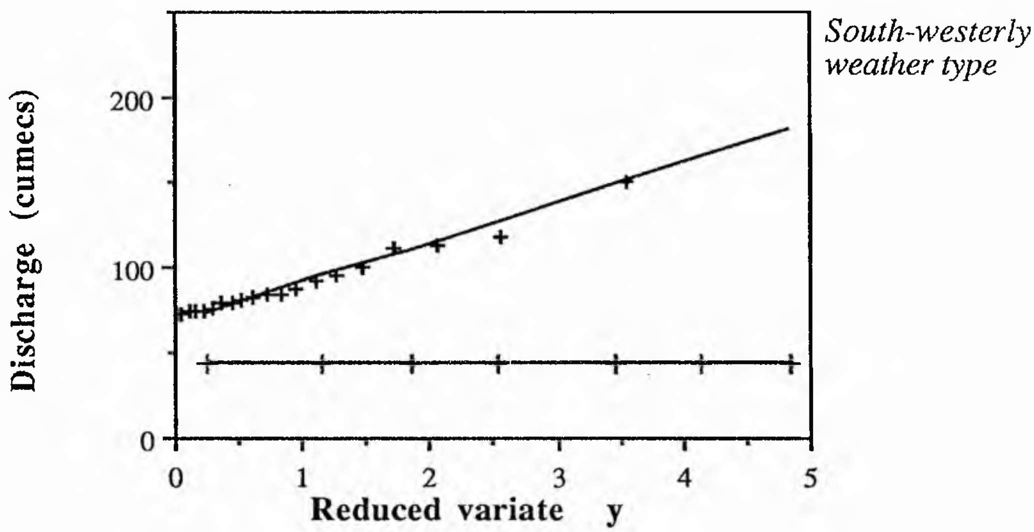
Cyclonic weather type

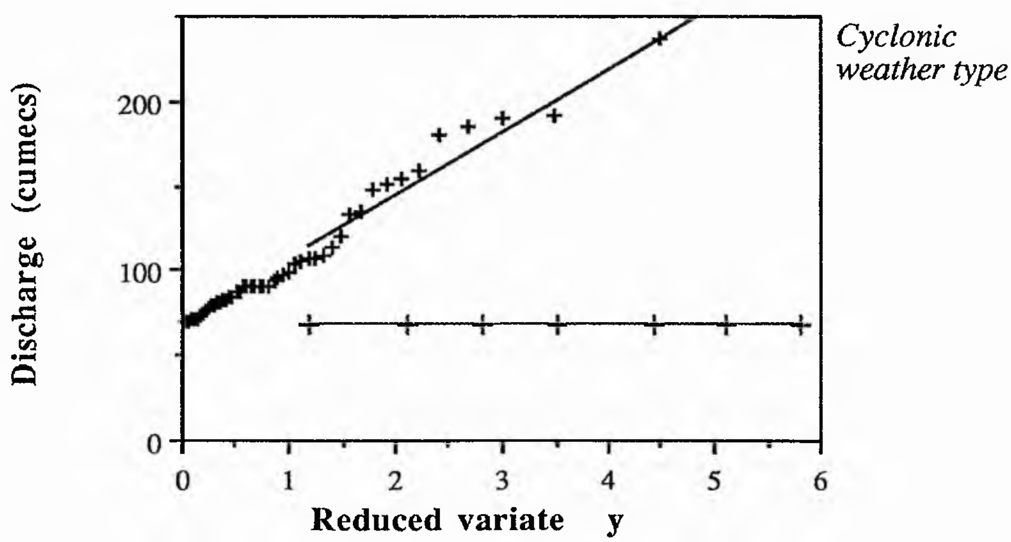
08010 Spey @ Grantown



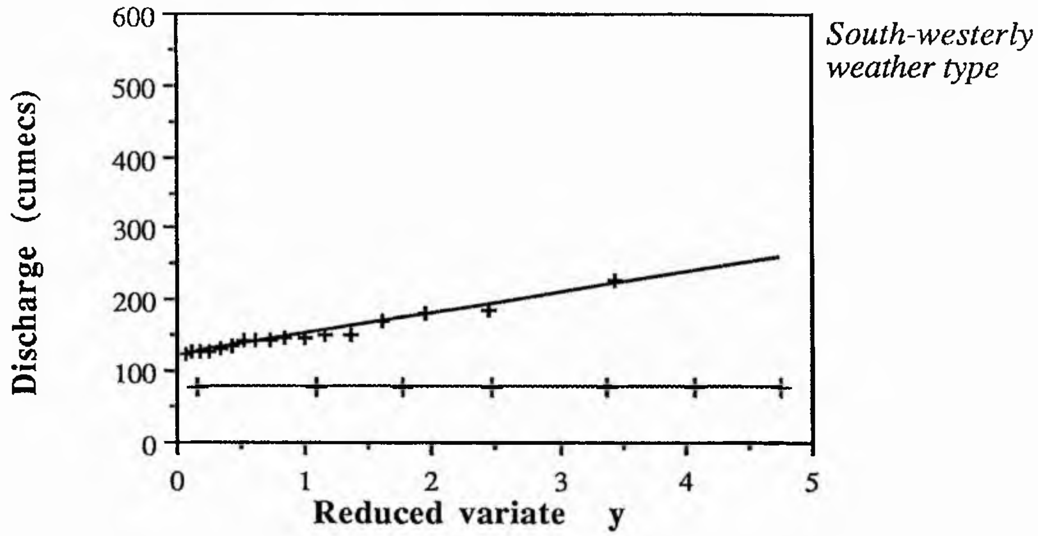


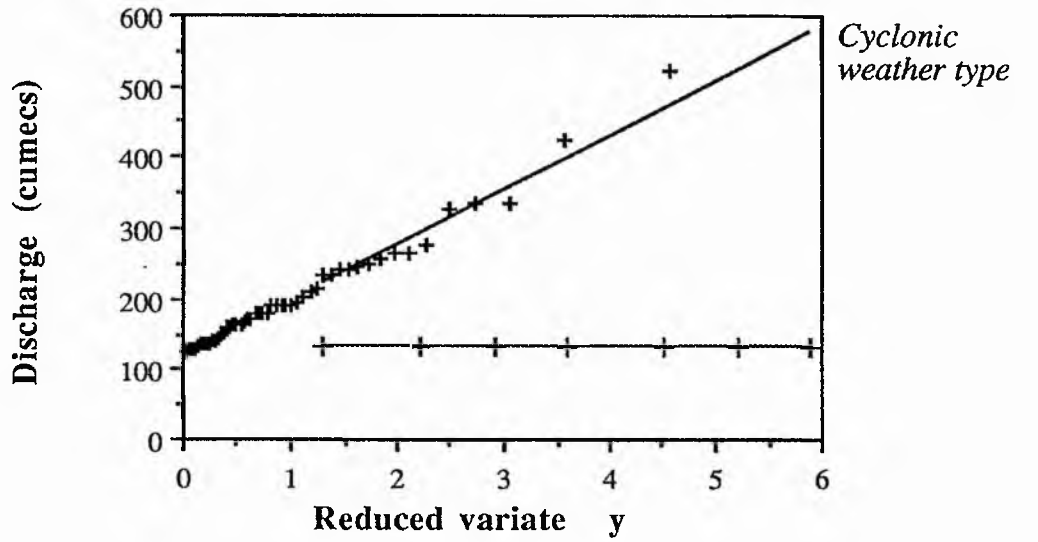
09001 Deveron @ Avochie



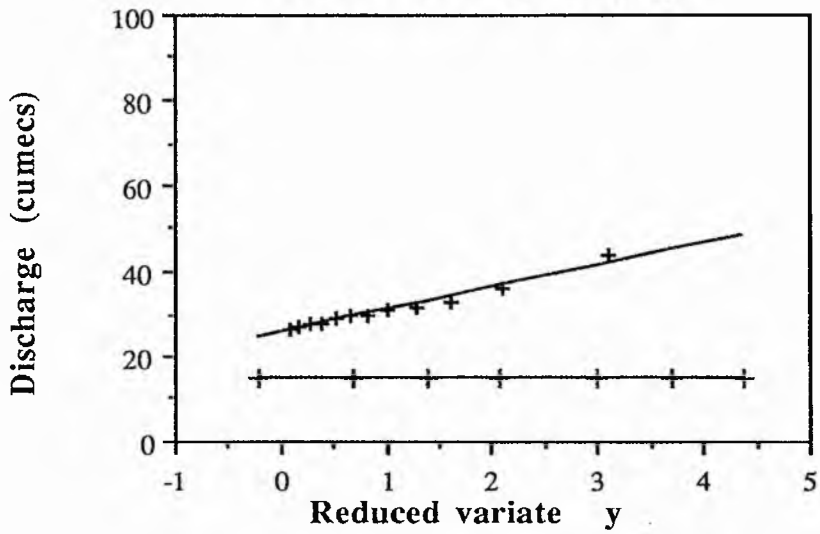


09002 Deveron @ Muiresk

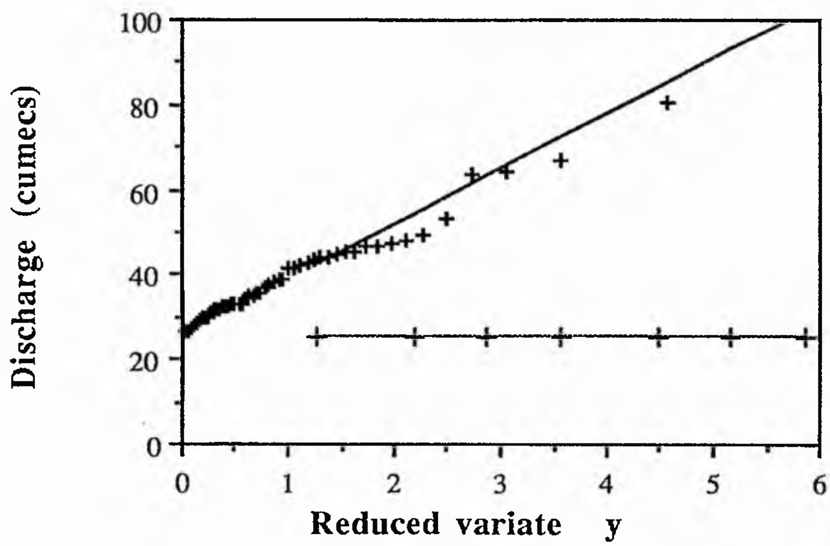




09003 Isla @ Grange

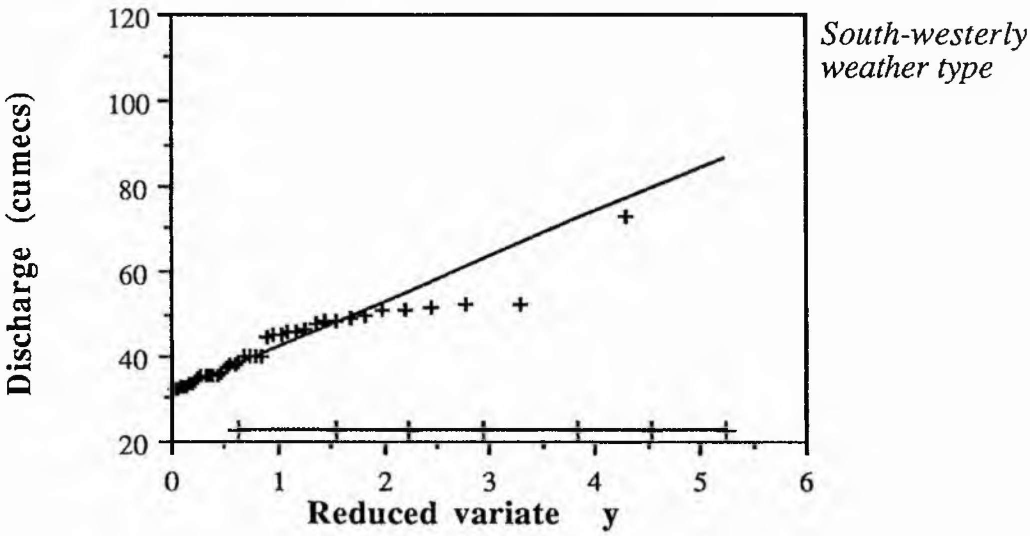


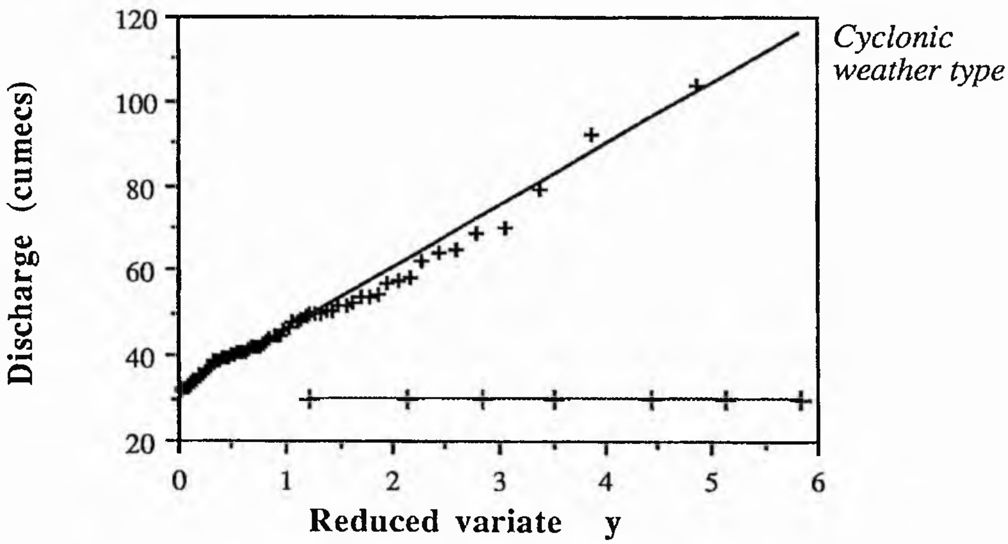
South-westerly weather type



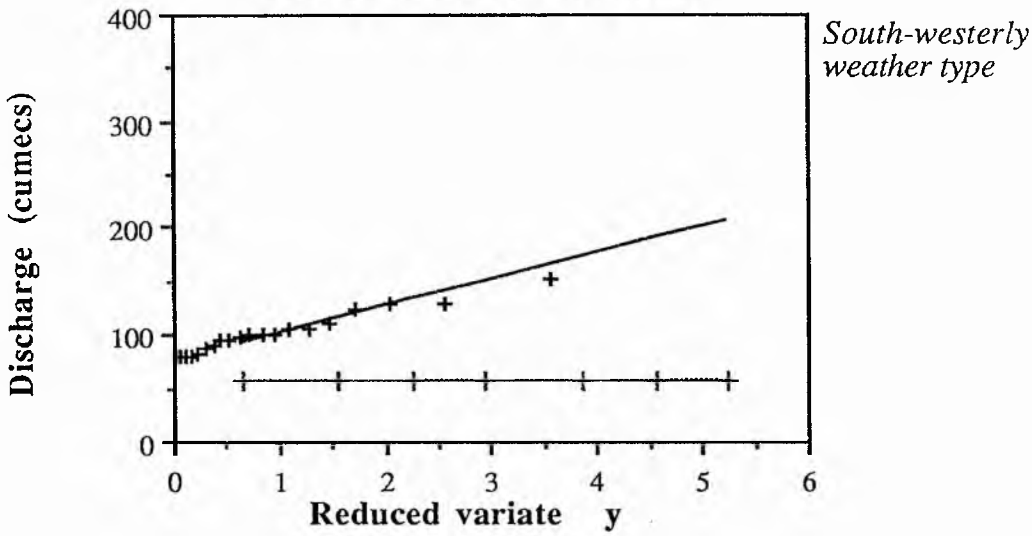
Cyclonic weather type

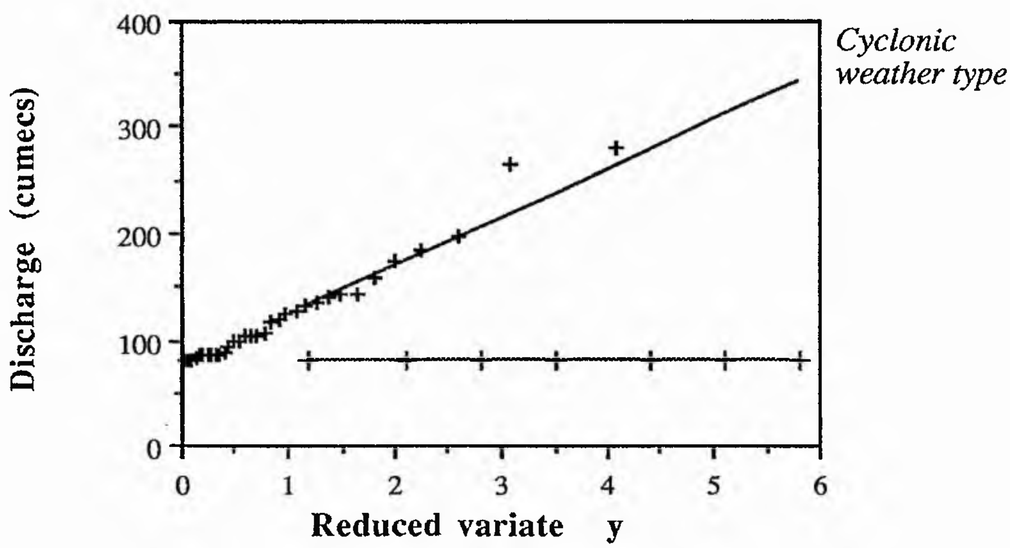
10001 Ythan @ Ardlethen



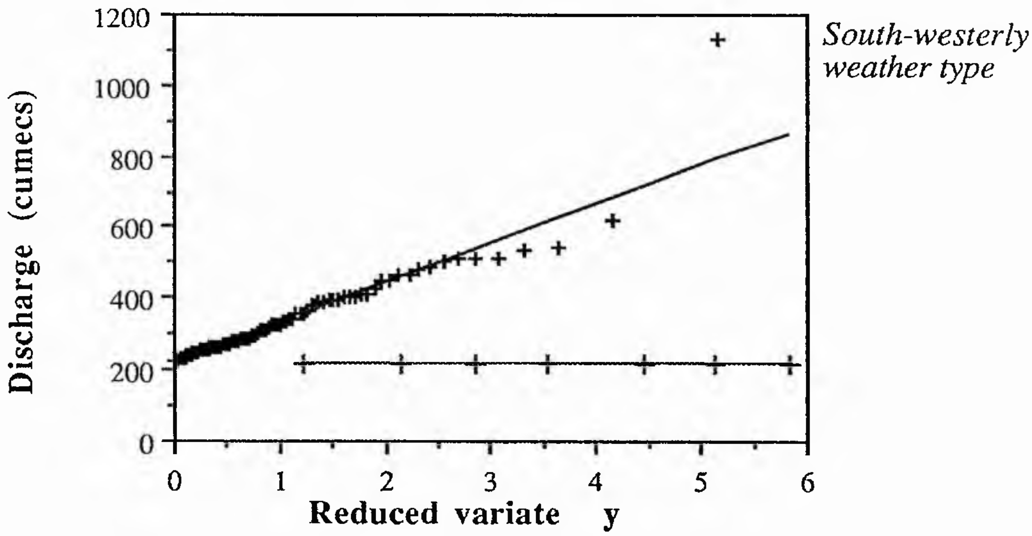


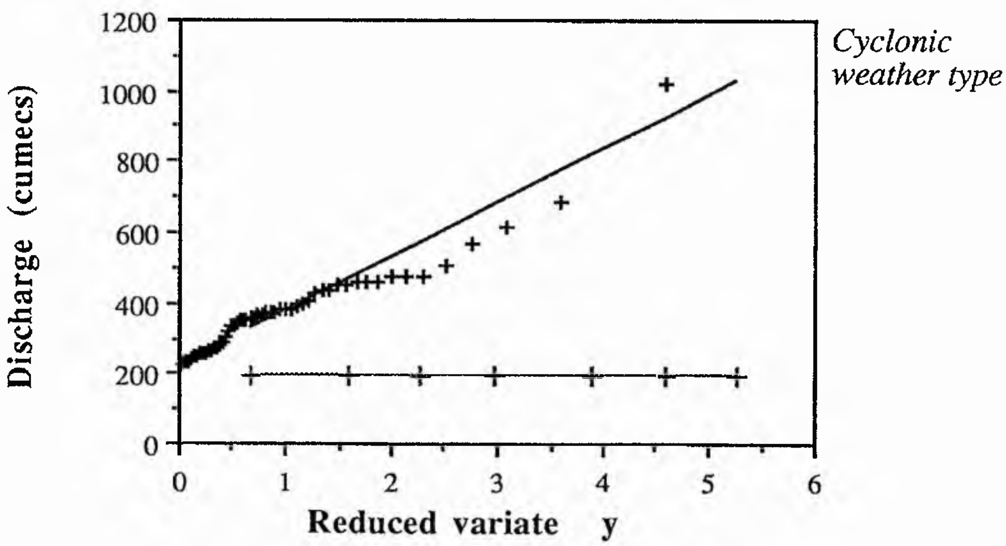
11001 Don @ Parkhill



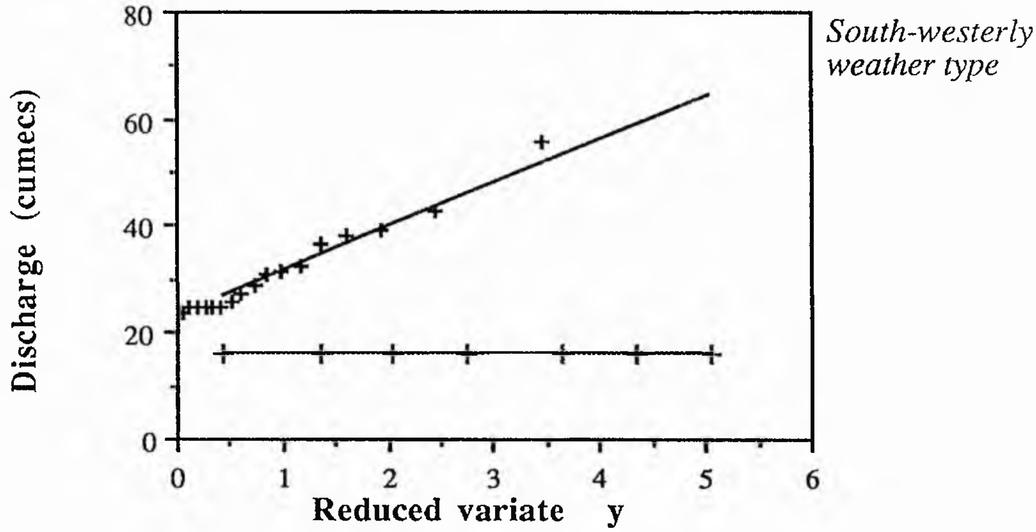


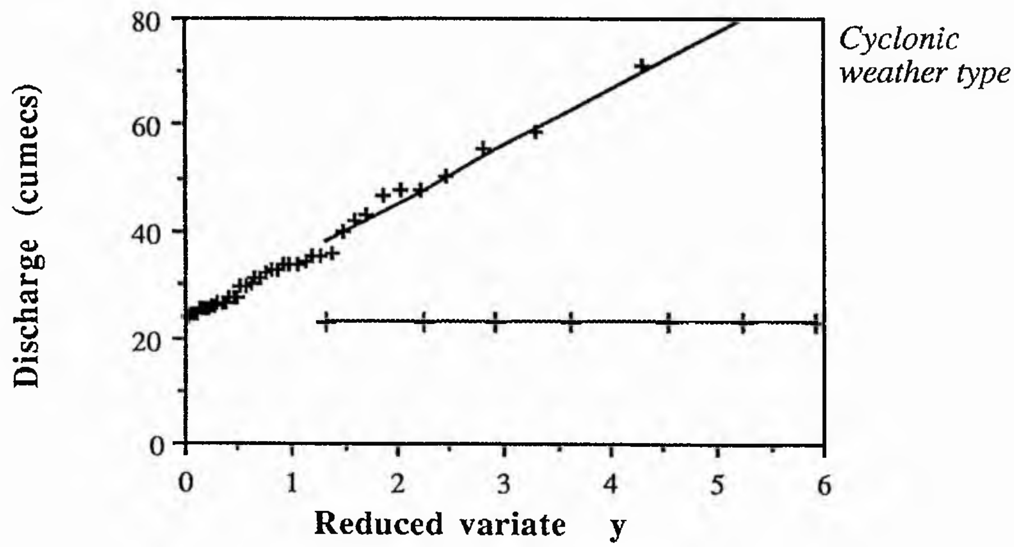
12001 Dee @ Woodend



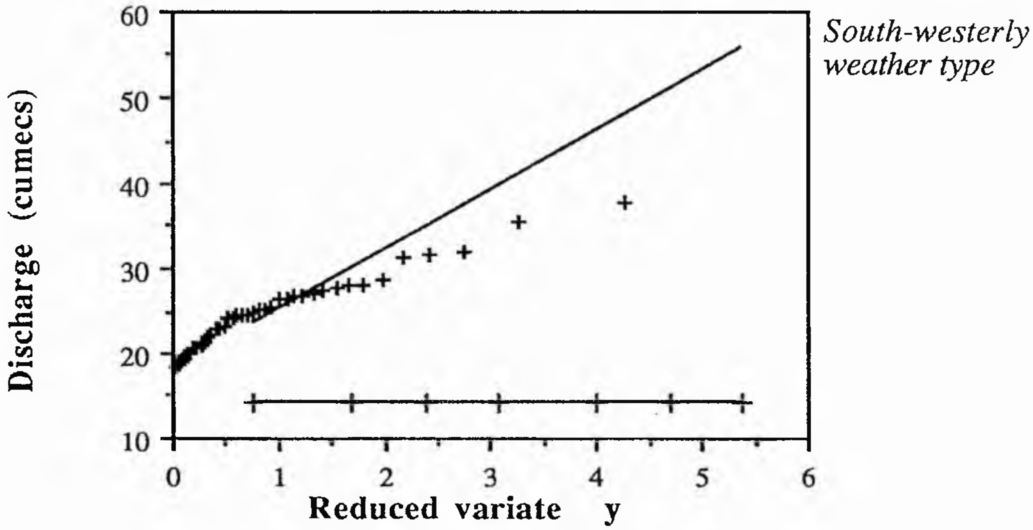


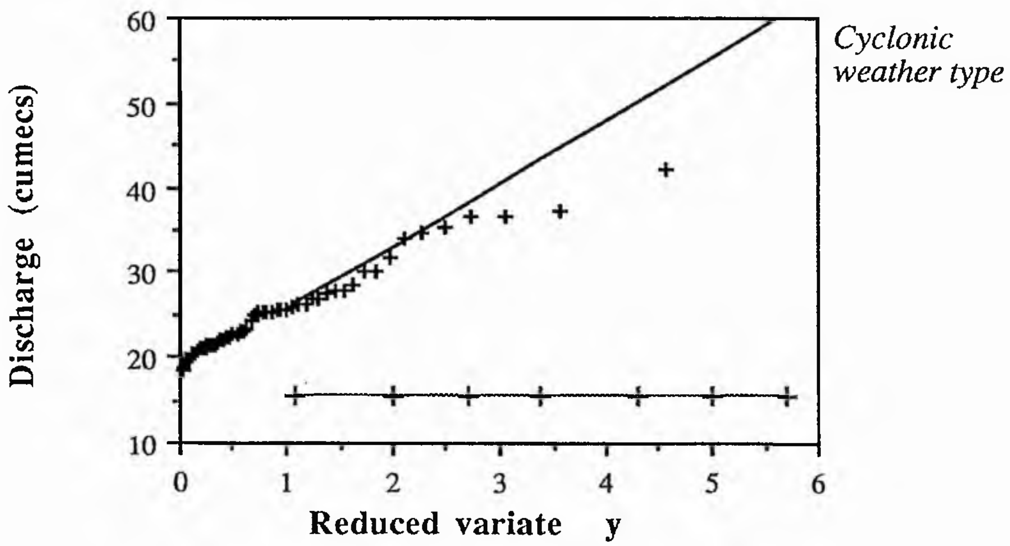
14001 Eden @ Kemback



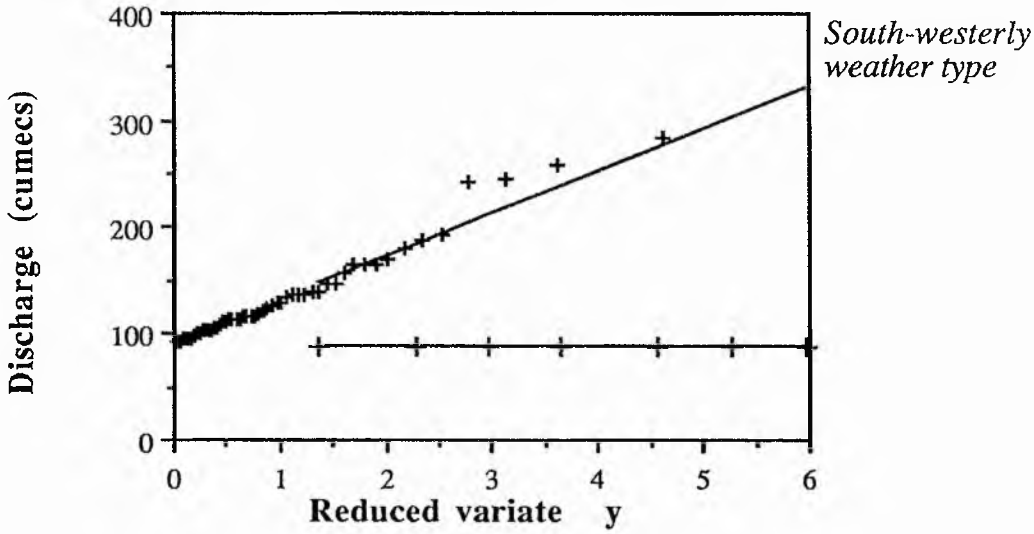


15008 Dean Water @ Cookston

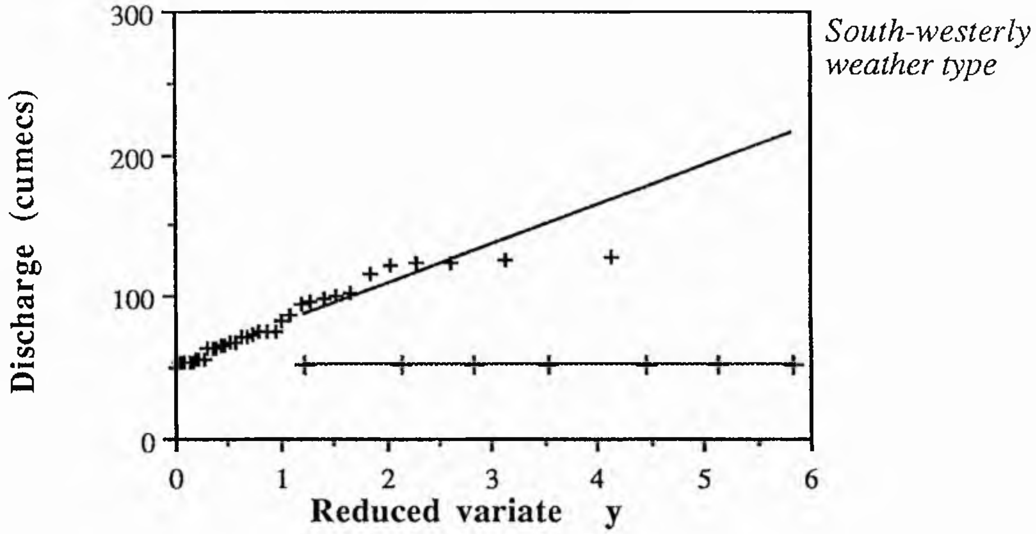


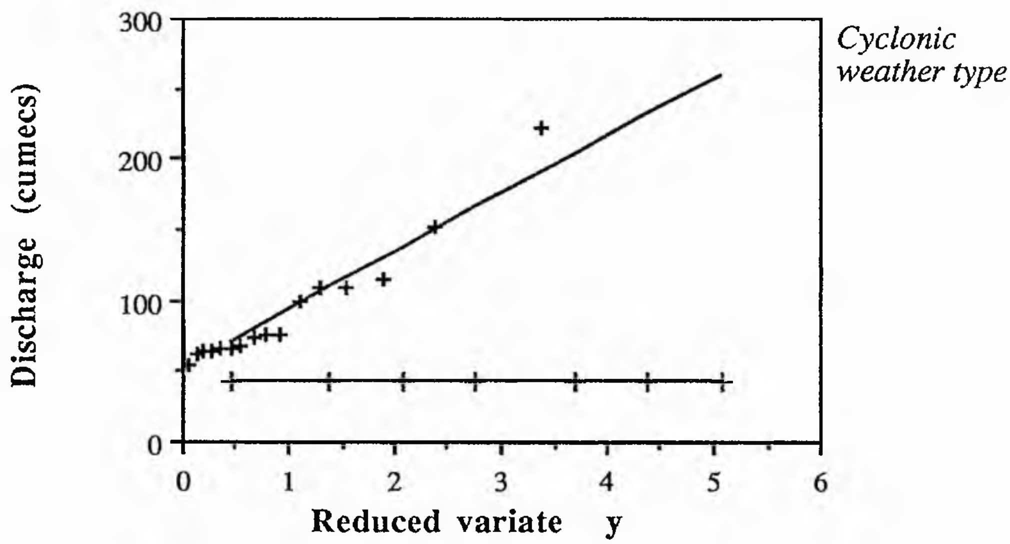


16003 Ruchill Water @ Cultybraggan

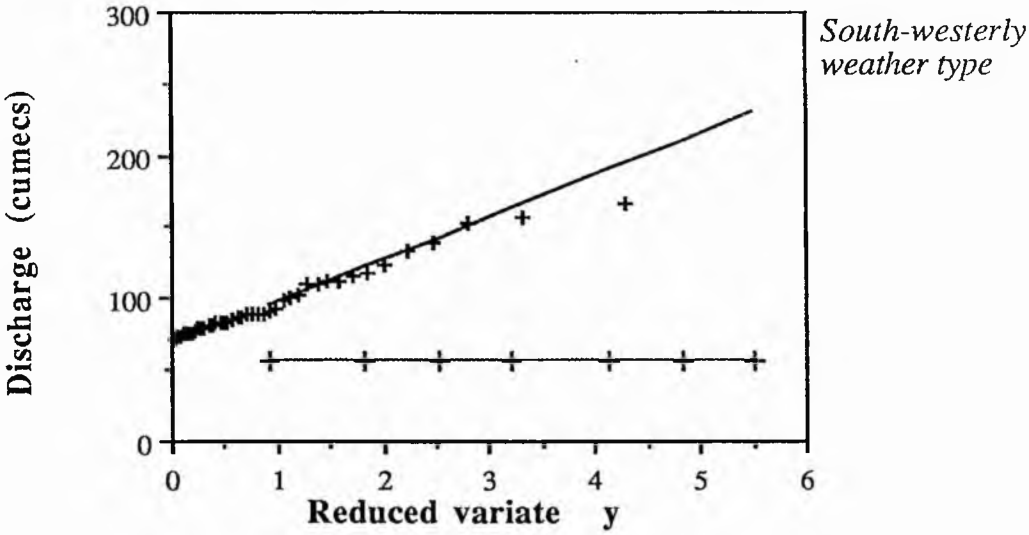


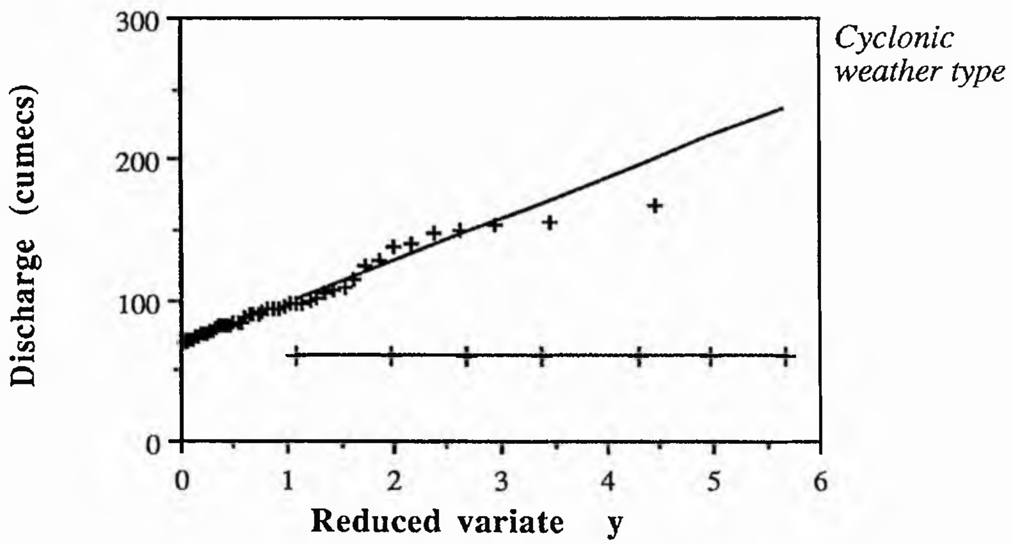
17001 Carron @ Headswood



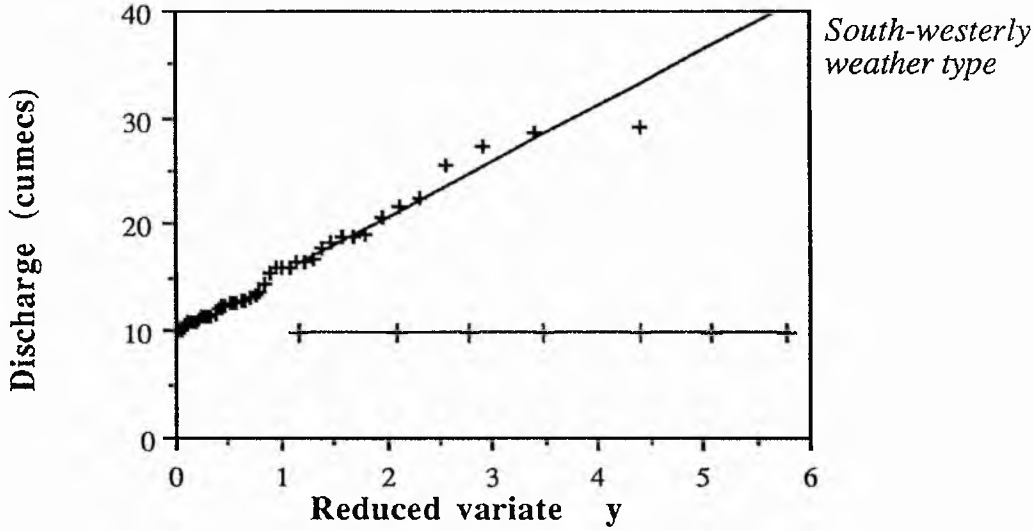


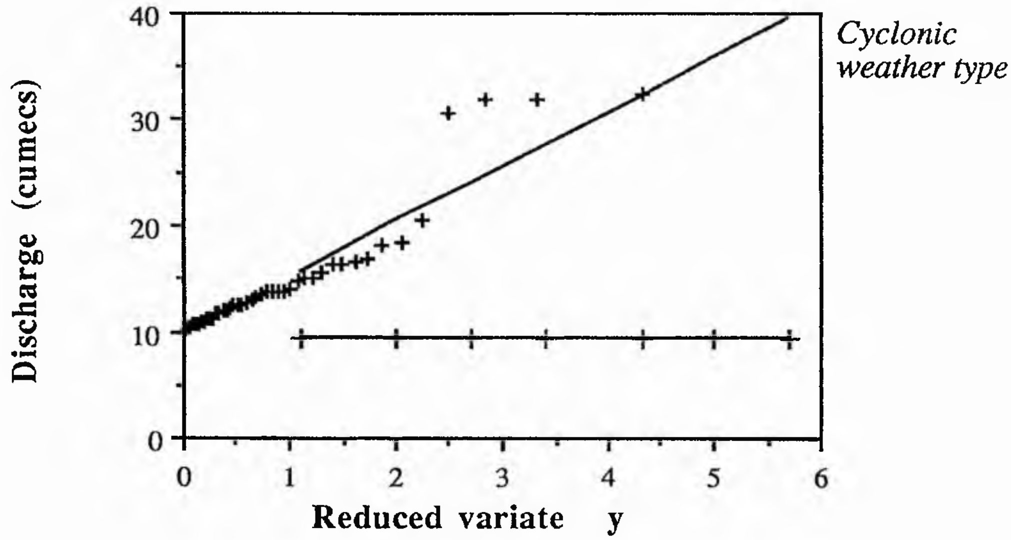
19001 Almond @ Craigiehall



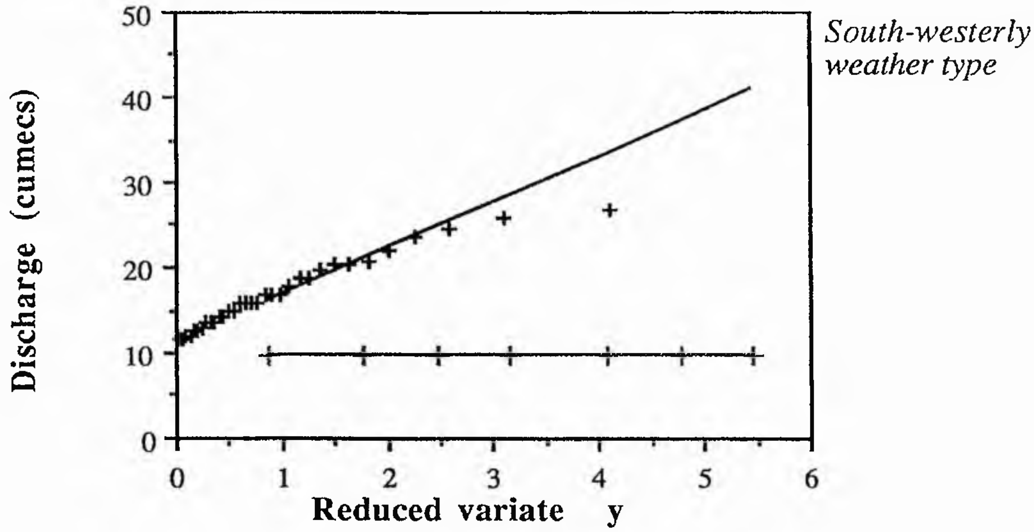


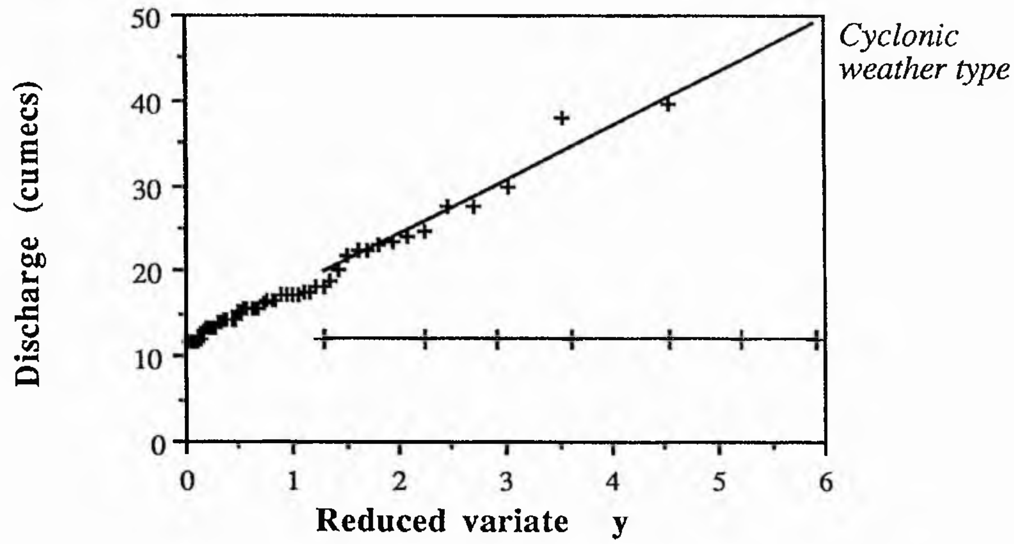
19002 Almond @ Almond Weir



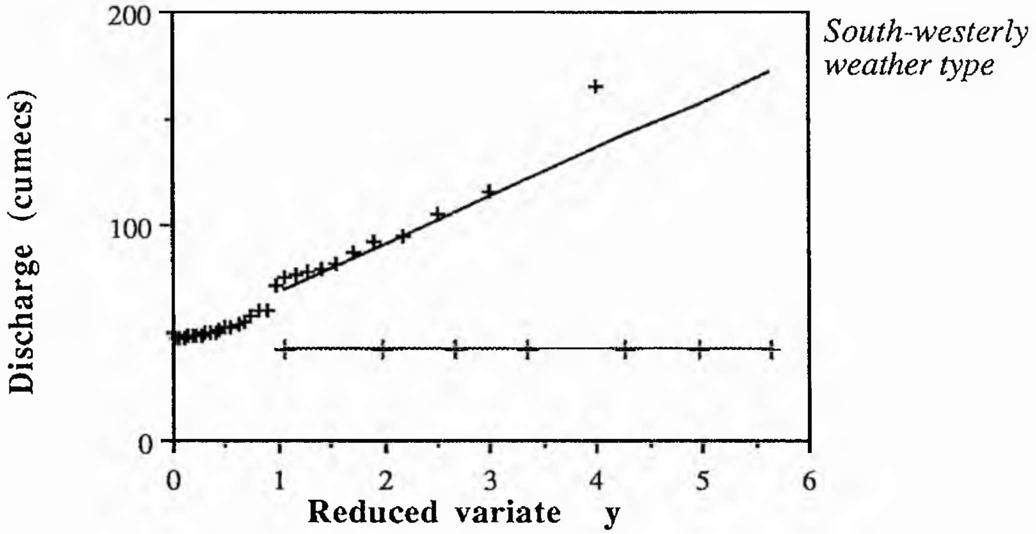


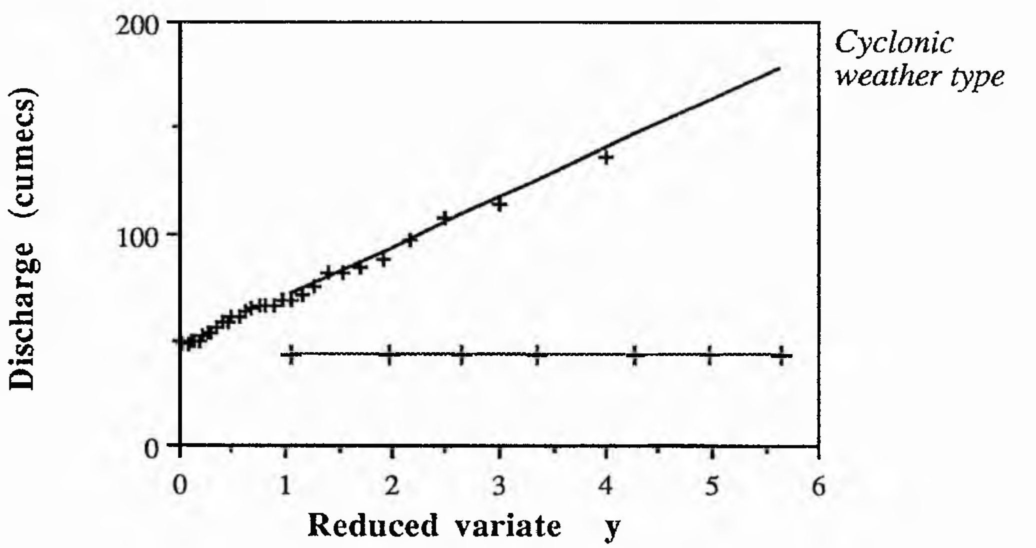
19004 North Esk @ Dalmore Weir



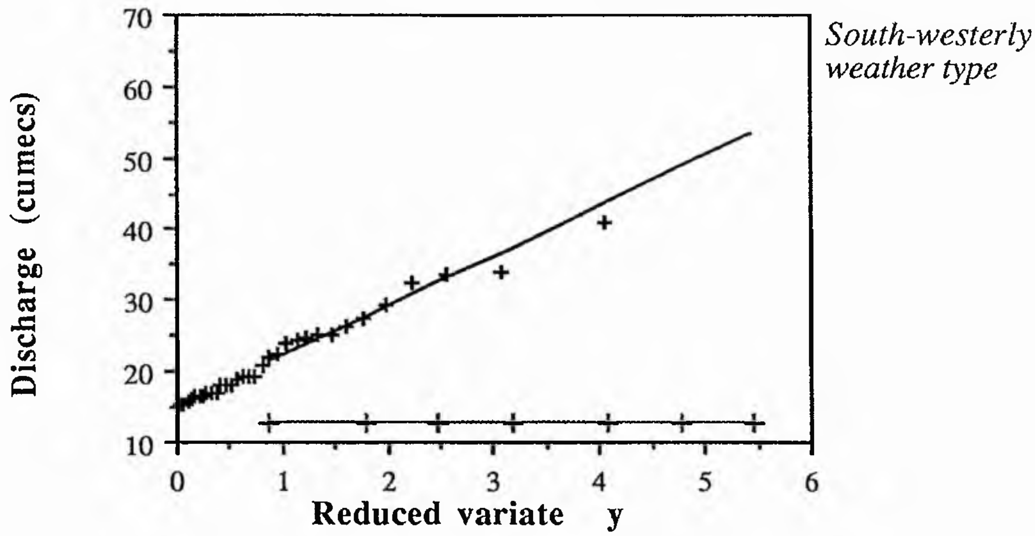


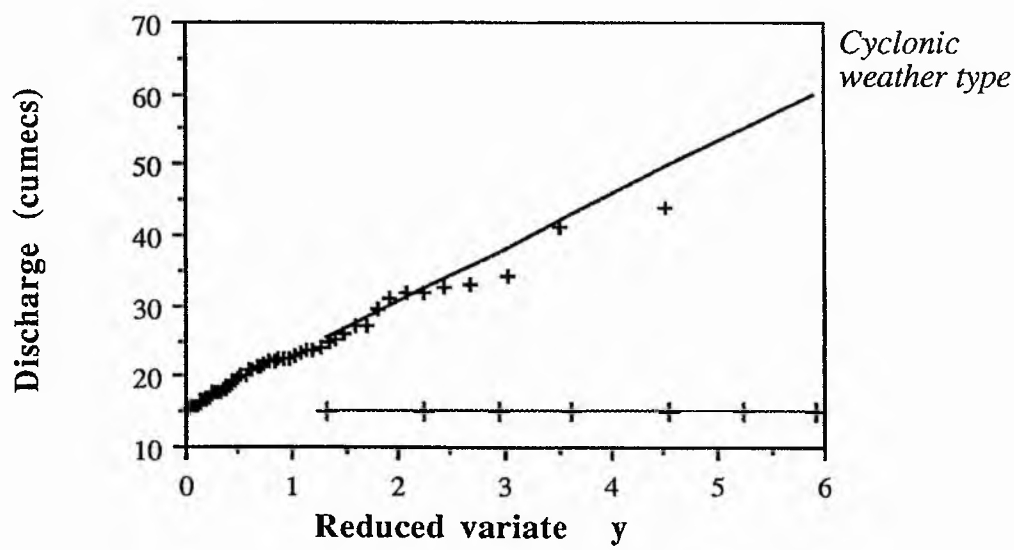
19005 Almond @ Almondell



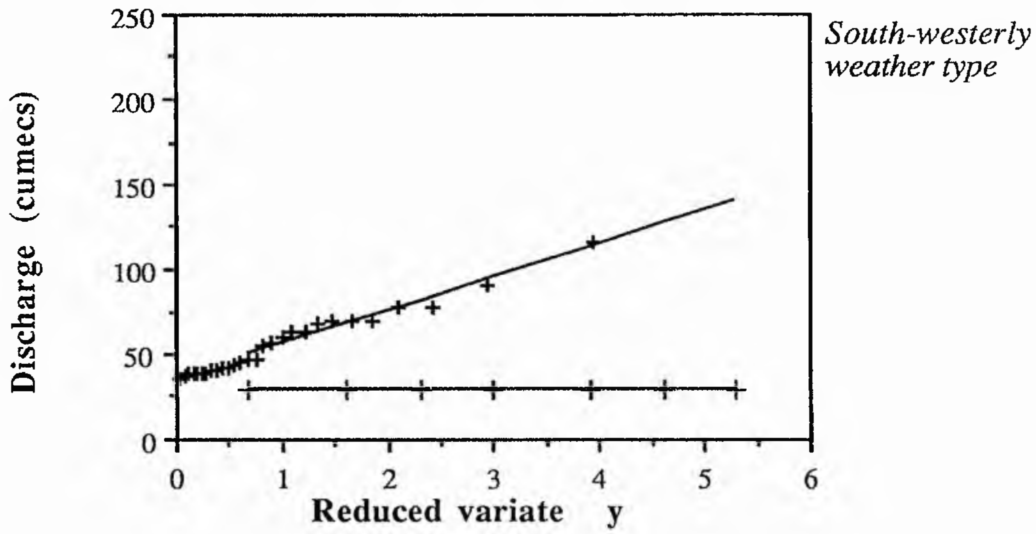


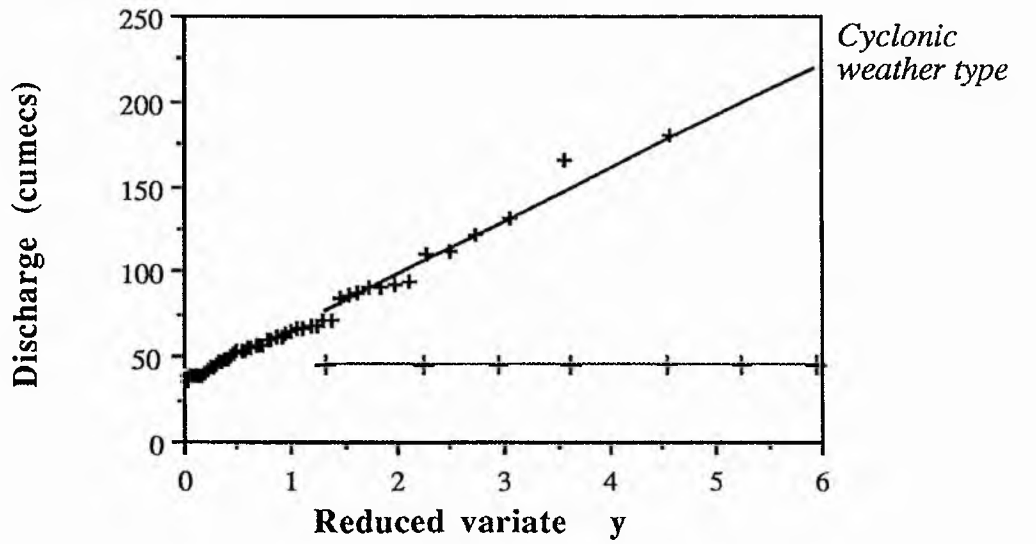
19006 Water of Leith @ Murrayfield



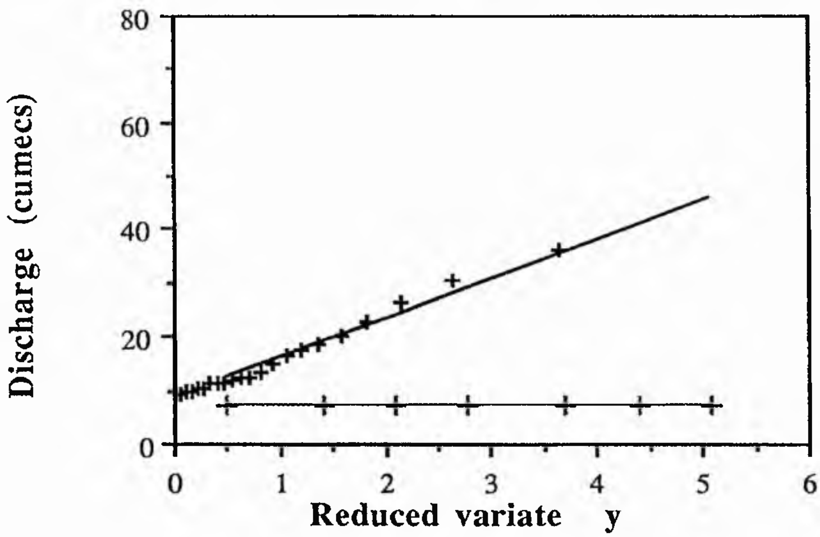


19007 Esk @ Musselburgh

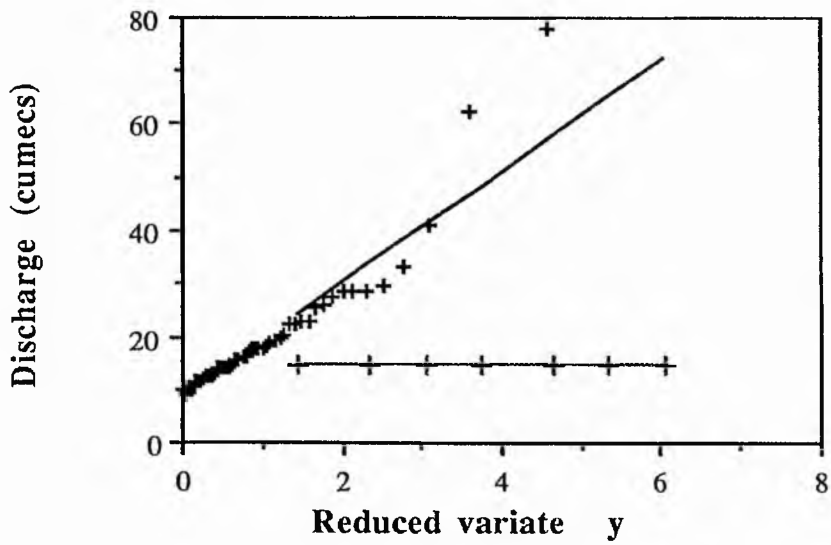




19008 South Esk @ Prestonholm

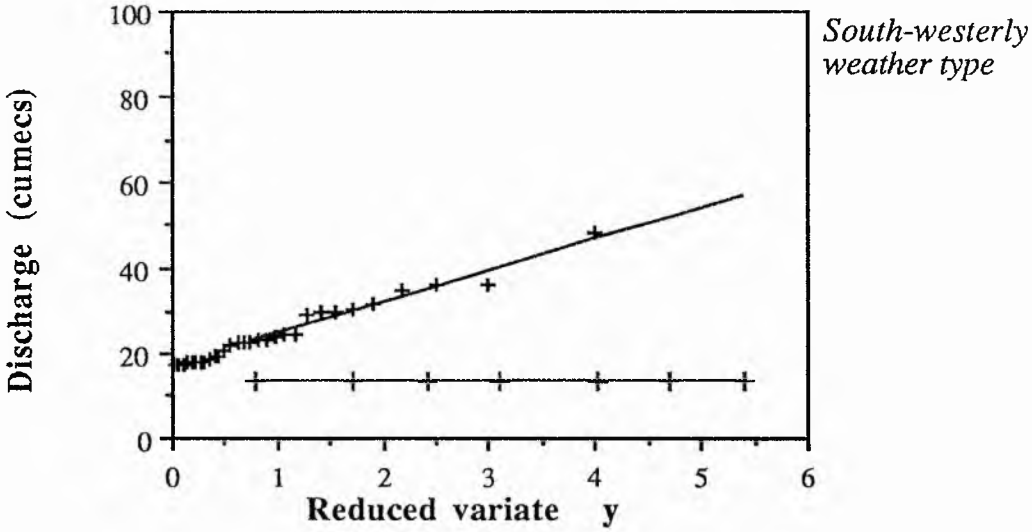


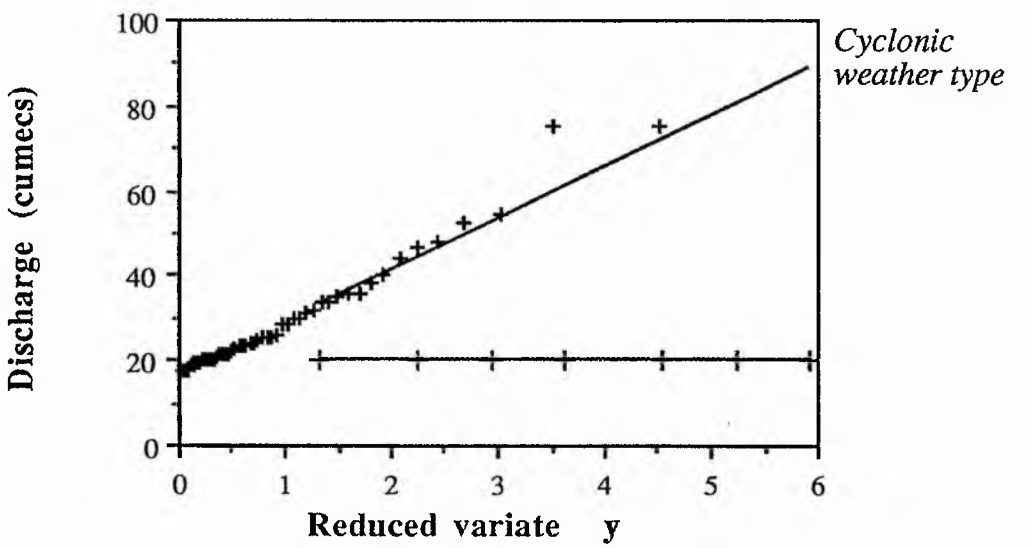
South-westerly weather type



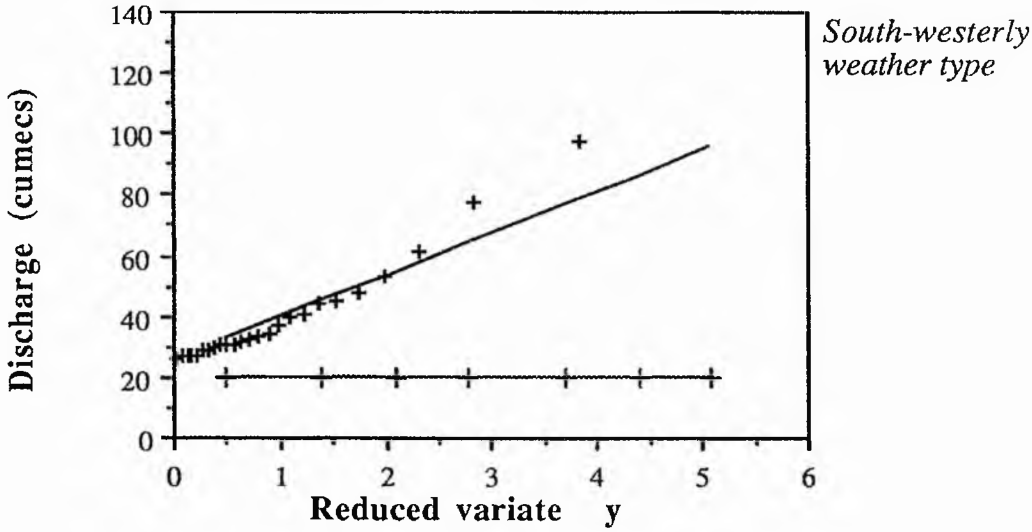
Cyclonic weather type

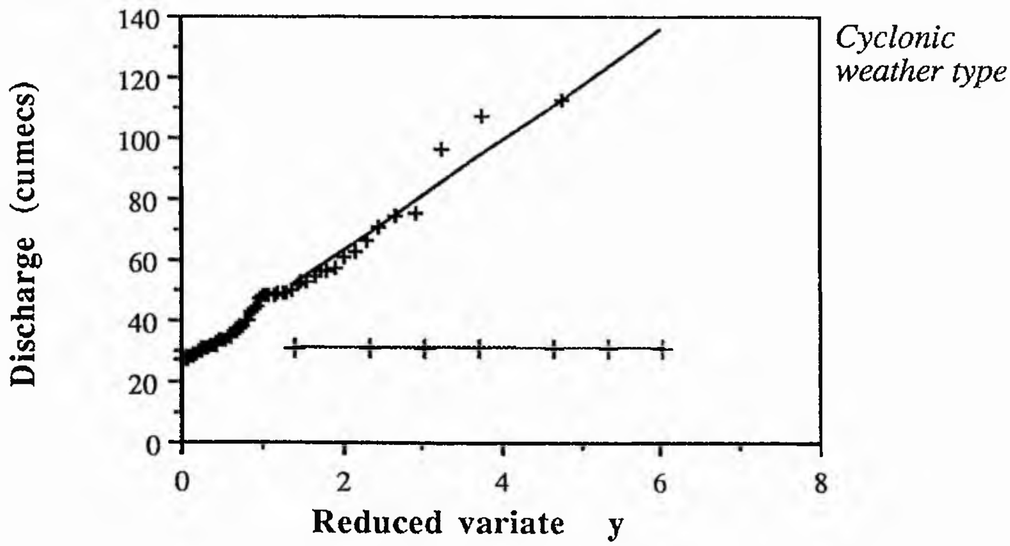
19011 North Esk @ Dalkeith Palace



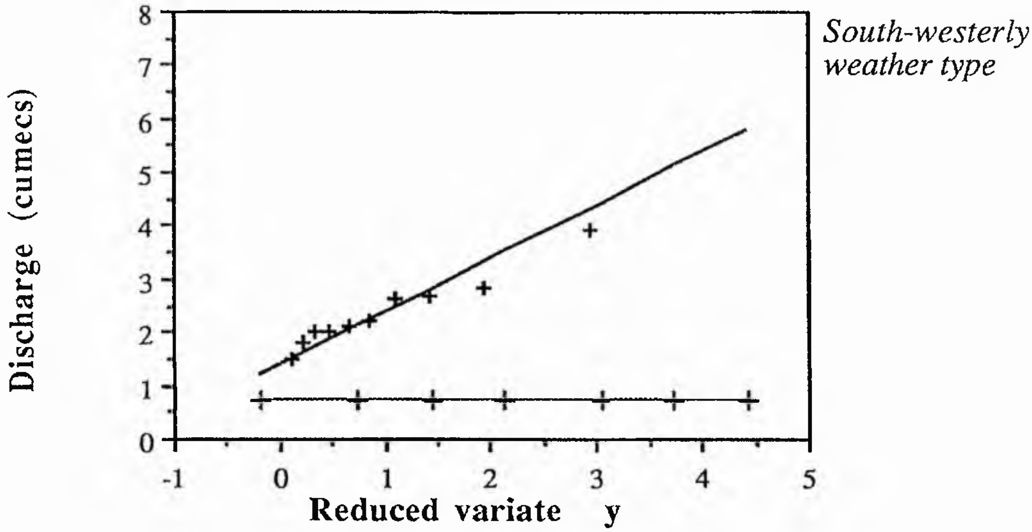


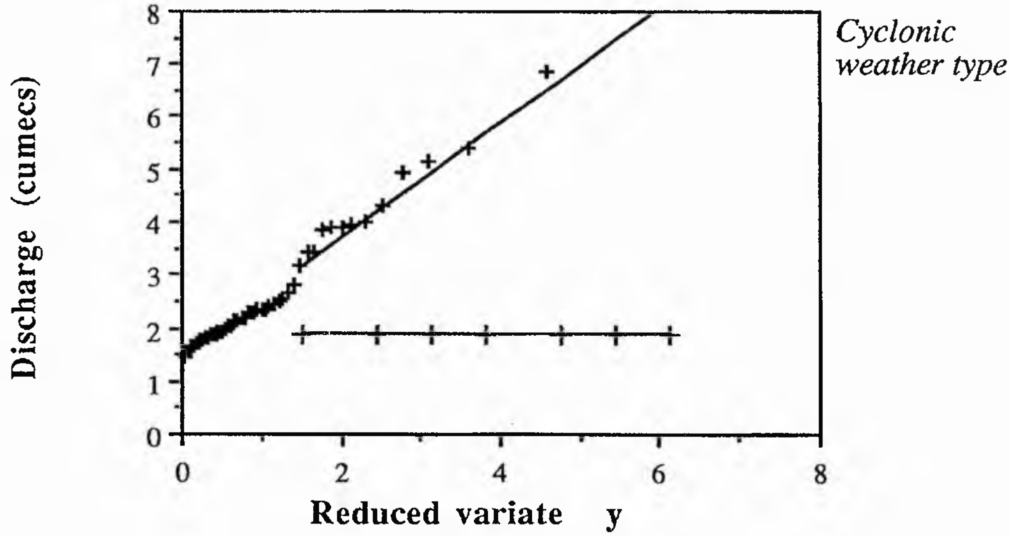
20001 Tyne @ East Linton



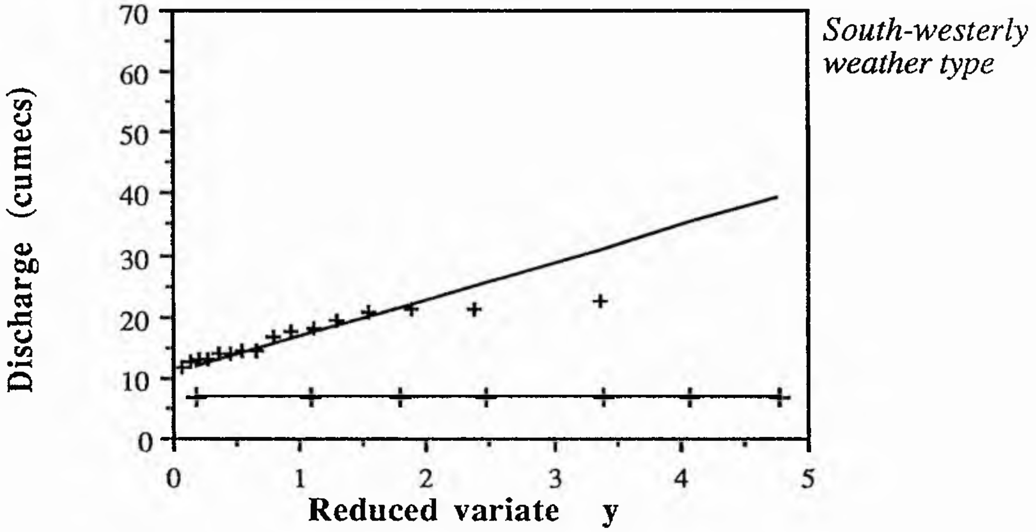


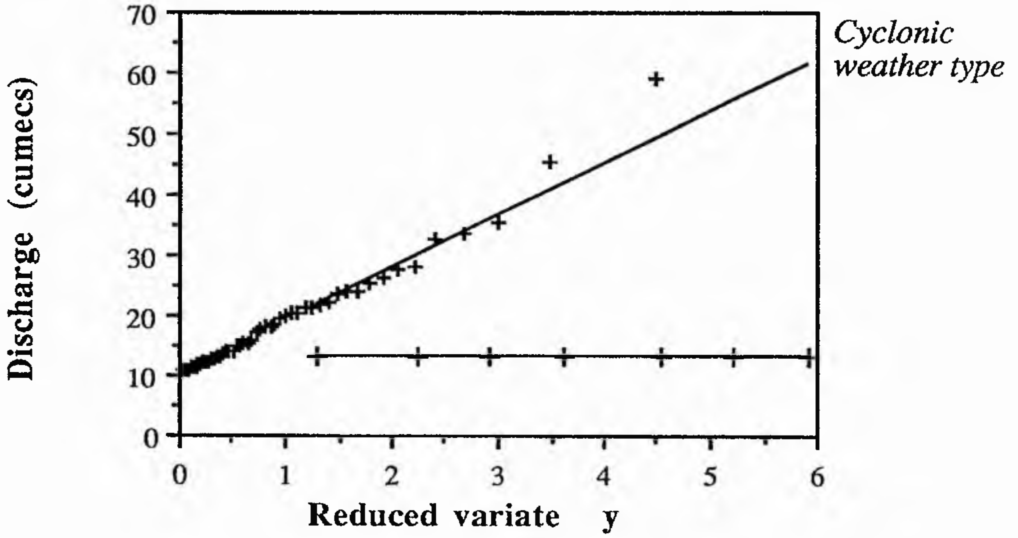
20002 West Peffer Burn @ Luffness Mains



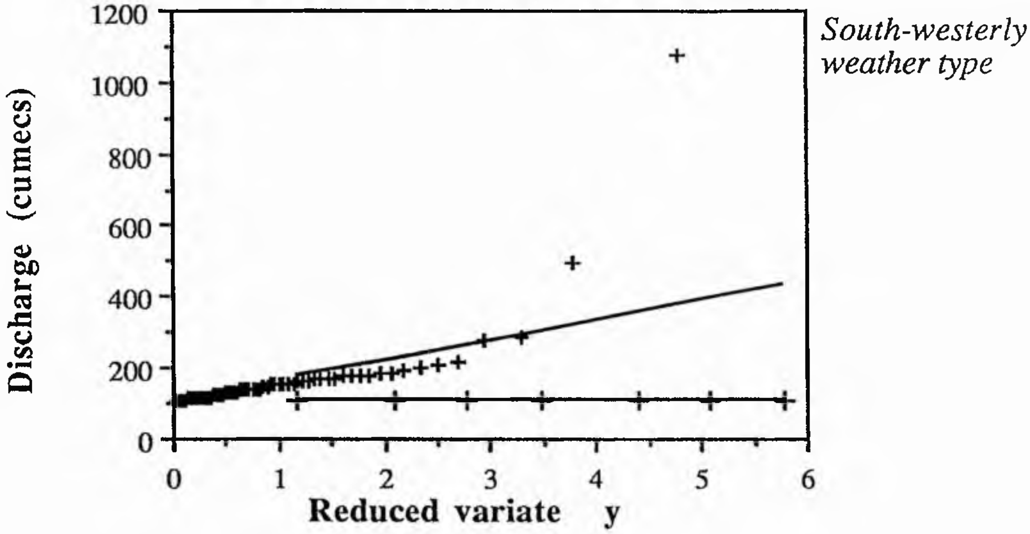


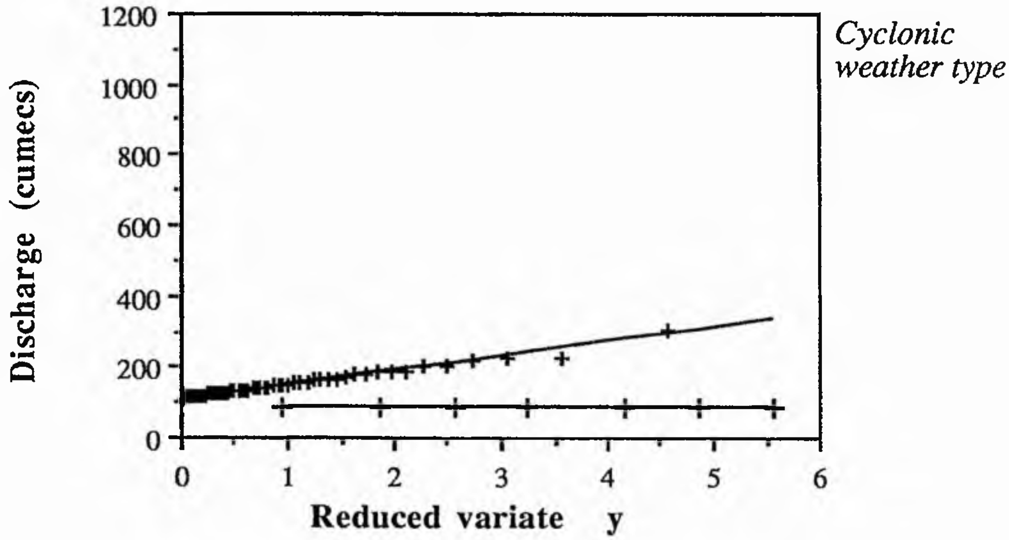
20005 Birns Water @ Saltoun Hall



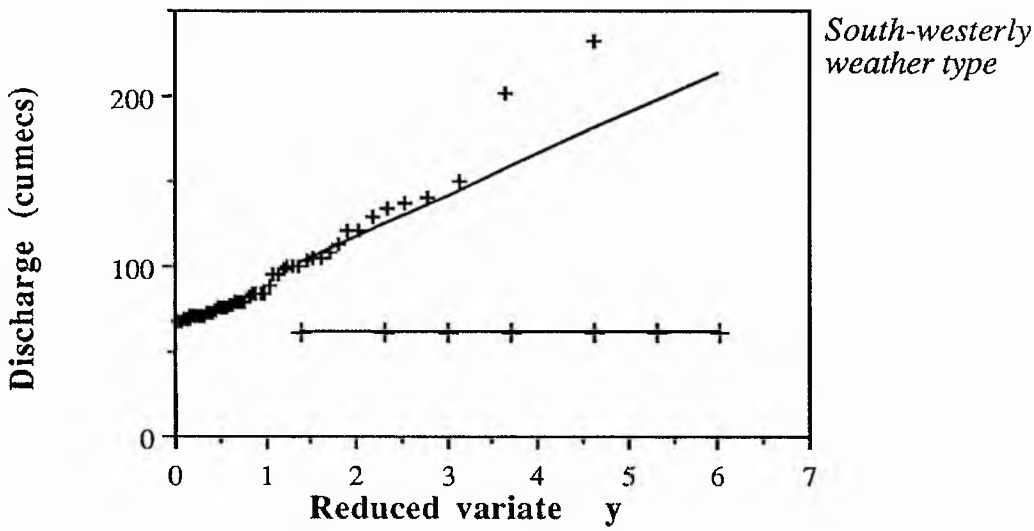


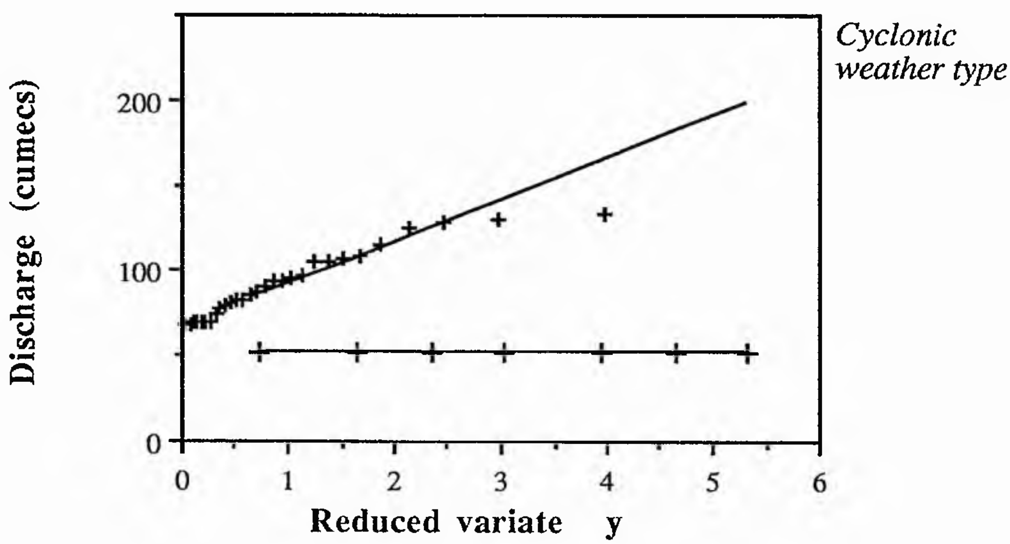
21003 Tweed @ Peebles



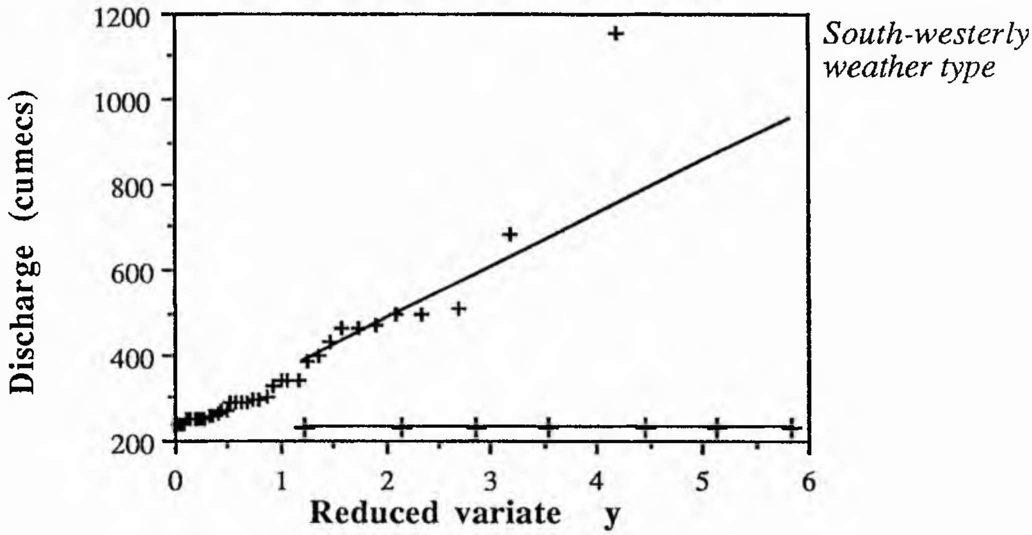


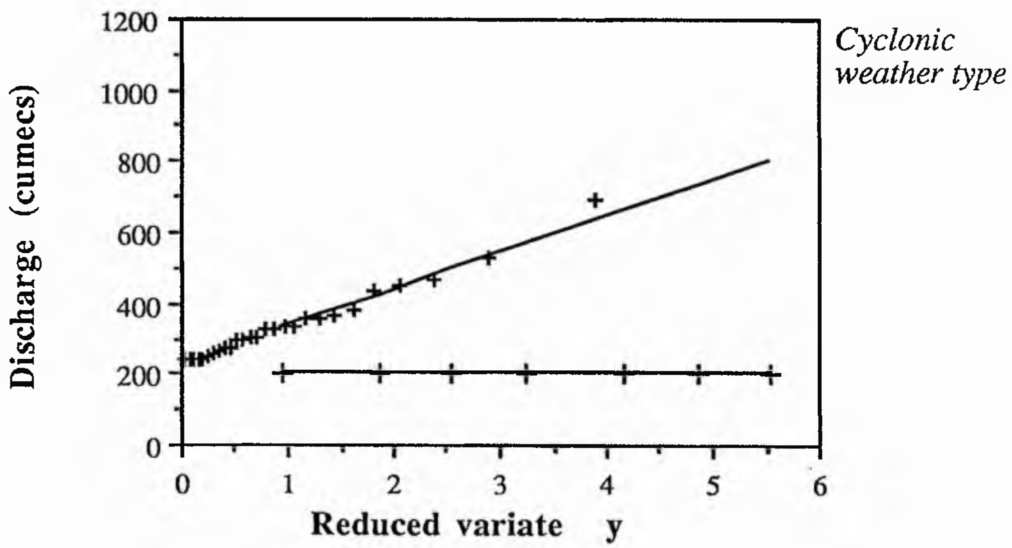
21005 Tweed @ Lyne Ford



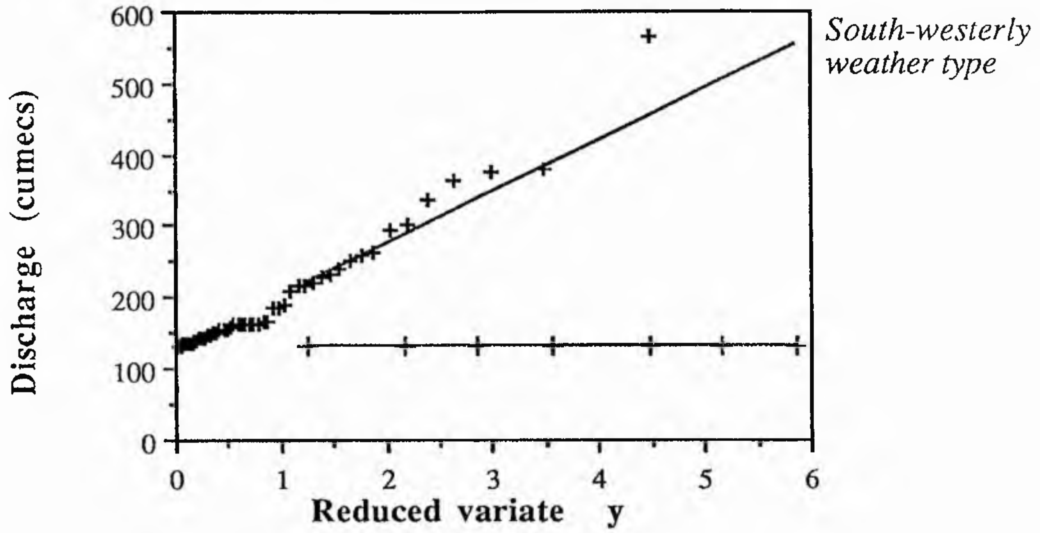


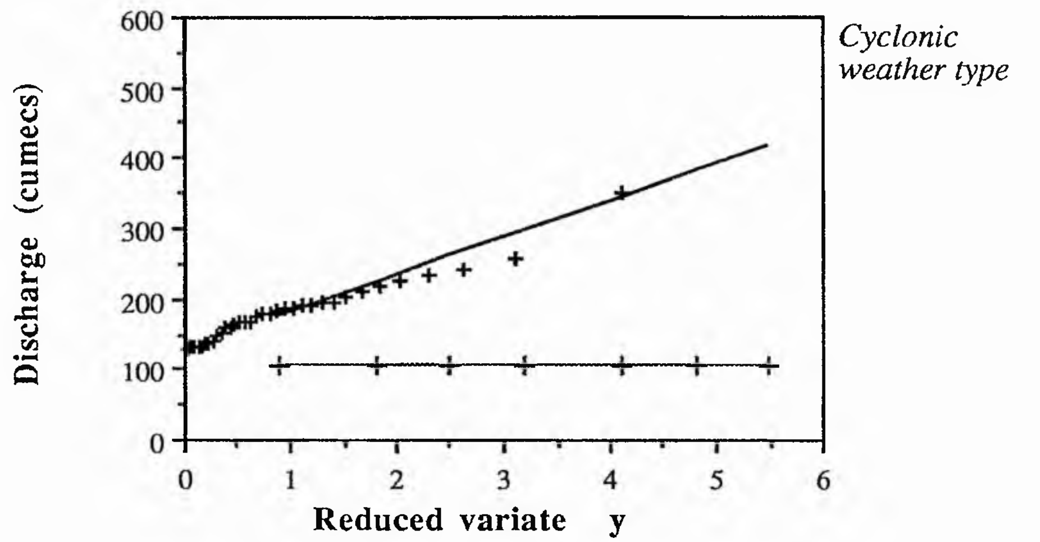
21006 Tweed @ Boleside



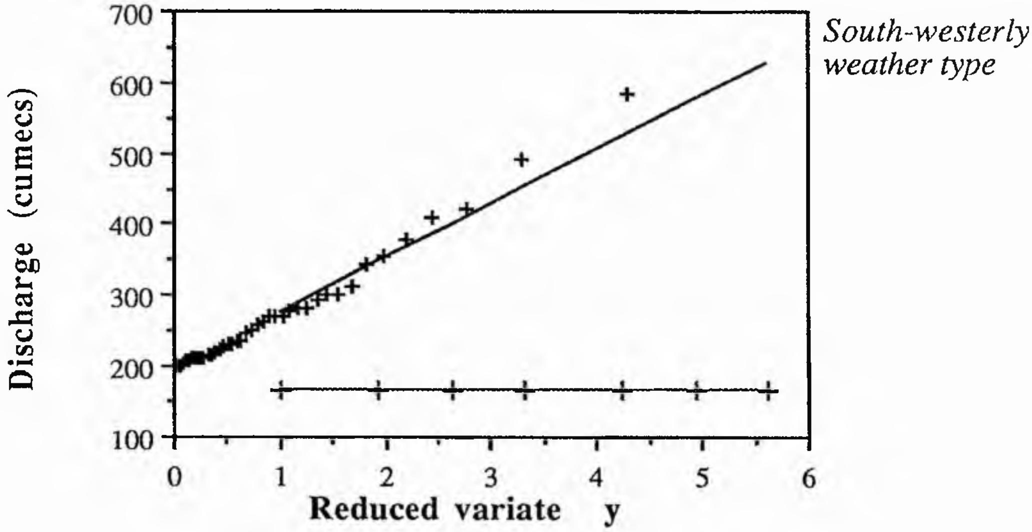


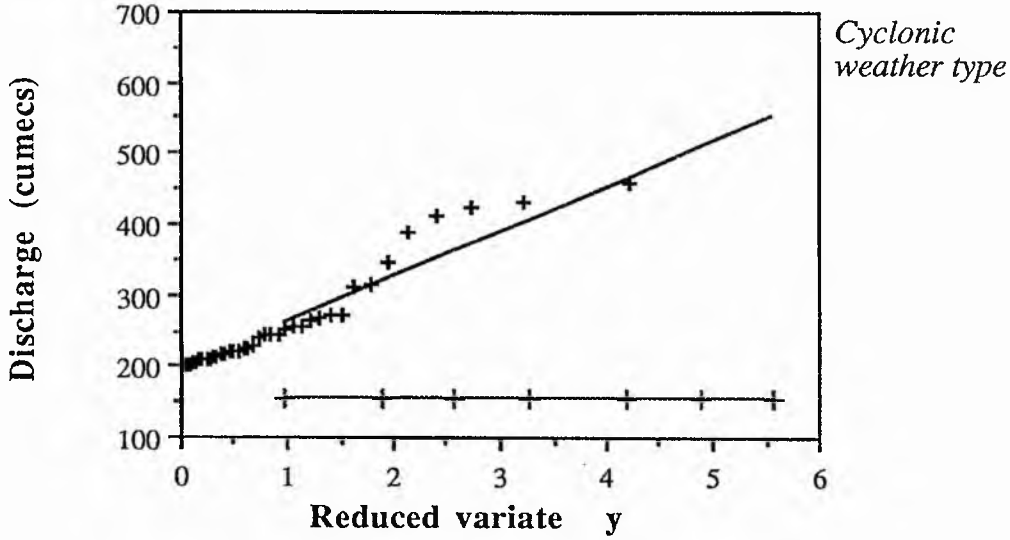
21007 Ettrick @ Lindean



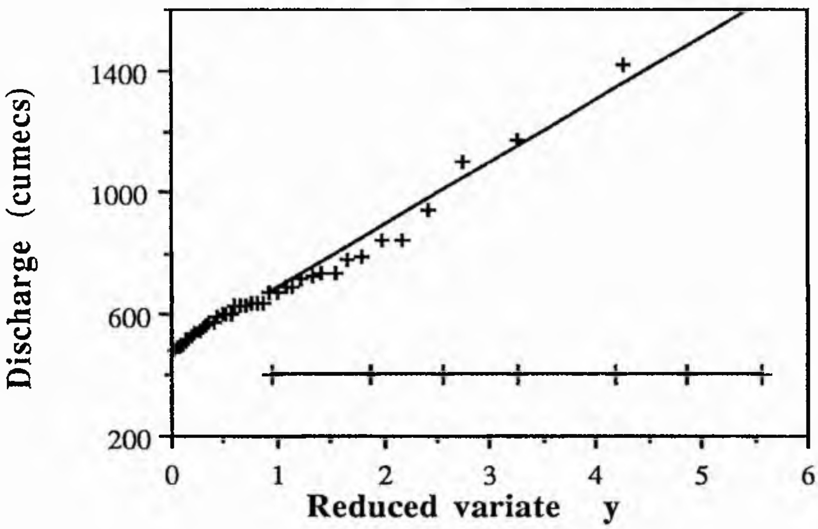


21008 Teviot @ Ormiston Mill

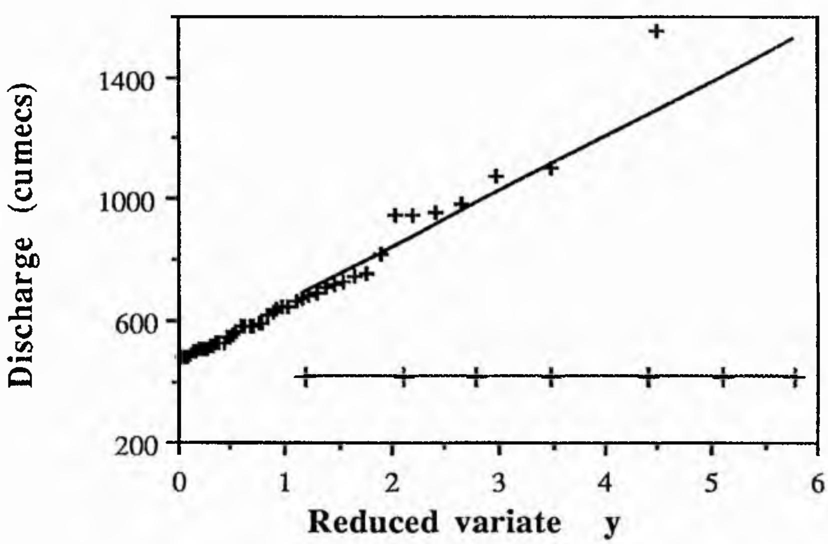




21009 Tweed @ Norham

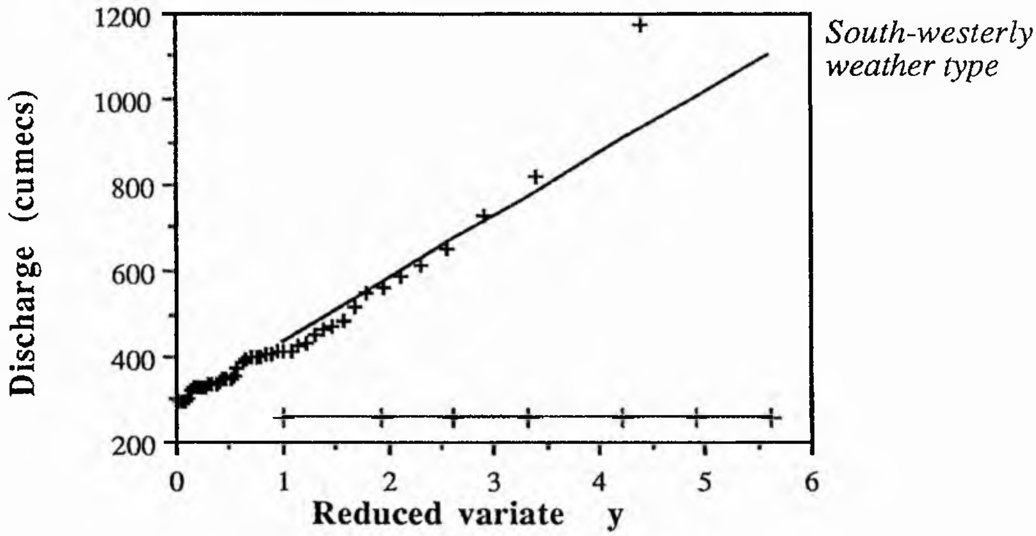


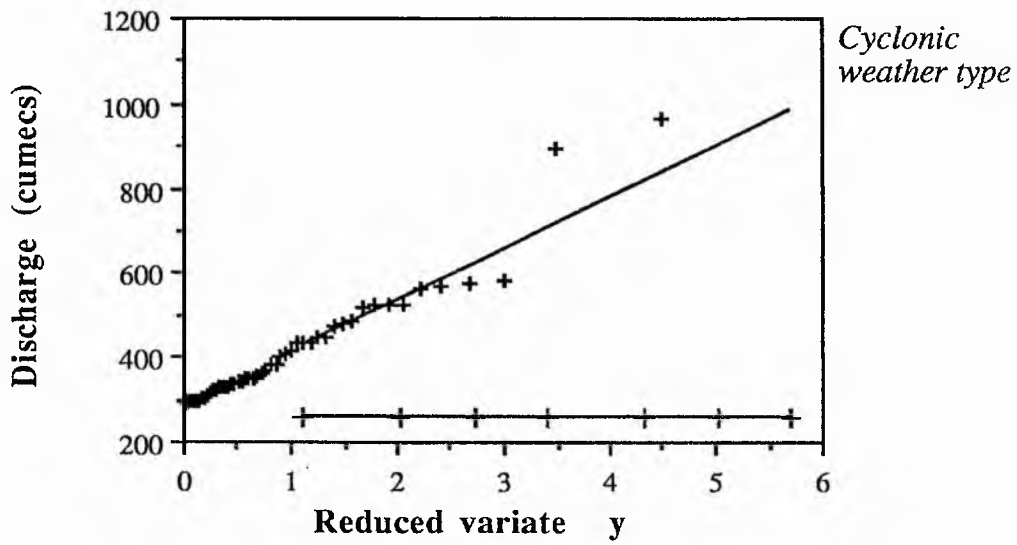
South-westerly weather type



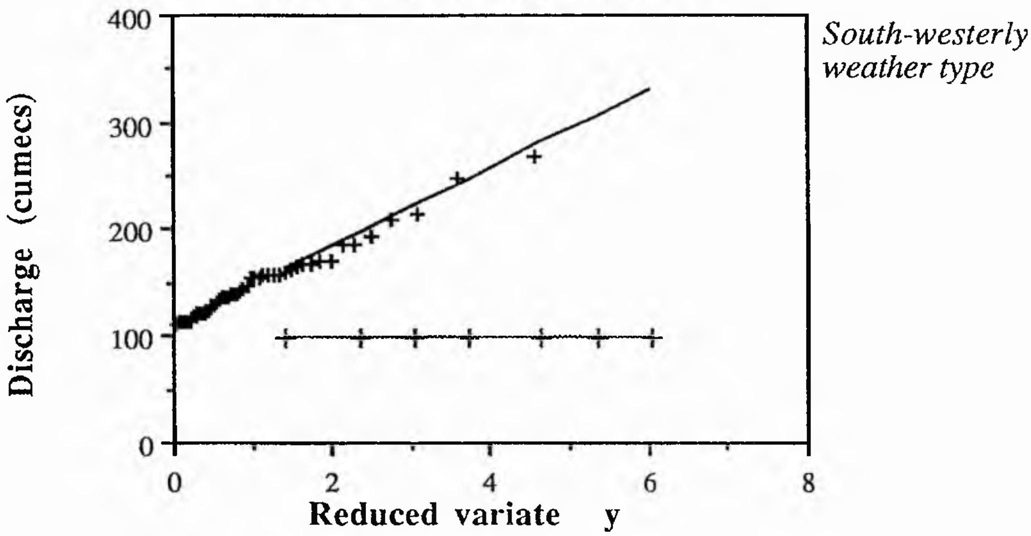
Cyclonic weather type

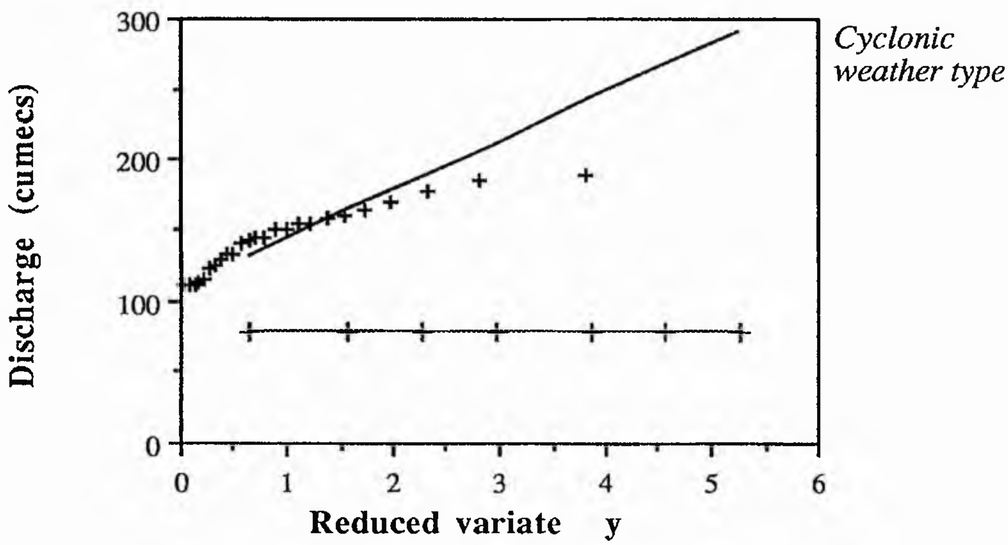
21010 Tweed @ Dryburgh



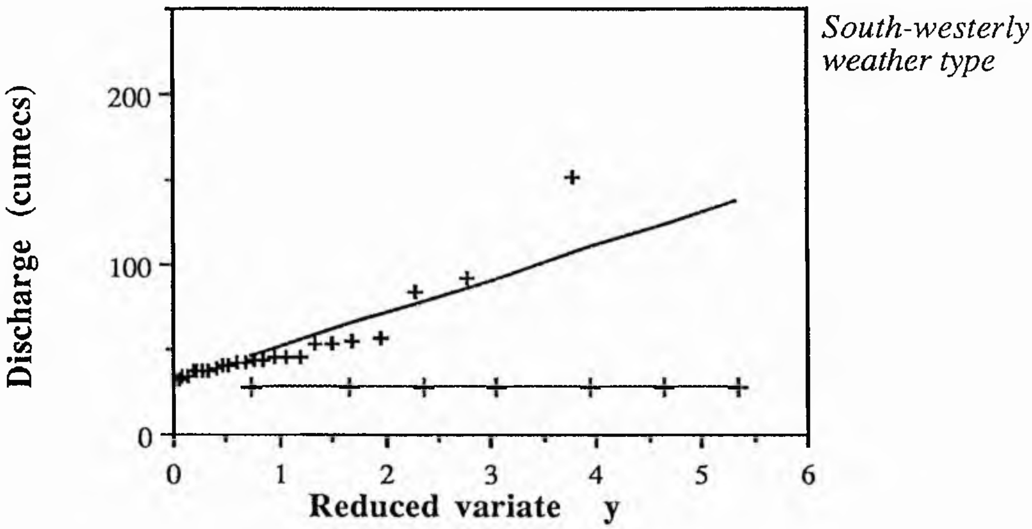


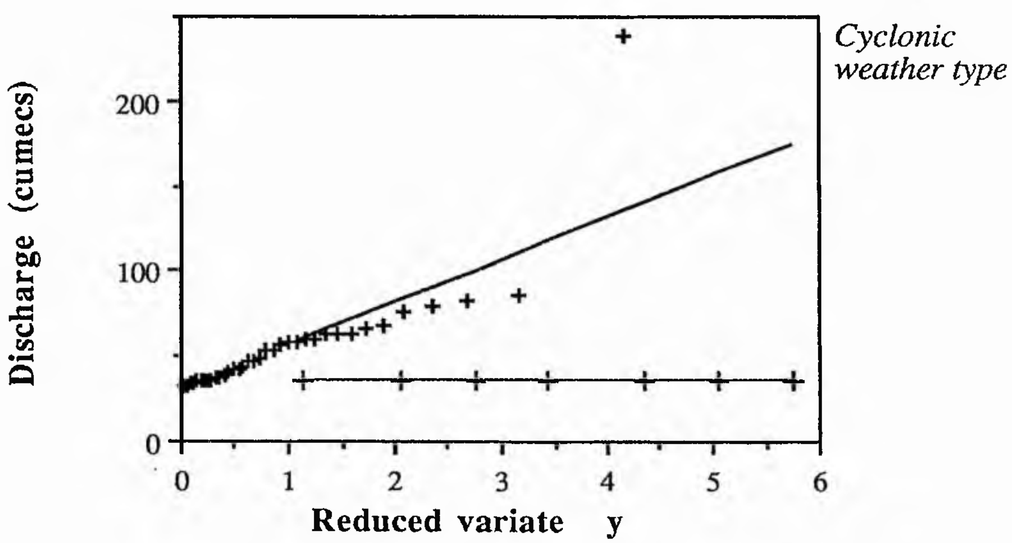
21012 Teviot @ Hawick



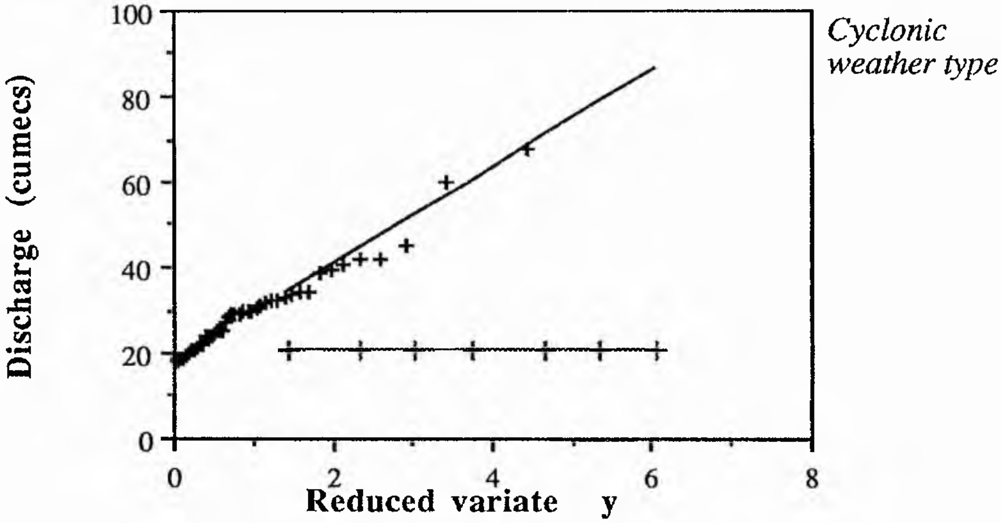


21015 Leader Water @ Earlston

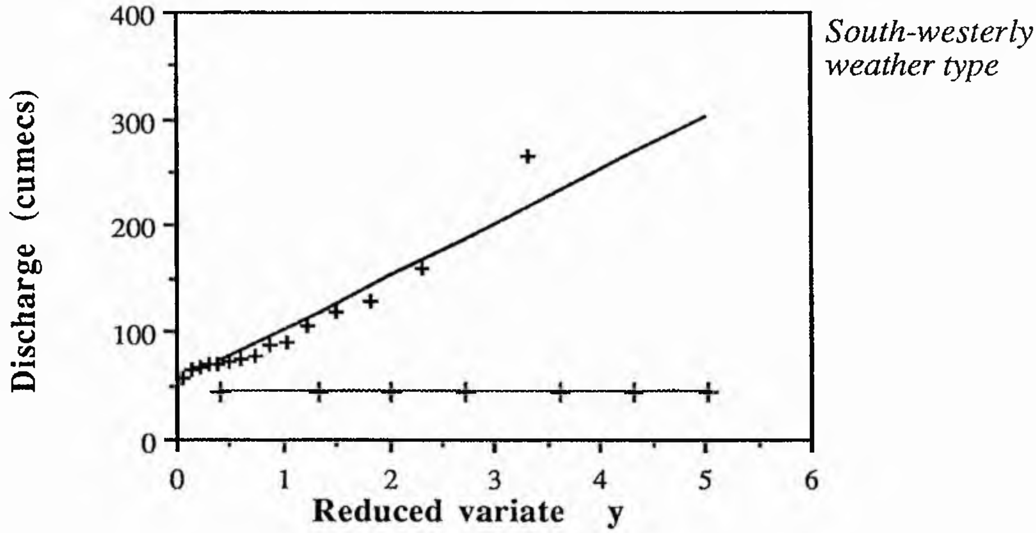


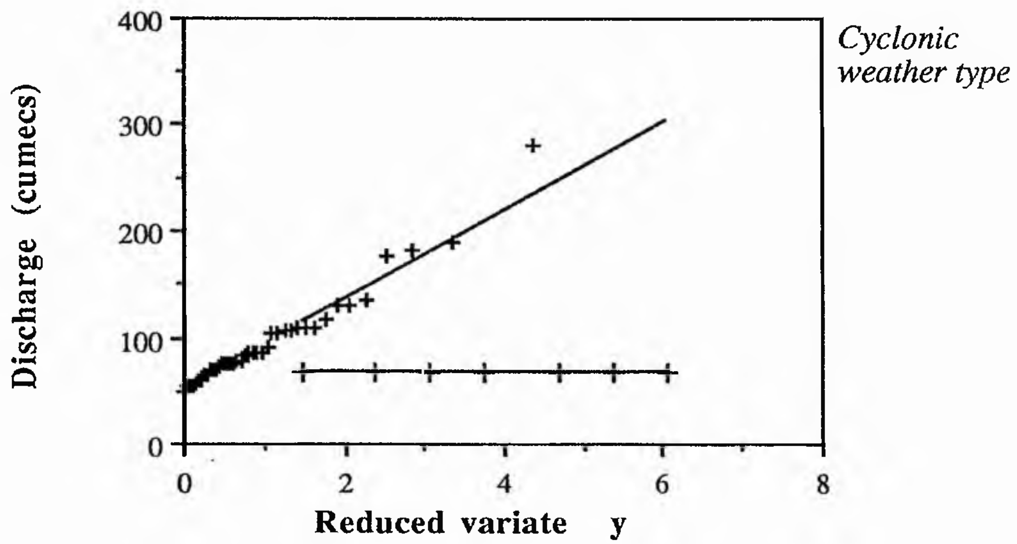


21016 Eye Water @ Eyemouth Mill

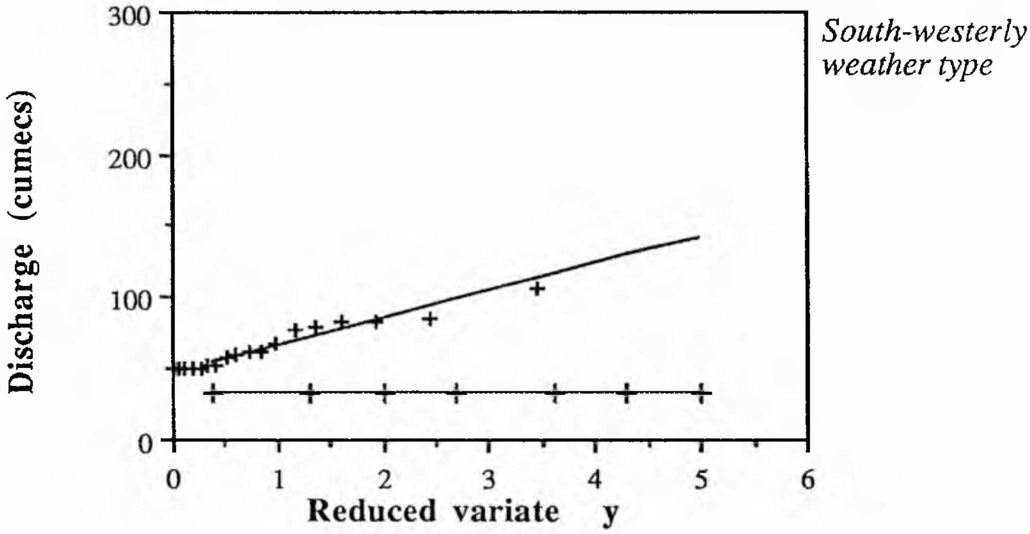


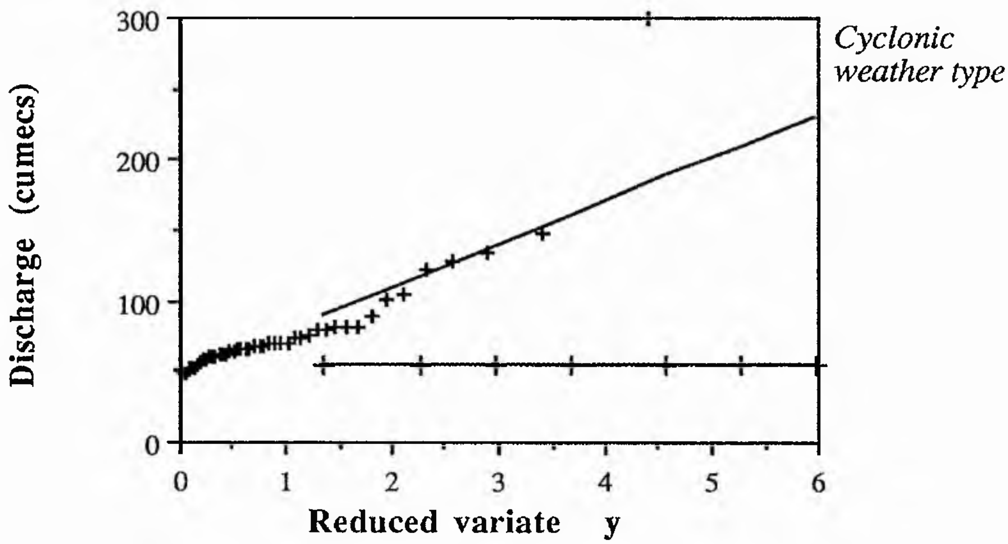
21022 Whiteadder Water @ Hutton Castle



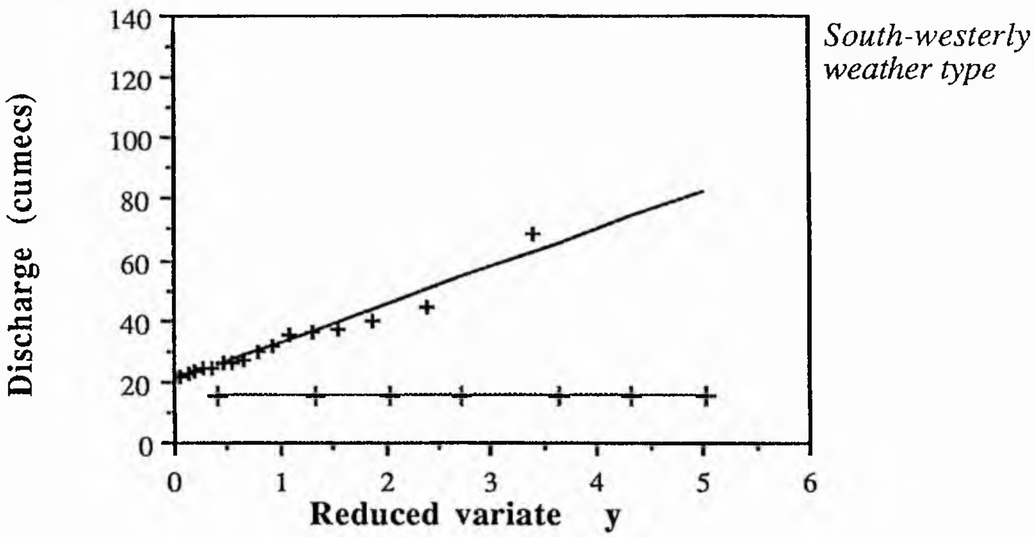


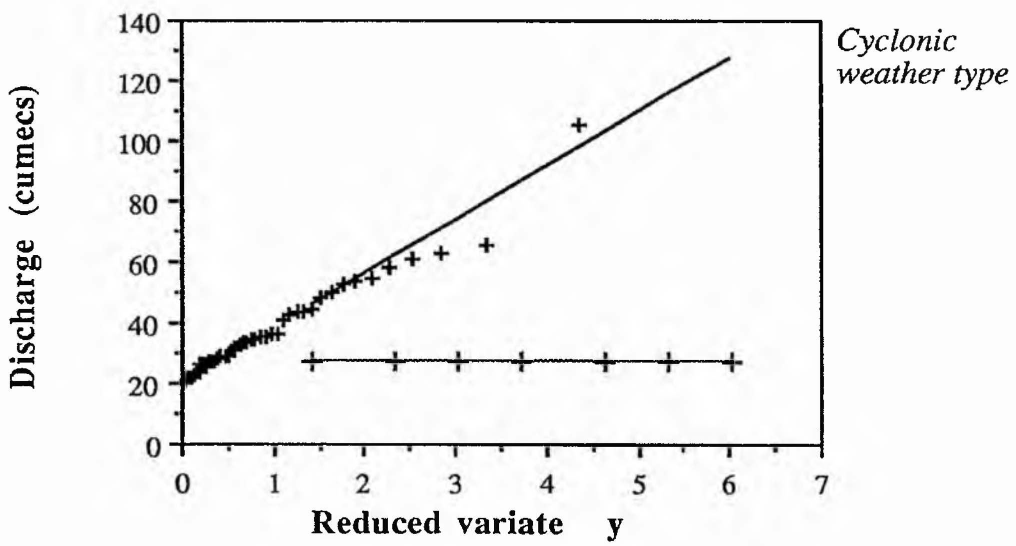
21031 Till @ Etal



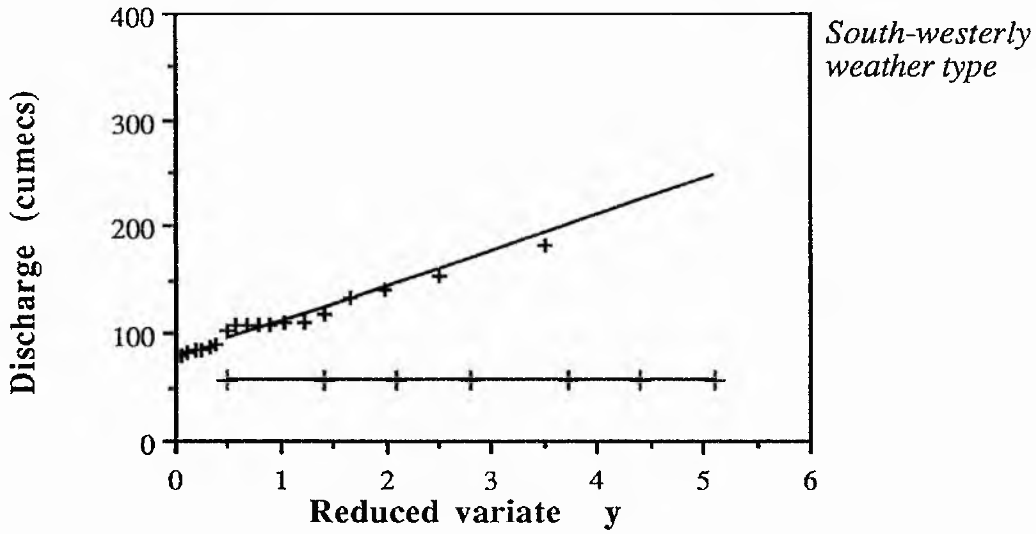


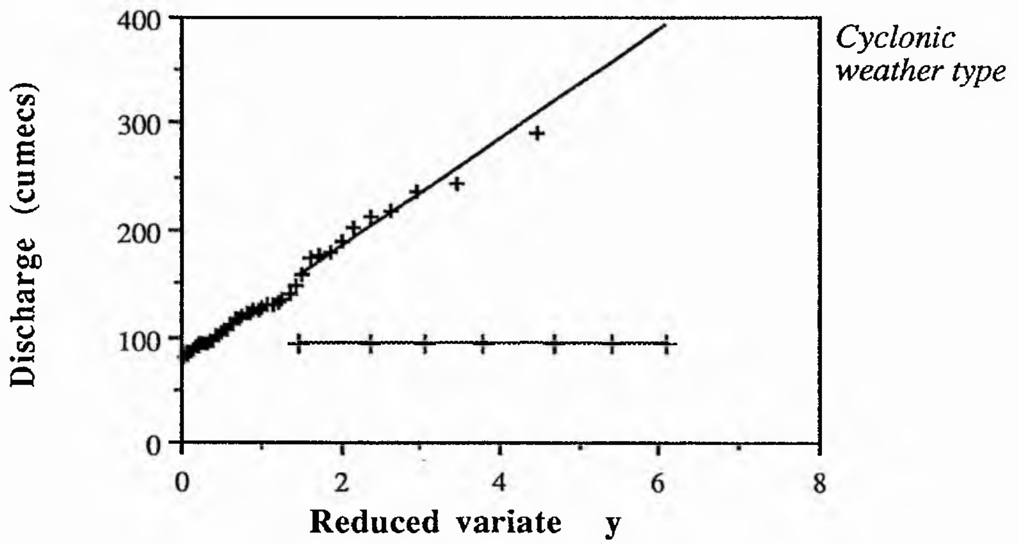
21032 Glen @ Kirknewton



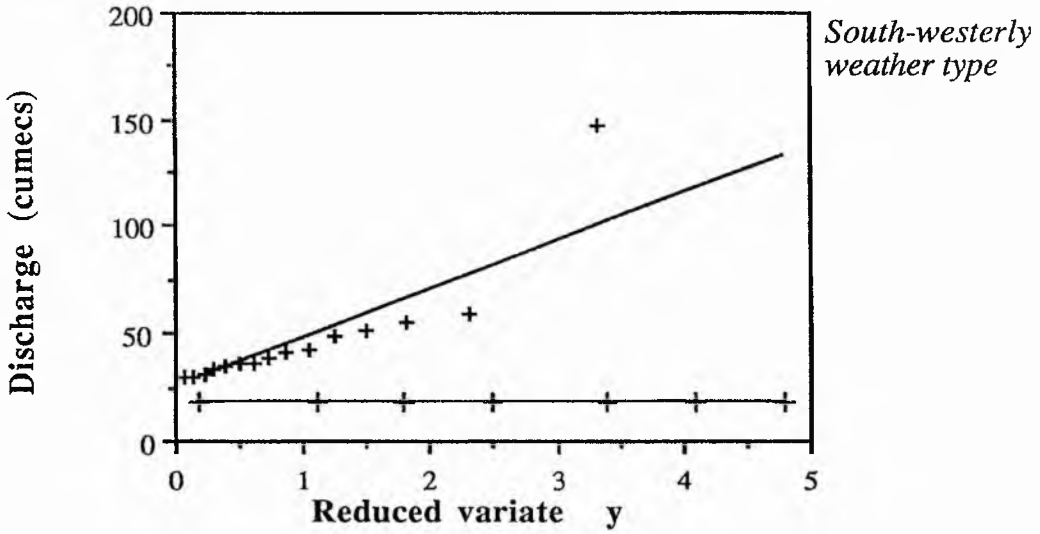


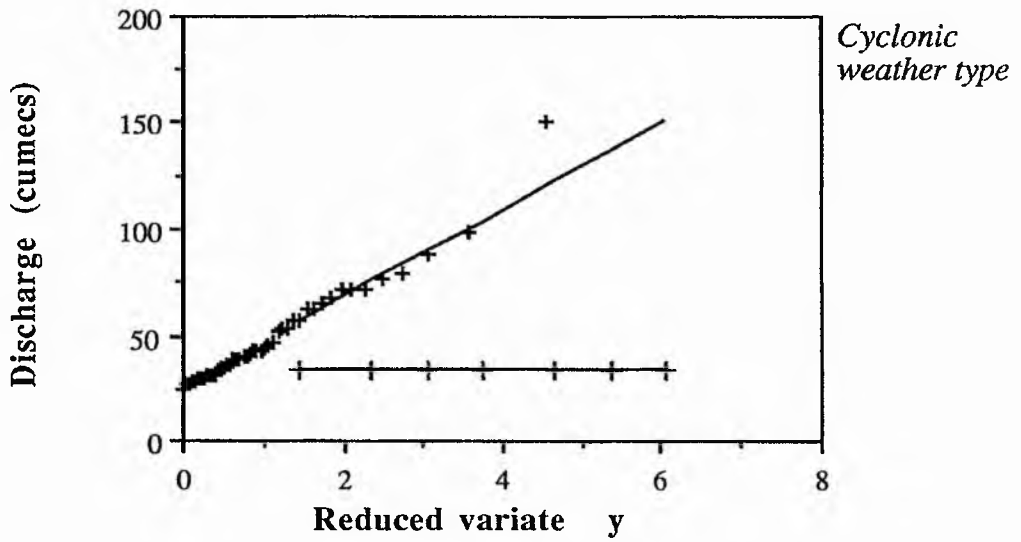
22001 Coquet @ Morwick



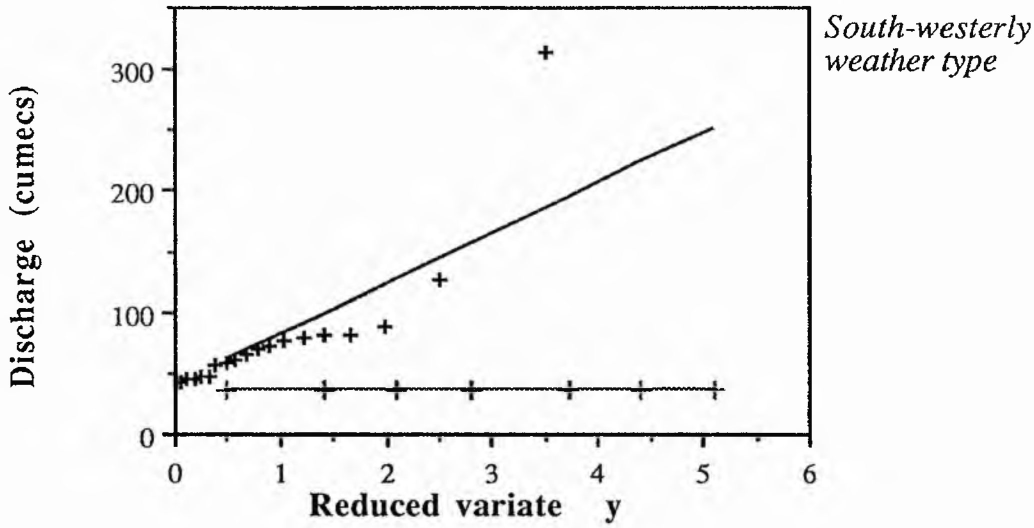


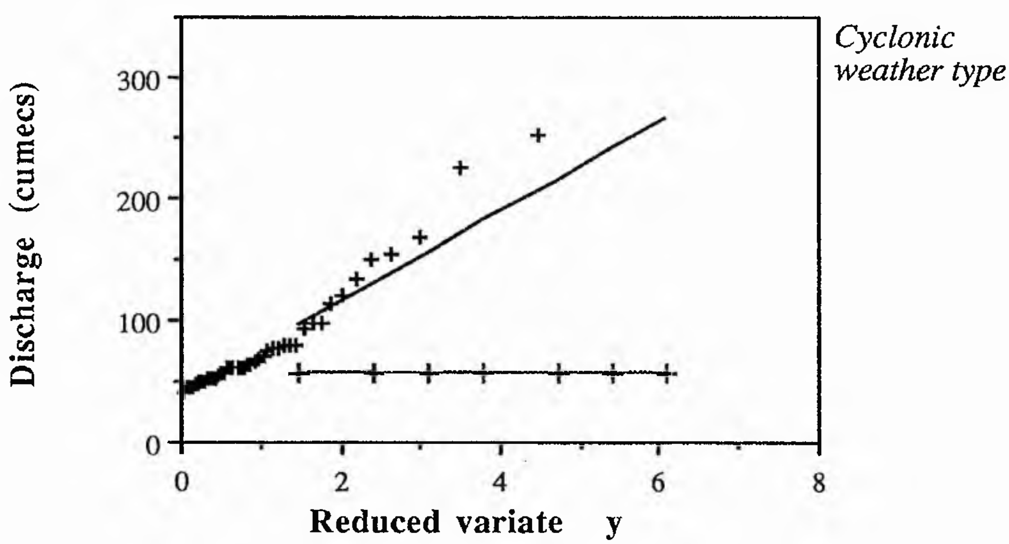
22006 Blyth @ Hartford Bridge



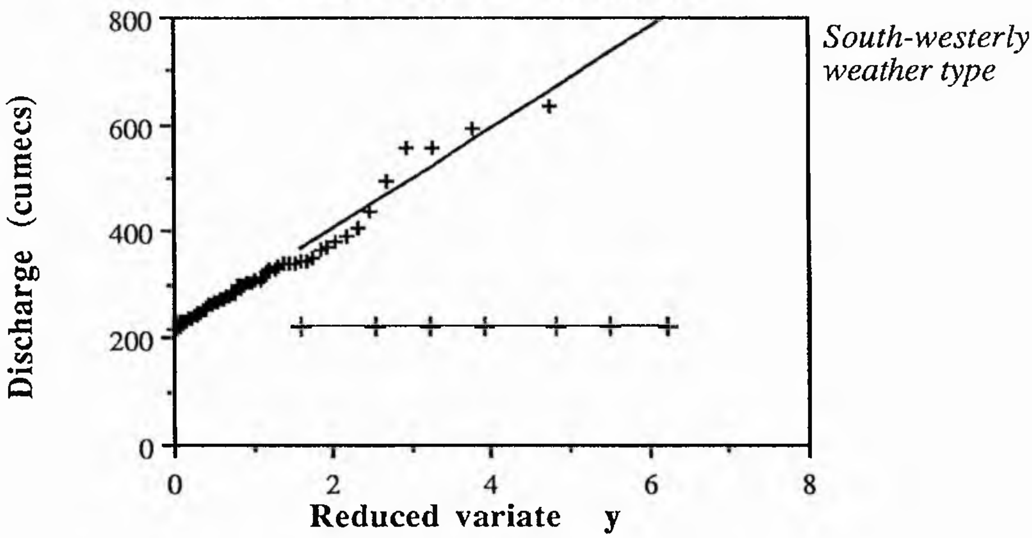


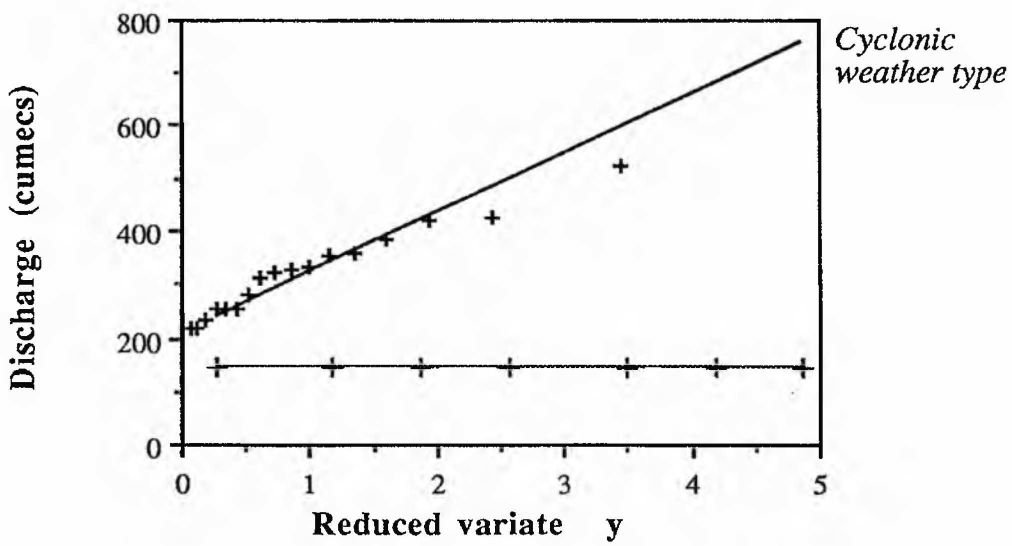
22007 Wansbeck @ Mitford



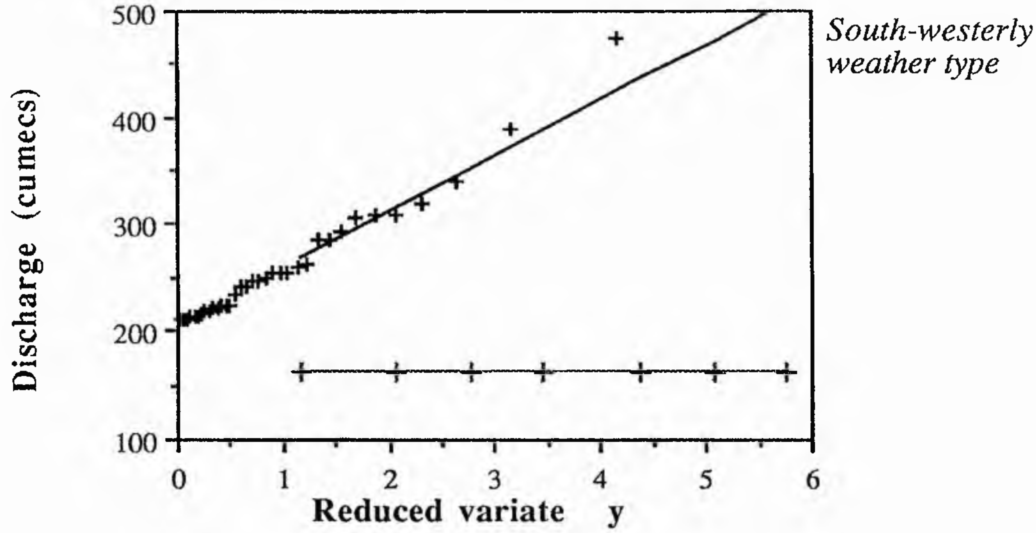


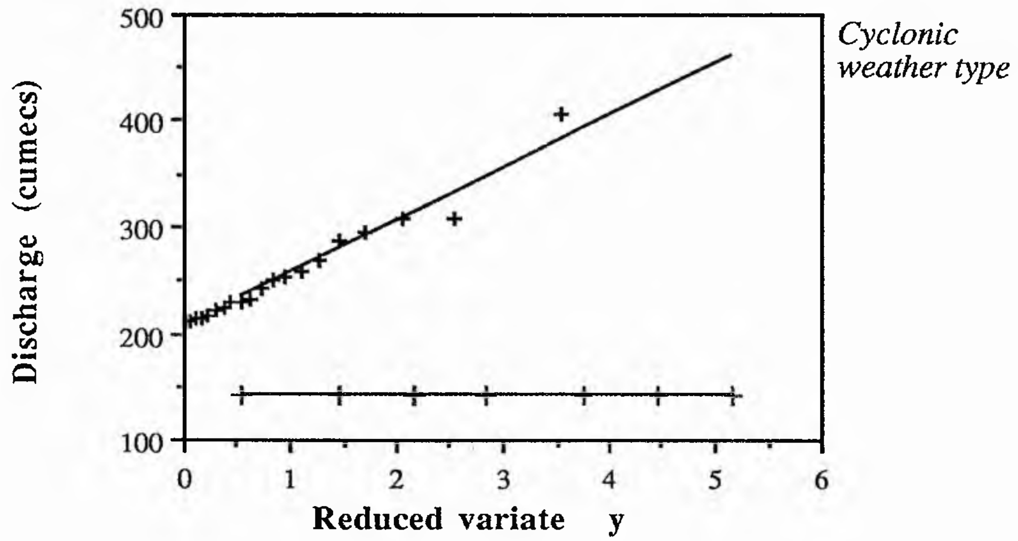
77002 Esk @ Canonbie



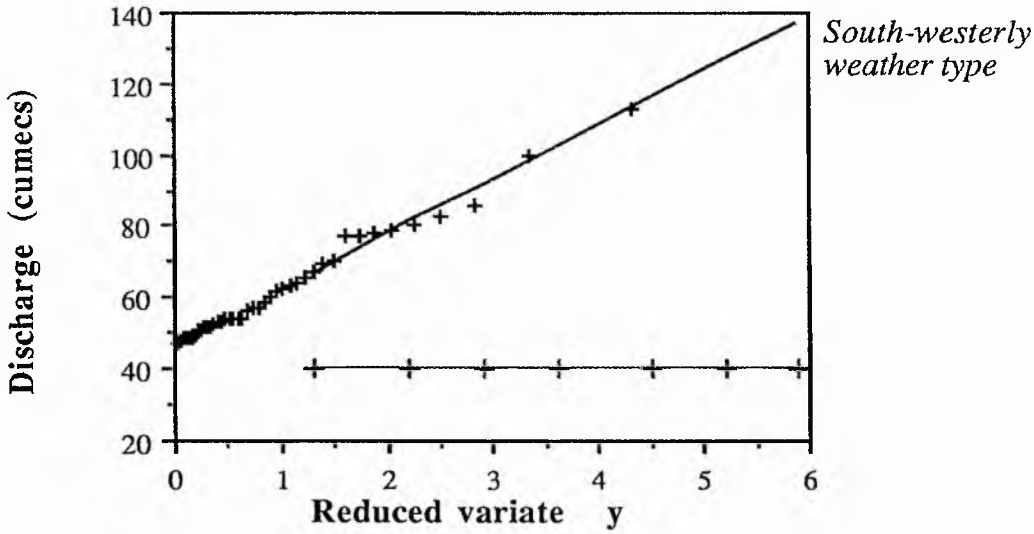


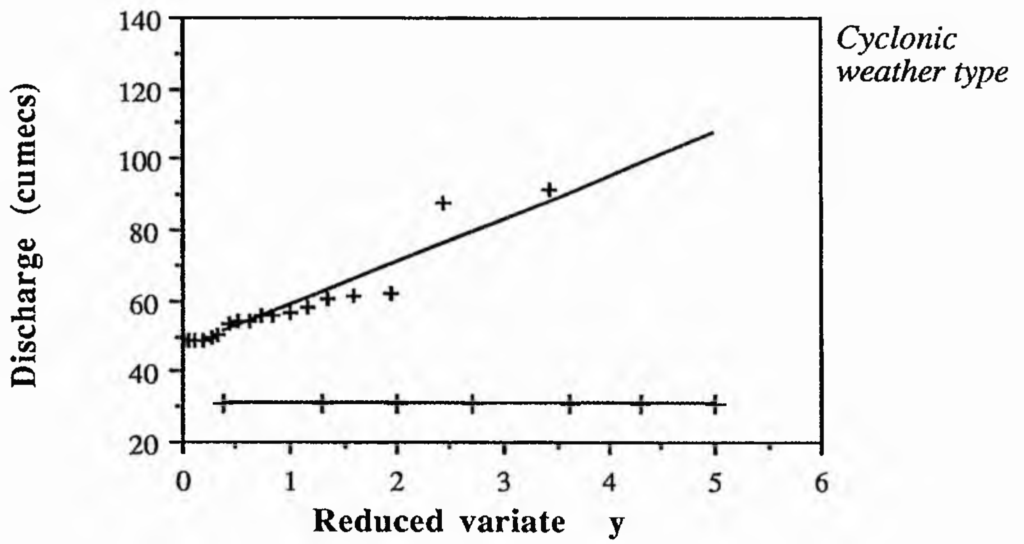
78003 Annan @ Brydekirk



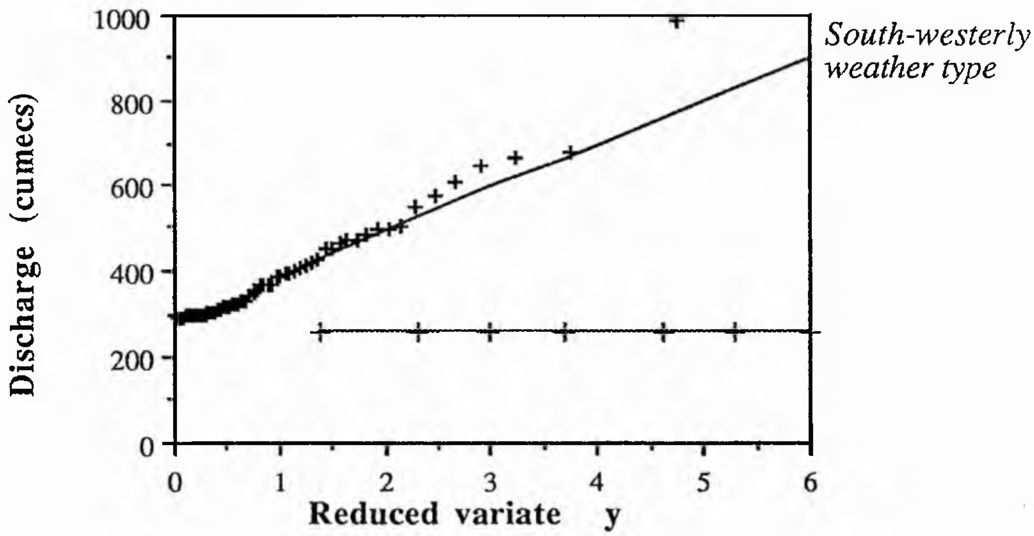


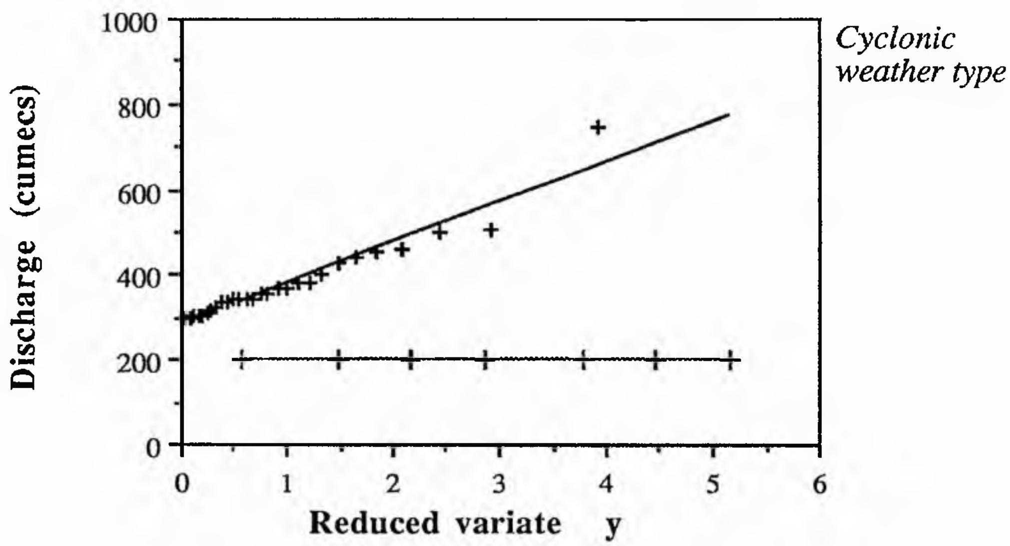
78004 Kinnel @ Redhall



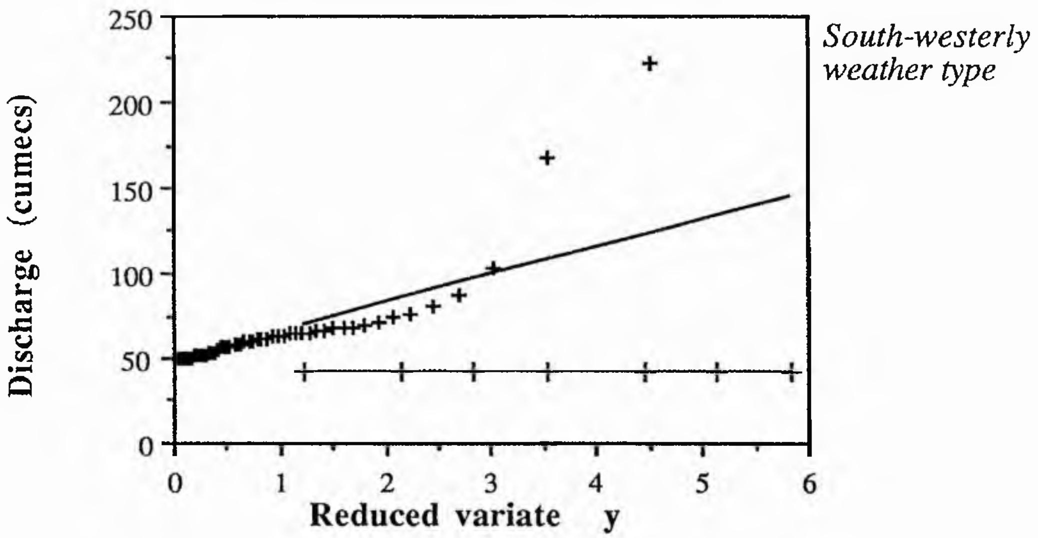


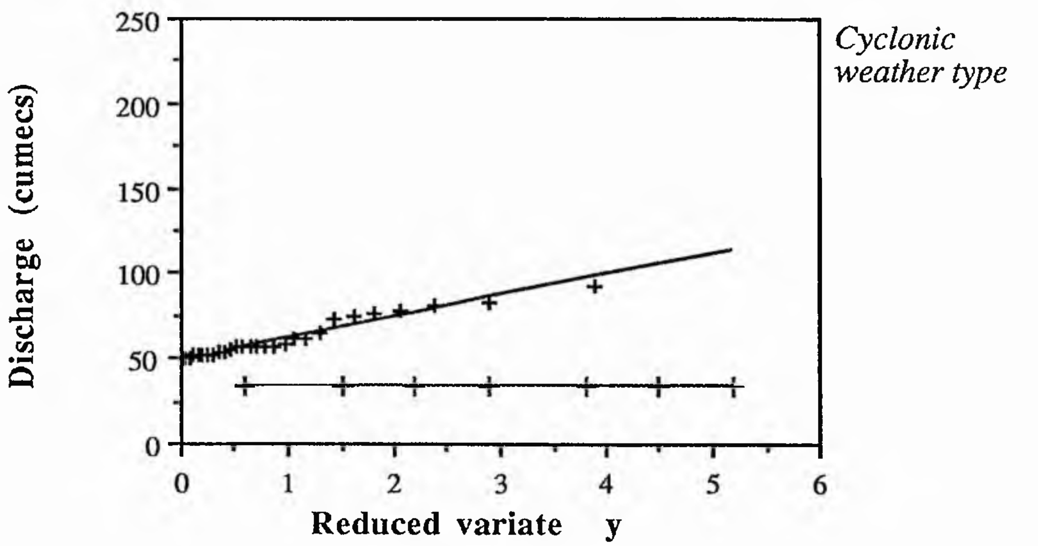
79002 Nith @ Friar's Carse



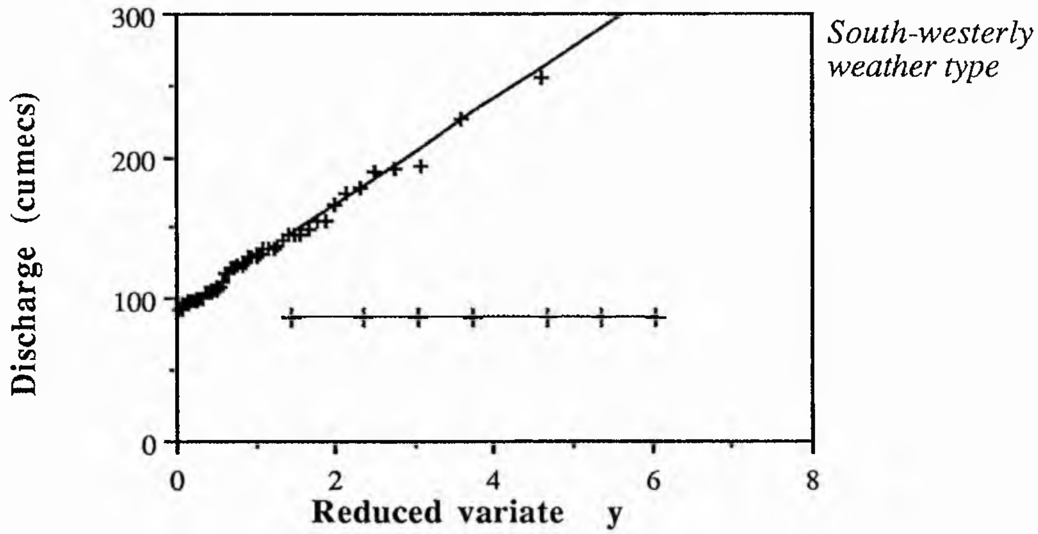


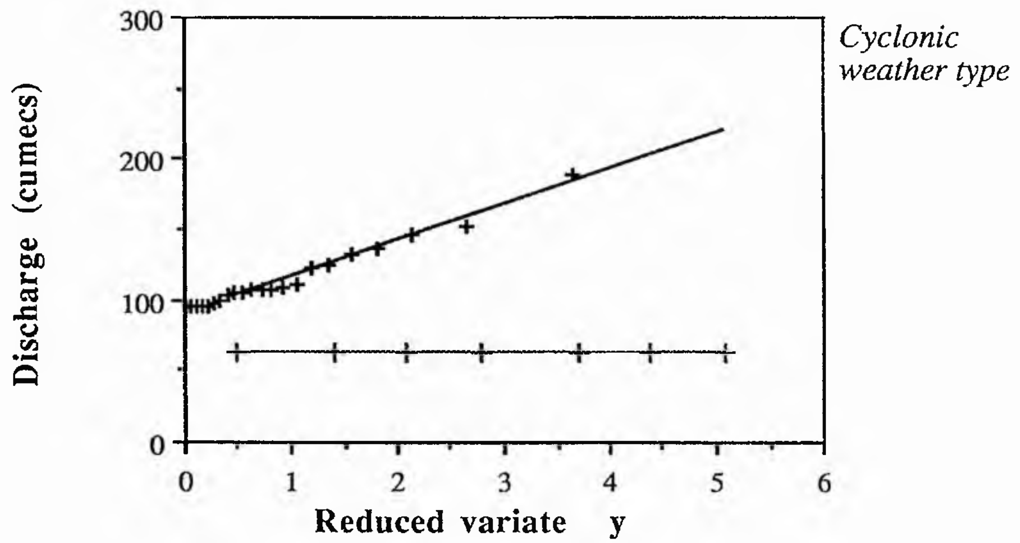
79003 Nith @ Hall Bridge



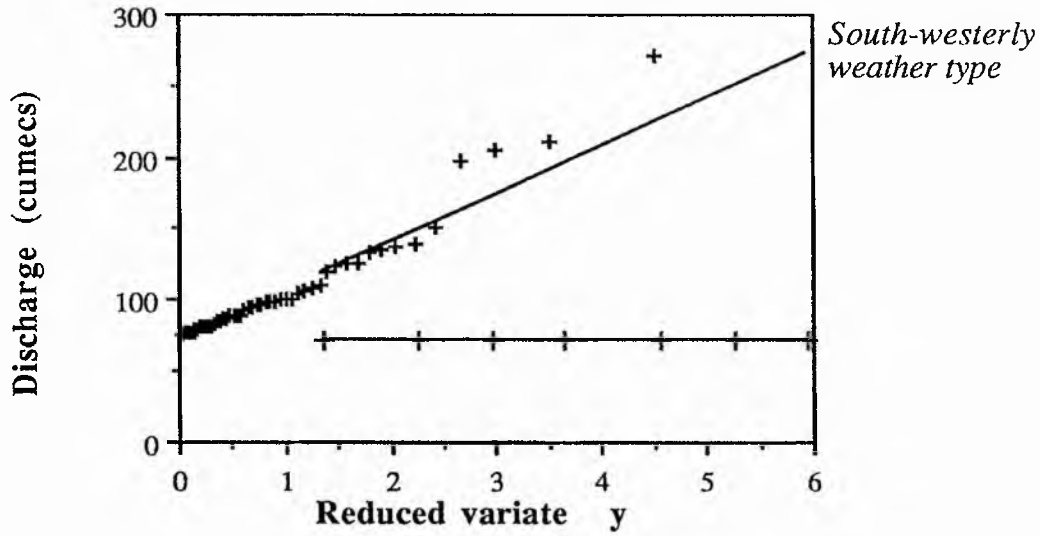


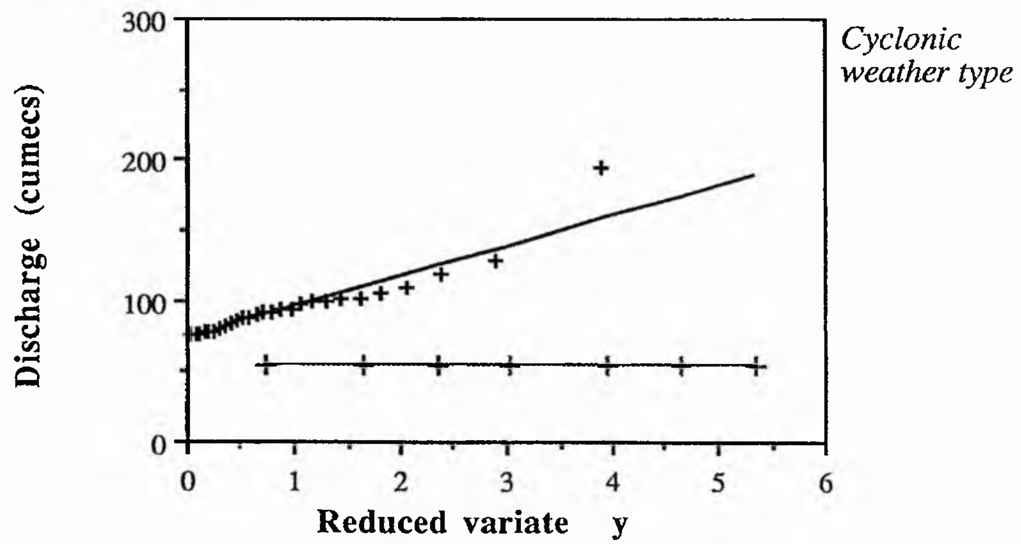
79004 Scar @ Capenoch



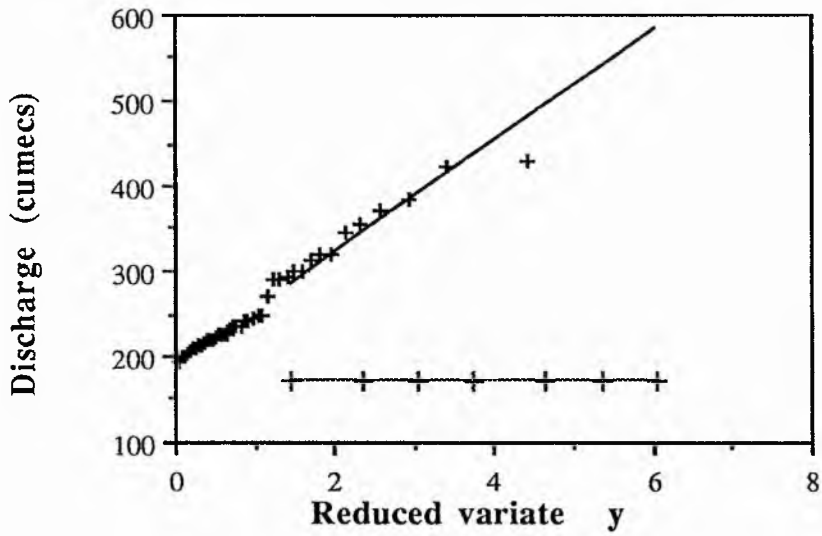


79005 Cluden @ Fiddler's Ford

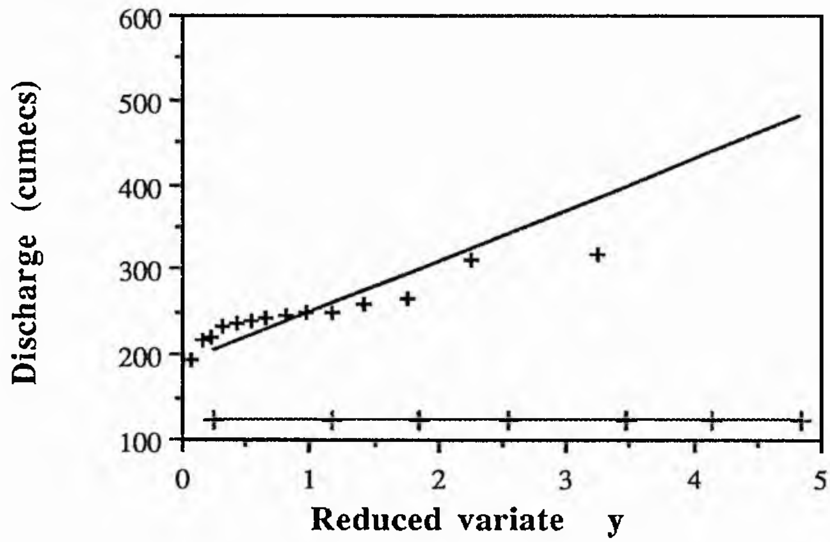




79006 Nith @ Drumlanrig

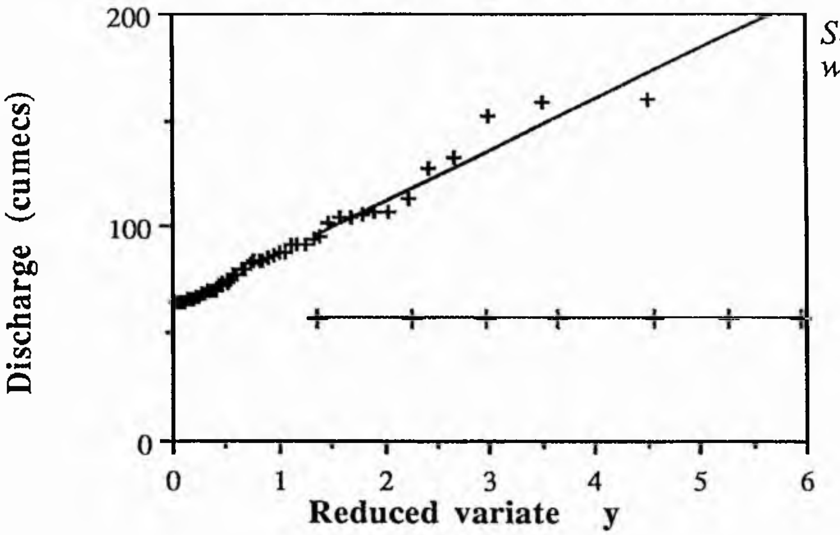


South-westerly weather type

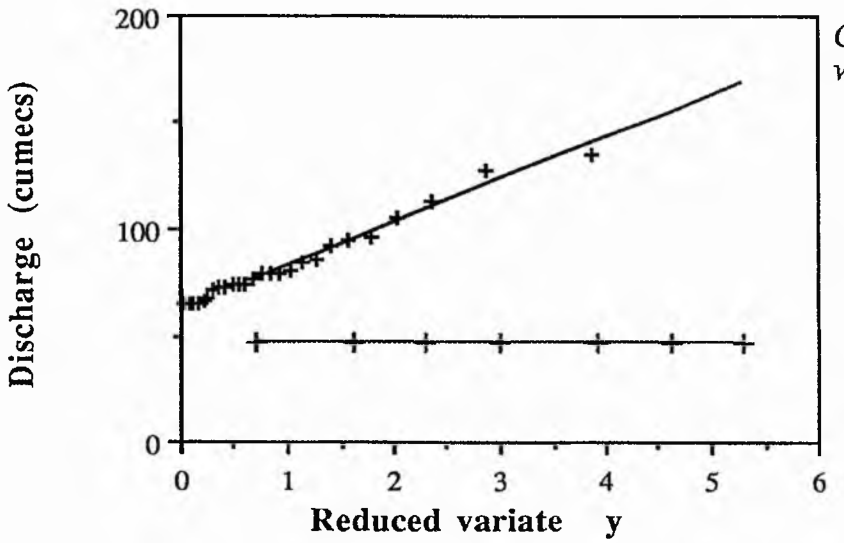


Cyclonic weather type

80001 Urr @ Dalbeattie

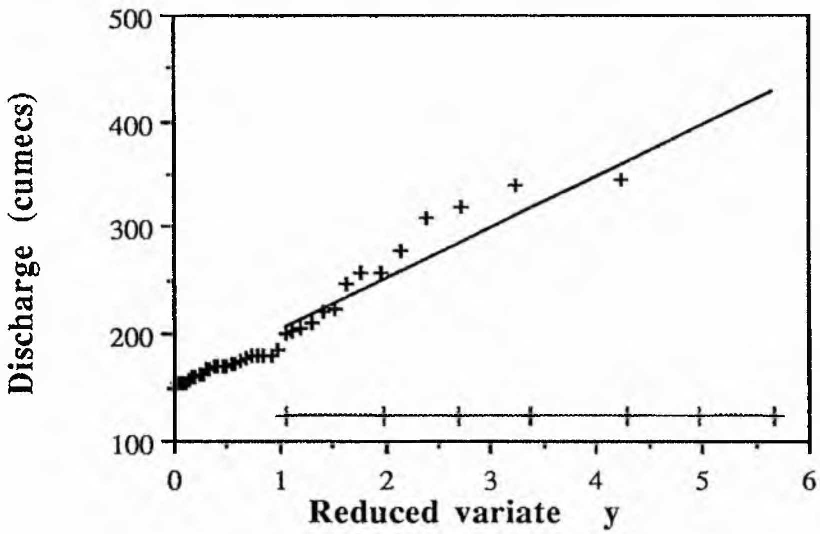


South-westerly weather type

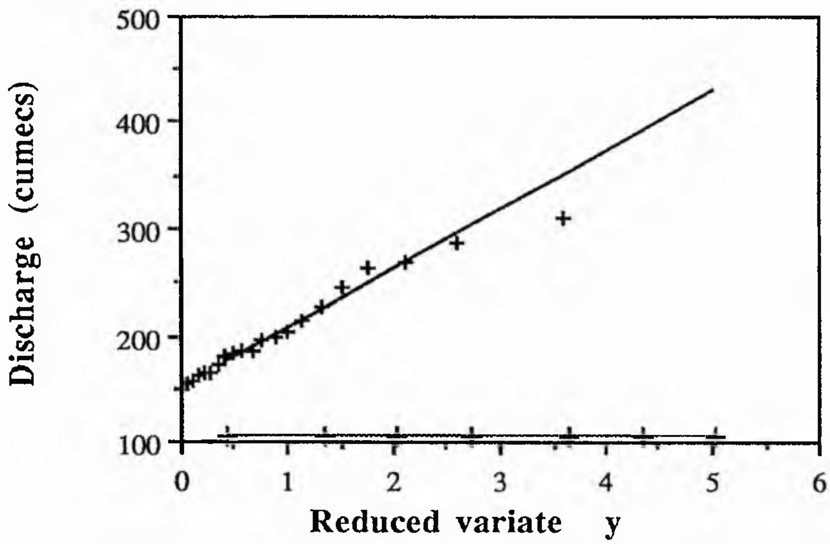


Cyclonic weather type

81002 Cree @ Newton Stewart

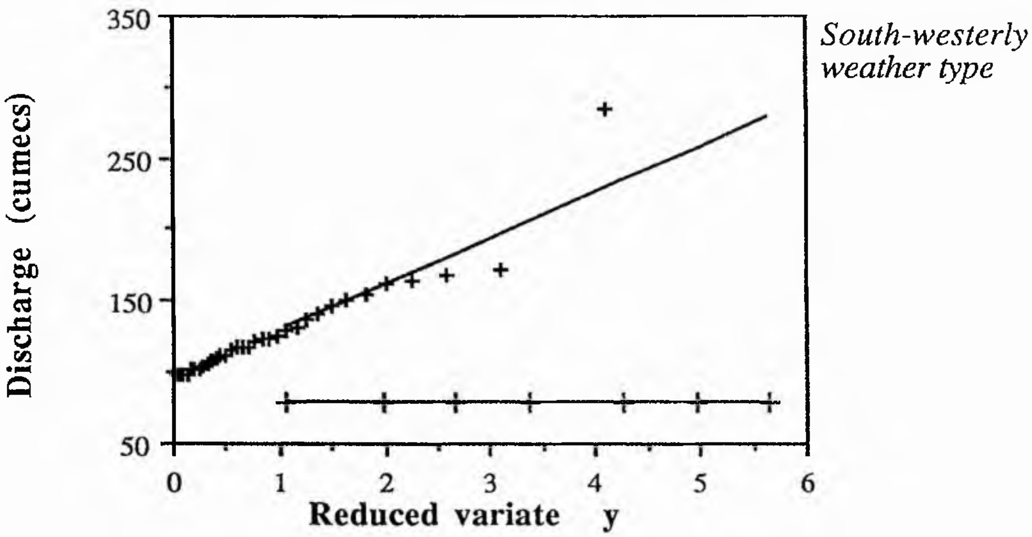


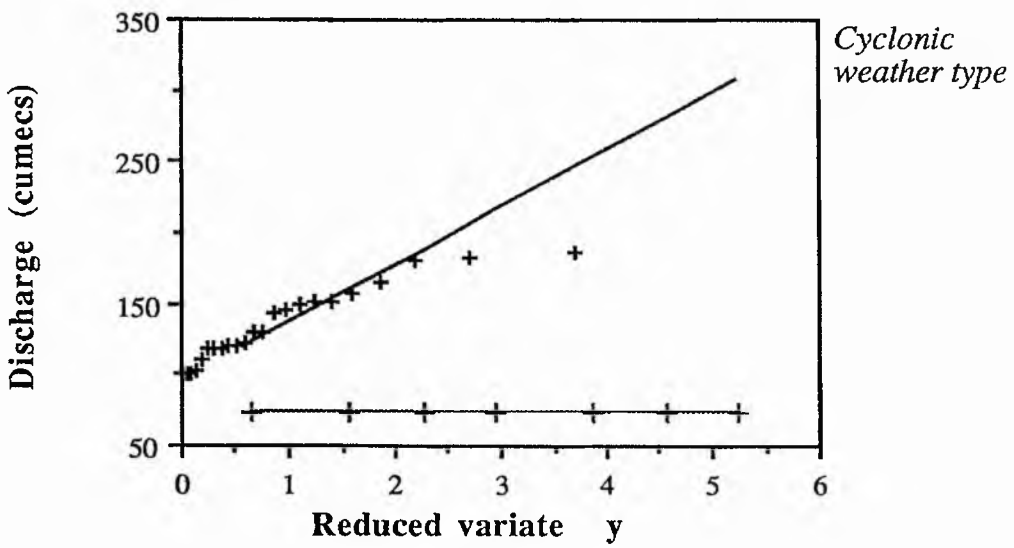
South-westerly weather type



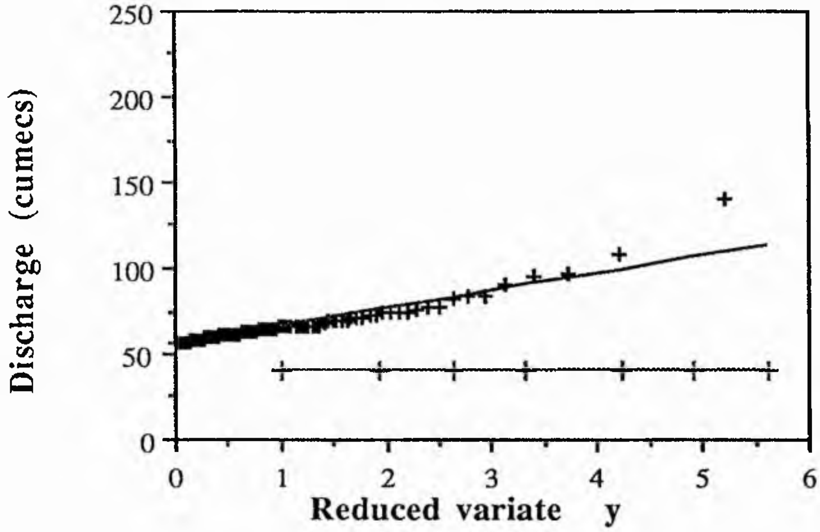
Cyclonic weather type

81003 Luce @ Airyhemming

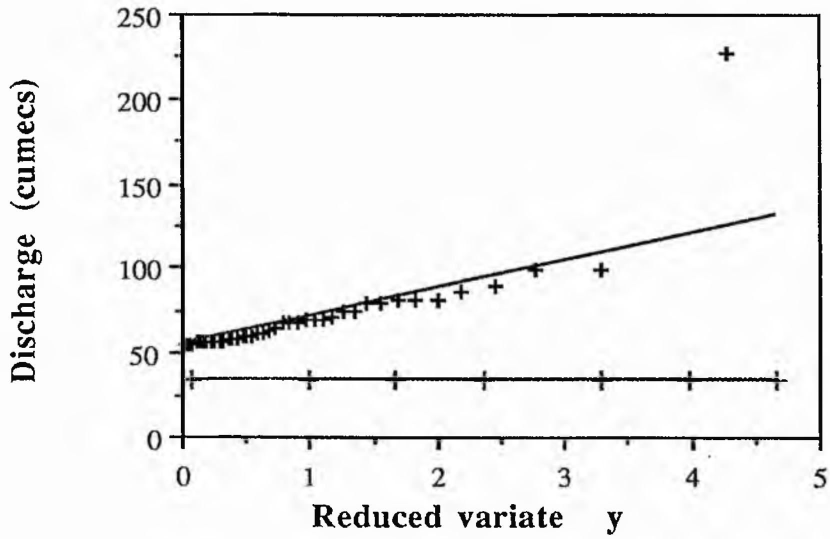




83802 Irvine @ Glenfield

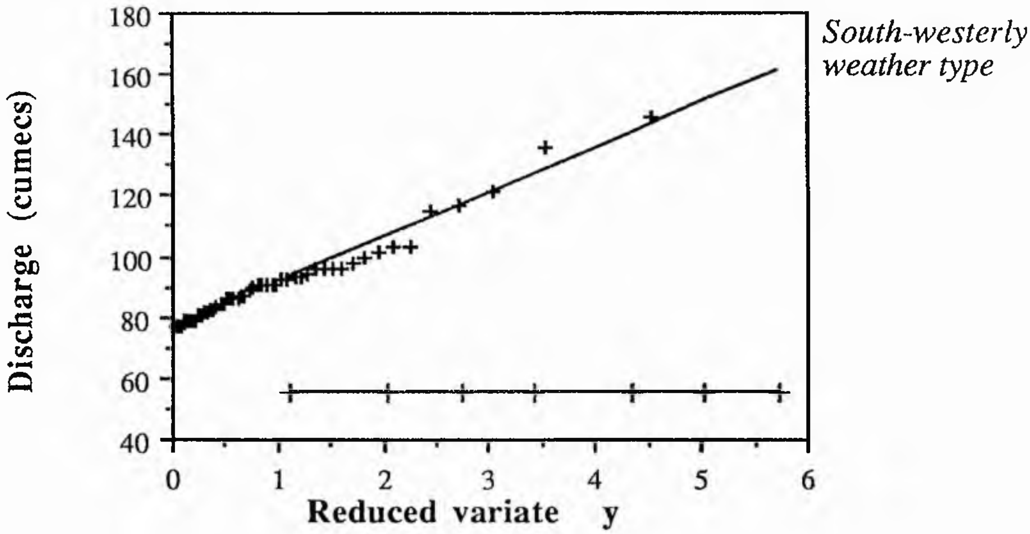


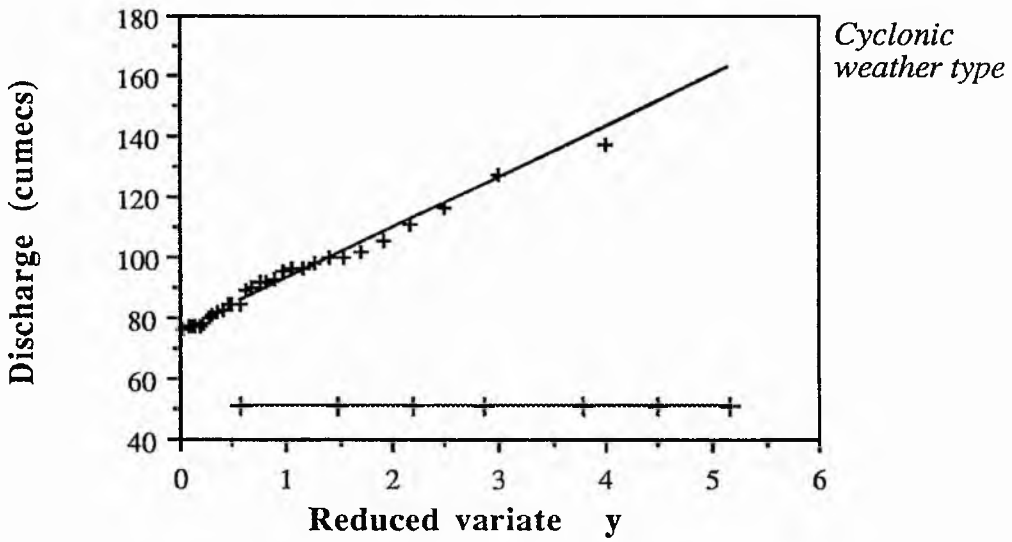
South-westerly weather type



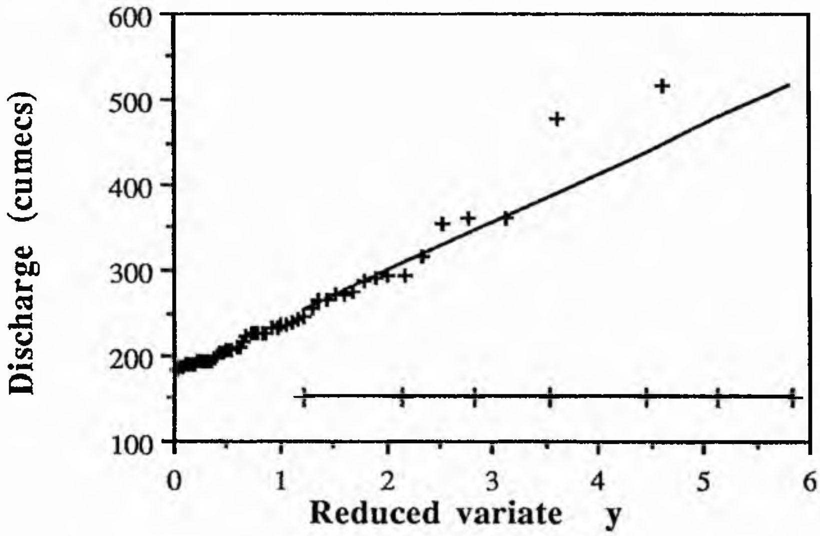
Cyclonic weather type

84001 Kelvin @ Killermont

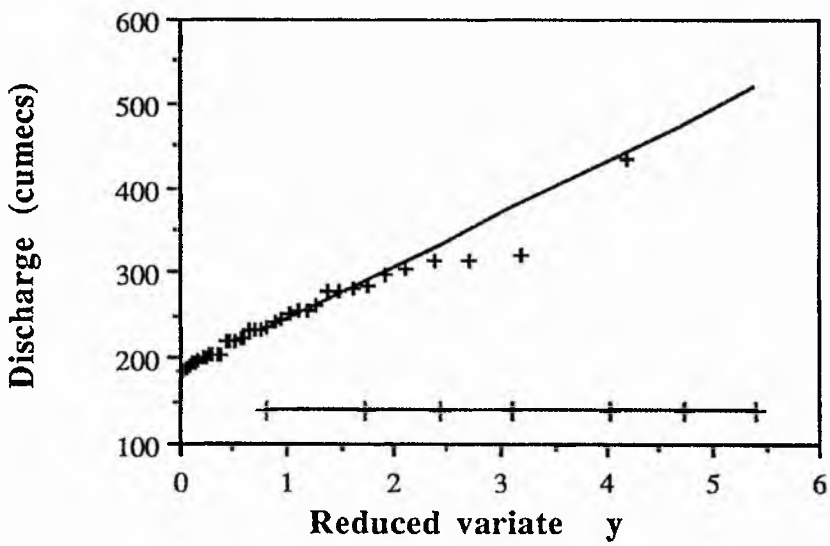




84003 Clyde @ Hazelbank

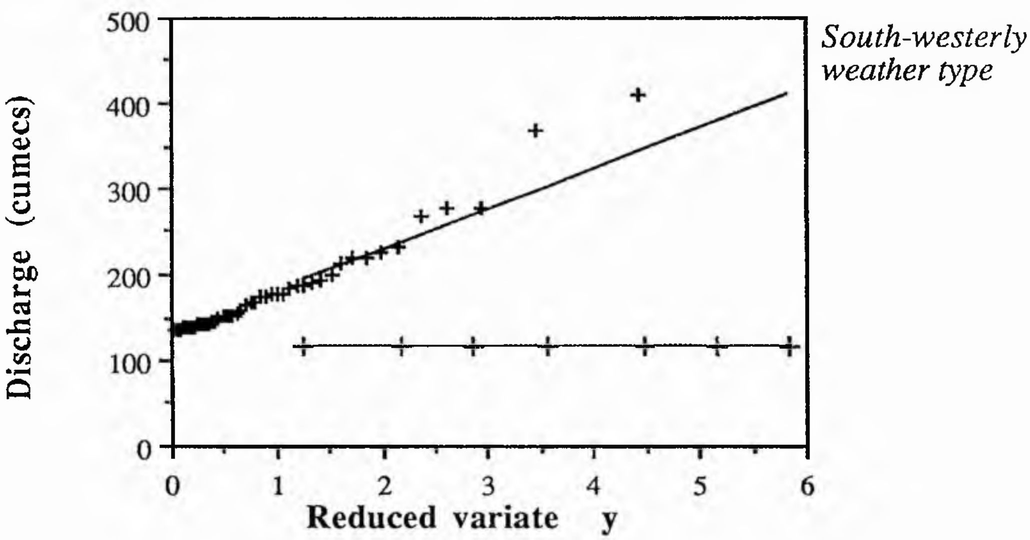


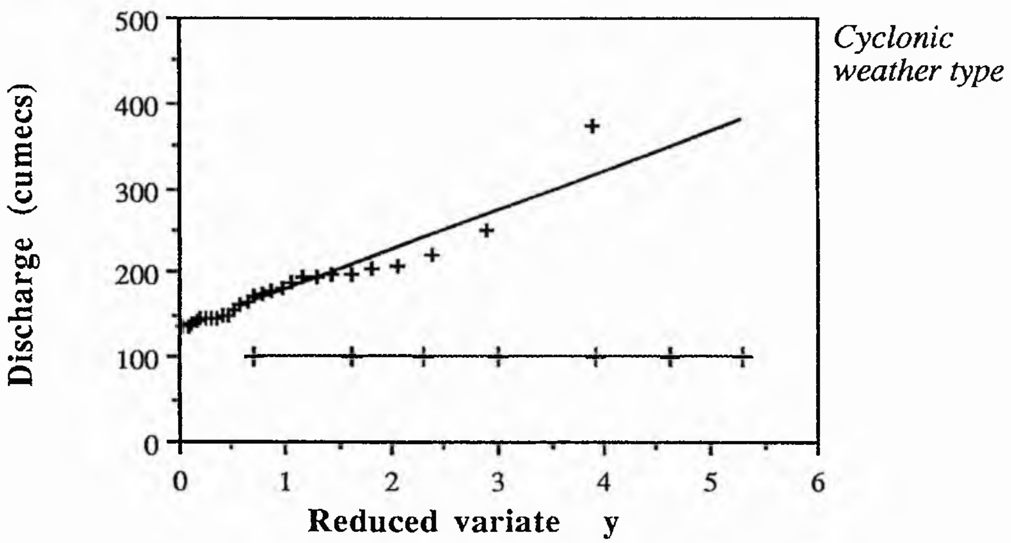
South-westerly weather type



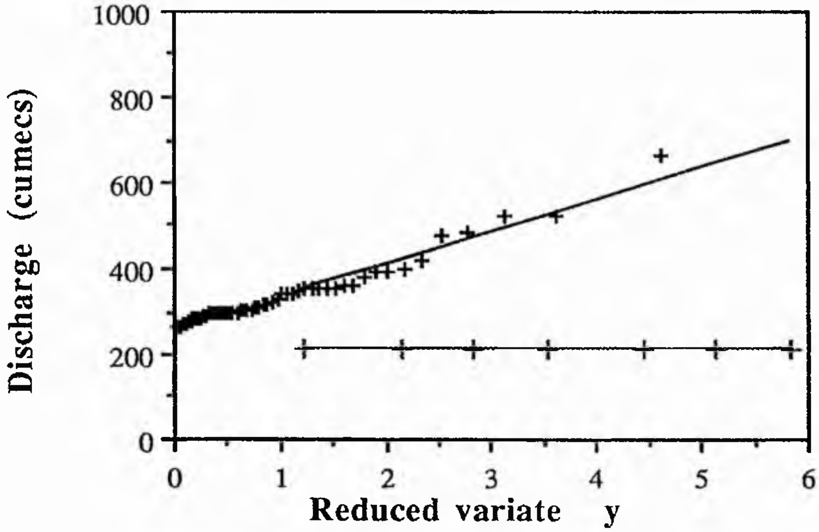
Cyclonic weather type

84004 Clyde @ Sills of Clyde

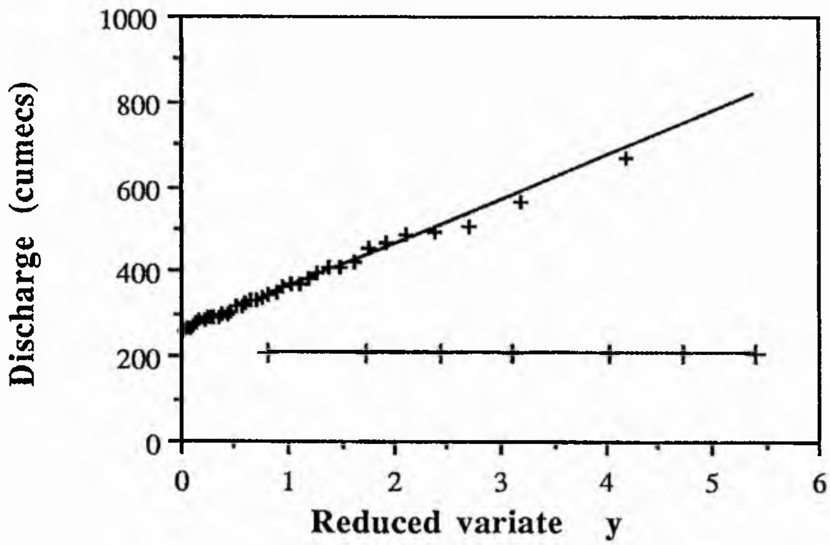




84005 Clyde @ Blairston

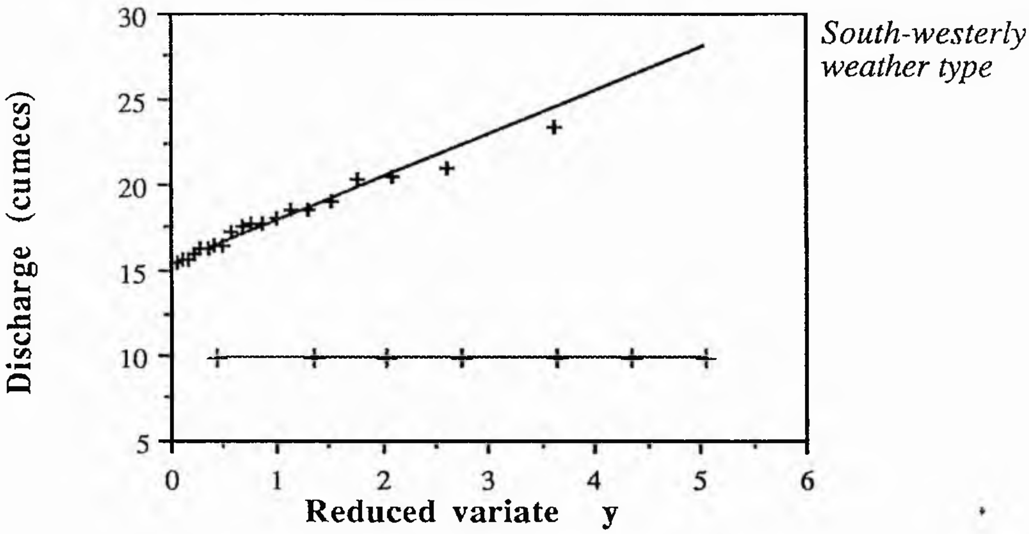


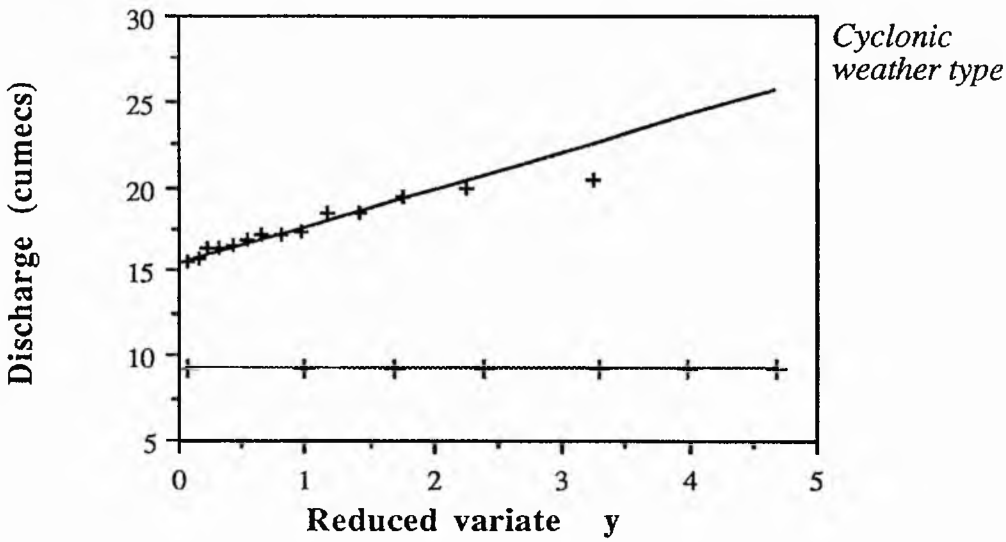
South-westerly weather type



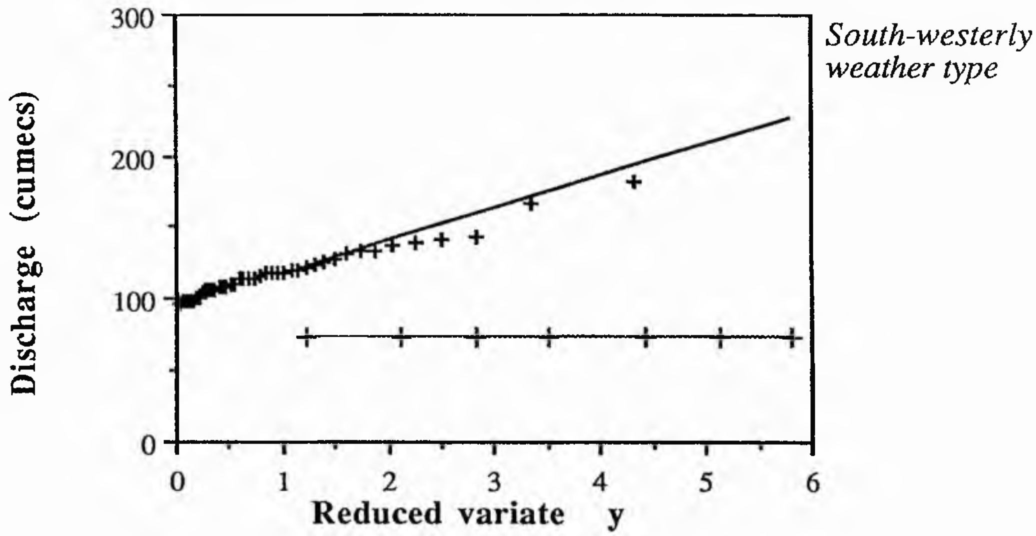
Cyclonic weather type

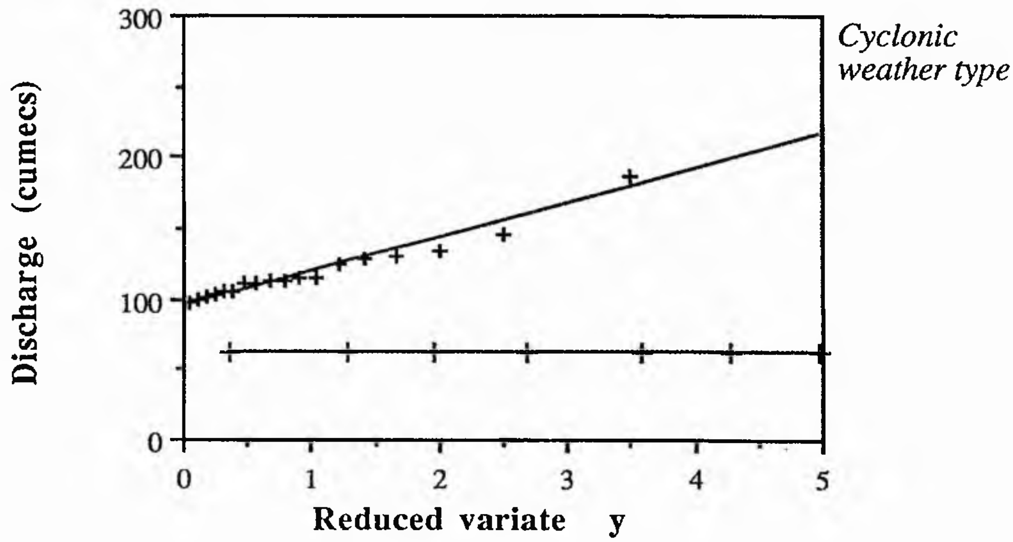
84006 Kelvin @ Bridgend



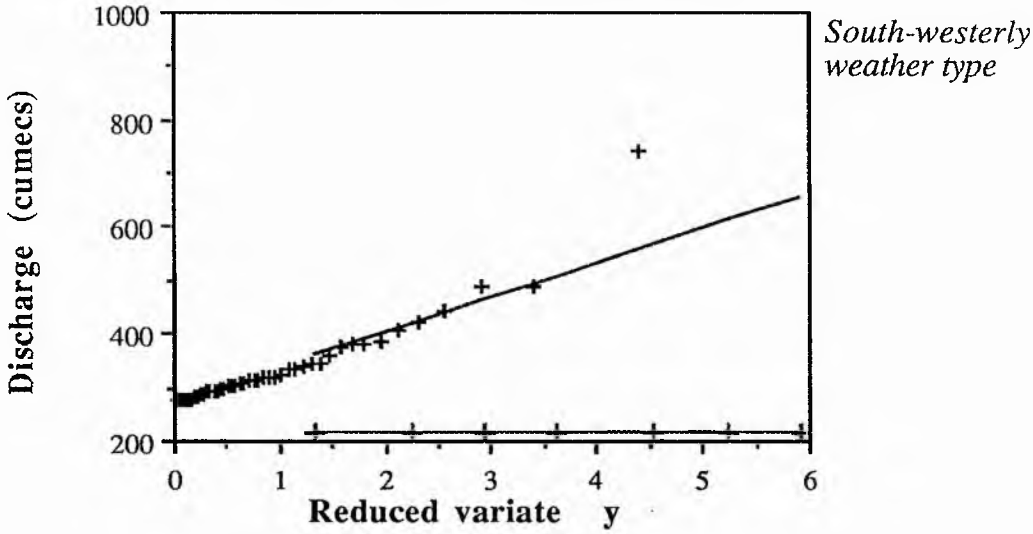


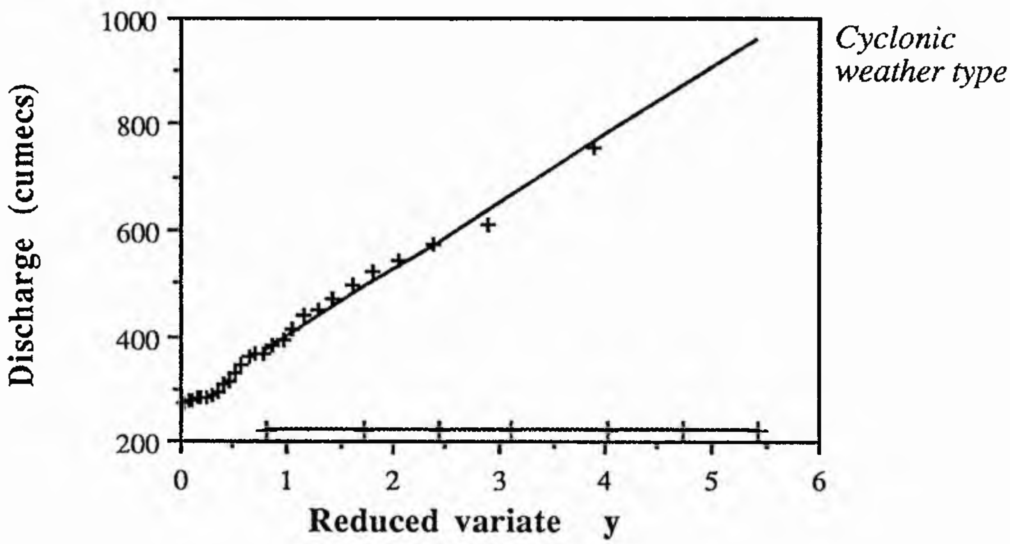
84012 White Cart Water @ Hawkhead



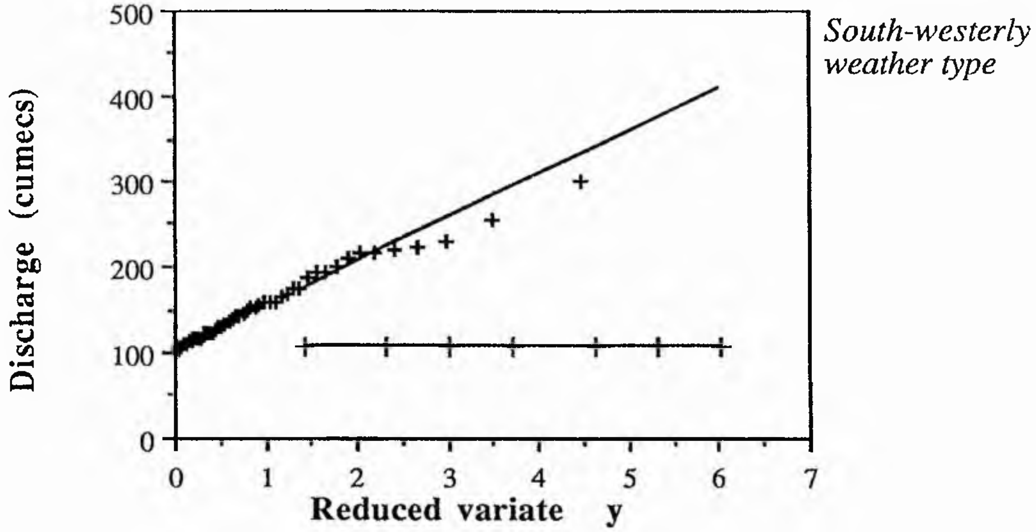


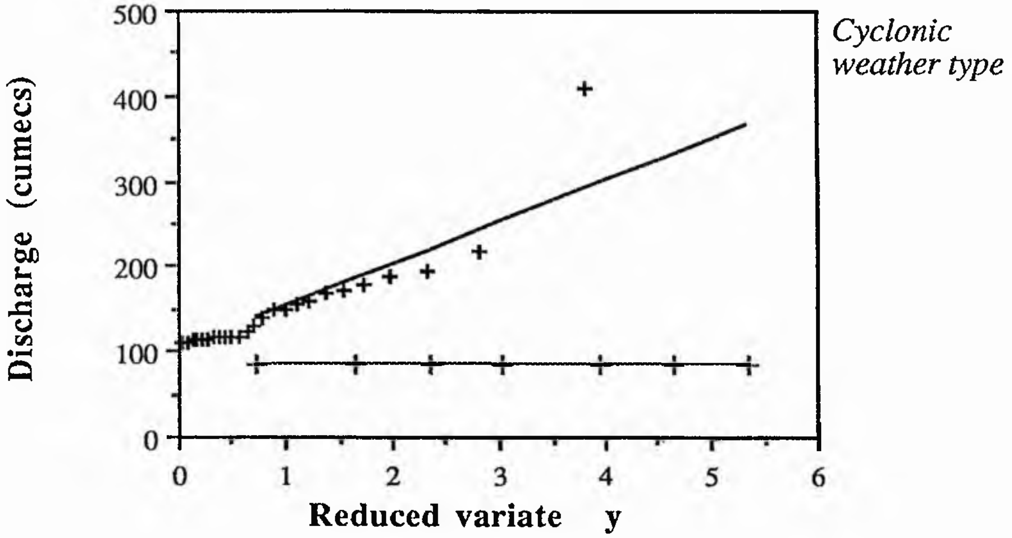
84013 Clyde @ Daldowie



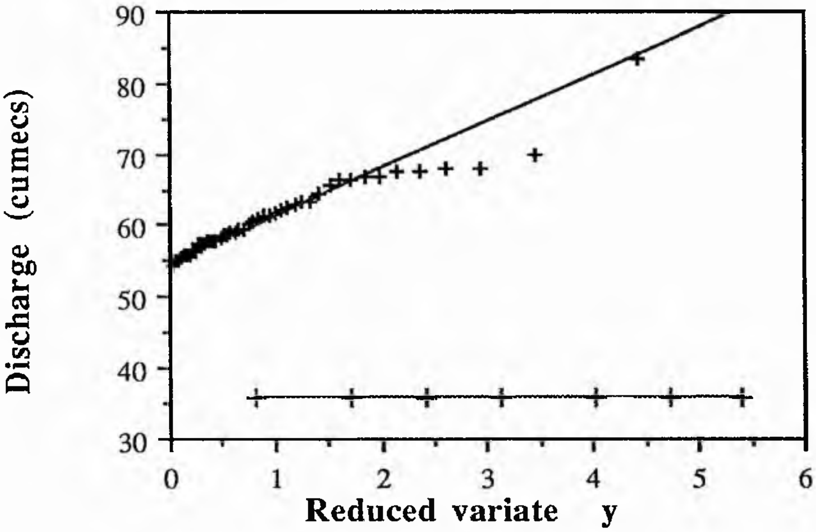


84014 Avon Water @ Fairholm

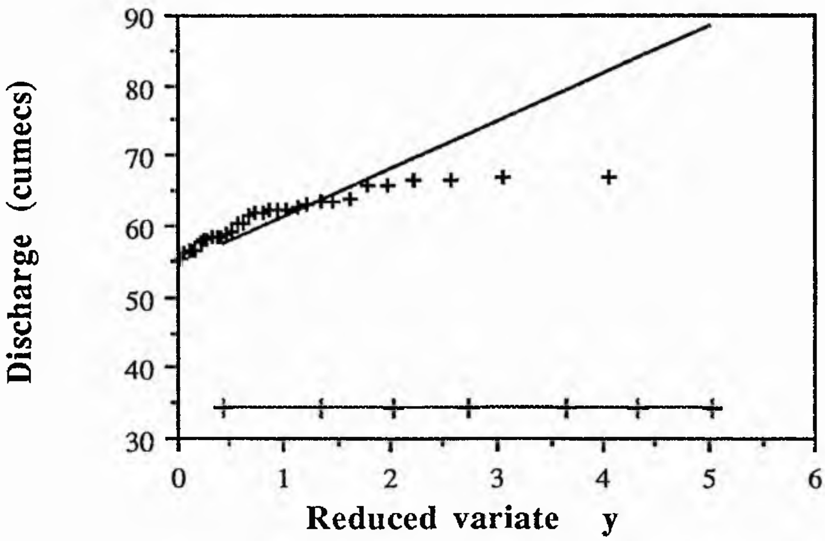




84015 Kelvin @ Dryfield

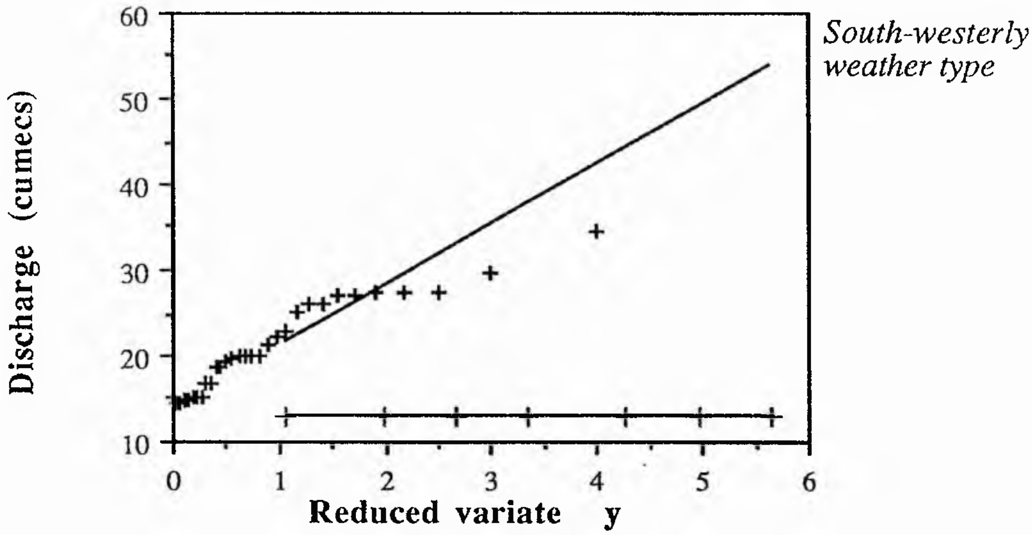


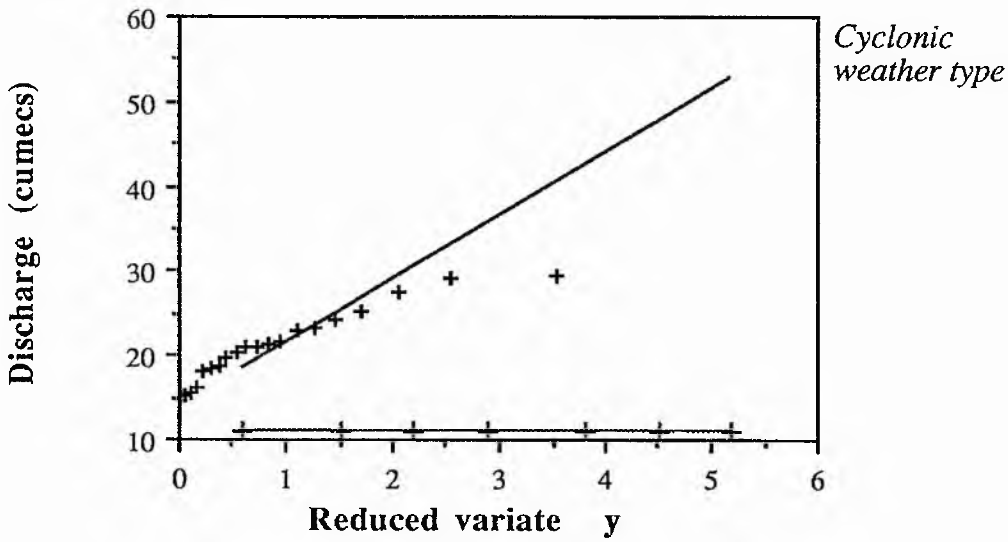
South-westerly weather type



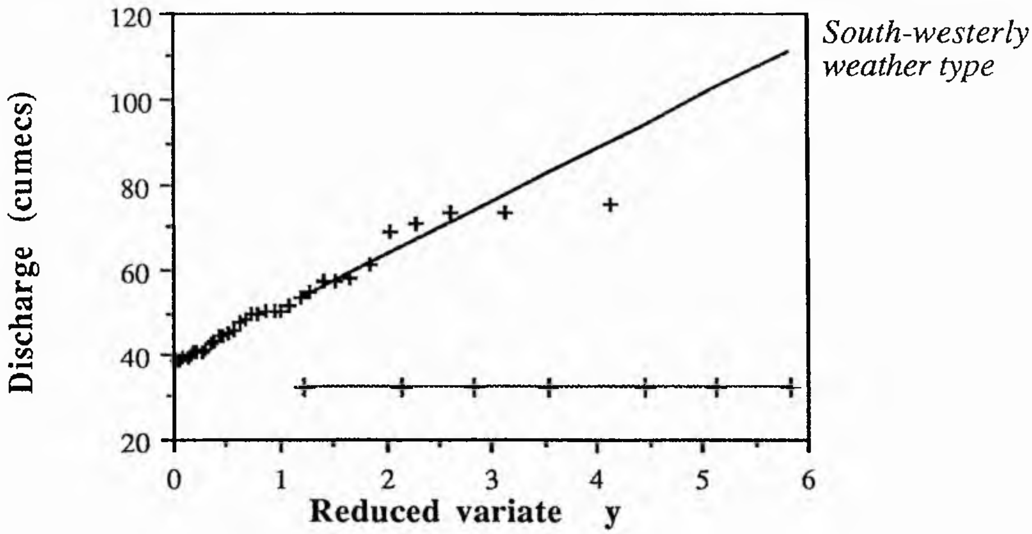
Cyclonic weather type

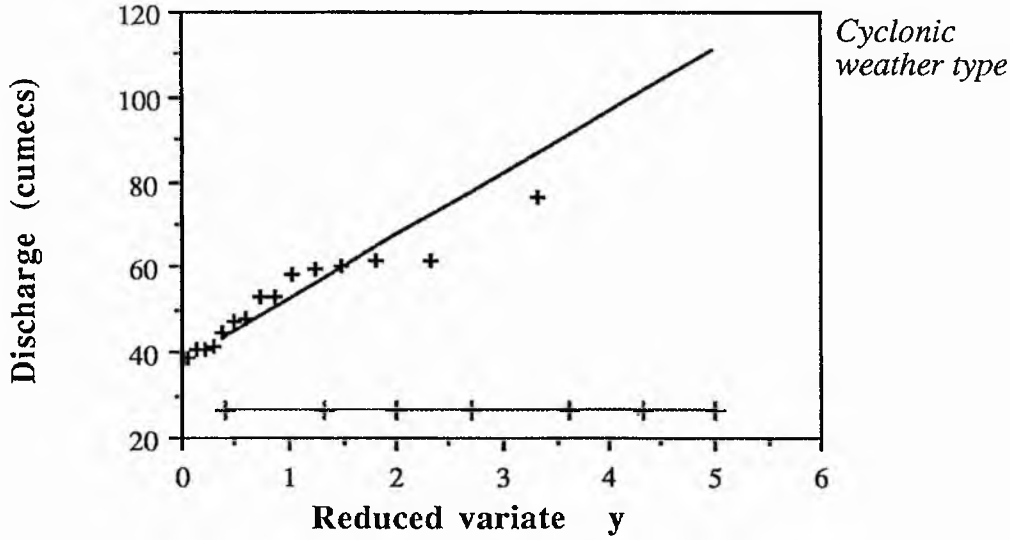
84016 Luggie Water @ Condorrat



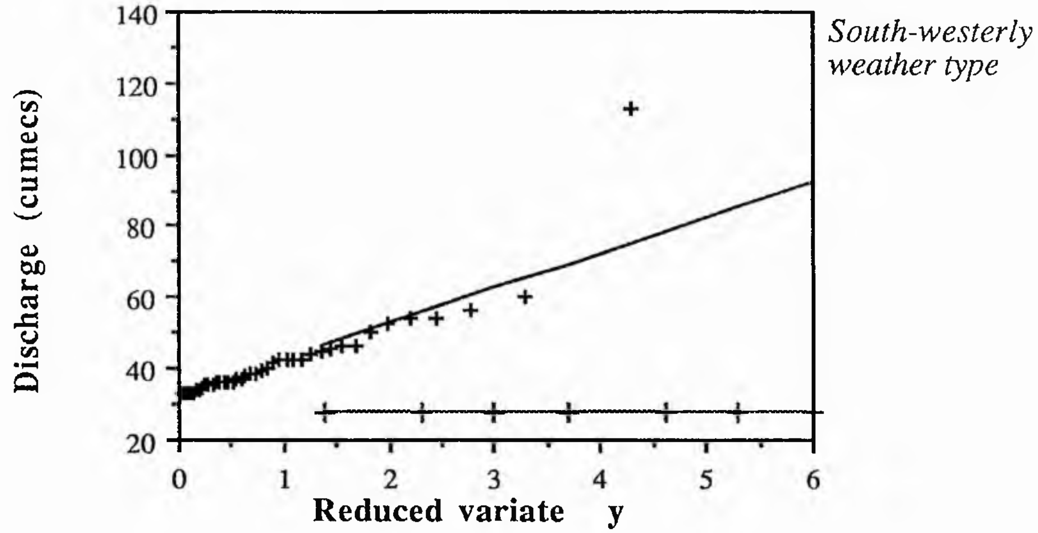


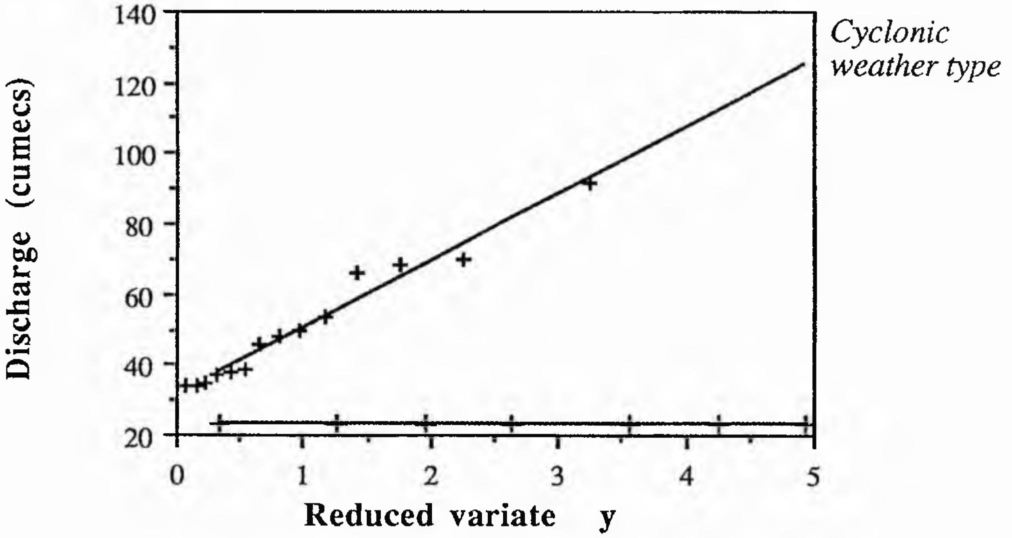
84020 Glazert Water @ Milton of Campsie



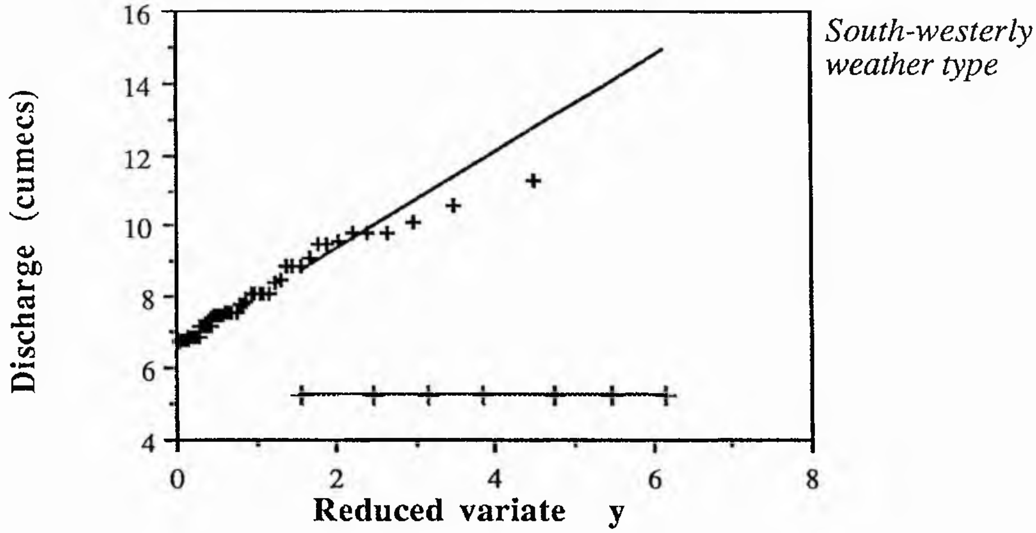


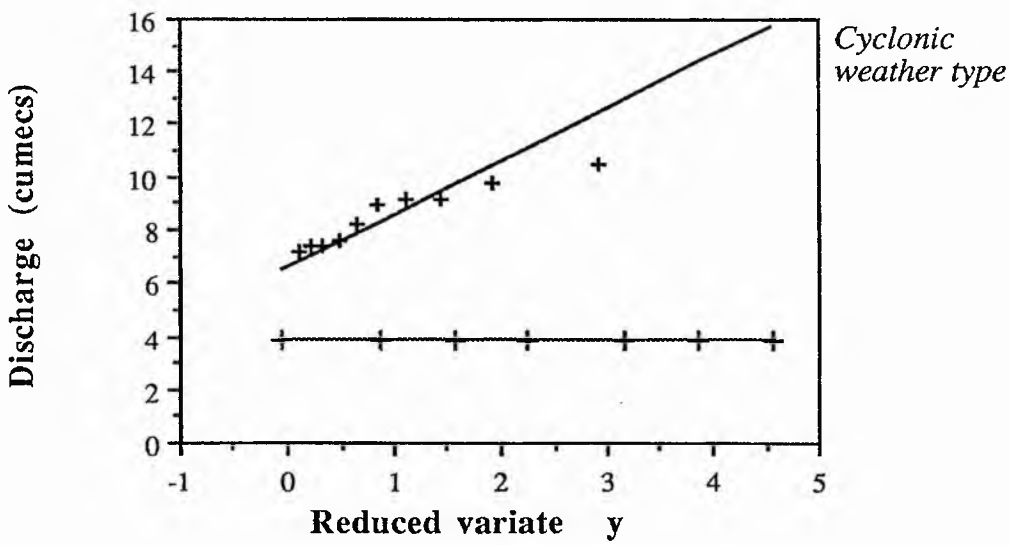
86001 Little Eachaig @ Dalinlongart

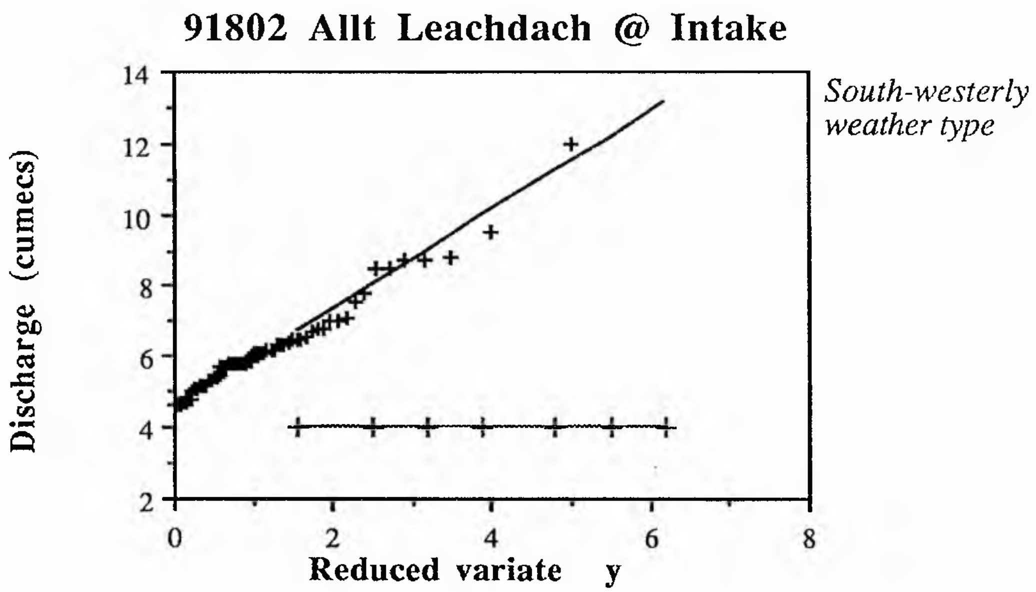




87801 Allt Uaine @ Loch Sloy Intake







91802 Allt Leachdach @ Intake
14
12
10
8
6
4
2
0
2
4
6
8
Discharge (cumecs)
Reduced variate y
South-westerly weather type