TEMPORAL VARIABILITY OF FLOODING IN SCOTTISH RIVERS

Helen Louise Grew

A Thesis Submitted for the Degree of PhD
at the
University of St Andrews

1997

TEMPORAL VARIABILITY OF FLOODING IN SCOTTISH RIVERS

Volume One

HELEN LOUISE GREW

A thesis submitted for the Degree of Doctor of Philosophy at the University of St Andrews

Department of Geography
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February 1996

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I, Helen Louise Grew, hereby certify that this thesis, which is approximately 52,000 words in length, has been written by me, that is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

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ABSTRACT

Over fifty peaks-over-threshold flood records from across Scotland are analysed for temporal and spatial variability over two standard periods, 1954-92 and 1964-1992, using a number of time series statistical techniques.

The results of this analysis demonstrate both clear temporal and spatial patterns in the frequency and magnitude of floods. The period 1964-73 is characterised by decreasing flood frequencies, with the early 1970s standing out as being "flood poor", particularly in the eastern regions of Scotland, whilst the 1950s and more recently, the late 1980s and early 1990s can be characterised as "flood rich". A broadly similar pattern is evident in many flood magnitude series.

The influence of climatic variability upon flood records is also examined over the same periods of time, using a regional synoptic classification of daily weather types. The Westerly, Cyclonic and South-Westerly weather types are identified as important mechanisms in initiating Scottish flood events. These weather types also show a strong link with catchment location, with the Westerly type being important in the more westerly catchments, the South-Westerly type being important in the south-west and west whilst flood events in the more eastern catchments are often associated with the incidence of the Cyclonic weather type.

The annual frequencies of these three key weather types also show clear patterns of temporal variability. However, a seasonal split of weather type frequencies also reveals some contrasting seasonal trends which are masked within the amalgamated annual series. The most dramatic variability is evident within the time series of the South-Westerly weather type, where frequencies have been increasing steadily since the mid 1970s in all seasons. Recent increases in the incidence of the most frequently occurring weather type - the Westerly - appear to be confined to the winter months (December to February).

The relationship between temporal variability within flood series and the climate are tentatively explored through a simple comparison exercise using the two sets of time series plots, linked by information obtained on trigger weather types and dominant seasons of flooding. This process suggests that the relationship between flood series and the climate is a complex one which cannot be adequately explained using the results of this research. More likely other factors, such as precipitation variability, need to be introduced into the equation before a more complete picture is acquired.

The possible consequences of the variability detected within flood series are highlighted with reference to flood frequency analysis, a technique which makes the assumption that flood records, and ultimately climatic records, are stationary through time. By splitting individual flood records into hydrologically similar sub-periods, it is revealed that frequency-magnitude relationships may vary considerably, depending upon the period of record used. It is recommended that, in future, hydrologists consider splitting flood series (into hydrologically similar sub-periods or in terms of the weather types linked to each flood) in order to examine the range of frequency-magnitude relationships which exist.

ACKNOWLEDGEMENTS

This PhD would not be here today but for the help and guidance given to me by a number of people. I am extremely grateful to you all. A number of individuals also deserve a special mention for the time that they have given me.

Thanks must first go to my two project supervisors, Professor Alan Werritty and Dr Andrew Black (both now at the University of Dundee) who combined excellent supervision and technical advice with continued encouragement and support throughout the past three years.

The Natural Environment Research Council are thanked for providing funding for this research project.

A number of individuals and organisations were also involved with specific aspects of this project. The staff of the seven River Purification Boards provided (much needed) guidance during the data collection process. I am also extremely grateful to Dr Julian Mayes (Roehampton Institute) who allowed access to his weather type database, from which this project greatly benefited. Similarly, the Climate Research Unit at the University of East Anglia, who provided the Lamb database, Campbell MacDonald at Scottish Hydro-Electric and the Institute of Hydrology, who allowed access to the World Meteorological Organisation Time Series Program, are all thanked.

Members of staff and fellow postgraduates from the Geography Department at St Andrews have also given help and advice in many different areas. Stuart Allison, Donald Herd, Kath Leys, Jeff Lord, Hamish Ross, Elisabeth Saiu and Simon Wathen all deserve a special mention.

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CHAPTER ONE

INTRODUCTION

Since the late 1980s, there has been growing concern that flood events in Scotland are becoming more frequent and greater in magnitude. This follows some extreme flood events on a number of rivers throughout Scotland, including the Conon (1989), Tay (1990 and 1993) and more recently the Kelvin (1994). Evidence from a number of other sources suggest that during this recent period, Scottish precipitation totals have reached levels not previously recorded, particularly in the west of Scotland (Curran and Robertson, 1991; Smith, 1995).

The aim of this study is to determine how flood characteristics, notably their frequencies and magnitudes, have varied through time, and whether those events recorded in recent years have been unusually extreme. It is foreseen that this study will concentrate on the period from the 1950s onwards, since flow data are limited prior to this period.

The implications of temporal variability within these flood series will also be explored, with reference to techniques of flood frequency analysis. Flood frequency analysis is a technique widely used to estimate the relationship between flood frequencies and magnitudes and to provide information useful in the design of structures within the floodplain. However, these frequency-magnitude relationships are estimated from the past record of flood events and the underlying assumption is that the flood record, and ultimately the climatic record, are stationary through time. The examination of Scottish flood series may reveal that this assumption is untrue and the effect of such variability will, therefore, be addressed with reference to flood frequency analysis.

Recent research carried out into Scottish precipitation records has suggested that whilst rainfall totals in the north and west has increased in recent years, totals in the east of Scotland have been decreasing (Arnell et al, 1990). If such a phenomenon is occurring, it is likely that there will be some repercussions in the Scottish flood series.

It is hoped, therefore, that spatial variability in flood characteristics will also be explored in addition to the detection of temporal variability.

If any variability, temporal or spatial, is detected within Scottish flood records, the question arises of what is actually causing this variability. Since flood events in Scotland are ultimately linked to extreme climatic events (rainfall, snowmelt or a combination of both), there is likely to be some relationship between flood series and climatic records. An additional aim in this project is, therefore, to examine variability within series depicting the climate of Scotland and to examine the nature of any relationship which exists between flood and climatic series.

Flooding is a common and largely natural environmental process which affects both coastal reaches and river systems. Whilst coastal flooding is a serious threat to the British Isles (Smith, 1992), riverine flood events are also a common phenomenon, particularly in Scotland. For the purpose of this project, the term ‘flood’ will apply to riverine events only. Such a peak flow event is simply the response of a river to an extreme input of water into the system. In Scotland this input may result from an extreme rainfall or snowmelt event, or a combination of both (Ward and Robinson, 1990). As a result of the extreme precipitation (rain and snow), some of the most extreme peak river flows experienced in the British Isles have been recorded on Scottish river systems. The maximum flow ever gauged, 2410 m^3s^{-1}, (NERC, 1993) was in fact recorded on the River Findhorn at Forres (Station number 07002) in August 1970. Although widespread gauging of Scottish river flows only began in the 1950s and 1960s (Lees, 1985), documentary evidence exists on a number of major flood events in the nineteenth and early twentieth centuries (Lauder, 1830; Reid, 1882; Nairne, 1895 etc.). However, past research into Scottish flood events has been fairly limited, partly as a reflection of the restricted length of available flow records.

Unfortunately, there is no clear-cut, universally accepted definition of a riverine flood since the term often has different meanings to different researcher (hydrologists, fluvial geomorphologists, engineers etc.). A common definition states that a flood is ‘a high flow of water which overtops either the natural or artificial banks of a river’

(Smith, 1992) and whilst this is useful for general descriptive purposes, a more robust definition is required for hydrological research. Typically, hydrologists use one of two techniques (either the Annual Maximum or Peaks-over-threshold) to create a flood series (Section 3.2.3). The 'peaks-over-threshold' technique involves setting a fixed flow discharge for any site where river flow is gauged and any independent flow event which exceeds this discharge is thus classified as a flood event. For a number of reasons (Section 3.2.3), this approach to flood database creation was favoured over the Annual Maximum.

To recap, therefore, the key aims of this project are:

- to detect and describe the level of variability within Scottish flood records, with regard to year-to-year changes in the frequencies and magnitudes of such events;
- to detect and describe any variability evident within Scottish climate records;
- to tentatively examine the nature of any links between climate and flood series;
- to examine the possible effects of variability with flood records upon standard techniques of flood frequency analysis.

These aims will be addressed individually, with the thesis following the format stated below.

Chapter Two will provide an introduction into the nature of riverine flooding in Scotland and a review of the associated areas of research (notably the climatic characteristics of Scotland, variability with runoff and climatic records and flood frequency analysis).

Chapter Three identifies the two sources of data chosen to fulfil the project aims, and describes the processes involved in the collection of these databases and the raw data manipulation required prior to analysis.

Chapter Four reviews the statistical techniques (within the field of time series analysis) available for the analysis of hydrological and climatic time series, with respect to detecting temporal and spatial variability within seasonal and annual indices.

Chapter Five documents the lengthy process of detecting, describing and explaining any temporal and spatial variability evident within a group of Scottish flood records.

Similarly, **chapter Six** recounts the detection, description and explanation of the temporal variability evident within climatic records, on both an annual and seasonal basis. This information is then combined with the analysis carried out in Chapter Five to explore the possible links which may exist between flood and climate time series.

Chapter Seven then examines the effect of any variability detected within these series upon the techniques current in use for flood frequency analysis. The second half of this chapter then documents any additional issues raised during the process of this research project and discusses possible research goals for the future.

Finally, **chapter Eight** acts as a concluding statement, by summarising the findings of chapters five, six and seven, and by evaluating the success of the project, in terms of examining how well the original research objectives have been fulfilled.

CHAPTER TWO

THE CLIMATIC AND HYDROLOGICAL ENVIRONMENT OF SCOTLAND

An introduction into the nature of riverine flooding in Scotland and a review of the associated areas of research

2.1 INTRODUCTION

The aim of this chapter is to provide an insight into the subject areas fundamental to this project, namely the hydrology and climatology of Scotland. This introduction will explore the physical environment of the study area in combination with a more detailed examination of these core topics, which will be explored by reviewing and evaluating previous literature and research in these areas.

Two major topics can be identified within this review:

- the characteristics of the Scottish flood record are of primary concern; emphasis will be placed upon understanding the causes of flooding in Scotland and the possible techniques for detecting variability within flood indices; the techniques of flood frequency analysis and the effect of variability upon such techniques will also be introduced;
- the second factor to be introduced is the climate of Scotland; a general introduction to climatic characteristics will be provided and the nature of climatic variability will be explored.

Although this review will initially deal with these topics separately, the nature of any links between the two subject areas will be explored in the concluding sections.

2.2 THE PHYSICAL ENVIRONMENT OF SCOTLAND

Any research project which aims to examine one or more aspects of the physical environment will inevitably incorporate a number of other factors into the discussion, either directly or indirectly. A study of flooding in Scotland, for example, cannot be undertaken without some knowledge of the characteristics of Scottish rivers and their catchments which, in turn, brings other environmental factors (topography, geology, climate, soil types, land use characteristics, for example) into the discussion. However, because a large proportion of Scottish catchments are included in this project, it is not possible to describe the physical characteristics of individual river systems in any great detail. Rather, a more generalised approach will be taken in combination with more detailed references where relevant.

2.2.1 TOPOGRAPHY AND GEOLOGY

Relief in Scotland is highly variable with a number of diverse topographic environments, ranging from the Highlands in the north and Southern Uplands in the south, to the Central Lowlands. The high ground in the north of Scotland is typically recognised as comprising the north-west Highlands, the Grampian Highlands and the Cairngorms (Map 2.1).

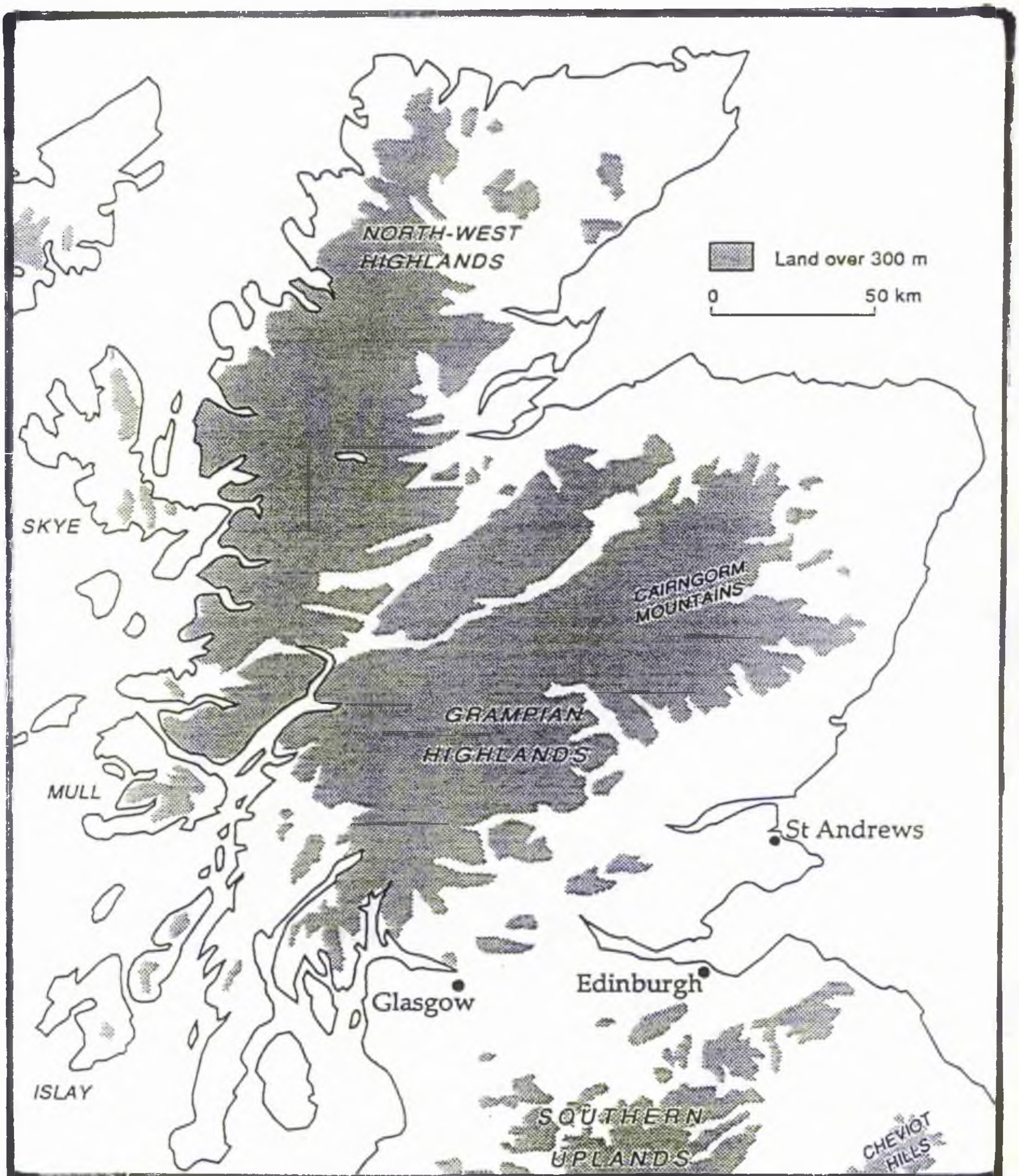
In many cases this topography can be directly related to the bedrock geology of Scotland. The low-lying ground and hilly regions of the Central Lowlands, for example, correspond to erodable sedimentary and resistant igneous rock respectively. The Southern Uplands, comprised of Silurian and Ordovician sedimentary rocks, form low, rounded hills with steep, narrow headwater valleys in contrast to the higher, rugged relief of the dominantly igneous Highlands (Sissons, 1976).

2.2.2 CLIMATE

Scotland is situated in the temperate mid-latitudes, a zone of prevailing Westerlies which extends from 30°-60° north and south of the equator. The pressure pattern within the north Atlantic area is dominated by the Azores High and the Icelandic low throughout the year, although the location and intensity of either can vary seasonally. Although frontal activity is obviously important within this zone (it constitutes a meeting point for polar and tropical air), the climate of Scotland may also be affected by coastal influences (File, 1990).

The daily weather being experienced in Scotland is largely affected by the properties of the air masses which are passing over the country. Three types of air mass

Map 2.1: Upland areas of Scotland



dominate the weather of Scotland and the British Isles: maritime tropical (mT), maritime polar (mP) and continental polar (cP), and the resultant weather conditions are very much dependent upon the properties of these air masses (Barry and Chorley, 1987).

A number of different variables are needed to characterise adequately the climate of Scotland. Tabony (1994) describes variability within the climate of Scotland in the last one hundred years (up to 1992) with respect to rainfall, temperature, snowfall, sunshine and wind:

- recent rainfall totals in the west are without precedent; total rainfall received in the five years 1988-92 are 50% above the long term average;
- there is no sign of a warming trend evident in the temperature series from Braemar;
- the six years 1987-92 had below average snowfalls (longest spell on record);
- a recent run of low sunshine totals is evident (1977 is the last year with above average values);
- there is no evidence of any change in the index of windiness.

In terms of this specific investigation, emphasis need only be placed upon the key variable, precipitation (rainfall and snowfall). Although other climatic factors, such as air temperature, wind speed and wind direction, can contribute to the flood generation process, largely by triggering snow and ice melt events, their importance is often localised and intermittent, and rather difficult to define in practice.

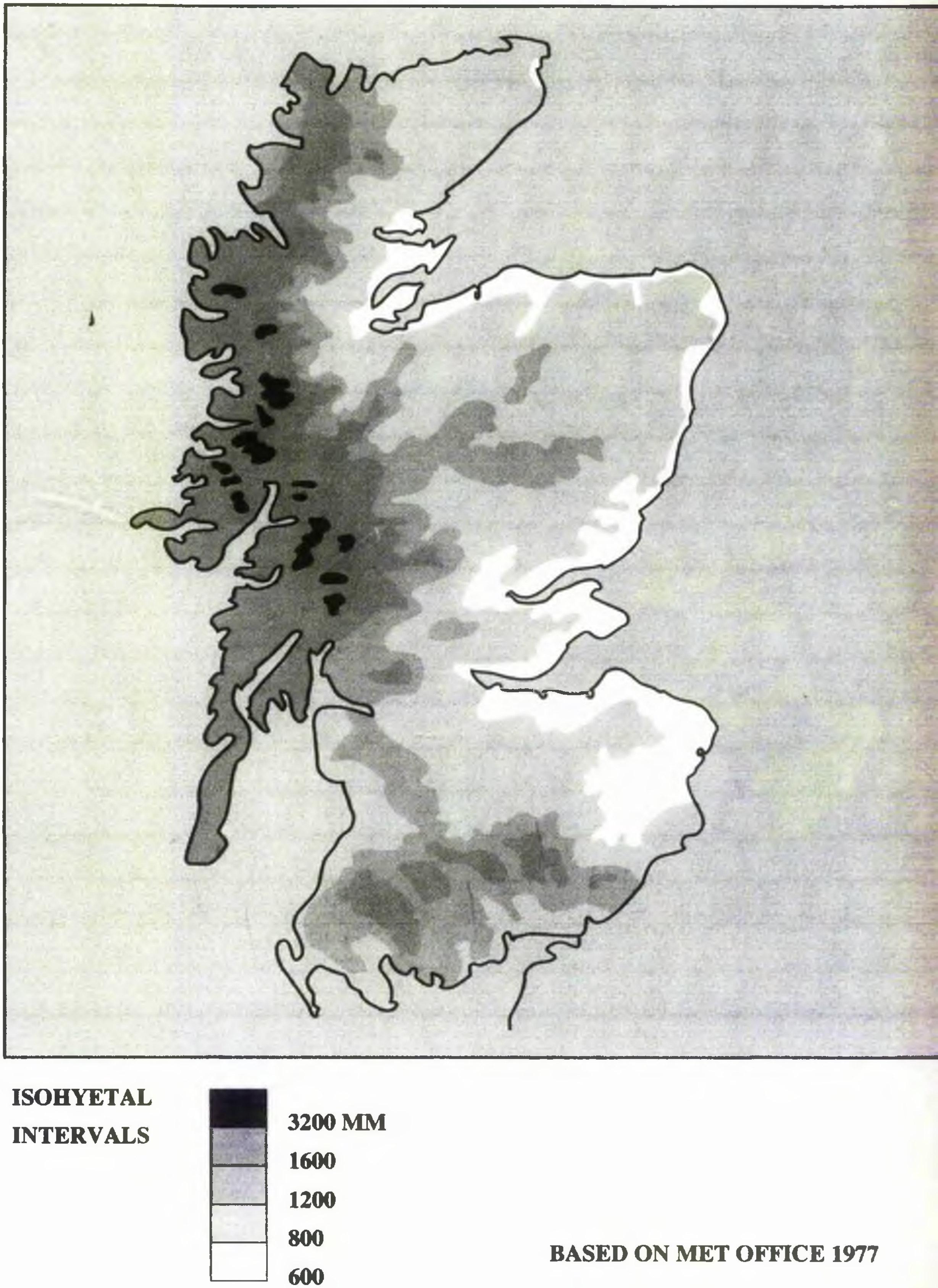
A distinction can be made between the types of precipitation that fall in Scotland. Convective precipitation, in the form of localised short duration, high intensity falls, is a result of strong heating of the land surface. Such falls are often confined to the summer months (Barry and Chorley, 1987). A minority of floods in Scotland are caused by convectional storms but unfortunately the characteristics of the precipitation (high intensity, short duration, localised) ensures that such events are often poorly gauged (Werritty and Acreman, 1984). If the location of the storm, however, coincides with a small drainage basin, one often sees some dramatic runoff events with a potentially high geomorphic impact (McEwen and Werritty, 1988).

Cyclonic precipitation can be classified as non-frontal or frontal. Non-frontal precipitation, which is generally long duration, moderate intensity, is a consequence of convergence and uplift of air within a low pressure system. Frontal precipitation occurs where warm moist air rises above cold air at the boundary between two air masses. A cold front, where warm air is being replaced by a colder air mass, is characterised by a steep frontal surface. This causes rapid lifting of the warm air and short duration, heavy precipitation results. Conversely a warm front, associated with a gentle frontal slope, causes less intense precipitation but of longer duration (Ward and Robinson, 1990). In the British Isles more than 60% of the annual rainfall is related to cyclones and their associated features (Shaw, 1988). Depressions in the summer months are less intense and are associated with weaker fronts. Cyclonic precipitation is therefore greatly reduced in summer (Barry and Chorley, 1987).

The third type of precipitation mechanism evident in Scotland is the lifting of moist air over mountain barriers. Orographic effects increase the frequency and intensity of precipitation, with the greater totals falling on the windward side of slopes whilst the leeward side remains in a rainshadow (Ward and Robinson, 1990). This mechanism is particularly important in the north and west of Scotland where high ground is a major feature of the landscape, although the quantitative effects of orographically enhanced rainfall does depend upon flow direction (Weston and Roy, 1994).

Generally speaking, the highest precipitation totals are recorded in the north and west of Scotland with a gradual decline in values as one moves across the country in an easterly direction. Mean annual precipitation totals in the west can reach four to five times the total experienced in the east (Map 2.2). This pattern is primarily a reflection of the Westerly airflows which dominate the climate of Scotland, but it is a pattern which is further enhanced by orographic effects. The probability that these rain-bearing westerly airflows will produce precipitation obviously decreases as one moves in across Scotland in an easterly direction. Consequently, these airflows have shed

Map 2.2: Average annual Scottish rainfall 1941-1970



much of their moisture as they descend in the lee of the mountain barrier into the more eastern regions, which are said to be in the 'rain-shadow'. Precipitation in the eastern regions of Scotland is often associated with slow-moving depressions situated in the North Sea (File, 1990). Consequently, it is not unusual for catchments in the north-west to record annual rainfall totals in excess of 3000mm whilst areas on the east coast often record values of less than 700mm (NERC, 1993). *The Flood Studies Report* (*FSR*, Volume II; NERC, 1975) provides accurate and detailed information on the return periods for precipitation events of given magnitudes and durations throughout Scotland.

Extreme precipitation events, falling as rainfall, are most commonly associated with initiating flood events. In Scotland, however, precipitation falling as snow can also play an important role in the flood generation process, if the melting of a snow or ice pack causes substantial runoff. The extent of snow cover and the possible effects of a rapid thaw can, in fact, have severe consequences in terms of flooding in Scotland (Manley, 1971).

Typically, snow fall in Scotland is often a result of cold moist air passing over from sub-Arctic or Arctic sources (Harrison, 1993). However, such falls and the subsequent snowcover are difficult to quantify. Rain gauges cannot typically differentiate between rain and snow (or sleet) and therefore the relative contribution that each type of precipitation makes to daily (or weekly) totals is not discernible. Similarly, the process of quantifying snowcover and assessing its water equivalent is complicated by the effects of slope, aspect, drifting and the physical properties of the snowpack itself such as age, compaction, temperature and layering (Ferguson, 1985). The question of melt rates is a further complicating factor with rates dependent upon the melt process involved (diurnal melting as a result of temperature changes and melting as a result of rain on snow). Unfortunately, techniques for accurately modelling snowmelt rates have yet to be produced, although the *Flood Studies Report* (Sections 7.1-7.6, Volume II, NERC, 1975) does address some of these problems by including a number of techniques for calculating return periods for maximum snow depths, densities of lying snow and estimates of rare snowmelt rates.

Such methods are, however, more suited to individual events than creating long-term snow cover records. The lack of any long-term data for Scotland means that temporal and spatial changes in the snowpack and the subsequent melt contributing to Scottish flood events cannot be properly assessed. The consequences of this are, however, limited since the aim of this research is to examine how variability within flood records relates to the synoptic climate, rather than individual rainfall or snowmelt components.

2.2.3 SCOTTISH RIVER SYSTEMS

The diversity of character (form, pattern and process) evident within Scottish river systems is a consequence of three factors, climate, geology and time (Werritty et al, 1994). Between 50% and 75% of the precipitation which falls annually in Scotland (Section 2.2.2) is converted to runoff and since there is a clear west-east precipitation gradient, one would expect the highest river discharges to be experienced in the west. The fact that this is not the case reflects the impact of the geological history of Scotland (in particular, geological events in the late Tertiary and the morphology of ice-streams during the Pleistocene) upon the current watershed. This watershed is asymmetrical, with short rivers flowing to the west (such as the Ewe and Inver) and much longer rivers flowing to the east (Spey, Dee etc.), although a more symmetrical pattern is evident in the far south (Maps 5.1-5.4).

2.2.4 LAND USE

The dominant land uses of a catchment are extremely important in understanding its response to precipitation since such features can affect infiltration, evaporation, runoff and hydrograph characteristics. However, land use is often highly variable within a catchment and very difficult to make generalised statements about. Across Scotland, contrasts in catchment land use are quite apparent with catchments in the north often dominated by forestry, moorland and rough grazing. In contrast, the more eastern catchments commonly involve pastoral or arable farming whilst catchments around Edinburgh and Glasgow are highly urbanised (NERC, 1993). Although changes in landuse cover within a catchment are likely to have some impact upon river flows, the effect will be localised and best dealt with by catchment studies. The impact of climatic variability is, however, more likely to have consequences upon flood series on a much wider scale.

2.3 FLOODING IN SCOTLAND

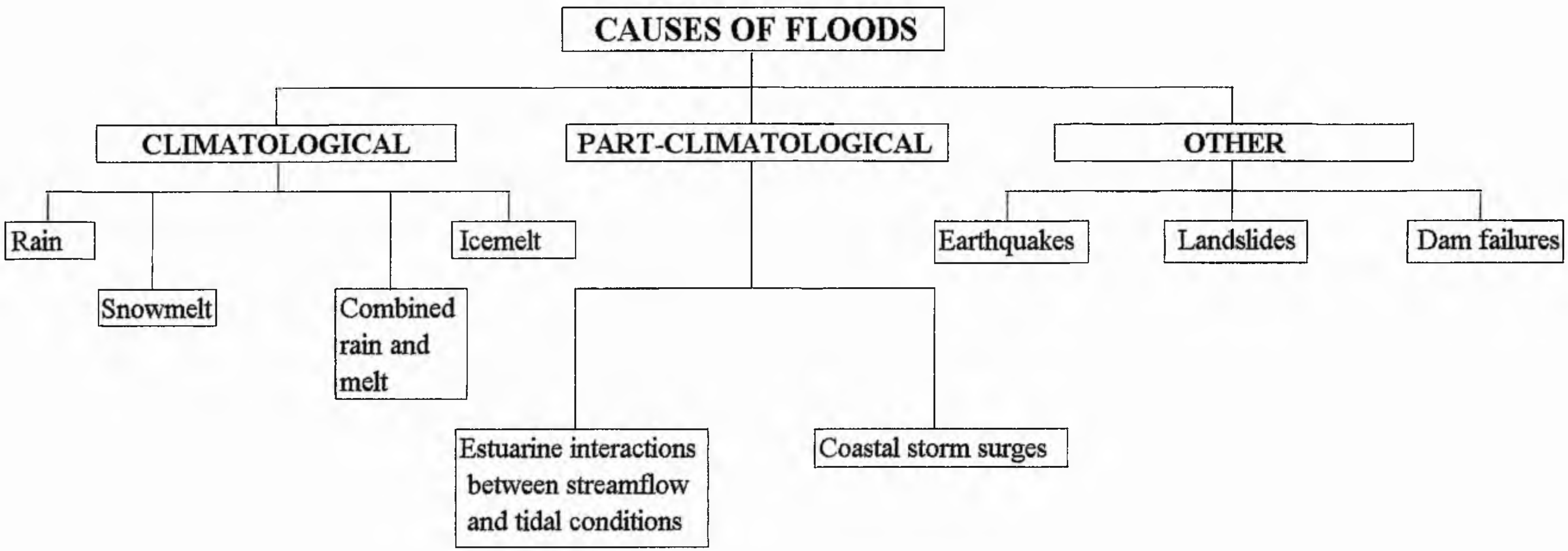
Extremes of river flow in the UK, and specifically flood peaks, are often attributed to extremes of climate (Figure 2.1) while flood events caused by landslides, earthquakes and dam failures are fortunately rare. More localised conditions, at the basin, network and catchment scales, play more significant roles in determining the characteristics of a flood event after its initiation. In Scotland, flood peak initiation may be attributed to precipitation, melt or combined rain and melt events.

Scotland has a fairly well documented history of flooding, with references to events which occurred in the eighteenth and nineteenth centuries often recorded in written eyewitness accounts, newspaper reports and other literature written at the time (Lauder, 1830; Reid, 1882 and Nairne, 1895 for example). The availability of material on pre-twentieth century events declines as one moves further back in time, as does the accuracy, reliability and value of the information given (McEwen, 1987). The gauging of river flows and the collection of accurate flood data is currently the responsibility of the seven Scottish River Purification Boards (RPBs) although widespread gauging has generally been limited to the last fifty years. The exception, however, is the pioneering gauging of the rivers Garry, Ness, Dee and Spey in the early part of this century by W.N. McClean (Werritty, 1987).

Acreman (1989) documents estimated and measured peak flow values for some of the major floods recorded in the UK since 1795, including twenty-nine Scottish floods. By recalling a small sample of these Scottish events, it will be possible to gain an insight into the different causes and subsequent characteristics of such floods.

Frontal storms are a common cause of flooding in Scotland. One of the earlier, more well documented events followed a widespread frontal storm in the Grampian region in August 1829. Estimates, made possible from documentary evidence (Lauder, 1830), place peak discharges at approximately $1900m^3s^{-1}$, $1665m^3s^{-1}$ and $1450m^3s^{-1}$ for the most severely affected rivers, the Dee, the Spey and the Findhorn respectively (Werritty and Acreman, 1984) with return periods in the region of 500 to 1000 years.

Figure 2.1: Causes of flooding (based on Figure 7.22, Ward and Robinson, 1990)



Other events linked to frontal precipitation include the Borders floods of 1948 when some 125mm of rain fell over the Lammermuir Hills in a twenty-four hour period (Douglas, 1949; Glasspoole, 1949). A combination of previously saturated soils and high intensity precipitation (40mm in two hours; Learmouth, 1950) led to extensive flooding on the rivers Tyne, Tweed, Eye, Blackadder and Whiteadder. The peak flow on the River Tyne at Haddington is estimated at $255m^3s^{-1}$ (Werritty and Acreman, 1984).

The Moray and Nairn districts of Scotland were also affected by a frontal storm over a forty-eight hour period in July 1956. Precipitation totals reached 250mm (Green, 1958) and caused severe flooding on the rivers Findhorn, Nairn, Lossie and tributaries of the Spey.

The Cairngorms are another region prone to flooding, with a major event occurring in 1956 as a result of a depression (Baird and Lewis, 1957) and a second in 1970, associated with an occluded front which produced high intensity (150mm in forty-eight hours) continuous rainfall (Green, 1971).

In December 1994, the Strathclyde region experienced heavy rain over a forty-eight hour period. This precipitation, associated with the warm sector of a stagnating frontal system, reached 165mm for a forty-eight hour period (Gleniffer Braes, Black Cart Water) suggesting return periods of 500 years. Rivers around Paisley and Glasgow were most severely affected and discharges reached unprecedented levels (Bennett and Black, 1995).

Although convective precipitation is less common in Scotland, rainfall totals can be sufficient to initiate flood events. A flash flood on the Hermitage Water in Roxburghshire in July 1983 followed a convectional storm where rainfall intensities exceeded 65mm in 75 minutes. Flows were not directly gauged but estimates are approximately $170m^3s^{-1}$ for a catchment of just $36.9km^2$. Extensive erosion was widespread as a direct consequence of such dramatic runoff events (Acreman, 1991).

Floods in Scotland are also initiated by snowmelt or icemelt, often in combination with precipitation. The River Tay has long been affected by extreme floods, with recorded evidence dating back to 1210 (Falconer and Anderson, 1993). In early February 1990, the Tay experienced a major flood event, with damage to property and land costing in excess of £3 million, and widespread disruption to roads and railways. Several days of heavy snowfall were followed by a rise in temperature and rainfall, which combined with meltwater leading to extreme river flows. Extreme discharges were recorded on the Rivers Tummel, Garry, Tay and Earn. The maximum discharge ($1747m^3s^{-1}$) was recorded on the Tay at Caputh (15003) and represents a return period of 70 years. Most other recorded flows in the Tay catchment had return periods between 30 and 70 years.

In January 1993, a similar event was experienced in the Tay and Earn catchments. A period of extensive snowfall and snowpack accumulation was again followed by a rapid rise in temperature and heavy rainfall. The peak discharge of $2269m^3s^{-1}$ was recorded on the Tay at Ballathie (15006) and the Earn peaked at $415m^3s^{-1}$ (station 16004). Return periods are estimated at 100 years for flows in the Tay catchment and 80 years for the Earn (Tay River Purification Board, 1993).

Although the events described here constitute only a very small proportion of the floods that have occurred on Scotland's rivers, is readily apparent that a variety of meteorological conditions (frontal rain, convective storms and snowmelt) can lead to flooding. It also highlights the fact that certain areas of Scotland are more prone to certain 'types' of flooding than others. The majority of Scottish floods can be linked with frontal rainfall during the autumn and winter months yet the area around the Moray Firth and the south-east of Scotland appear to be more prone to frontal rainfall during the summer months (Werritty and Acreman, 1984; Black, 1992). It is also important to consider the role of localised conditions (antecedent conditions, soil characteristics etc.) which can be of importance in intensifying or stifling a potential flood event.

2.3.1 FLOOD FREQUENCY ANALYSIS

Flooding is the response of a river system to excessive inputs of water and, as such, man can do little to stop what is in fact a natural phenomenon. However, through continued research and improved understanding of the fundamental aspects of flood hydrology we can seek to reduce the potential damage arising from future events. Flood protection schemes, such as levees and embankments, aim to contain the flood peak within artificially extended channels thus attempting to reduce the area likely to be flooded. Alternatively, flood warning schemes and flood-plain zoning are methods which aim to limit the damage to personal property and life rather than trying to limit the flood. Another approach which attempts to limit costs is to ensure that if structures are built within the flood-risk areas, they are designed to withstand a flood of given magnitude. It is this approach, more than any other, which has sustained the development of flood frequency analysis.

2.3.1.1 STATISTICAL TECHNIQUES OF FLOOD FREQUENCY ANALYSIS

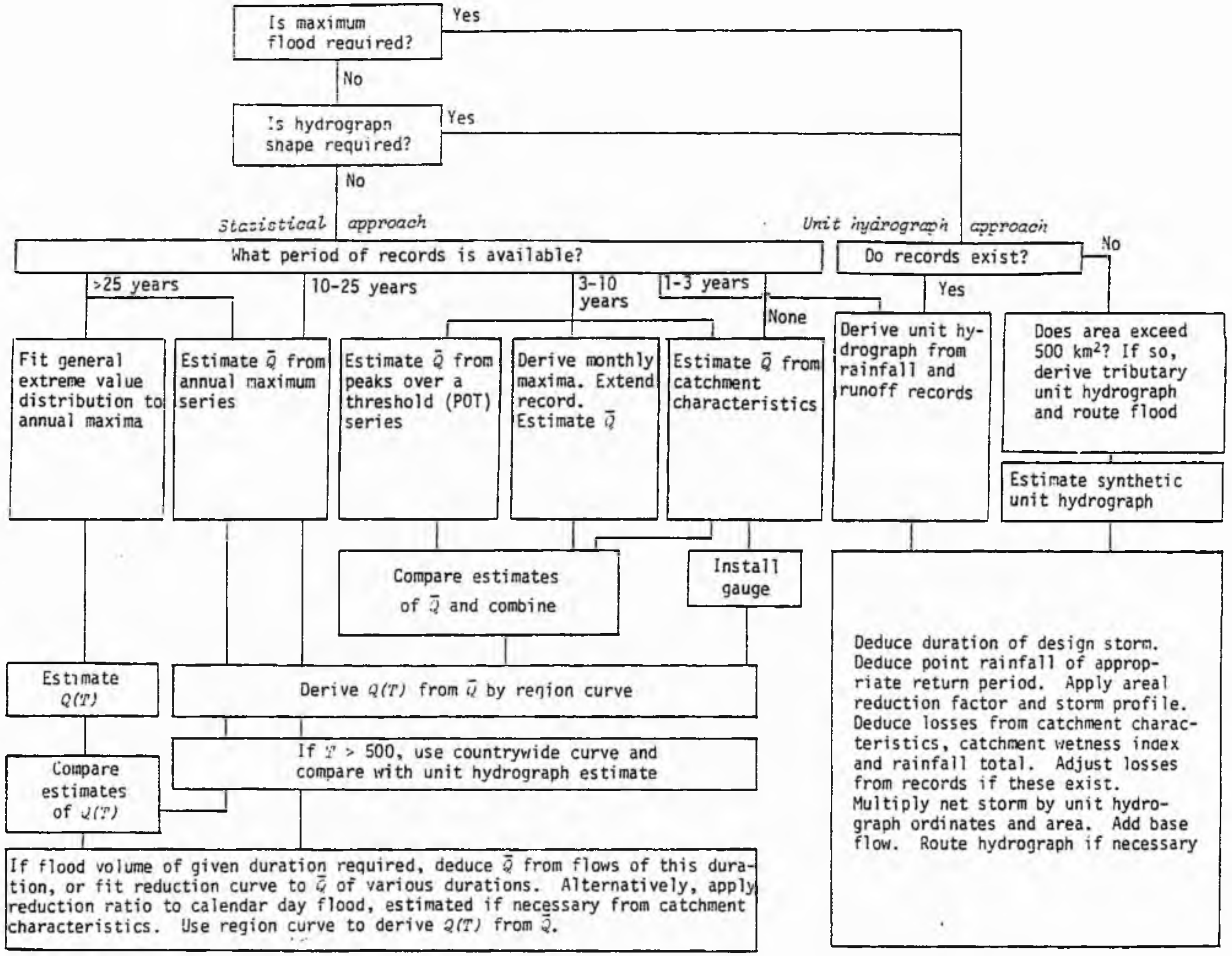
Estimating the 'probable maximum flood' likely to occur on a river was the first technique to be incorporated into the design of structures within a floodplain. These early methods, which related maximum discharges to catchment and rainfall characteristics (Newson, 1975), were quick and easy to use. Their simplicity was also a drawback. This was highlighted by a dam which failed in Snowdonia in the 1920s due to inadequate design specifications (Fearnsides and Wilcockson, 1928). As a consequence, the Reservoirs (Safety Provisions) Act of 1930 was introduced (Newson, 1975) and a report was published by the Institution of Civil Engineers (ICE) in 1933 to provide guidelines for planning and designing of dam spillways, thus ensuring the minimal probability of failure by overtopping (ICE, 1933). These guidelines were in the form of envelope curves which could be used to establish the relationship between catchment areas and peak discharge. However, these guidelines were much limited by the paucity of flood data, since gauging was still scarce at this time. The ICE subsequently published revised envelope curves including additional data (ICE, 1960).

One of the most significant advances in flood estimation introduced the concept of frequency in the prediction of flood magnitudes, thereby generating the term flood frequency analysis (Gumbel, 1958). Gumbel's approach treated each recorded flow value as one data item within a series of extreme flows which could be viewed as a statistical dataset of extremes. By fitting a statistical distribution to the data and calculating the distribution parameters, it is possible to determine relationships between flood magnitudes Q and their frequencies. This statistical relationship can be used further to extrapolate to unrecorded extremes. The choice of an optimal statistical distribution used to model a flood series is open to debate, and depends upon the type of flood series available (Annual Maximum or Peaks-Over-Threshold; Chapter Three). Cunane (1989) documents a large proportion of the numerous statistical distributions which have been proposed for flood frequency analysis.

The concept of frequency is incorporated using the idea of return period floods. The return period T is the long-term mean of the intervals between exceedances of a given flood magnitude Q_T (Shaw, 1988). An event with a 50-year return period, Q_{50}, will be equalled or exceeded *on average* once in every fifty years of record, although as with most data sets the interval between Q_{50} events will actually vary quite considerably.

In 1967, the ICE recommended an extensive investigation into floods and their characteristics on a national level. The resultant publication, the *Flood Studies Report* (NERC, 1975) provides the definitive statement (to date) on all aspects of flooding in the United Kingdom and includes Hydrological Studies and Data (Volumes I and IV), Meteorological Studies (Vol. II), Flood Routing Studies (Vol. III) and Maps (Vol. V). In terms of estimating flood frequency-magnitude relationships, the *FSR* makes certain recommendations for design flood estimation (Figure 2.2). Typically, the choice of statistical method is very much dependent upon the length of flow record available. Equations based upon catchment characteristics can be used to estimate Q_T (the discharge for any given return period T) where no flow records are available.

Figure 2.2: Techniques recommended for estimating the design flood (NERC, 1975)



The equations produced in the *FSR* (NERC, 1975) were later revised specifically for Scotland (Acreman, 1985).

The principal assumption of flood frequency analysis is that the frequency-magnitude relationship is quasi-stationary through time, since estimates for future events are based upon the past flood record.

2.4 SYNOPTIC CLIMATOLOGY

The general introduction to the climate of Scotland (Section 2.2.2) has been concerned with parameters such as precipitation and rainfall. Although such parameters can be used to describe climatic variability, they do little to explain the causal mechanisms behind such variability. It was therefore decided that a database of synoptic weather types would be used to address the question of variability within the climate of Scotland.

The aim of synoptic climatology is to explain how weather conditions experienced at the global, continental or even regional scale are related to atmospheric circulations, pressure patterns and associated wind directions (Lamb, 1972; Barry and Perry, 1973; Smithson, 1986). Hence, any variability within the climate can be explained with reference to variability in atmospheric conditions.

Any study of the synoptic climate will include a classification scheme, created by the identification of a limited number of frequently occurring pressure patterns or 'weather types' (El-Kadi and Smithson, 1992). The atmospheric patterns on any given day can then be categorised by reference to one of these weather types. Such synoptic classifications may either be subjective or objective. Subjective classifications involve identifying the commonly occurring circulation patterns by eye, using daily synoptic weather charts, whilst objective techniques apply statistical methods (correlation, principal component analysis etc.) to meteorological indices to characterise the most frequent 'weather types' (El-Kadi and Smithson, 1992). Long term records representing the synoptic climate of the British Isles are based upon subjective techniques.

2.4.1 SUBJECTIVE CLASSIFICATION SCHEMES

Numerous classification schemes, based upon subjective techniques, have been used to catalogue and study aspects of the weather and climate. In Europe, one of the most cited classifications is the European Grosswetter which is based upon daily sea-level pressure fields over Europe and the North Atlantic from 1881 onwards (Hess and Brezowsky, 1977 cited in Fraedrich, 1990). At the sub-continental scale, a number of techniques and classifications have been applied to the British Isles (O'Hare and Sweeney, 1993). However, it is the classification devised by Lamb (1972) and the resulting record of daily weather types which has been widely applied to research in the British Isles.

2.4.2 LAMB'S CLASSIFICATION OF DAILY WEATHER TYPES

Lamb's record of daily weather types (Lamb, 1972) is based upon the atmospheric circulation and pressure patterns at sea-level and at 500mb over the British Isles (50°-60°N, 10°W-2°E). It is assumed that knowledge on airstream origin, its probable history of heating and cooling and consequently its vertical thermal structure will help determine the weather conditions experienced in the British Isles. The subjective classification scheme devised by Lamb recognises twenty-seven frequently occurring circulation patterns:

- there are seven basic, nineteen hybrid and one unclassified weather types;
- the seven basic types include five directional types (Northerly, Easterly, Southerly, Westerly and North-Westerly) which represent the steering of synoptic weather systems rather than actual surface wind direction (Jones and Kelly, 1982) and two representing synoptic systems (Cyclonic and Anticyclonic);
- the nineteen hybrid types (Cyclonic-South-Westerly, North-Easterly etc.) are used to classify days when the definitions of more than one basic weather type are met.

In theory, each of the seven basic types are associated with characteristic weather conditions (Table 2.1)

Table 2.1: General weather characteristics and air masses associated with Lamb's weather types over the British Isles

TYPE	WEATHER CHARACTERISTICS
ANTICYCLONIC	warm and dry in summer, occasional thunderstorm (mT, cT); cold and frosty in winter with fog, especially in autumn (cP)
CYCLONIC	rainy, unsettled conditions often accompanied by gales and thunderstorms; this type may refer either to the rapid passage of depressions across the country or to the persistence of a deep depression (mP, mPw, mT)
EASTERLY	cold in the winter half of the year, sometimes very severe weather in the south and east with snow or sleet; warm in summer with dry weather in the west; occasionally thundery (cA, cP)
SOUTHERLY	warm and thundery in summer; in winter it may be associated with a low in the Atlantic giving mild, damp weather especially in the south-west or with a high over central Europe, in which case it is cold and dry (mT or cT, summer; mT or cP winter)
WESTERLY	unsettled weather with variable wind directions as depressions cross the country; mild and stormy in winter, generally cool and cloudy in summer (mP, mPw, mT)
NORTH-WESTERLY	cool, changeable conditions; strong winds and showers affect windward coasts especially, but the southern part of Britain may have dry, bright weather (mP, mA)
NORTHERLY	cold weather at all seasons, often associated with polar lows; snow and sleet showers in winter, especially in the north and east (mA)

Based upon Barry and Chorley (1987)

Airmass types:

mT	maritime Tropical	cT continental Tropical
mP(w)	maritime Polar (warm)	cP continental Polar
mA	maritime Arctic	cA continental Arctic

Lamb's classification has been applied to each daily weather chart for the British Isles from 1861 to the present day, and the length of this record has facilitated numerous studies into climatic variability and change. Lamb's early analyses emphasised annual, seasonal and monthly variations in the frequencies of each weather type and the evolution, persistence and decay of weather systems (Lamb, 1965; Lamb, 1972). Murray and Lewis (1966) additionally devised the PSCM index which can be applied to the Lamb database, to quantitatively measure progressive or westerliness (P-index), southerliness (S-index), cyclonicity (C-index) and meridionality (M-index) within any given period of time. Although these indices can be used to detect variability within the synoptic record, they imply that a very simple and mutually exclusive relationship exists between weather types (the S-index is positive when the frequency of the Southerly type is high, and low when the frequency of Northerlies is high). The realiity is likely to be much more complex.

Examination of the frequencies of the Lamb weather types has revealed that three types, the Westerly, Cyclonic and Anticyclonic, dominate the record (Lamb, 1972), and further research has revealed inter-annual and inter-seasonal variability in weather type frequencies. A major decrease in the incidence of westerly days occurred from the 1950s onwards (Lamb, 1972), a pattern reflected in all seasons (Briffa *et al*, 1990). Other noticeable features, identified using principal components, include the increase in the Anticyclonic and Cyclonic frequencies during the 1980s, an increase in the South-Westerly type since the 1960s, a decrease in the Northerly type during the latter half of this century and a more recent decline in the annual frequency of the North-Westerly (Briffa *et al*, 1990).

2.4.3 RELATIONSHIPS BETWEEN WEATHER TYPES AND PRECIPITATION

Lamb's record has been applied far beyond the simple description of seasonal and annual frequencies, with research carried out into the relationships between Lamb weather types (LWTs) and temperature and precipitation (O'Hare and Sweeney, 1993). For the purpose of this project, relationships with precipitation patterns hold the key for linking synoptic climatology to the Scottish flood record.

Perry (1968) found that periods of progressiveness (displayed by a high P-index) are strongly correlated with above average precipitation. The tracks of depressions across the country were also found to be influential: a depression tracking across the British Isles will give little precipitation in northern regions whilst one which moves mainly between Scotland and the Faroes is more likely to result in precipitation in the north west. Perry (1976) later noted that the general decrease in Westerlies experienced from the late 1950s onwards (Lamb, 1972) was likely to be associated with a specific decrease in January (and possibly the winter season as a whole) Westerly frequencies.

In order to explain the west-east precipitation gradient in Scotland, Smithson (1969) used an alternative to Lamb's classification to relate these rainfall patterns to their synoptic origin. Using three categories to classify the synoptic origin of precipitation (frontal, airstream and cyclonic), Smithson concluded that precipitation on the west coast was predominantly frontal in origin, whilst warm sector polar maritime air precipitation was dominant in mountainous regions. Precipitation in the east was found to be more variable but could often be linked to stagnating non-frontal depressions. This study is particularly relevant since it deals specifically with synoptic-precipitation relationships in Scotland. The over-riding problem is, however, the absence of a long-term record of precipitation origin which could be incorporated into this project.

Further studies on the incidence of LWTs indicate that during the period 1967-82, summers were dominated by blocked, anticyclonic conditions. Such conditions are often associated with easterly airflows over the British Isles, and under such circumstances a reversal of the usual west-east rainfall gradient could be expected. However, during this period the distribution of precipitation across Scotland was, in fact, typical of a dominance of Westerly airflows (Hughes, 1984). These findings cast some doubt on the accuracy of LWTs in representing the synoptic situation and consequent weather conditions to all locations in the British Isles, and Scotland in particular. This is a point noted by other authors (Sweeney and O'Hare, 1992).

Jones and Kelly (1982) used Principal Component Analysis (PCA) to establish what compensatory relationships exist between LWTs. The PSCM index (Murray and Lewis, 1966) assumes a rather simple dependent inverse relationship between weather types. A highly Cyclonic year, for example, is determined by looking at Cyclonic and Anticyclonic types only, and this paper questions the simplicity of that approach. PCA, a statistical technique which identifies groups of inter-correlated variables (Johnston, 1978), was applied to the database of annual frequencies of the 27 LWTs over the period 1861-1980. Four principal components (PC1-PC4) accounted for 71% of the variance displayed by the annual database:

- PC1 links years with a high (low) frequency of Anticyclones with a low (high) incidence of Westerlies;
- PC2 indicates a year with a high (low) frequency of Anticyclones and/or Westerlies, and a low (high) frequency of Cyclonic systems;
- PC3 represents years with a dominance (absence) of synoptic systems to an absence (dominance) of North West directional flows;
- PC4 indicates meridional flow: low (high) Southerly frequencies and high (low) frequencies of Northerly and/or North westerly flows.

Although this paper has emphasised the complex counteracting processes which exist between weather types, it provides useful information on which scenarios are likely to cause inter-annual variations in weather type frequencies.

Further analysis using these principal components (Briffa *et al*, 1990) suggest the decline in Westerlies since the 1950s is a feature mirrored in all seasons (but to a lesser extent in Autumn). Although this decrease can be associated with increases in the frequency of synoptic systems (Anticyclonic and Cyclonic), the precise relationship does vary at seasonal and annual scales. Sweeney and O'Hare (1992) found a continued decrease in Westerlies and Cyclonic-Westerlies during the late 1980s which again coincided with increases in both the Anticyclonic and Cyclonic weather types.

Although the variability displayed by the dominant weather types (Westerly, Cyclonic and Anticyclonic) is important in determining the effect upon the climate of the British Isles, the changing incidence of the less frequent weather types should not be overlooked. The last decade (1981-90) has seen an apparent increase in the frequency of Southerly airflows. Murray (1993) confirmed that the 1980s had the greatest (and the only positive) S-value (southerly index; Murray and Lewis, 1966) of any decade since 1861, a feature evident in all seasons, but most pronounced in autumn and spring. Whether this increase is simply a peculiarity within the climate or a possible indicator of climate change is not yet known. However, this paper does imply some recent distortions in the general circulation. Sweeney and O'Hare (1992) similarly observed a twofold increase in the frequency of the South-Westerly type over the period 1960-90 coupled with a sharp decrease in North Westerlies during the 1980s.

Sweeney and O'Hare (1992) provide a useful summary of the associations between LWTs and the resultant spatial precipitation patterns (Table 2.2). This information suggests that the Westerly, Cyclonic, Southerly and South-Westerly LWTs are associated with the highest precipitation totals in the British Isles. Westerlies, Southerlies and South-Westerlies are responsible for the west-east gradient apparent in the distribution of Scottish rainfall.

2.4.4 ADVANTAGES AND CRITICISMS OF THE LAMB RECORD

The limitations and benefits of using subjective synoptic classifications, such as the Lamb record, are well documented (El-Kadi and Smithson, 1992; O'Hare and Sweeney, 1993). Factors in favour of the Lamb classification are its ease of use, the length of record available for analysis and the possibility of relating each weather type to characteristic weather conditions. However, a number of criticisms have been levelled at the Lamb classification, which include its complexity (twenty-seven possible weather types), a lack of objectivity, within-type variation (the association between a weather type and precipitation yield may vary through time) and its coarseness in representing regional contrasts in weather conditions on any given day (O'Hare and Sweeney, 1993).

It is clear from previous investigations that the Lamb classification is far from perfect. However, none of the criticisms cited above are sufficient to reject the database from any further research, particularly since its most significant merit is that it provides a very valuable long term record of weather over the British Isles since 1861, a feature which cannot be matched by any other database.

Table 2.2: Associations between Lamb Weather Types and Scottish precipitation patterns (Based on Sweeney and O'Hare, 1992)

WEATHER TYPE	PRECIPITATION PATTERN
ANTICYCLONIC	dry conditions
CYCLONIC	varies according to the depression track; east receives enhanced precipitation from moist, North sea air; the north-west is sheltered; an increase in frequencies would reduce the west-east precipitation gradient
NORTH-EASTERLY	linked to blocking over the Atlantic with a splitting of the jet stream, thus producing a cut-off low to the south of the British Isles and a blocking Anticyclone to the north; a variable pattern of precipitation
EASTERLY	precipitation totals are highest on the east coast; totals highest for the Cyclonic-Easterly type and lowest for the Anticyclonic-Easterly
SOUTH-EASTERLY	uniform distributions of precipitation; a result of an Anticyclone over the North Sea and stable airflows with low moisture contents due to a short sea passage
SOUTHERLY	maritime tropical airmasses, laden with moisture which cause high precipitation in the west and a rainshadow in the east; Anticyclonic-Southerlies and Cyclonic-Southerlies produce similar patterns (totals slightly higher for the latter)
SOUTH-WESTERLY	produce a west-east gradient due to orographic forces
WESTERLY	a consequence of low pressure to the north of the British Isles and high pressure to the south; precipitation in west is five times that in the east (a reflection of the long sea passage of moist maritime airflows from the Atlantic in combination with orographic effects); Anticyclonic- Westerlies produce half as much precipitation, whilst Cyclonic-Westerlies are associated with high precipitation totals and few spatial contrasts
NORTH-WESTERLY	caused by a ridge of high pressure extending from the Azores anticyclone; depressions move in a nw-se direction; precipitation concentrated in the north-west, limited elsewhere
NORTHERLY	associated with high pressure to the west of Ireland; very dry conditions in the east and wetter conditions in the west; Anticyclonic-Northerlies generate a drier, weaker pattern but Cyclonic-Northerlies are linked to depressions which track southwards in the North Sea, producing rainfall in the south-east

2.4.5 REGIONAL CLASSIFICATIONS

The problem of using the Lamb classification to describe the atmospheric conditions and associated weather conditions in the British Isles on any one day, is the existence of regional contrasts in weather and precipitation characteristics. This problem has recently been addressed by the creation of a database of regional airflow types (Mayes, 1991). Mayes argues that since weather is experienced at the local scale, rather than the synoptic level, daily weather types should be based upon airflow patterns at or near the surface which are effective at the regional scale, rather than considering both surface and upper troposphere airflow patterns. Four such regions, Scotland, Ireland, south-west and south-east England were identified for inclusion in the Mayes database. Surface airflow charts were used to associate each day from 1950 onwards with one of twenty-seven weather types (identical to those distinguished by Lamb, 1972), using subjective techniques based upon the direction and curvature of surface isobars.

Subsequent analysis of the Mayes record (Mayes, 1991; Mayes, 1994) has revealed some interesting characteristics with respect to the Scottish record:

- years recording a high frequency of the Westerly type are characterised by a strong west-east precipitation gradient (as one would expect);
- using the PSCM index (Murray and Lewis, 1966), the period from 1950 to the late 1960s was characterised by a gradual decline in the Westerly index; the subsequent period has seen a similarly gradual increase;
- the Cyclonicity index shows an increase from 1950 to the late 1960s; a slight decline is then followed by a peak in the early 1980s;
- annual rainfall totals in the west of Scotland do not decline over the period 1951-80, as would be expected from a period of blocked conditions; during the 1980s precipitation in the west increased whilst little change in totals was apparent in the east; this suggests that Scotland was indeed experiencing an increase in Westerly airflows.

2.5 VARIABILITY WITHIN RUNOFF AND CLIMATIC RECORDS

Having provided a general introduction to the characteristics of the Scottish flood and climatic records, the question of detecting variability within such records can be explored. It is hoped that, through the examination of past studies in these areas, information will be provided on the statistical techniques most suitable for detecting variability, as well as background information on the nature of any variability previously detected.

The majority of studies which aim to examine variability within hydrologic indices will undoubtedly discuss the influence of climatic factors upon such series, largely because of the close relationship which exists between the two. For studies which examine the characteristics of flow indices, the most widely used climatic variable is precipitation (rainfall) although some attempts have been made to link flow characteristics to synoptic weather types (see below). Attempts to examine climatic variability may or may not consider flow indices in the analysis. Nonetheless studies into precipitation variability can often provide useful information on general climatic conditions.

Information on Scottish precipitation records can be provided from a number of sources, with emphasis often being placed on catchment studies. One such study, centred on the Findhorn and Spey catchments in the north-east of Scotland (McEwen, 1993), reveals extreme precipitation events to occur randomly through time. There is also a degree of spatial variability in the incidence of extreme events within the catchment, a factor which is linked to distance inland and distance west. It appears that the most intense rainfall cells have a tendency to be positioned over the Findhorn catchment, whilst extreme precipitation and subsequent flooding in the Spey can be linked to winter cyclonic storms in the upper catchment and to summer frontal storms in the lower catchment. Such information is extremely important when examining the characteristics evident within flood series.

The recent period of Scottish precipitation totals has recently been put into context by the creation of a time series which depicts monthly areal average precipitation from 1757-1992 (Smith, 1995), although data in the early part of this series (1757-1868) are the least reliable. Within this period, 1990 is the wettest year on record. The 1980s as a whole appear as a particularly wet phase, with the two periods 1981-1990 and 1983-1992 registering the highest ten-year precipitation totals. Conversely, the late 1960s and early 1970s register as a dry period. A seasonal split of the record reveals that autumn is generally the wettest season, although the increase in wetness during the 1980s is evident in all seasons except summer. The general characteristics described by Smith generally comply with the findings of other studies (Higgs, 1987; Rowling, 1989)

One of the great benefits of a having a database of daily synoptic weather types (Lamb, 1972; Mayes, 1991) is the ease with which climatic variability can be examined, either by investigating the changing frequency of weather types or alternatively using the PSCM index (Murray and Lewis, 1966). However, research into the relationship between synoptic weather types and river flow characteristics in the British Isles has unfortunately been limited.

One particularly interesting study has examined variability within flood characteristics (frequencies, magnitudes, seasonality etc.) on the Upper Severn with respect to climatic variability and changes in land-use catchment (Higgs, 1987). This research made extensive use of flood and precipitation data (both using the peaks-over-threshold format) in conjunction with the Lamb database and some very interesting and relevant conclusions are reached.

A period of increased flood frequencies in the mid 1960s, detected using a simple running mean plot, was found to coincide with heightened storm activity. The mid 1970s were then characterised by a lull in flood frequencies, although values started to increase in the early 1980s. Changes in flood frequency-magnitude relationships were explored through return period analysis, by splitting the POT series and examining recurrence intervals between periods. With regard to the Lamb database, Higgs showed that the Westerly and Cyclonic weather types accounted for over half of the heavy rainfall events experienced in the catchment and that the probability of a Cyclonic day producing heavy rainfall had increased over the period 1926-82. To conclude, Higgs stated that variability in heavy rainfalls and ultimately flood characteristics could be explained by changes in the likelihood of weather types producing heavy rainfall.

Higgs' study is valuable for a number of reasons. It is one of the few studies carried out in Britain which explores the specific nature of the relationship between flood characteristics and climatic variability. Although it deals with just one catchment, in Wales, it provides a first insight into how flood characteristics vary through time and how techniques such as running mean plots and return period analysis can be used to detect such variability. It also makes a very important link between flood events and the Cyclonic and Westerly weather types.

A number of studies have recently addressed the question of increasing river flows in Britain, with some reference to precipitation and weather type variability. A recent study by Arnell *et al* (1990) has found a degree of annual variation in flow records across the British Isles, from the period up to 1988. These patterns are linked to rainfall variability, although the strength of the relationship was found to vary on a seasonal basis with the strongest associations occurring in winter. In terms of the recent past, the 1980s were found to contain the highest annual runoff values for over one hundred years, with higher average seasonal flows than the previous decade. However, the number of extreme events was not found to be unusually high. Although this report makes some valuable findings, its applicability to detecting and describing flow variability from a Scottish perspective is limited, since those Scottish flow records used were confined to the south and east coast, whilst records from the west and north were largely ignored. It will be interesting to determine how data from the 1990s would affect these results.

A number of studies have also addressed the question of increased flows in Scotland. Evidence from the Clyde catchment (Curran and Robertson, 1991) indicates a substantial (42%) increase in total annual runoff over the period 1969-88, a reflection of increased precipitation during this period. This paper, however, deals with the impact of such variability upon water quality and makes no mention of changes in the magnitude or frequency of instantaneous peak flows. However, a study of the Allan catchment in Stirlingshire (Rowling, 1989) examined rainfall variability and its implications for flooding. Over the period, 1931-85, annual precipitation totals reached a minimum in 1934 and a maximum in 1947. The general characteristics of the precipitation record were derived from a simple running mean plot and explained with reference to variability on a seasonal basis. A rise in annual precipitation during the 1950s was a consequence of increased summer precipitation; a subsequent decrease during the 1960s and 1970s resulted from decreased precipitation in all seasons, and the final increase in precipitation from the 1970s onwards was due to a substantial rise in autumn precipitation. Flood series, examined over the period 1958-85, indicated that frequencies fell steadily over the period 1958-71 then rose from 1971 onwards. As with Higgs' study (1987), Rowling used return period analysis, based upon split periods of record, to examine changes in frequency-magnitude relationships. Generally speaking, a decrease in return periods for a given magnitude flood occurred with time.

Although limited to one catchment, this study provides an idea of how flood characteristics have varied over the recent past and how these changes can be linked to precipitation variability. It will be interesting to compare these findings with additional flood series and to explore the associations of increased flood frequency and autumn precipitation in the 1980s with the incidence of daily weather types.

Although not obviously related to climatic and flood variability in Scotland, a study carried out on historical runoff variations in the Nordic countries (NCH, 1995) is of particular relevance to this project for two reasons. There is a possibility that runoff characteristics in Norway may be similar to those in Scotland, largely because of the influence of westerly airflows on the climate of both countries. The techniques of analysis used to detect variations within the Nordic runoff series, a gaussian filter, a run test and a trend test, are relatively simple statistical techniques, recommended by the World Meteorological Organization (WMO, 1988). These techniques indicate an increase in runoff from the 1960s, with a distinct positive trend evident in the autumn runoff totals and a significant upward trend in the magnitude of the winter maximum flood in south-west Norway (WMO, 1988; also see Section 4.5).

2.6 SUMMARY STATEMENT

The information presented in this chapter has provided some very useful background information on the characteristics of flooding in Scottish rivers and the relationship with precipitation and synoptic weather type records. The key points to be drawn from this chapter provide background information which should prove valuable in subsequent stages of this project:

- flooding in Scotland is predominantly linked to extreme rainfall events;
- such rainfall events are most often convective or cyclonic in origin, with some orographic enhancement;
- the precipitation record for Scotland indicates that the most recent period (late 1980s/1990s) has been characterised by above average totals whilst the late 1960s and early 1970s were particularly dry; these recent increases may be showing seasonal patterns;
- there is some evidence to suggest runoff records are following a similar pattern;
- past studies on flood characteristics have revealed high flood frequencies in the 1950s and 1980s and lower frequencies in the 1960s and 1970s;
- return period analysis for split periods of record has been shown to be a successful technique for determining the effect of variability within flood series upon flood frequency-magnitude relationships;
- databases of daily synoptic weather types have been widely and successfully used to study climatic variability and its association with precipitation; research into links with flow record has, however, been limited especially in relation to peak flows;
- a number of techniques for detecting variability within time series have been examined, ranging from simple running mean plots to the more complex time series statistics used in Scandanavia.

CHAPTER THREE

DATA SOURCES AND METHODS OF COLLECTION

An introduction to the hydrologic and climatic databases collected and prepared for analysis

3.1 INTRODUCTION

In order to fulfil the proposed aims of this research, namely to examine how the characteristics of Scottish flood records have varied through time within the context of climatic variability, two key databases are obviously essential, the first being a record of flooding in Scotland and the second being a representative measure of the Scottish climate. Prior to identifying possible sources for these databases, a list of key data requirements was drawn up.

To complete a detailed and robust examination of variability within the Scottish flood record, the ideal database would combine high quality, long term flow data with an extensive spatial coverage of rivers. Obviously, the longer records will yield more information on temporal variations in flood events. However, an additional aspect worthy of study is to examine the dependence of temporal variations on geographical location. Since there is already some evidence to suggest a regional divergence in river flow patterns across Scotland (Arnell *et al*, 1990), the spatial dimension to flood variability should also be explored. In order to detect any such variability, the database should also yield information on flood characteristics (frequency and magnitude) which can then be analysed with reference to time and space.

The essential requirements of the climatic database are naturally similar to those identified for the flood data, with emphasis being placed upon adequate temporal and spatial coverage. It is anticipated that analysis of this database will reveal the extent of any variability within the Scottish climate and that these results may be compared with the flood record. Obviously, to make a direct and logical comparison between the two datasets, the climatic variable analysed must be one that is directly related with flood events.

3.2 THE FLOOD DATABASE

3.2.1 A HISTORICAL PERSPECTIVE ON SCOTTISH RUNOFF DATA

The collection of river flow data has long been established in Britain, with the earliest continuous runoff measurements beginning in the 19th Century on the River Thames at Teddington and at Feides Weir on the River Lee (Lees, 1987). In Scotland, the history of river flow measurement follows a somewhat different path from the rest of Britain. The earliest recording or gauging of Scottish river flows was introduced in 1913 by Captain W N McClean on the River Garry in Inverness-shire. This pioneering work consequently spread to include sites on the Rivers Ness, Foyers, Moriston, Lochy, Spey and Dee (McClean, 1927; Werritty, 1987) and continued into the 1930s and 1940s until the Water Act (Scotland) was introduced in 1946. This gave responsibility for the collection, preparation and publication of water resource data to the Department of Agriculture and Fisheries for Scotland, water supply authorities and the North of Scotland Hydro-Electric Board (NSHEB). In 1951, the Rivers (Prevention of Pollution - Scotland) Act was introduced, which recommended the formation of River Purification Boards (RPBs). Gradually, the RPBs were set up and by the early 1970s they had taken responsibility for the majority of Scottish gauging from the Scottish Development Department (SDD) (Lees, 1987). However, the speed at which the gauging network evolved in Scotland has varied quite considerably. In the south, the gauging station network is well established and emphasis is placed upon refining the existing gauging network by withdrawing those that are either surplus to requirements or where data are inaccurate. In the north-west, however, the network is still expanding. The formation of the Natural Environment Research Council (NERC) in 1965, with the authority to grant funds for hydrological research, led to the development of the Institute of Hydrology (IH), responsible for the Surface Water Archive for all areas of the UK during the 1980s and, from 1992, the National Water Archive (National River Flow Archive and the National Groundwater Archive).

The current situation in Scotland is that the RPBs still hold responsibility for the collection of river flow data although the Scottish water industry is due to be re-organised from April 1996 with the establishment of the Scottish Environment Protection Agency (SEPA).

3.2.2 METHODS OF RECORDING FLOW DATA

River flows are commonly represented as a discharge value (m^3s^{-1}), although flow velocities (ms^{-1}) may occasionally be used. Although one-off discharge measurements can be made, their use is limited and a continuous record of flow is much more useful. Discharge is, however, a very difficult variable to measure on a continuous basis although constant measurements of river level (stage) can be made. If a relationship between river stage and discharge can be defined for a suitable site, usually by a stage-discharge equation, it is possible to create a continuous discharge record.

Stage-discharge relationships are commonly derived using the velocity-area method. At a fixed site, known as a gauging station, the channel cross section is surveyed and the area calculated. Then, by measuring or gauging flow velocities at fixed intervals across the channel section, it is possible to calculate the flow discharge. By repeating this exercise at a range of given stages, it is possible to estimate the stage-discharge relationship (Dalrymple, 1960; Shaw, 1988). This accuracy of this process may be improved by building a flume or weir within the channel since such structures have a fixed cross sectional area, and are not subject to the changes that can occur in natural river beds (Shaw, 1988).

More sophisticated gauging techniques include the electromagnetic and ultrasonic methods. Electromagnetic gauging is appropriate for reaches where there is no stable stage-discharge relationship, whilst the ultrasonic method is highly accurate when the river bed is stable (Shaw, 1988).

For many years, methods of continuously recording the key hydrometric variable, river stage, remained unchanged with the standard instrumentation comprising an inlet pipe from the river into to a stilling well where a float resting on the water surface. This float is attached by a pulley mechanism to an autographic recorder where a pen records a trace, representing the stage, on a rotating paper chart. The movement of the pen reproduces the changes in river stage over time, scaled by an appropriate reduction factor (Shaw, 1988).

However, in recent years digital recorders have begun to replace these traditional techniques. Water levels are instead recorded onto a digital logger at regular fifteen minute intervals throughout the day, and therefore stage data can be loaded directly onto computer by the RPBs without the need for excessive paper charts. Although RPBs have begun to introduce digital recorders into some gauging stations, autographic recorders may often be used as a back-up in case the digital system fails. The only potential problem with digital recorders is that river stage is only recorded at fifteen minute intervals and it does not necessarily follow that the peak of a flood will coincide with a fifteen-minute reading. This is, however, only likely to be a problem on those rivers with a very flashy regime, where stage can rise and fall significantly within a fifteen minute period. Although it could be justified to omit digitally recorded data from this study, doing so would reduce the amount of recent data incorporated in the analysis since the use of digital recorders has increased substantially during the 1990s. On completing the data collection process, it was apparent that none of the gauging stations with digital loggers were on rivers with regimes flashy enough to warrant concern.

3.2.3 CREATING A FLOOD DATABASE

There are two recognised methods of creating a database of flood events from a continuous flow hydrograph, the Annual Maximum Series (AM) and the Peaks Over a Threshold Series (POT) or Partial Duration approach.

An Annual Maximum series comprises only one peak, the highest instantaneous discharge recorded, in each year of record, and therefore it is a fairly simple technique to employ. The technique for creating a Peaks over Threshold series is, however, more complicated and involves a flow discharge or threshold being set for individual gauging stations. Any instantaneous peak flow which exceeds this threshold is classified as a flood event. This process is, however, complicated by the fact that, for statistical analysis, all peaks must be independent of one another. Two rules of independence have therefore been derived to define and ensure independence (NERC, 1975):

- discharge must fall by at least one-third of a peak value before rising to another;
- the time between successive peaks must be at least three times the mean time to peak of the river (Figure 3.1).

Both methods are well documented and although the advantages and drawbacks of each have been presented in many hydrological publications (Dalrymple, 1960; Shaw, 1988), they are worth repeating here for the purpose of justifying the choice of technique used in this study. Of the two series, the AM is obviously easier and quicker to create, with a fixed value representing each year of record. In contrast, with a POT series the number of floods recorded in each year of record is highly variable and in some years no flows may exceed the discharge threshold. However, such occurrences may be limited by carefully setting the discharge threshold. Although creating a POT series is clearly a more complex process, the value of such a series lies in the additional information on secondary flood peaks that it contains. This is information which is overlooked when using an AM series.

For the purpose of this study, it was decided to apply the Peaks Over Threshold method to the data collection for two main reasons. With a POT database of Scottish river flows already in existence (Acreman, 1985; Black, 1992), the data collection process would be easier and quicker than if starting from scratch and it would, in fact, be sensible to make use of an existing database. POT series are also the most appropriate for a study of this kind, which aims to examine variability in all aspects of flooding (frequency as well as the magnitude); using AM series would only facilitate a study of the latter characteristic.

3.2.4 THE EXISTING POT DATABASE

A substantial amount of Scottish river flow data was collected during the production of the *Flood Studies Report* (Volume IV NERC, 1975) and this provided a great

Figure 3.1: Rules of independence for creating a POT series:

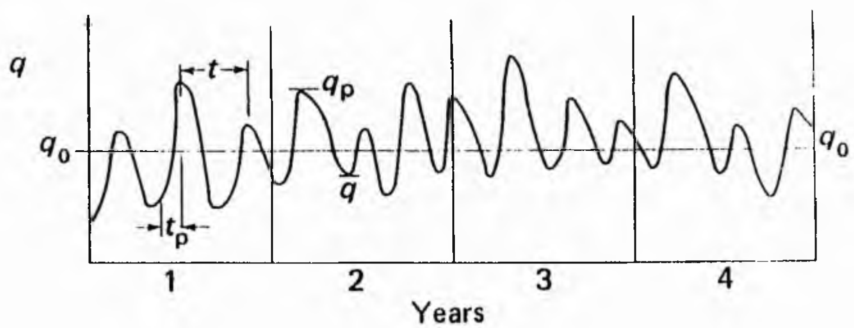
- discharge q must fall by at least one-third of a peak value before rising to another,

i.e. $q < 2/3\ q_p$

and

- the time between successive peaks must be at least three times the mean time to peak of the river

i.e. $t > 3t_p$



Years of record N = 4
Discharge threshold = q_0
Number of exceedances = 13

Based on Shaw, 1988

opportunity to research further the characteristics of Scottish floods. Research carried out by Acreman (1985) updated the *FSR* database during the early 1980s with further refinements and updating made in 1990 by Black (1992) for a study of the seasonality of flooding on Scottish rivers. This POT database contained over 4000 station-years of POT record for over 150 gauging stations in Scotland and Northumberland. Although this database was to provide the foundation for this study, a number of key amendments were necessary.

Black (1992) had previously used a comprehensive site selection procedure to refine the database, ensuring that all major drainage basins are represented with preference being given to the longer gauging stations records. Additional stations were chosen to fill in any apparent 'gaps' in the spatial coverage of Scotland. Given this information, it was felt that the database was appropriate to fulfil the required aims of this study, in terms of its spatial and temporal coverage. However, Black specifically designed this database for a study of flood seasonality and consequently emphasis was placed upon areas exhibiting unusual seasonal patterns (Northumberland, the Moray Firth and the East Lothian regions). Conversely, the Tay catchment area was under-represented in the database, largely because the hydro-electric schemes were seen to affect the natural seasonal patterns of river flooding. As a result of these specific features, the list of gauging stations within the database was amended slightly. The POT records from Northumberland were excluded from the database since they were originally included in the interests of seasonality only. The need to incorporate more data from the Tay RPB region was recognised as this is an area where flooding can be an important phenomenon. It was felt that the data from this area could be included in the database. Since these hydro-electric schemes were installed prior to river gauging, the resultant flow time series are valid since data are recorded under the same environmental conditions throughout the period of record. Although such schemes may have localised effects upon variability patterns within flood frequency and magnitude series, it is hoped that any underlying theme related to climatic variability will also be evident.

The final list of 122 gauging stations included in the updated POT database (Table 3.1 (Appendix One); Maps 5.1-5.4) represents all major drainage basins in Scotland, with the maximum spatial coverage possible. In some cases, these gauging station records had previously been used by Acreman (1985) and/or Black (1992); in other cases, the flow records were previously unused.

3.2.5 DATA COLLECTION

With a finalised list of gauging station records to be included in the database, the process of updating the existing POT records (and the creation of new POT series from gauging station records not used by previous researchers) could begin. To ensure uniformity within individual POT series, it was necessary to apply methods of data collection identical to those used and previously described by Acreman (1985) and Black (1992; also see Section 3.2.10 for details on setting a POT threshold).

3.2.5.1 PRELIMINARY PREPARATION

A small amount of preliminary preparation was necessary to ensure the data extraction process was carried out accurately and efficiently. This involved noting the discharge threshold, the stage-discharge rating equation and the dates of any previous POT data collected. The discharge threshold and the equivalent stage value (calculated from the stage-discharge equation) provide a guideline in the data collection. Dates of any previously collected POT series were necessary to ensure the new data collected followed concurrently from the previous record.

3.2.5.2 COLLECTION OF STAGE DATA

The majority of Scottish flow records are maintained and archived by the seven RPBs. Therefore, in order to update the POT database, it was necessary to visit the offices of each RPB. For each gauging station included in the database, the river flow records needed to update the existing series (or to create a new POT series) were identified. In the majority of cases, the process of data extraction involved manually viewing these records which are in the form of weekly charts of continuous river stage produced by autographic recorders. Where digital recorders were in use, the trace of water stage could also be viewed, usually on computer screen. From these charts and traces it is possible to identify peak flow events (represented as peak river stages). Within the existing POT database, all thresholds are set to record an average of four to five floods per year, a feature which is achieved by setting the threshold to ensure exactly forty-five events are recorded in a standard ten year period, from 1979 to 1988. However, it was decided that in the data collection process, information on the ten highest stages in each year would be recorded. This was thought necessary since there is the possibility that a change may have occurred in the stage-discharge rating equation, and that the stage level which coincides with the discharge threshold may have decreased. It is, on reflection, better to be over-cautious and collect too much information than to be left with insufficient data which would require the data extraction process to be repeated.

Having identified these possible flood events, it was then necessary to ensure that each peak complied with the rules of independence created for POT series (Section 3.2.3). In order to do this an additional parameter, the 'time to peak' had to be calculated. The procedure adopted for doing this (Black, 1992) is to note the time taken for each river to reach its peak for the first five peaks in the period of record studied, and to calculate the average of these values. The time to peak can then be noted and incorporated in the rules of independence. If these rules were met, then information on a peak (date, time and stage level) was recorded.

In addition to recording information on flood peaks, the dates and duration of any gaps within a gauging station record were noted (it is worth noting that, for the purpose of this project, the date confirms to a 'water day' which runs from 0900 to 0859 hrs. Having recorded information on all independent flood peaks and gaps within a gauging station record, the final task was to record the date of the last chart examined. This is required if the process of updating is repeated in future.

3.2.6 GAPS AND MISSING CHARTS

Although both autographic and digital recorders are designed to take continuous readings of stage, occasionally this is not achieved. A gap in record may result from mechanical breakdown, such as the failure of the rotating drum or a problem with the recording pen. In winter months, ice frequently freezes the float in place, preventing accurate recording. In some cases, gauging stations are vandalised and charts are destroyed. If a record contains a number of gaps which coincide with peak flow events at nearby gauging stations, one would expect the value of the record, for statistical analysis of flood events, to diminish. Specifications for including or excluding records based upon the length of any gaps is addressed in Section 5.3.3.3.

3.2.7 STAGE TO DISCHARGE CONVERSION

On completion of the visits to the RPBs, the large database of independent peak stage levels collected was put onto computer. In order to update the existing POT series, the next step in the process was to convert this information into peak discharge values. This was achieved using stage-discharge rating equations.

Stage-discharge rating equations are based upon the direct gauging of river flows. These gaugings are easiest to carry out at low or average flows, whilst extreme flow events are unfortunately rare and rather difficult to gauge. Therefore, although we can be fairly confident about the predictive abilities of rating equations at average water levels, the degree of confidence in their accuracy diminishes as the stage and discharge increase, particularly when a river exceeds the confines of the channel. Whilst the rating equations produced by the RPB are applicable to the full range of flows during the period within which the equation is valid, rating equations derived specifically for flood events are likely to offer greater consistency and accuracy. Although the stage-discharge rating at low and medium flows is likely to vary with time, particularly as the bed configuration changes and affects the nature of the relationship, such changes are likely to be of little significance to peak flow events.

Both Acreman (1985) and Black (1992) produced rating equations specifically for peak flow events, applicable to high stage values only. This was achieved by collecting as much information on peak stage and discharge measurements, as well as rating equations, from the *FSR*, the Surface Water Archive and from the RPBs themselves. This information was then used in combination with the software package HYDATA - a hydrological database which includes a facility for generating rating equations - to produce customised equations for high flows. This process was last bought up-to-date in 1990. Although it was anticipated that the majority of 1990 flood rating equations could be maintained for the newly collected data, to ensure the continued high quality information in the new database, it was decided to test the accuracy of those rating equations available.

In the first instance, advice was sought from the RPBs, to obtain opinions based upon their more localised knowledge of the river systems. For the majority of gauging station records, the RPB hydrologists felt that the high flow rating was unlikely to have changed in the period since 1990 and that the most appropriate course of action was to continue using these flood rating equations previously derived. For some of these records, the RPBs were able to provide details of gaugings carried out at high stage levels in the period subsequent to the previous flood rating equation being produced. These high flow gaugings allowed the accuracy of the existing flood rating equations to be checked, simply by comparing the gauged discharge with that calculated from the rating equation, given the recorded river stage. Where the rating equation could be tested in this way, it was found that the majority of equations were estimating discharges to within +/- 10% of the gauged flow. Given the degree of uncertainty in producing stage-discharge equations at the high end of the scale, these results were seen as being very satisfactory. However, in a very small number of cases, and particularly for those gauging stations which had been used in Acreman's study (1985) but not by Black (1992), the estimated discharge was found to be in error by up to 30%. Obviously in such extreme situations a new flood rating equation was required. The decision was also made to set up an arbitrary threshold of +/- 20% whereby if the degree of inaccuracy between the actual and estimated discharges exceeded this threshold, the current rating equation would have to be changed. A warning to investigate the situation further was flagged if inaccuracies were exceeding the +/- 15% level. For those stations where the rating was deemed unusable a new equation was produced. It was also necessary to create rating equations for those new gauging stations introduced into the database for the first time.

3.2.8 CREATION OF PEAK FLOW RATING EQUATIONS

The creation of peak flow rating equations is a complicated process with several contentious issues. The initial question which must be asked is from what point in the record should the previous rating equation be rejected in favour of the new. In the majority of cases, it was possible to identify a time period during which the stage-discharge had changed (commonly the period from when the equation was last applied until the date of the gauging which suggests an inaccurate prediction). One could suggest numerous possibilities about when the stage-discharge relationship changed. It is possible that the bed configuration has changed following an extreme event or it may be a consequence of acquiring more flood data which has improved the ability of HYDATA to model the frequency-magnitude relationship. For simplicity's sake it was decided to apply the new equations after the date of the largest flood event in the stated time period.

Having decided on the date from which the new equation should be applied, it was necessary to create the new equation. One of the functions of the IH software package, HYDATA, is to create rating equations. To produce the rating equation, at least two flow gaugings must be input into the program but obviously accuracy increases with the amount of data available. For a number of the gauging stations requiring a new flood equation, only one or two high flow gaugings were available and it was therefore necessary to input additional information into the HYDATA program. This additional data was taken from the Institute of Hydrology (IH) Hydrological Yearbooks which contain accurate discharge data for major flood events. Combined with the stage levels recorded for these flood events (noted during the data collection process), it was possible to enter these flows as pseudo-gaugings. A peak flow rating equation, with distinct stage limits, was then created.

3.2.9 THE APPLICATION OF RATING EQUATIONS

The flood equations, or set of equations, deemed satisfactory for each gauging station within the POT database, were then applied to the stage data collected, in order to create a set of peak discharges. It was then possible to extract those events which did not exceed the pre-defined discharge threshold. These 'new' data, most commonly covering the period from 1990 until mid 1993, were added to the existing POT series.

3.2.10 SETTING A POT THRESHOLD

Thresholds within the POT database, set to record an average of four to five floods per year, were standardised by Black (1992) to allow direct comparison between different gauging station records. This standardisation process involved a standard ten-year period being defined from 1979 to 1988. During this period, all thresholds were adjusted to give exactly forty-five POT events, thus producing an exact average of four and a half events per year, a value which complies with *FSR* recommendations (NERC, 1975). This allows all other periods to be contrasted with this standard, hence making it possible to determine the time periods displaying above or below average flood frequencies. One key point of setting a threshold, however, is that it is only possible to retrospectively increase it but not to lower it without the need to collect additional data. During standardisation, a small number of POT records were found to have less than forty-five events in the standard period so the current threshold is and remains set too high to allow direct comparison with standardised series (Table 3.1).

For those POT series not previously included in the database and those records only previously used in Acreman's study (1985), it was necessary to create the same standardised thresholds, applying the same rule of setting the threshold to record exactly forty-five POT events in the ten-year period from 1979-88.

3.2.11 SUMMARY REMARKS

Following the processes of data collection, stage-discharge conversion and the setting of thresholds described above, it is hoped that the POT records are as accurate as possible, given the difficult and contentious issue of flood ratings.

3.3 CLIMATIC DATA

3.3.1 AVAILABLE SOURCES OF CLIMATIC DATA

Having updated and amended the existing POT flow database, it was necessary to address the question of how to study climatic variability in Scotland. One of the basic requirements is that it should be possible to directly link the variable chosen to the incidence of flood events.

The most obvious choice would be to create a Scottish rainfall database since flood events are most closely related to peak rainfall events. The most appropriate method of doing this would be to collect data from raingauges in catchments in close proximity to those gauging station records included in the POT database and to use a similar POT approach to data collection. It was, however, envisaged that such a method would be very time consuming since determining the link between precipitation and discharge is a complex process which requires a considerable degree of spatial and temporal detail. Similarly, the results of any such analysis would be limited since variability in flood series is generally assumed to be some reflection of rainfall patterns. The key point to be discussed is what is causing the variability (if any is detected) in flood (and possibly rainfall) series.

A second variable which is often associated with Scottish floods is snowfall and subsequent melt events. The relative importance that melt makes upon flood events is highly variable and it is, in fact, a very difficult variable to measure. There are very few data available on snowpack characteristics in Scotland and consequently it could not be included as a quantitative value in a study such as this.

A third method available for study is the daily record of synoptic weather types. Such records are a measure of the daily airflow direction or isobaric pressure patterns (Barry and Chorley, 1987). In the UK, the Lamb classification is one such well established method which has often been used to study climatic variability in the past (Section 2.5.3). This method was seen as appropriate for this study since it would be possible to relate any variability within flood patterns to variability within the synoptic climate of Britain. Flood events in Scotland are most commonly driven by the passage of rain-bearing winds, so ultimately the use of weather types is a fundamental part of searching for an explanation of the temporal and spatial patterns detected in flood series, and goes one step further than the examination of rainfall data could. In using these data, it would also be necessary to identify those weather types which are most commonly associated with rainfall events which lead to flooding. However, because of the criticisms often cited at the Lamb record (Section 2.4.4), it was also decided to incorporate the Mayes regional record (Section 2.4.5) into the analysis process.

In summary, therefore, it was decided to use daily synoptic weather type as the index with which to study climatic variability, mainly because it offers the opportunity to study how and why flood patterns vary in the context of the synoptic scale. This could not be achieved by using any other climatic variables. Both the Lamb and Mayes daily weather type records would be analysed, in order to examine climatic variability but it was hoped that the inclusion of the Mayes record would reveal more precisely the nature of climatic variability in Scotland.

3.3.2 DATA COLLECTION

One of the advantages of using the Lamb and Mayes records is that the data are stored and updated on computer. The daily Lamb record was made available from the Climatic Research Unit at the University of East Anglia, for the period 1861-1992. In its raw data format, it consisted of a list of daily weather types, each with a numeric code. It was therefore necessary to convert this information into the correct alpha-numeric code (A for Anticyclonic, SW for South-Westerly etc.) and to sort the raw data into monthly and yearly blocks. The daily regional record for Scotland, 1950-92, was supplied by Dr Julian Mayes at Roehampton Institute.

3.4 SUMMARY STATEMENT

To summarise, therefore, at this stage of the project, one-hundred and thirty-four POT records and two synoptic weather type databases had been created and input onto computer. Having acquired this information, it was then necessary to explore the available methods of data analysis in order to fulfil the key project aims.

CHAPTER FOUR

TECHNIQUES OF DATA ANALYSIS

A review of the statistical techniques available for the analysis of hydrological and climatic time series

4.1 INTRODUCTION

In any research project, the acquisition of a suitable database only solves half of the problem. To address the key project aims and objectives, sufficient information must be obtained from the raw data and therefore the most appropriate statistical techniques must be applied. This chapter describes and evaluates a range of methods which may be suited to the research aims of this specific project.

To determine which statistical techniques are appropriate to this study, the main research goals were considered in detail. With respect to the Scottish flood record, the key objectives were identified as follows:

- to determine how the frequencies and magnitudes of flood events vary from year to year within individual records;
- to divide individual records into smaller sub-periods, according to the above results in order to examine the effect of temporal variability upon traditional methods of flood frequency analysis;
- to determine whether there is a common theme (or set of themes) to the temporal variability patterns;
- to determine whether temporal variability patterns are linked to the geographical location of gauging stations.

Similarly, with the Scottish climatic series, the aim is:

- to determine how the climate of Scotland (in terms of the annual frequencies of synoptic weather types) has varied, over similar time spans as the flood series.

This analysis should then facilitate a comparison between the two sets of results to explore whether a relationship can be hypothesised between climatic variability and the characteristics of Scottish flood events.

4.2 TIME SERIES ANALYSIS

Having established what was hoped to be achieved from the data analysis process, the techniques available to fulfil these aims were investigated and evaluated. From the project aims set out in Section 4.1, it was clear that the principal techniques would need to examine how a variable (annual flood frequencies, magnitudes or synoptic weather type frequencies) has fluctuated with time and therefore the appropriate type of statistics to use would be Time Series Analysis.

A time series is simply a collection of observations of the same phenomenon, made sequentially in time (Chatfield, 1984). Commonly, a distinction can be made between discrete and continuous time series, the former applying to a series of observations made at set times, over equally spaced intervals and the latter series comprised of observations made on a continuous basis. Very often, however, discrete time series are created as aggregates of a continuous record, where continuous observations are accumulated over equal periods of time (weekly, monthly or annual observations, for example; Chatfield, 1984).

The creation of a time series allows a number of important objectives to be fulfilled regarding the nature of the raw data collected, although all observations must be made under the same environmental conditions if the analysis is valid (Yevjevich, 1972). At the most basic level, time series analysis can be a good *descriptive* tool by allowing simple observations on how variables behave over time. This is commonly achieved via graphical plots of the data series (Diggle, 1990). Such methods also provide useful indications of the presence of extreme observations or outliers within the data series.

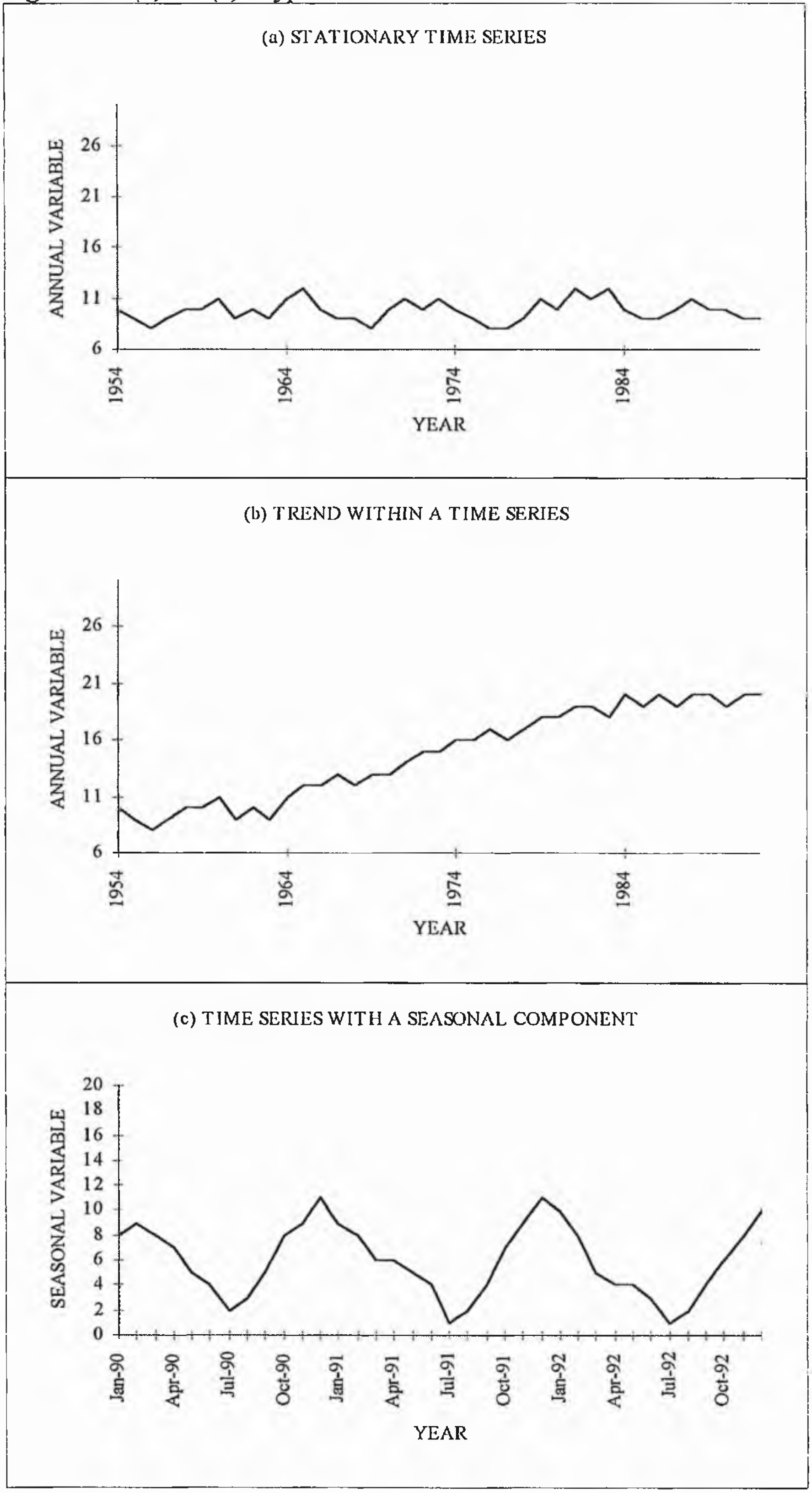
A slightly more complex objective of time series analysis is the process of *explanation*. This can be achieved when two or more related series, covering the same time interval, are available. Under such circumstances, it may possible to explain some of the variation in one time series with reference to the variation in the other, thus identifying some link. It is also possible to *predict* and *control* the behaviour of a data series. Prediction techniques aim to model the future behaviour of a time series, whilst methods of control involve the identification and modification of the causal mechanisms within a series, to ensure future values meet specified requirements (Chatfield, 1984). Of these four time series applications, techniques for description and explanation are the most widely used since prediction and control methods tend to be extremely complex with often greatly reduced levels of reliability. Certainly, for the purpose of this project, time series analysis should only need to concentrate upon techniques of description and explanation.

In the process of time series description, a number of features may be detected within the time series, most notably stationarity (Figure 4.1a), trend (Figure 4.1b) and seasonality (Figure 4.1c). A data series displaying stationarity is one whose statistical properties, such as the mean and variance, do not change to any significant extent with absolute time. Conversely, a trend within a time series will be characterised by a long term change in values, which will be exhibited by changes in the statistical properties of the series. A seasonal effect within a series may be occurring if there is a repetitive variation within the data values, on an annual basis. Similarly, time series analysis can detect cyclical components which may occur over longer periods of time (Yevjevich, 1972).

One extremely important factor which must always be taken into consideration, when using time series analysis to detect any such features, is the length of record which is being analysed. A record which covers just twenty observations may, for example, appear to be displaying an upward trend in values. However, this apparent trend may in fact be a component of a thirty-year cyclical variation which would only be detected over a much longer period of record (Chatfield, 1984).

In summary, therefore, the main functions of time series analysis are to describe the temporal behaviour of a data set and attempt to explain any possible causal relationships with other time series. In some circumstances, advanced analysis may allow predictions on how the time series may behave in the future and, if possible, attempts can be made to control this behaviour.

Figures 4.1(a)-4.1(c): Typical Characteristics evident within time series



4.3 TIME SERIES STATISTICS

A wide range of time series statistics are available, from simple descriptive methods to the more complex spectral analysis techniques. The benefits of each method are very much dependent upon what one is seeking to achieve from the analysis process.

4.3.1 SIMPLE DESCRIPTIVE TECHNIQUES

The most basic time series technique, which should always be used as the first stage of analysis, is the time series plot. This is simply a graphical representation of the data series, which is created by plotting the value of each observation against time. Although this is a simple technique, it provides a useful first impression of how the data series has behaved prior to the application of more advanced techniques. The plot may be enhanced by joining the points together but this often gives the impression of a continuous series, which is not always the case (Diggle, 1990).

A time series may also be described using basic statistics, such as the mean, standard deviation and coefficient of variation. Although such statistics are commonly calculated from the entire period of record available, basic statistics based upon shorter sub-periods of a record can be useful for detecting variability within a series.

4.3.2 FILTERING AND SMOOTHING

Filtering or smoothing techniques pass a time series through a mathematical filter, such as a statistical formula, in order to suppress random or local fluctuations. The series output allows the true variability in the data to be observed (Chatfield, 1984). The process of smoothing is one type of filter which separates the long term, meaningful information from any white (random) noise within a record .The 'smooth' components, such as trends and cycles are therefore separated from the 'rough' component (white noise). One of the simplest, most widely used types of filter is the moving average or running mean method. This smooths the time series, such that the output value is dependent not only upon the relevant input value but also upon preceding and subsequent values (Davis, 1986).

4.3.3 AUTOCORRELATION AND PARTIAL AUTOCORRELATION

Correlation coefficients are used in time series analysis to assess the correlation between observations in the series at certain distances, or lags, apart. This helps to determine whether observations are independent of one another, or whether there is a degree of 'memory' within the series (Haan, 1977). Autocorrelation coefficients or functions (ACF) can then be plotted as correlograms, graphs of correlation coefficient against lag time.

The correlogram produced by a purely random time series should, in theory, contain correlation coefficients approximate to zero for any given lag, since there should be no correlation between values. However, this is rarely seen in practice and purely random time series can often display significant correlation coefficients. If a correlogram displays high correlation values at short lags, and gradually decaying values as the lag increases, the time series is said to be stationary whilst a non-random time series will rarely show zero correlation coefficients and trends will be depicted by very slowly decreasing correlation values. Seasonal fluctuations are represented as correlations which fluctuate at the same frequencies (Chatfield, 1984).

Partial autocorrelation functions (PACF) may also be used to classify a time series, and are broadly similar to ACFs in that they also measure the relationship between pairs of values. However, PACFs measure the relationship between X_t (an observation X at time t) and X_{t+k} (at lag k) whilst accounting for the effects of intervening X values (Pankratz, 1983). However, a criticism often directed at ACF and PACF is that very different time series can produce the same autocorrelation function:

"autocorrelation function is, in general, an incomplete descriptor of serial dependence, in the sense that random processes whose realisations are qualitatively different can share the same autocorrelation function" (p.35 Diggle, 1990)

4.3.4 SPECTRAL ANALYSIS AND PERIODOGRAMS

Spectral analysis is useful for describing the nature of cyclical phenomena within a time series, where processes are repeating themselves in a regular fashion (Kendall and Ord, 1990). The aim is to break the time series up into periods and explain each variation as a spectral function, according to the frequency, wavelength and amplitude of the cycle (Davis, 1986). The nature of these cycles are often plotted as periodograms (Chatfield, 1984).

4.3.5 CUSUM CHARTS

Cusum, or cumulative sum, charts graphically depict changes in the mean within a time series, and are useful in locating the point at which such changes occur. This is a possible technique for detecting variability with flood and climate series. However, a great deal of preparation is required to produce individual charts and the technique is best applied to data from normal distributions (Bissell, 1985).

4.3.6 RUNS TESTS

The detection of runs within a data series is a method which may be used to distinguish random and non-random time series. A run is simply an interrupted sequence of data of the same state or type, such as values above/below a long term mean. A runs test compares the actual number of runs observed with the number of runs that would be expected in a purely random time series (Davis, 1986).

4.4 HYDROLOGICAL AND CLIMATIC TIME SERIES

Time series analysis often plays an important role in assessing how hydrological and climatic variables change with time, largely because such data are commonly measured at fixed locations (rain gauges and gauging stations, typically) over specified periods of time. A common technique in hydrological and climatic analysis is to aggregate continuously measured values into discrete ones which cover fixed intervals of time (Section 4.2; Yevjevich, 1972).

Numerous techniques have been employed, such as mean daily and mean monthly flows, in order to create discrete series from the continually recorded river flow records. Discrete sequences may also be obtained by rule-selecting particular values (Yevjevich, 1972). In hydrology, such an approach is commonly used in creating peak flow series using the Peaks Over Threshold (POT) technique. Climatic indices are similarly aggregated in such ways, with total annual rainfall and monthly frequencies of synoptic weather types being just two examples of the many different methods used.

If changes in the nature of discrete hydrological time series are visible, they are most probable gradual changes or fluctuations which result from similar fluctuations in either the natural environment or as a reflection of man's impact on the environment. In exceptional circumstances there can be a rather dramatic 'jump' or step-change in the hydrological series, as a direct consequence of a unique, one-off event, such as the construction of a dam or flood defences (Haan, 1977). Similarly, climatic fluctuations are typically gradual rather than sudden.

4.5. THE WORLD METEOROLOGICAL ORGANISATION

Having gained an understanding of the main time series techniques available for the analysis, an examination was made into existing studies and recommendations for analysing hydrological and climatic series with respect to detecting variability. One such study was initiated by the World Meteorological Organisation (WMO) as part of the World Climate Programme (WCP) in the 1980s, in order to:

"assist societies to improve their capabilities to carry out various activities and to obtain maximum economic and social benefit under different climatic conditions while maintaining environmental integrity".

(Section 1.1, WMO, 1988)

Within the WCP, four key components were identified for further research and attention. Consequently four key programmes were initiated, for Climatic Data, Climate Applications, Climate Impact Studies and Climate Research Programme (Section 1.1 WMO, 1988). Since some aspects of hydrology and water resources are common to all four programmes, a separate body, WCP-Water, was established to oversee all water related activities. Its written objective is to:

"meet more effectively the socio-economic needs which depend on water resource systems, through the improved application of climate data and information".

(Section 1.2, WMO, 1988)

As part of WCP-Water, two projects were established to deal specifically with the analysis of hydrological data and related information, the first with respect to climate and the second with respect to climate variability (Section 1.3, WMO, 1988). It is the second project which is of concern here since its key aims are to improve knowledge of hydrological variability in the context of climatic variability, to provide information on the effects of climatic variability on hydrological systems, to provide information on possible trends in climatic variability that are evident in the hydrological series and to encourage the collection and analysis of long term hydrological data (Section 1.5, WMO, 1988).

As part of this project a computer program of time series statistics was produced for the purpose of analysing hydrologic and climatic series for variability. By producing this program, it was hoped that it could be applied to time series world-wide, creating a consistent set of analyses. This would therefore allow direct comparisons between time series from different regions, countries and even continents. This program includes an extensive collection of time series statistics which can directly detect temporal variability within any time series and can facilitate a study of spatial variability (Sections 6.1 - 6.2, WMO 1988). As this computer program was available for use and had previously been used in a successful study of flow variability (NCH, 1995), it was decided to evaluate its functions in the context of this research project, and to determine whether it would fulfil the key project aims. This assessment process involved a pilot study, analysing a small group of POT series using the WMO time series program (WMO, 1988).

4.5.1 DATA MANIPULATION

In order to analyse any time series with the time series program (WMO, 1988), certain data input requirements have to be met. In order to fulfil these requirements, a degree of data manipulation was required on the POT series.

4.5.1.1 TIME SERIES REQUIREMENTS

Each POT data series follows the format displayed in Table 4.1, to include information on the discharge threshold, the start and end of record dates, the date and discharge ($m^3 s^{-1}$) of each flood event and any gaps within the record.

Table 4.1: Standard format of a peaks-over-threshold data series

DATE	DISCHARGE m^3s^{-1}	CODE
1964 1 10	105.000	101
1964 1170	108.245	104
1964 2 20	110.540	104
1964 3110	126.750	104
1964 9300	98.000	103
196411 50	95.680	103
196411100	154.320	104
196412 10	111.500	104
1965 1 70	128.000	104
1965 4260	0.000	105
1965 4300	0.000	106
1965 9110	99.100	103
1965 9180	109.611	104
196510 10	134.800	104
.		
.		
.		
.		
.		
1992 2 20	141.200	104
1992 3 10	97.000	103
1992 6300	0.000	105
1992 7 30	0.000	106
199211100	132.000	104
199212120	156.000	104
199212310	0.000	108

1992 6300	signifies the date of the POT event (in this case 30/6/1992)
Code 101	signifies the start date of the record and the standardised POT threshold
Code 103	signifies a POT event which exceeds a previous threshold but does NOT exceed the standardised threshold
Code 104	signifies a POT event which exceeds the standardised threshold
Code 105	signifies the start date of any gaps
Code 106	signifies the end data of any gaps
Code 108	signifies the end date of the POT record

The WMO program allows the input of a time series which can contain data on either a monthly or yearly basis (*one value* for either each month or year of record). The monthly format was dismissed as being inappropriate since, on average, only four or five events floods occur each year. Therefore, a large proportion of months in any one year are characterised by no POT events and consequently would be represented by a zero value (whether they were representing flood frequencies or magnitudes). This makes the calculation of meaningful time series statistics difficult. The annual interval was therefore adopted as being most suitable for this study.

4.5.1.2 FLOOD FREQUENCIES AND MAGNITUDES

The original project aims clearly state that variability is to be explored in both the context of flood frequencies and flood magnitudes. Consequently, it was necessary to create annual series on both parameters from the original POT data. Creating an annual flood frequency series using a single yearly value was a fairly straightforward process which could be achieved by simply counting the frequency of POT events above the standardised threshold in each year of record (Table 4.2). Retrieving a single, annual value to represent flood magnitudes was a process requiring further thought. A number of possibilities were explored but the method finally chosen, known as the 'Mean Exceedance' or 'Mean Excess' method (Naden, 1992), is a single value which represents the mean exceedance of POT events above the standardised threshold in each year of record. This annual value was calculated using the following formula:

$$\text{Annual Mean Exceedance} = \frac{\sum_{i=1}^{n} (d_i - T)}{n_i}$$

where

d = discharge of POT event

T = POT threshold

n = annual frequency of POT events

This method seemed appropriate since it computes an annual value relative to a specified base point, the discharge threshold.

4.5.2 PROGRAM REQUIREMENTS

The WMO computer program also makes certain restrictions on the data that are input:

'The program allows up to max. 200 years of monthly values, plus up to a maximum five optional data sets on an annual basis, each of them of the length maximum 200 years (annual extremes for instance) to be examined'

and

'Time Series must contain only complete years'.

(WCP - Water Project A.2 Computer Program User Manual, WMO 1988)

Since the flood data series were based on annual time intervals, they were input as one of the optional data sets on an annual basis (see above), which are designed for the analysis of extremes values, such as peak flow events. Unfortunately, the program can only be run for optional annual sets in addition to a standard monthly data set, although the statistical analysis is carried out separately. Hence, it was necessary to input a 'dummy' monthly data set for each optional set entered.

It is also a requirement that any time series analysed includes data for complete years only. Typically each POT record within the database begins on the first day of the calendar year although the end of record date is more variable. Since the process of updating the existing POT records occurred during the spring and summer of 1993, the majority of records finish sometime during this period. Unfortunately those POT events recorded in 1993 could not be included in the analysis since they did not constitute an entire year of data. Therefore, for those updated records, the series analysed were complete until 31/12/92 and for those records taken out of use prior to this date, the time series analysed were terminated at the end of the last complete calendar year.

Along with the time series to be analysed, a number of control parameters must also be included as data input:

'An input data set consists of two control input records, the set of input monthly data records, and none or up to five optional sets of data on an annual basis' and

'The 2nd (annual optional set) record of input control parameters (read by the main program):

NYRS - total number of years of the input data series

IFY - first year of given time series period

ICY - coincident year of analysis
(the year in which all sub periods are to coincide)

NA - number of data sets on an annual basis'.

(WCP - Water Project A.2 Computer Program User Manual, WMO 1988)

Of these input parameters, the most obvious are NYRS, IFY and NA. The former two varied according to the record analysed, whilst NA was typically set at a value to two, (there were two time series produced from each original POT series, one representing flood frequencies and one representing mean exceedances). The coincident year of analysis (ICY), which specifies a year at which all sub-periods coincide, remained for all time series analysed to allow a direct comparison of results.

The program manual also makes recommendations concerning the quality of the data series input, with respect to its consistency, homogeneity and accuracy. Specifications regarding consistency in the measurement of data, processing techniques and the environmental conditions of data and regarding the quality of river flow data (Sections 3.2-3.4, WMO, 1988) were all observed. Very precise recommendations are also made concerning the presence of gaps within the time series analysed:
'Few long time series are continuous but, if possible, those used in the project should not have gaps totalling more than 5% of the record and these gaps should be filled in by the data owner using recognised methods'.

(Section 3.5.2, WCP - Water Project A.2 Program User Manual, WMO 1988)

Although a proportion of the original POT series do contain gaps, these generally cover two or three consecutive days, at most, and certainly do not usually constitute more than 5% of record. However, a very small number of POT series were rejected from the analysis process either because there were long continuous periods when no data were available (at times when records from adjacent rivers were recording flood events) or because there were too many gaps for the time series to be wholly reliable. Although it could have been possible to create artificial data for these records, it was decided that the time involved in such tasks would outweigh the benefits of including a very small number of records, which were, in fact, in areas already adequately represented by other series.

For any time series to be included in the analysis process, minimum time durations are recommended (Section 3.5, WMO, 1988). For precipitation and air temperature data, a minimum record length of fifty years is suggested, whilst this value is lowered to thirty years for all other data sets. Stations with forty years of record or more are deemed long enough to study both spatial and temporal variability, whilst records of less than forty years are seen as suitable for spatial variability studies only (Section 3.5.1, WMO, 1988). These recommendations are discussed in further detail, with reference to this study, in Section 5.7.

4.5.3 STATISTICAL METHODS

Once it was decided that the sub-sample of POT series had met the project requirements specified above, analysis using the time series program was carried out. A brief summary of the statistical output and its potential benefit to this study follows.

A considerable array of Basic Statistics (Section 5.A-G, Appendix C, WMO, 1988), which range from means and standard deviations to the coefficients of skew and kurtosis, are calculated for the entire period of record input as well as shorter sub-periods (five, ten and twenty-years long), specified by the parameters described in Section 4.5.2. Sub-periods which are displaying unusual characteristics in comparison with other sub-periods can therefore be identified. Similarly, it is also possible to detect gradual increases or decreases in values, by observing the value of sub-period means. The variables likely to be most relevant are the means, standard deviations and coefficients of variation.

The Kruskal-Wallis test of equality of sub-period means is carried out to test whether the sub-period means previously calculated are statistically equal (Section 5S,

Appendix C, WMO, 1988). The same test is also computed for sub-period variances (Section 5T, Appendix C, WMO, 1988). Having analysed the subsample of POT records, it was found that this test yields some useful information on the nature of the time series, by identifying periods with particularly high or low flood frequencies or mean exceedances. However, one possible drawback with this technique is that the sub-periods tested are based upon fixed intervals (five-years, for example) and it does not necessary follow that the timing of changes within the time series will coincide with these sub-period divisions. Consequently, this sub-period analysis does little to specify the *exact* timing of changes in sub-period statistics (Table 4.2(a))

The Runs test (Section 5P, Appendix C, WMO, 1988) is also carried out upon the input series. This compares the actual number of runs (a set of consecutive observations above or below the median observation) within the time series with the number expected from a random time series of the same length. If the number of runs is particularly low, there is the possibility that there is a trend within the data. Although this technique is useful for categorising a time series as either random or non-random, it also produces a possible method for dividing a time series into hydrologically similar sub-periods (Table 4.2(b)).

A cumulative periodogram (Section 5K, Appendix C, WMO, 1988) is also included in the analysis, in order to determine whether the series approximates to a white noise process. This technique appeared to have very limited importance during the sample analysis, since it sheds very little light on the pattern of temporal variability within a time series.

More useful techniques are the Mann's tests for trend in the mean and trend in the variance (Section 5Q-5R, Appendix C, WMO, 1988). The output, in the form of test statistics and graphics, can be used to determine whether the mean (or variance) of the time series behaves in a random, stable manner or whether variability exists. During the preliminary analysis, it was apparent that the graphical analysis depicts a plot very similar to a running mean (or variance). However, its additional value is that it is possible to determine the statistical significance of fluctuations within the series, such that statistical trends can be identified. Under the null hypothesis of a random series, the test statistic u(i) is approximately zero. If u(i) is decreasing or increasing away from zero then the series is displaying decreased or increased values respectively. If the test statistic crosses certain confidence intervals, then this can be interpreted as a statistical trend. First impressions point towards these diagrams as being the most valuable in the identification of hydrologically similar sub-periods. The advantage of this technique is that it reveals changes in the mean on an annual basis and will therefore indicate precisely the occurrence of turning points within the data series. This specific test statistic is based upon Kendall's rank correlation coefficient *t* and is statistically very efficient when compared with the corresponding parametric test (Table 4.2(c)).

The Mann's trend in the mean technique is not, however, without limitations. During the preliminary analysis, a number of key points were raised. These points suggest that the value of the test statistic is very much dependant upon the previous state of the time series. If a raw data time series is displaying a large increase (or decrease) in values and, whilst the test statistic is mimicking this change, it is not exceeding levels of a significant upward (or downward) trend, it is likely that the test statistic has had to recover from a very low (or high) base point. Similarly, if a minor increase (or decrease) follows on from a period when values were already at a high (or low) level, a significant trend may be registered as a highly significant upward (or downward) trend. It is therefore extremely important to be aware of the 'state' of a time series prior to any trends observed and to consider this limitation in the data interpretation process. Similarly, it is also necessary to be aware of the length of time period over which decreases/increases in values have occurred. Very recent changes, which have occurred over a few years of record will rarely register as statistically significant trends.

Although these limitations are evident, they do not affect the ability of this technique to determine the timing of any changes and turning points in a time series, and its use for dividing a time series into hydrological sub-periods. Additional techniques, such as basic sub-period statistics, may aid the interpretation of the Mann's trend test.

Table 4.2: A list of the formulae used in the WMO time series program (WMO, 1988)

(a) THE KRUSKAL-WALLIS TEST OF EQUALITY OF SUB-PERIOD MEANS (Sneyers, 1975; WMO, 1988)

H_0 = *Equal sub-period means*

H_1 = *Unequal sub-period means*

Let m *be the number of sub-periods with lengths* n_j (j = 1, 2, ..., m) *and* R_{ij} *the rank of the* ith *observations of the* jth *sub-sample in the ordered complete sample*

Let $R_j = \sum_i R_{ij}$

Let $N = \sum_i n_j$

The test statistic is

$$XS = 12\sum_j (R_j^2 / n_j) / [N(N+1)] - 3(N+1)$$

Under the null hypothesis of equal sub-period means, this statistic follows the Chi-square distribution with (m-1) degrees of freedom

(b) THE RUNS TEST (WMO, 1988)

H_0 = *Random time series*

H_1 = *Non-random time series*

Let n = *number of data in the series*

Let n_r = *number of runs*

Under H_0 *the expected number of runs is:*

$$E(n_r) = 1 + (n/2)$$

and the variance

$$Var(n_r) = n(n-2)/[4(n-1)]$$

The test statistic is:

$$Z = [n_r - E(n_r)] / [Var(n_r)]^{1/2}$$

Table 4.2(cont): A list of the formulae used in the WMO time series program (WMO, 1988)

(c) THE MANN'S TEST FOR TREND IN THE MEAN (Sneyers, 1975; WMO, 1988)

For a given time series $x_1, x_2, \ldots\ldots\ldots, x_n$

the corresponding ranks of data elements are $y_1, y_2, \ldots\ldots\ldots, y_n$

The hypotheses to be tested then become:

H_0: *observations are randomly ordered in time*

H_1: *a trend over time (direction unspecified)*

For each element x_i, *or its rank* y_i, *the number* n_i *of elements* y_j *preceding it, where* $i>j$, *is calculated such that* $y_i>y_j$

The statistic t *is then given by:*

$$t = \sum_1 n_i$$

and its distribution function, under H_0 *is asymptotically normal, with mean and variance:*

$$E(t) = \frac{n(n-1)}{4}$$

and

$$Var(t) = \frac{n(n-1)(2n+5)}{72}$$

In the absence of any assumption regarding the existence of a trend in a given direction, the test is correct only in its two-sided form

H_0 *must therefore be rejected for high values of the test statistic* $|u(i)|$ *with:*

$$u(i) = \frac{[t - E(t)]}{\sqrt{Var(t)}}$$

In particular, if the probability α_1 *is determined using a standard normal distribution table such that* $\alpha_1 = p(|u| \rangle |u(i)|)$ *the null hypothesis is accepted or rejected at the level* α_1 *depending on whether* $\alpha_1 \rangle \alpha_0$ *or* $\alpha_1 \langle \alpha_0$

When the values of u(i) *are significant, an increasing or decreasing trend can be observed depending on whether* $u(i) \rangle 0$ or $u(i) \langle 0$

At the 0.05 confidence interval, the critical value of u(i) *is 1.96 whilst at the 0.10 confidence interval, the critical value is 1.645.*

A method for smoothing the time series, a Gaussian filter (Section 5V, Appendix C, WMO, 1988), is included in the program. This is particularly useful for eliminating short-term fluctuations (low pass filter). Prior to using this technique, it was hoped that this may also provide information on variability and trends within the time series. However, it was later found that the records being used for this study were, however, too short to create a meaningful output from the filter.

The final statistic computed for annual time series is the Jump in the Mean (Section 5U, Appendix C, WMO, 1988), a method useful in detecting sudden changes in the value of the mean. Two methods of identifying jumps are provided, and test statistics are output such that the statistical significance of these jumps can be determined. Since jumps in hydrologic time series are most likely to result from sudden environmental changes, either natural or man-made (Haan, 1977), it is unlikely that this method would be sensitive enough to determine gradual patterns of variability.

4.5.4 SUMMARY REMARKS

Having used the WMO statistical package on a small subsample of POT records, it was decided that there was a sufficient range of time series techniques to fulfil the questions posed on the detection of temporal variability within flood records. The one real omission is a filter which can be used on relatively short records, to remove short-term fluctuations in the series to reveal the underlying pattern. It was decided that a five-year running mean filter would be used in addition to the WMO statistics in order to compensate for this omission.

Although not tested, it was felt that these statistics could similarly be applied to the climatic database in order to describe temporal variability. With a one value per year limitation, it was decided that the series analysed would constitute the annual or seasonal frequency (days per year or per season) of each weather type being recorded.

By applying the same techniques to each data series, whether it is a flood frequency, mean exceedance or climatic series, the remaining project goals could be achieved, by comparing results from different geographical locations and to determine the nature of any relationship between flood series and the climate.

4.6. MINITAB

While the time series software (WMO, 1988) incorporates some of the more complex statistical techniques, it overlooks some of the simpler techniques which often give a good first impression of the behaviour of the raw data. It was therefore decided to seek additional techniques which could provide this first insight into the nature of a time series.

Minitab (Version 7.2) is a 'general purpose data analysis system for organising, analysing and reporting statistical data' (Minitab, 1989). The Minitab software does incorporate a wide variety of statistical techniques, including some time series statistics. Using the subsample of flood series used to test the WMO program, a number of Minitab commands were explored. Those listed below were found to give some very useful descriptive information on the data series.

HISTOGRAM (Section 5-2) and DOTPLOT (Section 5-3) are both techniques which graphically display the distribution of data values, so that the range of values can be emphasised whilst identifying extreme observations or outliers. The RANK command (Section 16-2) ranks each year within the series (in ascending order) according to the flood frequency or mean excess value. This enables those years recording extreme values to be identified. These extremes can be further emphasised by the BOXPLOT command (Section 14-4), which depicts the important statistical features of a data series, including the median, the upper and the lower quartiles, and possible and probable outliers. The final command used for simple descriptive purposes was the Time Series Plot (TSPLOT; Sections 5-11, 5-14), a simple plot of the time series.

4.7 SUMMARY STATEMENT

Having explored a range of statistical techniques available for the analysis of the hydrologic and climatic series, it was concluded that a number of simple Minitab techniques could be employed to gain preliminary information on the behaviour of the hydrological time series collected.

In addition to these statistics, a number of methods included in the WMO program could then be used to fulfil the key project aims, i.e. to provide a greater understanding of the variability within climatic and flood series, and to explore the links between these two components. It was felt that this piece of software was the most suitable option since it was designed specifically for studying hydrologically variability and has been widely used in other areas of Europe (NCH, 1995).

Following a pilot study of the time series statistics, the Mann's trend test was judged to be the most robust for describing the year-to-year variability within a time series, and allowing key turning points to be detected. Nonetheless, additional techniques (notably time series plots, running mean plots and sub-period statistics) were seen to be necessary to confirm the findings of the previous methods and to overcome some of the problems associated with the Mann's trend test (Section 4.5.3).

CHAPTER FIVE

VARIABILITY WITHIN SCOTTISH FLOOD RECORDS

A detailed account of the detection, description and explanation of variability within Scottish flood records

5.1 INTRODUCTION

The purpose of this chapter is to address those aims primarily concerned with the detection and description of variability within Scottish flood series. The key points to be determined are:

- what, if any, levels of variability are apparent within individual flood frequency and magnitude series;
- to detect any common patterns of variability which may exist between series;
- to examine whether there is any strong spatial coherence to patterns of variability.

It is hoped that answers can be provided to these questions by describing and interpreting the results of time series analyses, having applied those techniques listed in Chapter Four to the flood frequency and mean exceedance series (Chapter Three). These results can then be compared to patterns of climatic variability (Chapter Six) and incorporated in an investigation into the effect of variability upon current techniques of flood frequency analysis (Chapter Seven).

5.2 TECHNIQUES OF ANALYSIS

Using the simple descriptive statistical techniques and the more discriminating and rigorous time series statistics (WMO, 1988; Chapter Four), data analysis was carried out on each of the POT series listed in Table 3.1. However, as with the sub-sample of POT records used in the preliminary analysis, a certain degree of data manipulation was required prior to analysis (Section 4.5.1).

5.3 DATA MANIPULATION

To recap, the required processes of data manipulation included the creation of two separate time series from each POT record, one depicting flood frequencies and the other mean exceedances (Section 4.5.1.2), with additional checks made to ensure that series to be included in the analysis process met the program specifications (Section 4.5.2).

5.4 SUMMARY OF DATA SETS ANALYSED

Table 3.1 (Appendix One) lists every POT record and the subsequent frequency and mean exceedance series (gauging station name, number, length of record etc.) analysed using the chosen time series statistics (Section 4.5.3).

Attention must be drawn to those POT series without a standardised threshold. Such cases have arisen because of insufficient peak flows (less than forty-five events) being recorded during the standard period 1979-88, as a result of the discharge threshold being set too high. Although these records contain accurate data and are appropriate for analysis in their own right, they should not be compared directly with those records adjusted by standardised thresholds. In order to meet the requirements of the standardised period, the discharge threshold would need to be retrospectively lowered and additional data collected from the entire period of record. This would be an extremely time consuming task. It is also very difficult to judge the precise effect of an unstandardised threshold upon the nature of a POT record; if the threshold has been set only slightly too high (recording forty-three or forty-four events during the standard period), then some comparison with standardised records may be possible. Having weighed up all these considerations, it was decided to include those records without a standardised threshold in the analysis process, whilst emphasising their possible limitations in the comparison process.

5.5 STANDARD OUTPUT

Table 5.1 illustrates a sample of the statistical output from the time series program (WMO, 1988), using the flood frequency time series derived from the POT record from the River Dee at Woodend (12001) as an example.

Table 5.1: A sample of the Standard Output from the WMO Time Series Program (WMO, 1988) using the River Dee at Woodend (12001) Flood Frequency Series

INPUT SERIES : RIVER DEE AT WOODEND (12001)
INPUT PARAMETERS :
NUMBER OF YEARS OF INPUT SERIES 59
FIRST YEAR OF THE SERIES 1934
COINCIDENT YEAR OF ANALYSIS 1993
OPTIONAL DATA SETS (ANNUAL) 1

5-YEAR PERIOD(S)
BASIC STATISTICS

YR	MEAN	S.E.	SD	S.E.	CV	CS	CK
1938	5.200	1.068	2.387	0.755	0.459	-0.206	5.736
1943	4.600	0.980	2.191	0.693	0.476	0.846	8.121
1948	3.600	0.872	1.949	0.616	0.541	1.944	10.141
1953	4.600	1.288	2.881	0.911	0.626	0.874	7.050
1958	4.400	1.030	2.302	0.728	0.523	1.033	7.607
1963	1.200	0.490	1.095	0.346	0.913	-0.609	3.889
1968	1.400	0.872	1.949	0.616	1.392	0.756	4.601
1973	3.400	1.364	3.050	0.964	0.897	0.162	4.583
1978	5.400	1.691	3.782	1.196	0.700	1.981	10.023
1983	3.800	0.735	1.643	0.520	0.432	0.518	5.261
1988	3.600	0.678	1.517	0.480	0.421	1.118	7.880

1938 - denotes 5 year period 1938 to 1942 inclusive etc.

59-YEAR PERIOD(S)
BASIC STATISTICS

YEAR	MEAN	S.E.	SD	S.E.	CV	CS	CK
1934	3.831	0.333	2.561	0.236	0.668	0.776	3.824

1934 - denotes entire period of record 1934 to 1992 inclusive

30-YEAR PERIOD(S)
KRUSKAL-WALLIS TEST OF EQUALITY OF SUB-PERIOD MEANS
3 SUB-PERIODS OF 10 OBSERVATIONS:

		0.0 0.5 1.0
1963	0.2867	. * . .
1973	0.6417	. . * .
1983	0.6217	. . * .

K-W TEST STATISTIC IS 9.606 WITH 2 degrees of freedom

1963 - denotes ten-year period 1963 to 1972 inclusive etc.

RUNS TEST
59-YEAR PERIOD(S)
NUMBER OF RUNS (NR) 31
Expected (NR) = 30 Variance (NR) = 14.50
TEST STATISTIC 0.263

Where:
S.E. = standard error
S.D = standard deviation
CV = coefficient of variation
CS = coefficient of skewness
CK = coefficient of kurtosis

MANN'S TEST - TREND IN THE MEAN
(See also Table 4.2)

YEAR	S	S.D.(S)	U(I)	-4.0 0.0 4.0
1935	-1	1.000	-1.000	. * . .
1936	-3	1.915	-1.567	. * . .
1937	-2	2.944	-0.679	. * . .
1938	0	4.082	0.000	. * .
1939	-1	5.323	-0.188	. *. .
1940	-5	6.658	-0.751	. * . .
1941	-2	8.083	-0.247	. *. .
1942	-5	9.539	-0.524	. * . .
1943	-11	11.091	-0.992	. * . .
1944	-13	12.662	-1.027	. * . .
1945	-5	14.387	-0.348	. *. .
1946	-8	16.062	-0.498	. * . .
1947	-6	17.944	-0.334	. *. .
1948	1	19.891	0.050	. * .
1949	-10	21.863	-0.457	. * . .
1950	-18	23.958	-0.751	. * . .
1951	-26	26.090	-0.997	. * . .
1952	-34	28.249	-1.204	. * . .
1953	-48	30.430	-1.577	. * . .
1954	-29	32.736	-0.886	. * . .
1955	-44	34.995	-1.257	. * . .
1956	-38	37.390	-1.016	. * . .
1957	-32	39.808	-0.804	. * . .
1958	-34	42.245	-0.805	. * . .
1959	-44	44.774	-0.983	. * . .
1960	-24	47.378	-0.507	. * . .
1961	-44	49.940	-0.881	. * . .
1962	-36	52.593	-0.685	. * . .
1963	-57	55.224	-1.032	. * . .
1964	-87	58.049	-1.499	. * . .
1965	-117	60.907	-1.921	. * . .
1966	-136	63.650	-2.137	. * . .
1967	-155	66.405	-2.334	. * . .
1968	-187	69.390	-2.695	. * . .
1969	-219	72.399	-3.025	. * . .
1970	-214	75.406	-2.838	. * . .
1971	-247	78.479	-3.147	. * . .
1972	-251	81.595	-3.076	. * . .
1973	-285	84.729	-3.364	. * . .
1974	-257	87.956	-2.922	. * . .
1975	-285	91.230	-3.124	. * . .
1976	-288	94.485	-3.048	. * . .
1977	-262	97.833	-2.678	. * . .
1978	-243	101.165	-2.402	. * . .
1979	-248	104.515	-2.373	. * . .
1980	-253	107.881	-2.345	. * . .
1981	-244	111.310	-2.192	. * . .
1982	-196	114.848	-1.707	. * . .
1983	-203	118.306	-1.716	. * . .
1984	-173	121.903	-1.419	. * . .
1985	-181	125.413	-1.443	. * . .
1986	-159	129.028	-1.232	. * . .
1987	-187	132.616	-1.410	. * . .
1988	-178	136.286	-1.306	. * . .
1989	-187	139.925	-1.336	. * . .
1990	-196	143.576	-1.365	. * . .
1991	-160	147.411	-1.085	. * . .
1992	-192	151.162	-1.270	. * . .

Where: u(i) = test statistic
Typical range -4.0 < u(i) > 4.0
If u(i) > | 1.96 | trend is significant at 5% level

5.6 RESULTS OF ANALYSIS FROM POT RECORDS

Since the number of POT series included in the database exceeds one-hundred-and-thirty, over two-hundred-and sixty flood frequency and mean exceedance time series were involved in the analysis process. Describing the results from each individual time series would be both a tedious and time-consuming process with limited benefits, particularly since the wide variety of record lengths and time periods covered by individual series would not allow a full comparison between results. However, a small number of records which cover particularly long time periods were selected for inclusion, to provide information on flood characteristics in the first half of this century when gauging was rather limited and to put the recent period (characterised by widespread gauging) into context.

5.6.1 RIVER DEE AT WOODEND (12001): 1934-92

This is one of the earliest gauging stations in Scotland still in use today. Although the present station, constructed in 1972, replaced an earlier site on the same reach of river (NERC, 1993), this is not seen as affecting the validity of the record. Although the length of record is highly advantageous, a previous study of flood seasonalities in Scotland (Black, 1992) suggested its behaviour may be contrary to other rivers in the region.

The key points to note from the analysis of the flood frequency series from the River Dee at Woodend (12001) are that:

- flood frequencies are clearly highest in the 1930s, 1940s and 1980s and show a distinct minimum during the 1960s and 1970s, as depicted by the time series and five-year running mean plots (Figure 5.1(a));
- the basic statistics calculated for five-year sub-periods of the series reveal the period 1978-82 as recording the highest mean flood frequency, although this may reflect the extreme number of events recorded in 1982; the consecutive five-year sub-periods 1963-67 and 1968-72 are characterised by the lowest mean frequencies on record;

Figure 5.1(a): RIVER DEE AT WOODEND (12001)
Flood Frequency Series 1934-92: Annual Frequencies and a Five-Year Running Mean

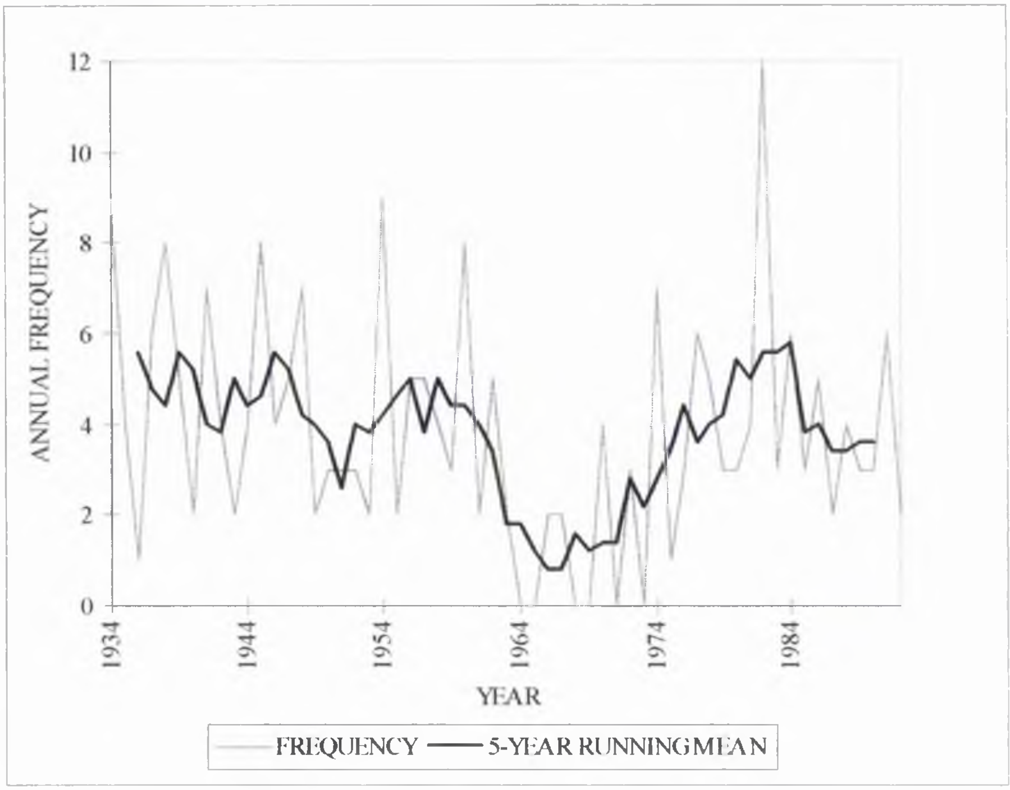
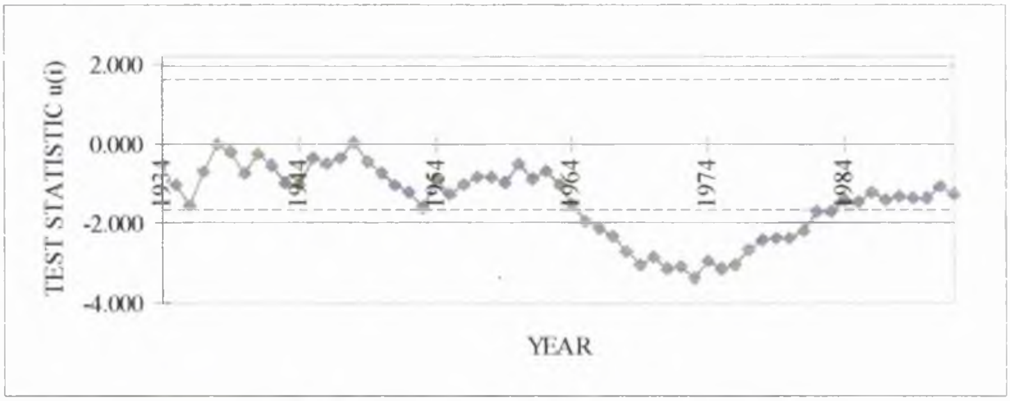


Figure 5.1(b): RIVER DEE AT WOODEND (12001)
Mann's Test for Trend in the Mean: Flood Frequency Series 1934-92



NB. The Dotted Line signifies the 10% Confidence Level for a significant trend
The Solid Line signifies the 5% Confidence Level for a significant trend

Legends are applicable to ALL charts presented in Appendices Two and Four

- the Kruskall-Wallis test statistic is significant at the 10% confidence level; this suggests that mean flood frequencies calculated for ten-year sub-periods of the record are statistically different; this appears to be related to a low mean flood frequency for the period 1963-72;
- the number of runs observed within the frequency series is 31; the number expected in a purely random series is 30; the test statistic confirms that the time series is random;
- the Mann's test for trend in the mean reveals the decline in frequencies began in 1962 and continued until 1976; this indicates a significant downward trend at the 5% confidence level by 1966 (the test statistic u(i) is lower than -1.96), and at the 1% confidence level by 1968 (u(i) is lower than -2.054); flood frequencies then increase from the mid 1970s, although values of u(i) do not signify upward trends, largely because the test statistic must increase from a very low turning point in 1976 (Figure 5.1(b)).

A number of key points were also extracted on the pattern of flood magnitudes, represented by the mean exceedance series (Figure 5.1(c)):

- although a fairly variable pattern of mean exceedances is evident, periods of high mean excess can be detected in the 1930s, 1950s and 1980s and low mean exceedances in the 1960s and 1970s; this follows a similar pattern to the flood frequency series;
- in particular, 1937, 1951 and 1975 are identified as possible outliers, recording extremely high mean exceedances;
- five-year subdivisions of magnitudes associate the period 1958-62 with the highest mean value and 1968-72 with the lowest
- the Kruskall-Wallis test suggests that ten-year sub-period means are statistically unequal (at the 5% confidence level), as the 1963-72 mean is particularly low in comparison with other periods;
- the observed number of runs is significantly less (at the 10% confidence level) than expected from a random time series;
- as with the flood frequency series, the Mann's test reveals a decline in mean exceedances which begins in 1963, sufficient to signify a downward trend (at the

Figure 5.1(c): RIVER DEE AT WOODEND (12001)
Flood Magnitude Series 1934-92: Annual Mean Exceedances and a Five-Year Running Mean

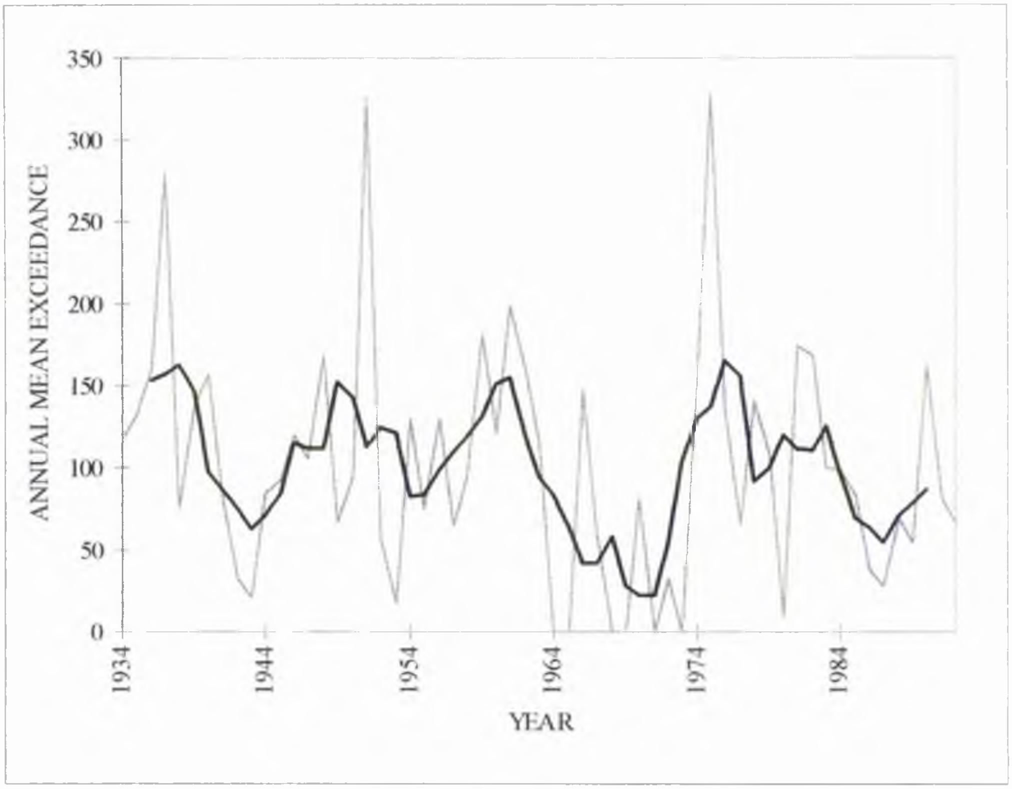
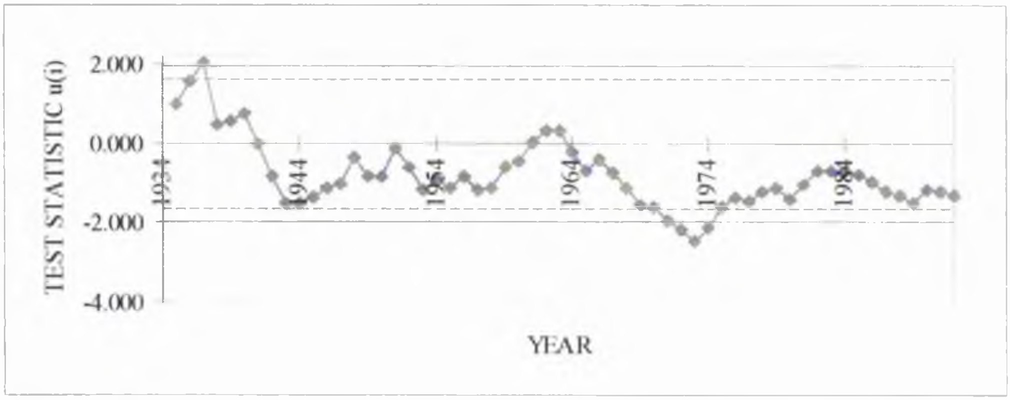


Figure 5.1(d): RIVER DEE AT WOODEND (12001)
Mann's Test for Trend in the Mean: Flood Magnitude Series 1934-92



5% confidence level) by 1973; mean exceedances increase slightly and then stabilise to 1992; once again values of the test statistic u(i) do not recover from the low base point to reach the zero level by the end of record (Figure 5.1(d)).

These results reveal a degree of variability within both flood frequency and mean exceedance series from the River Dee at Woodend (12001), over the period 1934-92. Within this period, flood frequencies reached similar peak levels in the 1930s, 1940s and more recently in the mid 1980s. The 1960s and 1970s can clearly be classified as 'flood-poor'. The recent period (1988-92) has been characterised by a slight decline in the incidence of floods seen earlier in the 1980s. The record of flood magnitudes (mean exceedances) reflects a similar pattern, with reduced discharges in the 1960s and early 1970s. The raw data series and filtered running mean plot appears more 'peaky'; this may be due to the effect of one-off high magnitude events which influence the annual mean exceedance value, rather than any underlying trend. Whether this record is displaying patterns of variability typical of the north-east region has yet to be determined, although it must be emphasised that a large proportion of the catchment area is within the western half of Scotland.

5.6.2 RIVER IRVINE AT GLENFIELD (83802): 1914-88

Although this record is one of the longest flow records in Scotland, its value as a homogenous series was affected by flood defences built upstream of the gauging station in 1977. This resulted in a loss of storage within the catchment and consequently the nature of flood events has changed (Black, pers comm.). The data series is, however, consistent until 1977 and valuable for analysis; it will also be interesting to see how well the time series statistics depict the effect of flood defences upon hydrological characteristics. The frequency series from the Irvine clearly shows the influence of the flood defence scheme:

- both the time series and running mean plots (Figure 5.2(a)) show a sudden jump in frequencies from the late 1970s onwards;
- four years within this latter period (1985, 1986, 1987 and 1988) are identified by Minitab as statistical extremes (outliers);
- the highest recorded sub-period mean frequencies occur in the periods 1983-87 and 1978-87 (based upon five and ten-year divisions respectively);

Figure 5.2(a): RIVER IRVINE AT GLENFIELD (83802)
Flood Frequency Series 1914-88: Annual Frequencies and a Five-Year Running Mean

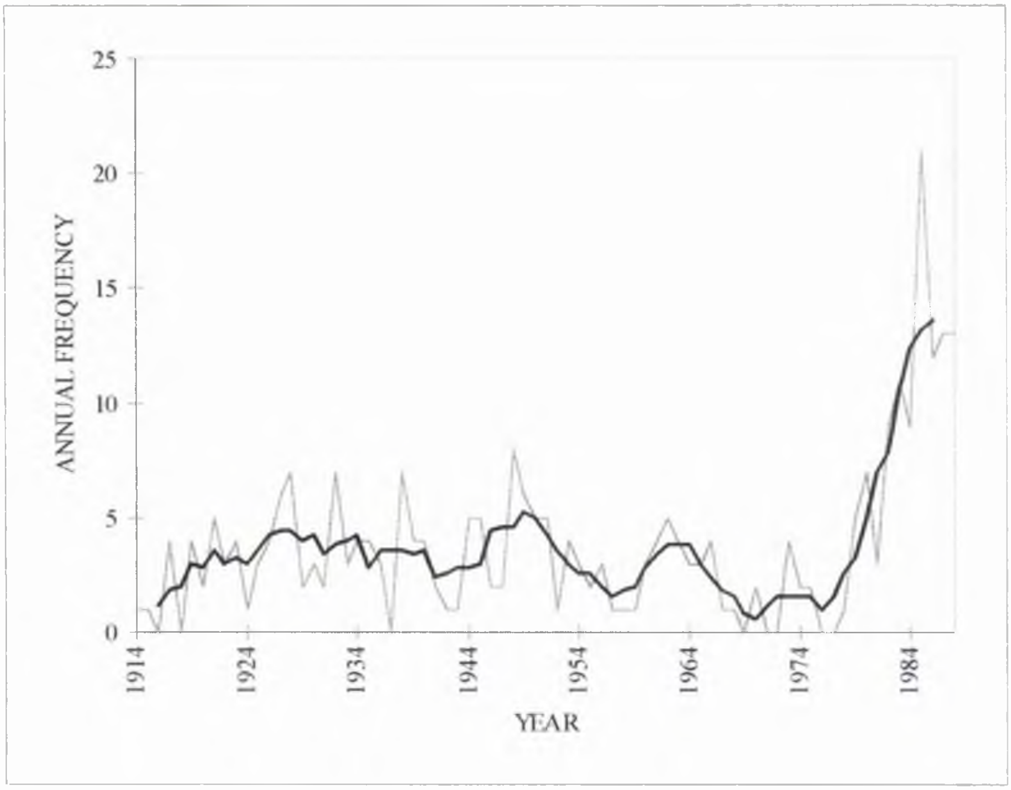


Figure 5.2(b): RIVER IRVINE AT GLENFIELD (83802)
Mann's Test for Trend in the Mean: Flood Frequency Series 1914-88

- the Kruskall-Wallis test provides evidence (at the 10% confidence level) that ten-year sub-period mean frequencies are statistically unequal; this is likely to relate to the low mean frequency for the 1968-77 period and the high mean for 1978-87;
- prior to 1977, frequencies are clearly lowest in the late 1960s and early 1970s, and peak during the late 1940s/early 1950s;
- the observed number of runs is significantly less (at the 10% confidence level) than expected in a random series;
- the Mann's trend statistic (Figure 5.2(b)) reveals an increase in frequencies in the 1910s and 1920s, which is followed by a period of fluctuating values; the 1960s and 1970s are then characterised by a decline in frequencies, which is indicative of a downward trend by 1978 (0.10 CI); a steady increase in frequencies occurs from 1977 onwards although this does not cross the level of a significant upward trend;
- given the nature of the previous statistical information, one would expect a sudden step up in frequencies from 1977 onwards; this is reflected in all statistical techniques used; the Mann's trend technique clearly depicts 1977 as a significant turning point followed by a continued increase in the test statistic; however, this does not signify a significant upward trend as the value of the test statistic is highly dependant upon the state of the time series prior to any change; in this case, the period to 1977 is 'flood-poor' and the test statistic does not recover sufficiently from this very low base point by 1977 (Section 4.5.3); one may expect data from the late 1980s and 1990s to depict frequencies stabilising at this higher level.

The mean exceedance series from the River Irvine show a more variable pattern (Figure 5.2(c)):

- years identified as outliers by Minitab (1953, 1954, 1959, 1961, 1966 and 1982) are not confined to the period since 1977, unlike the flood frequency series;
- the highest recorded sub-period mean value occurs in the period 1953-57, and the lowest mean in 1933-37;
- consequently, the Kruskall-Wallis test indicates statistically unequal sub-period means (at the 5% confidence level);
- the number of runs signifies a non-random series (at the 5% confidence level);

Figure 5.2(c): RIVER IRVINE AT GLENFIELD (83802)
Flood Magnitude Series 1914-88: Annual Mean Exceedances and a Five-Year Running Mean

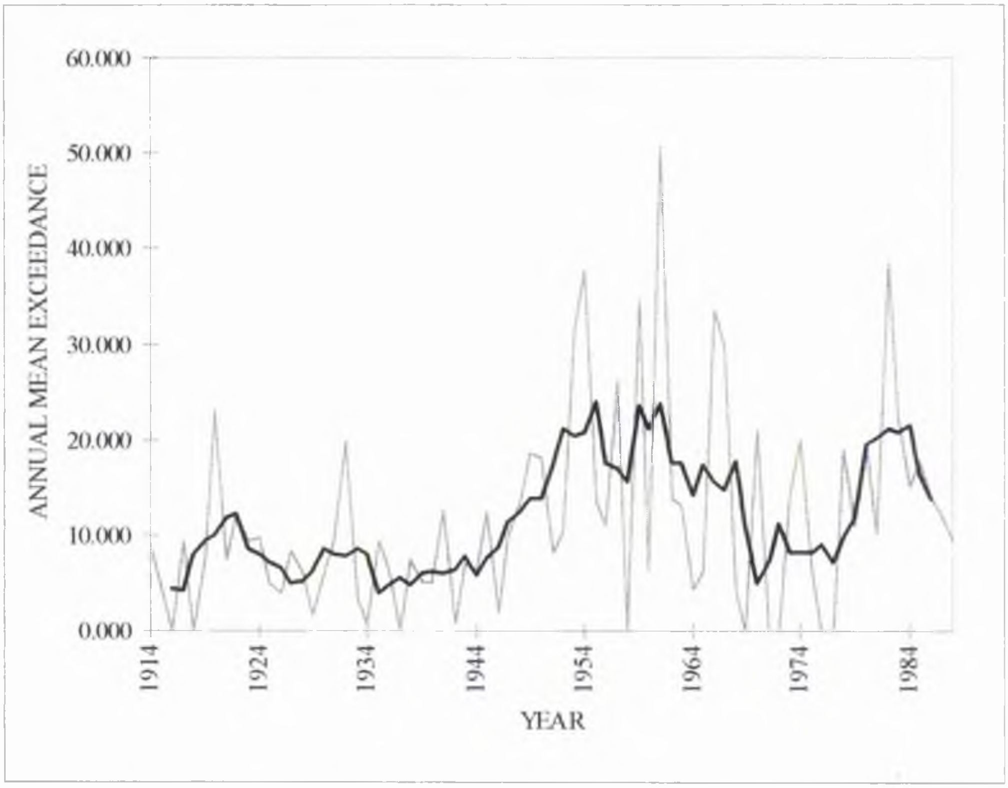
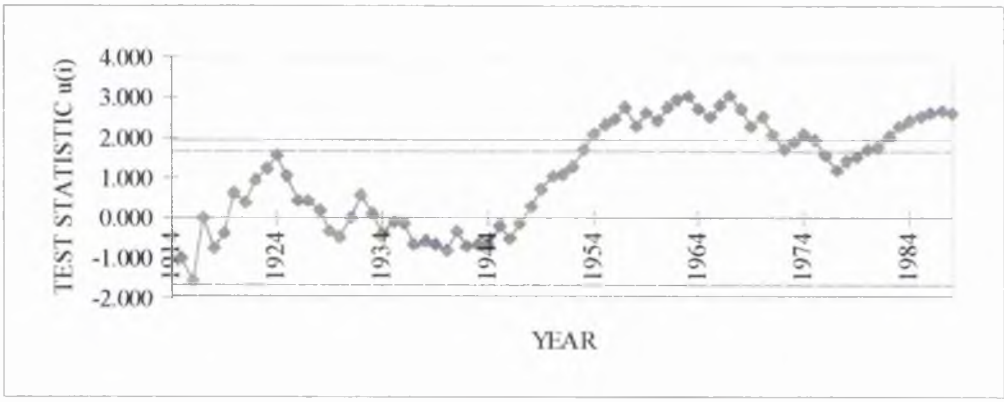


Figure 5.2(d): RIVER IRVINE AT GLENFIELD (83802)
Mann's Test for Trend in the Mean: Flood Magnitude Series 1914-88



- the Mann's trend test (Figure 5.2(d)) confirms that flood magnitudes were generally stationary until the late 1940s, when a period of increased values occurred (1948-57); this signifies an upward trend (at the 5% confidence level) by 1954; over the next ten years, values stabilise but decrease slightly until 1977, when a further increase follows (significant at the 5% confidence level by 1982);
- the influence of base points with the Mann's plot is evident again; the decrease in values in the 1970s occurs from a high start point, and therefore does not constitute a significant downward trend as one may have expected.

The frequency series from the River Irvine at Glenfield (83802) clearly depicts the effect of the flood defences built in 1977, with sudden increases in annual frequencies revealed by every statistical technique. For the period of record prior to 1977, the 1960s and 1970s again register as the period when frequencies were at a minimum, as did the Dee at Woodend (12001) record. There is no marked maximum in this period, although frequencies seem slightly higher in the late 1940s and 1950s. The flood magnitude series from this station shows a more variable pattern with only limited similarities to the frequency series. The series suggest that flood events have become more frequent since 1977 but whilst magnitudes also increased, they did not reach the levels recorded in the 1950s and 1960s.

The approach to the analysis carried out thus far has been to deal with the flood frequency and magnitude series separately. In the light of these early results, it is clear that this is the most sensible approach since the relationship between the two series is seemingly quite variable. While there is some direct relationship between the two series from the Dee at Woodend series (12001), there is no such relationship for the Irvine at Glenfield series (83802).

5.6.3 ALLT LEACHDACH AT INTAKE (91802): 1939-80

The original POT series from the Allt Leachdach was available for the period 1939-74 but has recently been updated, by Andrew Black for the Institute of Hydrology, until 1992 with data made available by Alcan Highland Smelters. This is of considerable benefit since the record covers an area of Scotland poorly gauged, with few records of any useful length. However, the period subsequent to 1974 contains a considerable number of gaps, with flow records from over two hundred days missing. In this state, it would not be possible to include these additional data since the accuracy of the record would be highly questionable. Techniques such as rainfall-runoff modelling were considered as sources of additional data to 'fill' these gaps but the limited time availability and the possibility of inaccuracies within the modelled data combined to reject this idea.

On examining the additional POT series, it was discovered that the majority of gaps occur from the 1980s onwards and this allowed the record suitable for analysis to be extended to include data until the end of 1980 without the value of the data being reduced. Hence the period of record covers forty-two years, from 1939 to 1980.

Analysis of the flood frequency series from the Allt Leachdach (91802) reveals a fairly stable record:

- the raw data and running mean series (Figure 5.3(a)) reveal peak frequencies in the late 1940s and 1960s, and lower values in the 1950s; however, the range between these extremes is limited;
- five-year sub-period mean frequencies are rather stable with the exception of a higher mean in the 1943-47 period, and a lower mean in 1948-52; however, there is no statistical evidence of inequality in these sub-period means;
- the Mann's trend plot (Figure 5.3(b)) also indicates a generally stationary record, although once again a period of increased frequencies is evident during the late 1940s; although this constitutes a significant upward trend (at the 5% confidence level) by 1947, this is an extremely quick and short-lived increase.

The record of mean exceedances is also stable, with only minor fluctuations:

- an extreme mean exceedance value occurs in 1966 and is apparent in the running mean plot (Figure 5.3(c)); this also depicts a possible decrease in values during the late 1950s and early 1960s;

Figure 5.3(a): ALLT LEACHDACH AT INTAKE (91802)
Flood Frequency Series 1939-80: Annual Frequencies and a Five-Year Running Mean

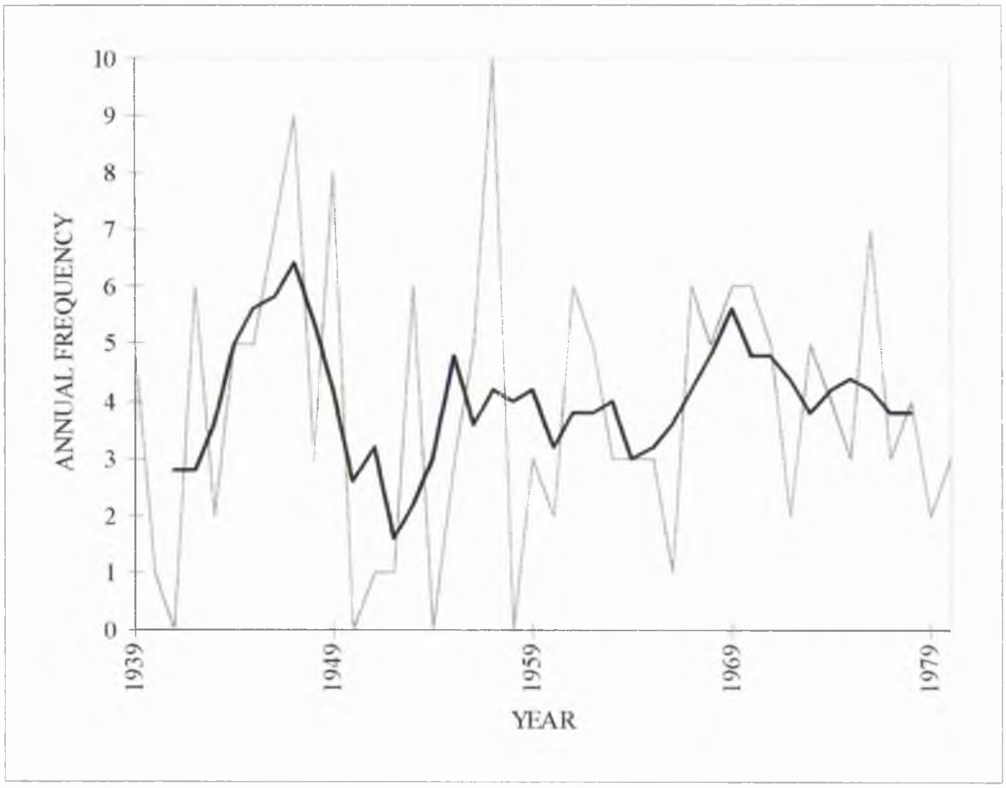


Figure 5.3(b): ALLT LEACHDACH AT INTAKE (91802)
Mann's Test for Trend in the Mean: Flood Frequency Series 1939-80

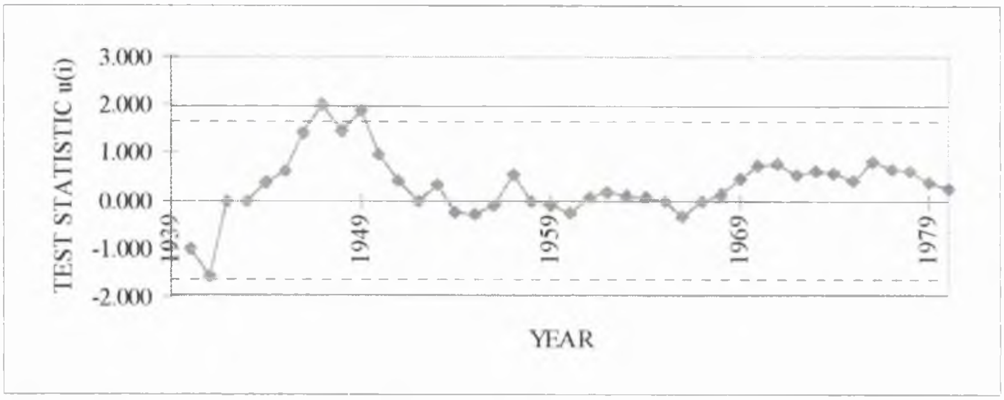


Figure 5.3(c): ALLT LEACHDACH AT INTAKE (91802)
Flood Magnitude Series 1939-80: Annual Mean Exceedances and a Five-Year Running Mean

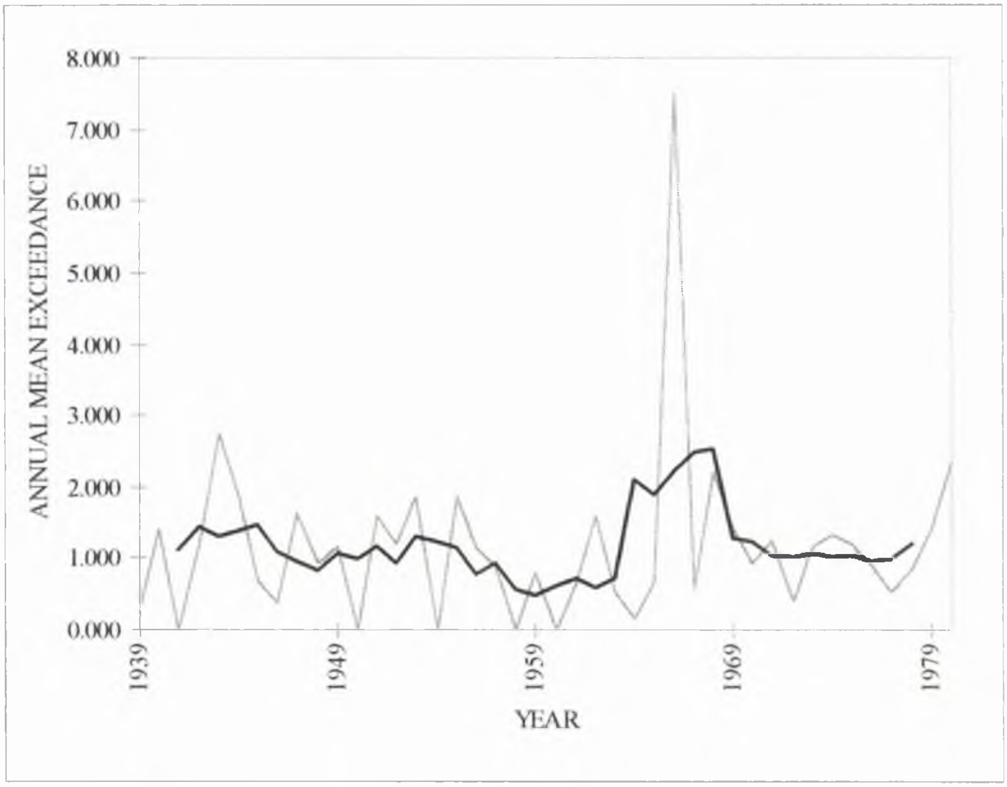
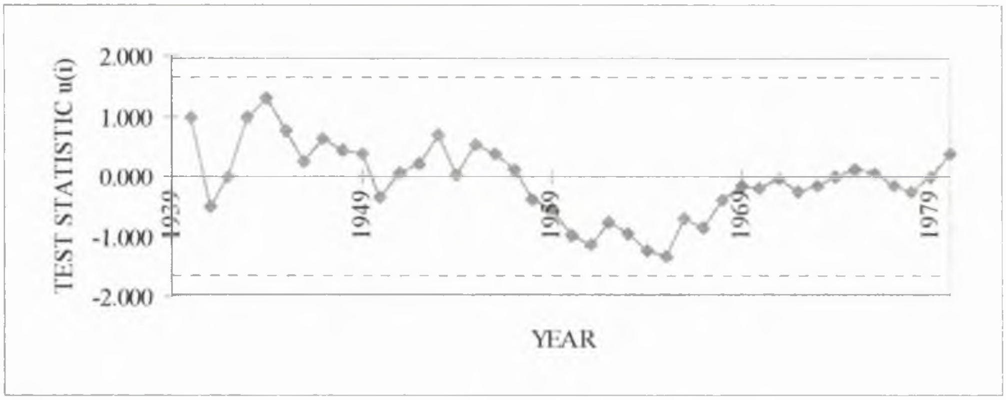


Figure 5.3(d): ALLT LEACHDACH AT INTAKE (91802)
Mann's Test for Trend in the Mean: Flood Magnitude Series 1939-80



- the extreme mean exceedance from 1966 appears to have influenced five-year sub-period means, which clearly peak in the 1963-67 period; the influence of this value is reduced in the ten-year sub-period means which are reasonably stable and show no evidence of statistical inequality using the Kruskall-Wallis test;
- once again, the Mann's test suggests the series is stable, with the exception of a slight decrease in frequencies in the period 1955-65; however, this does not constitute a significant trend (Figure 5.3(d)).

Evidence from the Allt Leachdach record (91802) suggests that over the period 1939-80, flood frequencies and magnitudes were generally stable, with only short-lived fluctuations. The decline in flood frequencies and, to a lesser extent, magnitudes seen during the late 1960s and 1970s in the previous series examined, is not evident within this record. This may be connected to the small size of the catchment or may be a feature of west coast flows, or may even be a combination of both.

5.7 CHOICE OF RECORD LENGTH

Analysing and interpreting the flood frequency and mean exceedance series created from individual POT records in their entirety allows one to detect patterns of temporal variability over the period of record and to gain a greater insight into the changes of flooding patterns at specific sites. However, such an approach hinders direct comparisons between records unless they cover identical time spans. Consequently, it was decided to limit records to specific time intervals so direct comparisons could be made.

Standard periods were originally created to cover intervals incremented by ten years, ending in 1992 since the majority of records were updated to this point. The resultant subsets and period covered are listed in Table 5.2.

A small subset of records were edited to cover these periods and analysed using the proposed methods of analysis as a preliminary exercise. At this stage a problem was detected with the time series program (WMO, 1988) when calculating statistics for records covering time periods divisible by ten years (ten, twenty years etc.). These errors suggest that the program is reading the parameter *NYRS* (which specifies the number of years in the record; Section 4.5.2) incorrectly. Further experimentation showed this problem is limited to these record lengths only. It was therefore necessary to adjust the proposed subset intervals to overcome this problem, by simply reducing the period by one year (Table 5.3) thus eradicating all program errors. The revised division was convenient since a number of gauging records commence in 1964 and this therefore substantially increased the number of series covering the period of subset C. Table 5.3 shows that the number of records applicable to these sub-periods decreases as the time period increases. There is also an uneven geographical distribution of records within each subset, particularly in the longer sub-periods where the majority of records are located in the east and south of Scotland where widespread gauging began (Maps 5.1-5.4).

Of these proposed sub-periods, records covering the longer time spans (subsets D, E or F) would be useful in providing a detailed view of temporal variability within flood records. Their applicability, however, to studies of spatial variability would be highly limited due to the concentration of records in the east of Scotland. On the other hand, a wide spatial view of flood variability could be achieved if emphasis was placed on those records in subsets A or B where the spatial coverage is more extensive. Since these records cover restricted time periods, a clear pattern of temporal variability might not be detected. Therefore, if an adequate study of both temporal and spatial variability is required, then a compromise must be reached. It was therefore decided to concentrate analysis on those periods and records in subsets B and C whilst including the results from subset D and E records when emphasising temporal variability.

It is recommended that river flow records to be analysed using the time series program (WMO, 1988) should cover a minimum duration of thirty years. For the purposes of examining spatial variability, a thirty year record is acceptable but forty years or more of data are recommended for a study of temporal variability (Section 3.5.2, WMO, 1988). Thirty years is specified as a minimum since it is the standard

Table 5.2: Proposed subsets and time intervals covered

SUBSET	PERIOD COVERED	SUBSET LENGTH
Subset A:	1983 - 1992	10-years
Subset B:	1973 - 1992	20-years
Subset C:	1963 - 1992	30-years
Subset D:	1953 - 1992	40-years
Subset E:	1943 - 1992	50-years

Table 5.3: Revised subsets and sub-periods, and the number of records included (A list of the gauging stations included in each cluster is given in Table 3.1)

SUBSET	PERIOD COVERED	SUBSET LENGTH	NO.OF RECORDS IN SUBSET
Subset A:	1984 - 1992	9-year period	120 records
Subset B:	1974 - 1992	19-year period	101 records
Subset C:	1964 - 1992	29-year period	51 records
Subset D:	1954 - 1992	39-year period	14 records
Subset E:	1944 - 1992	49-year period	1 record
Subset F:	1934 - 1992	59-year period	1 record*

* Analysed in Section 5.6.1

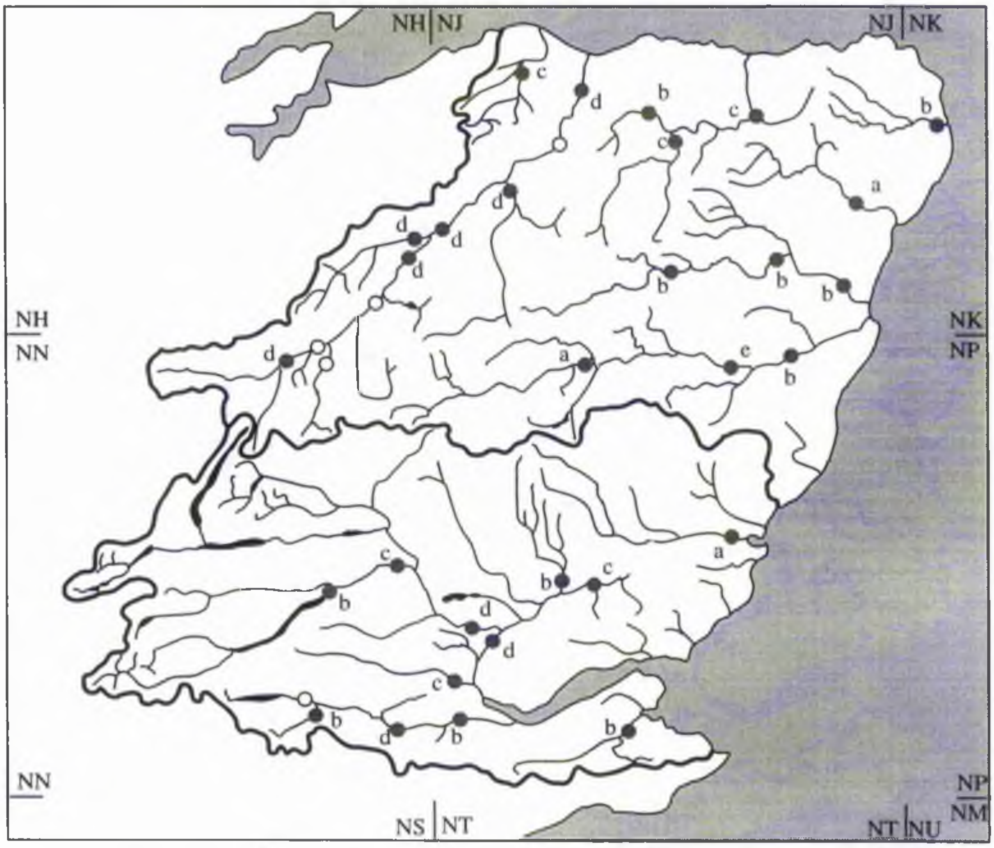
Map 5.1: Records from the Highland RPB region with subset groupings

AREA 23,110 KM^2

RPB BOUNDARIES	——
GAUGING STATIONS	
Subset A records	● a
Subset A and B records	● b
Subset A, B and C records	● c
Subset A, B, C and D records	● d
Subset A, B, C, D and E records	● e
Records not covering subset periods or records with extensive gaps	○

BASED ON: HYDROLOGICAL DATA UK - HYDROMETRIC REGISTER AND STATISTICS 1986-1990 (NERC, 1993)

Map 5.2: Records from the North East and Tay RPB regions with subset groupings

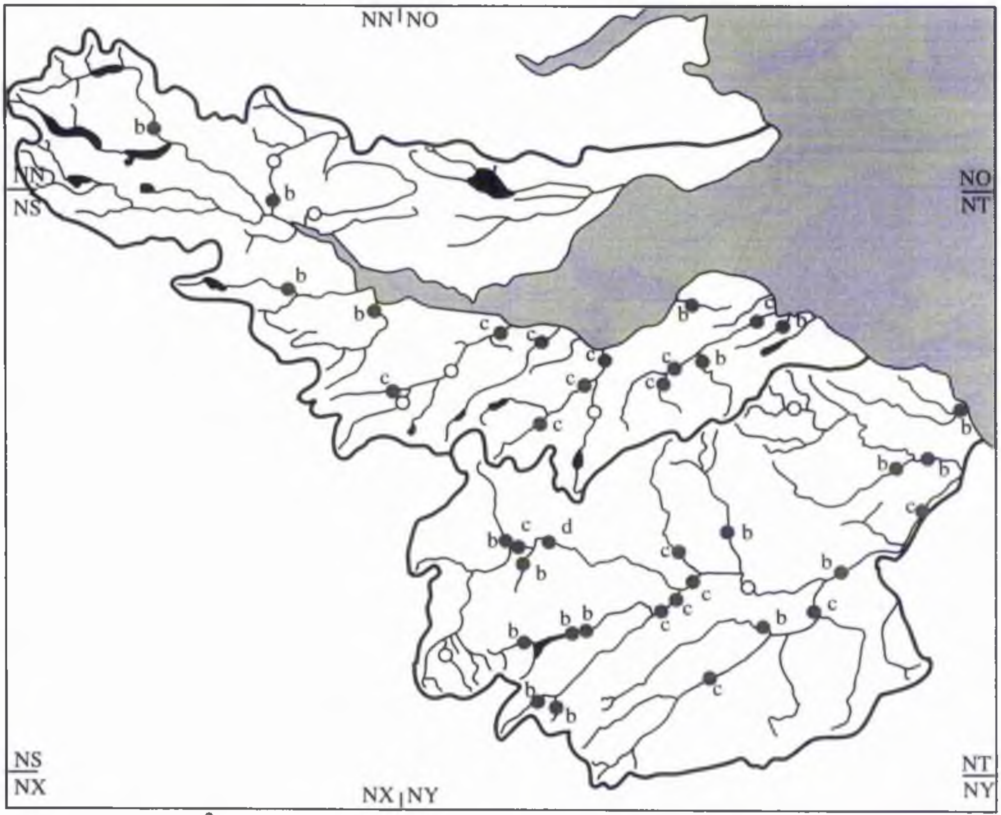


NERPB Area 10,420 km^2
TPRB Area 8,710 km^2

RPB BOUNDARIES
GAUGING STATIONS
Subset A records a
Subset A and B records b
Subset A, B and C records c
Subset A, B, C and D records d
Subset A, B, C, D and E records e
Records not covering subset periods
or records with extensive gaps

BASED ON: HYDROLOGICAL DATA UK - HYDROMETRIC REGISTER AND STATISTICS 1986-1990 (NERC, 1993)

Map 5.3: Records from the Forth and Tweed RPB regions with subset groupings

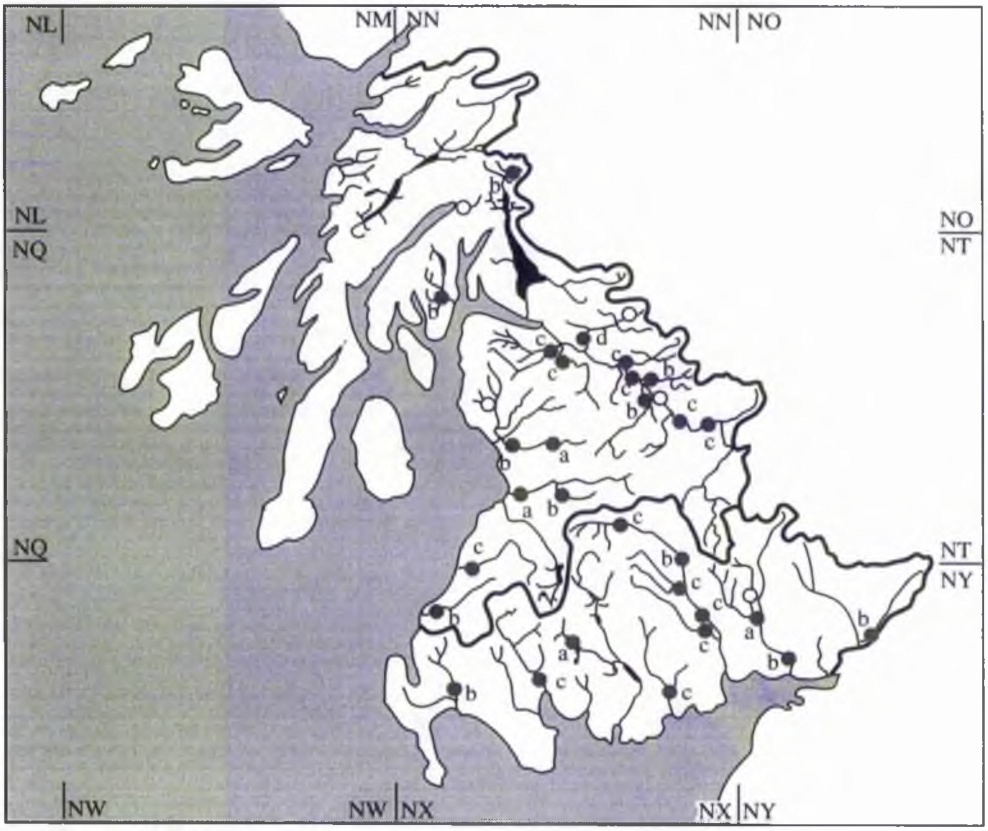


FRPB Area 4,520 km^2
TWRPB Area 4,580 km^2

RPB BOUNDARIES	——
GAUGING STATIONS	
Subset A records	● a
Subset A and B records	● b
Subset A, B and C records	● c
Subset A, B, C and D records	● d
Subset A, B, C, D and E records	● e
Records not covering subset periods or records with extensive gaps	O

BASED ON: HYDROLOGICAL DATA UK - HYDROMETRIC REGISTER AND STATISTICS 1986-1990 (NERC, 1993)

Map 5.4: Records from the Solway and Clyde RPB regions with subset groupings



SRPB Area 6,790 km^2
CRPB Area 13,555 km^2

RPB BOUNDARIES	▬
GAUGING STATIONS	
Subset A records	● a
Subset A and B records	● b
Subset A, B and C records	● c
Subset A, B, C and D records	● d
Subset A, B, C, D and E records	● e
Records not covering subset periods or records with extensive gaps	O

BASED ON: HYDROLOGICAL DATA UK - HYDROMETRIC REGISTER AND STATISTICS 1986-90 (NERC, 1993)

period generally adopted as a reference period for climatic data (although twenty-nine years is also likely to be acceptable), and because it should contain a sufficiently large sample of data for estimating confidence limits (Section 4.1, WMO, 1988).

The reference period for subset C is acceptable for a study of spatial variability under the WMO recommendations but not for studying temporal variability. Using these guidelines, temporal analysis would be limited to records included in subset D only, which clearly reduces the spatial diversity of the series available. However, since the period covered by subset C is a sufficiently large sample of data, it was decided to proceed with the use of this reference period as a minimum for detecting both temporal and spatial variability.

5.8 DATA SUBSET E: 1944 - 1992

The limited availability of Scottish flow records is highlighted by the inclusion of just one record in subset E, from the River Dee at Woodend (12001). The complete record for this site in fact covers a period from 1934 to present and analysis of both the frequency and mean exceedance series over the 1944-92 period just confirm the findings stated in Section 5.6.1.

For the flood frequency record (Figure 5.4(a)), these key points are:

- 'flood-rich' periods in the 1940s, 1950s and 1980s;
- a 'flood-poor' period from 1964 until 1973, characterised by the fewest flood events since 1944;
- the Mann test statistic reveals that, from 1948 until 1953, flood frequencies declined sufficiently to indicate a significant downward trend (at the 5% confidence level); a further significant downward trend occurs from 1962 until 1969 (at the 1% confidence level); frequencies generally increase until the late 1980s (Figure 5.4(b)).

The key points from the mean exceedance series include:

- the presence of numerous peaks in flood magnitude in the 1940s, 1950s and 1970s;
- a period of low flood magnitudes occurs in the 1960s and 1970s (Figure 5.4(c));

Figure 5.4(a): RIVER DEE AT WOODEND (12001)
Flood Frequency Series 1944-92: Annual Frequencies and a Five-Year Running Mean

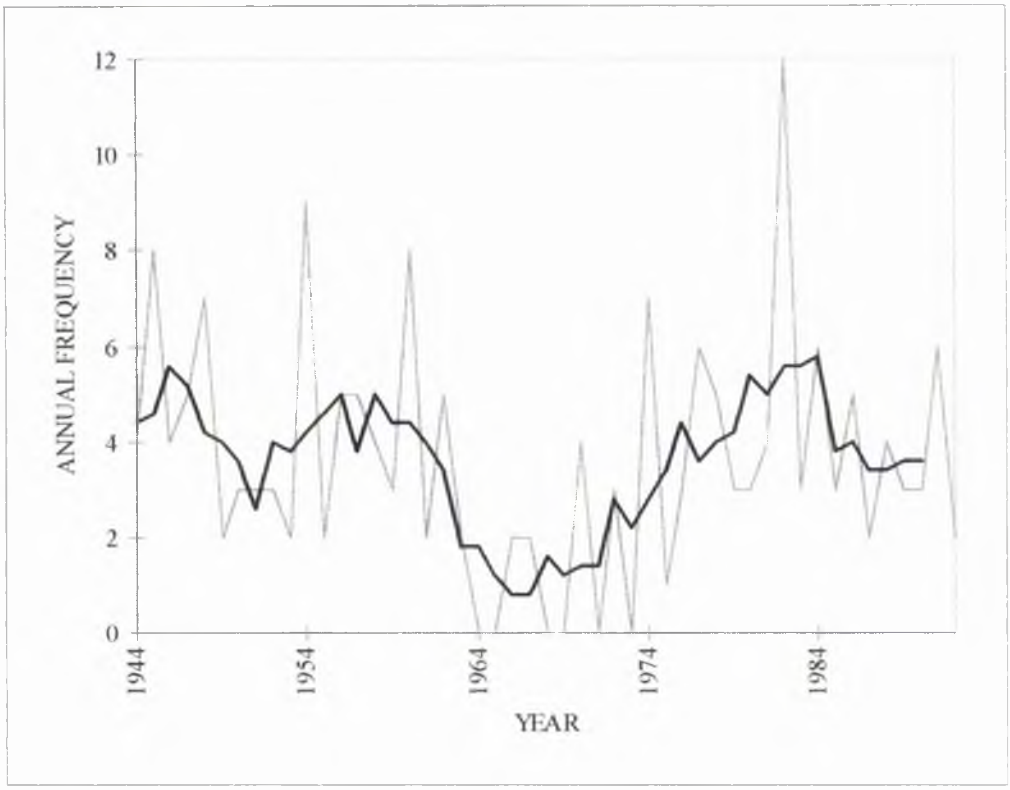


Figure 5.4(b): RIVER DEE AT WOODEND (12001)
Mann's Test for Trend in the Mean: Flood Frequency Series 1944-92

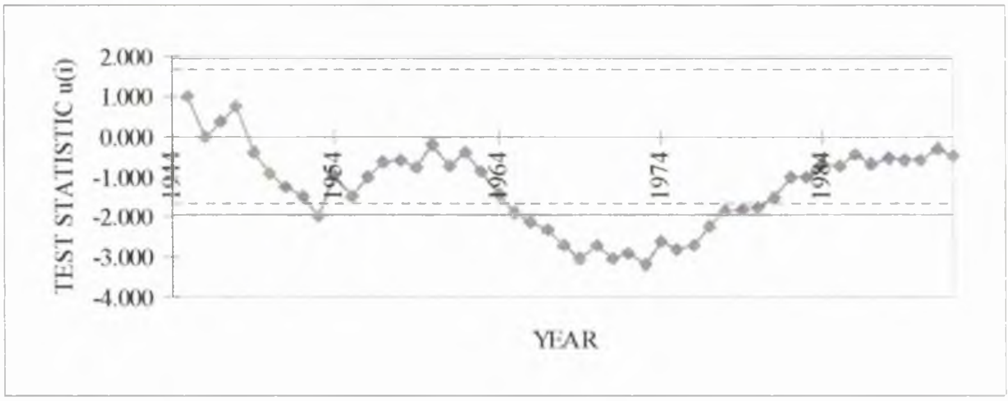


Figure 5.4(c): RIVER DEE AT WOODEND (12001)
Flood Magnitude Series 1944-92: Annual Mean Exceedances and a Five-Year Running Mean

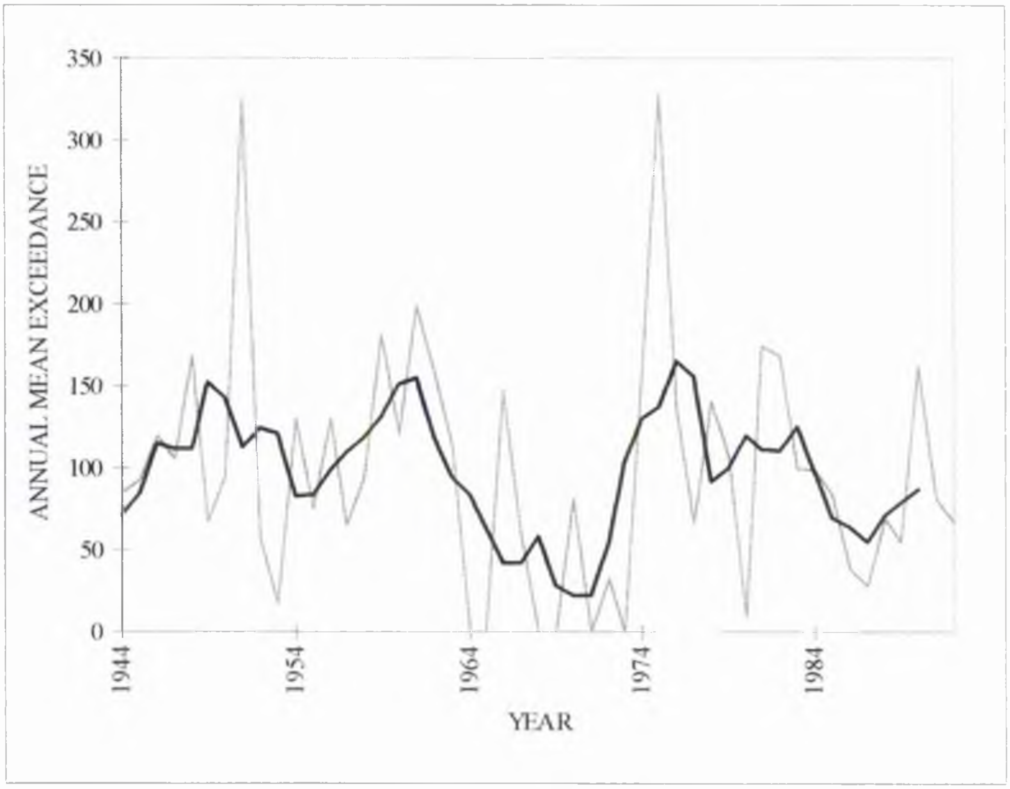
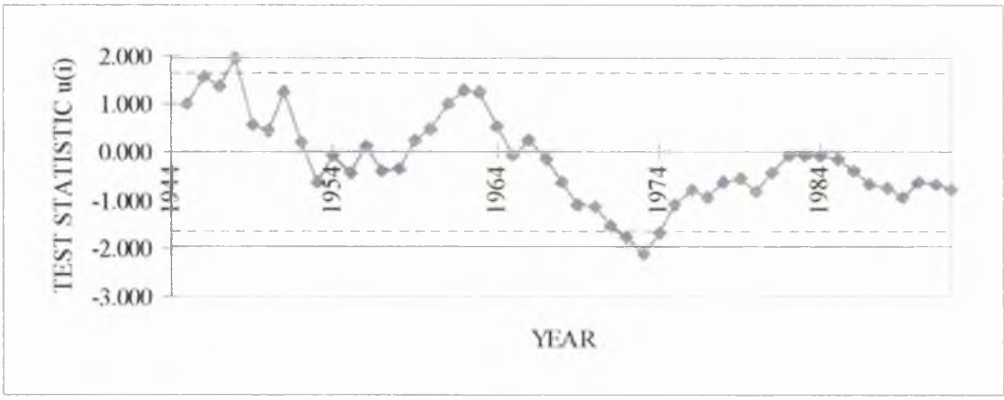


Figure 5.4(d): RIVER DEE AT WOODEND (12001)
Mann's Test for Trend in the Mean: Flood Magnitude Series 1944-92



- the plot of the Mann's test statistic (Figure 5.4(d)) indicates that annual mean exceedances remained fairly stable until the late 1960s, when a slight decrease in values occurred; this decline is maintained until 1973 and is classified as a significant downward trend (at the 5% confidence level); mean exceedances increase slightly and then appear to stabilise again.

5.9 DATA SUBSET D: 1954 - 1992

Fourteen POT records cover the period from 1954 until 1992, and can therefore be included in subset B (Appendix One, Table 3.1). It is clear from their geographical location (Maps 5.1-5.4) that there is an uneven spatial coverage of records; six are within the River Spey catchment and four are from the Tay catchment; unfortunately, the concentration of series within these regions is a problem caused by network evolution rather than choice of record.

Information on these gauging stations was acquired from the Hydrometric Register and Statistics 1986-90 (NERC, 1993). The most notable remark concerned the gauging station on the River Spey at Boat of Brig (08006), where extreme flow events often bypass the station. Although this may have some effect on the POT series, a considerable degree of effort has been put in to estimating discharges at very high stages (Black, pers comm).

5.9.1 FLOOD FREQUENCY SERIES

The pattern of annual flood frequencies for each of the fourteen records are depicted in Figures 5.5(a)-5.18(a) (Appendix Two). Although a general pattern of high flood frequencies in the 1950s, low frequencies in the 1970s and a return to higher values into the 1980s, is clearly displayed in many records, it is not universal to all records. Some frequency series, such as the Tay at Pitnacree (15007) and Dean Water at Cookston (15008) records, show no obvious pattern on first inspection. The Avon at Delnashaugh flood frequency series (08004) appears to display a unique pattern, with annual values showing an almost continual decline from the mid 1950s. This is where the value of the time series program lies (WMO, 1988), as it should be possible to extract more detailed information on the significance of variability which is not readily apparent from observing raw data and running mean series.

A number of years within the period 1954-92 are associated with extreme flood frequency values:

- 1954 is recognised as an extreme value (by Minitab) in records from the Spey at Grantown (08010), Tay at Caputh (15003), Tay at Ballathie (15006), Tay at Pitnacree (15007) and the Tweed at Peebles (21003);
- 1962 and 1990 also record extreme frequencies in the Tweed at Peebles (21003) record;
- 1982 is classified as an extreme in the Dee at Woodend (12001) series.

When examining how mean flood frequencies vary through time, the analysis of sub-period statistics within the time series program (WMO, 1988) reveal four general scenarios:

- Similarly high mean frequencies in the early and latter sub-periods of the record, with the 1970s associated with the lowest sub-period means:
  Spey at Boat of Brig (08006), Tay at Caputh (15003), Earn at Kinkell (16001) and the Tweed at Peebles (21003);
- The most recent sub-period, 1988-92, recording the highest mean flood frequency whilst the lowest mean is reached in the late 1960s:
  Spey at Invertruim (08007), Dulnain at Balnaan (08009), and the Tay at Ballathie (15006) and Pitnacree (15007);
- A peak in the mean flood frequency occurring in either sub-period 1978-82 or 1983-87, following the lowest mean recorded in the late 1960s and early 1970s:
  Spey at Boat of Garten (08005) and Invertruim (08010), the Dee at Woodend (12001), Dean Water at Cookston (15008) and the Kelvin at Killermont (84001));
- The highest mean frequency associated with the earliest sub-period and a general decline thereafter:
  Avon at Delnashaugh (08004).

The equality of these sub-period means was tested using the Kruskall-Wallis test. Using division of ten years (1963-72 etc.) and six years (1954-59 etc.), statistical inequality was detected in eight of the flood frequency series, at either the 10% or 5% confidence levels. In addition to detecting this equality, it is also important to understand why it has occurred. Very often inequality may be associated with one period recording an extreme mean frequency:

- the Dee at Woodend (12001) and Tay at Pitnacree (15007) both record very low mean frequencies in the period 1963-72;
- a very high mean frequency for the 1983-92 sub-period is evident in the Tay at Ballathie (15006) record.

However, inequality may also result from an extreme range of mean values, as evident in the following records:

- the Spey at Boat of Brig (08006), Dulnain at Balnaan Bridge (08009), Earn at Kinkell Bridge (16001), Tweed at Peebles (21003) and the Kelvin at Killermont (84001).

Runs tests carried out on each series detected just four series which could be classified as non-random. Three of these series (Spey at Invertruim (08007) and the Tay at Ballathie (15006) and Pitnacree (15007)) had previously been identified as displaying a high mean flood frequency in the final sub-period of record (1988-92). The fourth series is the Kelvin at Killermont (84001). The number of runs observed in each of these series was statistically less than expected from a random series (at the 10% confidence interval) which indicates the presence of a possible trend.

The graphical output from the Mann's test for trend in the mean, applied to each series, is given in Figures 5.5(b)-5.18(b) (Appendix Two). The key points and general patterns of these plots are described in Table 5.4 for groups of records which display similar trend patterns, rather than for individual series. These similarities between series were detected by correlating all of the individual Mann's trend plots (depicted by the sequence of the test statistic u(i)). The groups are based upon flood frequency series linked by high (+0.80 and above) correlation coefficients (Table 5.4).

Table 5.4: Characteristics of the Mann's Test for Trend in the Mean 1954-92: Flood Frequency Series

Avon at Delnashaugh (08004) **Spey at Boat of Brig (08006)**	*Random series until late 1960s. Frequencies decline thereafter until* *(a)1992 (08004)* *(b)1980 (08006) when an increase occurs:* u(i): varies around zero (a) u(i):downward trend (5% conf.level) by 1977 (1% conf.level) by 1988 (b) u(i):downward trend (1% conf.level) by 1977 Figure 5.5(b) and 5.7(b) respectively
Spey at Boat of Garten (08005) **Spey at Grantown (08010)**	*Variable series, no significant trends recorded:* u(i): negative during 1960s/1970; positive after 1982 Figures 5.6(b) and 5.10(b)
Spey at Invertruim (08007) **Kelvin at Killermont (84001)** **Dulnain at Balnaan Bridge (08009)**	*Random series until 1978 when frequencies increase to 1992:* u(i): upward trend (5% conf.level) by late 1980s Figures 5.8(b), 5.18(b) and 5.9(b) respectively
Dee at Woodend (12001) **Tay at Pitnacree (15007)** **Dean Water at Cookston (15008)**	*Frequencies decrease from late 1950s to late 1960s; an increase follows to early 1980s and random behaviour follows:* u(i): downward trend (5% conf.level) late 1960s u(i): returns to zero level by 1982 Figures 5.11(b), 5.14(b) and 5.15(b) respectively
Tay at Caputh (15003) **Tay at Ballathie (15006)** **Tweed at Peebles (21003)** **Earn at Kinkell Bridge (16001)**	*Random series until late 1960s; frequencies decline during 1970s but increase from the early 1980s:* u(i):downward trend (5% conf.level) late1970s u(i): reaches zero level by 1992 Figures 5.12(b), 5.13(b), 5.17(b) and 5.16(b)

5.9.2 SUMMARY REMARKS ON FLOOD FREQUENCY SERIES 1954-92

From the statistical information summarised above, it can be seen that flood frequencies vary in all records over the period 1954-92. Although individual series do display anomalies which are unique to that record, it is possible to detect general patterns of flood frequency variability. Originally, it was suggested that a pattern of high flood frequencies in the earlier and later parts of the record may exist. Use of sub-period means then suggested three possible patterns and the Mann's test of trend in the mean revealed a possible five. By combining this information, it is possible to join some of these more rigid groupings to create two general groupings.

A pattern of similarly high frequencies in the 1950s and 1980s, split by a period of low values in the 1970s is a true reflection of six of the records (Spey at Boat of Brig (08006), Dee at Woodend (12001), Tay at Caputh and Ballathie (15003 and 15006), Earn at Kinkell (16001) and the Tweed at Peebles (21003)). For the majority of these records this pattern was clearly evident in the statistical analysis; in others the Mann's test was required to bring out the true picture of changes in the mean value. The record from the Avon at Delnashaugh (08004) behaves in a similar manner to these records until the 1980s, when flood frequencies continue to decrease rather than recover.Of this group of records, three (the Avon (08004), Spey (08006) and Tweed (21003)) are without a standardised discharge threshold. This may indeed explain the unusual behaviour evident within the Avon flood frequency series from the 1980s onwards.

The second general pattern is evident in records from the Spey at Boat of Garten (08005), Invertruim (08007) and Grantown (08010), the Balnaan at Dulnain Bridge (08009), Dee at Woodend (12001), Tay at Pitnacree (15007) and Dean Water at Cookston (15008). The pattern is one of a clear peak in frequencies during the 1980s, whilst a period of low flood activity seems to have occurred in the late 1960s or was not evident at all. The Kelvin record (84001) seems to display characteristics from both groupings, with the general timing of the first group of records and the peak in frequencies of the second group, but again this may be a consequence of the omission of a standardised threshold.

It is clear, therefore, that two patterns or themes are broadly apparent within the flood frequency series, although it is important to note that a degree of variability will always be found within individual records (a likely consequence of localised conditions).

The question must also arise concerning whether there is any link between flood frequency variability and geographical location. Unfortunately, the two broad groupings identified above show no strong links to geographical location, although it would be extrememly difficult to infer too much information from these series since their geographical coverage is somewhat restricted.

5.9.3 FLOOD MAGNITUDE SERIES

Time series and running mean plots produced from the mean exceedance series (Figures 5.5(c)-5.18(c), Appendix Two) show a more diverse range of characteristics than the flood frequency series. In the majority of cases, the running mean plots helped clarify any underlying pattern which was not readily apparent in the raw data. In a number of records (Spey at Grantown (08010) and the Tweed (21003), for example) annual mean exceedances did appear fairly stable through time whilst other time series characteristics were similar to some of the flood frequency series, including the Dee (12001) and Tay at Ballathie (15006) records.

Extreme mean exceedances do not seem to be associated with particular years within the 1954 to 1992 period. Instead outlier values seem to be specific to individual series only. In some cases, such as in the Tay at Pitnacree series (15007), extreme mean exceedance values occur in years where an extreme flood frequency value has been recorded. However, even within this series, it is also apparent that high mean exceedance values can occur in years where flood frequencies are low. The relationship between flood frequencies and mean exceedances does, therefore, appear to be random with no clear association discernible.

Observation of the five-year sub-period mean values once again backed up the view that there is a considerable degree of variety in the behaviour of the mean exceedance series, although coincidental patterns of behaviour were detected in some series:

- The Avon (08004) and Dee (12001) series, which are actually from adjacent catchments, display a maximum sub-period mean value early within the series (1958-62) with a low in the period 1968-72;
- Series from the Spey at Boat of Garten (08005), and Tay at Ballathie (15006) and Pitnacree (15007) (similarly in adjacent catchments) are also characterised by the lowest mean magnitude in the sub-period 1968-72; however, the highest mean is linked to the most recent sub-period 1988-92.

The Kruskall-Wallis test implies that, for the majority of series, sub-period mean exceedances are generally stable throughout the period 1954-92. The two exceptions are the Dee (12001) and Tay at Pitnacree (15007) series, which both indicate sub-period means are statistically unequal. Inequality in the former series is due to a low sub-period mean in the 1960s, whilst in the latter it is due to a very high sub-period mean in the 1980s.

Just one of the fourteen records, from the Dean Water at Cookston (15008), showed statistical evidence (at the 1% confidence level) of being a non-random series using the Runs test.

The output from the Mann's test for trend in the mean (Figures 5.5(d)-5.18(d), Appendix Two) were again used to produce a correlation matrix, to group together those series displaying similar trend characteristics. Typically, correlation values between records were somewhat lower than for with the flood frequency data and therefore the groupings presented below are less rigid. This suggests that flood magnitude records are perhaps displaying more individual patterns of behaviour. The general characteristics of the Mann trend plots and the grouping of similar plots based upon the correlation matrix are presented in Table 5.5.

Table 5.5: Characteristics of the Mann's Test for Trend in the Mean 1954-92: Mean Exceedance Series

Avon at Delnashaugh (08004) **Dee at Woodend (12001)**	*Magnitudes decrease to late 1960s and stabilise. A slight increase occurs and then values stabilise again:* u(i):downward trend (5% conf.level) by mid 1970s u(i):increases but remains below zero Figures 5.5(d) and 5.11(d) respectively
Spey at Boat of Garten (08005) **Tay at Pitnacree (15007)**	*Magnitudes decline to mid 1960s. A gradual increase follows throughout the entire length of record:* u(i):downward trend (5% conf.level) by mid 1960s u(i): increases but reaches zero by 1992 Figures 5.6(d) and 5.14(d)
Tay at Ballathie (15006) **Dean Water at Cookston (15008)** **Kelvin at Killermont (84001)**	*Magnitudes decrease until early 1970s; values increase thereafter:* u(i):downward trend (1% conf.level) by early 1970s u(i):increases but does not exceed zero Figures 5.13(d), 5.15(d) and 5.18(d) respectively
Spey at Invertruim (08007)	*A similar pattern to Boat of Garten and Pitnacree but the increase is enhanced:* u(i):downward trend by 1960s (5% conf.level) u(i): upward trend by 1992 (10% conf.level) Figure 5.8(d)
Tay at Caputh (15003) **Earn at Kinkell Bridge (16001)** **Tweed at Peebles (21003)**	*Magnitudes appear lower in the early part of the record, but no statistical trends are maintained:* u(i):fluctuates, mainly below zero Figures 5.12(d), 5.16(d) and 5.17(d) respectively
Spey at Boat of Brig (08006)	*An almost constant decrease in magnitudes during the period of record:* u(i): significant downward trend (10% conf.level) in mid 1970s; though values then increase slightly t Figure 5.7(d)

Table 5.5 (cont): Characteristics of the Mann's Test for Trend in the Mean 1954-92: Mean Exceedance Series

Spey at Grantown (08010)	*Mean magnitudes do appear to vary but to no great extent:* u(i): fluctuates but does not exceed significant trend values Figure 5.10(d)
Dulnain at Balnaan Bridge (08009)	*Magnitudes appear relatively stable until the mid 1970s when they increase:* u(i): no trends exceeded Figure 5.9(d)

5.9.4 SUMMARY REMARKS ON FLOOD MAGNITUDE SERIES 1954-92

The general conclusion from examining the mean exceedance series from the period 1954-92 is that there was less variability within the records (i.e. it was more difficult to distinguish periods of high and low mean exceedances) and there is greater variability between records. Although it was possible to pick out groups of records with similar patterns of variability, it is likely that there will be greater variability *within* these groups than with the frequency series. Nonetheless, four groups could be identified, in terms of the temporal signatures and trends:

- The largest group, containing series from the Spey at Boat of Garten (08005) and Invertruim (08007), the Tay at Ballathie (15006) and Pitnacree (15007), Dean Water (15008) and the Kelvin (84001), is characterised by a general increase in mean exceedances from the 1970s onwards (although a standard threshold is absent from the Kelvin record);
- The second group contains a number of records where mean exceedances clearly peak in the late 1950s and 1980s, with the lowest mean exceedances recorded in the intervening period (Avon (08004), Dulnain (08009) and the Dee (12001)) (although a standard threshold is absent from the Avon record);
- A further group of records (Spey at Grantown (08010), Tay at Caputh (15003), Earn (16001) and the Tweed (21003)) display no real change in values over the standard period (although a standard threshold is absent from the Tweed record);
- The Spey at Boat of Brig (08006) is rather unique in that mean exceedances show a constant decrease throughout the standard period. This may be a result of the fact that extreme floods may bypass the gauged river cross section (Section 5.9).

As with the flood frequency series, there appears to be no strong geographical link to the temporal patterns of variability displayed in the mean exceedance series. Examining spatial variability is obviously bestsuited to a sample of data with a wide geographical distribution; this is clearly not the case for the records included in subset D.

5.9.5 SUMMARY REMARKS

The most obvious point to be noted from the analysis described above is the need to combine the results from all statistical techniques in the interpretation process. Although the Mann's test for trend is an excellent tool for examining trends and identifying turning point, it tends to depict changes *relative* to the preceding state of the time series. In the Avon (08004) mean exceedance series 1954-92, for example, annual values clearly peak at similar levels in the 1950s and mid 1980s (Figure 5.5(c), Appendix Two). If one observes the subsequent Mann plot (Figure 5.5(d), Appendix Two), the first peak is clearly represented but, whilst the second peak does register in the plot, the test statistic does not reach the same significance levels as the first peak. This is because the test statistic remained at a low level during the 1970s and the increase, therefore, began from a low base point. It is essential, therefore, to combine other statistics (such as the running mean plots, sub-period basic statistics etc.) with the Mann plot, in order to acquire a full and accurate interpretation of the time series.

5.10 DATA SUBSET C: 1964 - 1992

In addition to the period 1954-92, extensive analysis was carried out on records covering the interval 1964-92, in the hope of gaining a better understanding of how temporal variability within flood frequency and magnitude series are spatially related. Fifty-one records (Table 3.1 (Appendix One); Map 5.7) contain data for this period and, although there is still a noticeable bias towards the south and east, the spatial coverage is more extensive than with the longer subsets of records. The greatest drawback is that no records from the north-west are included in this group but additional data from Scottish Hydro-Electric (SHE) has provided some insight into flow variability (Section 5.11).

Within this group of records, a wide range of hydrological regime and catchment characteristics are represented. Catchment areas, for example, range from 4587.1km^2 (Tay at Ballathie (15006)) to just 43.8km^2 (Almond at Almond Weir (19002); NERC, 1993). Other catchment characteristics such as land use, soil characteristics and channel features also vary, but such features tend to vary locally and it is therefore difficult to make generalised statements. Hydrological characteristics are also highly variable, and tend to be associated with the nature of the physical environment. Mean annual rainfall values, for example, are typically highest in north and west Scotland although these areas are poorly represented in the data set. Of those records analysed, rainfall values are highest in the west and south-west; the Gryfe at Craigend catchment (84011) has a mean annual precipitation of 1795mm in contrast to lower values in the east, such as the Esk at Musselburgh catchment (19007) where a mean of 847mm is recorded (NERC, 1993). Peak flow events also vary between records, although they are likely to be a function of catchment size and geographical location. The Tay at Ballathie (15006) has a large catchment area and relatively high mean annual rainfall (1904mm); consequently the mean annual flood is high (955.6$m^3 s^{-1}$). Smaller catchments with lower precipitation inputs, such as the Esk at Musselburgh (19007) have lower mean annual flood values (71.1 $m^3 s^{-1}$).

5.10.1 FLOOD FREQUENCY SERIES

First impressions of the temporal variability within the frequency series, using time series and running mean plots (Figures 5.19(a)-5.69(a)), indicate highly variable series although some general patterns can be identified, particularly within the RPB regions:

- *Highland RPB*: the Findhorn at Shenachie record (07001) shows a possible increase in frequencies although no clear pattern appears downstream at Forres (07002); this may be related to the incidence of thunderstorms which are common in this region (McEwen, 1993);
- *North-East RPB*: a number of series clearly show a 'flood-poor' period in the 1970s;
- *Tay RPB*: the majority of records show no discernible pattern although records from the Tay at Pitnacree (15007) and Ruchill Water at Cultybraggan (16003) indicate a possible increase in frequencies over recent years;
- *Forth RPB*: all records show a clear 'flood-poor' period in the late 1960s and early 1970s;
- *Tweed RPB*: few records show any clear pattern, although the 'flood-poor' period of the early 1970s is evident in the Tweed at Peebles (21003) and Gala Water at Galashiels (21013) records;

- *Solway RPB*: the Cree at Newton Stewart (81002) series shows a distinct increase in frequencies during the second half of the record;
- *Clyde RPB*: few series show any clear pattern of frequencies.

Although it is apparent that some distinct changes in flood frequency behaviour have been detected using these plots, it is often difficult to draw out any finer details on any changes (the exact timing, the significance, etc.). The value of the additional time series statistics are clearly evident under such circumstances. Within these raw data series, a number of years are associated with extreme flood frequencies. A large proportion of these extremes are confined to the period since 1980, and in particular 1982 and 1990 are often associated with high frequencies. Whether this period signifies a general increase (and possible trend) in the occurrence of floods or whether these events are isolated occurrences has yet to be determined.

5.10.1.1 CLUSTER ANALYSIS

Having generated time series statistics from each of the fifty-one flood frequency records, it was again clear that many records appeared to display similar characteristics. In an attempt to group together those records which share a *broadly* similar pattern of temporal variability, cluster (or classification) analysis was used. This classification was based upon the Mann's trend plots (the sequence of the test statistics u(i) derived from the Mann's test for trend in the mean) derived from each of the fifty-one flood frequency series, since this provides a good measure of year-to-year temporal variability. This analysis was undertaken for two reasons. Firstly, it provided an overall temporal variability pattern for groups of stations and secondly, to provide a means of ascertaining how temporal variability is spatially coherent.

For those series included in subset D, similar trend signatures have previously been grouped together using simple correlation techniques. This was feasible since there were only fourteen series included in the subset. With over fifty series a correlation matrix would, in fact, be too complex to retrieve any clear groupings. Hence the cluster analysis technique was favoured.

Classification analysis is a way of grouping objects which display similar characteristics using a set of computer-based algorithms (Wishart, 1987). Clustering begins with the two objects (in this case the u(i) plots for two gauging stations) closest in *n*-dimensional space merging to form the nucleus of a cluster. The process continues with further objects (i.e. plots for gauging stations which have not yet merged into a cluster) either joining this nucleus or one of the remaining single objects to form a new nucleus. The process continues until all the objects have been allocated to the desired number of clusters. Merging may proceed either by hierarchical fusion of clusters, iterative relocation of individual objects, or by a combination of the two methods (Gordon, 1981). A sequential application of Ward's method, hierarchical fusion and then iterative location to these data series was carried out, based upon recommended guidelines (Wishart, 1987), with the resultant outputs producing three optimum clusters for the flood frequency database (Clusters A-C). The size of these optimum clusters was determined on the basis of the maximum rate of change in the D^2 statistic at each successive fusion, where D^2 represents the square of the average inter-group distance. The characteristic trend patterns of each cluster are presented below. However, the results of all time series techniques carried out on the fifty-one flood frequency series are presented with reference to the clusters or groups identified in the classification process.

Mean flood frequencies calculated for five-year sub-periods of a record can be useful in identifying periods of extreme (high or low) values and gradual changes in the mean. Table 5.6 identifies the sub-periods displaying the maximum and minimum mean flood frequencies for the fifty-one time series covering the period 1964-92. Although it is clear from this table that *within* the frequency cluster groupings there is a degree of variation on the timing of maximum and minimum sub-period means, a general theme is evident, with high sub-period means being recorded in the 1980s and 1990s and low means in the late 1960s and the first half of the 1970s. This theme is apparent in all three cluster groupings, which suggests that one over-riding factor which has influenced a large proportion of the flood frequency series.

Table 5.6: Five-year sub-periods recording the highest and lowest mean flood frequencies, 1964-92

CLUSTER	STATION NUMBERS	PERIOD OF HIGH MEAN	PERIOD OF LOW MEAN
A	07001, 84012	1988-92	1968-72 /1973-77
A	12001, 80001	1978-82	1968-72
A	15008	1978-82	1988-92
A	16003, 81002	1983-87 /1988-92	1968-72
B	07002, 08007, 08009, 21007, 84019	1988-92	1968-72 /1973-77
B	08005, 08006, 08010, 82001	1978-82	1968-72
B	15006, 15007	1983-87 /1988-92	1968-72
B	19006, 84001	1983-87	1968-72 /1973-77
B	79003	1988-92	STABLE
B	84011	1988-92	1973-77 /1978-82
C	07003	STABLE	1973-77
C	08004	1968-72	1983-87 /1988-92
C	09001, 09002	1978-82	1988-92
C	09003	1983-87	1968-72
C	15003	1983-87 /1988-92	1968-72
C	16001, 19007, 21006, 21009, 21013	1988-92	1973-77
C	19001, 19002, 19004, 19011, 20005	1983-87	1968-72 /1973-77
C	20001, 20003	1983-87	1988-92
C	21003		
C	21005, 21008, 21012, 79005, 84003, 84004, 84005	1988-92	1968-72
C	21011, 79002	1978-82	1968-72
C	79004	1978-82	1973-77

The Kruskall-Wallis test of inequality within sub-period means is based upon seven sub-divisions covering four-year periods within the record, commencing in 1968. Fifteen of the fifty-one records indicate that sub-period means are statistically unequal and these include a number of records from each cluster. Table 5.7 provides suggested explanations for those stations which register a significant difference between sub-period mean values.

Using the Runs test as a measure of detecting random behaviour, fifteen series showed statistical evidence for being non-random. In all cases, the observed number of runs in these series were significantly less than expected from a random series, which indicates a possible trend within the data (Table 5.8).

Since the cluster analysis is based upon the series derived from the Mann's test statistic, one would expect a high degree of similarity in those frequency trend plots grouped together. The trend plots derived from each individual flood frequency series are depicted in Figures 5.19(b)-5.69(b) and the characteristics of grouped plots are described in Tables 5.9(a)-5.9(c).

5.10.2 SUMMARY OF FLOOD FREQUENCY SERIES 1964-92

Within each of the fifty-one series analysed, it was possible to detect variability within the annual frequency of floods. Visually, there appeared to be a common theme within simple time series and running mean plots: that of a decrease in flood frequencies during the late 1960s and early 1970s, which was followed by an increase in values into the 1980s and 1990s. The technique of classification was therefore employed to identify members of similar groups.

The classification was based upon the values of the Mann's test statistic derived from each series. Consequently, three groups of records (Clusters A, B, C) displaying similar temporal trend patterns were identified. Figures 5.70(a)-(c) display the general characteristics of each cluster, represented by the median values of the Mann's test statistic u(i), taken from each series within the cluster.

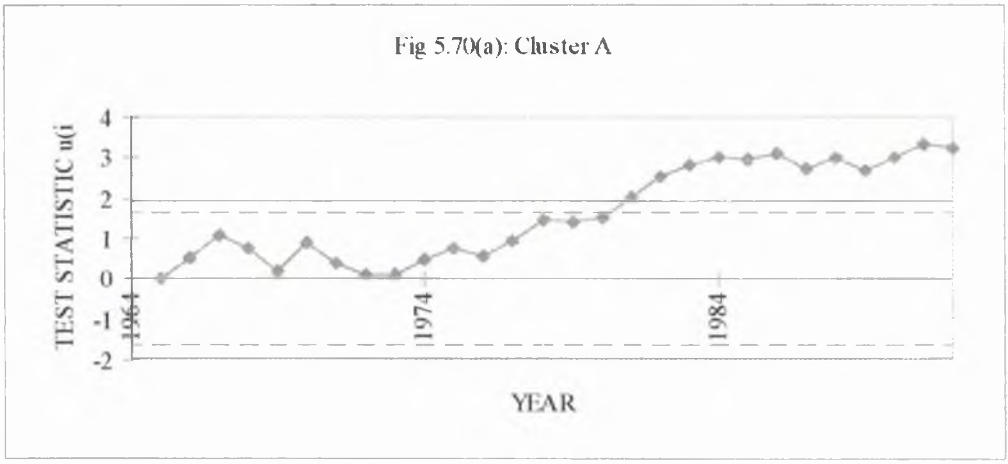
Table 5.7: Possible causes of statistical inequality in flood frequency series 1964-92

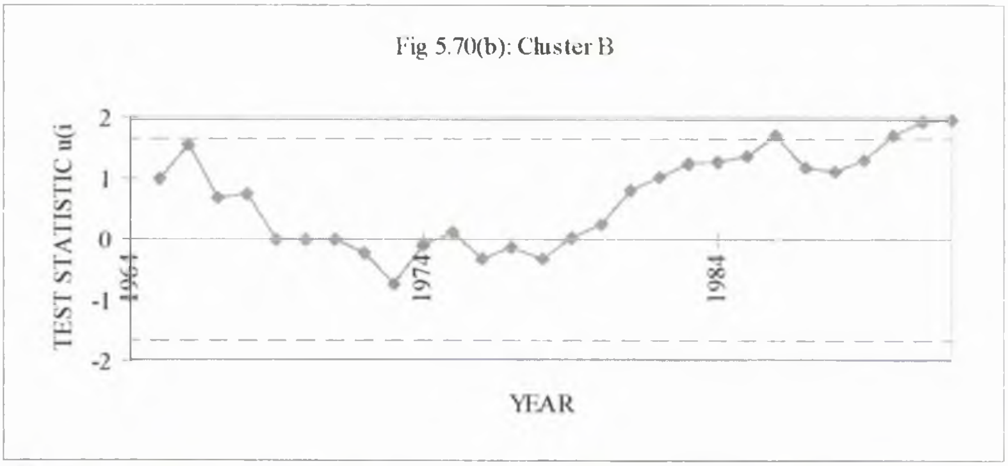
CLUSTER A:	
Findhorn at Shenachie (07001)	Unequal (5% confidence level)
• inequality appears to be related to particularly high mean frequencies for the periods 1980-83 and 1988-91	
Dee at Woodend (12001)	Unequal (10% confidence level)
• very low mean frequencies in the 1960s (1964-67 and 1968-71)	
Ruchill Water at Cultybraggan (16003)	Unequal (1% confidence level)
• highly variable sub-period means throughout the period of record	
White Cart Water at Hawkhead (84012)	Unequal (10% confidence level)
• a clear difference between means in the earlier and latter periods of record	
CLUSTER B:	
Findhorn at Forres (07002) **Spey at Invertruim (08007)**	Unequal (1% confidence level) Unequal (10% confidence level)
• a particularly high mean frequencies for the period 1980-83	
Kelvin at Killermont (84001)	Unequal (5% confidence level)
• a wide spread of sub-period mean frequencies	
N.Calder Water at Calderpark (84019)	Unequal (10% confidence level)
• an extremely low mean frequency in the period 1972-75	
CLUSTER C:	
Isla at Grange (09003)	Unequal (10% confidence level)
• an exceptionally high mean frequency in the early 1980s	
Almond at Craigiehall (19001) **North Esk at Dalmore Weir (19004)** **Tyne at East Linton (20001)** **Tweed at Norham (21009)**	Unequal (5% confidence level) Unequal (5% confidence level) Unequal (10% confidence level) Unequal (5% confidence level)
• a particularly low mean frequency in the period 1972-75	
Esk at Musselburgh (19007) **Birns Water at Saltoun Hall (20005)**	Unequal (10% confidence level) Unequal (5% confidence level)
• very variable mean frequencies are the likely cause of inequality	

Table 5.8: Non-random flood frequency series, as detected by the Runs test

CLUSTER	GAUGING STATION RECORD	CONFIDENCE LEVEL
A	Findhorn at Shenachie (07001)	5%
A	White Cart Water at Hawkhead (84012)	1%
B	Findhorn at Shenachie (07002)	10%
B	Tay at Ballathie (15006)	5%
B	Tay at Pitnacree (15007)	1%
B	N.Calder Water at Calderpark (84019)	1%
C	Deveron at Muiresk (09002)	1%
C	Isla at Grange (09003)	10%
C	Almond at Craigiehall (19001)	1%
C	Almond at Almond Weir (19002)	1%
C	North Esk at Dalmore Weir (19004)	10%
C	Esk at Musselburgh (19007)	5%
C	Tyne at Spilmersford (20003)	10%
C	Gala Water at Galashiels (21013)	10%
C	Clyde at Blairston (84005)	5%

Figures 5.70(a)-5.70(b): Flood Frequency Clusters - Mann's Test for Trend in the Mean 1964-92 (based upon median values of the test statistic u(i))





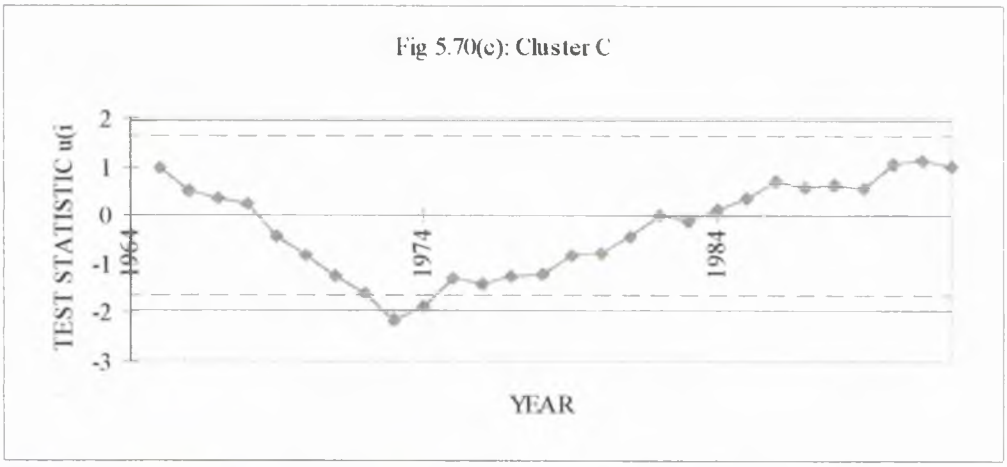
NB. The Dotted Line signifies the 10% Confidence Level for a significant trend
The Solid Line signifies the 5% Confidence Level for a significant trend

Cluster A records appear to show random behaviour, based upon the value of the test statistic u(i), until the mid 1970s when an increase in frequencies occurs. Typically, this increase signifies a significant trend by the mid 1980s. Cluster B and C series typically display a decline in frequency values between 1964 and 1973; typically this decline is likely to be most enhanced and representative of a significant downward trend in the Cluster C grouping. From this point, the test statistic u(i) increases steadily to 1992, by which time the significance level for an upward trend has often been exceeded. These increases appear to occur in a roughly parallel manner to the cluster A records. There is a hint of a more stable period between 1986 and 1989 within records from all three clusters. These patterns back up initial observations on many of the flood frequency series.

On plotting the geographical location of flood frequency cluster members (Map 5.5) some interesting spatial patterns are revealed. A tentative distinction can be made between the cluster B sites (typically forming a western grouping) and the cluster C sites (comprising a more easterly grouping), with the small number of sites in cluster A, forming a predominantly westerly grouping. Relating these spatial patterns to the temporal patterns in the test statistics, it would seem that those rivers draining the more easterly part of Scotland most strongly registered the downturn in flood frequencies in the early 1970s and although a subsequent increase in frequencies has been experienced, this has not yet registered as a significant increase (the test statistic u(i) started from a lower base point in 1973). By contrast, the rivers draining the more westerly parts did not register such a decline in flood frequency in the early 1970s and, starting from a higher base point in the mid 1970s, have yielded a steady increase in flood frequency which became statistically significant in the early 1990s. If these patterns can be linked to a comparable trend in weather types (Chapter Six), a link with climatic variability can be postulated.

It is, however, important to consider the drawbacks of using the classification technique. Very often, series displaying unusual or unique characteristics will be joined to a cluster with which they show few similarities simply because they must be grouped to one of the clusters. For the purpose of this study, such series were

Figure 5.70(c): Flood Frequency Clusters - Mann's Test for Trend in the Mean 1964-92 (based upon median values of the test statistic u(i))



NB. The Dotted Line signifies the 10% Confidence Level for a significant trend
The Solid Line signifies the 5% Confidence Level for a significant trend

Map 5.5: Membership of flood frequency clusters 1964 - 1992

+ Cluster A records	+ Cluster A records (unrepresentative)
■ Cluster B records	■ Cluster B records (unrepresentative)
o Cluster C records	o Cluster C records (unrepresentative)

identified using simple correlation techniques: the Mann's trend plot for each series within a cluster was correlated with the median characteristics of that grouping. For the majority of series, correlation coefficients were between +0.80 and +0.95. However, a small number of series had correlation coefficients of around +0.50 or less, and consequently these series were identified as not being truly representative of the cluster grouping. These series are:

- the Dean Water (15008) and Urr (80001) series from cluster A;
- the Girvan (82001) and Gryfe (84011) series from cluster B;
- the Avon (08004), Deveron at Avochie (09001) and Yarrow Water (21011) series from cluster C (see also Map 5.5)

In the case of the later four series, it appears that the unusual patterns of variability may relate to the omission of a standardised threshold.

Classification analysis implies discrete boundaries between groups of records when, in reality, it is possible that there may be a continuous merging of the three groups of records, particularly because of the sometimes near-parallel pattern of behaviour between the clusters.

The use of the clustering technique has also confirmed that the different time series statistics used in this project reveal different aspects of temporal variability within a series. The process of cluster analysis has successfully grouped together the Mann trend plots, to display similar patterns of variability within a time series on a year-to-year basis. However, it is also evident that there tends to be a wide range of results from other statistical techniques, such as sub-period means and Kruskall-Wallis tests, within cluster groupings. This suggest that annual variations within a time series are most clearly depicted using either a running mean or Mann trend plot, whilst the other techniques are best suited to providing only generalised descriptions of time series behaviour.

5.10.3 FLOOD MAGNITUDE SERIES

The pattern of annual mean exceedances, as revealed by simple time series and running mean plots, is displayed in Figures 5.19(c)-5.69(c). A number of key points are evident from these plots and from simple Minitab analysis carried out :

- *Highland RPB*: A definite increase in flood magnitudes occurs throughout the period 1964-92 in the Findhorn at Shenachie (07001) record, though no clear pattern is discernible from the downstream series at Forres (07002);
- *Tay RPB*: The Tay at Pitnacree series (15007) shows a possible increase in magnitudes over recent years;
- *Forth RPB*: A number of records show a possible decrease in flood magnitudes during the early 1970s;
- *North-East, Tweed, Solway and Clyde RPBs*: No clear patterns were discernible.

To summarise the flood magnitude series, in their most basic form, the majority of records show no clear pattern, unlike the flood frequency series where there was clearly an underlying theme. It seems that annual mean excess series are often rather stable, interrupted only by years that record extreme or outlier values. Any years within each individual series when flood magnitudes reached such extreme levels were identified using the Minitab statistical package. Years classified as either possible or probable outliers within individual series do not seem to appear within specific periods of time, rather they are randomly spread throughout the 1964-92 period. Similarly, there do not appear to be any years when extreme mean exceedances occurred in a number of gauging station records.

5.10.3.1 CLUSTER ANALYSIS

The fifty-one flood magnitude series were also grouped together according to the characteristics of the annual sequence of the Manns test for trend in the mean statistic, using the techniques of classification analysis described in Section 5.10.1.1. In the case of this group of series, the optimum number of clusters was four (Clusters 1-4). The characteristics of each cluster grouping are described below and, as with the flood frequency clusters, the results of all additional time series techniques applied to each individual mean exceedance series will be presented according to the cluster grouping.

Table 5.10 lists the minimum and maximum sub-period mean exceedances for the period 1964-92. In most cases, the sub-period recording the lowest mean value is in the 1970s and the highest mean is most likely to have been recorded in the 1980s although there is a degree of diversity in these results. However, the general pattern of lower mean exceedances in the 1970s occurs in a number of series within each cluster grouping.

Any statistical inequality in these sub-period means can be detected using the Kruskall-Wallis test, based upon a sub-period division of seven four-year periods. However, just three series displayed evidence for significant inequality of sub-period means. These series, and the possible reasons why statistical inequality exists are given in Table 5.11. All of these records identified relate to adjacent catchments and this suggests a common cause for the statistical inequality (and the low mean exceedance values in the 1970s), which may be a combination of weather conditions and catchment characteristics.

Table 5.11: Possible causes of statistical inequality in mean exceedance series 1964-92

CLUSTER 4:	
Almond at Almond Weir (19002)	Unequal (5% confidence level)
Water of Leith at Murrayfield (19006)	Unequal (5% confidence level)
Esk at Musselburgh (19007)	Unequal (5% confidence level)
• inequality appears to be related to a particularly low mean exceedance for the sub-periods in the 1970s	

Very few station records showed evidence that the number of runs differed significantly from that displayed by a random time series. These series, with representatives within all four clusters, once again showed significantly fewer runs

Table 5.10: Five-year sub-periods recording the highest and lowest mean flood exceedances, 1964-92 (Clusters 1 and 2)

CLUSTER	STATION NUMBERS	PERIOD OF HIGH MEAN	PERIOD OF LOW MEAN
1	07003	1983-87	1973-77 /1988-92
1	09001	1968-72	1973-77 /1988-92
1	09002	1978-82	1973-77
1	19004	1968-72	1973-77
1	20001	1988-92	1973-77
1	21003	1968-72	1973-77
1	21005, 84005	1988-92	1968-72
1	21006	1978-82	1968-72 /1983-87
1	21007	1973-77	1988-92
1	21008, 21009	1988-92	1973-77
1	21011,84003, 84004	1978-82	1968-72
1	79003	1973-77	1968-72
2	07001, 08009	1978-82	1973-77
2	12001	1973-77	1968-72
2	16003	1973-77	1978-82
2	21013	1983-87	1968-72
2	80001	1983-87	1988-92

Table 5.10(cont): Five-year sub-periods recording the highest and lowest mean flood exceedances, 1964-92 (Clusters 3 and 4)

CLUSTER	STATION NUMBERS	PERIOD OF HIGH MEAN	PERIOD OF LOW MEAN
3	08004	1978-82	1973-77
3	08005, 15006, 84001	1988-92	1968-72
3	08006, 08007	1968-72	1973-77
3	08010	1988-92	1983-87
3	09003	1988-92	1973-77
3	15008	1978-82 /1983-87	1988-92
3	16001	1983-87	1978-82
3	20003	1983-87	1968-72
3	20005	1983-87	1973-77
3	21012	1988-92	STABLE
3	79002, 79004	1973-77	1968-72
3	79005	1973-77	1988-92
3	81002	1968-72	1983-87
3	82001	1978-82	1983-87 /1988-92
3	84011	1978-82	1988-92
3	84012	1978-82 /1988-92	1968-72
4	07002, 19006, 19007, 19011	1978-82	1973-77
4	15003, 15007	1988-92	1968-72
4	19001	1968-72	1973-77
4	19002	STABLE	1973-77
4	84019	1978-82	1968-72

than the expected number, in a similar manner to flood frequency records (Table 5.12).

The output from the final time series technique, the Mann's test of trend in the mean, is plotted in Figures 5.19(d)-5.69(d) (Appendix Two) These individual trend plots provided the basis for creating clusters or groups of similar mean exceedance series and a brief summary of the trend characteristics of each series within a cluster is presented in Tables 5.13(a)-5.13(d) (Appendix Two).

5.10.4 SUMMARY REMARKS ON FLOOD MAGNITUDE SERIES 1964-92

The mean exceedance series analysed did appear to show less temporal variability than was apparent in the frequency series. Cluster analysis identified four groups of records which display similar trend characteristics, according to the Mann's test statistics. Figures 5.71(a)-(d) display the general characteristics of each of these groupings, based upon the median values of the test statistic u(i).

The mean exceedance series in Cluster 1 generally register a decline in values throughout the 1970s, which typically signifies a downward trend at either the 10% or 5% confidence level by the mid 1970s. From this point, values show a steady increase until the mid 1970s when values stabilise. The last few years of record do signify a slight increase in mean exceedances.

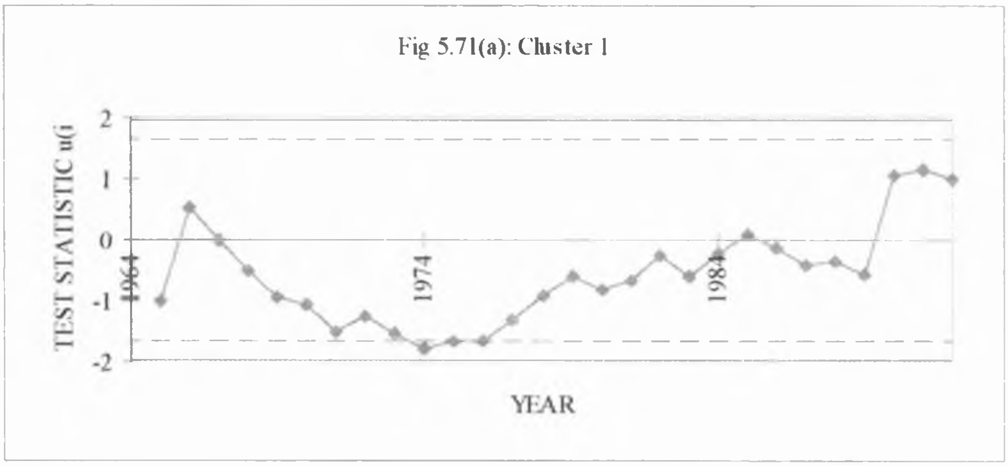
Cluster 2 records show stable magnitudes until 1973 when an increase follows. This increase in magnitude peaks around 1985 and is indicative of an upward trend (at the 5% confidence level). Following 1985, magnitudes decrease slightly and stabilise. This pattern is very similar to the trend plots observed in the cluster A grouping of flood frequency series.

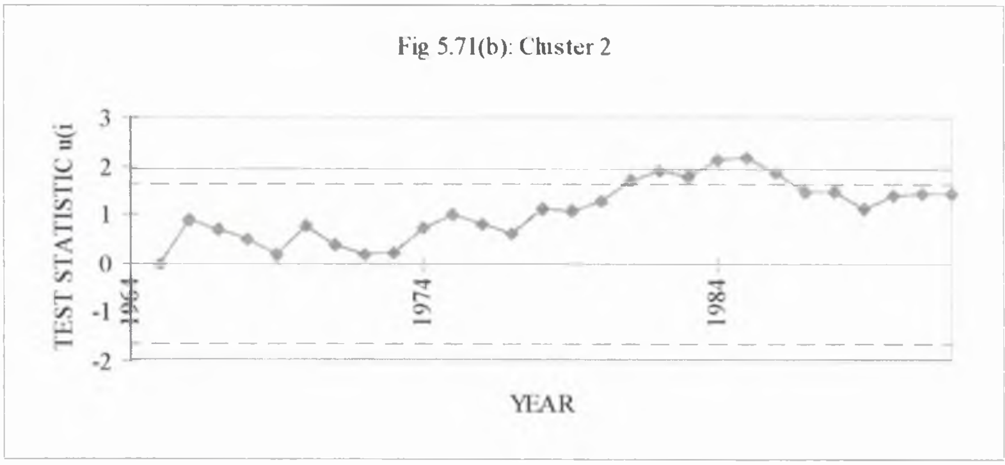
Cluster 3 series show a slight decline in mean exceedances during the early 1970s. However, the test statistic u(i) suggests no significant trends.

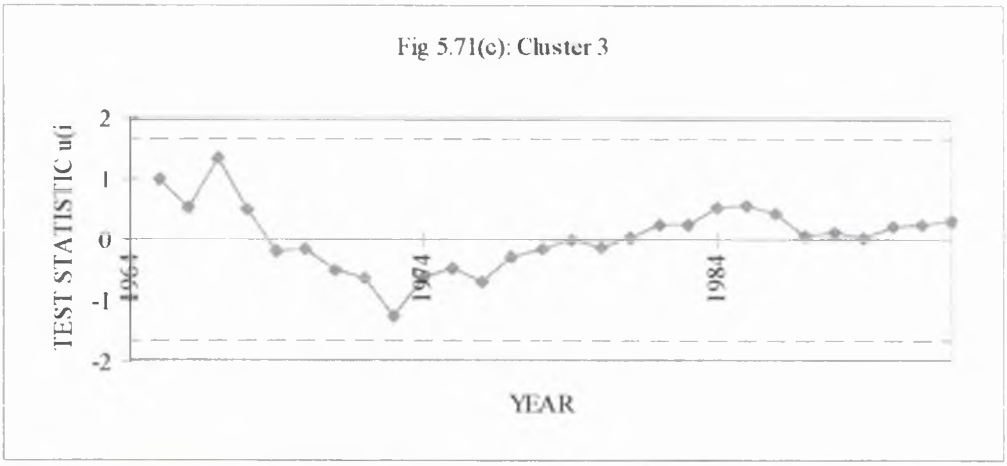
Table 5.12: Non-random mean exceedance series, as detected by the Runs test

CLUSTER	GAUGING STATION RECORD	CONFIDENCE LEVEL
1	North Esk at Dalmore Weir (19004)	5%
2	Findhorn at Shenachie (07001)	5%
3	Scar Water at Capenoch (79004)	1%
4	Almond at Almond Weir (19002)	1%
4	Water of Leith at Murrayfield (19006)	1%
4	Esk at Musselburgh (19007)	5%

Figures 5.71(a)-5.71(c): Flood Magnitude Clusters - Mann's Test for Trend in the Mean 1964-92 (based upon median values of the test statistic u(i))

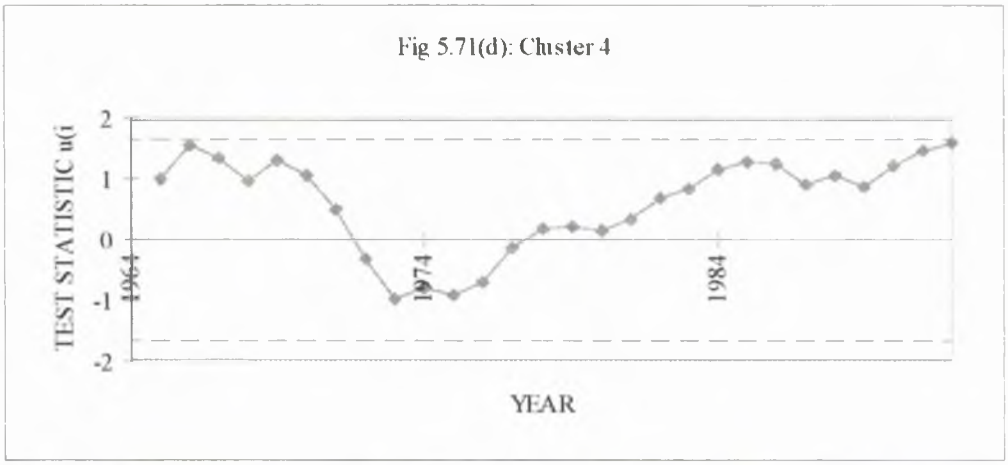






NB. The Dotted Line signifies the 10% Confidence Level for a significant trend
The Solid Line signifies the 5% Confidence Level for a significant trend

Figures 5.71(d): Flood Magnitude Cluster - Mann's Test for Trend in the Mean 1964-92 (based upon median values of the test statistic u(i))



NB. The Dotted Line signifies the 10% Confidence Level for a significant trend
The Solid Line signifies the 5% Confidence Level for a significant trend

The final group of series , Cluster 4, show peaks in mean exceedances in the early and latter parts of the record (just reaching the 10% confidence level) separated by a decline in values during the 1970s.

The degree of variability within cluster groupings is much greater than with the frequency records, evident from much lower correlation values between individual series trend plots and the median properties of the clusters to which they belong. Once again the unrepresentative series within these clusters were identified using this correlation technique:

- the Avochie at Muiresk and Deveron (09001 and 09002) and North Esk (19004) series in Cluster 1;
- the Ruchill Water (16003) and Urr (80001) series in Cluster 2;
- the Spey at Boat of Brig (08006), Earn (16001), Teviot at Hawick (21012), Cluden (79005), Cree (81002), Girvan (82001) and Gryfe (84011) series in Cluster 3.

Of these series, the Deveron at Avochie (09001), Spey at Boat of Brig (08006) and Gryfe at Craigend (84011) may be unrepresentative due to the absence of a standardised threshold.

A spatial pattern is less evident in the mean exceedance records (Map 5.6) than in the frequency series. The series from each of the four clusters appear to be randomly distributed in space, although there is perhaps a tendency for cluster 1 and 4 records to be located in the south. However, with the exception of cluster 2 series, all of the mean exceedance clusters show a broadly similar pattern, with a decline in values during the late 1960s and early 1970s and a rise from the mid 1970s until the mid 1980s. This suggests that an underlying pattern does exist, and it is likely that this is, in some way, influenced by the climate of Scotland.

5.11 SCOTTISH HYDRO-ELECTRIC RECORDS

The over-riding problem with emphasising the standard periods 1954-92 and 1964-92 is the lack of data from the north-west of Scotland, notably the area covered by the

Map 5.6: Membership of flood magnitude clusters 1964 - 1992

□	Cluster 1 records	□	Cluster 1 records (unrepresentative)
○	Cluster 2 records	○	Cluster 2 records (unrepresentative)
●	Cluster 3 records	●	Cluster 3 records (unrepresentative)
+	Cluster 4 records		

Highland RPB. Widespread gauging was only undertaken in this area during the 1970s and although POT records do exist for a number of rivers in this area, they are simply too short to be of any value in the analysis process. However, one source of runoff data in the north-west is from Scottish Hydro-Electric plc (Northern Group).

Scottish Hydro-Electric (SHE) operate four hydro-electric schemes in the north-west of Scotland (Shin, Conon, Affric/Beauly and Garry/Moristonl; Map 5.7), harnessing water from rivers and lochs in the area to generate electricity. As a consequence of their operations, SHE hold monthly, and sometimes weekly, records of variables such reservoir level, change in water storage, water released etc. for a number of catchments within each of the four systems. From this information, it is possible to calculate total monthly (or weekly) runoff into each catchment, expressed in millions of cubic feet (mcf) of water.

Although the catchments used by SHE are heavily developed with a number of aqueducts and tunnels built to divert water, it is possible to identify several catchments where runoff records are reliable and consistent (where runoff cannot be artifically diverted away from the catchment if required by Hydro-Electric). On investigation, it was found that SHE held runoff records dating back to the 1960s for some of these catchments. The final set of records suitable for analysis are:

- Shin system: Shin and Cassley catchments 1976-92;
- Conon system: Achanalt, Luichart and Orrin 1964-92;
- Affric/Beauly system: Mullardoch, Benevean, Culligran and Aigas 1964-72, 1989-92;
- Garry/Moriston system: Quoich, Garry, Ceannacroc, and Moriston 1968-92.

Unfortunately, these records are of limited value in relation to the current objectives. The data can be used to represent total annual runoff only and, with the exception of the Conon catchments, do not cover the entire standard period 1964-92. Consequently, these records cannot be directly compared with the instantaneous peak flow (POT) records. Nonetheless, they can be used to represent runoff variability in the north-west of Scotland. Figures 5.72(a)-5.72(m) depict the total annual runoff

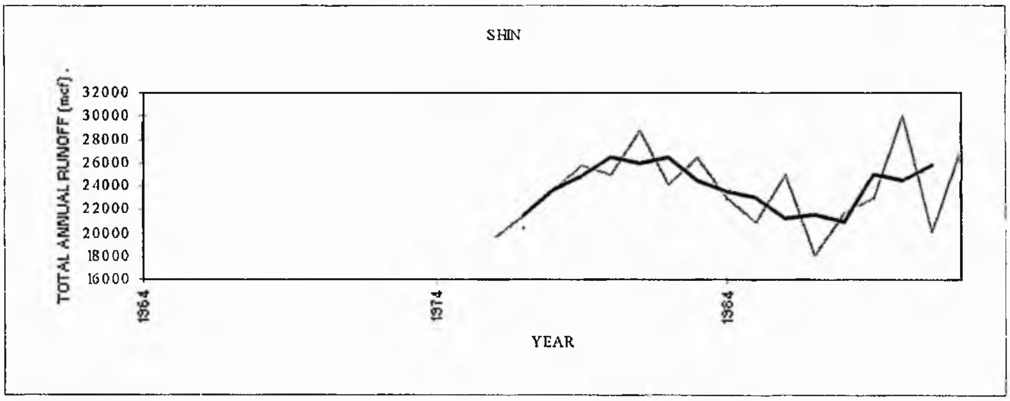
Map 5.7: Gauging stations included in the 1954-92 and 1964-92 subsets and catchments covered by Scottish Hydro-Electric Northern Group

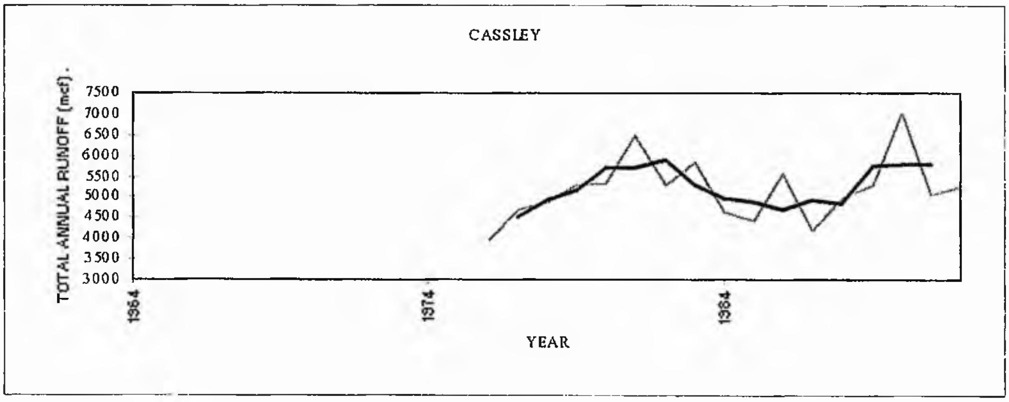
values derived from the monthly records using simple time series plots of raw and smoothed data. It was decided to restrict the analysis carried out on these records to simple techniques (running mean plots and basic statistics) because of the short record lengths and the limited scope for comparison with the previously analysed flood frequency and mean exceedance series. This analysis reveals the following characteristics:

- annual runoff values from the Shin system peak in the early 1980s and again in the 1990s (Figures 5.72(a)-5.72(b)); these catchments drain the far north-west of Scotland;
- records from the Conon system are characterised by high runoff values in the early 1960s, early 1980s and the 1990s; the Luichart catchment drains both the north and west of this region, and shows maximum runoff values in the 1960s and a distinct minimum in the 1970s (Figure 5.72(d)); the Achanalt and Orrin catchments, which drain from the west, show a clear maximum in the 1990s with no obvious 'dry' period (Figures 5.72(c) and 5.72(e));
- with such a long gap in each of the four Affric/Beauly records, it is difficult to infer a great deal from the data, other than to say the annual runoff totals are clearly higher in the 1990s than in the 1960s (Figures 5.72(f)-5.72(i));
- the four records from the Garry/Moriston system all register a peak in total annual runoff values in the 1990s with a secondary peak in the early 1980s; the late 1960s and early 1970s are characterised by lower values (Figures 5.72(j)-5.72(m)); each catchment drains an area near the west coast of Scotland.

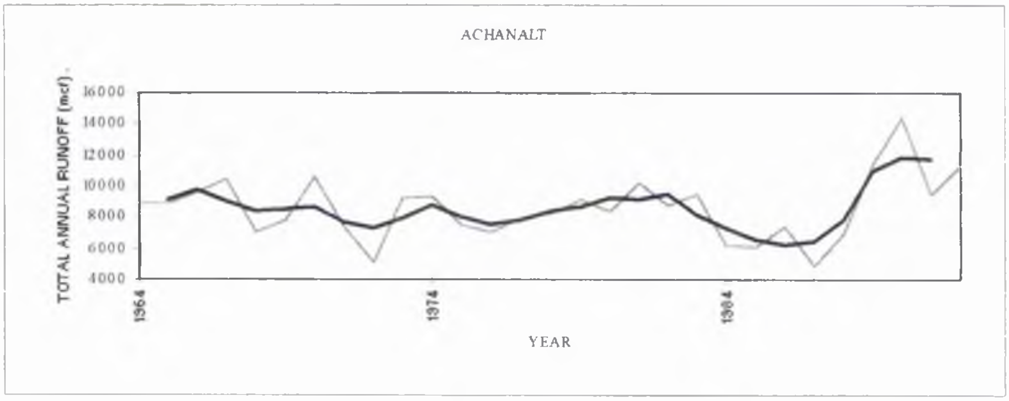
Information from these catchments suggests that, in the period of record available, annual runoff totals have only recently (in the late 1980s and early 1990s) reached a maximum. Values in the mid 1980s also seem to be rather high, particularly for those catchments with north-draining river systems (the Shin, Cassley and Luichart catchments). The late 1960s and early 1970s, a period previously characterised by low flood frequencies and mean exceedances, register only a slight decrease in annual runoff values in the majority of the SHE records which cover this period. Whilst these general comments can be made about possible relationships between annual runoff

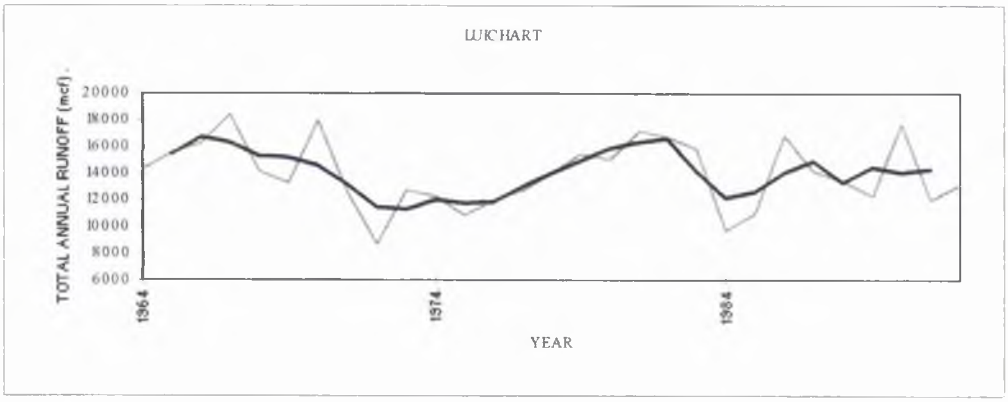
Figures 5.72(a)-5.72(b): Scottish Hydro-Electric schemes: Shin System Total Annual Runoff and a Three-Year Running Mean 1964-92

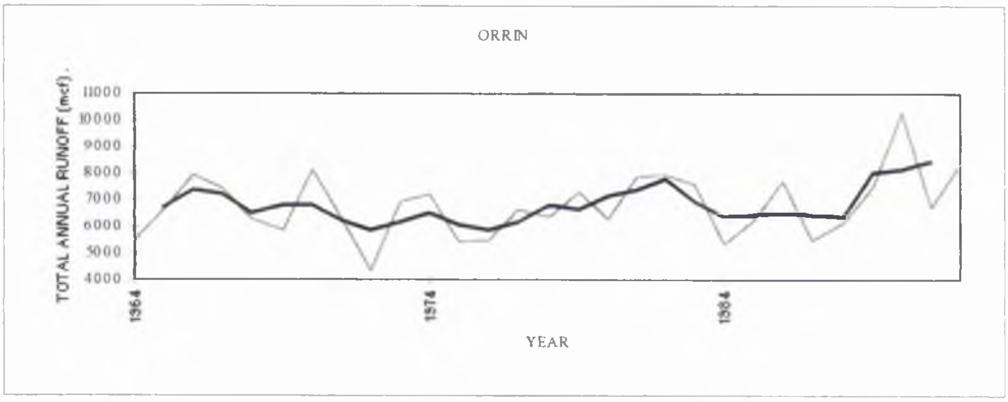




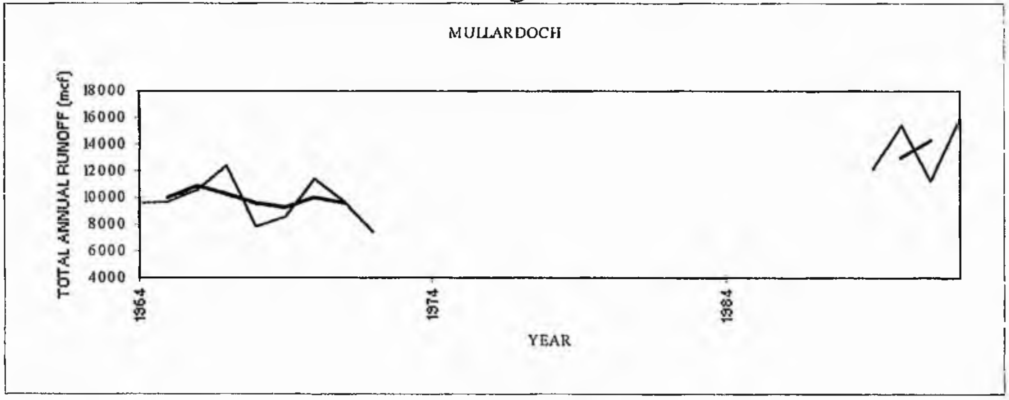
Figures 5.72(c)-5.72(e): Scottish Hydro-Electric schemes: Conon System Total Annual Runoff and a Three-Year Running Mean 1964-92

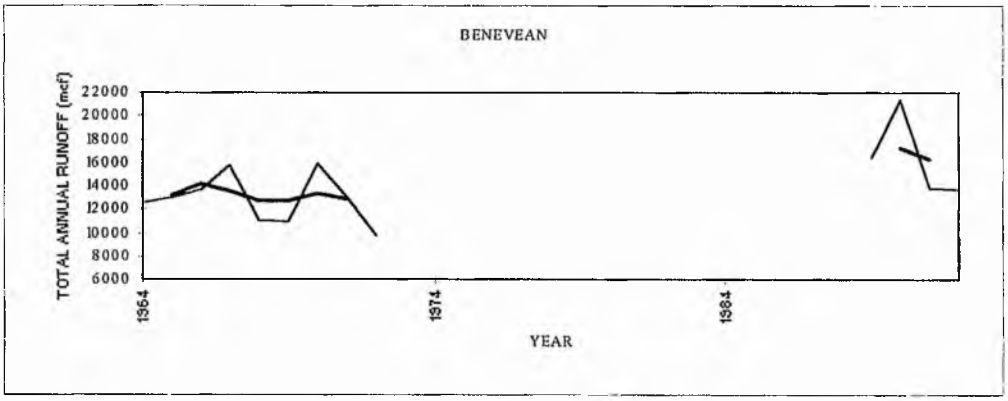


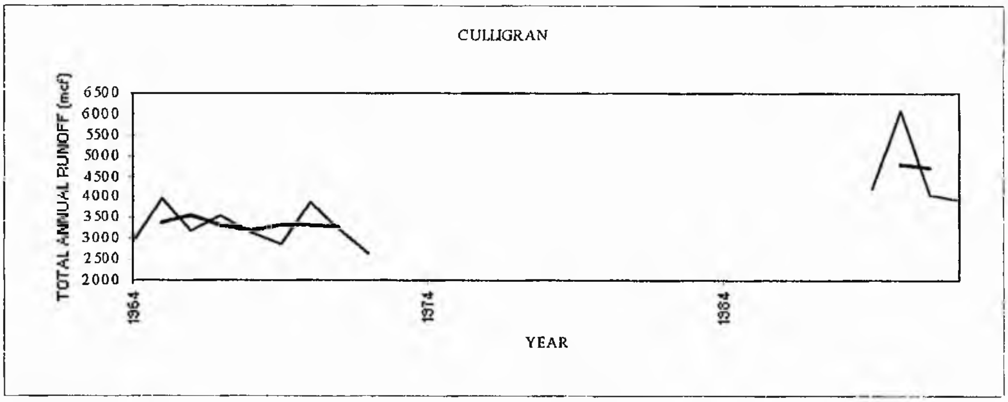


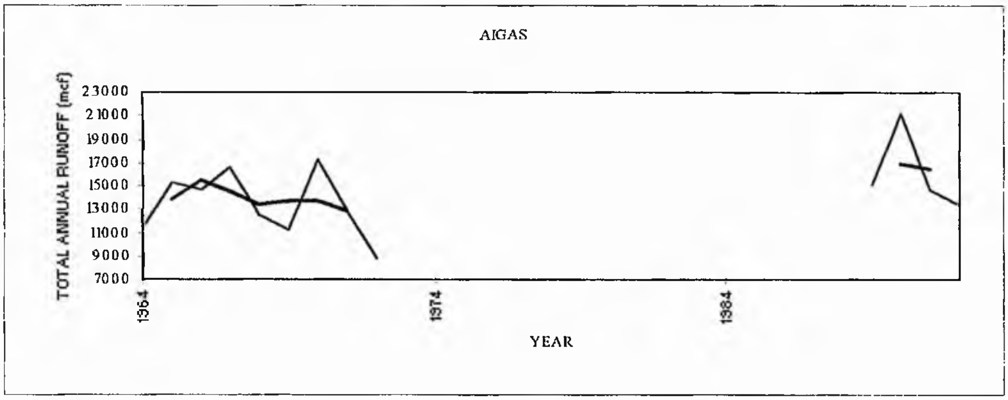


Figures 5.72(f)-5.72(i): Scottish Hydro-Electric schemes: Affric/Beauly System Total Annual Runoff and a Three-Year Running Mean 1964-92

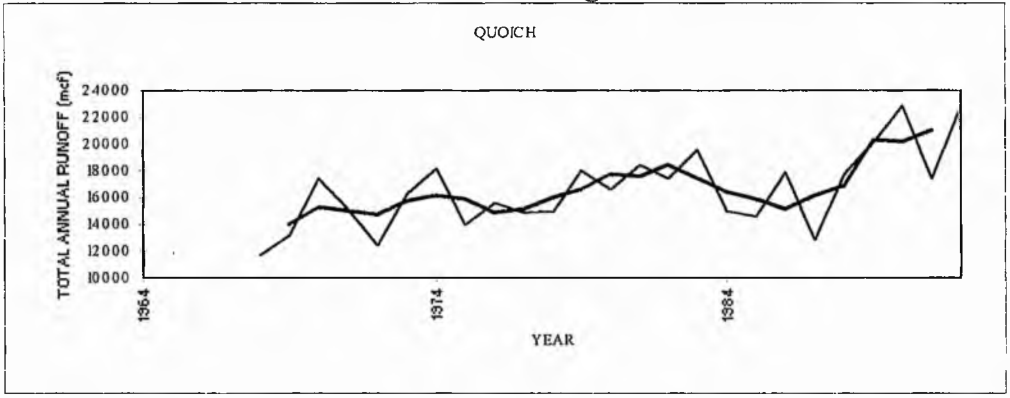


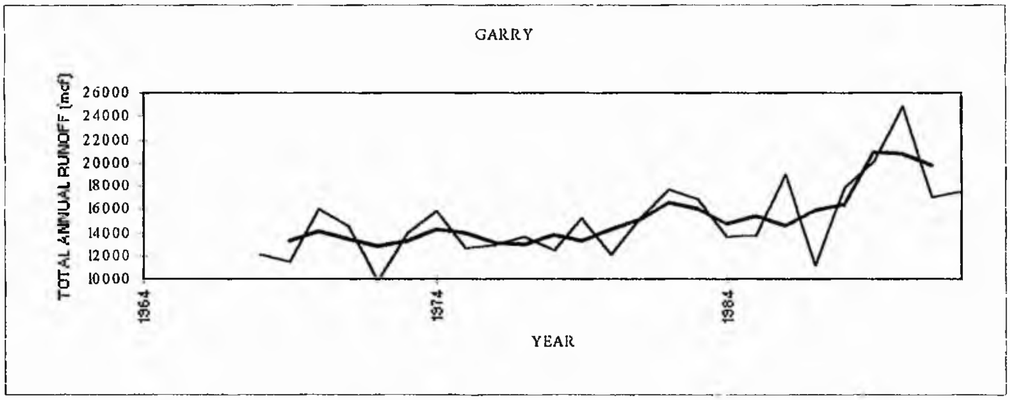


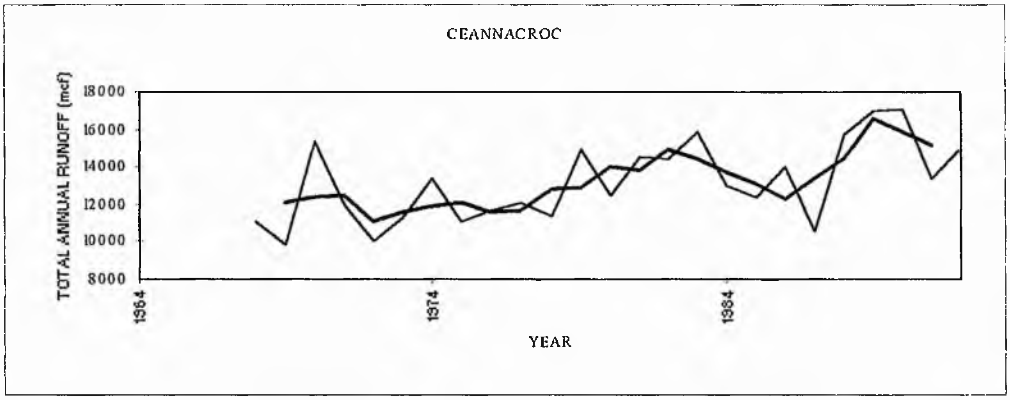


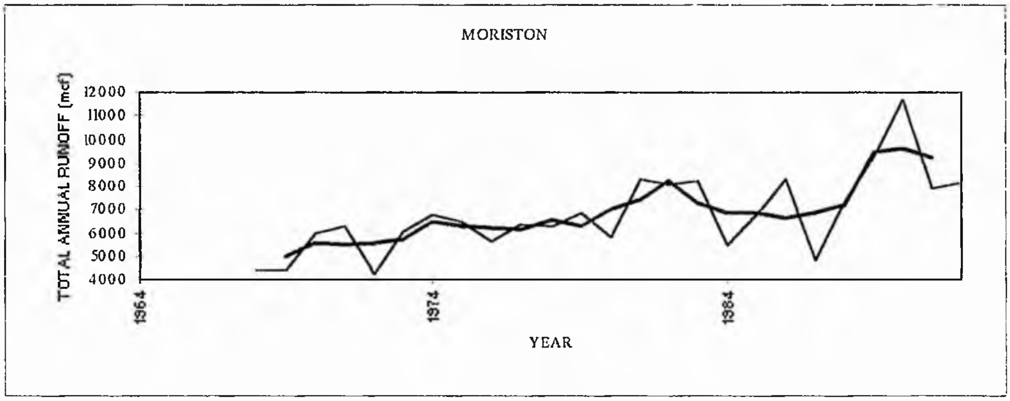


Figures 5.72(j)-5.72(m): Scottish Hydro-Electric schemes: Garry/Moriston System Total Annual Runoff and a Three-Year Running Mean 1964-92









and flood frequencies and mean exceedances, it is extremely difficult to infer any further information.

5.12 SUMMARY AND CONCLUDING REMARKS

In order to fulfil the key objectives of this project, with respect to detecting variability within flood series, a great deal of information has been presented in this chapter. The aim of this section is simply to draw out the important points from this extensive analysis, whilst retrospectively reviewing the techniques used to acquire this information.

Over the period 1954-92, the general pattern of variability exhibited within the flood frequency series is one of similarly high annual frequencies in the early (in the 1950s or early 1960s) and latter parts (mid to late 1980s) of the record, split by a period of low values in the 1970s. However, this is a generalised pattern which will vary, particularly in the timing, magnitude and range of minimum and maximum values, in individual series. In terms of mean exceedance series, the early and latter parts of the period 1954-92 can be characterised by high values in a number of series. However, some series display a continued increase in mean exceedances from the 1970s whilst in others no clear variability in values was evident.

Trying to establish any clear spatial link to these patterns of flood series variability is rather difficult when the geographical distribution of the gauging station records is limited. Although there appears to be some association in the characteristics of flood frequency series (those series exhibiting the most substantial decline in frequencies tend to be in the more easterly locations), further information is required before these links can be confirmed. An additional standard period, 1964-92, was included in the examination of flood variability to try and reveal such spatial patterns.

Detecting general patterns of variability within fifty-one flood series, over the period 1964-92, was made more manageable by cluster analysis. Three groups displaying similar temporal trend patterns of flood frequencies were identified. A common theme to each group of frequency series is an increase in frequencies from 1973 onwards, with some stability in values in the late 1980s. Prior to this, there is a lesser variation in frequency values. A small group of records (cluster A) show stable frequencies prior to 1973 whilst other series show a decline (from the higher values of the mid 1960s) during the late 1960s and early 1970s. However, the length and extent of this decline does vary (between cluster B and C records). These findings confirm the general characteristics evident in the longer records (1954-92) and also portray a similar pattern in flood frequencies identified in previous projects (Higgs, 1987; Rowling, 1989).

The geographical location of these flood frequency cluster members reveals possible spatial coherence to the patterns of variability. Generally speaking, those series from the west of Scotland show a limited decline in frequencies (if at all) during the 1960s and 1970s (hence forming clusters A and B) whilst series comprising a more easterly grouping show a greater decline in frequencies (cluster C). However, in a number of cases, series from the same catchment are grouped in different clusters. This may simply be a reflection of the clustering technique (which suggest the boundaries between cluster groupings are discrete when in fact there may be a gradual change in characteristic from one group to another) or may be due to a variable pattern of precipitation (and hence flooding) within a catchment (McEwen, 1989).

General patterns of variability with mean exceedance series were less easily identified and showed less temporal variability. Cluster analysis identified four general patterns. Series in clusters 1, 3 and 4 all register declines in mean exceedances in the 1970s, although once again the characteristics of this decline do vary. Cluster 2 records display a general pattern of variability similar to the flood frequency series grouped in cluster A.

There is limited spatial coherence to the variability within mean exceedance series. However, there does seem to be a relationship between the characteristics of the flood frequency and mean exceedance series. These associations suggest a broadly direct relationship between flood frequencies and mean exceedances:

- if a frequency series is grouped is in cluster A, the associated mean exceedance series is likely to be grouped in cluster 2; both show a clear increase in values from the mid 1970s;
- if a frequency series is grouped is in clusters B and C, the associated mean exceedance series is likely to be grouped into cluster 3 or 4; both register a slight decline in values during the 1970s;
- if a frequency series is grouped in clusters C, the associated mean exceedance series is likely to be grouped in cluster 1; clearly, both groups of series register the longest and most significant decline in values during the 1970s.

Unfortunately, with the lack of long flow records, it is difficult to put these standard periods into a longer term context. Evidence from the Dee at Woodend record (12001), which covers the period 1934-92, suggests that the lowest flood frequencies on record occurred in the late 1960s and the highest values in the 1930s and 1980s. The lowest mean exceedances on record also occurred in the 1960s whilst the highest values occurred in the late 1950s and late 1970s. However, this record alone does not adequately portray a long-term history of flooding in Scotland.

The techniques of time series analysis applied to the raw data series have, in retrospect, successfully provided a view on how flood frequencies and magnitudes (mean exceedances) vary through time. Although the majority of statistics used are fairly simple, non-parametric techniques, it has been possible to detect the timing and magnitude of variability within mean values.

One of the most useful techniques has been the Mann's test for trend in the mean. However, during the analysis process a number of disadvantages with this test were identified:

- the starting point of the test statistic is important for determining whether future changes in the series register as future trends; if a series begins during a period characterised by low values, a subsequent recovery of values may register as a significant upward trend; clearly this would be an unrepresentative trend;

- similarly, it is also important to consider the previous state of the series prior to any trends; if an increase, for example, begins from a relatively high base point (the test statistic u(i)>0) then it may register as a significant upward trend; however, if an increase of a similar magnitude begins from a very low base point (u(i)<0), the test statistic may not increase to levels which signify an upward trend;
- by comparing the same series analysed over two different time periods, it is apparent that variability, in terms of changes in the value of u(i), can be exaggerated over shorter periods; some caution should therefore be exerted when making statements concerning significant trends.

Nonetheless, this technique is ideal for identifying the timing of any changes within a time series. Provided that a standard period of analysis is adopted and that additional statistics (a running mean plot, sub-period basic statistics, the Kruskall-Wallis test) are used, the results of the trend test can be interpreted accurately.

The Mann's test can also be used to detect changes in the variance within a time series (the extent to which values fluctuate around the mean). However, for the purpose of this study it was decided to concentrate on changes in the mean only, rather than complicating the analysis process by incorporating a trend in the variance plot for each frequency and mean exceedance series analysed.

The analysis carried out has revealed that flood frequencies and mean exceedances have varied over the standard periods 1954-92 and 1964-92. In particular, the 1950s, 1980s and 1990s have been characterised by high flood frequencies, whilst the early 1970s can be classified as a 'flood-poor' period. Variability within mean exceedances is more difficult to make generalised statements about, although the 1970s can often be associated with lower values, and the 1990s by higher values.

A degree of spatial coherence can also be identified in these patterns of variability. Although a distinction can be made in flood frequency series from the east and west of Scotland, a pattern in the mean exceedance series is less easy to decipher. In retrospect, the question of spatial variability could have been better addressed. Rather than dealing with gauging stations as point locations, alternatives such as basing the analysis upon catchment locations or catchment centroids may have revealed more information on spatial coherence. An additional possibility is to include details on catchment characteristics when attempting an explanation of what links flood series within cluster groupings. It is hoped that future research may encompass some or all of these ideas.

The results of the time series analysis have been presented in a very general way, particularly through the use of cluster analysis. Although general patterns of variability clearly exist, individual series will always display anomalies which cannot be represented adequately by generalised statements. Such characteristics can, however, be portrayed by simple time series and running mean plots. Having identified the variability apparent within a number of Scottish flood series, the relationship between these series and the climatic record of Scotland can now be explored.

CHAPTER SIX

CLIMATIC VARIABILITY AND ITS INFLUENCE UPON SCOTTISH FLOOD RECORDS

Detecting variability within climatic records and understanding the links with hydrological time series

6.1 INTRODUCTION

Having addressed the subject of variability within Scottish flood series in Chapter Five, the next logical step in explaining these patterns is to explore the level of variability within the climate since ultimately it is climatic events (precipitation, snowfall and melt events) which drive flooding in Scotland. One may expect, therefore, some underlying relationship between the two sets of time series. However, the strength and the exact nature of this relationship is, as yet, unclear.

To examine the nature of temporal variability within the climate, records of daily synoptic weather types were chosen as an appropriate long term source of data (Section 3.3). In particular, two suitable records were identified and incorporated into the analysis: the Lamb record of daily weather types for the United Kingdom, 1861-1992, and the Mayes record of daily weather types for Scotland, 1950-92.

The aims of this chapter are twofold:

- to detect and describe any patterns of variability within the Scottish climate, using daily synoptic weather records as a reliable source of long-term climatic data;
- to improve the understanding of the relationship between climatic variability and flood time series, by proposing possible links between the two sets of data.

In the case of the second aim, it is hoped that an initial (and rather broad) understanding of the links between climate and flood series will be presented, rather than producing a definative statement. To achieve the latter, it would be necessary to break down and examine each individual flood frequency and magnitude series in great detail. Unfortunately, this will not be possible given the time constraints of this project. However, it is hoped that this preliminary examination may prove the first step in deciding what path such an examination would take in future.

The process of detecting variability within climate records will incorporate those statistical techniques identified in Chapter four and previously applied to flood series in Chapter Five. Postulating links between the climate and flood records is a more complex process, which requires the consideration of additional factors such as the identification of key weather types and the seasonality of weather type frequencies.

The key process in understanding the link between the climate and the Scottish flood records is to identify which synoptic weather types commonly precede or 'trigger' flood events in Scotland. These key weather types are most likely to be associated with precipitation events of sufficient magnitude to raise flows above POT thresholds. By identifying these key weather types, it will be possible to highlight those climatic series, and their temporal variability patterns or 'signatures' which are central to understanding the influence of climatic variability upon flood series. There is a strong possibility, however, that the key weather types identified will vary with geographical location and possibly with time.

Seasonality is also an important consideration in the explanation process. Black (1992) has shown that Scottish flood events are commonly confined to specific seasons of the year, and that this seasonality varies with geographical location. It would therefore be inappropriate to relate variability within a POT series dominated by winter floods, for example, to a climatic series where the pattern of variability is based upon the *annual* incidence of certain weather types. The more suitable approach would be to study seasonal climatic series.

6.2 FLOOD 'TRIGGER' MECHANISMS

It is extremely unlikely that each of the twenty-seven individual weather types within the Lamb and Mayes databases have a direct association with precipitation events sufficient to cause an incidence of flooding. Instead, those synoptic situations and the associated weather types which most commonly precede flood events must be identified. Only then will it be possible to link weather type variability to changes in the incidence of the resultant flood events. The key point is, therefore, to determine what weather types most commonly 'trigger' Scottish flood events. It is envisaged that these 'trigger' weather types may vary in both the spatial and temporal dimensions.

Therefore, prior to commencing any time series analysis upon the climatic databases, it was necessary to identify those weather types which commonly precede or 'trigger' flooding on Scottish rivers, thus ensuring a direct link can be made between climatic and flood variability.

The task of determining which weather types act as important 'trigger' mechanisms for flooding was a straightforward one, which involved combining information on the date of a POT flood event with the daily synoptic record of weather types. Thus it was possible to discover the daily weather for every flood within a POT record; information was also extracted on the sequence of weather types preceding each flood event. For the purpose of this exercise, the Mayes synoptic database was favoured over the Lamb record (Section 6.6).

To gain a general understanding of how flood generating weather types vary with geographical location, and perhaps river orientation, this part of the analysis was not confined to those POT records analysed in Chapter Five; instead *every* POT record within the database, whatever the length of record, was included in the analysis.

6.2.1 COMPLETE RECORDS: ALL POT EVENTS

When establishing the trigger weather types, it was decided that information would be extracted on the climatic conditions on the day of flood and preceding day only. In reality, it is very difficult to determine retrospectively over what time period climatic conditions were important for triggering a flood event. Similarly, it is extremely likely that the important time period will vary greatly from one flood event to another. One would expect the majority of flood events to be influenced by the climatic conditions within the preceding forty-eight hour period (Black, per comm.). It is very difficult to determine whether the climatic conditions prior to this period are relevant to the flood 'triggering' process. It is dependant upon the influence of antecedent conditions in the flood generation process. Within every POT record, therefore, each flood event was linked to a sequence of two weather types, representing the climatic conditions in this forty-eight hour period. The key trigger weather types were then simply identified by recording the frequency (number of occasions) that each weather type had acted as a trigger mechanism on the day of flood and on the preceding day.

For the majority of POT records, one weather type was most frequent (and, in fact, dominant) on the day of flood and these were classified as the primary trigger weather types. In some situations a second weather type could also be identified. Although not occurring as frequently (around 50% to 75% as often) as the primary types, these weather types were obviously acting as trigger mechanisms for a proportion of floods, and were classified as secondary weather types. Similarly, the primary and secondary weather types were identified for the day preceding each POT event (Table 6.1)

This list of primary and secondary flood trigger mechanisms (Table 6.1), clearly pinpoints a limited group of individual weather types which are commonly associated with flood events. The Cyclonic, Westerly and South-Westerly types are the three dominant weather types, with Southerly, Cyclonic-Easterly and Cyclonic-Westerly having some limited importance. The degree to which these primary and secondary 'trigger' types vary with geographical location can be explored by mapping these types. These maps (Maps 6.1-6.4) clearly portray some clear spatial patterns.

In the Highland RPB area, Westerly airflow was the most frequently occurring weather type on flood days (Map 6.1, Appendix Three). This type is associated with moisture-laden winds which from the Atlantic which rise when they reach high ground along the west coast. This leads to extensive precipitation in western regions. Since the Westerly is one of the most frequently occurring weather types in the climate

Table 6.1: The Primary and Secondary Key Weather Types on the Day of Flood and the Preceding Day

	DAY OF FLOOD		PRECEDING DAY	
STATION	PRIMARY	SECONDARY	PRIMARY	SECONDARY
02001	C	W	W	-
03002	W	C / SW	W	SW
03003	W	-	W	-
03801	W	-	W	-
03803	W	-	W	-
03901	W	-	W	NW
04001	W	-	W	-
04003	W	-	W	-
05901	W	-	W	-
06007	W	SW	W	SW
06008	SW / W	-	SW / W	-
07001	W	SW	W	SW
07002	W	C	W	SW
07003	C	-	C	-
08001	W	C	W	SW
08004	C	-	C / W	SW
08005	W	SW	W	SW
08006	C / W	SW	W	C / SW
08007	W	SW	W	SW
08008	SW / W	-	SW / W	W
08009	W	SW	W	SW
08010	W	C / SW	W	SW
08903	W	SW	W	SW
09001	C	-	C	W
09002	C	W	C	-
09003	C	-	C	-
10001	C	-	C	-
10002	C	-	C	-
11001	C	W	C	SW / W
11002	C	W	C	-
11003	C / W	SW	SW	W
12001	SW / W	C / S	SW	S / W
12002	SW	C	SW	S / W
12003	SW	W	SW	W
14001	C	SW	C / SW / W	-
15003	SW / W	-	W	SW
15006	W	SW	SW / W	-
15007	W	SW	W	SW
15008	C	SW	S / SW	C
15010	S / SW	-	SW	S
15013	SW	W	SW	W
15016	W	SW	W	SW

Table 6.1(cont): The Primary and Secondary Key Weather Types on the Day of Flood and the Preceding Day

	DAY OF FLOOD		PRECEDING DAY	
STATION	**PRIMARY**	**SECONDARY**	**PRIMARY**	**SECONDARY**
16001	SW / W	C	W	SW
16003	SW	W	W	SW
16004	SW	W	SW	W
17001	W	SW	W	SW
17005	SW / W	C	W	SW
18001	W	SW	W	SW
18002	W	C	W	SW
18005	W	SW	W	SW
18008	W	SW	S	SW
19001	C / W	SW	W	C / SW
19002	W	C / SW	W	C / SW
19004	C	W	W	C / SW
19005	C / W	SW	W	C
19006	C	SW / W	W	C
19007	C	SW / W	W	C
19008	C	W	C / W	-
19011	C	W	W	C / SW
20001	C	-	C	-
20002	C	-	C	-
20003	C	-	C / W	-
20005	C	W	C	SW / W
20006	C	CE	C	-
20007	C	-	C	-
21001	W	SW	SW / W	-
21002	C	-	C	-
21003	C / W	SW	W	SW
21005	SW	C	W	SW
21006	SW	C / W	W	SW
21007	SW	C / W	W	SW
21008	C / SW /W	-	SW / W	-
21009	C / SW / W	-	SW / W	-
21010	C / W	SW	W	SW
21011	SW	C / W	W	SW
21012	SW	W	W	SW
21013	C	W	W	C
21015	C / W	-	W	-
21016	C	CE	C	S
21017	SW	W	SW / W	-
21018	W	C	W	SW
21019	SW / W	-	SW / W	-
21020	SW	C / W	SW	W
21021	SW	C / W	SW	W
21025	SW	C / W	SW	W

Table 6.1(cont): The Primary and Secondary Key Weather Types on the Day of Flood and the Preceding Day

	DAY OF FLOOD		PRECEDING DAY	
STATION	**PRIMARY**	**SECONDARY**	**PRIMARY**	**SECONDARY**
21026	SW	W	SW / W	-
21027	C	-	C / W	-
21030	SW / W	-	W	SW
21034	SW / W	C	SW / W	-
77003	SW	W	SW / W	-
78003	SW	W	SW	W
78004	SW	W	SW / W	-
78005	SW	W	SW	W
79002	SW	C	W	SW
79003	SW / W	-	W	SW
79004	SW	W	SW / W	-
79005	SW	C	SW / W	-
79006	SW	-	SW / W	-
80001	SW	C / W	SW / W	-
80003	SW	-	SW / W	-
81002	SW	C / W	SW / W	-
81003	SW	C / W	SW	W
82001	W	C / SW	W	SW
82003	SW	W	SW / W	-
83002	W	-	W	-
83004	W	C / SW	W	SW
83005	W	SW	W	SW
83006	W	C	W	SW
83802	W	C	W	SW
84001	W	C / CW	W	SW
84003	W	C / SW	W	SW
84004	W	C / SW	W	SW
84005	W	C	W	SW
84006	W	C / CW	W	SW
84007	C / W	SW	W	SW
84011	W	SW	W	SW
84012	W	C / SW	W	SW
84014	W	C / SW	W	SW
84019	C / W	CW	W	C / SW
84806	C / W	-	W	-
85003	W	SW	W	-
86001	W	SW	W	SW
87801	W	-	W	-
91002	W	SW	W	SW
91802	W	SW	W	SW
93001	W	SW	W	SW
94001	W	-	W	-

Table 6.1(cont): The Primary and Secondary Key Weather Types on the Day of Flood and the Preceding Day

	DAY OF FLOOD		PRECEDING DAY	
STATION	**PRIMARY**	**SECONDARY**	**PRIMARY**	**SECONDARY**
96001	C	W	C / W	-
96002	W	-	W	-
97002	C	W	C	W

Based upon all POT data available in conjunction with the Mayes record

W denotes the Westerly weather type
C denotes the Cyclonic weather type
SW denotes the South-Westerly weather type
S denotes the Southerly weather type
NW denotes the North-Westerly weather type
CW denotes the Cyclonic-Westerly weather type

precipitation totals are reasonably high, particularly in the more western regions which are directly in the path of the Westerly airflows. The link between flooding in this region and the Westerlies is therefore understandable. The exception to this relationship is a small group of stations in the far north-east of the region, which are dominated by the Cyclonic weather type on the day of flood. This suggests that Cyclonic weather systems or depressions centred over Scotland produce heavy precipitation and flood events in the north-east (possibly being associated with south-easterly winds coming in from the North Sea)..

The North-East and Tay RPB region (Map 6.2, Appendix Three) show a similar pattern to Map 6.1, with a small group of records in the north-east corner showing a link between Cyclonic weather systems and flood events. This strengthens a possible association between stagnating depressions over Scotland and heavy precipitation in the north-east of Scotland, which may result in peak flow events in these more easterly regions. The majority of the remaining rivers drain areas much further to the west of Scotland and, as would be expected, are associated with Westerly weather conditions. The relationship between the South-Westerly weather type and flood events seems to strengthen as one moves in a Southerly direction. The South-Westerly is commonly associated with warm, moist tropical air which enhances the west-east rainfall gradient in Scotland, although the south-west regions are more likely to receive greater precipitation totals from this source than areas in the north-west.

The Forth and Tweed RPB regions (Map 6.3, Appendix Three) show similar associations, with events on westerly-draining rivers to be linked to Westerly and South-Westerly conditions, the latter becoming more important in the south of the Tweed region. As one moves in a more Easterly direction, towards the coast, Cyclonic conditions become more important.

Finally the Solway and Clyde RPBs (Map 6.4, Appendix Three) show the dominance of the Westerly weather type on the more westerly located rivers; within the Solway (more southerly located) region, the South-Westerly type is dominant at most gauging stations.

These maps provide evidence of a strong relationship between the location of a river and the weather types which are most often associated with peak flow generation. Cyclonic weather systems are the most likely cause of flood events in the more easterly and north-easterly draining rivers. A second link exists between floods occurring the more south-western regions and South-Westerly weather systems as does the strong relationship between gauging stations draining the more western regions and the Westerly weather type (Map 6.5, Appendix Three).

Maps 6.6-6.9 (Appendix Three) show the weather types which are of secondary importance as flood generating mechanisms. Spatial patterns are, however, less clear although it is possible to highlight a number of key points. Typically, the South-Westerly weather type seems to have secondary importance at a number of stations, particularly at those where Westerly activity was dominant.

6.2.2 COMPLETE RECORDS: HIGH MAGNITUDE EVENTS

The information described thus far has identified the important flood generating mechanisms for each gauging station within the POT database, and is based upon data from *all* flood events within each record. There is, however, a possibility that there is a different relationship between the extreme flood events and the trigger weather types. To explore such a possibility, the twenty highest discharge events were extracted from each POT record and the weather types occurring at the time of these floods were noted. Obviously, the length of the record used is a factor which should be considered when interpreting these results: twenty events taken from a long record are likely to be representative of the most extreme discharges, whilst with a shorter record the subset of twenty events is more likely to include some less extreme discharges.

It is interesting to note that typically these results are generally in agreement with the results when using information on all events within a record (Table 6.2 lists those

Table 6.2: The Primary Weather Types on the Day of Flood: Twenty highest discharges

STATION	PRIMARY TYPE ON DAY OF FLOOD
06007	SW
07001	C
07002	C
08001	C
08006	C
08008	W
08009	C
11003	C
12001	SW
14001	CE
15003	W
15008	CS
15010	SW
16001	SW
17005	SW
18001	SW
18002	C
18008	SW
19001	C
20002	CE
21008	SW
21009	C / SW
21012	SW / W
21015	C
21016	C / CE
21018	C
21019	SW
21021	SW / W
21030	SW
21034	SW
78003	SW / C
79003	SW
83802	C
84003	SW / C
84004	SW
84005	C
84007	W
84019	C
84806	W
86001	SW

Based upon twenty highest recorded POT events only in conjunction with the Mayes record
NB: Only records where the Primary Weather Type for High Magnitude Events is different from the Primary Weather Type for all Events are included

POT records where there is difference). Once again, the majority of trigger weather types are either Cyclonic, Westerly or South-Westerly with similar degrees of spatial coherence (Maps 6.10-6.13, Appendix Three).

6.2.3 SUBSET RECORDS 1954-92 AND 1964-92

To directly compare the analysis of climatic data with the POT records, comparable periods of time must be used. Hence the 'trigger' weather types were identified for those records within the two standard periods, using all POT events from these pre-defined sub-periods 1954-92 and 1964-92 only. Although the spatial distribution of records within these subsets are not ideal, the main types of trigger mechanism, the Westerly, South-Westerly and Cyclonic, are reasonably well represented (Tables 6.3(a) and 6.3(b)).

6.2.4 SUMMARY REMARKS

The analysis of flood trigger mechanisms has revealed that there are three individual weather types, the Cyclonic, Westerly and South-Westerly, which commonly trigger flood events in Scotland. Noticeably, these trigger types appear closely linked to the geographical location of the catchments.

Although not identified as primary or secondary weather types, an additional group of weather types appear to be linked to a small proportion of flood events. Records from the most easterly located rivers indicate that the Cyclonic-Easterly and Cyclonic-Northerly are subsidiary flood trigger mechanisms, whilst in more westerly and south-westerly locations the Cyclonic-Westerly and Cyclonic-South-Westerly appear to show secondary importance.

In terms of those gauging stations whose POT series have been analysed for the standard periods 1954-92 and 1964-92, the three key weather types to analyse are the Westerly, Cyclonic and South-Westerly. However, the Southerly and Cyclonic-Westerly types are acting as trigger mechanisms at a limited number of gauging stations (Dee at Woodend (12001) and Kelvin at Killermont (84001) respectively).

Table 6.3(a): Primary and Secondary Weather Types on the Day of Flood: Stations sorted according to flood frequency clusters

STATION and Frequency Clusters		SUBSET 1954-92	SUBSET 1964-92	PRIMARY WEATHER TYPE	SECONDARY WEATHER TYPE
07001	A		✓	W	C
12001	A	✓	✓	SW	C / S
15008	A	✓	✓	C	-
16003	A		✓	SW	W
80001	A		✓	C / SW	W
84012	A		✓	W	SW
07002	B		✓	W	C
08005	B	✓	✓	W	SW
08006	B	✓	✓	C / W	SW
08007	B	✓	✓	W	SW
08009	B	✓	✓	W	SW
08010	B	✓	✓	W	SW
15006	B	✓	✓	W / SW	-
15007	B	✓	✓	W	SW
19006	B		✓	C / SW	-
21007	B		✓	SW	W
79003	B		✓	W / SW	-
81002	B		✓	SW	C
82001	B		✓	W	C / SW
84001	B	✓	✓	W	C / CW
84011	B		✓	W	SW
07003	C		✓	C	-
08004	C	✓	✓	C	-
09001	C		✓	C	-
09002	C		✓	C	-
09003	C		✓	C	-
15003	C	✓	✓	W / SW	-
16001	C	✓	✓	SW	W
19001	C		✓	C	W / SW
19002	C		✓	W	C / SW
19004	C		✓	C	W
19007	C		✓	C	W
19011	C		✓	C	W / SW
20001	C		✓	C	-
20003	C		✓	C	-
20005	C		✓	C	-
21003	C	✓	✓	SW	C / W
21005	C		✓	SW	-
21006	C		✓	SW	C / W
21008	C		✓	C / W	SW
21009	C		✓	SW	C / W
21011	C		✓	SW	C / W

Table 6.3(a)cont: Primary and Secondary Weather Types on the Day of Flood: Stations sorted according to flood frequency clusters

STATION and Frequency Clusters		SUBSET 1954-92	SUBSET 1964-92	PRIMARY WEATHER TYPE	SECONDARY WEATHER TYPE
21012	C		✓	SW	W
21013	C		✓	C	-
79002	C		✓	SW	-
79004	C		✓	SW	W
79005	C		✓	SW	C
84003	C		✓	W	SW
84004	C		✓	W	SW
84005	C		✓	W	C
84019	B		✓	C / W	SW

Based on all POT events 1954-92 and 1964-92 in conjunction with the Mayes record

Table 6.3(b): Primary and Secondary Weather Types on the Day of Flood: Stations sorted according to mean exceedance clusters

STATION and Mean Exceedance Clusters		SUBSET 1954-92	SUBSET 1964-92	PRIMARY WEATHER TYPE	SECONDARY WEATHER TYPE
07003	1		✓	C	-
09001	1		✓	C	-
09002	1		✓	C	-
19004	1		✓	C	W
20001	1		✓	C	-
21003	1	✓	✓	SW	C / W
21005	1		✓	SW	-
21006	1		✓	SW	C / W
21007	1		✓	SW	W
21008	1		✓	C / W	SW
21009	1		✓	SW	C / W
21011	1		✓	SW	C / W
79003	1		✓	W / SW	-
84003	1		✓	W	SW
84004	1		✓	W	SW
84005	1		✓	W	C
07001	2		✓	W	C
08009	2	✓	✓	W	SW
12001	2	✓	✓	SW	C / W / S
16003	2		✓	SW	W
21013	2		✓	C	-
80001	2		✓	C / SW	W
08004	3	✓	✓	C	-
08005	3	✓	✓	W	SW
08006	3	✓	✓	C / W	SW
08007	3	✓	✓	W	SW
08010	3	✓	✓	W	SW
09003	3		✓	C	-
15006	3	✓	✓	W / SW	-
15008	3	✓	✓	C	-
16001	3	✓	✓	SW	W
20003	3		✓	C	-
20005	3		✓	C	-
21012	3		✓	SW	W
79002	3		✓	SW	-
79004	3		✓	SW	W
79005	3		✓	SW	C
81002	3		✓	SW	C
82001	3		✓	W	C / SW
84001	3	✓	✓	W	C / CW
84011	3		✓	W	SW

Table 6.3(b)cont: Primary and Secondary Weather Types on the Day of Flood: Stations sorted according to mean exceedance clusters

STATION and Mean Exceedance Clusters		**SUBSET 1954-92**	**SUBSET 1964-92**	**PRIMARY WEATHER TYPE**	**SECONDARY WEATHER TYPE**
84012	3		✓	W	SW
07002	4		✓	W	C
15003	4	✓	✓	W / SW	-
15007	4	✓	✓	W	SW
19001	4		✓	C	W / SW
19002	4		✓	W	C / SW
19006	4		✓	C / SW	-
19007	4		✓	C	W
19011	4		✓	C	W / SW
84019	4		✓	C / W	SW

Based on all POT events 1954-92 and 1964-92 in conjunction with the Mayes record

6.3 TECHNIQUES OF ANALYSIS

Having identified which synoptic weather types are important in the process of 'triggering' flood events, these climatic series can be analysed for variability. To enable comparisons to be made between climatic and flood variability, it is necessary to be consistent with the techniques and methods of analysis. Once again, the Minitab and Time Series programs, introduced in Chapter Four, were used to analyse the climatic datasets for signs of variability. As with the flood series, a certain degree of raw data manipulation was required prior to data analysis.

6.4 RAW DATA MANIPULATION

In order to describe climatic variability on a scale appropriate to flood records and to allow comparison between the two components, it was necessary to limit these climate records to the study periods used with reference to the flood series (1954-92 and 1964-92; Section 5.7). For the purpose of describing the *general* patterns of climatic variability, it was also decided to do some preliminary analysis on the complete Lamb database since it will provide a long term record of climatic variability and allow the shorter study periods to be put into context. However, since the complete Mayes database is only four years longer than the 1954-92 study period, there seemed little value in analysing this record in its entirety.

6.4.1 CREATION OF ANNUAL AND SEASONAL TIME SERIES

In their original format, both the Lamb and Mayes databases simply comprise a continuous sequence of daily weather types (or an equivalent code), recorded for each day since the register began. From these databases it is possible to create annual and seasonal time series for each of the trigger weather types identified:

- Each annual series records, for each year, the number of days on which a given weather type (the South-Westerly, for example) occurred;
- Each seasonal series represents the number of days on which a given weather type occurred within a given season.

For the general description of climatic variability in Scotland, analysis on annual time series is sufficient. However, if the links between variability in flood series and the climate are to be explored in detail then analysis must be extended to detecting weather type variability on a seasonal basis, since flooding on Scottish rivers is often a seasonal phenomenon. Tables 6.4(a) and (b) show the dominant season of flooding for those flood series which cover the study periods 1954-92 and 1964-92. Opposing seasonal climatic trends can, in fact, cancel each other out when the data are amalgamated into annual series and this may be important within the context of flood variability and seasonality. The division of seasons was based upon the standard method of four periods of three months: December-February (DJF), March-May (MAM), June-August (JJA) and September-November (SON).

6.4.2 PROGRAM REQUIREMENTS

To analyse any such synoptic series using the time series program (WMO, 1988), the necessary control parameters (Section 5.3.3.2) were adjusted according to the number of data sets included, the number of years of record and the start of record date. The coincident year of analysis remained unaltered to ensure consistency between records. Gaps in the climatic databases are isolated and typically rare and constitute considerably less than the recommended 5% of record (Section 5.3.3.3). Although a number of days in any year may be 'unclassified', this does not constitute a gap but may result from a number of synoptic situations (Lamb, 1972):

- weak flows and/or small size circulation systems,
- incompatible hybrid types, or
- quick changes during the twenty-four hour period.

6.5 ANALYSIS OF LONG TERM CLIMATIC TIME SERIES 1861-1992

The complete set of weather types in Lamb's record covers the period from 1861 to the present day and is one of the longest and most reliable climatic databases in the UK. Analysis of such a record provides valuable information on long term climatic variability within the UK.

Although this record is considerably longer than any of the flood series included in this project, it can be extremely useful in considering the historical context within which this project is set. It was therefore decided that prior to analysing either of the

Table 6.4(a): Mean Day of Flood and Dominant Season of Flooding: Stations sorted to flood frequency clusters

STATION and Frequency Clusters		MEAN DAY OF FLOOD	DOMINANT SEASON OF FLOODING
07001	A	158.0	SON
12001	A	198.1	DJF
15008	A	224.0	DJF
16003	A	179.3	SON
80001	A	178.2	SON
84012	A	180.9	SON
07002	B	159.1	SON
08005	B	190.3	DJF
08006	B	Information Not Available	Information Not Available
08007	B	193.4	DJF
08009	B	184.0	DJF
08010	B	199.4	DJF
15006	B	Information Not Available	Information Not Available
15007	B	Information Not Available	Information Not Available
19006	B	189.9	DJF
21007	B	188.0	DJF
79003	B	191.4	DJF
81002	B	172.1	SON
82001	B	166.4	SON
84001	B	174.1	SON
84011	B	188.3	DJF
84019	B	180.5	SON
07003	C	176.0	SON
08004	C	Information Not Available	Information Not Available
09001	C	Information Not Available	Information Not Available
09002	C	192.5	DJF
09003	C	176.6	SON
15003	C	Information Not Available	Information Not Available
16001	C	Information Not Available	Information Not Available
19001	C	182.1	SON
19002	C	182.2	SON
19004	C	182.5	SON
19007	C	196.2	DJF
19011	C	185.9	DJF
20001	C	197.1	DJF
20003	C	Information Not Available	Information Not Available
20005	C	193.4	DJF
21003	C	Information Not Available	Information Not Available
21005	C	Information Not Available	Information Not Available

Table 6.4(a)cont: Mean Day of Flood and Dominant Season of Flooding: Stations sorted to flood frequency clusters

STATION and Frequency Clusters		MEAN DAY OF FLOOD	DOMINANT SEASON OF FLOODING
21006	C	Information Not Available	Information Not Available
21008	C	198.4	DJF
21009	C	201.4	DJF
21011	C	Information Not Available	Information Not Available
21012	C	192.2	DJF
21013	C	Information Not Available	Information Not Available
79002	C	178.9	SON
79004	C	174.1	SON
79005	C	180.9	SON
84003	C	196.9	DJF
84004	C	199.1	DJF
84005	C	192.5	DJF

Mean Day of Flood expressed as days after 31 May
Based on all POT events between 1959-88
SOURCE: Black, 1992

Table 6.4(b): Mean Day of Flood and Dominant Season of Flooding: Stations sorted to mean exceedance clusters

STATION and Mean Exceedance Clusters		MEAN DAY OF FLOOD	DOMINANT SEASON OF FLOODING
07003	1	176.0	SON
09001	1	Information Not Available	Information Not Available
09002	1	192.5	DJF
19004	1	182.5	SON
20001	1	197.1	DJF
21003	1	Information Not Available	Information Not Available
21005	1	Information Not Available	Information Not Available
21006	1	Information Not Available	Information Not Available
21007	1	188.0	DJF
21008	1	198.4	DJF
21009	1	201.4	DJF
21011	1	Information Not Available	Information Not Available
79003	1	191.4	DJF
84003	1	196.9	DJF
84004	1	199.1	DJF
84005	1	192.5	DJF
07001	2	158.0	SON
08009	2	184.0	DJF
12001	2	198.1	DJF
16003	2	179.3	SON
21013	2	Information Not Available	Information Not Available
80001	2	178.2	SON
08004	3	Information Not Available	Information Not Available
08005	3	190.3	DJF
08006	3	Information Not Available	Information Not Available
08007	3	193.4	DJF
08010	3	199.4	DJF
09003	3	176.6	SON
15006	3	Information Not Available	Information Not Available
15008	3	224.0	DJF
16001	3	Information Not Available	Information Not Available
20003	3	Information Not Available	Information Not Available
20005	3	193.4	DJF
21012	3	192.2	DJF
79002	3	178.9	SON
79004	3	174.1	SON
79005	3	180.9	SON
81002	3	172.1	SON
82001	3	166.4	SON

Table 6.4(b)cont: Mean Day of Flood and Dominant Season of Flooding: Stations sorted to mean exceedance clusters

STATION and Mean Exceedance Clusters		MEAN DAY OF FLOOD	DOMINANT SEASON OF FLOODING
84001	3	174.1	SON
84011	3	188.3	DJF
84012	3	180.9	SON
07002	4	159.1	SON
15003	4	Information Not Available	Information Not Available
15007	4	Information Not Available	Information Not Available
19001	4	182.1	SON
19002	4	182.2	SON
19006	4	189.9	DJF
19007	4	196.2	DJF
19011	4	185.9	DJF
84019	4	180.5	SON

Mean Day of Flood expressed as days after 31 May
Based on all POT events between 1959-88
SOURCE: Black, 1992

synoptic databases within the context of these study periods, a long term view of climatic variability would be obtained from the Lamb database. Since the aim of this analysis is purely descriptive, and is in no way linked to explaining flood series variability, the climatic series will represent annual weather type frequencies only. However, this analysis will be limited to those weather types identified as flood trigger mechanisms (Section 6.2).

Determining the relative importance of each individual weather type within the Lamb database, in terms of typical annual frequencies and percentage contributions (Table 6.5), is an important point to consider since it allows variability within the frequency of a weather type to be put into context. Variability within the annual incidence of a dominant trigger weather type, such as the Westerly, is likely to have a more noticeable effect upon flood series than variability in one of the less frequently trigger types.

Fluctuations in the annual frequencies of the individual trigger weather types (1861-1992) were detected using simple running mean plots. Since only general descriptions of long term climatic variability were required, there was no additional benefit in using more complex techniques. A number of key characteristics were clearly evident (Figures 6.1(a)-6.1(f), Appendix Four):

- The Westerly weather type (Figure 6.1(a)) shows a sustained peak from the 1900s until the early 1950s;
- Peaks in the incidence of the Cyclonic weather type (Figure 6.1(b)) occur in the early 1870s, the late 1960s and also during the 1980s (maximum frequencies recorded); there are no distinct periods within the record when Cyclonic frequencies remain at particularly low levels;
- Annual frequencies of the South-Westerly weather type (Figure 6.1(c)) are relatively stable until the mid 1960s when a dramatic increase in frequencies occurs; this is sustained throughout the remaining period of record;
- The Southerly (Figure 6.1(d)) weather type record, which is often associated with high precipitation totals in the west whilst the east remains in a rainshadow, is a relatively stable one;

Table 6.5: Typical annual occurrences of individual weather types, expressed as frequencies (days per year) and percentage contributions to the Lamb annual record

WEATHER TYPE	**MINIMUM FREQ(%)**	**MAXIMUM FREQ(%)**	**MEDIAN FREQ(%)**
ANTICYCLONIC	24 (7%)	102 (28%)	66 (18%)
CYCLONIC	**25 (7%)**	**78 (21%)**	**48 (13%)**
EASTERLY	3 (1%)	33 (9%)	12 (3%)
ANTICYCLONIC-EASTERLY	1 (<1%)	20 (5%)	9 (2%)
CYCLONIC-EASTERLY	0 (0%)	13 (4%)	4 (1%)
SOUTH-EASTERLY	1 (<1%)	21 (6%)	6 (2%)
ANTICYCLONIC-SOUTH-EASTERLY	0 (0%)	12 (3%)	3 (1%)
CYCLONIC-SOUTH-EASTERLY	0 (0%)	7 (2%)	1 (<1%)
SOUTHERLY	**0 (0%)**	**31 (8%)**	**15 (4%)**
ANTICYCLONIC-SOUTHERLY	0 (0%)	11 (3%)	4 (1%)
CYCLONIC-SOUTHERLY	0 (0%)	14 (4%)	4 (1%)
SOUTH-WESTERLY	**1 (<1%)**	**29 (8%)**	**9 (2%)**
ANTICYCLONIC-SOUTH-WESTERLY	0 (0%)	12 (3%)	3 (1%)
CYCLONIC-SOUTH-WESTERLY	0 (0%)	11 (3%)	2 (<1%)
WESTERLY	**32 (9%)**	**107 (29%)**	**66 (18%)**
ANTICYCLONIC-WESTERLY	6 (2%)	42 (12%)	16 (4%)
CYCLONIC-WESTERLY	**3 (1%)**	**35 (10%)**	**14 (4%)**
NORTH-WESTERLY	2 (<1%)	35 (10%)	14 (4%)
ANTICYCLONIC-NORTH-WESTERLY	0 (0%)	13 (4%)	5 (1%)
CYCLONIC-NORTH-WESTERLY	0 (0%)	9 (2%)	3 (1%)
NORTHERLY	3 (1%)	35 (10%)	17 (5%)
ANTICYCLONIC-NORTHERLY	1 (<1%)	23 (6%)	7 (2%)
CYCLONIC-NORTHERLY	0 (0%)	14 (4%)	4 (1%)
NORTH-EASTERLY	0 (0%)	14 (4%)	3 (1%)
ANTICYCLONIC-NORTH-EASTERLY	0 (0%)	16 (4%)	5 (1%)
CYCLONIC-NORTH-EASTERLY	0 (0%)	7 (2%)	1 (<1%)
UNCLASSIFIED	5 (1%)	28 (8%)	14 (4%)

Based upon the Lamb record 1861-1992
Primary and Secondary trigger weather types are highlighted in bold

- The record of the Cyclonic-Westerly (Figure 6.1(e)) type, associated with high precipitation totals throughout Scotland, appears stable until the early 1920s from which point onwards a steady decrease in frequencies occurs.

These running mean plots (Figures 6.1(a)-6.1(e), Appendix Four) show clear temporal variations in the annual frequencies of the individual trigger weather types. In those cases where the annual frequency of a weather type is approximately ten days per year fluctuations are often limited to a small range of frequencies. Such minor fluctuations are therefore likely to have a minimal effect upon flood series, particularly when the trigger weather type is only of secondary importance to the flood generating process. Variability within the more frequently occurring weather types (the Westerly and Cyclonic types, for example) often occurs over a greater range of values. Such extensive fluctuations within these primary weather types are likely to be more influential upon Scottish flood series.

Within the complete Lamb database, the Cyclonic and Westerly weather types are the most frequently occurring of the trigger types identified in Section 6.1. Figure 6.1(a) indicates that annual Westerly frequencies experienced a sustained high during the first half of this century. Consequently, precipitation is likely to have been relatively high during this period, particularly in the west, in contrast to the drier east which remains in a rainshadow. Figure 6.1(b) reveals that increased Cyclonic frequencies, which can be linked with to increased precipitation in the more eastern regions, were experienced in the 1870s, mid 1960s and the 1980s.

The value of observing this long record lies in comparing the period from 1954 onwards with earlier climatic conditions. Hence, the study periods created in Chapter Five can be put into context:

- in comparison with the earlier record, the period 1954-92 displays a sustained low in the annual frequencies of the Westerly weather type (Figure 6.1(a));
- conversely, this recent period has experienced the highest annual frequencies of the Cyclonic weather type (Figure 6.1(b));

- the recent record of the South-Westerly type has shown a dramatic increase in annual frequencies, in what previously was a relatively stable time series; annual frequencies have reached values never previously recorded (Figure 6.1(c));
- the Southerly series (Figure 6.1(d)) has shown no real changes over the last forty years, in comparison with the earlier record;
- a sharp decline in the annual frequency of the Cyclonic-Westerly type has coincided with the period of study; annual frequencies have dropped to values not previously recorded (Figure 6.1(e)).

6.6 COMPARISON BETWEEN LAMB AND MAYES WEATHER TYPES

The analysis into climatic variability carried out thus far has used time series from the Lamb database only. This has enabled long term climatic variability, within the context of the trigger weather types, to be explored with reference to the much shorter study periods. However, further in-depth analysis is required before links between climatic and flood records can be postulated. For the sake of simplicity, it was decided that this analysis would proceed with just one of the two synoptic databases. In order to make an informed decision on which database to favour, a simple comparison exercise was carried out, to compare the time series of annual weather type frequencies between the two databases.

To ensure this comparison was valid, both synoptic databases were limited to data from the standard period 1954-92 only. Rather than compare each of the twenty-seven pairs of time series, it was decided to compress each database into a smaller, more manageable number of time series. Lamb (1972) suggests a technique for reducing the data to seven basic groups or series (Anticyclonic, Cyclonic, Easterly, Southerly, Westerly, North-Westerly and Northerly), whilst maintaining the benefit of the extended classification of twenty-seven types. Frequency totals are calculated for each group in the following way:

- for any day classified by one weather type alone (e.g. Westerly, Cyclonic etc.), then the frequency total of that group is increased by one;

- for days classified as a hybrid of two weather types (e.g. Cyclonic-Westerly or South-Easterly) a frequency of one-half should be added to *each* of the two group totals;
- when a hybrid of three weather types is experienced (e.g. Anticyclonic-South-Westerly), the frequency total of *each* of the three types should be increased by one-third.

This technique was applied to both the Lamb and Mayes databases to create seven annual time series covering the standard period 1954-92. Each time series was then analysed using the Mann's test for trend in the mean, and the results are presented in Figures 6.2(a)-6.2(g) (Appendix Four). These figures provide a useful method of comparison between the two records. In the majority of cases, a very similar pattern of behaviour is evident in the frequencies of weather types, in terms of the direction and timing of changes although the extent of these changes, in terms of statistical trends, can differ substantially.

Analysis of the Westerly weather type series over the period 1954-92 provides an interesting example. A clear point of divergence occurs from 1969 onwards: annual frequencies within the Lamb record decrease to levels coincident with a significant downward trend whilst Westerly frequencies over Scotland (Mayes database) remain stable rather than decrease. Although both records show increases in the frequencies of Westerly weather types since 1989, the value of the test statistic in the Mayes record is much higher because of the higher base point from which the increase originates. This information suggests that the period of low Westerly activity which was evident over the UK from the 1960s until the late 1980s was not reflected over Scotland, and it is likely that this was a continued source of precipitation in Scotland, particularly in the west.

A choice was made to proceed with the Mayes record only. This was preferred simply for the reason that it is appears to be more 'finely tuned' to the true climate patterns over Scotland. The Lamb record is often criticised for not adequately representing the true weather conditions being experienced in the extreme regions of its reference square 50°-60°N, 10°W-2E°, and particularly in Scotland (Sweeney and O'Hare, 1992). Rather the Lamb daily index is often based upon the pressure patterns and weather conditions experienced in central England and it is often likely that the situation is different over Scotland. The danger is that whilst the database is adequately representing the pattern of climatic variability across England, it may be an inaccurate and misleading record for Scotland. Comparison between the two databases reveals some key differences - the importance of the South-Westerly type in Scotland and the continued presence of Westerly airflows across Scotland during the 1970s and 1980s - which may make important differences in the analysis process.

6.7 ANALYSIS OF MAYES WEATHER TYPES 1954-92 and 1964-92

The Mayes record (Mayes, 1991) covers the period from 1950 onwards. Although this is short in comparison to Lamb's database, it is still sufficient in length to analyse climatic variability with respect to the standard periods adopted in Chapter Five. As with the Lamb record, it is also important to determine the relative importance of each of the key weather types within this regional database (Table 6.6). It is interesting to note that whilst the Anticyclonic, Cyclonic and Westerly weather types dominate the record (as with the Lamb database), a fourth type (the South-Westerly) is also of significance in the climate of Scotland.

In order to relate variability within these climatic indices to the flood records, it is also important to understand how the frequencies of weather types vary on a seasonal basis (Table 6.7). Of the five trigger weather types, only the Cyclonic-Easterly type shows no real seasonal variation. The Westerly, South-Westerly and Southerly types, however, show a clear increase in frequencies in SON and DJF. The Cyclonic type occurs more often in MAM and JJA, whilst the Cyclonic-Westerly occurs more frequently in SON.

The analysis of these trigger weather types was carried out with reference to the standard periods 1954-92 and 1964-92, using annual and seasonal time series. These series were then analysed in the standard way, with preliminary analysis using simple time series and running mean plots in combination with Minitab statistics, to provide a

Table 6.6: Typical annual occurrences of individual weather types, expressed as frequencies (days per year) and percentage contributions to the Mayes annual record

WEATHER TYPE	MINIMUM FREQ(%)	MAXIMUM FREQ(%)	MEDIAN FREQ(%)
ANTICYCLONIC	19 (5%)	69 (19%)	40 (11%)
CYCLONIC	**19 (5%)**	**52 (14%)**	**28 (8%)**
EASTERLY	1 (< 1%)	23 (6%)	8 (2%)
ANTICYCLONIC-EASTERLY	1 (<1%)	20 (5%)	7 (2%)
CYCLONIC-EASTERLY	0 (0%)	10 (3%)	4 (1%)
SOUTH-EASTERLY	2 (<1%)	23 (6%)	9 (2%)
ANTICYCLONIC-SOUTH-EASTERLY	1 (<1%)	19 (3%)	4 (1%)
CYCLONIC-SOUTH-EASTERLY	0 (0%)	8 (2%)	3 (<1%)
SOUTHERLY	**8 (2%)**	**33 (9%)**	**17 (5%)**
ANTICYCLONIC-SOUTHERLY	1 (<1%)	18 (5%)	8 (2%)
CYCLONIC-SOUTHERLY	2 (<1%)	15 (4%)	6 (2%)
SOUTH-WESTERLY	**13 (4%)**	**62 (17%)**	**26 (7%)**
ANTICYCLONIC-SOUTH-WESTERLY	3 (1%)	20 (5%)	9 (2%)
CYCLONIC-SOUTH-WESTERLY	1 (<1%)	13 (4%)	7 (2%)
WESTERLY	**29 (8%)**	**83 (23%)**	**58 (16%)**
ANTICYCLONIC-WESTERLY	8 (2%)	33 (9%)	21 (6%)
CYCLONIC-WESTERLY	**6 (2%)**	**33 (9%)**	**16 (4%)**
NORTH-WESTERLY	9 (2%)	36 (10%)	20 (5%)
ANTICYCLONIC-NORTH-WESTERLY	2 (<1%)	19 (5%)	8 (2%)
CYCLONIC-NORTH-WESTERLY	1 (<1%)	16 (4%)	6 (2%)
NORTHERLY	5 (1%)	33 (9%)	15 (4%)
ANTICYCLONIC-NORTHERLY	2 (<1%)	14 (4%)	8 (2%)
CYCLONIC-NORTHERLY	1 (<1%)	18 (5%)	7 (2%)
NORTH-EASTERLY	0 (0%)	15 (4%)	5 (2%)
ANTICYCLONIC-NORTH-EASTERLY	1 (<1%)	22 (6%)	4 (1%)
CYCLONIC-NORTH-EASTERLY	0 (0%)	5 (2%)	2 (1%)
UNCLASSIFIED	0 (0%)	12 (3%)	7 (2%)

Based upon the Mayes record 1950-1992
Primary and Secondary trigger weather types are highlighted in bold

Table 6.7 Typical seasonal occurrences of the weather types, expressed as typical seasonal frequencies and percentage contributions to the seasonal record

TRIGGER WEATHER TYPES	**DJF Freq (%)**	**MAM Freq (%)**	**JJA Freq (%)**	**SON Freq (%)**
Cyclonic	6 (7%)	7 (8%)	9 (10%)	7 (7%)
Westerly	15 (17%)	11 (12%)	14 (15%)	17 (19%)
South-Westerly	10 (11%)	6 (6%)	5 (5%)	8 (9%)
Southerly	6 (7%)	5 (5%)	2 (2%)	5 (6%)
Cyclonic-Westerly	4 (4%)	3 (3%)	4 (4%)	5 (6%)

Based upon the Mayes record 1954-92

first impression of how seasonal frequencies have varied through time, and the more complex time series techniques (WMO, 1988).

The annual and seasonal incidence of the Westerly weather type shows very variable patterns (Figures 6.3(a)-(e) , 6.8(a)-(e) and 6.13(a)-(e), Appendix Four):

- annual frequencies appear to be slightly higher in the late 1960s (Figures 6.3(a), 6.8(a) and 6.13(a));
- time series analysis reveals variable behaviour in the seasonal time series;
- the time series plot (Figure 6.3(b)), five-year sub-period mean frequencies and the Mann's trend test indicate that frequencies in DJF increase from 1973 onwards (Figures 6.8(b) and 6.13(b));
- these statistics also suggest that the mid to late 1960s represent a period of increased frequencies, in MAM and JJA (Figures 6.3(c), 6.8(c) and 6.13(c));
- the SON series shows a peak in Westerly frequencies in the late 1960s and early 1970s (Figures 6.3(d), 6.8(d) and 6.13(d)).

The time series depicting the frequencies of the Cyclonic weather type show the following characteristics 1980s (Figures 6.4(a)-(e), 6.9(a)-(e) and 6.14(a)-(e), Appendix Four):

- annual frequencies peak in the late 1950s and again in the early 1980s (Figures 6.4(a), 6.9(a) and 6.14(a));
- frequencies in DJF are clearly highest in the 1950s and stable thereafter (Figures 6.4(b), 6.9(b) and 6.14(b));
- the MAM series shows a general increase in frequencies from the early 1970s onwards, with perhaps a slight decrease from 1989 onwards (Figures 6.4(c), 6.9(c) and 6.14(c));
- in the JJA series, frequencies peak early in the 1950s and again in the mid 1980s (Figures 6.4(d), 6.9(d) and 6.14(d));
- frequencies in SON also display two peaks, the first in the late 1960s and a second in the early 1980s (Figures 6.4(e), 6.9(e) and 6.14(e)).

The seasonal series of the South-Westerly weather type portray similar characteristics to the annual series (Figures 6.5(a)-(e), 6.10(a)-(e) and 6.15(a)-(e), Appendix Four):

- the annual record is characterised by increased frequencies from the late 1960s onwards; this is classified as a statistically significant increase (at the 1% confidence level) in the Mann's trend test by the mid 1980s (Figures 6.5(a), 6.10(a) and 6.15(a));
- each of the four seasonal series displays a similar increase in frequencies, although the timing and magnitude of these increases do differ;
- the increase in frequencies in the DJF series begins in 1970, but is most enhanced from 1981 onwards; a significant upward trend is apparent by the late 1980s (at the 1% confidence level; Figures 6.5(b), 6.10(b) and 6.15(b));
- for the three remaining seasonal series, the increase begins in 1974;
- the increase in the MAM series is insufficient to signify a significant increase according to the Mann's test statistic; this may be to due to the low starting point of the test statistic in the mid 1970s (Figures 6.5(c), 6.10(c) and 6.15(c));
- in the JJA series this increase can be classified as a significant upward trend (at the 1% confidence level) by the late 1980s using the Mann's test (Figures 6.5(d), 6.10(d) and 6.15(d));
- the increase in the SON series registers as a significant upward trend (at the 1% confidence level) by the mid 1980s (Figures 6.5(d), 6.10(d) and 6.15(d)).

The remaining two weather types included in the analysis process, the Southerly and the Cyclonic-Westerly, are of limited importance as flood trigger mechanisms. Nonetheless, they were identified as being important in the POT series from the Dee at Woodend (12001) and the Kelvin at Killermont (84001) respectively.

The time series representing the annual and seasonal frequencies of the Southerly weather type show the following characteristics (Figures 6.6(a)-(e), 6.11(a)-(e) and 6.16(a)-(e), Appendix Four):

- the series of annual frequencies appears stable to the early 1980s, when a decrease occurs (Figures 6.6(a), 6.11(a) and 6.16(a));

- frequencies in DJF show a similar decrease although there is also a slight increase in values in the late 1960s and early 1970s (Figures 6.6(b), 6.11(b) and 6.16(b));
- with the exception of high seasonal frequencies in the 1950s, the MAM series is generally a stable one (Figures 6.6(c), 6.11(c) and 6.16(c));
- seasonal frequencies in JJA are relatively low (around five days per season) and it is difficult to determine the extent of any variability using simple plots and statistics; the Mann's test enhances periods of high frequencies in late 1960s and the late 1980s (Figures 6.6(d), 6.11(d) and 6.16(d));
- peak frequencies occur in the 1950s, late 1960s and mid 1970s in the SON series (Figures 6.6(e), 6.11(e) and 6.16(e));

The final series to be analysed represent the annual and seasonal frequencies of the Cyclonic-Westerly weather types. Seasonal frequencies are typically within the range of five to ten days per season (Figures 6.7(a)-(e), 6.12(a)-(e) and 6.17(a)-(e), Appendix Four):

- the annual record shows a peak in frequencies in the 1970s and a steady decrease thereafter (Figures 6.7(a), 6.12(a) and 6.17(a));
- a slight peak in frequencies occurs in the late 1960s/early 1970s in the DJF series (Figures 6.7(b), 6.12(b) and 6.17(b));
- the MAM series shows numerous peaks in seasonal frequencies from the mid 1960s onwards (Figures 6.7(c), 6.12(c) and 6.17(c));
- similarly, there are numerous peaks in frequencies in the JJA series (Figures 6.7(d), 6.12(d) and 6.17(d));
- the SON series shows a peak in seasonal frequencies in the mid 1970s.

6.7.1 SUMMARY REMARKS

The time series analysis carried out on the frequencies of weather types has revealed some interesting characteristics. A general view of the variability within the frequencies of a weather type can be provided by examining the series of annual frequencies. However, for the majority of the weather types analysed in this project, it is obvious that the characteristics of the annual series are 'masking' contrasting patterns of variability which are occurring on a seasonal basis.

The annual series of the Westerly weather type, for example, shows a peak in frequencies in the 1960s. However, a breakdown of the annual series into seasonal components reveals contrasting patterns. Whilst the MAM and JJA series show peaks in frequencies in the 1960s and early 1970s, and the SON series show peaks in the 1970s, the seasonal frequencies in the DJF show an increase from the mid 1970s onwards. A combination of contrasting seasonal patterns have therefore combined to produce the characteristics evident within the annual series.

However, a very different situation exists within the series depicting frequencies within the South-Westerly weather type, with the annual and each of the seasonal series showing a similar pattern. The distinctive feature of each of these series is the clear increase in frequencies evident in the latter part of the record. However, the timing and magnitude of this increase does vary with season.

It is clear, therefore, that by breaking down the annual weather type series into seasonal components, it is sometimes possible to reveal contrasting seasonal changes. In others cases, this seasonal breakdown merely reinforces the behaviour evident within the annual series. However, it is important to bear in mind the actual frequencies of these individual weather types when interpreting the results of time series analysis. An increase which is registered in a seasonal series of the Westerly weather type is likely to have a greater effect upon the characteristics of the climate and flood records than an increase in the Cyclonic-Westerly type. This is because the Westerly contributes significantly to the climate of Scotland and acts as one of the primary trigger weather types.

6.8 ESTABLISHING THE RELATIONSHIP BETWEEN CLIMATE AND FLOOD SERIES

The analysis carried out thus far has enabled the variability within flood and climatic series to be detected over two specified time periods, 1954-92 and 1964-92. However, the links between the two sets of results have yet to be explored.

The aim of this analysis is to qualitatively explore what, if any, relationships may exist between the two sets of series. This will be achieved by simply comparing the flood series with the climatic series representing the frequencies of the 'trigger' weather types in the dominant season of flooding. Any similarities during this comparison may be further investigated by breaking down individual flood series to examine whether the floods associated with a certain weather type (or combination of types) are becoming more or less frequent, or similarly increasing or decreasing in magnitude. Due solely to time constraints, the approach to this process will be generalised and will be qualitative rather than quantitative; the latter analysis likely to constitute the beginnings of a new research project. It is hoped that these preliminary findings will raise new hypotheses which can be tested in future.

6.8.1 FLOOD FREQUENCY SERIES: 1964-92

For the fifty-one flood frequency series analysed for the period 1964-92, three general patterns of flood frequency were detected using classification analysis (Section 5.10.1), although these groupings should always be viewed with some caution as many series display rather unique and individual characteristics. Having identified the general patterns of flood frequencies over this period (Figures 5.70(a)-5.70(c)), the question to be addressed is what climatic mechanisms were responsible for:

- stable flood frequencies during the 1960s (cluster A series);
- a decline in frequencies during the 1960s and early 1970s (series grouped in clusters B and C);
- the increase in flood frequencies evident in all clusters from the early 1970s?

Tables 6.3(a) and 6.4(a) suggest that a straightforward relationship between the pattern of flood frequencies and trigger weather types and/or flood seasonality does not exist. Within each flood frequency cluster, there is a degree of variability in the primary weather types and the dominant season of flooding. However, more information can be revealed on the climatic causes of flood frequency variability by determining how the annual frequencies of floods associated with different weather types (Cyclonic-floods, Westerly-floods etc.) have varied through time.

6.8.1.1 CLUSTER A SERIES

Previous analysis (Section 5.10.2) has revealed that there is no obvious geographical association between the flood frequency series comprising cluster A. However, a comparison of flood trigger weather types and flood seasonality (Tables 6.3(a) and 6.4(a)) indicates a common link, with the South-Westerly weather type and the SON season being important at a number of these gauging stations. The Dean Water record (15008), previously highlighted as an unrepresentative series in this cluster (Section 5.10.2), cannot, however, be linked to either season or trigger weather type.

Flood frequencies appear stable in the early part of these records, a feature which cannot be linked to any one weather type. Rather, it is a combination of weather types which maintain frequencies during this period. The increase in frequencies which then begins in the early 1970s is associated with the dramatic increase in South-Westerly frequencies (in SON) which begins around 1973 (Figures 6.5(e) and 6.15(e), Appendix Four).

6.8.1.2 CLUSTER B SERIES

Geographically speaking, cluster B series are located in the western half of Scotland. As one may expect, Westerly and South-Westerly weather types most frequently act as flood trigger mechanisms, with the Cyclonic type having limited importance (Table 6.3(a)). The dominant season of flooding (Table 6.4(a)) is most frequently DJF; two of the four series dominated by flooding in SON (the Girvan at Robstone (82001) and Kelvin at Killermont (84001)) were judged to be unrepresentative (Section 5.10.2).

The general pattern of flood frequencies begins with a slight decline in frequencies during the late 1960s and early 1970s. This reflects a slight decrease in Westerly or South-Westerly frequencies in DJF over this period. The increase in frequencies which follows is associated with the increase which again occur in both the DJF series of South-Westerly and Westerly frequencies (Figures 6.3(b), 6.5(b), 6.13(b) and 6.15, Appendix Four).

6.8.1.3 CLUSTER C SERIES

The final group of flood frequency series are commonly located in the easterly regions of Scotland. Consequently, the Cyclonic weather type plays a more important role in triggering flood events than in other series (Table 6.3(a)), whilst the dominant season of flooding varies between SON and DJF (Table 6.4(a)). The general pattern of frequencies within this grouping is a decline to the early 1970s. A similar decline in the frequency of the Cyclonic weather type was apparent, in both the DJF and SON series (Figures 6.4(b), 6.4(e), 6.14(b) and 6.4(e), Appendix Four). The subsequent increase in frequencies which follows is less easy to explain. Cyclonic frequencies in DJF do not increase over this period, and for the SON series the increase only occurs from the late 1970s. However, Cyclonic frequencies do increase over this period in the MAM record (Figure 6.14(c), Appendix Four) although this season cannot be directly associated with flooding. The increase may be related to an increase in Westerly and South-Westerly frequencies, although these weather types have limited importance as flood trigger mechanisms in a number of these series.

6.8.2 FLOOD FREQUENCY SERIES: 1954-92

Having discussed possible links between the pattern of flood frequencies and seasonal weather types for the period 1964-92, some reference should be made to the period 1954-63 for those records where POT data cover the extended standard period.

The fourteen frequency series analysed for this sub-period indicate high values during either the early or late 1950s (Section 5.9.2). This sample represent series where Cyclonic, Westerly and South-Westerly weather types act as trigger mechanisms (Table 6.3(a)), although the dominant season of flooding is limited to DJF, where data are available (Table 6.4(a)). The Cyclonic record for DJF is the only series where relatively high frequencies were experienced in the early 1950s (Figures 6.4(b) and 6.14(b), Appendix Four).

6.8.3 FLOOD MAGNITUDE SERIES: 1964-92

Within the set of flood magnitude series, four general patterns of variability were identified (Section 5.10.3). As with the flood frequency series, associations between flood magnitudes and synoptic weather types can be explored by determining what climatic mechanisms generate the observed changes in mean exceedances (Figures 5.71(a)-5.71(d)):

- the observed decrease in mean exceedances during the 1970s, for those series in clusters 1, 3 and 4;
- the stable mean exceedances during this period in cluster 2 series;
- the increase in magnitudes during the 1980s (clusters 1, 2 and 3).

However, postulating the nature of relationships between flood magnitudes (mean exceedances) and weather types is more complex than when dealing with flood frequencies. Whilst an increase in the frequency of a trigger weather type may logically be associated with increased flood frequencies, it does not follow that such an increase will result in increased flood magnitudes. It is more important to determine how the magnitude of precipitation events associated with a weather type vary through time. This information can be indirectly retrieved by examining how flood magnitudes (mean exceedances) associated with a particular weather type (e.g. Westerly-floods) have varied over the standard period.

6.8.3.1 CLUSTER 1 SERIES

The series included in this cluster are dominated by Cyclonic and South-Westerly weather types on the day of flood, whilst DJF appears to be the dominant season of flooding (Tables 6.3(b) and 6.4(b)). The pattern of mean exceedances in this grouping is a decrease in values from the mid 1960s to mid 1970s, followed by an increase in magnitudes throughout the 1980s. A breakdown of each individual flood series suggests that this pattern may reflect changes in the magnitude of Cyclonic floods although for the majority of mean exceedance series, a rather complex pattern of changing flood magnitudes exists.

6.8.3.2 CLUSTER 2 SERIES

This small group of records register stable magnitudes until 1973. At a number of stations, this is a reflection of stable Westerly flood magnitudes (the Findhorn at Shenachie (07001), Dee (12001) and Urr (80001) series), whilst in other series this is a period characterised by stable South-Westerly flood magnitudes (Ruchill Water (16003)). The increase in flood magnitudes which follows seems to be associated with increased Westerly and/or South-Westerly flood magnitudes (the Findhorn at Shenachie (07001), the Dulnain (08009), Gala Water (21013) and Urr (80001) series).

6.8.3.3 CLUSTER 3 SERIES

The pattern of flood magnitudes is similar to that of Cluster 1 records. The pattern of flood magnitudes relates to changes in the magnitude of Cyclonic and/or South-Westerly floods (the Avon (08004), Spey at Boat of Brig and Invertruim (08006 and 08007), Dean Water (15008), the Dulnain (08009) and Cree (81002) series).

6.8.3.4 CLUSTER 4 SERIES

The final group of records shows a similar pattern to Cluster 2, although there is a very minor decrease in the 1970s. Changes in the magnitude of Cyclonic, South-Westerly and Westerly weather types all combine to produce the pattern of flood magnitudes.

6.8.4 FLOOD MAGNITUDE SERIES: 1954-92

The pattern of flood magnitudes in the ten-year period prior to the standard period 1964-92 is, once again, fairly variable with some records recording stable magnitudes and others showing relatively high magnitudes (Section 5.9.3). Over such a short period of ten years, it is very difficult to find a general reasoning behind these patterns.

6.9 SUMMARY AND CONCLUDING REMARKS

By combining the Mayes record of daily weather types with over one hundred POT records, a very strong link has been established between synoptic weather types and the incidence of a peak flow events in Scotland. This relationship, summarised in Maps 6.1-6.13 (Appendix Three), confirms that extreme precipitation events in Scotland arise from a number of different synoptic situations and that different sources of precipitation are important to different geographical areas.

As one may expect, for those rivers in the west of Scotland and for those with source areas predominantly in the west, Westerly airflows are most frequently associated with POT events. Of some secondary significance to flooding in these areas and of primary importance to catchments in southern regions is the incidence of the South-Westerly weather type. Commonly associated with a west-east precipitation gradient similar to that produced by the Westerly type (Sweeney and O'Hare, 1992), the South-Westerly plays a key role in 'triggering' flood events in the Solway region and the parts of the Tweed catchment which drain from the west.

Precipitation in the east of Scotland is often associated with slow-moving depressions (File, 1990) and this is a relationship clearly evident between weather types and POT events. A number of flood series located in the north-east and along the east coast of Scotland show a clear association with the Cyclonic weather types. The spatial distribution of these series suggests that cyclonic systems which move or stagnate over Scotland may be associated with easterly rain-bearing winds moving in from the North Sea.

Since these three weather types were identified as catalysts to the flood initiation process, it is logical to assume that changes in the incidence of these types will have some effect on the characteristics of Scottish flood records. The nature of climatic variability was therefore explored with reference to the annual and seasonal frequencies (number of days identified per year or per season) of the Westerly, Cyclonic and South-Westerly weather types.

The most significant finding in the examination of weather type variability was with regard to the frequencies of the South-Westerly type, a feature also detected by a number of other authors (Sweeney and O'Hare, 1992; Murray, 1993). Annual frequencies have increased from an average of around twenty-five days per year in the 1950s to exceed over fifty days per year in the 1990s, a feature which is reflected in all seasons. The incidence of the Westerly and Cyclonic weather types has also been shown to vary through time, and by breaking down the annual series into seasonal components it has been possible to identify some contrasting patterns. Whilst the annual frequencies of the Westerly weather type shows little variation over the period 1954-92, the series for the season DJF alone exhibits an steady increase in frequencies from 1973.

In terms of precipitation totals, the 1980s and 1990s have been characterised by increased precipitation in Scotland, particularly in the west (Curran and Robertson, 1991; Smith, 1995). This complies with the increase in the winter frequencies of both the Westerly and South-Westerly types during this period, although increased autumn precipitation (Rowling, 1989; Smith, 1995) can only be associated with an increase in South-Westerly frequencies.

The influence of climatic variability upon flood series has been tentatively explored in preceding sections. By classifying each POT event within an individual flood series according to the Mayes weather type recorded on the day of flood, it has been possible to determine the reasons why patterns of flood frequencies and mean exceedances have been experienced.

With regard to the flood frequency series, it is apparent that changes in the seasonal frequencies of trigger weather types can have an important effect on the incidence of POT events. In the case of the South-Westerly weather type, the dramatic increase in frequencies across all seasons appears to have had some effect on the incidence of floods, particularly in the more western regions of Scotland which are likely to receive increased precipitation from these weather systems. However, there are some flood frequency patterns which show no simple relationship to weather type frequencies. Increased flood frequencies in series in the east of Scotland cannot be linked by increases in the key weather type, the Cyclonic. It is, therefore, not always possible to make simple associations between flood and climatic series by simply examining the seasonal frequencies of the relevant weather types.

The relationship between the mean exceedances and weather type frequencies is one which cannot be readily explained by this research. It is highly likely that a number of other factors (precipitation totals, intensity, water levels, antecedent moisture conditions etc.) will combine to establish such relationships.

There are a great deal of additional information needed to establish the precise nature of the flood-climate relationship, and to substantiate the generalised statements made thus far. This information could only be provided by an extensive study into the relationship between Scottish precipitation and the incidence of Mayes weather types. In particular, it will be necessary to establish:

- the precipitation totals and durations associated with individual Mayes weather types;
- the spatial distribution of precipitation associated with each type;
- the probability that each weather type produces a flood event;
- if, and how, these precipitation totals, intensities, distributions and probabilities have varied through time.

This information can only be derived from an extensive study, combining the Mayes weather type record with Scottish precipitation series. Only then will it be possible to determine precisely how the variability in weather type frequencies is linked to the characteristics of the Scottish flood series. Unfortunately, such an extensive exercise is beyond the time constraints of this project but may provide a useful starting point for additional research.

This research could be further enhanced by additional work to explain the factors which link those flood series grouped into flood frequency and magnitude clusters (Section 5.12). This will allow a more detailed analysis into the relationship between flood variability, catchment locations / characteristics and the importance of key weather types.

CHAPTER SEVEN

THE WIDER IMPLICATIONS OF FLOOD SERIES VARIABILITY AND FUTURE RESEARCH AIMS

An examination of the effect of variability within flood, and ultimately climatic, series upon return period analysis and a discussion on future research goals

7.1 INTRODUCTION

Techniques of time series analysis have been used to assess variability within flood series (representing both frequencies and magnitudes; Chapter Five), and climatic series (expressed in terms of the annual and seasonal incidence of daily weather types; Chapter Six). This chapter addresses the wider implications of these results, with reference to current methods of flood frequency analysis.

Through the process of detecting variability with a view to answering the original research aims, a number of new issues have also been raise, and the second part of this chapter will address those areas where future research could be directed.

7.2 THE IMPLICATIONS OF VARIABILITY UPON FLOOD FREQUENCY ANALYSIS

The collection of flow data is necessary to understand the hydrological characteristics and regimes of river systems. Peak flow data are useful, though not essential, for predictive purposes, to determine the nature of the relationship between the magnitude and probable frequency of recurrence (Dalrymple, 1960). This information can then be applied to the design of structures (dams, bridges etc.) within the floodplain since the likely frequency that a structure will be damaged or destroyed by flooding is a key factor to the design engineer. Both over-design and under-design are costly, in economic terms.

7.2.1 ASSUMPTIONS OF FLOOD FREQUENCY ANALYSIS

The aim of flood frequency analysis is to predict flood-magnitude relationships for the future from past records of flood events. Such past series are considered to be samples of the *total* statistical population consisting of all past and future floods. The key assumption of flood frequency analysis is therefore stationarity, i.e. that the flooding regime is stationary through time. Consequently all hydrological records are assumed to be stationary, with all peaks mutually independent of one another. If there is some serial dependence or trend within a series, then flood frequency analysis becomes invalid (Cunnane, 1989). Concern has often been expressed over the use of POT series for flood frequency analysis, because of the danger that they will include dependent peaks. However, the use of POT series is valid, given that the rules of independence (NERC, 1975) are adhered to. If a trend is evident within any flood series (annual maximum or peaks-over-threshold) then it is necessary for it can possibly be removed before flood frequency analysis can be carried out (Cunane, 1989). Cunnane also recommends that a test for trend be carried out on all series prior to flood frequency analysis.

The work carried out in this project has identified the presence of temporal variability within climatic and flood indices. The significance of this variability has been determined using the Mann's test for trend although the effect of other factors (length of record, starting point of trend) upon these results does limit the results somewhat. Nonetheless variability has clearly been detected within the key variables (climate and flood indices), although the effect of this variability upon flood frequency analysis is not yet known. The aim of this chapter is to complete a process of exploration. Using time series statistics to split flood records into sub-periods, it will be possible to compare and contrast frequency-magnitude relationships, therefore examining whether or not variability does have an effect on such relationships, rather than making precise statements on *exactly* how variability within Scottish flood series has affected frequency-magnitude relationships.

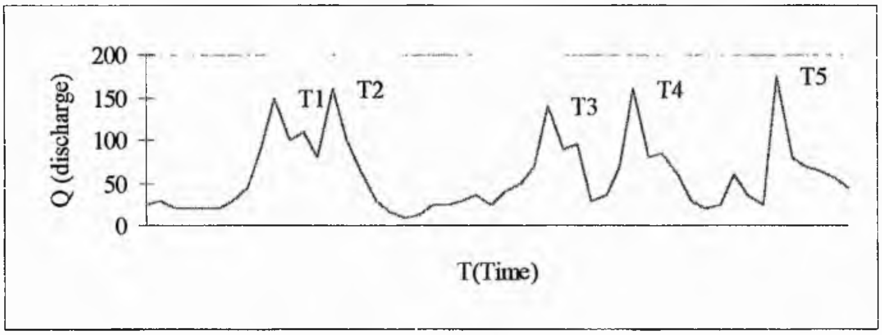
These goals can be achieved by simply deriving and comparing frequency-magnitude relationships from different periods of record, a technique which has previously been used with success (Higgs, 1987; Rowling, 1989). In the first instance, the frequency-magnitude relationship can be derived from the complete period of record available. The effect of variability within a flood series can then detected by splitting each individual record into distinct hydrological sub-periods, based upon the results of time series analysis described in Chapter Five. Frequency-magnitude relationships will then be calculated for these sub-periods and changes in the nature of the relationships can then be examined. This will allow the effect of variability upon flood frequency analysis to be explored.

7.2.2 THEORY OF FLOOD FREQUENCY ANALYSIS

The aim of flood frequency analysis is to estimate a relationship between flood discharge Q and return period or recurrence interval T (Sutcliffe, 1978), where T is the long term average of the intervals between successive exceedances of this magnitude (Shaw, 1988). Taking Figure 7.1 as an example:

- for a discharge Q of 130 cumecs, the return period T is the average time interval between events which equal or exceed that discharge;
- i.e. T(130 cumecs) = average ([T2-T1], [T3-T2], [T4-T3], [T5-T4],..[Tn-T(n-1)]), where n is the number of events in the series which equal or exceed this discharge

Figure 7.1: Quantities used in the definition of a return period (Cunnane, 1989)



Frequency-magnitude (Q-T) relationships can be established for a catchment from a number of different techniques, including equations based upon catchment characteristics, regional growth curves or by using the statistical properties of their flood series. If the latter technique is used, a flood series must be created using one of two methods, the Annual Maximum (AM) or a Peaks-over-Threshold (POT). The Q-

T relationships inferred from either type of series are generally in close agreement particularly for high return period events (Sutcliffe, 1978), although divergences are more common for low return period events (where T is less than ten years; Shaw, 1988). The POT method is less widely used for flood frequency analysis simply because of the greater difficulty in collecting (independent) data although there is no reason why it should not be used in preference to an AM series (Wang, 1991). Since the flood series used throughout this project have been derived using the POT approach, it follows logically that the flood frequency analysis will be based upon the POT data.

7.2.3 POT MODEL

The Q-T relationship derived using the POT model is based upon all independent flows which exceed a set threshold q_0. The mean annual number of flows λ which exceed the threshold q_0 in a given time interval is assumed to follow a Poisson distribution:

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

M = the number of peaks within the series

N = the number of years in the series

Therefore, a flood with return period T-years or more will occur once, *on average*, among every λT flood peaks in the series

i.e. the annual exceedance probability of Q_T in the population of peaks which exceed q_0 is $\frac{1}{\lambda T}$

If this conditional distribution has distribution function $F(q / q \geq q_0)$, then the Q-T relationship can be defined as follows:

$$1 - F(QT / QT \geq q_0) = 1 / \lambda T$$

or $$F(QT / QT \geq q_0) = 1 - 1 / \lambda T \qquad (1)$$

Since the lower tail of the POT distribution is clearly truncated by the threshold, the

POT function is assumed to be exponential:

$$F(q / q \geq q_0) = 1 - \exp\left[-(q - q_0) / \beta\right] \tag{2}$$

where β = standard deviation

Equation (1) then gives:

$$Q_T = q_0 + \beta \ln(\lambda T)$$
$$or \tag{3}$$
$$Q_T = q_0 + \beta \ln \lambda + \beta \ln T$$

The Q-T relationship may be plotted graphically on a probability plot having an exponential base or on ordinary graph paper. For the purpose of this project, the latter plot will be produced by using plotting positions (y_i) which are expressed as the expected values of the reduced variate order statistics $E(y_{(i)})$:

$$y_i = E(y_{(i)})$$

for the exponential distribution, the exact expression for $E(y_{(i)})$ is given, and the exponential model therefore plots as a straight line:

$$E(y_{(i)}) = \sum_{j=1}^{i} \frac{1}{N + 1 - j}$$

SOURCE: Cunnane, 1989; Black, 1992

In addition to choosing a distribution to fit to the data, the number of peaks (M) to be included in the series must also be decided since this factor determines the mean annual number of floods λ. Whilst including a large number of peaks within the POT series obviously increases the amount of information available to determine Q-T relationships, it may also hinder the choice and fit of the distribution used in the modelling procedure (Section 7.2.5).

7.2.4 DATA SERIES: COMPLETE AND SPLIT RECORDS

Since a great deal of time and effort has previously been put into the examination of flood variability in a subsample of Scottish POT records (Chapter Five), it seemed logical to explore the effect of variability upon flood frequency analysis using these series.

In order to judge how variability can affect the results of flood frequency analysis, it was decided to compare the Q-T relationship estimated from the complete periods of record studied (1944-92, 1954-92 or 1964-92) with those estimated from split sub-periods of each series. These splits were determined subjectively from the hydrological characteristics of the record. It was decided that the Mann's test for trend in the mean plots would be used, and that sub-periods would be split according to turning points within the time series. This is not, however, the only means by which a series can be split. An alternative technique would be to separate a series into 'flood-rich' and 'flood-poor' periods, and periods of 'high-magnitude' floods could be distinguished from 'low-magnitude' periods. Under such circumstances, these splits would occur either side of a turning point. However, the point in question is to examine how frequency-magnitude relationships can vary through time, rather than which technique is most appropriate for dividing a time series for the examination process. Table 7.1 (Appendix Five) lists the splits derived for each flood series from the flood frequency and magnitude trend plots.

Temporal changes in the Q-T relationship can be determined by comparing a number of parameters:

- discharge (Q) for a set return period (T)
- return period (T) for a given discharge (Q);
- growth rates (Q_{100}/Q_5 floods, for example), a measure of the 'steepness' of the best-fit line which depicts the Q-T relationship;

for these specific periods of record.

These parameters can be calculated for the complete period of data available and also for the sub-periods created; changes in the nature of the frequency magnitude relationship may then be compared between periods.

7.2.5 THRESHOLDS

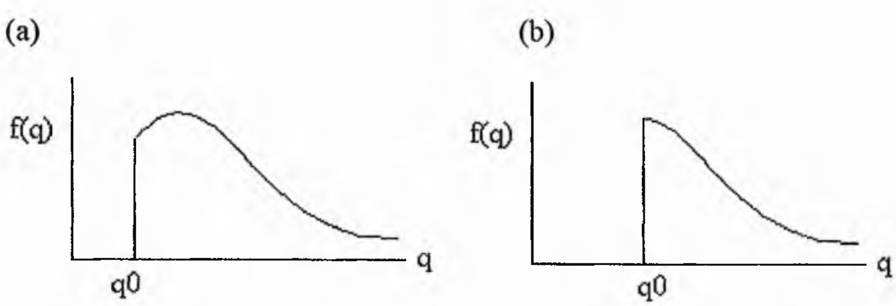
The choice of discharge threshold used to collect the POT series plays an important role in determining how well the Exponential distribution fits the data series. For the majority of those records included in the analysis, the flow threshold was set to record a standard frequency of exactly forty-five events in the period 1979-88, producing a mean frequency of 4.5 events per year in this ten year period. Setting a relatively low threshold in this way has allowed a considerable amount of flood data to be analysed and thus the patterns of variability within these series can be easily explored. This is something that would not have been possible if a higher threshold had been set. However, for the purpose of flood frequency analysis, higher discharge thresholds are recommended, to ensure the exponential distribution models the frequency-magnitude relationship accurately.

Naden (1992) discusses the importance of choosing the correct threshold and identifies two methods, the mean excess plot and the log-survivor function, which can be used to determine the correct value of λ (mean number of floods per year). Using a number of examples, Naden confirms the findings of Hosking and Wallis (1987), that the threshold should be set fairly high, and cites examples where the best fit is provided by $\lambda = 3$ or less.

Cunnane (1989) suggests that the exponential distribution is satisfactory where λ is less than or equal to 2.0. However, the ability of the distribution to model the series declines as λ increases beyond 3.0 . particularly at the lower tail of the data. If the threshold is set too low the distribution displays a mode greater than q_0 (Figure 7.2a), which is a difficult distribution to model. In such cases, increasing the threshold will produce a truncated distribution with the mode at q_0. This may be modelled more easily, particularly with the exponential distribution (Figure 7.2b; Cunnane, 1989)

Figures 7.2(a) Distribution of POT series with a low threshold: truncated distribution with mode > q_0

Figure 7.2(b) Distribution of POT series with a medium-high threshold: truncated distribution with mode = q_0



For the purpose of this project, it was therefore decided to follow these guidelines, and the discharge threshold was raised for each series to ensure λ =2.0 for the period of record in question.

7.2.6 FLOOD FREQUENCY ANALYSIS: COMPLETE AND SPLIT PERIODS

A FORTRAN computer program was written (Black, 1992) to calculate the Q-T relationship from a POT series of flood data using the exponential statistical distribution. This program allowed two parameters, the number of years of record (N) and the pre-set average number of peaks per year λ, to be controlled. In the case of the second parameter λ, the value was set as 2.0 throughout the analysis. By varying the parameter (N) and the POT series input into the program, it is possible to calculate the Q-T relationship for different periods of record: for the complete data set available, for the specified sub-periods 1954-92 and 1964-92, and also for the split periods of record (Table 7.1, Appendix Five).

One problem associated with fixing λ at 2.0 for all periods of record (whether they are complete or just a subsample) is that the discharge threshold q_0 will differ between the data samples which are to be compared. Nonetheless, it should still be possible to show the dependency of Q-T relationships upon the hydrological characteristics of the time period used.

7.2.6.1 SPLIT RECORDS: LONG RECORDS

DEE AT WOODEND (12001): 1934-92

The Dee at Woodend record, in its entirety, covers a period of fifty-nine years (Figure 5.1(a)-5.1(d)). The chosen sub-periods within this record were based upon:

- 1934-62, characterised by stable frequencies and mean exceedances;
- 1963-82, a period of variable flood frequencies;
- 1983-92, a period of stable frequencies;
- 1963-92, characterised by decreasing then stable magnitudes.

IRVINE AT KILMARNOCK (83802): 1914-88

Based upon the graphs of the Mann's trend in the mean test statistic (Figures 5.2(b) and 5.2(d)), the frequency and mean exceedance series for the Irvine record can be split into the following hydrologically similar periods:

- 1914-28, a period of increasing frequencies;
- 1929-51, generally stable frequencies;
- 1952-77, decreasing frequencies;
- 1978-88, a substantial increase in frequencies associated with the building of a flood prevention scheme;
- 1914-46, characterised by stable mean exceedances;
- 1947-88, a general increase in mean exceedances.

ALLT LEACHDACH AT INTAKE (91802): 1939-80

The final long record analysed, from the Allt Leachdach, can be split into five sub-periods, two based upon the frequency series (Figures 5.3(a) and 5.3(b)) and three upon the characteristics of the mean exceedance series (Figures 5.3(c) and 5.3(d)):

- 1939-49, characterised by increasing flood frequencies;
- 1950-80, stable frequencies;
- 1939-55, a period with generally stable mean exceedances;
- 1956-69, variable mean exceedances;
- 1970-80, a further period of stable mean exceedances.

7.2.6.2 SPLIT RECORDS: 1944-92 RECORDS

The Dee at Woodend record (12001) is also used to depict changes in flood frequencies and magnitudes over the period 1944-92. Based upon the Mann's test statistics (Figures 5.4(b) and 5.4(d)) both flood series can be subjectively split into two sub-periods, based upon their flood characteristics:

- 1944-62, and
- 1963-92.

7.2.6.3 SPLIT RECORDS: 1954-92 RECORDS

The fourteen flood frequency series which cover the standard period 1954-92 (Figures 5.5(b)-5.18(c)) can generally be split into two hydrological sub-periods for the purpose of flood frequency analysis (the exception being the Boat of Brig (08006) series), and there is also some degree of similarity in the timing of these periods:

- 1954-66 and 1967-92: the Avon (08004);
- 1954-73 and 1974-92: the Dee (12001), Tay at Caputh (15003), Ballathie (15006) and Pitnacree (15007), Dean Water (15008) and Tweed at Peebles (21003);
- 1954-76 and 1977-92: the Earn (16001);
- 1954-77 and 1978-92: the Spey at Invertruim (08007), Dulnain (08009) and Kelvin (84001);
- 1954-80 and 1981-92: the Spey at Boat of Garten (08005) and Grantown (08010);
- 1954-66, 1967-82 and 1983-92: the Spey at Boat of Brig (08006).

Similarly, for these fourteen POT records, the divisions based upon the Mann's test statistic for the flood magnitude series (Figures 5.5(d)-5.18(d)) are largely twofold:

- 1954-60 and 1961-92: the Spey at Invertruim (08007);
- 1954-65 and 1966-92: the Avon (08004), Spey at Boat of Garten (08005) and Grantown (08010) and Tay at Pitnacree (15007);
- 1964-73 and 1974-92: the Dee (12001), Tay at Caputh (15003) and Ballathie (15006), Dean Water (15008) and Kelvin (84001);
- 1954-77 and 1978-92: the Spey at Boat of Brig (08006) and the Dulnain (08006);
- no obvious splits are possible in the Earn (16001) and Tweed (21003) series.

7.2.6.4 SPLIT RECORDS: 1964-92 RECORDS

One would expect that the fifty-one flood frequency series included in this subset would be split into two sub-periods, pre-1973 and post-1973, following the general pattern of the Mann's test statistic described in Section 5.10.2. One may also expect the timing of the splits to be similar in all series, irrespective of the grouping or classification (clusters A, B or C) to which they belong, since the timing of changes in flood frequencies were similar in all clusters.

Although the majority of series showed a distinct change in the behaviour of flood frequencies in 1973 (based upon the Mann's test statistic (Figures 5.19(b)-5.69(b)) twenty-four series were split in this way), there was some degree of variability. Once again, this reflects the individual nature of many of the series, which may not be represented clearly when using classification analysis. However, if not at 1973, the clear turning point in a series was typically in 1972, 1974 or 1975. A small number of series showed a slightly later turning point, such as 1980 in the Tay at Ballathie (15006) series (Table 7.1, Appendix Five).

The fifty-one mean exceedance series showed a much greater degree of variability in both the timing and extent of turning points (Figures 5.19(d)-5.69(d)). Although 1973 was, once again, a key turning point in a number of series, it was clearly not universal to all series. This variability is indeed reflected in how the magnitude series are split with a number of key turning points being noted between 1970 and 1980. The majority of turning points do, however, lie in the period 1972-76. For experimental purposes, it was decided that these splits would be used in addition to those derived from the frequency series. Table 7.1 (Appendix Five) summarises how all POT record included in the analysis were split into sub-periods.

7.2.7 RESULTS OF FLOOD FREQUENCY ANALYSIS

Having identified these distinct sub-periods, using the results of the Mann's test for trends in the mean, it was possible to examine how variability with flood frequencies and mean exceedances can affect the frequency-magnitude (Q-T) relationship. Simply, the Q-T relationship was calculated for the entire period of data available (1944-92, 1954-92 etc.) and for each of the sub-periods identified (Table 7.1, Appendix Five). The Q-T relationships estimated for each POT record (complete and split periods) are depicted in Figures 7.3-7.71 (Appendix Five). The extent to which the Q-T relationship is dependent upon the hydrological characteristics of the sub-sample of data used can be determined by observing changes in those parameters previously identified (Section 7.2.4).

One of the most obvious methods is to examine how the discharge (m^3s^{-1}) of a given return period flood varies for different samples of data. This comparison is particularly interesting when dealing with high return period events (in excess of one hundred years), particularly since the magnitude of such extreme events may act as a guide in the design and construction of large structures (dams, bridges etc.) within the flood plain. However, a certain degree of caution must be exerted when examining high return period events since estimates of discharge are least reliable at this end of the scale. Very often the presence of an extreme discharge event (or outlier) affects the ability of the exponential distribution in accurately modelling the Q-T relationship, for high magnitude events (for example Figure 7.3, split period 1934-62).

An alternative to this technique is to examine how the estimated return period (in years) of a specified discharge varies with the period of flood data used. This allows the question of probabilities to be introduced into the discussion.

Changes in the estimated frequency-magnitude relationship can also be explored through an examination of the growth factor. The growth factor depicts the ratio of high magnitude to low magnitude events to be observed, Q_{100}: Q_5 for example. It is therefore possible to determine whether the magnitude of high return period events is increasing, decreasing or remaining stable in comparison with low return period events. However, it must be understood that a change in the growth factor may reflect a change in the magnitude of the low return period event rather than in the high return period event.

7.2.7.1 CHANGES IN THE MAGNITUDE OF THE ONE-HUNDRED YEAR FLOOD

The one hundred year flood (Q_{100}) was chosen as a parameter to compare how the estimated discharge of a given return period event varies with the sample of data used. The magnitude of the Q_{100} estimated for complete and split periods of record are displayed in Tables 7.2-7.5 (Appendix Five).

7.2.7.1.1 LONG RECORDS

With the exception of the most recent period (1983-92), there appears to be very little variation in the estimated discharge of the Q_{100} event (Table 7.2, Appendix Five) from the Dee at Woodend (12001). The sample of flood data from the period 1983-92 estimates a discharge Q_{100} 20% lower than that calculated from the complete data set available.

The Irvine record (83802) indicates that the estimated magnitude of Q_{100} is more dependent upon the sample of flood data used (the estimated magnitude of Q_{100} based on data for the record 1914-46 is over 30% lower than that based upon the complete set of data 1914-88 (Table 7.2, Appendix Five).

7.2.7.1.2 1954-92 RECORDS

For six of the fourteen POT series covering the period 1954-92, the estimated discharge of Q_{100} is clearly higher when the Q-T relationship is based upon data from the latter half of the series (the Spey at Boat of Garten (08005) and Invertruim (08007), Dee (12001) and the Tay at Caputh (15003), Ballathie (15006) and Pitnacree (15007) series). For a smaller group of records (the Avon (08004), Spey at Boat of Brig (08006), Tweed (21003) and Kelvin (84001) series), the magnitude of Q_{100} is higher when estimated from flood in the early half of the record. For a number of series (the Dulnain (08009), Spey at Grantown (08010), Dean Water (15008) and the Earn (16001)) the estimate of Q_{100} shows little dependency on the period of data used (Table 7.4, Appendix Five).

7.2.7.1.3 1964-92 RECORDS

The POT records used to describe the hydrological characteristics of the period 1964-92 can generally be split into two hydrologically similar sub-periods. Comparison of the Q-T relationship based on these different sub-periods of data reveals the following patterns (Table 7.5, Appendix Five):

- in thirty-four of the fifty-one records a clear increase in the magnitude of Q_{100} occurs when the Q-T relationship is based on the later part of the record;
- for seven series the reverse relationship is true;

- for the remaining ten series, the Q-T relationship seems reasonably stable whatever period of record is used in the modelling process.

7.2.7.2 CHANGES IN THE RETURN PERIOD OF A HIGH MAGNITUDE EVENT

An alternative method of establishing how the modelled Q-T relationship varies with the period of flood data used is by examining the estimated return period or probability for a fixed discharge event. This is of particular use when information on a specific discharge is required. Table 7.10 (Appendix Five) depicts the dependence of the estimated return period for a flood of fixed discharge on the period of record used for a small sample of records (where the most extreme differences (+/-20%) in the estimated magnitude of Q_{100} were found.

These results suggest that a wide range of return periods may indeed be estimated from a single flood series. The Tay at Pitnacree (15007) series is an extreme example, with the estimated return period of a 600 cumec event ranging from 10 - 15 years (based upon the flood series from 1974 onwards) to in excess of 100 years in the period 1964 - 73. However, whilst these findings are extremely useful in displaying the variability of estimated frequency- magnitude relationships, we must also consider additional factors which may be similarly affecting these results. These include the length of record used in the estimation process (the most extreme return period from the Pitnacree record is indeed based upon the shortest period of record) and also the possible influence of an outlier within the subset of data used (as in the case of the Dee at Woodend (12001) record, where the influence of two outlier events in the period 1964 - 73 is seen to greatly influence the estimated relationship (Figure 7.33, Appendix Five).

7.2.7.3 CHANGES IN THE GROWTH FACTOR

Tables 7.6-7.9 (Appendix Five) display the growth factors (ratios) of Q_{100} to Q_5 of all series included in the analysis, for all complete and split periods. It is clearly evident that, in the majority of series, the growth factor is not highly dependent upon the period of record used to model the Q-T relationship. This suggests that as the magnitude of the Q_{100} flood increases/decreases, the magnitude of the Q_5 flood (and all other return period floods) increases/decreases at a proportionate rate. There are, however, a small number of records where there is a noticeable change in the growth factor:

- the growth factor based on the Irvine (83802) record for the period 1952-77 is higher than that modelled by other periods (Table 7.6, Appendix Five);
- from the 1954-92 subset of records, the Kelvin (84001) series displays a reduced growth factor, based on the split period 1978-92 (Table 7.8, Appendix Five);
- the Gala Water (21013) and White Cart Water (84012) series from the 1964-92 subset of records both display variable growth factors; with the Gala Water series relatively low factor is estimated using data from the period 1964-73, whilst a relatively high factor is estimated for the White Cart record, based upon the POT data from the period 1964-75 (Table 7.9, Appendix Five).

These results suggest that, for those series where an unusually high growth factor has been modelled, either the estimated magnitude of the high return period event (Q_{100}) has increased or the estimated magnitude of the low return period events (Q_5) has decreased, and vice versa where a decrease in the growth factor has been observed. In the three of the four cases listed above, the change in growth factor appears to be related to a change in the estimated magnitude of Q_{100} (Tables 7.2-7.5, Appendix Five). In the case of the Kelvin series (84001), the decrease in the growth factor seems to be associated with an increase in the estimated magnitude of Q_5. This is clearly evident in Figure 7.20.

7.2.8 SUMMARY STATEMENT

The effect of variability within flood indices (frequencies and mean exceedances) upon frequency-magnitude relationships has been explored by splitting individual flood series into distinct hydrological sub-periods. By comparing a number of parameters (growth factors, Q_{100} floods etc.) it is possible to assess the representativeness of sub-periods are for depicting the Q-T relationship. The results of this analysis have revealed a number of interesting features, regarding the effect of flood variability upon frequency-analysis relationships. Clearly, in some series the hydrological characteristics of a sub-sample of flood data has a more noticeable effect upon the estimated Q-T relationship than in others.

It is clear that, for the majority of records, differences are evident in the frequency-magnitude relationship estimated from the exponential model, when different sub-samples of flood data are used. These differences may be manifested in the magnitudes of fixed return period events, although noticeable differences in growth factors are less frequent. This suggests that these changes in the estimated frequency-magnitude relationship are occurring at similar rates for all return periods and magnitudes.

Although Q-T relationships show some dependence upon the sample of hydrological data used, one must always consider why this occurs. Whilst it is possible that changes in flood characteristics (frequencies and magnitudes) may lead to changes in the modelled Q-T relationship, the limited length of the POT series and the reduced sub-samples used may be an additional factor to consider.

Changes in the estimated Q-T relationships do appear to exhibit some general themes. The greatest differences (+/-20%) between the magnitude of Q_{100} estimated from the complete period of record (1954-92) and from sub-periods occur within the Spey catchment (Table 7.4, Appendix Five).

Although it is not possible to simply connect characteristics of flood indices (frequencies and magnitudes) with a specific change in the estimated Q-T relationship, some patterns are evident. For the majority of other POT records (with catchments either entirely or partly located in the west) the estimated discharge of Q_{100} increases in the latter sub-period of record. This information suggests that because of the increased frequencies and high magnitude floods, estimates of high return period flood magnitudes based on data from the 1970s onwards are higher than those based on earlier periods. Generally speaking, these series are associated with flood events triggered by Westerly and South-Westerly weather types. A possible area for future research would be to determine whether an increase in the frequency of these weather types, and a subsequent increase in floods associated with these weather types, would result in a difference in the Q-T relationship.

By contrast, a small number of POT records indicate a decrease in the estimated discharge of Q_{100} in the period since the mid 1970s. It is interesting to note that with the exception of the Kelvin record (84001), these series are derived from catchments in the north-east of Scotland, where Cyclonic weather types act as the main trigger mechanism. Any possible association between the frequency of Cyclonic weather types and the Q-T relationship needs further exploration.

The work presented in this chapter has not set out to provide a definitive piece of work on changes in flood frequency-magnitude relationships estimated for a set of rivers in Scotland, particularly when there are a number of additional complications to consider (the length of record used, the setting of discharge thresholds etc.). Rather, the aim has been to show that variability within flood characteristics may alter what is assumed to be a quasi-stationary relationship. For certain records, it is apparent that the characteristics of the flood series vary sufficiently to cause a noticeable change in the estimated Q-T relationship, and the assumption of stationarity may therefore be invalid. Under such circumstances, it may prove useful to estimate the Q-T relationship for different periods of the flood record, thus considering the range of these estimates, prior to making any direct use of flood frequency information.

7.3 FUTURE RESEARCH GOALS

The implications of flood series, and ultimately climatic, variability has been directly examined with reference to flood frequency analysis. However, in the process of detecting and describing this temporal variability, a number of new issues, which may merit further research, have been raised.

The work presented in preceding chapters has provided a very general description of the variability evident within Scottish flood records. When dealing with a combined total of over one hundred time series, depicting both annual flood frequencies and mean exceedances, the best approach is to provide generalised statements on common patterns or themes, rather than dealing with the characteristics of each individual series. Consequently, it has been possible to describe the general changes in flood indices which have occurred over the last thirty to forty years, and to make some associations between temporal and spatial variability. Although this analysis has provided a very useful introduction, it should merely act as a starting point for more in-depth analysis. I feel that the next logical step would be to reduce the analysis to the catchment scale. Consequently, by greatly reducing the number of series to be interpreted, it will be far easier to attempt an explanation of how and why individual flood series behave as they do, and similarly to explain why flood series from different sites in the same river catchment display contrasting patterns of variability.

As mentioned in chapter Six, it may also prove useful for a study to be carried out in the relationship between the Mayes record of daily weather types and a record of daily precipitation totals across Scotland. By establishing the links that exist between individual weather types and precipitation totals, distributions and intensities, and by determining how these relationships have varied through time, it may be possible to postulate stronger links between the frequencies of these weather types and the frequencies and magnitudes of Scottish flood events.

The nature of the relationship between daily synoptic weather types, precipitation totals and the incidence of flooding may be further enhanced by the introduction of a frontal component into the discussion. Wilby *et al* (1994) have assessed a procedure for quantifying the frequency and type of weather front associated with each daily Lamb weather type. If such a component were incorporated into the Mayes database, it may be possible to determine whether the frequency or type of front associated with a certain weather type has varied through time, and to establish weather the frontal component shows any direct relationship with peak flow events.

One of the most important findings of this project is the strong association between the geographical location of a gauging station and the type of weather type which is most frequently associated with causing a flood event. Not only can this be used to obtain a greater understanding of how past climatic variability has influenced the pattern of flood variability, but it could also be used for modelling and predictive purposes. If the output from General Circulation Models can be downscaled sufficiently to determine the likely changes in regional circulation patterns under future climate change scenarios (Wilby, 1994), it may be possible to predict the likely consequences upon future flood events in Scotland.

CHAPTER EIGHT

SUMMARY AND CONCLUDING REMARKS

As stated in Chapter One, the original aims of this research project were fourfold. The aim of this final chapter is simply to summarise the key findings of this project, with respect to completing the original objectives.

- **to detect and describe the level of variability within Scottish flood records, with regard to year-to-year changes in the frequencies and magnitudes of such events;**

A total of over one hundred flood frequency and flood magnitude (represented by the mean exceedance parameter) series were examined for year-to-year variability. The patterns of temporal variability were presented for individual series using a combination of simple running mean plots and more robust time series statistics. Groups of series displaying similar characteristics were then identified using cluster analysis, allowing a more generalised approach to description to be carried out.

Evidence of variability within the flood frequency series analysed were readily apparent, using two standard periods of data, 1954-92 and 1964-92. Periods of high annual flood frequencies were identified as the 1950s, 1980s and 1990s whilst the late 1960s and 1970s could clearly be characterised as 'flood-poor'. Although it was possible to make generalised statements concerning the nature of such variability, anomalies within individual time series were also identified. Patterns of variability within the flood magnitude series, measured by the mean exceedance variable, were less easy to characterise. Whilst values clearly declined during the early 1970s in many of the flood records analysed, the characteristics of magnitudes prior and subsequent to this period were less clear.

The question of spatial variability in flood frequencies and magnitudes were also explored using simple mapping techniques. Whilst the pattern of flood frequencies 1964-92 showed a possible west-east contrast (series from the easterly stations recording the most enhanced decline in frequencies during the 1970s), the spatial pattern of flood magnitude series was again less clear. The spatial distribution of flood records used was an additional hindrance to this analysis, with large areas in the north and west excluded from the project (due to the limited time span of flow records from these areas).

- **to detect and describe any variability evident within Scottish climate records;**
- **to tentatively examine the nature of any links between climate and flood series;**

Variability within the climate of Scotland was also examined, by adopting the same time series statistics and standard periods used to study flood variability. The analysis was based upon annual and seasonal frequencies of daily weather types, derived from Mayes' regional classification for Scotland.

Three of the twenty-seven individual daily weather types were found to show strong associations with flood events in Scotland: the Westerly, Cyclonic and South-Westerly types. The importance of each weather type in 'triggering' a flood event was also found to be closely associated with catchment location. Flood events occurring in westerly and south-westerly catchments were most frequently triggered by the Westerly and South-Westerly weather types whilst the Cyclonic type was found to be linked to 'triggering' flood events in the more easterly located catchments.

Variability within the frequencies of these three weather types was emphasised because of their close associations with flood events. Initial analysis revealed a degree of variability in the annual incidence of each weather type, although a seasonal breakdown of the time series identified some contrasting patterns which were being masked by the annual record. One of the more noticeable features was the dramatic increase in the frequencies (in all seasons) of the South-Westerly weather type, from the mid 1970s onwards.

Links between flood and climatic series were also tentatively explored. Whilst it was possible to make some simple qualitative links between the seasonal frequencies of weather types and the frequencies of flood events, it was more difficult to explain the variability evident within the flood magnitudes with reference to these weather types. This is an area where an extensive amount of additional research is required.

- **to examine the possible effects of variability with flood records upon standard techniques of flood frequency analysis.**

The final part of this project examined the possible effects of variability with flood series upon current techniques of flood frequency analysis. This question was addressed by comparing the frequency-magnitude relationships estimated for distinct sub-periods of a flood record. Although this was largely a process of experimentation, the results clearly show that frequency-magnitude relationships are very much dependent upon the period of record used (and indeed the hydrological characteristics) used in the estimation process. This analysis suggests that a 'range' of frequency-magnitude relationships will exist within a flood series, rather than a static relationship. It is extremely important to be aware of this variability when techniques of flood frequency analysis are being used.

In terms of practical advice to the hydrologist or engineer, a number of recommendations can be made in the light of these results. However, the extent to which these guidelines are followed is very much dependant upon the desired accuracy of the estimated frequency - magnitude relationship.

- In order to gain an in-depth understanding of how flood characteristics vary through time within a particular river catchment, time series analysis is required. Even if techniques such as the Mann's trend test are not available or not favoured, simple techniques such as running mean plots and sub-period statistics can provide a valuable insight into changing flood characteristics. Such statistics may be used on either POT or AM series (although in the latter case, only changes in flood magnitudes can be examined).

- Additionally, information on the links between flood events and daily weather types may prove useful in flood frequency analysis (and even in flood forecasting), using the techniques described in Chapter Six.

Incorporating either or both of these two steps may indeed enhance the process of flood frequency analysis. Using some of the techniques described in Chapter Seven, the first step may allow a flood series to be subjectively split into distinct hydrological sub-periods, which subsequently allows an exploration of how frequency - magnitude relationships have varied through time. This can only add to the understanding of how such estimations are dependent upon the characteristics of the period of record used.

Similarly, if the second guideline reveals a flood series to be linked to two or more key weather types, it may also be worthwhile treating the series as a multiple component distribution. In such a situation, the possibility arises that the estimated frequency - magnitude relationship varies according to the weather type 'triggering' the flood event. By splitting the flood series into Cyclonic floods and Westerly floods, for example, and modelling their frequency - magnitude relationships separately, it will be clear whether this is an additional factor for consideration.

In summary, therefore, the key to enhancing the process of flood frequency analysis is experimentation. By carrying out the steps recommended above, at the very least a greater understanding of the factors controlling the characteristics of a flood series will be acquired. Additionally, this analysis may increase awareness of how (and why) frequency - magnitudes relationships vary through time such that they may be treated as dynamic relationships rather than static ones.

In the final concluding stages of this research project, it is perhaps worth stepping back from the regional scale and examining how these findings may be enhanced, particularly with a global context.

A number of studies world-wide, notable in Europe and North America, have examined the relationship between climate and runoff variability. It is indeed a popular research topic. However, as opposed to linking flow characteristics to the weather conditions within a restricted geographical frame (Scotland or the British Isles, for example), emphasis has been placed upon making associations with large scale circulation patterns.

Waylen and Caviedes (1990) have examined the influence of the El Nino Southern Oscillation (ENSO) upon precipitation and streamflow in Chile, with some significant results. It is extremely interesting to note that the warm El Nino phase not only has a significant relationship with increased winter precipitation but that the likelihood of a rain or rain-on-snow induced flood increases in the succeeding year as does the size of the spring snowmelt.

A similar study in the United States (Dracup and Kahya, 1994) has also indicated that a strong relationship exists between both cold and warm phases of ENSO and streamflow. This research has also confirmed that the effect of either phases is strongest in the second half of the event year or in the subsequent year.

Whilst Chile and the United States are geographically remote from Scotland, the effect of ENSO has also been examined closer to home, in Europe with a significant link between ENSO and precipitation, pressure and temperature anomalies being made (Fraedrich and Muller, 1992). Both the warm and cold phases of ENSO have been shown to have positive links with European climatic anomalies. The exact nature of these links is dependent upon geographical location, which is, in turn, related the dominant Cyclonic storm tracks. During warm events, a negative pressure anomaly indicates enhanced (more frequent and / or more intense) cyclonic activity across central Europe. The response in Scotland appears to be increased precipitation. During cold events, the dominant cyclone track moves further north, resulting in below average precipitation in Scotland.

These results are extremely interesting, and indeed suggest that the framework for a study of Scottish flood events could be justifiably increased to incorporate the effect of global circulation patterns. The research of Fraedrich and Muller (1992) does suggest that a global phenomenon such as ENSO can have repercussions on a very large scale. The work carried out in Chile and the United States also indicates that such events are likely to have a direct influence upon streamflow (and indeed flood) behaviour. This is an avenue which needs further exploration in Scotland, but one which may add to the understanding of the patterns of flood and climate variability described here.

A number of other studies (Cayan *et al*, 1993; Ely *at al*, 1994) have directly examined the relationship between anomalous atmospheric circulation patterns and flood events. In addition to revealing how the characteristics of climate anomalies - such as the intensity of pressure systems and their locations - affect runoff events, smaller scale catchment characteristics have been found to be an additional consideration. Cayan *et al* (1993) found that low elevation, relatively warm catchments, where snow had little influence on flow events, have very little 'memory' in terms of the prior season's characteristics and variability, whilst higher altitude and subsequently cooler catchments (where snowmelt is a dominant factor) have a longer 'memory' and can still exhibit the influence of the previous seasons climatic characteristics. This is a factor which could arguably be seen to influence flood characteristics in Scotland.

The one over-riding factor to emerge from these studies is that, although pressure patterns at the regional scale are a good starting point from which to examine climatic and subsequently runoff variability, they are unlikely to provide a complete answer to any research questions. At some point, two additional directions need to be taken:

- to explore climatic characteristics and anomalies on a larger scale; this may begin by looking at European climatic characteristics but should not exclude climatic events throughout the world; this may even help to explain why the pattern of regional weather type frequencies in Scotland (such as the increase in the South-Westerly weather type) occur as they do;
- to explore the effect of climatic variability on a much smaller scale; since it has been shown that catchment characteristics (elevation, temperature etc.) can interact with large scale climatic fluctuation to influence their effect upon runoff characteristics.

It is clear from this summary statement that the four key research aims have been addressed during the evolution of this project. However, in the process of fulfilling these key research objectives, a number of new issues and questions have been raised.

There is, therefore, scope for additional research to be carried in future, and in particular a great deal more work is required if we are to acquire a more detailed and deeper understanding of the relationship between the climate (at both the global and regional scales) and the Scottish flood record.

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TEMPORAL VARIABILITY OF FLOODING IN SCOTTISH RIVERS

Volume Two

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A thesis submitted for the
Degree of Doctor of Philosophy
at the University of St Andrews

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School of Geography and Geology
University of St Andrews
February 1996

LIST OF APPENDICES

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APPENDIX ONE

Table 3.1: List of all POT records

STATION NUMBER AND NAME	PERIOD OF RECORD	DATA SUBSETS
02001 Helmsdale @ Kilphedir	1975-92	A
03002 Carron @ Sgodachail	1974-92	A, B
03003 Oykel @ Easter Turnaig	1978-92 *	A
03801 Cassley @ Duchally	1951-58	
03803 Tirry @Rhian Bridge	1951-57	
03901 Shin @ Lairg	1951-56	
04001 Conon @ Moy Bridge	1948-56	
04003 Alness @ Alness	1974-92	A, B
05901 Beauly @ Erchless	1950-62	
06007 Ness @ Ness-side	1974-92	A, B
06008 Enrick @ Mill of Tore	1980-92 *	A
06903 Moriston @ Invermoriston	1931-43	
07001 Findhorn @ Shenachie	1961-92	A, B, C
07002 Findhorn @ Forres	1959-92	A, B, C
07003 Lossie @ Sheriffmills	1959-92	A, B, C
08004 Avon @ Delnashaugh	1953-92 *	A, B, C, D
08005 Spey @ Boat @ of Garten	1952-92	A, B, C, D
08006 Spey @ Boat@ of Brig	1953-92 *	A, B, C, D
08007 Spey @ Invertruim	1953-92	A, B, C, D
08009 Dulnain @ Balnaan Bridge	1953-92	A, B, C, D
08010 Spey @ Grantown	1952-92	A, B, C, D
08903 Spey @ Ruthven Bridge	1952-74	
09001 Deveron @ Avochie	1960-92 *	A, B, C
09002 Deveron @ Muiresk	1961-92	A, B, C
09003 Isla @ Grange	1960-92	A, B, C
10001 Ythan @ Ardlethan	1940-84	
10002 Ugie @ Inverugie	1972-92	A, B

KEY

Subset A	Period 1984 - 92
Subset B	Period 1974 - 92
Subset C	Period 1964 - 92
Subset D	Period 1954 - 92
Subset E	Period 1944 - 92

* denotes the absence of a standardised threshold

A - Period 1984 - 92
B - Period 1974 - 92
C - Period 1964 - 92
D - Period 1954 - 92
E - Period 1944 - 92

Table 3.1(cont): List of all POT records

STATION NUMBER AND NAME	PERIOD OF RECORD
11001 Don @ Parkhill	1970-92
11002 Don @ Haughton	1972-92
11003 Don @ Bridge of Alford	1974-92
12001 Dee @ Woodend	1934-92
12002 Dee @ Park	1974-92
12003 Dee @ Polhollick	1976-92
14001 Eden @ Kemback	1968-92
15003 Tay @ Caputh	1952-92
15006 Tay @ Ballathie	1953-92
15007 Tay @ Pitnacree	1952-92
15008 Dean Water @ Cookston	1954-92
15010 Isla @ Wester Cardean	1972-92
15016 Tay @ Kenmore	1975-92
16001 Earn @ Kinkell Bridge	1949-92
16003 Ruchill Water @ Cultybraggan	1960-92
16004 Earn @ Forteviot	1974-92
17001 Carron @ Headswood	1969-92
17005 Avon @ Polmonthill	1971-92
18001 Allan @ Kinbuck	1958-82
18002 Devon @ Glenochil	1957-92
18005 Allan Water @ Bridge of Allan	1972-92
18008 Leny @ Anie	1974-92
19001 Almond @ Craigiehall	1957-92
19002 Almond @ Almond Weir	1962-92
19003 Breich Water @ Breich Weir	1962-79
19004 North Esk @ Dalmore Weir	1962-92
19006 Water of Leith @ Murrayfield	1963-92

* denotes the absence of a standardised threshold

A - Period 1984 - 92

B - Period 1974 - 92

C - Period 1964 - 92

D - Period 1954 - 92

E - Period 1944 - 92

DATA SUBSETS

A, B
A, B
A, B
A, B, C, D, E
A, B
A
A, B
A, B, C, D
A, B, C, D
A, B, C, D
A, B, C, D
A, B
A
A, B, C, D
A, B, C
A, B
A, B
A, B

A, B, C
A, B
A, B
A, B, C
A, B, C

A, B, C
A, B, C

Table 3.1(cont): List of all POT records

STATION NUMBER AND NAME	PERIOD OF RECORD
19007 Esk @ Musselburgh	1962-92
19008 South Esk @ Prestonholme	1964-89
19011 North Esk @ Dalkeith Palace	1963-92
20001 Tyne @ East Linton	1959-92
20002 West Peffer Burn @ Luffness	1966-92
20003 Tyne @ Spilmersford	1963-92 *
20005 Birns Water @ Saltoun Hall	1963-92
20006 Biel Water @ Beltoun Hall	1972-92
20007 Gifford Water @ Lennoxlove	1974-92
21002 Whitadder @ Hungry Snout	1959-67
21003 Tweed @ Peebles	1949-92 *
21005 Tweed @ Lyne Ford	1962-92 *
21006 Tweed @ Boleside	1962-92 *
21007 Ettrick water @ Lindean	1962-92
21008 Teviot @ Ormiston Mill	1961-92
21009 Tweed @ Norham	1960-92
21010 Tweed @ Dryburgh	1950-82
21011 Yarrow Water @ Philiphaugh	1963-92 *
21012 Teviot @ Hawick	1964-92
21013 Gala Water @ Galashiels	1964-92 *
21015 Leader Water @ Earlston	1967-92
21016 Eye Water @ Eyemouth Mill	1968-92
21017 Ettrick Water @ Brockhoperig	1966-92 *
21018 Lyne Water @ Lyne Station	1969-92 *
21019 Manor Water @ Cademuir	1969-92
21020 Yarrow Water @ Gordon Arms	1968-92 *
21021 Tweed @ Sprouston	1970-92 *

* denotes the absence of a standardised threshold

A - Period 1984 - 92

B - Period 1974 - 92

C - Period 1964 - 92

D - Period 1954 - 92

E - Period 1944 - 92

DATA SUBSETS

A, B, C

A, B, C
A, B, C
A, B
A, B, C
A, B, C
A, B
A, B

A, B, C, D
A, B, C
A, B, C
A, B, C
A, B, C
A, B, C

A, B, C
A, B, C
A, B, C
A, B
A, B
A, B
A, B
A, B
A, B
A, B

Table 3.1(cont): List of all POT records

STATION NUMBER AND NAME	PERIOD OF RECORD	DATA SUBSETS
21025 Ale Water @ Ancrum	1974-92	A, B
21026 Tima Water @ Deephope	1974-92	A, B
21027 Blackadder @ Mouthbridge	1974-92 *	A, B
21030 Megget Water @ Henderland	1969-81 *	
21034 Yarrow Water @ Craigdouglas	1969-92	A, B
77003 Liddel Water @ Rowanburnfoot	1974-92 *	A, B
78003 Annan @ Brydekirk	1968-92	A, B
78004 Kinell Water @ Redhall	1967-92	A, B
78005 Kinell Water @ Bridgemuir	1979-92	A, B
79002 Nith @ Friar's Carse	1958-92 *	A, B, C
79003 Nith @ Hall Bridge	1960-92	A, B, C
79004 Scar Water @ Capenoch	1964-92	A, B, C
79005 Cluden Water @ Fiddler's Ford	1964-92	A, B, C
79006 Nith @ Drumlanrig	1968-92	A, B
80001 Urr @ Dalbeattie	1964-92	A, B, C
80003 White Laggan @ Loch Dee	1981-92 *	A
81002 Cree @ Newton Stewart	1964-92	A, B, C
81003 Luce @ Airyhemming	1967-92	A, B
82001 Girvan @ Robstone	1964-92	A, B, C
82003 Stinchar @ Balnowlart	1975-92 *	A
83002 Garock @ Dalry	1961-69	
83004 Lugar @ Langholm	1974-92 *	A, B
83005 Irvine @ Shewalton	1974-92	A, B
83802 Irvine @ Glenfield	1914-88	
83006 Ayr @ Mainholm	1976-92	A, B
84001 Kelvin @ Killermont	1949-92 *	A, B, C, D
84003 Clyde @ Hazelbank	1956-92	A, B, C

* denotes the absence of a standardised threshold

A - Period 1984 - 92

B - Period 1974 - 92

C - Period 1964 - 92

D - Period 1954 - 92

E - Period 1944 - 92

Table 3.1(cont): List of all POT records

STATION NUMBER AND NAME	PERIOD OF RECORD	DATA SUBSETS
84004 Clyde @ Sills	1956-92	A, B, C
84005 Cylde @ Blairston	1956-92	A, B, C
84007 South Calder water @ Forgewood	1967-92	A, B
84011 Gryfe @ Craigend	1964-92 *	A, B, C
84012 White Cart Water @ Hawkhead	1964-92	A, B, C
84014 Avon water @ Fairholm	1965-92	A, B
84019 North Calder Water @ Calderpark	1964-92 *	A, B, C
84806 Clyde @ Cambusnethan	1956-63	
86001 Little eachaig @ Dalinlongart	1968-92	A, B
87801 Allt Uaine @ Loch Sloy Intake	1951-71	
91802 Allt Leachdach @ Intake	1939-80	
96001 Halladale @ Halladale	1975-92	A
96002 Naver @ Apigill	1978-92	A
97002 Thurso @ Halkirk	1972-92	A, B

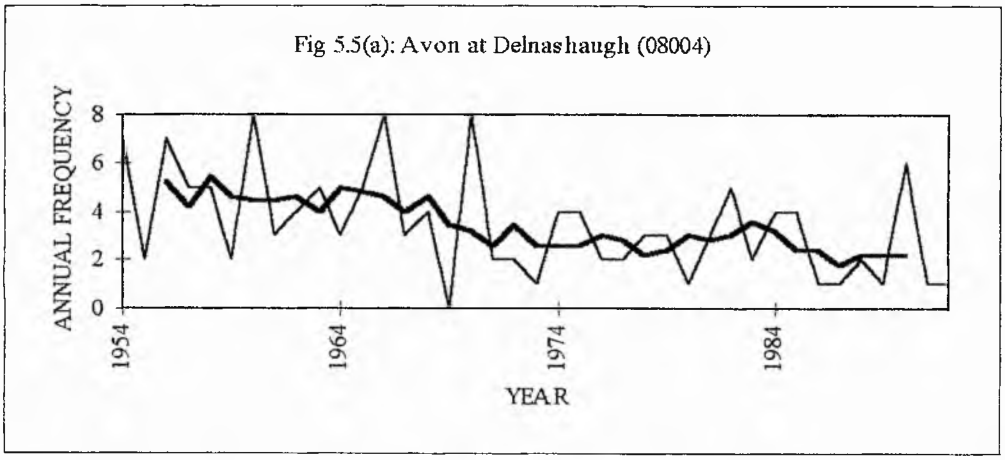
* denotes the absence of a standardised threshold

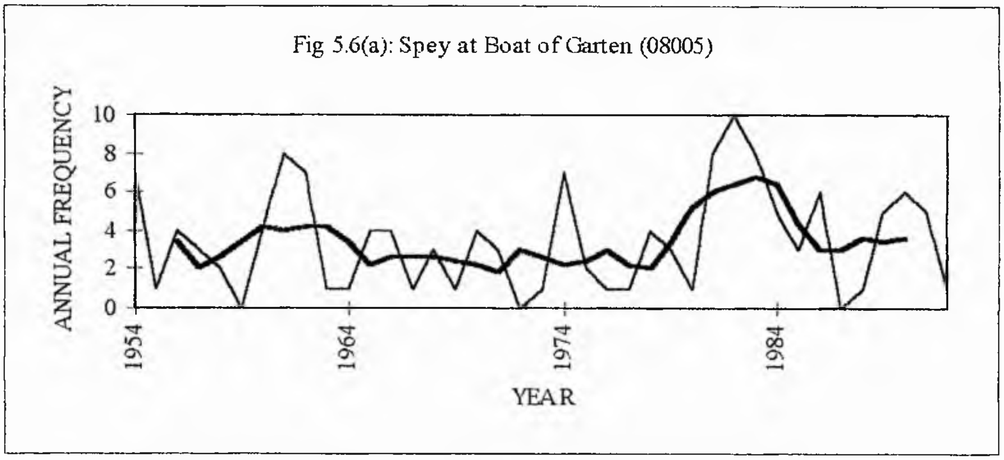
A - Period 1984 - 92
B - Period 1974 - 92
C - Period 1964 - 92
D - Period 1954 - 92
E - Period 1944 - 92

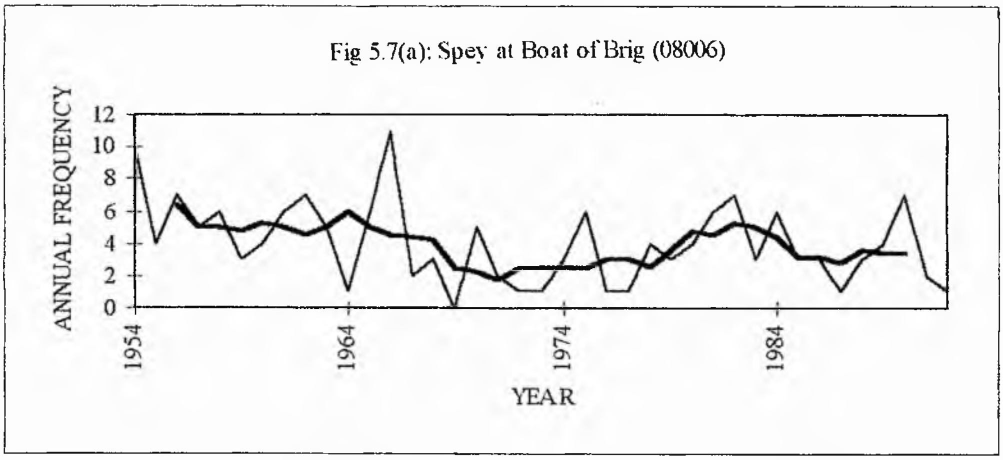
APPENDIX TWO

Appendix Two

Figures 5.5(a)-5.7(a)
Flood Frequency Series 1954-92: Annual Frequencies and a Five-Year Running Mean







Appendix Two

Figures 5.8(a)-5.10(a)
Flood Frequency Series 1954-92: Annual Frequencies and a Five-Year Running Mean

Fig 5.8(a): Spey at Invertruim (08007)

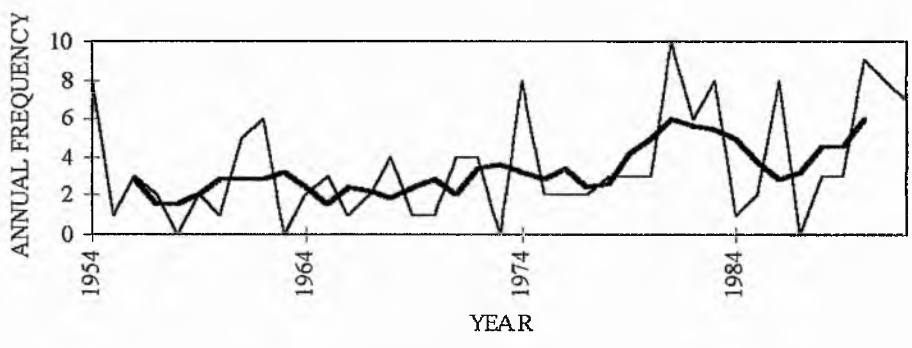


Fig 5.9(a): Dulnain at Balnaan Bridge (08009)

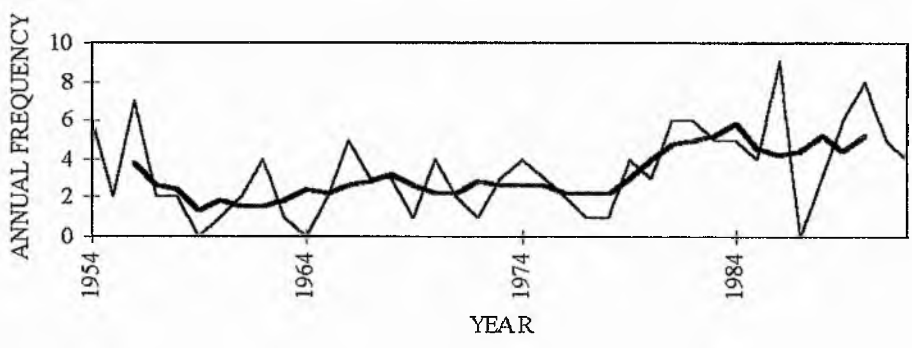
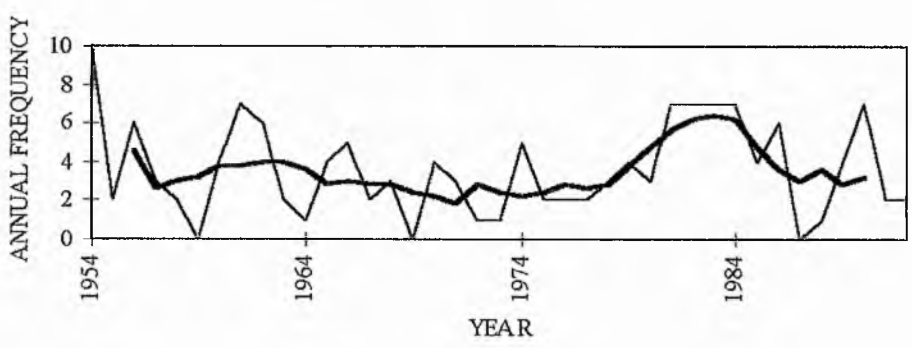


Fig 5.10(a): Spey at Grantown (08010)



Appendix Two

Figures 5.11(a)-5.13(a)
Flood Frequency Series 1954-92: Annual Frequencies and a Five-Year Running Mean

Fig 5.11(a): Dee at Woodend (12001)

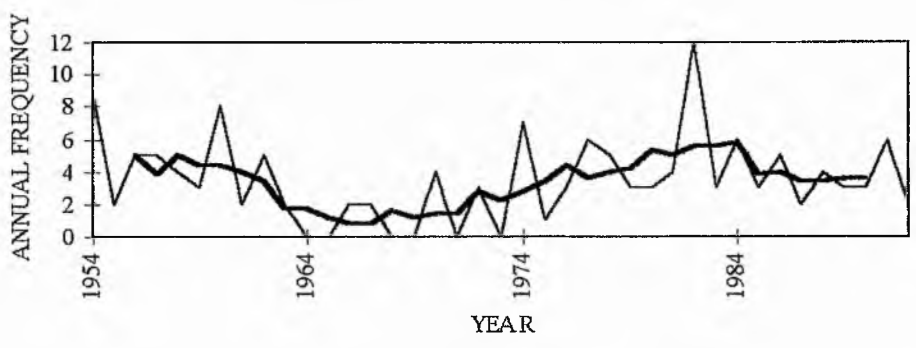


Fig 5.12(a):Tay at Caputh (15003)

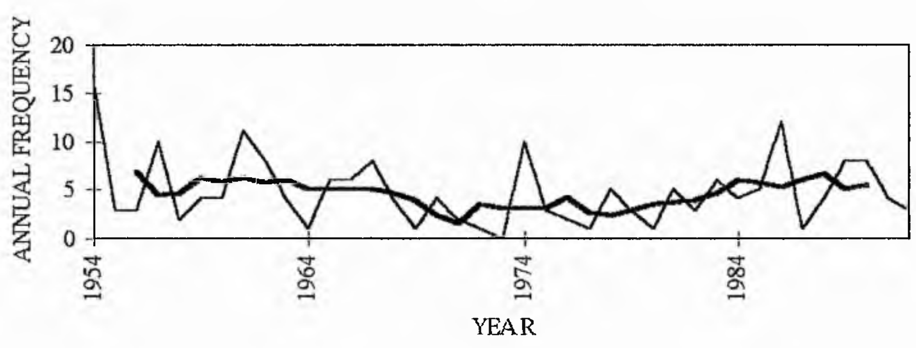
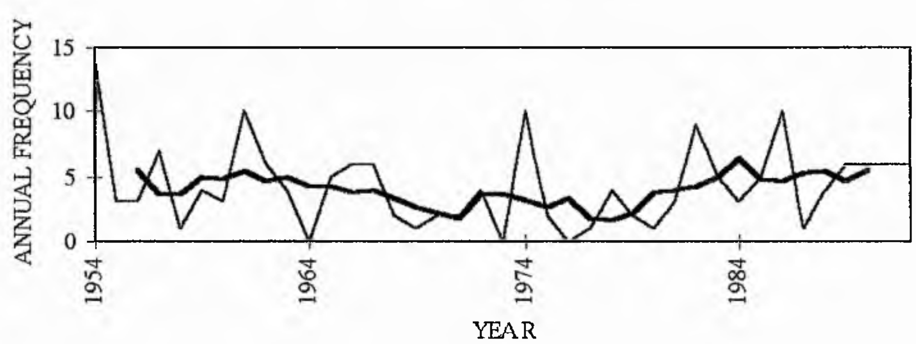


Fig 5.13(a): Tay at Ballathie (15006)



Appendix Two

Figures 5.14(a)-5.16(a)
Flood Frequency Series 1954-92: Annual Frequencies and a Five-Year Running Mean

Fig 5.14(a): Tay at Pitnacree (15007)

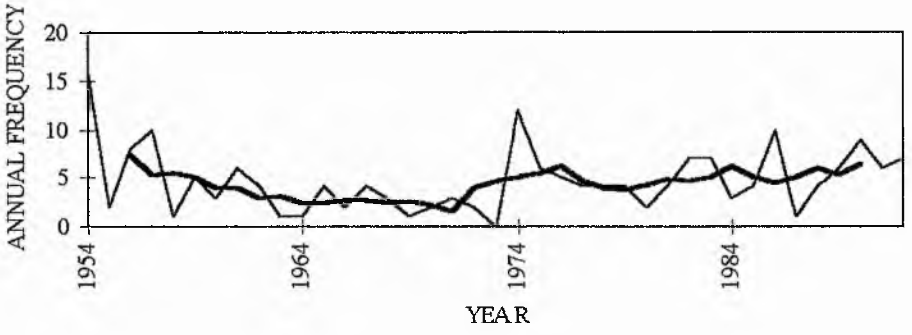


Fig 5.15(a): Dean Water at Cookston (15008)

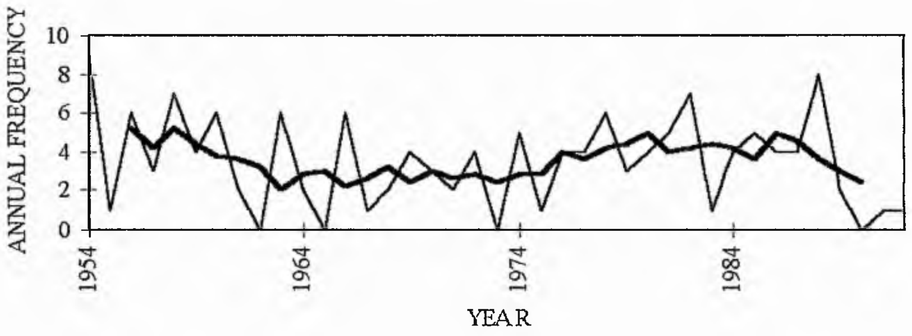
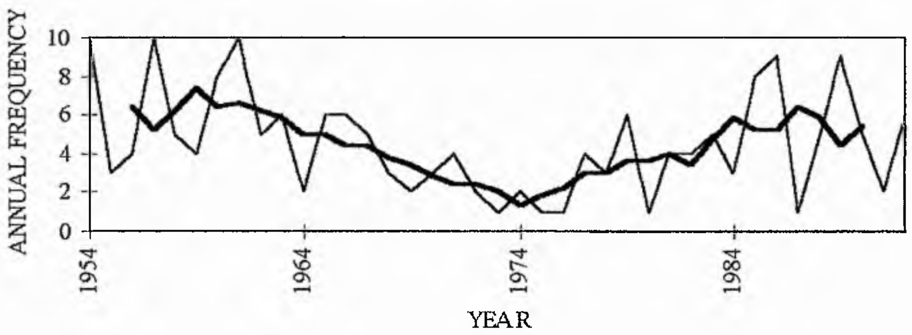
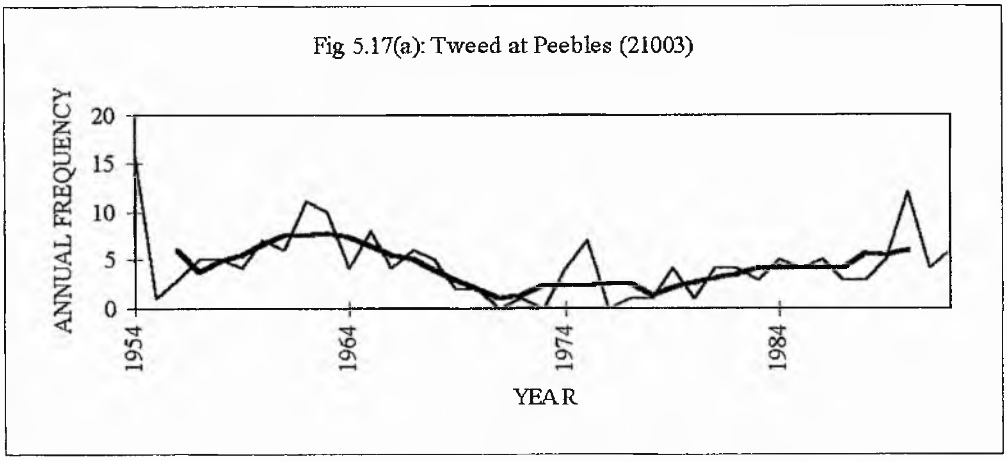


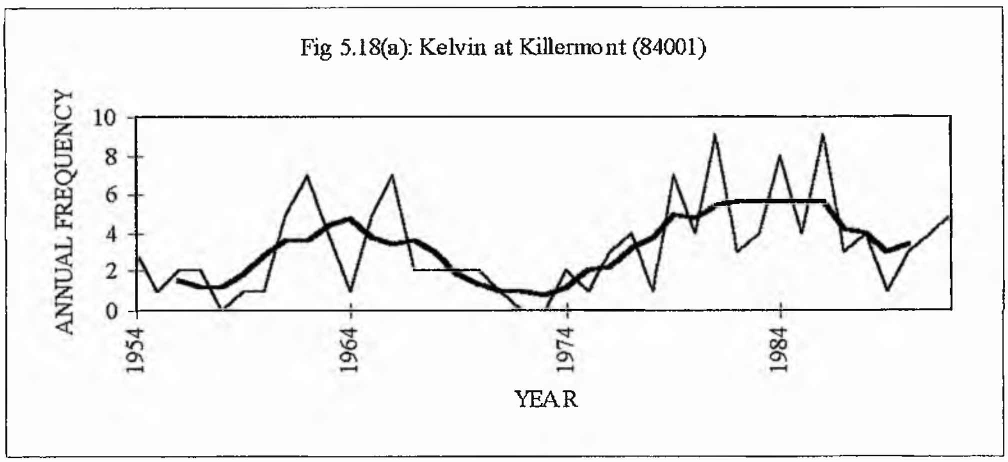
Fig 5.16(a): Earn at Kinkell Bridge (16001)



Appendix Two

Figures 5.17(a)-5.18(a)
Flood Frequency Series 1954-92: Annual Frequencies and a Five-Year Running Mean





Appendix Two

Figures 5.5(b)-5.7(b)
Mann's Test for Trend in the Mean: Flood Frequency Series 1954-92

Fig 5.5(b): Avon at Delnashaugh (08004)

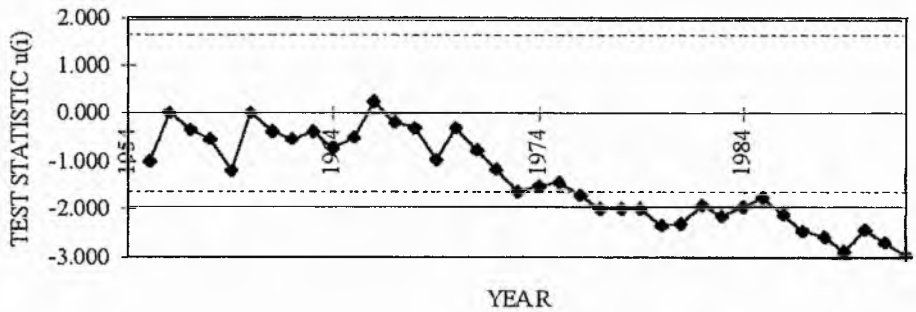


Fig 5.6(b): Spey at Boat of Garten (08005)

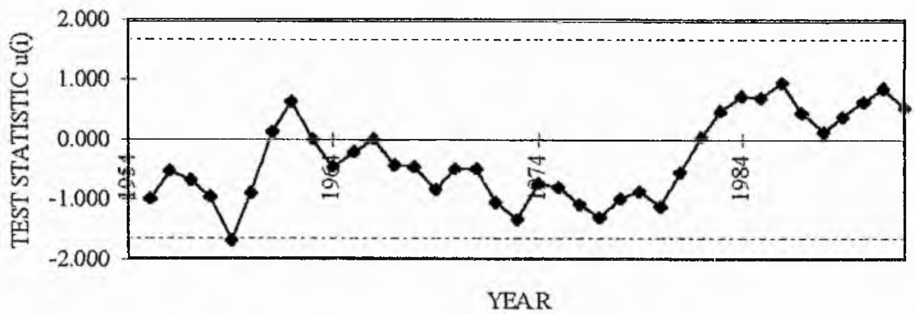
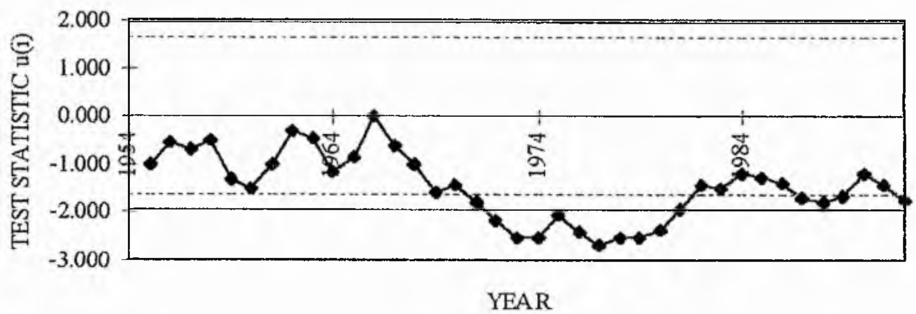
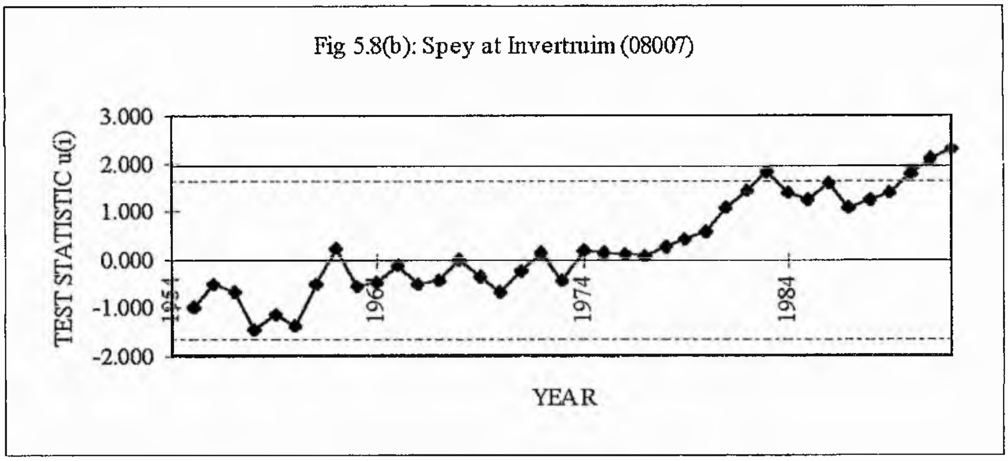


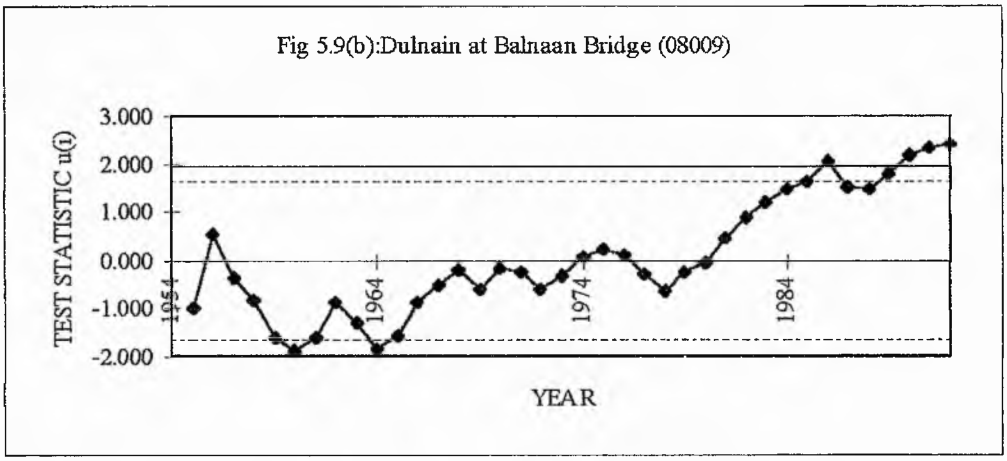
Fig 5.7(b) Spey at Boat of Brig (08006)

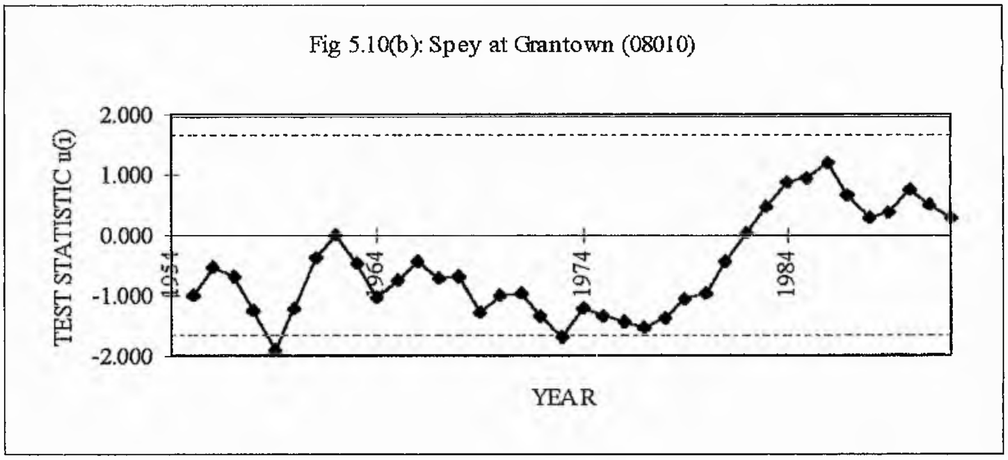


Appendix Two

Figures 5.8(b)-5.10(b)
Mann's Test for Trend in the Mean: Flood Frequency Series 1954-92

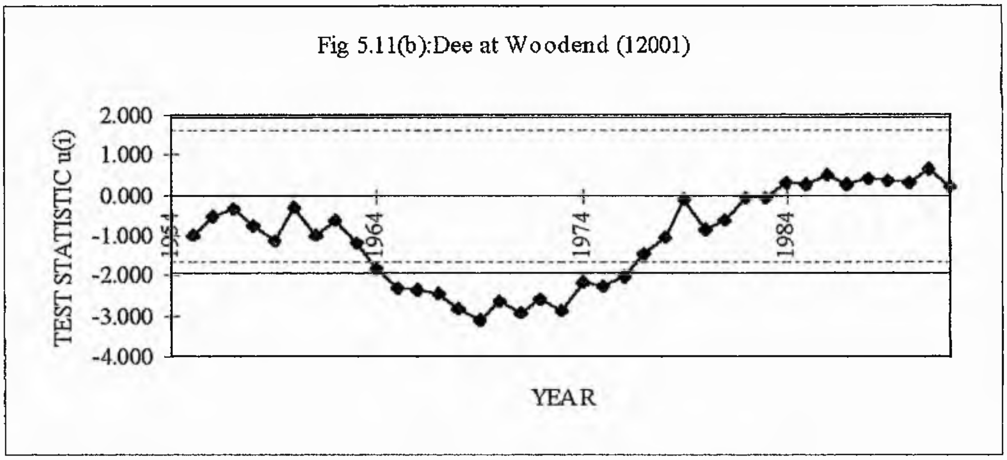


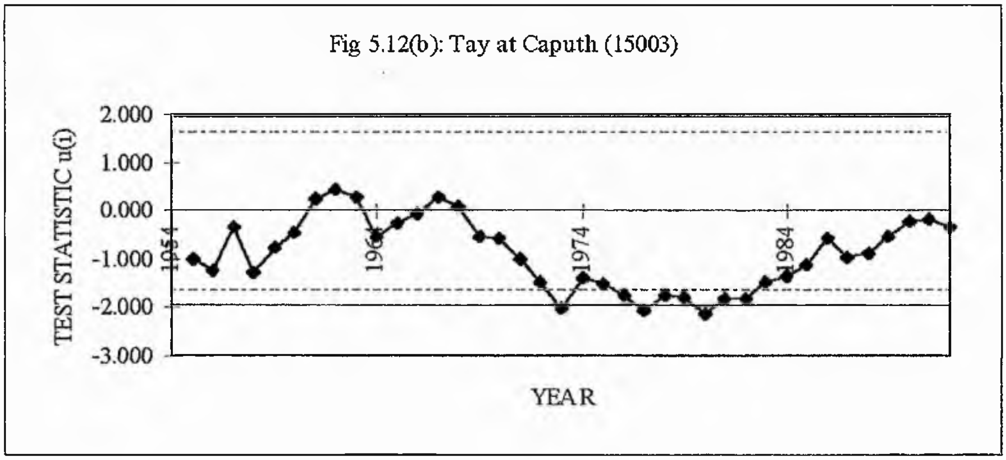


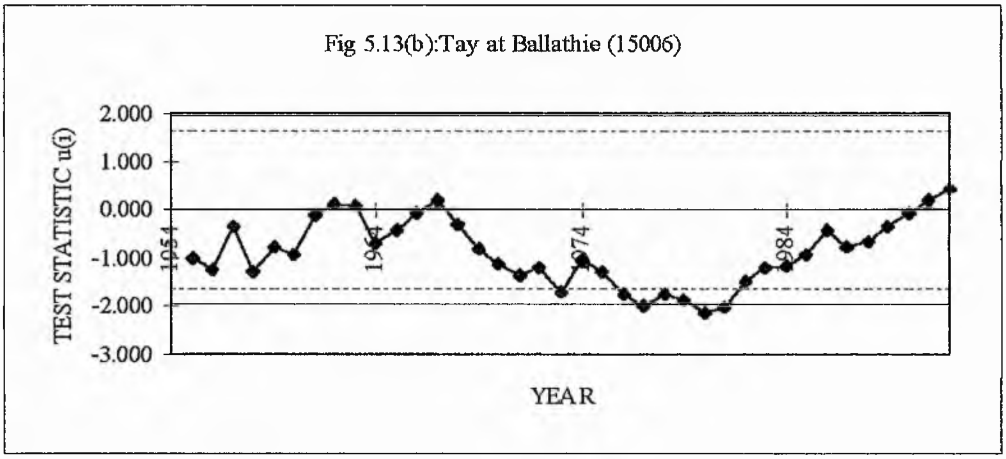


Appendix Two

Figures 5.11(b)-5.13(b)
Mann's Test for Trend in the Mean: Flood Frequency Series 1954-92







Appendix Two

Figures 5.14(b)-5.16(b)
Mann's Test for Trend in the Mean: Flood Frequency Series 1954-92

Fig 5.14(b): Tay at Pitnacree (15007)

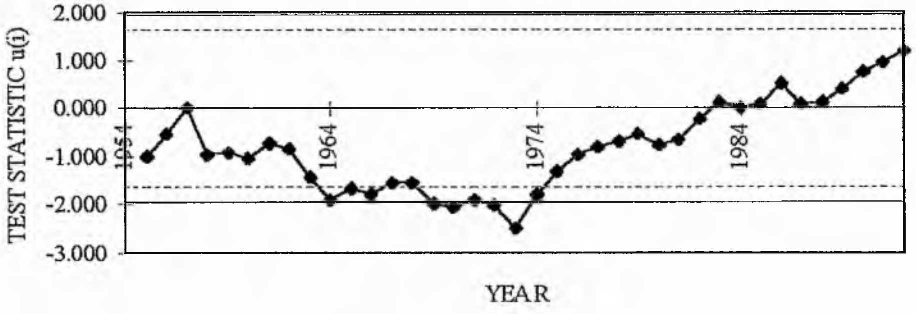


Fig 5.15(b): Dean Water at Cookston (15008)

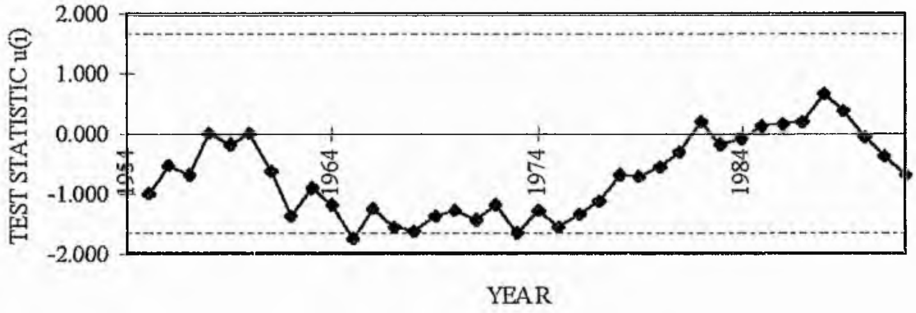
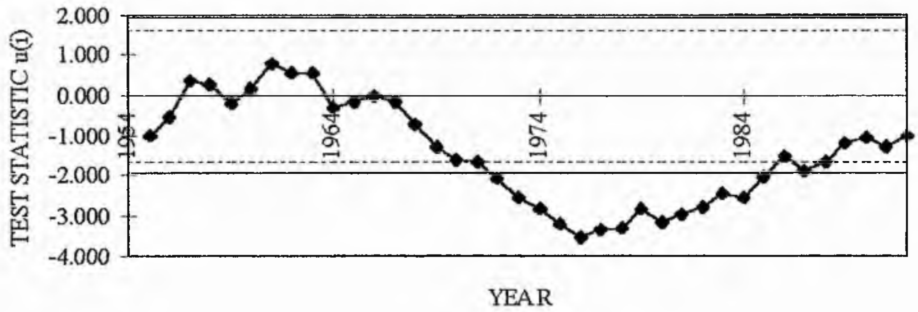
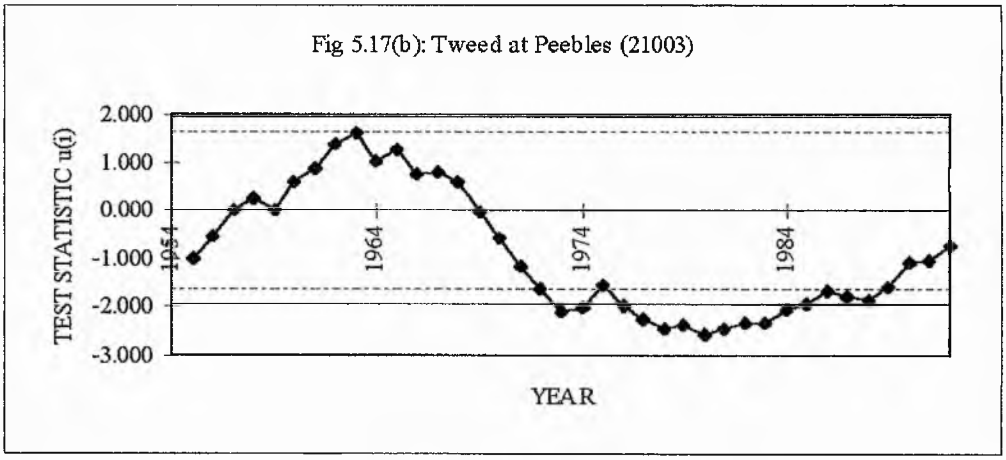


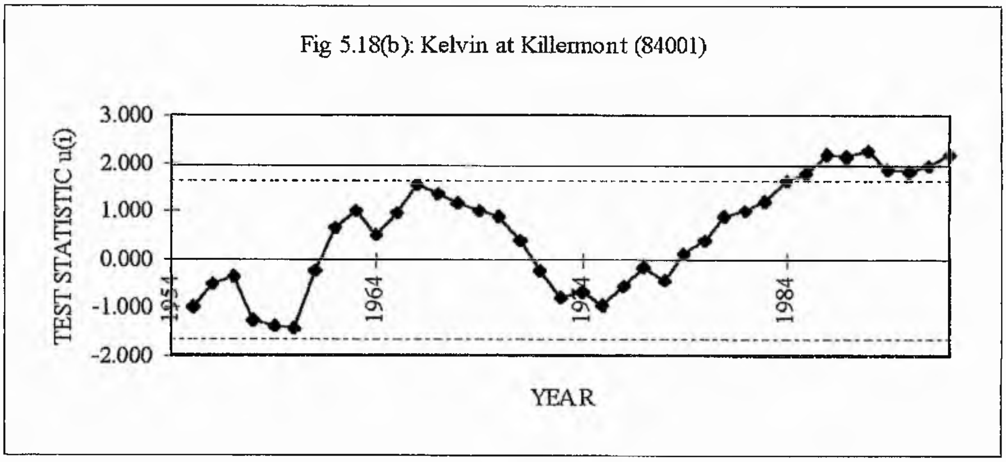
Fig 5.16(b): Earn at Kinkell Bridge (16001)



Appendix Two

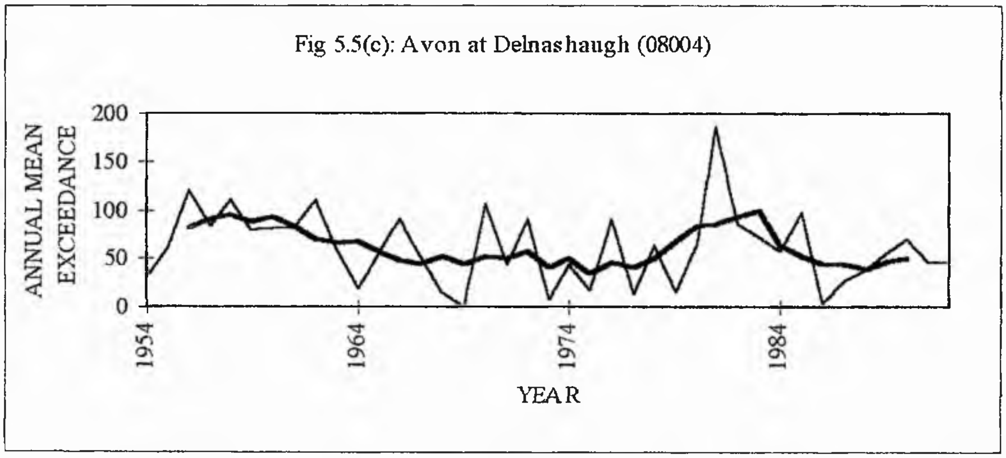
Figures 5.17(b)-5.18(b)
Mann's Test for Trend in the Mean: Flood Frequency Series 1954-92

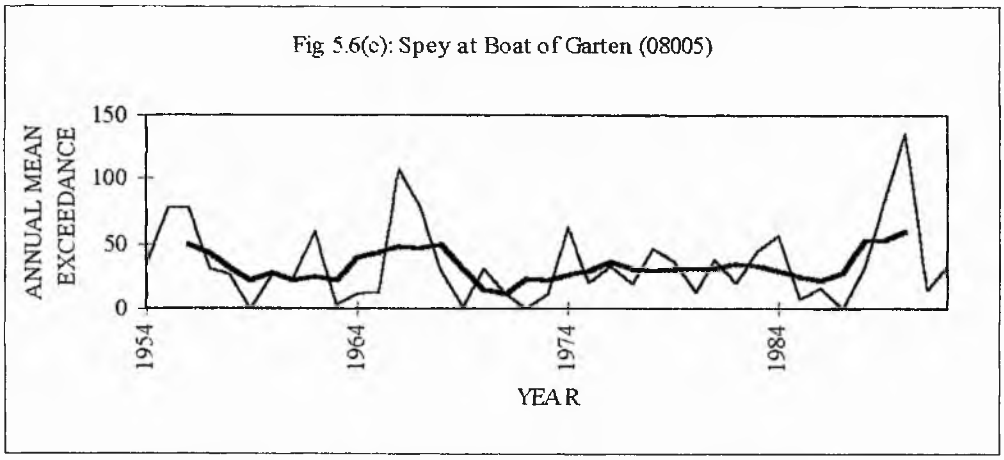


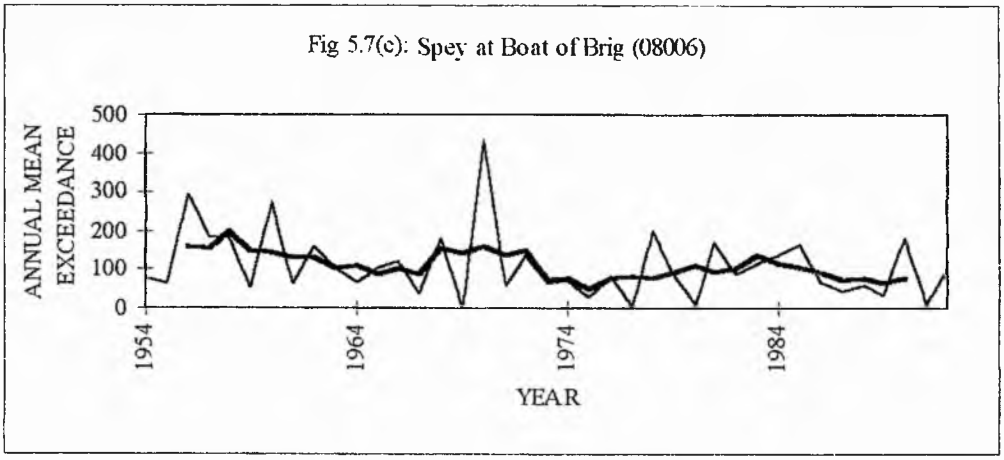


Appendix Two

Figures 5.5(c)-5.7(c)
Flood Magnitude Series 1954-92: Annual Mean Exceedances and a Five-Year Running Mean







Appendix Two

Figures 5.8(c)-5.10(c)
Flood Magnitude Series 1954-92: Annual Mean Exceedances and a Five-Year Running Mean

Fig 5.8(c): Spey at Invertruim (08007)

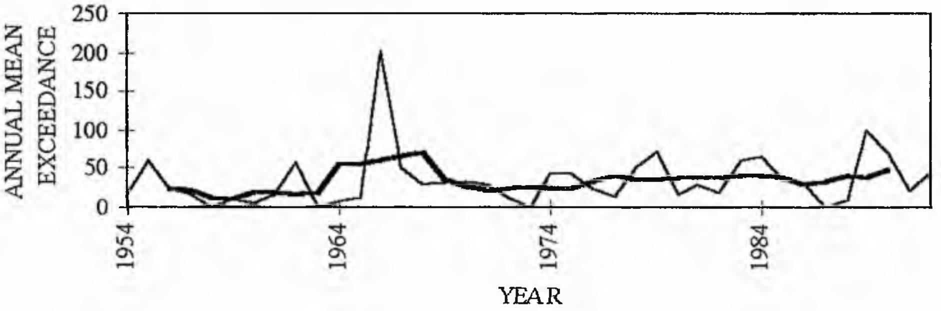


Fig 5.9(c): Dulnain at Balnaan Bridge (08009)

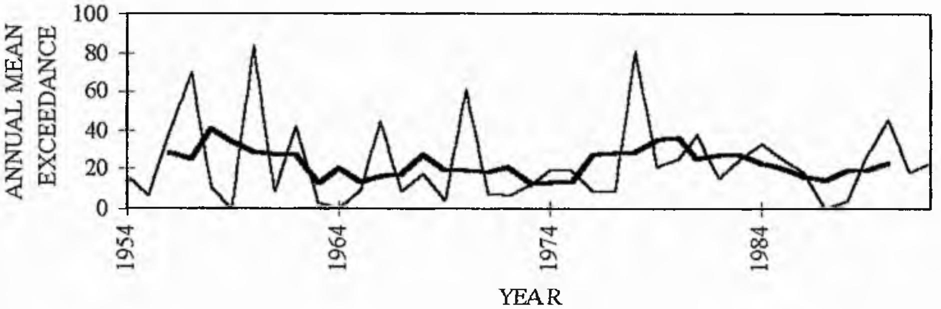
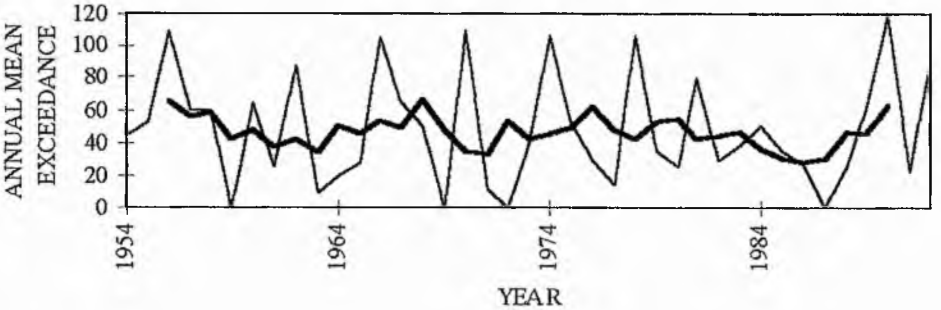
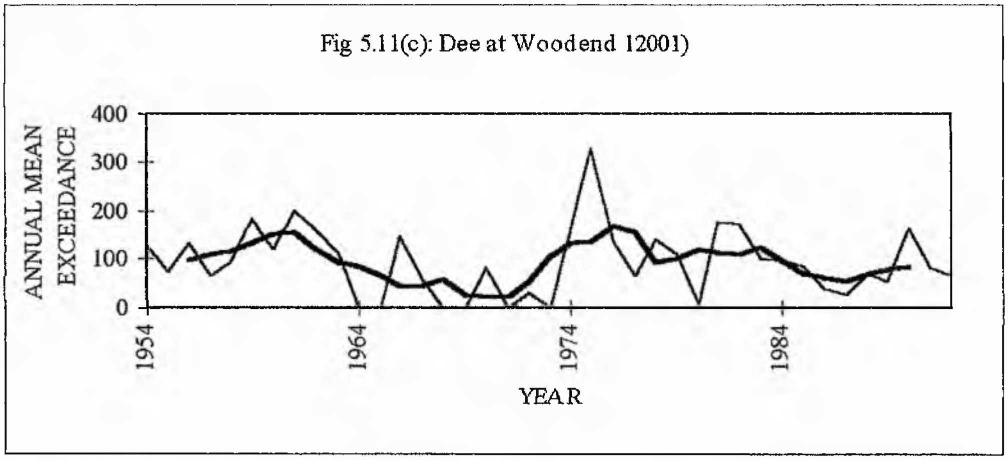


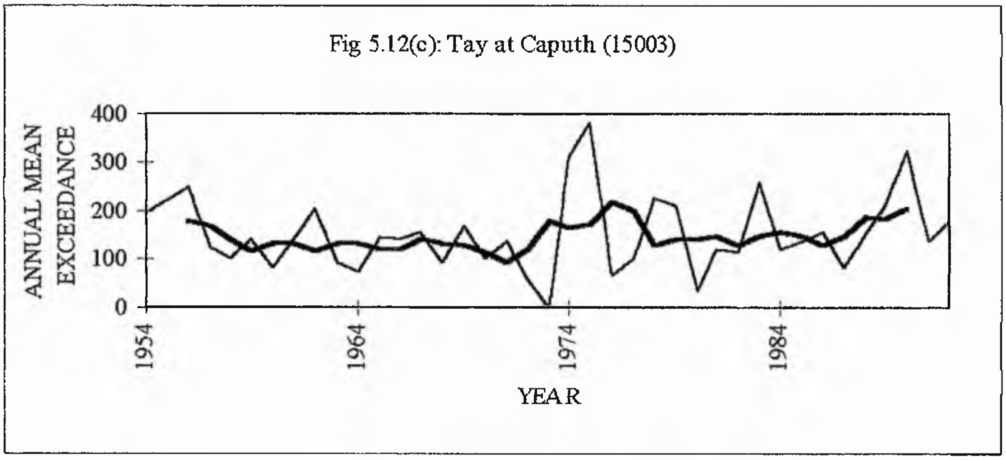
Fig 5.10(c): Spey at Grantown (08010)

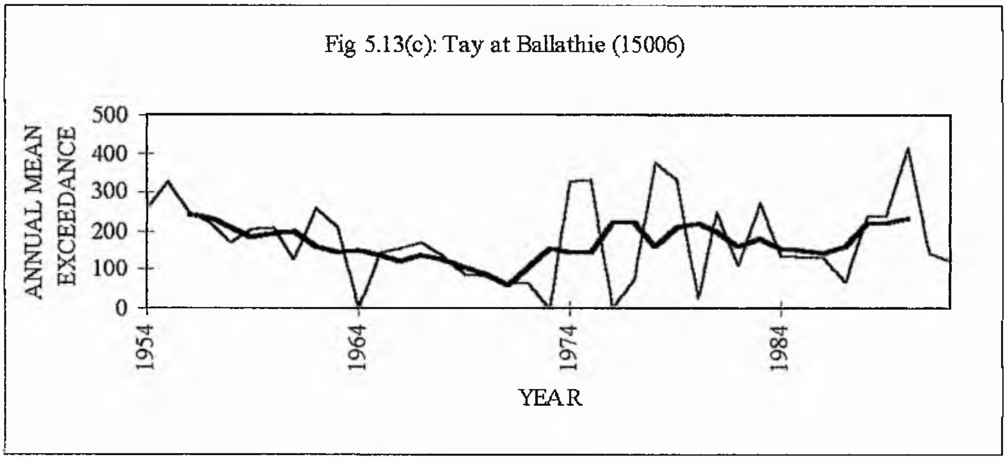


Appendix Two

Figures 5.11(c)-5.13(c)
Flood Magnitude Series 1954-92: Annual Mean Exceedances and a Five-Year Running Mean

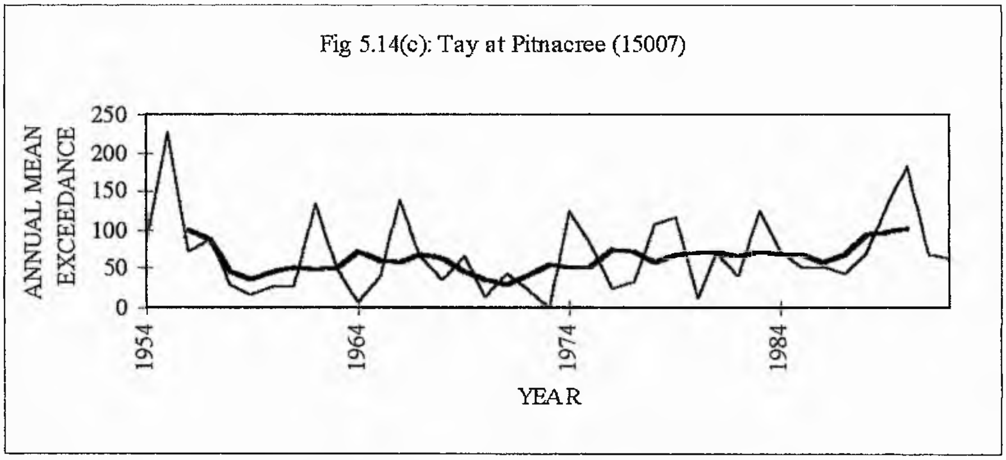


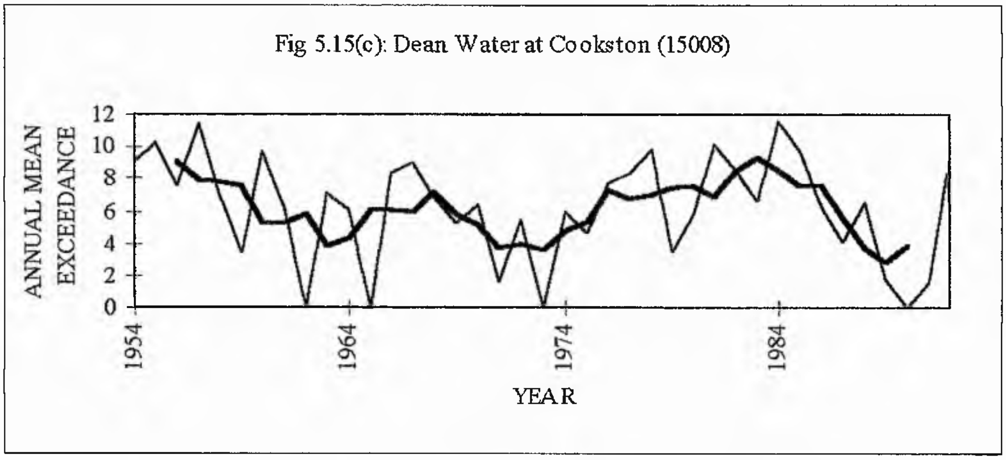


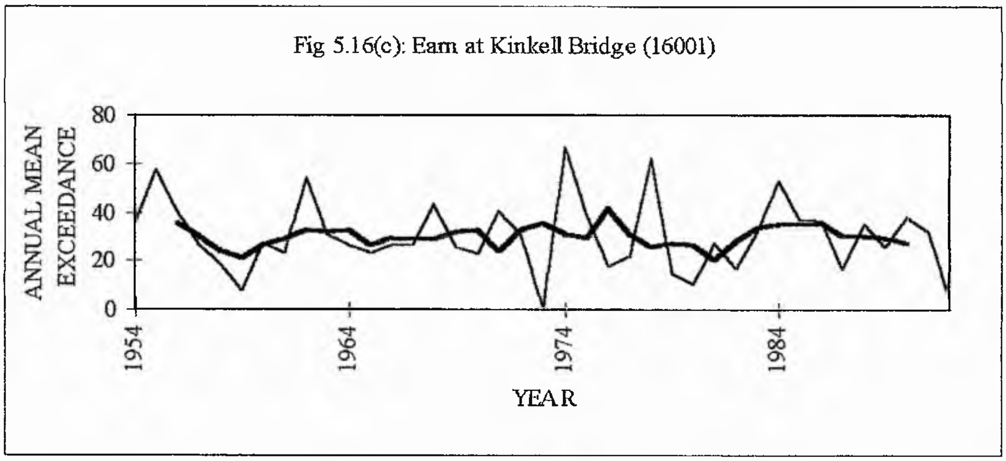


Appendix Two

Figures 5.14(c)-5.16(c)
Flood Magnitude Series 1954-92: Annual Mean Exceedances and a Five-Year Running Mean

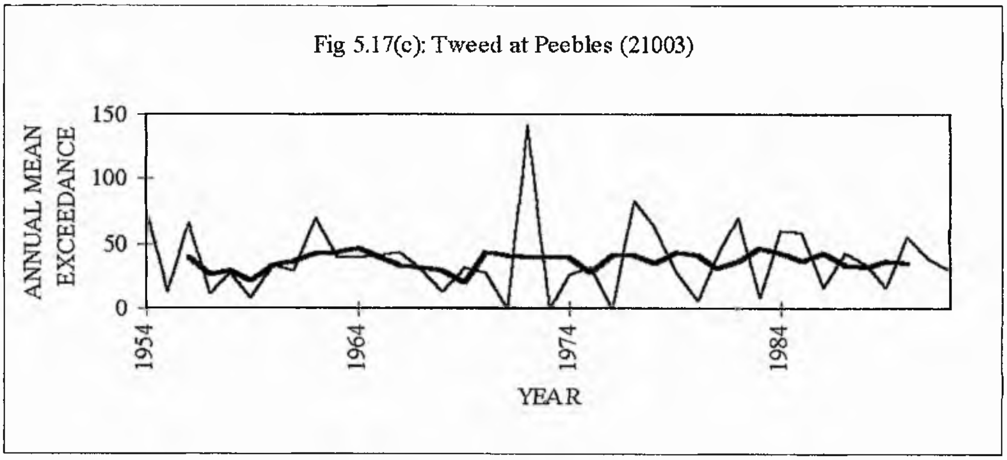


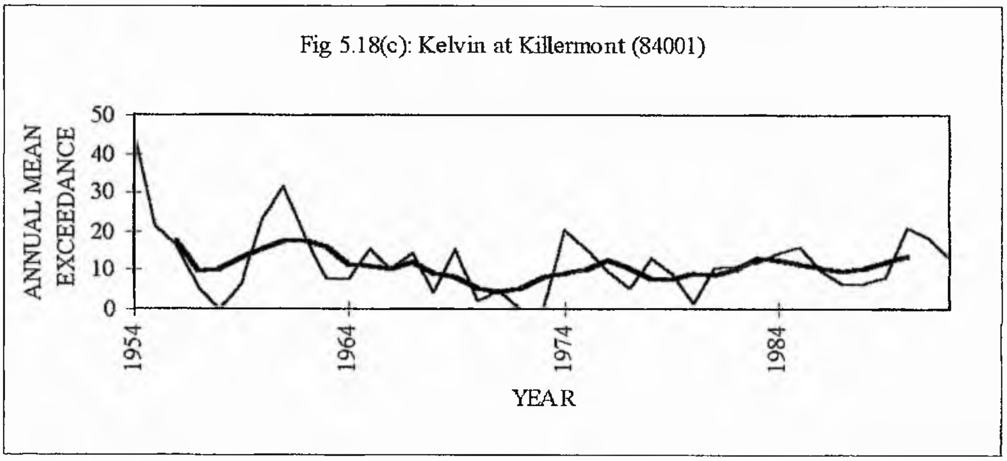




Appendix Two

Figures 5.17(c)-5.18(c)
Flood Magnitude Series 1954-92: Annual Mean Exceedances and a Five-Year Running Mean





Figures 5.5(d)-5.7(d)
Mann's Test for Trend in the Mean: Flood Magnitude Series 1954-92

Fig 5.5(d): Avon at Delnashaugh (08004)

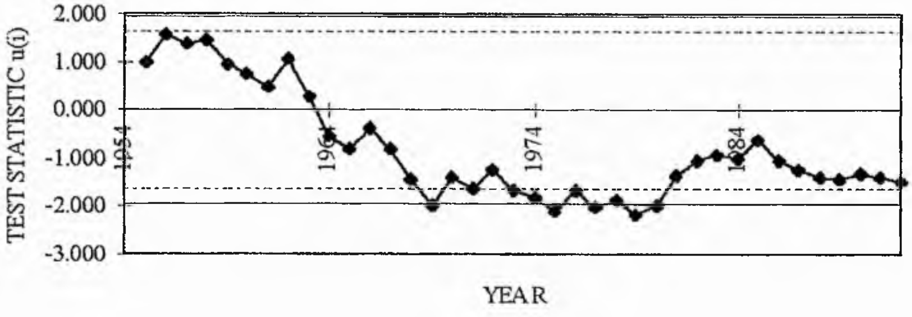


Fig 5.6(d): Spey at Boat of Garten (08005)

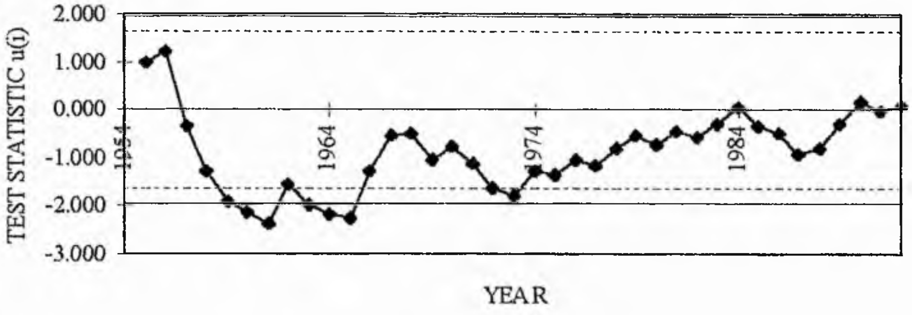
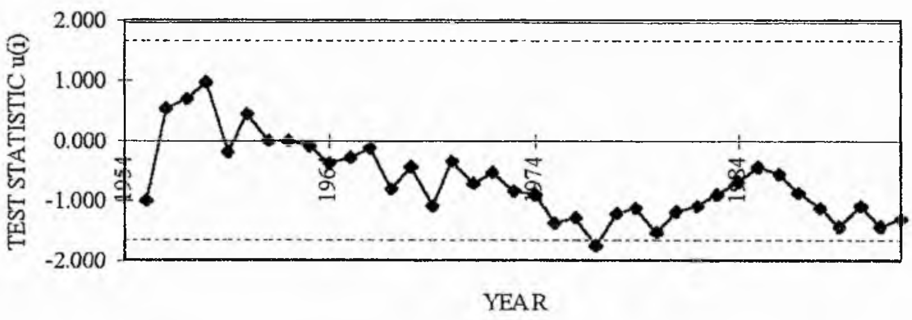
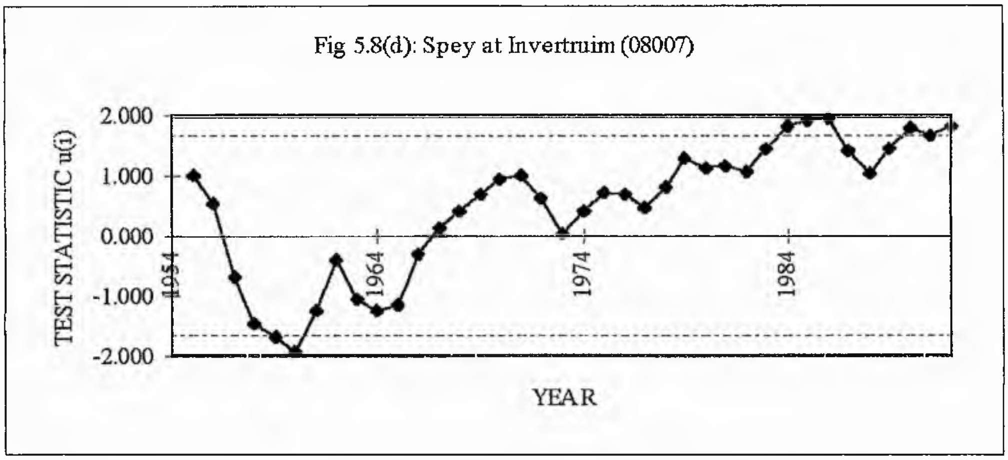


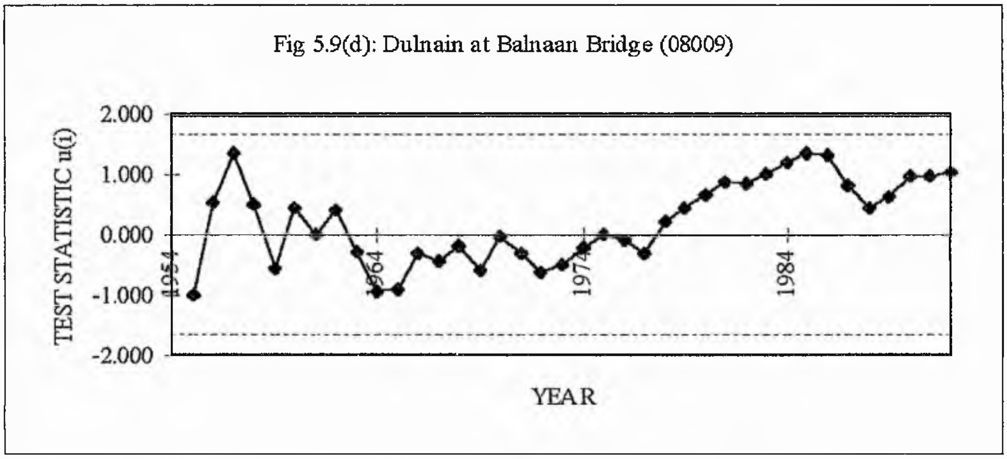
Fig 5.7(d): Spey at Boat of Brig (08006)

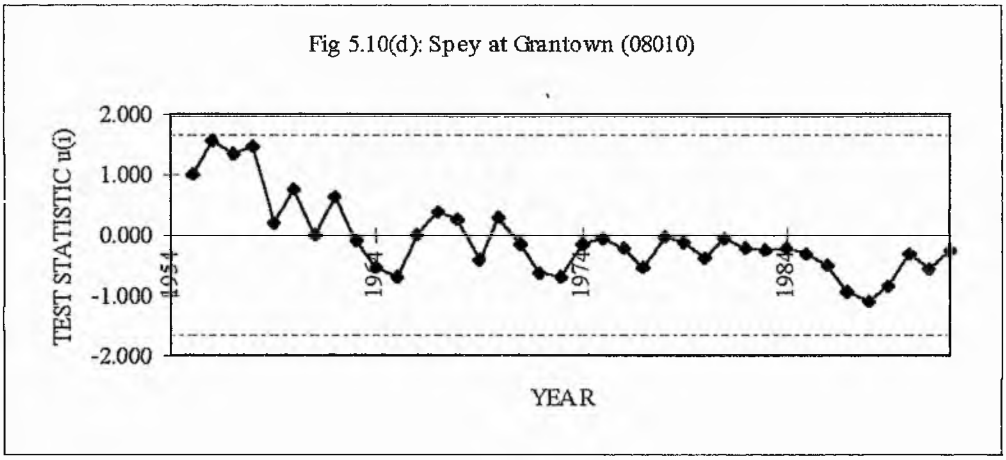


Appendix Two

Figures 5.8(d)-5.10(d)
Mann's Test for Trend in the Mean: Flood Magnitude Series 1954-92







Appendix Two

Figures 5.11(d)-5.13(d)
Mann's Test for Trend in the Mean: Flood Magnitude Series 1954-92

Fig 5.11(d): Dee at Woodend (12001)

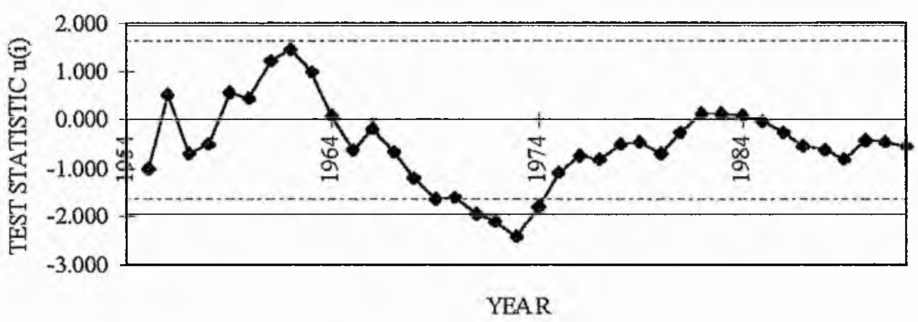


Fig 5.12(d): Tay at Caputh (15003)

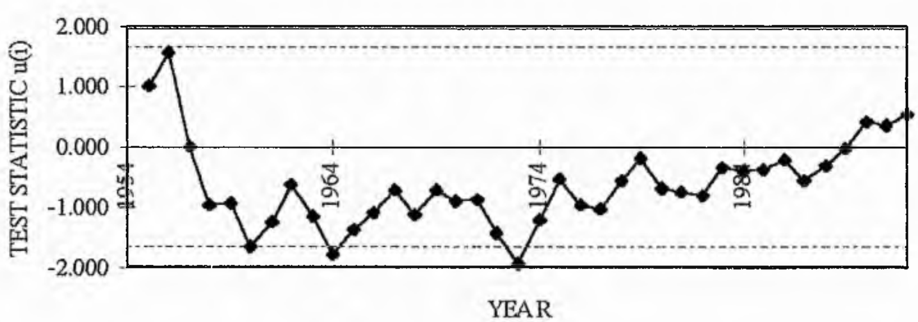
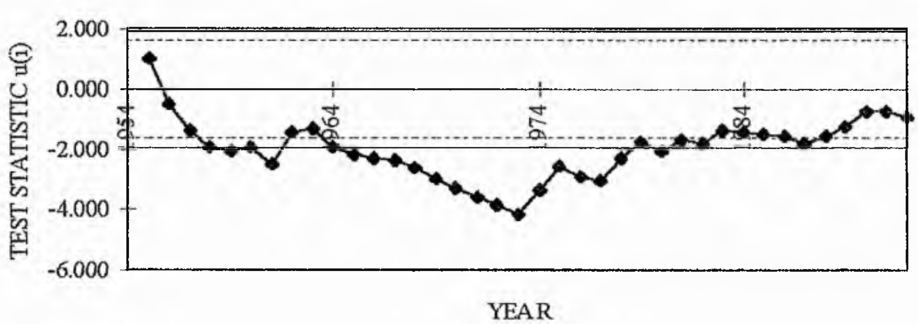
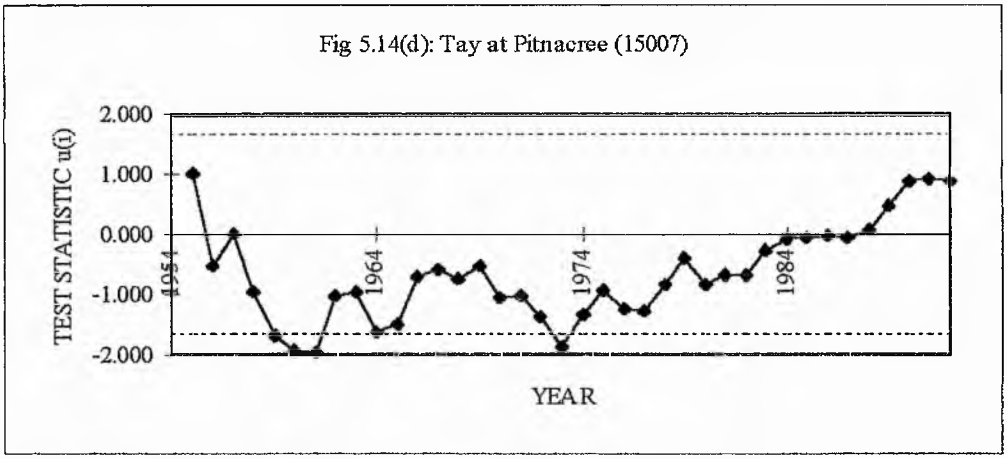


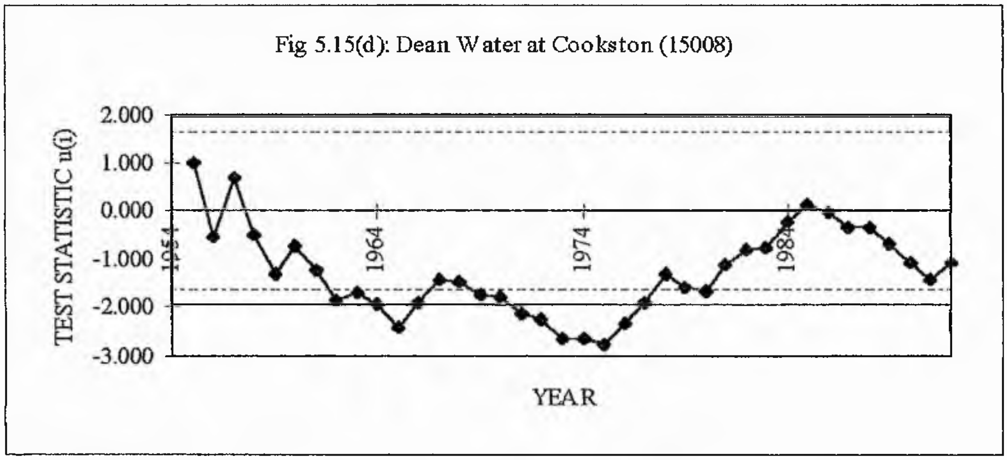
Fig 5.13(d): Tay at Ballathie (15006)

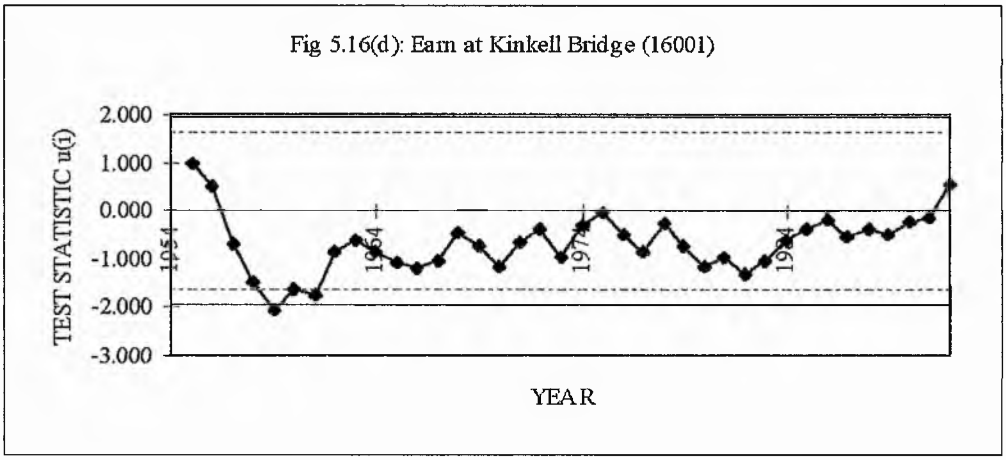


Appendix Two

Figures 5.14(d)-5.16(d)
Mann's Test for Trend in the Mean: Flood Magnitude Series 1954-92







Appendix Two

Figures 5.17(d)-5.18(d)
Mann's Test for Trend in the Mean: Flood Magnitude Series 1954-92

Fig 5.17(d): Tweed at Peebles (21003)

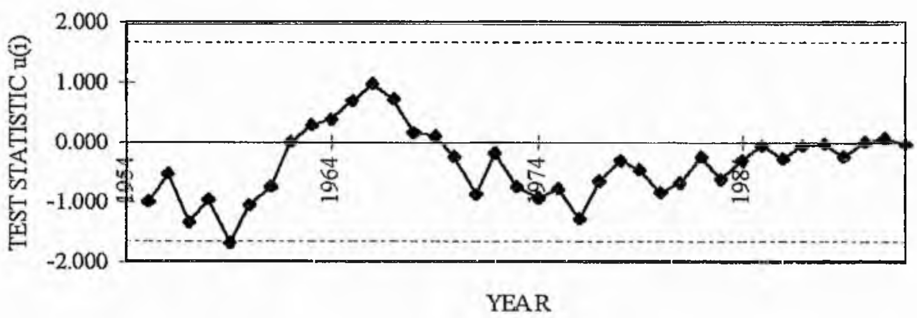
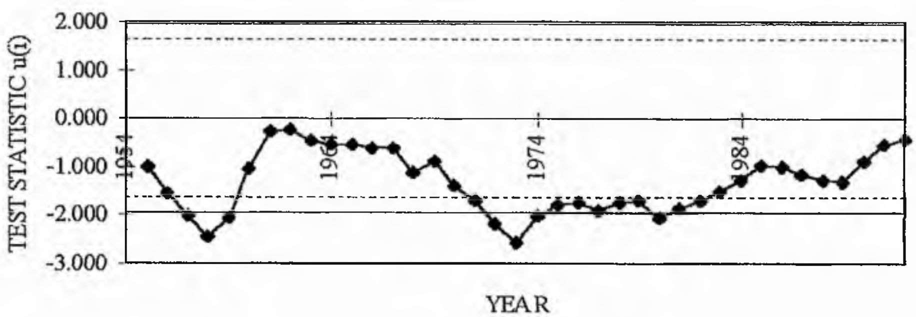


Fig 5.18(d): Kelvin at Killermont (84001)



Appendix Two

Figures 5.19(a)-5.26(a)
Flood Frequency Series 1964-92: Annual Frequencies and a Five-Year Running Mean

Fig 5.19(a): Findhorn at Shenachie (07001)

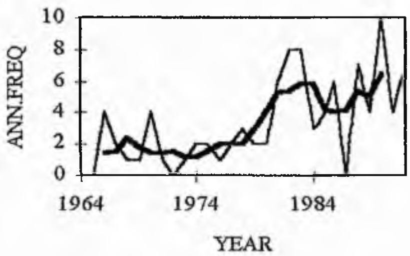


Fig 5.20(a): Findhorn at Forres (07002)

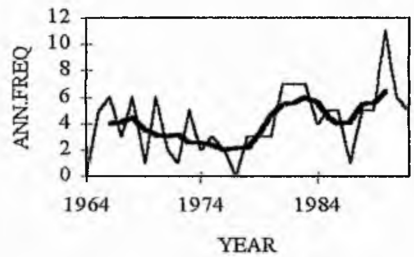


Fig 5.21(a): Lossie at Sheriffmills (07003)

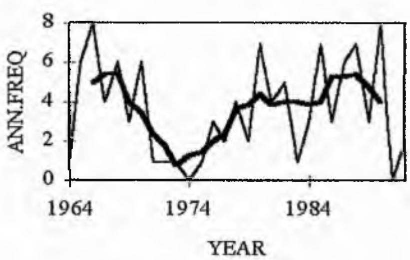


Fig 5.22(a): Avon at Delnashaugh (08004)

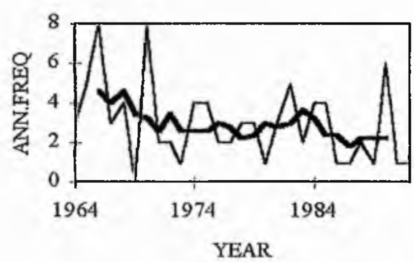


Fig 5.23(a): Spey at Boat of Garten (08005)

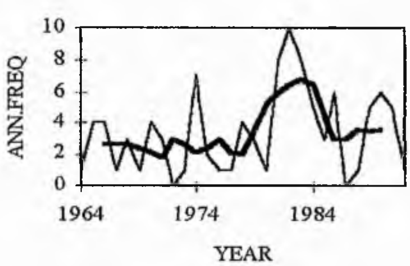


Fig 5.24(a): Spey at Boat O'Brig (08006)

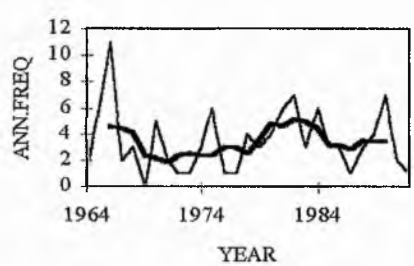


Fig 5.25(a): Spey at Invertruim (08007)

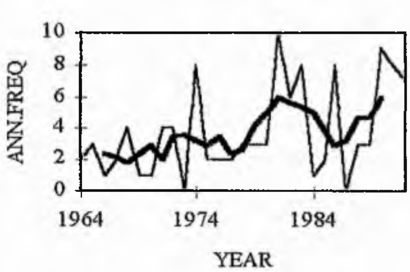
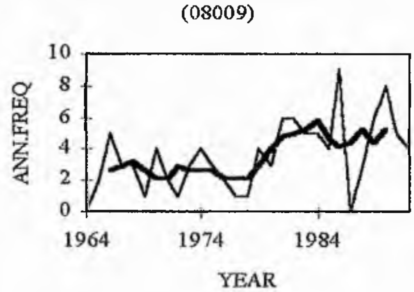


Fig 5.26(a): Dulnain at Balnaan Bridge (08009)



Appendix Two

Figures 5.27(a)-5.34(a)
Flood Frequency Series 1964-92: Annual Frequencies and a Five-Year Running Mean

Fig 5.27(a): Spey at Grantown (08010)

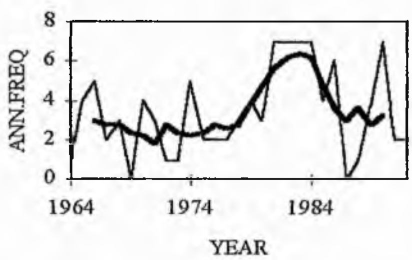


Fig 5.28(a):Deveron at Avochie (09001)

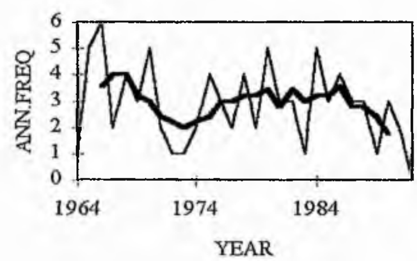


Fig 5.29(a): Deveron at Muiresk (09002)

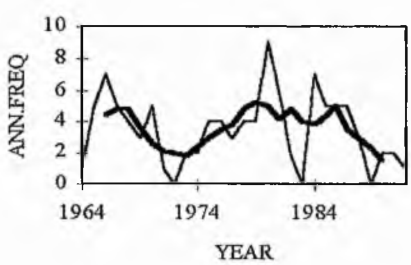


Fig 5.30(a): Isla at Grange (09003)

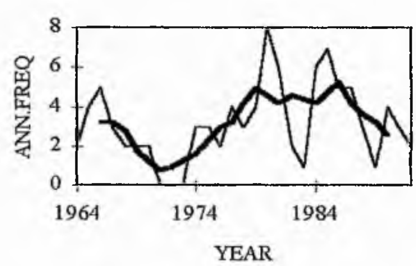


Fig 5.31(a): Dee at Woodend (12001)

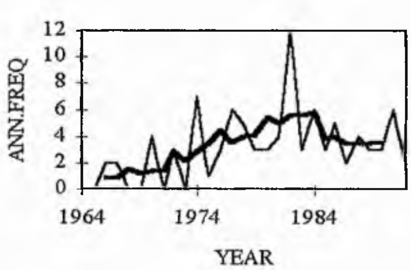


Fig 5.32(a):Tay at Caputh (15003)

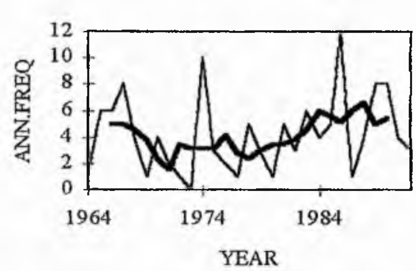


Fig 5.33(a): Tay at Ballathie (15006)

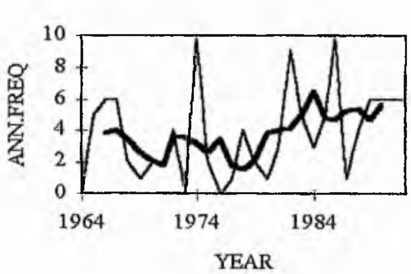
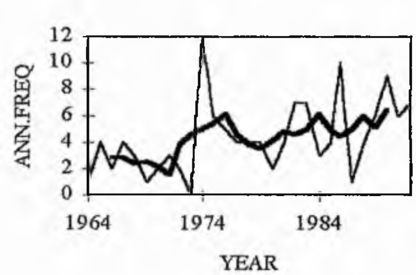


Fig 5.34(a):Tay at Pitnacree (15007)



Appendix Two

Figures 5.35(a)-5.42(a)
Flood Frequency Series 1964-92: Annual Frequencies and a Five-Year Running Mean

Fig 5.35(a): Dean Water at Cookston (15008)

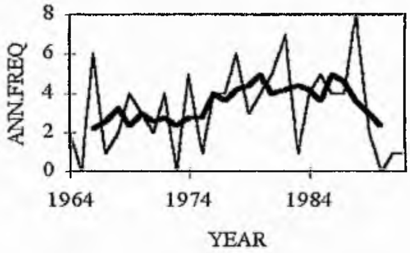


Fig 5.36(a):Earn at Kinkell Bridge (16001)

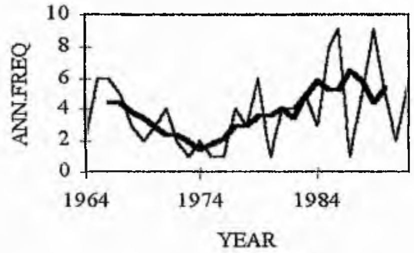


Fig 5.37(a): Ruchill Water at Cultybraggan (16003)

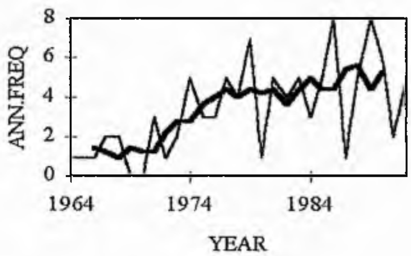


Fig 5.38(a):Almond at Craigiehall (19001)

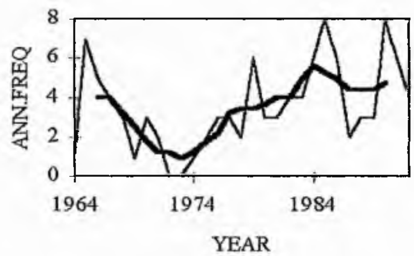


Fig 5.39(a):Almond at Almond Weir (19002)

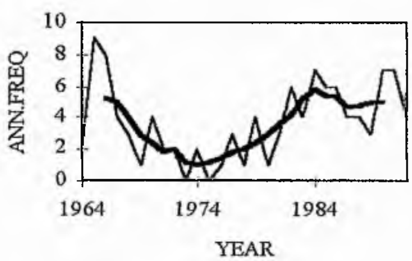


Fig 5.40(a):North Esk at Dalmore Weir (19004)

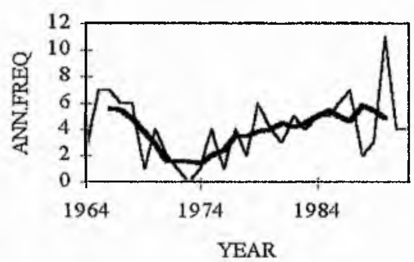


Fig 5.41(a): Water of Leith at Murrayfield (19006)

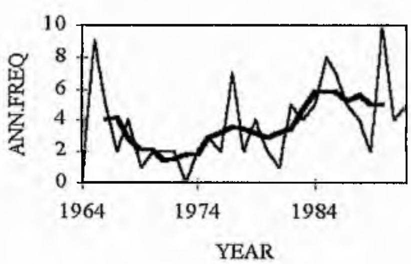
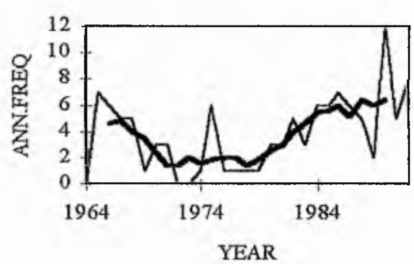


Fig 5.42(a):Esk at Musselburgh (19007)



Appendix Two

Figures 5.43(a)-5.50(a)
Flood Frequency Series 1964-92: Annual Frequencies and a Five-Year Running Mean

Fig 5.43(a):North Esk at Dalkeith Place (19011)

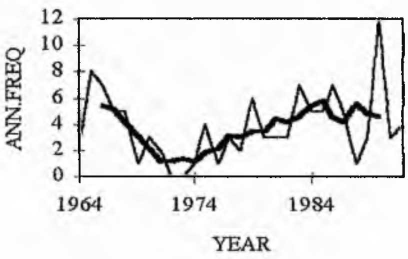


Fig 5.44(a):Tyne at East Linton (20001)

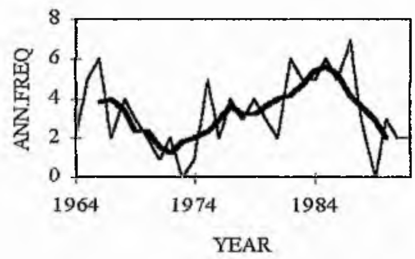


Fig 5.45(a): Tyne at Spilmersford (20003)

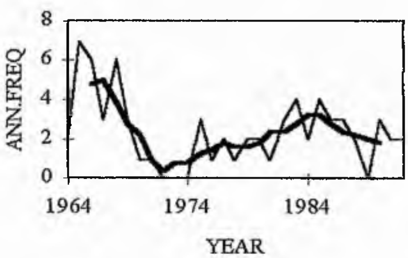


Fig 5.46(a):Birns Water at Saltoun Hall (20005)

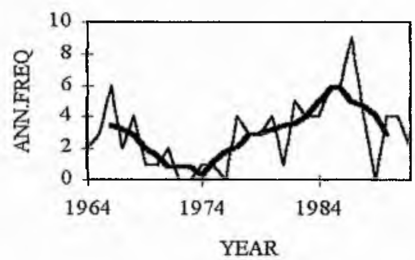


Fig 5.47(a):Tweed at Peebles (21003)

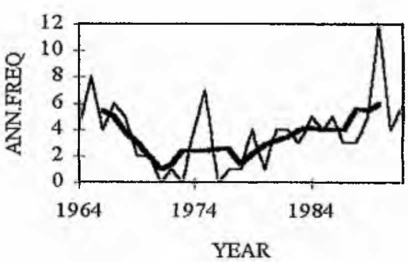


Fig 5.48(a):Tweed at Lyne Ford (21005)

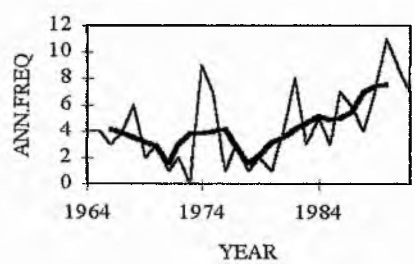


Fig 5.49(a): Tweed at Boleside (21006)

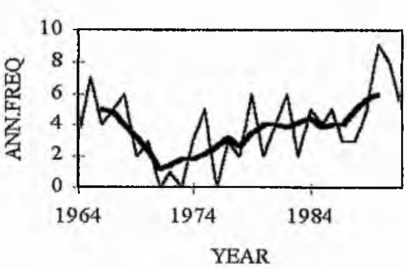
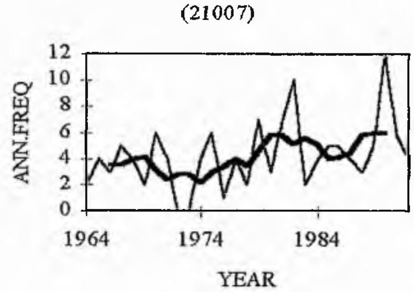


Fig 5.50(a):Ettrick Water at Lindean (21007)



Appendix Two

Figures 5.51(a)-5.58(a)
Flood Frequency Series 1964-92: Annual Frequencies and a Five-Year Running Mean

Fig 5.51(a):Teviot at Ormiston Mill (21008)

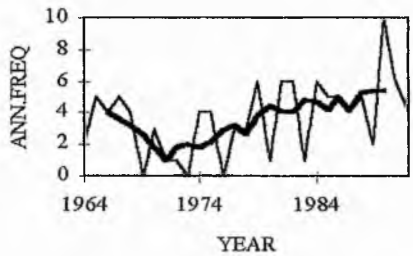


Fig 5.52(a):Tweed at Norham (21009)

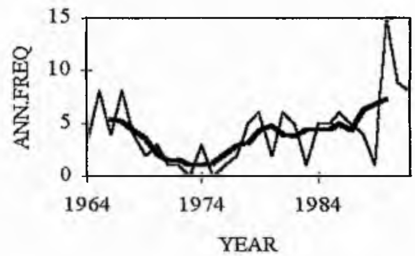


Fig 5.53(a): Yarrow Water at Philiphaugh (21011)

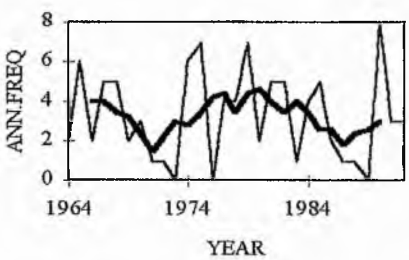


Fig 5.54(a):Teviot at Hawick (21012)

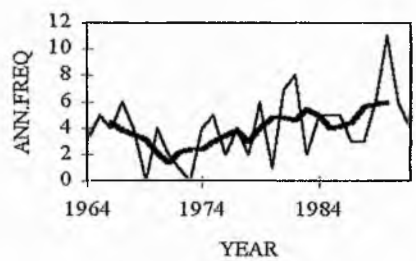


Fig 5.55(a):Gala Water at Galashiels (21013)

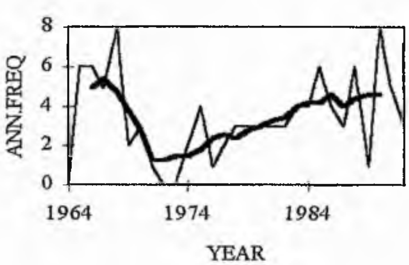


Fig 5.56(a):Nith at Friar's Carse (79002)

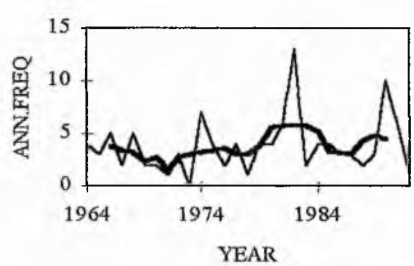


Fig 5.57(a): Nith at Hallbridge (79003)

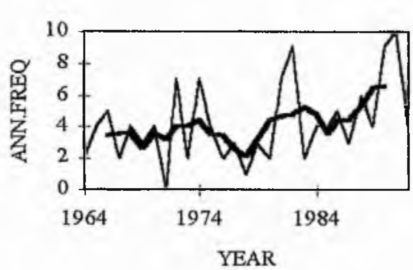
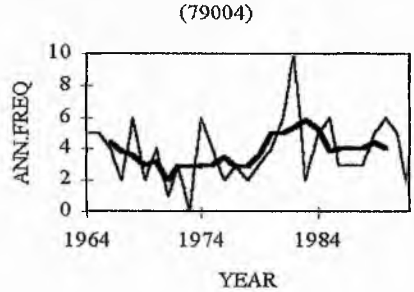


Fig 5.58(a):Scar Water at Capenoch (79004)



Appendix Two

Figures 5.59(a)-5.66(a)
Flood Frequency Series 1964-92: Annual Frequencies and a Five-Year Running Mean

Fig 5.59(a):Cluden Water at Fiddler's Ford (79005)

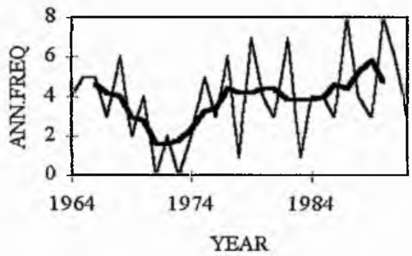


Fig 5.60(a):Urr at Dalbeattie (80001)

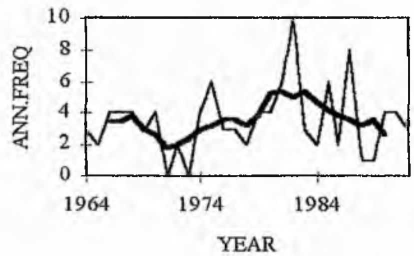


Fig 5.61(a):Cree at Newton Stewart (81002)

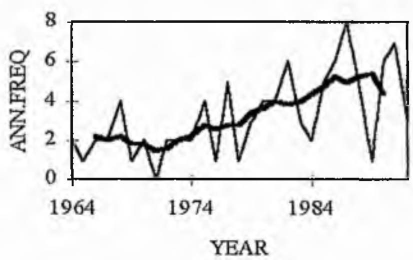


Fig 5.62(a):Girvan at Robstone (82001)

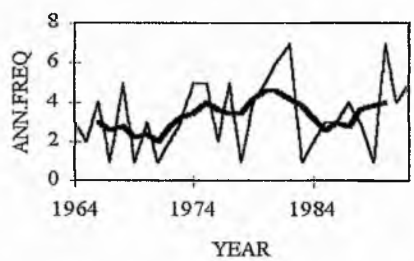


Fig 5.63(a):Kelvin at Killermont (84001)

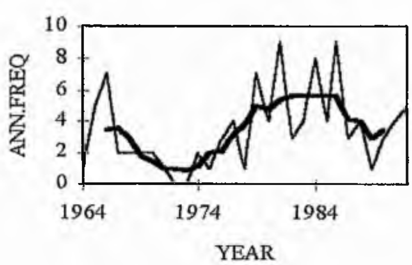


Fig 5.64(a):Clyde at Hazelbank (84003)

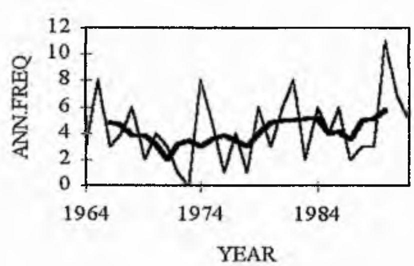


Fig 5.65(a):Clyde at Sills (84004))

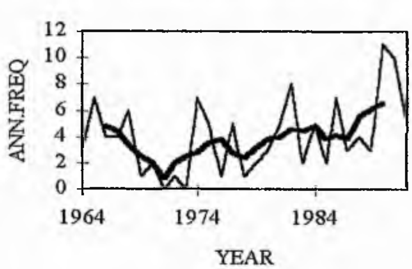
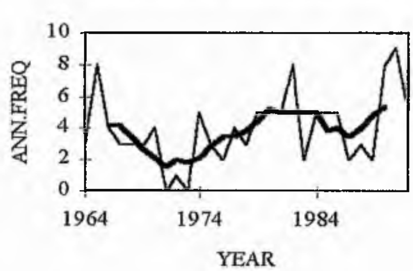
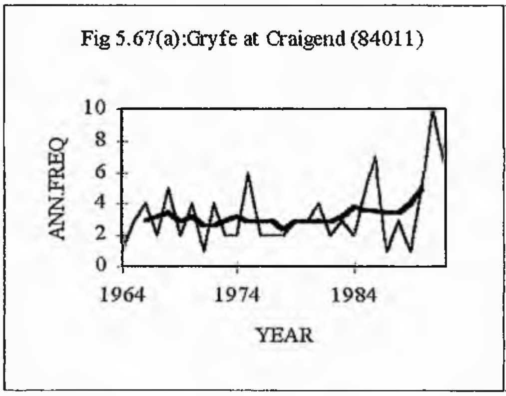


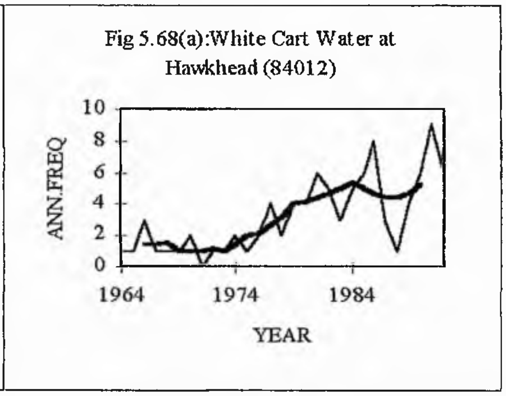
Fig 5.66(a):Clyde at Blairston (84005)

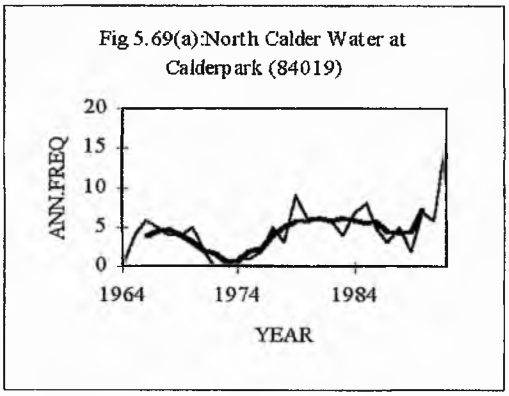


Appendix Two

Figures 5.67(a)-5.69(a)
Flood Frequency Series 1964-92: Annual Frequencies and a Five-Year Running Mean







Appendix Two

Figure 5.19(b)-5.26(b): Mann's Test for Trend in the Mean: Flood Frequency Series 1964-92

Fig 5.19(b): Findhorn at Shenachie (07001)

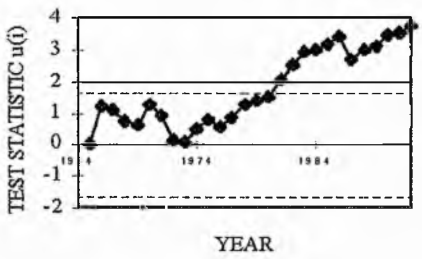


Fig 5.20(b): Findhorn at Forres (07002)

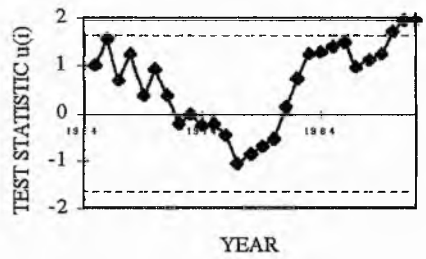


Fig 5.21(b): Lossie at Sheriffmills (07003)

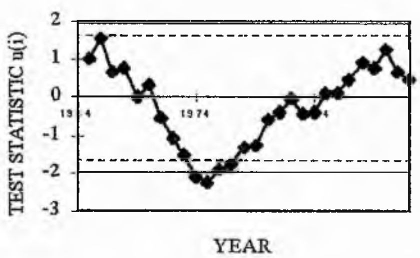


Fig 5.22(b): Avon at Delnashaugh (08004)

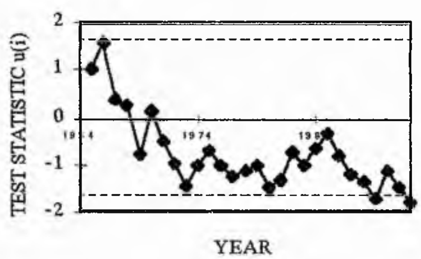


Fig 5.23(b): Spey at Boat of Garten (08005)

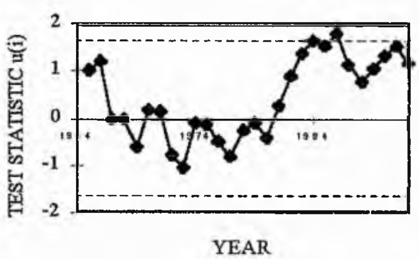


Fig 5.24(b): Spey at Boat O'Brig (08006)

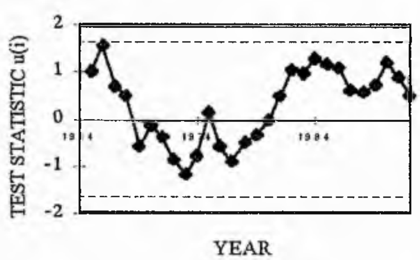


Fig 5.25(b): Spey at Invertruim (08007)

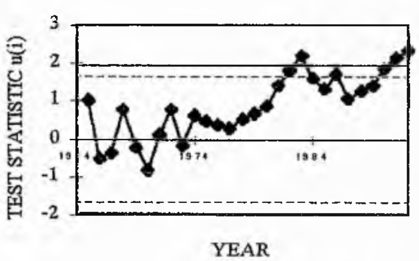
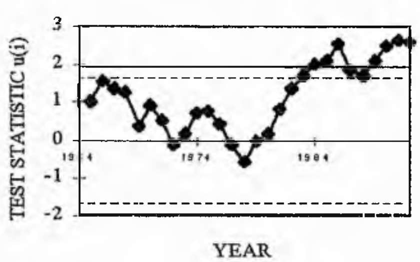


Fig 5.26(b): Dulnain at Balnaan Bridge (08009)



Appendix Two

Figure 5.27(b)-5.34(b): Mann's Test for Trend in the Mean: Flood Frequency Series 1964-92

Fig 5.27(b): Spey at Grantown (08010)

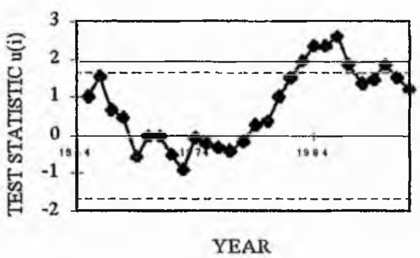


Fig 5.28(b): Deveron at Avochie (09001)

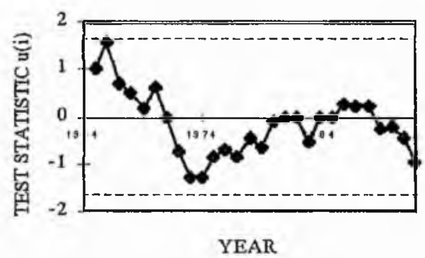


Fig 5.29(b): Deveron at Muiresk (09002)

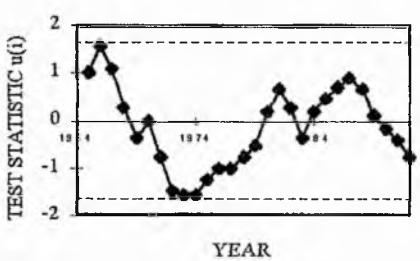


Fig 5.30(b): Isla at Grange (09003)

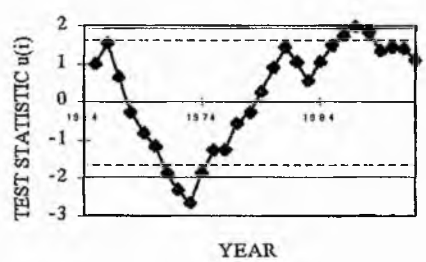


Fig 5.31(b): Dee at Woodend (12001)

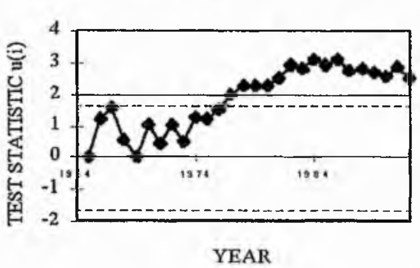


Fig 5.32(b): Tay at Caputh (15003)

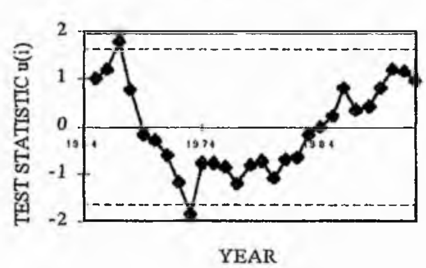


Fig 5.33(b): Tay at Ballathie (15006)

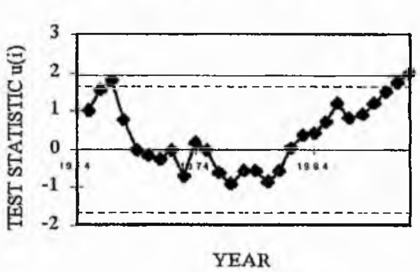
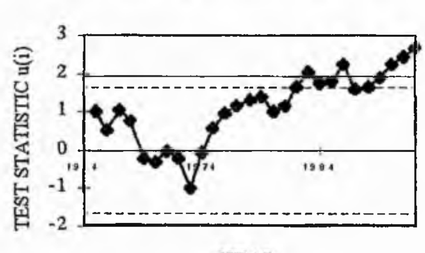
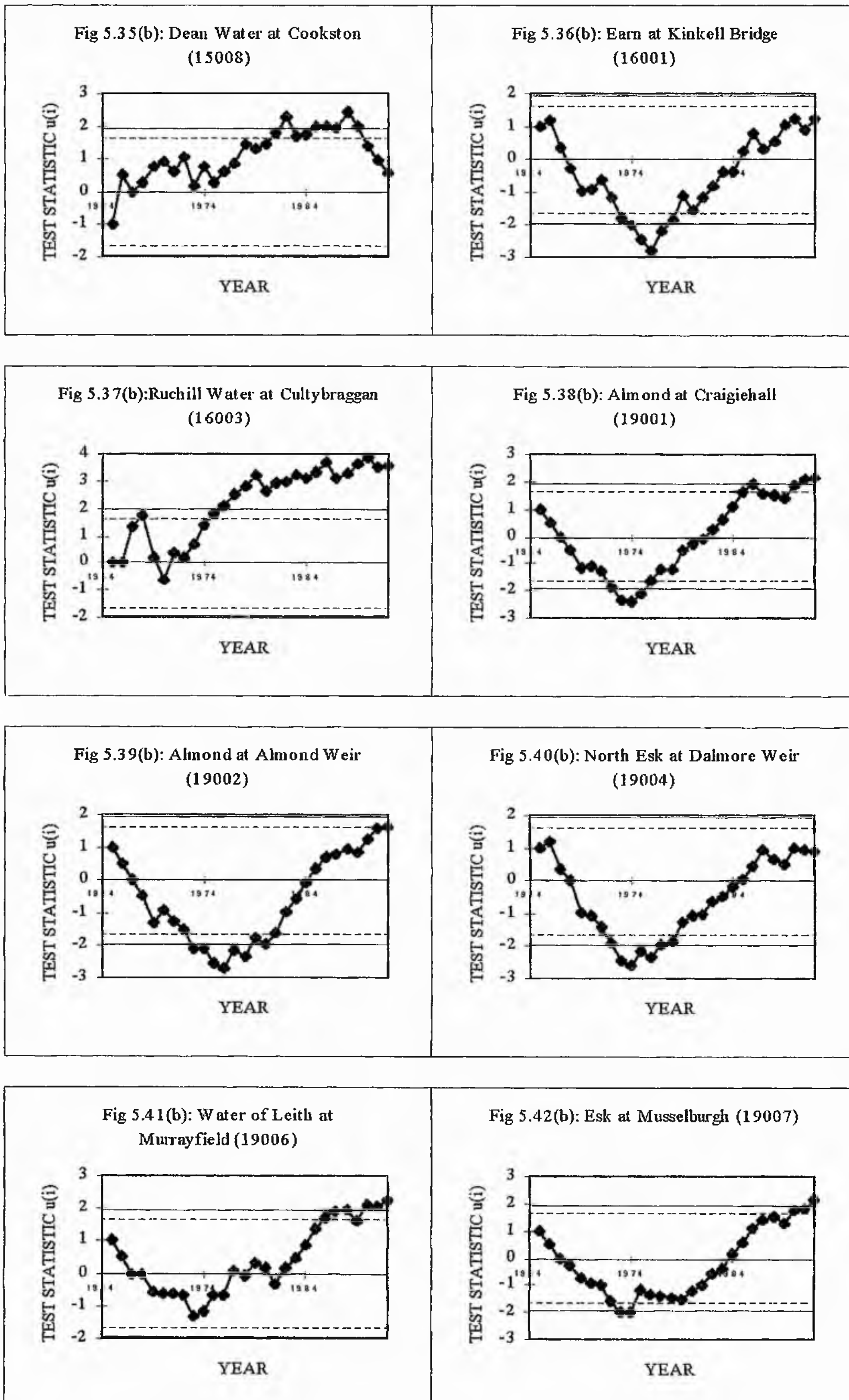


Fig 5.34(b): Tay at Pitnacree (15007)



Appendix Two

Figure 5.35(b)-5.42(b): Mann's Test for Trend in the Mean: Flood Frequency Series 1964-92



Appendix Two

Figure 5.43(b)-5.50(b): Mann's Test for Trend in the Mean: Flood Frequency Series 1964-92

Fig 5.43(b): North Esk at Dalkeith Place (19011)

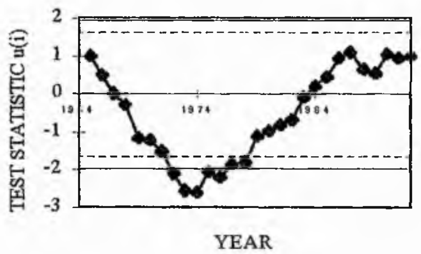


Fig 5.44(b):Tyne at East Linton (20001)

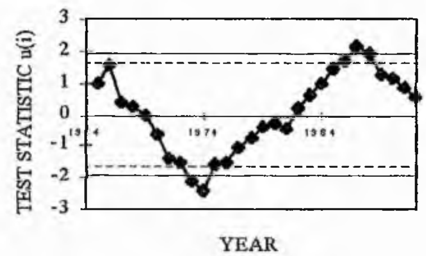


Fig 5.45(b):Tyne at Spilmersford (20003)

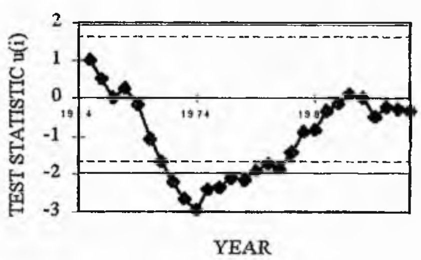


Fig 5.46(b): Birns Water at Saltoun Hall (20005)

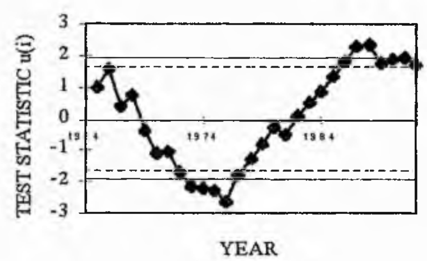


Fig 5.47(b): Tweed at Peebles (21003)

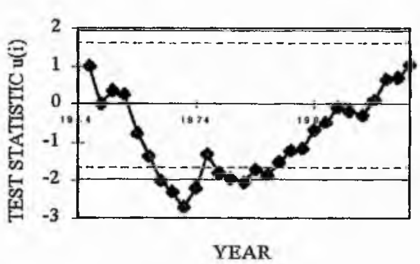


Fig 5.48(b): Tweed at Lyne Ford (21005)

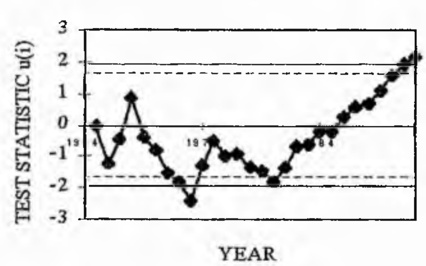


Fig 5.49(b): Tweed at Boleside (21006)

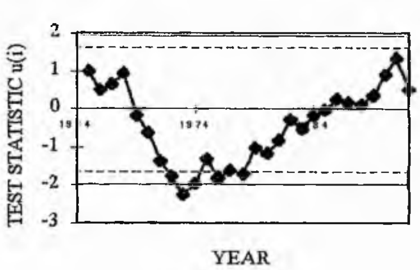
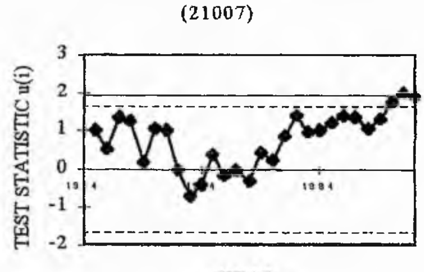


Fig 5.50(b): Ettrick Water at Lindean (21007)



Appendix Two

Figure 5.51(b)-5.58(b): Mann's Test for Trend in the Mean: Flood Frequency Series 1964-92

Fig 5.51(b): Teviot at Ormiston Mill (21008)

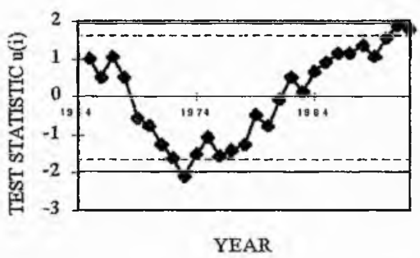


Fig 5.52(b):Tweed at Norham (21009)

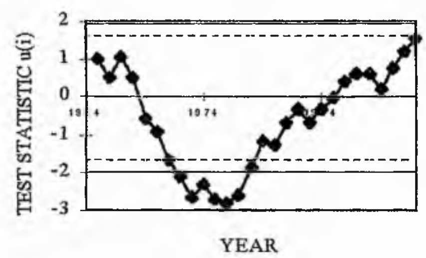


Fig 5.53(b):Yarrow Water at Philiphaugh (21011)

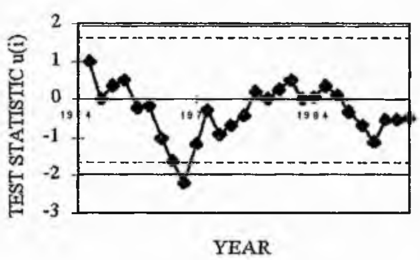


Fig 5.54(b): Teviot at Hawick (21012)

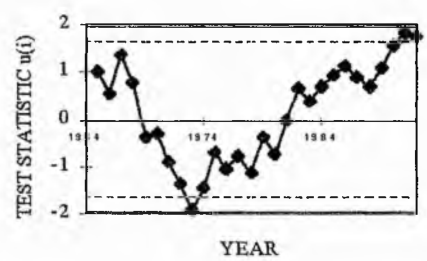


Fig 5.55(b): Gala Water at Galashiels (21013)

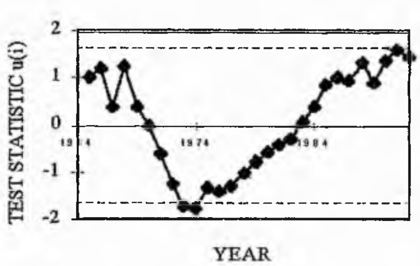


Fig 5.56(b): Nith at Friar's Carse (79002)

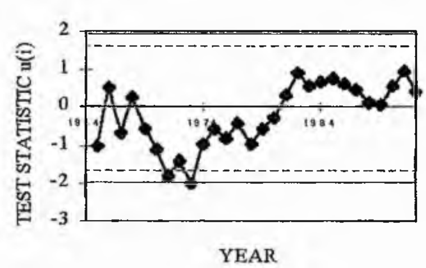


Fig 5.57(b): Nith at Hallbridge (79003)

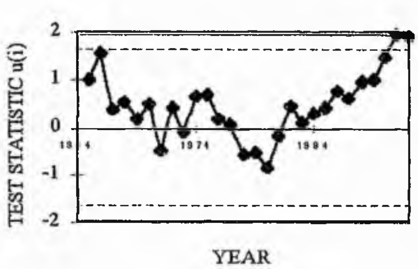
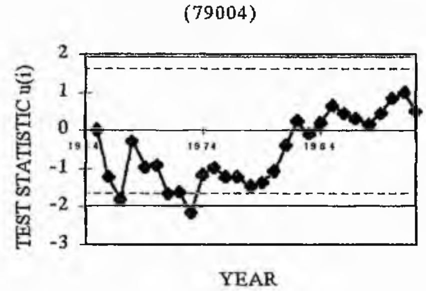


Fig 5.58(b): Scar Water at Capenoch (79004)



Appendix Two

Figure 5.59(b)-5.66(b): Mann's Test for Trend in the Mean: Flood Frequency Series 1964-92

Fig 5.59(b): Cluden Water at Fiddler's Ford (79005)

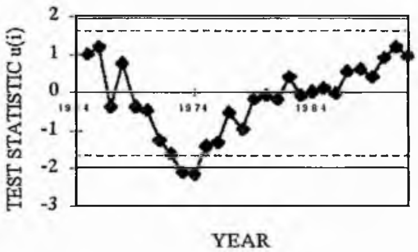


Fig 5.60(b):Urr at Dalbeattie (80001)

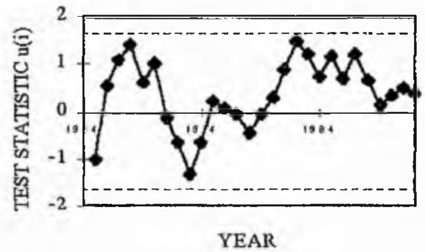


Fig 5.61(b):Cree at Newton Stewart (81002)

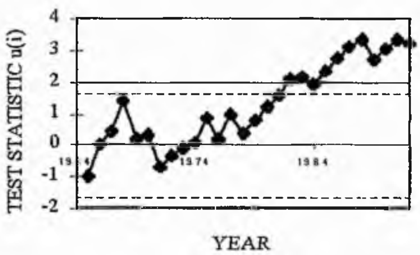


Fig 5.62(b): Girvan at Robstone (82001)

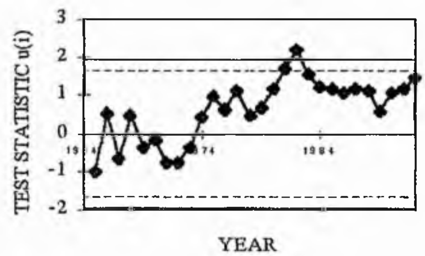


Fig 5.63(b): Kelvin at Killermont (84001)

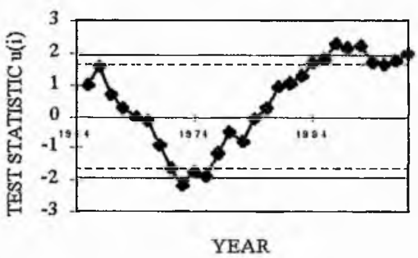


Fig 5.64(b): Clyde at Hazelbank (84003)

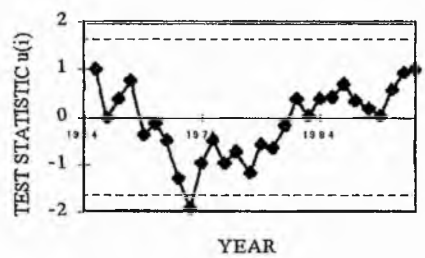


Fig 5.65(b): Clyde at Sills (84004)

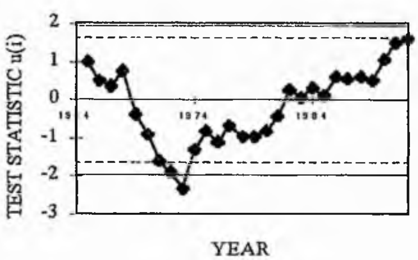
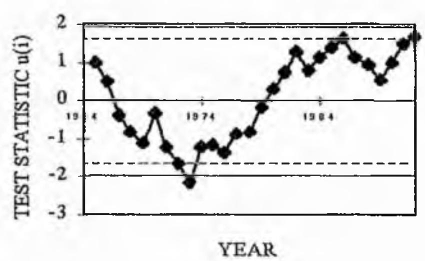


Fig 5.66(b): Clyde at Blairston (84005)



Appendix Two

Figure 5.67(b)-5.69(b): Mann's Test for Trend in the Mean: Flood Frequency Series 1964-92

Fig 5.67(b): Gryfe at Craigend (84011)

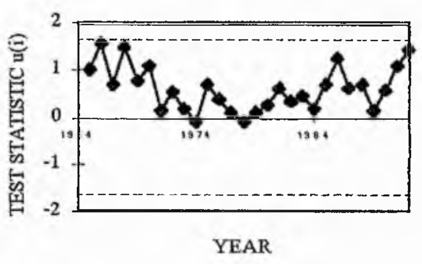


Fig 5.68(b):White Cart Water at Hawkhead (84012)

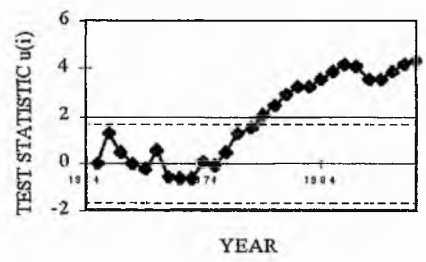


Fig 5.69(b):North Calder Water at Calderpark (84019)

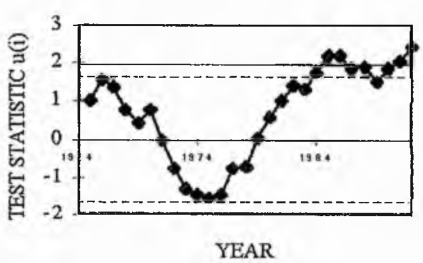


Table 5.9(a): Cluster A frequency series 1964-92: Mann's Test for Trend in the Mean

FREQUENCY SERIES	**CHARACTERISTICS**
Findhorn at Shenachie (07001) **Dee at Woodend (12001)** **Ruchill Water at Cultybraggan (16003)** **Cree at Newton Stewart (81002)** **White Cart Water at Craigend (84012)**	*Frequencies stable to mid 1970s then increase:* u(i): upward trend (1% conf.level) by mid 1980s Figures 5.19(b), 5.31(b), 5.37(b), 5.61(b) and 5.68(b)
Dean Water at Cookston (15008)	*Frequencies stable until 1975 then increase to 1982; further stability follows until 1988 when values decrease:* u(i):upward trend (5% conf.level) by mid 1980s Figure 5.35(b)
Urr at Dalbeattie (80001)	*Frequencies stable until 1975 then increase to 1982; further stability follows until 1988 when values decrease:* u(i): no trends observed Figure 5.60(b)

Table 5.9(b): Cluster B frequency series 1964-92: Mann's Test for Trend in the Mean

FREQUENCY SERIES	CHARACTERISTICS
Findhorn at Forres (07002) **Spey at Invertruim (08007)** **Dulnain at Balnann Bridge (08009)** **Tay at Ballathie (15006)** **Tay at Pitnacree (15007)** **Water of Leith at Murrayfield (19006)** **Ettrick Water at Lindean (21007)** **Nith at Hall Bridge (79003)** **Kelvin at Killermont (84001)** **N.Calder Water at Calderpark (84019)**	*Frequencies decrease to mid 1970s then increase to 1992; a period of stability occurs in late 1980s:* u(i): upward trend (10% conf.level) by late 1980s and (5% conf.level) by 1992 Figures 5.20(b), 5.25(b), 5.26(b), 5.33(b), 5.34(b), 5.41(b), 5.50(b), 5.57(b), 5.63(b) and 5.69(b)
Spey at Boat of Garten (08005) **Spey at Boat o'Brig (08006)** **Spey at Grantown (08010)**	*Similar to 07002, although frequencies stabilise in late 1980s, rather than increase* Figures 5.23(b), 5.24(b) and 5.27(b)
Girvan at Robstone (82001)	*Frequencies decrease to mid 1970s, then increase to 1985 and stabilise:* u(i): no significant trends Figure 5.62(b)
Gryfe at Craigend (84011)	*Frequencies decline slightly until the mid 1970s, and also increase from the mid 1980s:* u(i): no significant trends Figure 5.67(b)

Table 5.9(c): Cluster C frequency series 1964-92: Mann's Test for Trend in the Mean

FREQUENCY SERIES	CHARACTERISTICS
Lossie at Sherrifmills (07003) **Isla at Grange (09003)** **Tay at Caputh (15003)** **Earn at Kinkell Bridge (16001)** **Almond at Craigie Hall (19001)** **Almond at Almond Weir (19002)** **North Esk at Dalmore Weir (19004)** **Esk at Musselburgh (19007)** **North Esk at Dalkeith Place (19011)** **Tyne at East Linton (20001)** **Tyne at Spilmersford (20003)** **Birns Water at Saltoun Hall (20005)** **Tweed at Peebles (21003)** **Tweed at Lyne Ford (21005)** **Tweed at Boleside (21006)** **Teviot at Ormiston Mill (21008)** **Tweed at Norham (21009)** **Teviot at Hawick (21012)** **Gala Water at Galashiels (21013)** **Clyde at Sills (84004)** **Clyde at Blairston (84005)**	*Frequencies decrease to mid 1970s, then generally increase to the late 1980s; values vary over the period since 1989:* u(i): downward trend (5% conf.level) by mid 1970s u(i): increase shows varying degrees of significance Figures 5.21(b), 5.30(b), 5.32(b), 5.36(b), 5.38(b)-5.40(b), 5.42(b)-5.52(b), 5.54(b), 5.55(b), 5.65(b) and 5.66(b)
Avon at Delnashaugh (08004) **Yarrow Water at Philiphaugh (21011)**	Frequencies decrease *until 1973 then stabilise; a decrease occurs from 1985-92:* u(i): downward trend (10% conf.level) by 1992 Figures 5.22(b) and 5.53(b)
Deveron at Avochie (09001) **Deveron at Muiresk (09002)**	*Frequencies decrease to mid 1970s, then increase again until mid 1980s; a slight decrease then follows:* u(i): no significant trends Figures 5.28(b) and 5.29(b)
Nith at Friar's Carse (79002) **Scar Water at Capenoch (79004)** **Cluden Water at Fiddler's Ford (79005)** **Clyde at Hazelbank (84003)**	*Frequencies decrease until 1973 then values increase slightly and display random behaviour:* u(i):downward trend by 1973 (5% conf.level) Figures 5.56(b), 5.58(b), 5.59(b) and 5.64(b)

Appendix Two

Figures 5.19(c)-5.26(c)
Flood Magnitude Series 1964-92: Annual Mean Exceedances and a Five-Year Running Mean

Fig 5.19(c): Findhorn at Shenachie (07001)

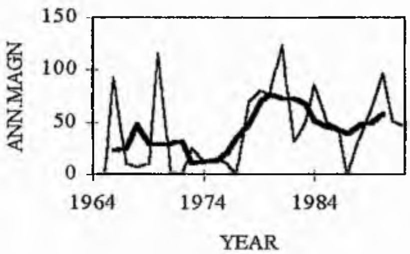


Fig 5.20(c): Findhorn at Forres (07002)

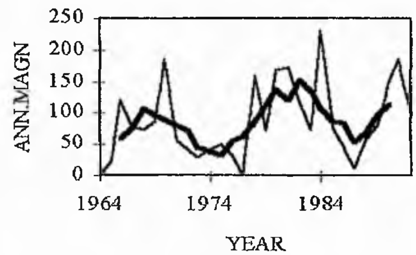


Fig 5.21(c): Lossie at Sheriffmills (07003)

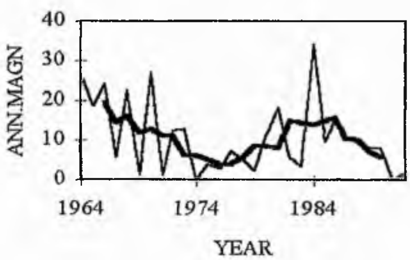


Fig 5.22(c): Avon at Delnashaugh (08004)

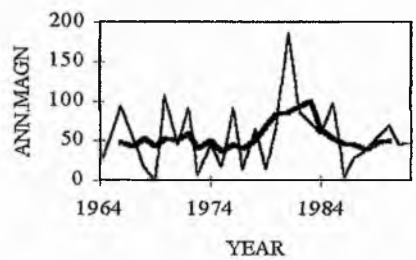


Fig 5.23(c): Spey at Boat of Garten (08005)

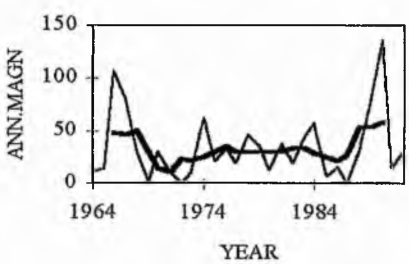


Fig 5.24(c): Spey at Boat O'Brig (08006)

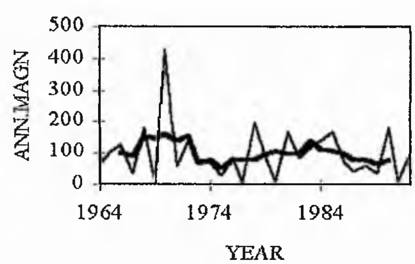


Fig 5.25(c): Spey at Invertruim (08007))

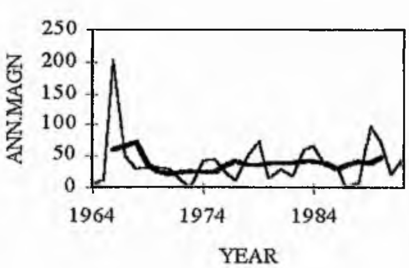
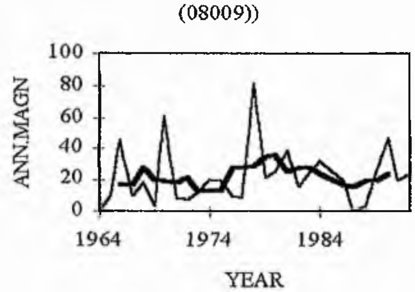


Fig 5.26(c): Dulnain at Balnaan Bridge (08009))



Appendix Two

Figures 5.27(c)-5.34(c)
Flood Magnitude Series 1964-92: Annual Mean Exceedances and a Five-Year Running Mean

Fig 5.27(c): Spey at Grantown (08010)

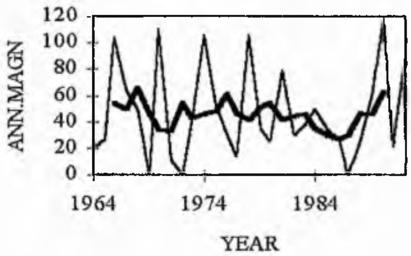


Fig 5.28(c): Deveron at Avochie (09001)

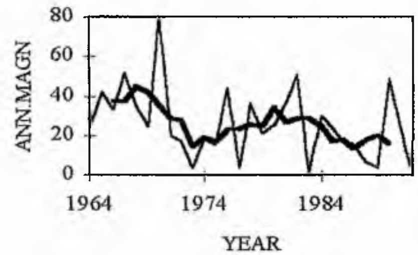


Fig 5.29(c): Deveron at Muiresk (09002)

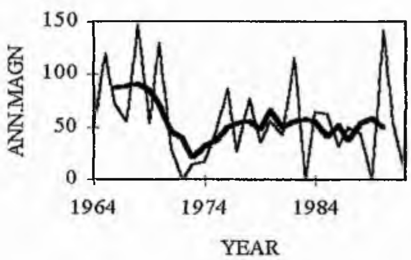


Fig 5.30(c):Isla at Grange (09003)

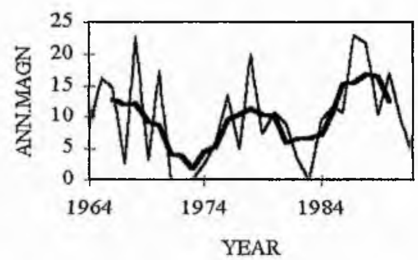


Fig 5.31(c): Dee at Woodend (12001)

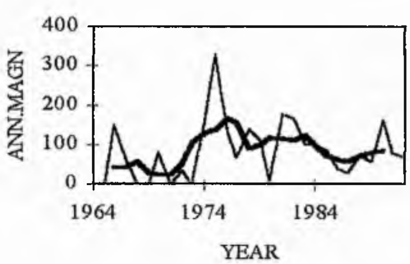


Fig 5.32(c): Tay at Caputh (15003)

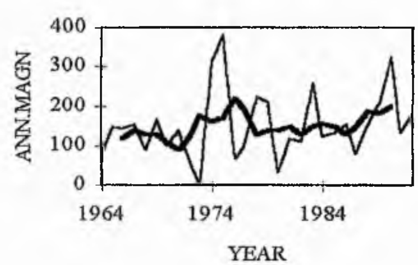


Fig 5.33(c): Tay at Ballathie (15006)

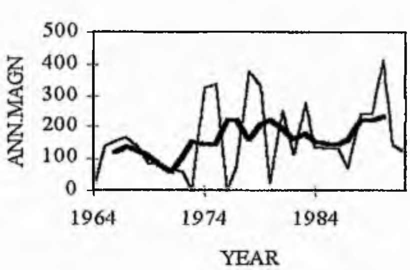
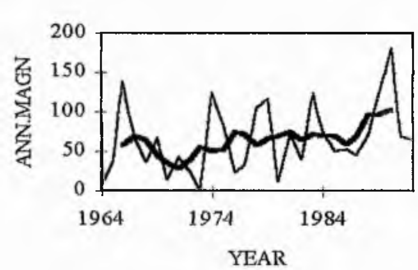


Fig 5.34(c):Tay at Pitnacree (15007)



Appendix Two

Figures 5.35(c)-5.42(c)
Flood Magnitude Series 1964-92: Annual Mean Exceedances and a Five-Year Running Mean

Fig 5.35(c): Dean Water at Cookston (15008)

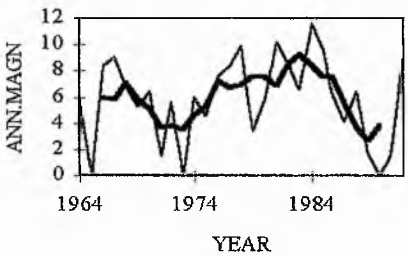


Fig 5.36(c): Earn at Kinkell Bridge (16001)

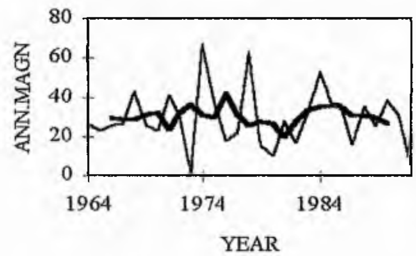


Fig 5.37(c): Ruchill Water at Cultybraggan (16003)

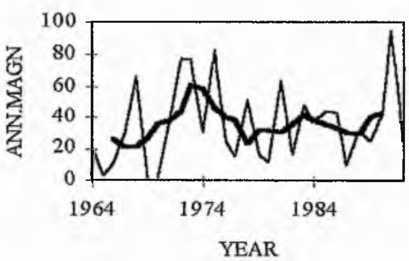


Fig 5.38(c):Almond at Craigiehall (19001)

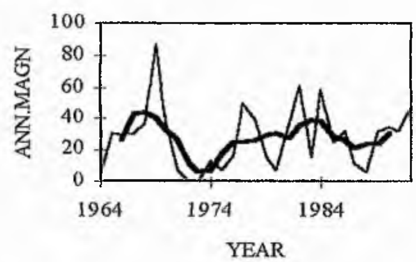


Fig 5.39(c): Almond at Almond Weir (19002)

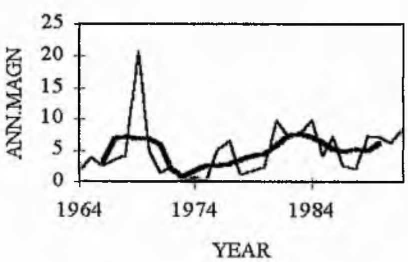


Fig 5.40(c): North Esk at Dalmore Weir (19004)

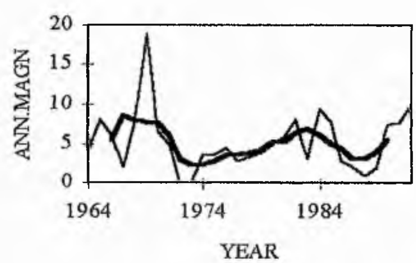


Fig 5.41(c): Water of Leith at Murrayfield (19006)

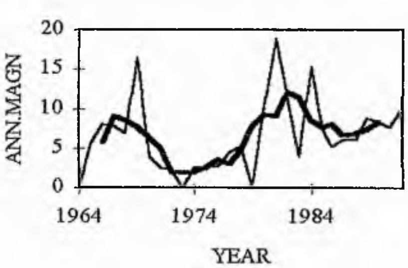
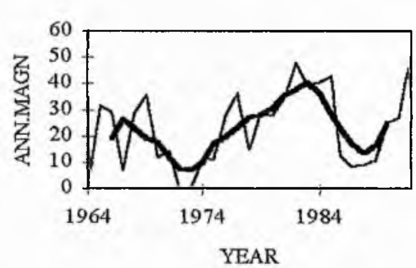


Fig 5.42(c):Esk at Musselburgh (19007)



Appendix Two

Figures 5.43(c)-5.50(c)
Flood Magnitude Series 1964-92: Annual Mean Exceedances and a Five-Year Running Mean

Fig 5.43(c): North Esk at Dalkeith Place (19011)

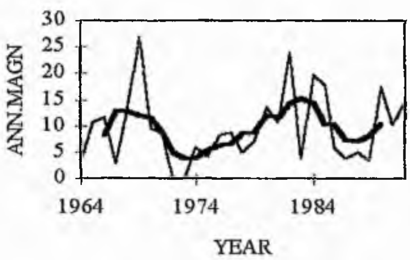


Fig 5.44(c): Tyne at East Linton (20001)

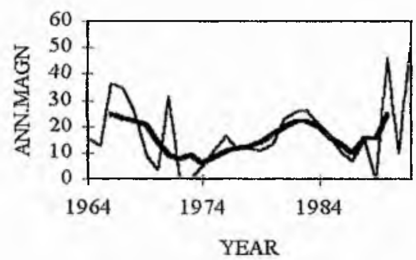


Fig 5.45(c): Tyne at Spilmersford (20003)

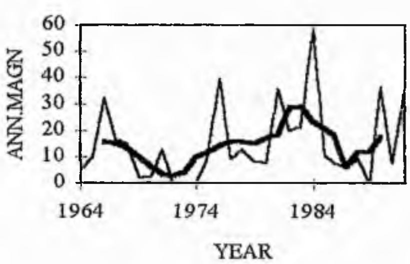


Fig 5.46(c):Birns Water at Saltoun Hall (20005)

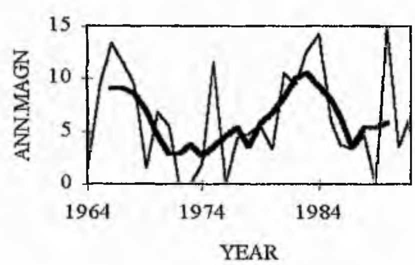


Fig 5.47(c): Tweed at Peebles (21003)

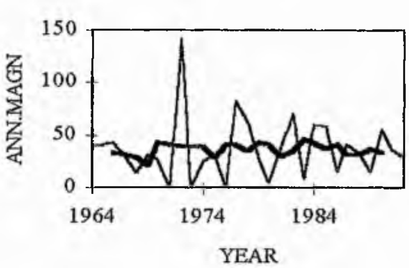


Fig 5.48(c): Tweed at Lyne Ford (21005)

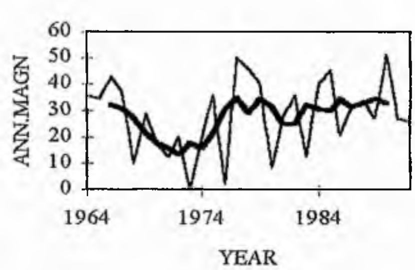


Fig 5.49(c): Tweed at Boleside (21006)

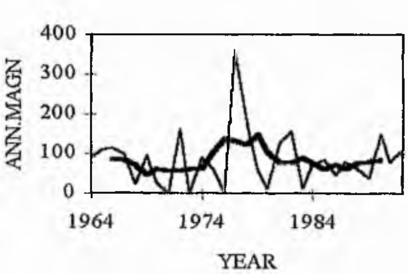
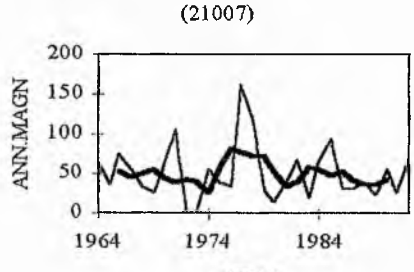


Fig 5.50(c):Ettrick Water at Lindean (21007)



Appendix Two

Figures 5.51(c)-5.58(c)
Flood Magnitude Series 1964-92: Annual Mean Exceedances and a Five-Year Running Mean

Fig 5.51(c): Teviot at Ormiston Mill (21008)

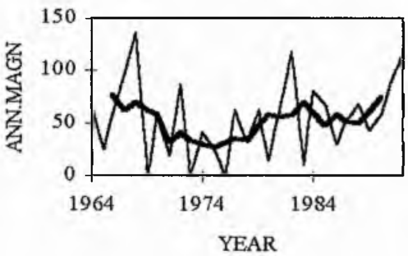


Fig 5.52(c): Tweed at Norham (21009)

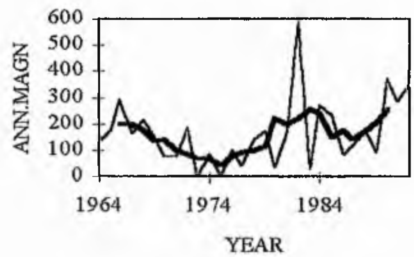


Fig 5.53(c): Yarrow Water at Philiphaugh (21011)

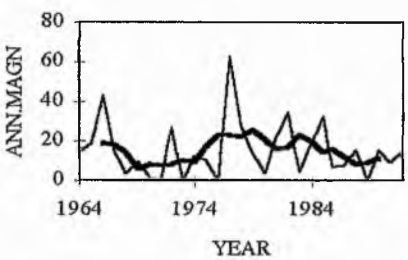


Fig 5.54(c):Teviot at Hawick (21012)

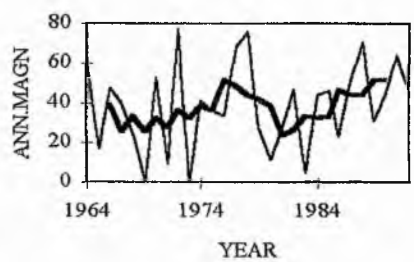


Fig 5.55(c): Gala Water at Galashiels (21013)

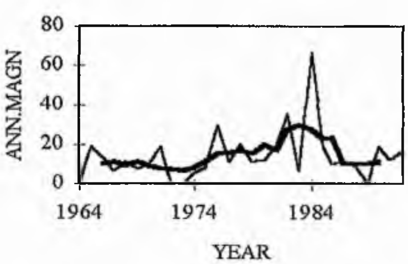


Fig 5.56(c): Nith at Friar's Carse (79002)

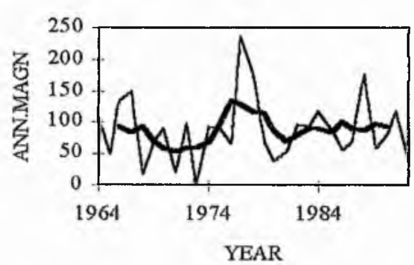


Fig 5.57(c): Nith at Hallbridge (79003)

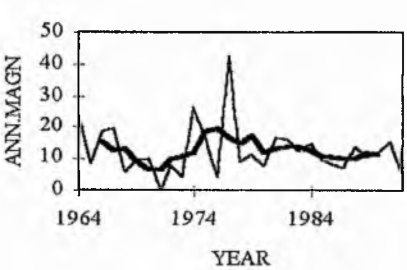
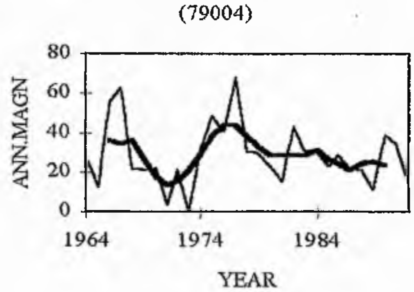


Fig 5.58(c):Scar Water at Capenoch (79004)



Appendix Two

Figures 5.59(c)-5.66(c)
Flood Magnitude Series 1964-92: Annual Mean Exceedances and a Five-Year Running Mean

Fig 5.59(c): Cluden Water at Fiddler's Ford (79005)

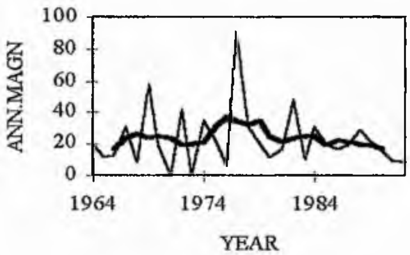


Fig 5.60(c): Urr at Dalbeattie (80001)

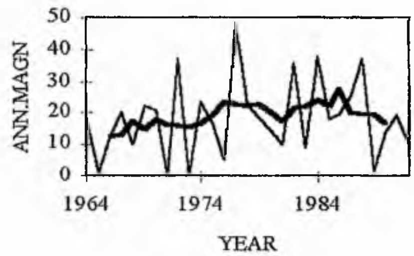


Fig 5.61(c): Cree at Newton Stewart (81002)

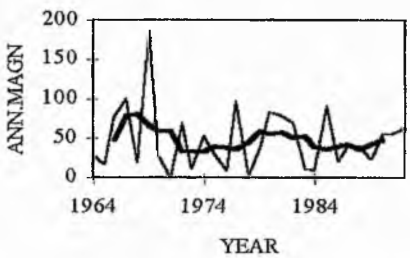


Fig 5.62(c):Girvan at Robstone (82001)

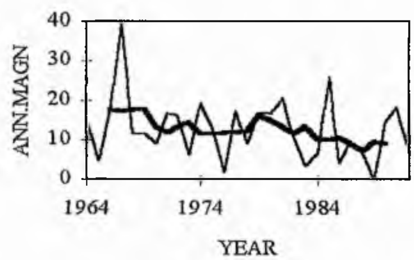


Fig 5.63(c): Kelvin at Killermont (84001)

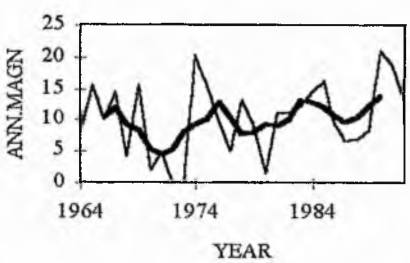


Fig 5.64(c): Clyde at Hazelbank (84003)

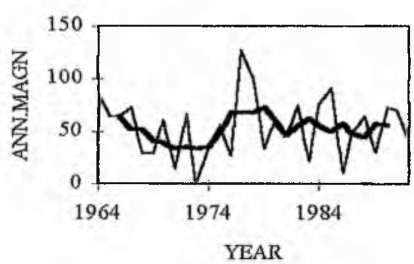


Fig 5.65(c): Clyde at Sills (84004)

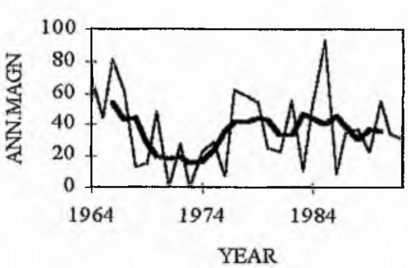
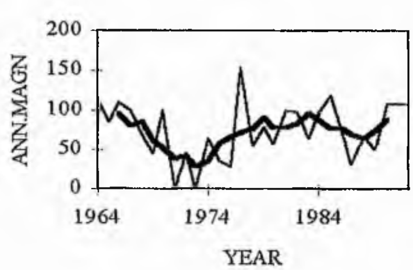


Fig 5.66(c):Clyde at Blairston (84005)



Appendix Two

Figures 5.67(c)-5.69(c)
Flood Magnitude Series 1964-92: Annual Mean Exceedances and a Five-Year Running Mean

Fig 5.67(c): Gryfe at Craigend (84011)

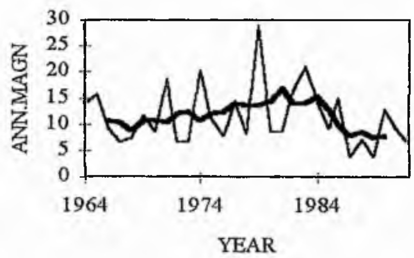


Fig 5.68(c): White Cart Water at Hawkhead (84012)

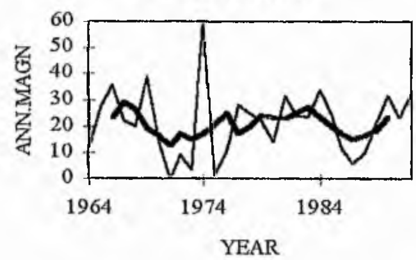
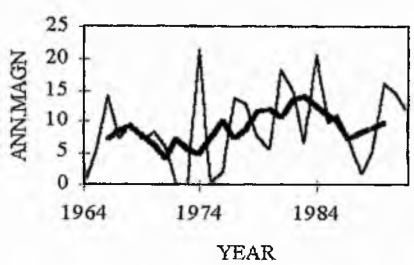


Fig 5.69(c): North Calder Water at Calderpark (84019)



Appendix Two

Figure 5.19(d)-5.26(d): Mann's Test for Trend in the Mean: Flood Magnitude Series 1964-92

Fig 5.19(d): Findhorn at Shenachie (07001)

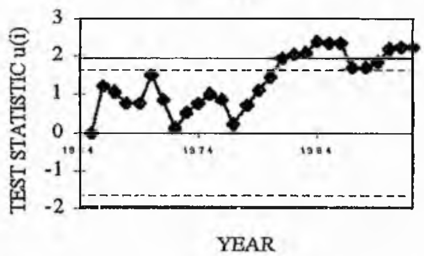


Fig 5.20(d):Findhorn at Forres (07002)

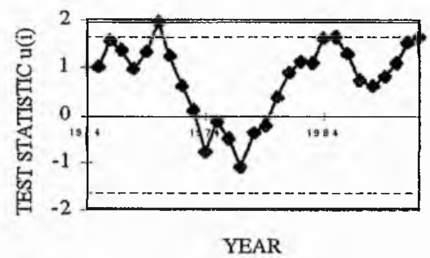


Fig 5.21(d):Lossie at Sheriffmills (07003)

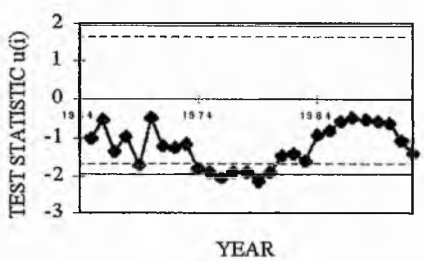


Fig 5.22(d): Avon at Delnashaugh (08004)

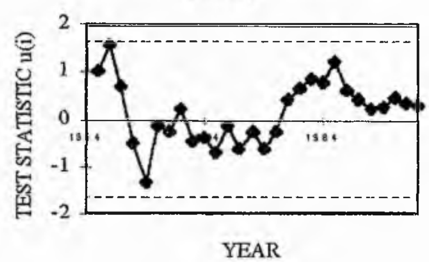


Fig 5.23(d):Spey at Boat of Garten (08005)

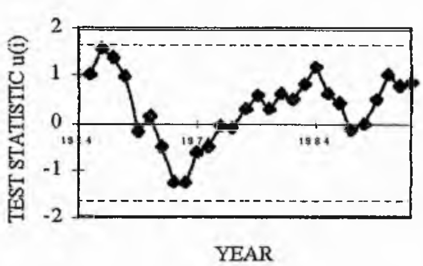


Fig 5.24(d): Spey at Boat O'Brig (08006)

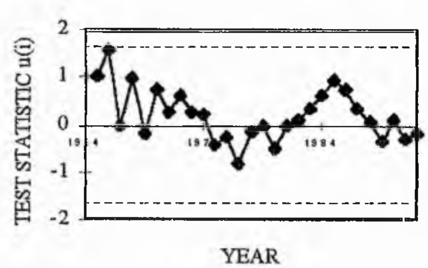


Fig 5.25(d): Spey at Invertruim (08007)

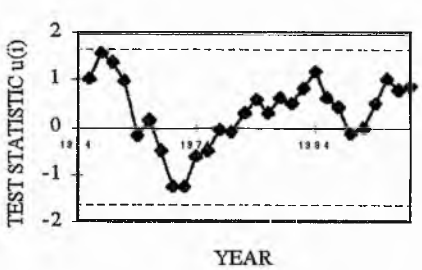
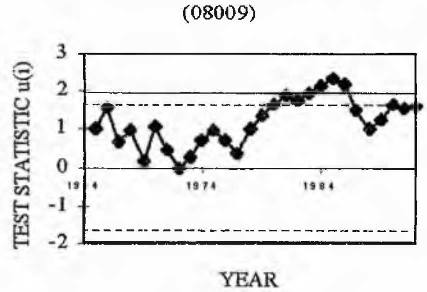


Fig 5.26(d): Dulnain at Balnaan Bridge (08009)



Appendix Two

Figure 5.27(d)-5.34(d): Mann's Test for Trend in the Mean: Flood Magnitude Series 1964-92

Fig 5.27(d): Spey at Grantown (08010)

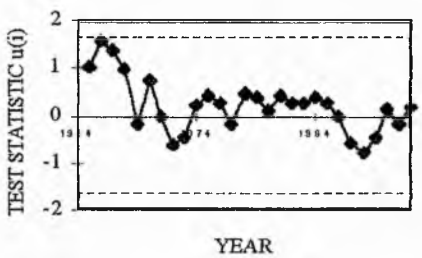


Fig 5.28(d):Deveron at Avochie (09001)

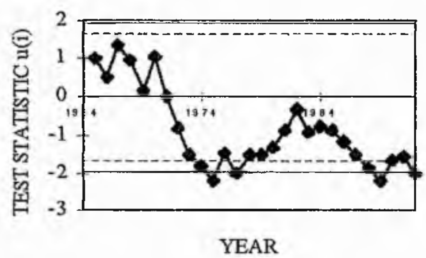


Fig 5.29(d):Deveron at Muiresk (09002)

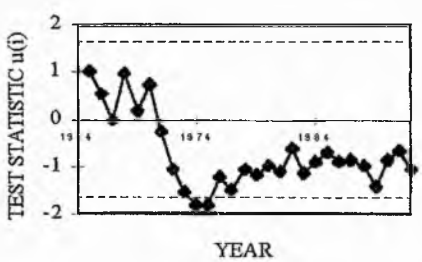


Fig 5.30(d): Isla at Grange (09003)

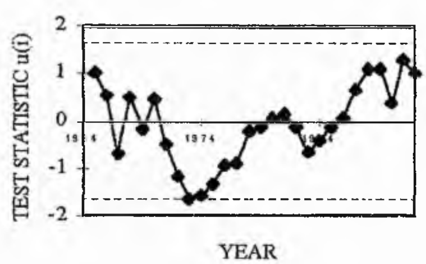


Fig 5.31(d):Dee at Woodend (12001)

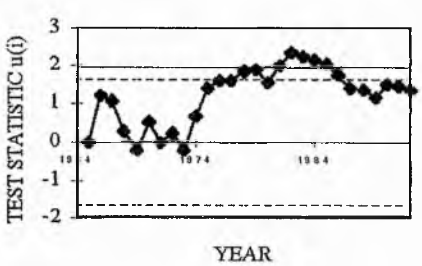


Fig 5.32(d): Tay at Caputh (15003)

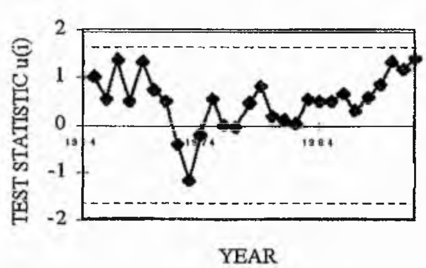


Fig 5.33(d): Tay at Ballathie (15006)

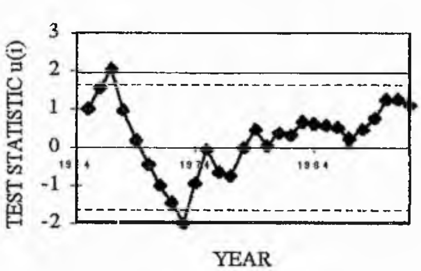
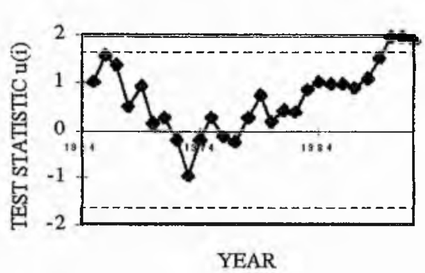


Fig 5.34(d):Tay at Pitnacree (15007)



Appendix Two

Figure 5.35(d)-5.42(d): Mann's Test for Trend in the Mean: Flood Magnitude Series 1964-92

Fig 5.35(d): Dean Water at Cookston (15008)

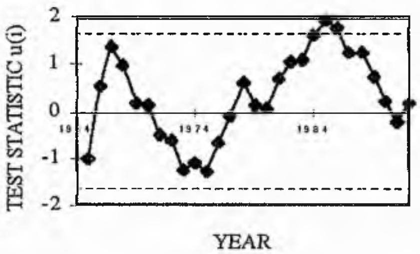


Fig 5.36(d):Earn at Kinkell Bridge (16001)

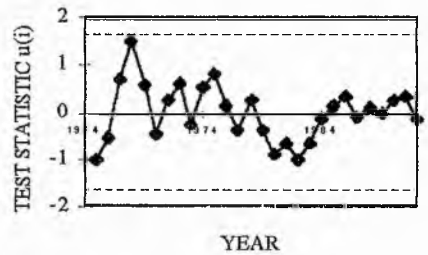


Fig 5.37(d):Ruchill Water at Cultybraggan (16003)

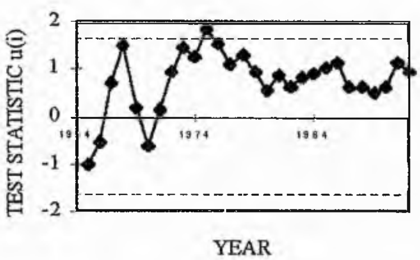


Fig 5.38(d): Almond at Craigiehall (19001)

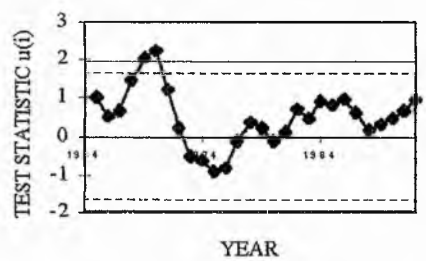


Fig 5.39(d):Almond at Almond Weir (19002)

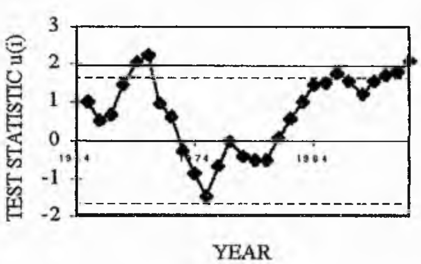


Fig 5.40(d): North Esk at Dalmore Weir (19004)

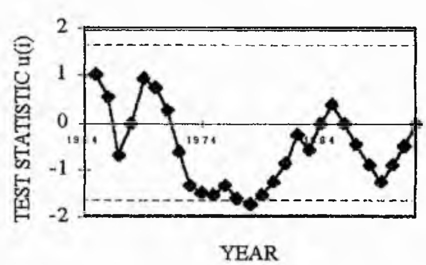


Fig 5.41(d): Water of Leith at Murrayfield (19006)

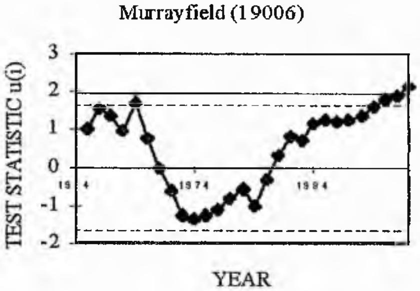
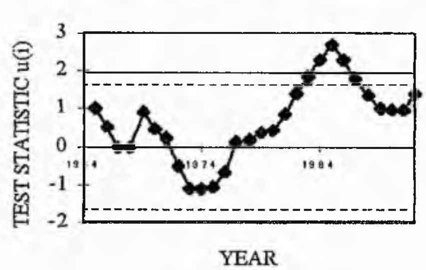


Fig 5.42(d): Esk at Musselburgh (19007)



Appendix Two

Figure 5.43(d)-5.50(d): Mann's Test for Trend in the Mean: Flood Magnitude Series 1964-92

Fig 5.43(d): North Esk at Dalkeith Place (19011)

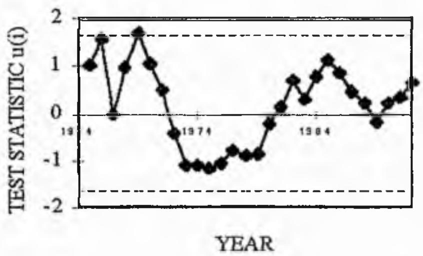


Fig 5.44(d):Tyne at East Linton (20001)

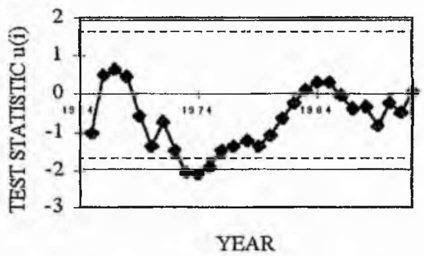


Fig 5.45(d):Tyne at Spilmersford (20003)

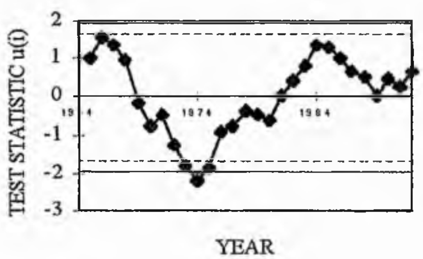


Fig 5.46(d): Birns Water at Saltoun Hall (20005)

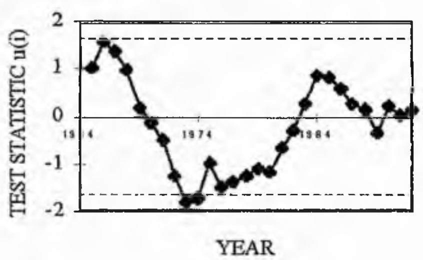


Fig 5.47(d):Tweed at Peebles (21003)

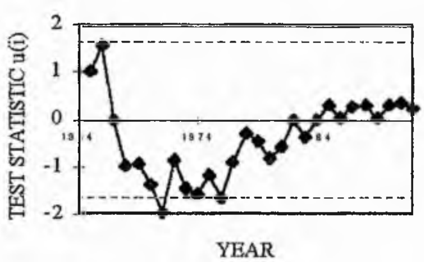


Fig 5.48(d): Tweed at Lyne Ford (21005)

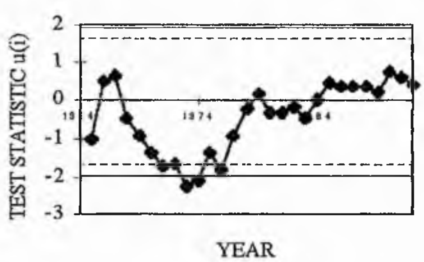


Fig 5.49(d): Tweed at Boleside (21006)

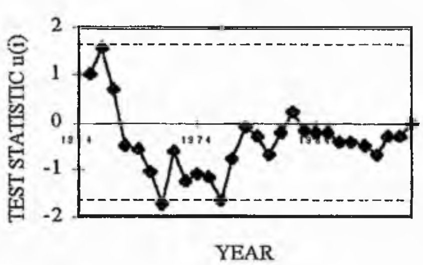
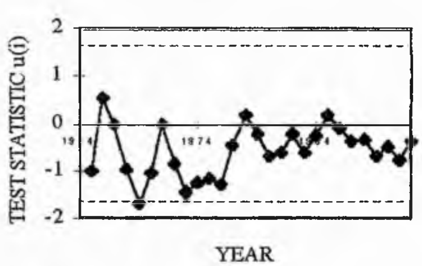


Fig 5.50(d): Ettrick Water at Lindean (21007)



Appendix Two

Figure 5.51(d)-5.58(d): Mann's Test for Trend in the Mean: Flood Magnitude Series 1964-92

Fig 5.51(d): Teviot at Ormiston Mill (21008)

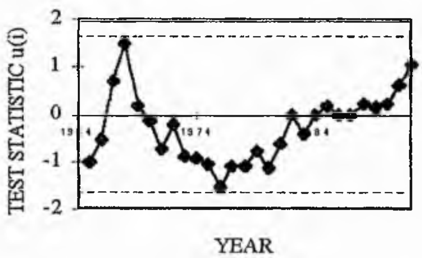


Fig 5.52(d):Tweed at Norham (21009)

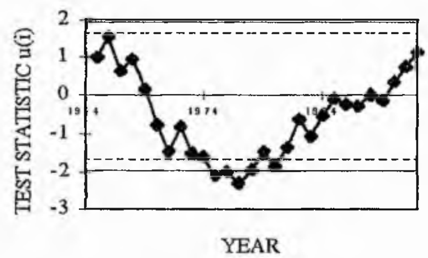


Fig 5.53(d):Yarrow Water at Philiphaugh (21011)

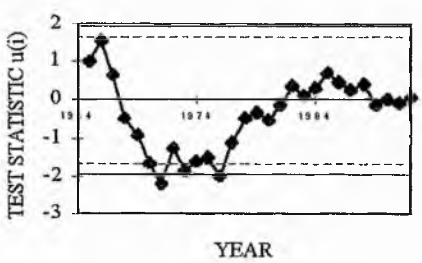


Fig 5.54(d): Teviot at Hawick (21012)

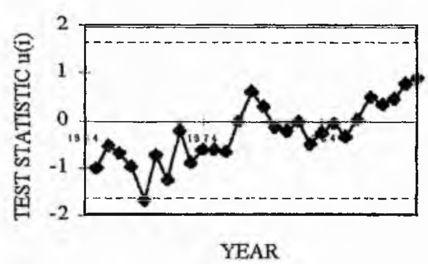


Fig 5.55(d):Gala Water at Galashiels (21013)

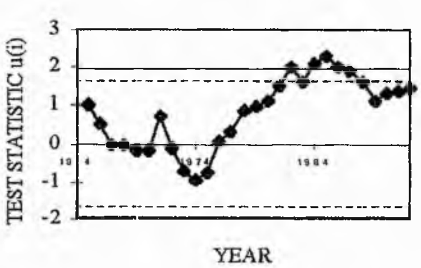


Fig 5.56(d): Nith at Friar's Carse (79002)

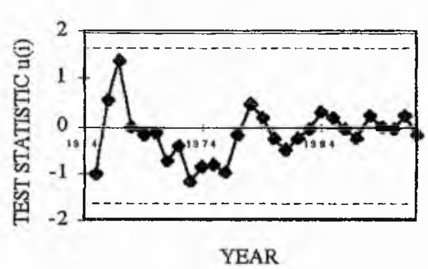


Fig 5.57(d): Nith at Hallbridge (79003)

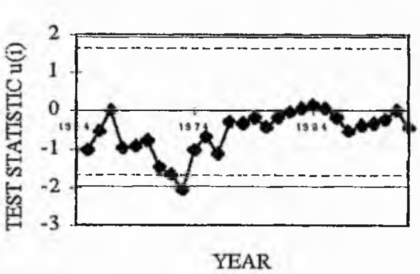
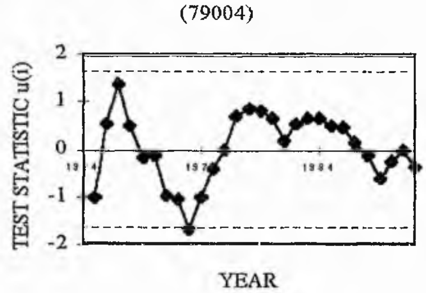


Fig 5.58(d):Scar Water at Capenoch (79004)



Appendix Two

Figure 5.59(d)-5.66(d): Mann's Test for Trend in the Mean: Flood Magnitude Series 1964-92

Fig 5.59(d): Cluden Water at Fiddler's Ford (79005)

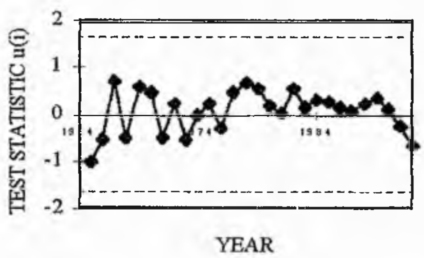


Fig 5.60(d):Urr at Dalbeattie (80001)

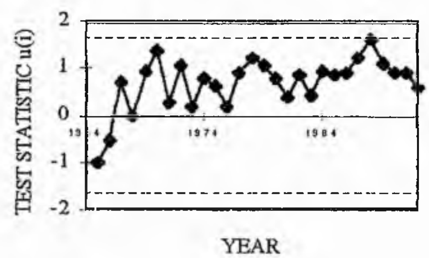


Fig 5.61(d):Cree at Newton Stewart (81002)

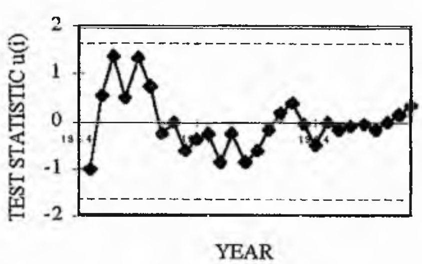


Fig 5.62(d): Girvan at Robstone (82001)

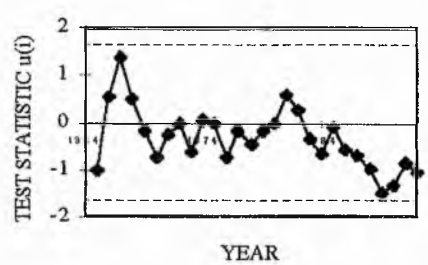


Fig 5.63(d):Kelvin at Killermont (84001)

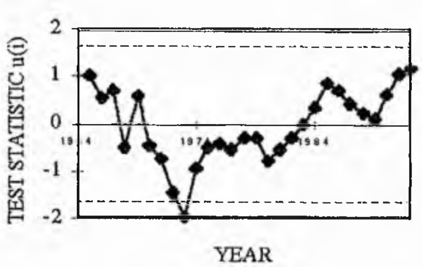


Fig 5.64(d): Clyde at Hazelbank (84003)

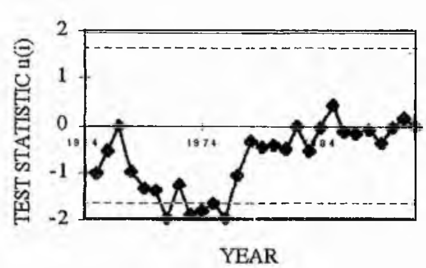


Fig 5.65(d): Clyde at Sills (84004)

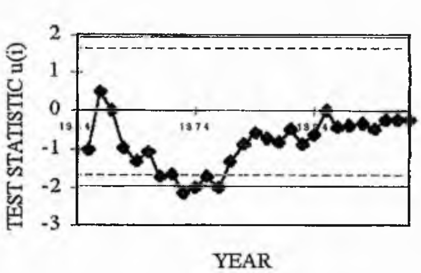
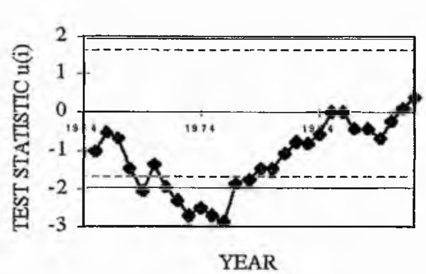
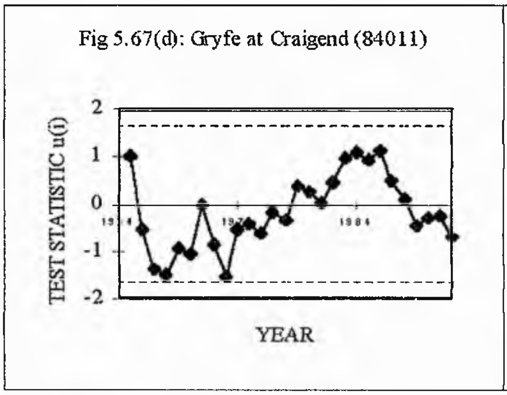


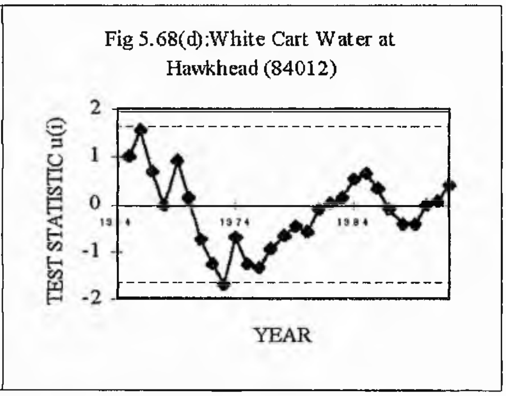
Fig 5.66(d): Clyde at Blairston (84005)

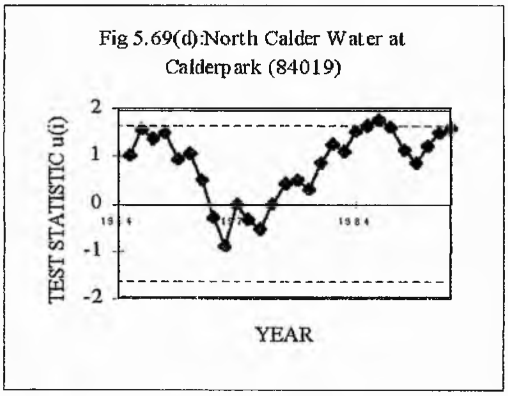


Appendix Two

Figure 5.67(d)-5.69(d): Mann's Test for Trend in the Mean: Flood Magnitude Series 1964-92







Appendix Two

Table 5.13(a): Cluster 1 mean exceedance series 1964-92: Mann's Test for Trend in the Mean

MEAN EXCEEDANCE SERIES	CHARACTERISTICS
Lossie at Sheriffmills (07003)	*Gradual decline in magnitudes until the early 1980s then values increase slightly and stabilise:* u(i): downward trend by mid 1970s (5% conf.level) Figure 5.21(d)
Deveron at Avochie (09001)	*Magnitudes decline to mid 1970s, then increase until early 1980s then decrease once more:* u(i):downward trend (5% conf.level) by 1977 u(i):downward trend (5% conf.level) by 1989 Figure 5.28(d)
Deveron at Muiresk (09002)	*Magnitudes decline until the early 1970s and remain generally low:* u(i):downward trend (10% conf.level) Figure 5.29(d)
North Esk at Dalmore Weir (19004)	*A decrease in values occurs until the mid 1970s; magnitudes continue to fluctuate* Figure 5.40(d)
Tyne at East Linton (20001) **Tweed at Peebles (21003)** **Tweed at Lyne Ford (21005)** **Tweed at Boleside (21006)** **Ettrick Water at Lindean (21007)** **Yarrow Water at Philiphaugh (21011)**	*Magnitudes decrease to the mid 1970s, then increase and remain stable during the 1980s:* u(i): downward trend in 1970s (5% conf.level) Figures 5.44(d), 5.47(d)-5.50(d) and 5.53(d)
Tweed at Norham (21009) **Clyde at Blairston (84005)**	*Magnitudes decrease during the 1970s and increase thereafter:* u(i):downward trend (5% conf.level) Figures 5.52(d) and 5.66(d)

Table 5.13(b): Cluster 2 mean exceedance series 1964-92: Mann's Test for Trend in the Mean

MEAN EXCEEDANCE SERIES	CHARACTERISTICS
Findhorn at Shenachie (07001) **Dulnain at Balnaan Bridge (08009)** **Dee at Woodend (12001)** **Teviot at Hawick (21012)**	*Magnitudes stable until mid 1970s, then increase until late 1980s and then decrease slightly:* u(i):upward trend by 1981 (5% conf.level) Figures 5.19(d), 5.26(d), 5.31(d) and 5.54(d)
Ruchill Water at Cultybraggan (16003)	*Magnitudes increase gradually throughout the record:* u(i): upward trend (5% conf.level) Figure 5.37(d)
Urr at Dalbeattie (80001)	*Magnitudes increase to mid 1970s, then decrease slightly and stabilise:* u(i): upward trend (5% conf.level) Figure 5.60(d)

Table 5.13(c): Cluster 3 mean exceedance series 1964-92: Mann's Test for Trend in the Mean

MEAN EXCEEDANCE SERIES	CHARACTERISTICS
Avon at Delnashaugh (08004) **Spey at Boat of Garten (08005)** **Spey at Invertruim (08007)** **Spey at Grantown (08010)** **Isla at Grange (09003)** **Tay at Ballathie (15006)** **Dean Water at Cookston (15008)** **Tyne at Spilmersford (20003)** **Birns Water at Saltoun Hall (20005)** **Teviot at Ormiston Mill (21008)** **Nith at Friar's Carse (79002)** **Nith at Hall Bridge (79003)** **Scar Water at Capenoch (79004)** **Kelvin at Killermont (84001)** **Clyde at Hazelbank (84003)** **Clyde at Sills (84004)** **White Cart Water at Hawkhead (84012)**	*Magnitudes show a short, sharp decline to the mid 1970s, then an increase to the mid 1980s* u(i): some downward trends apparent but not highly significant Figures 5.22(d), 5.23(d), 5.25(d), 5.27(d), 5.30(d), 5.33(d), 5.35(d), 5.45(d), 5.46(d), 5.51(d), 5.56(d)-5.58(d), 5.63(d)-5.65(d) and 5.68(d)
Spey at Boat o'Brig (08006) **Cluden Water at Fiddler's Ford (79005)**	*Random time series as* u(i): approximately zero Figures 5.24(d) and 5.59(d)
Earn at Kinkell Bridge (16001)	*Magnitudes appear slightly lower in the early 1980s* u(i): no trends Figure 5.36(d)
Teviot at Hawick (21012)	*Magnitudes increase throughout the period of record;* u(i): no trends Figure 5.54(d)
Cree at Newton Stewart (81002)	*Magnitudes are higher in the early part of the record, then stabilise;* u(i): no trends Figure 5.61(d)
Girvan at Robstone (82001)	*Magnitudes stable until a decrease in the mid 1980s* u(i): no trends Figure 5.62(d)
Gryfe at Craigend (84011)	*Magnitudes appear lower in the 1960s and 1970s, peak in the 1980s and then decline again;* u(i): no trends Figure 5.67(d)

Appendix Two

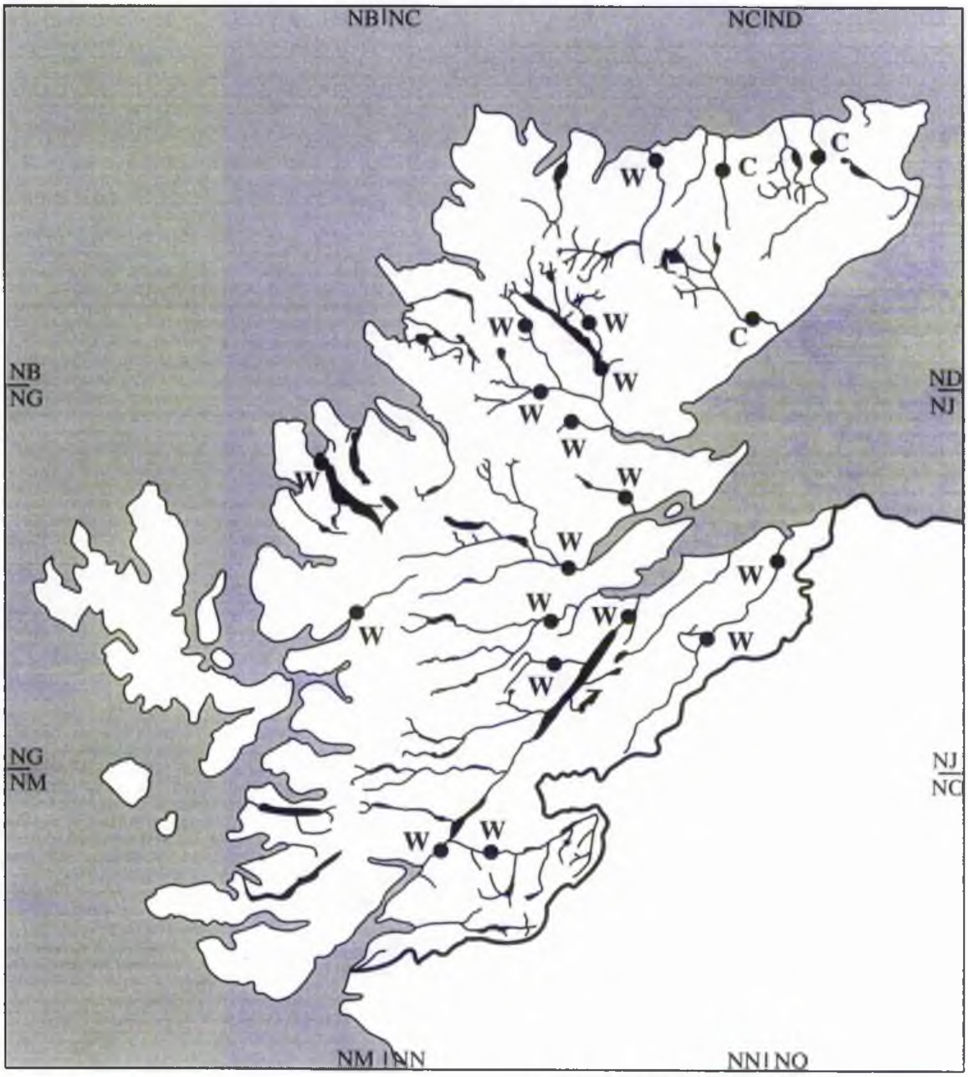
Table 5.13(d): Cluster 4 mean exceedance series 1964-92: Mann's Test for Trend in the Mean

MEAN EXCEEDANCE SERIES	CHARACTERISTICS
Findhorn at Forres (07002) **Tay at Caputh (15003)** **Tay at Pitnacree (15007)** **Almond at Craigiehall (19001)** **Almond at Almond Weir (19002)** **Water of Leith at Murrayfield (19006)** **Esk at Musselburgh (19007)** **North Esk at Dalkeith Place (19011)** **N.Calder Water at Calderpark (84019)**	*Magnitudes peak early in the early 1970s, then decrease until the mid 1970s and increase thereafter:* u(i):upward trend (5% conf.level) Figures 5.20(d), 5.32(d), 5.34(d), 5.38(d), 5.39(d), 5.41(d)-5.43(d) and 5.69(d)

APPENDIX THREE

Appendix Three

Map 6.1: Highland RPB: Primary Mayes Weather Type on the 'Day of Flood'

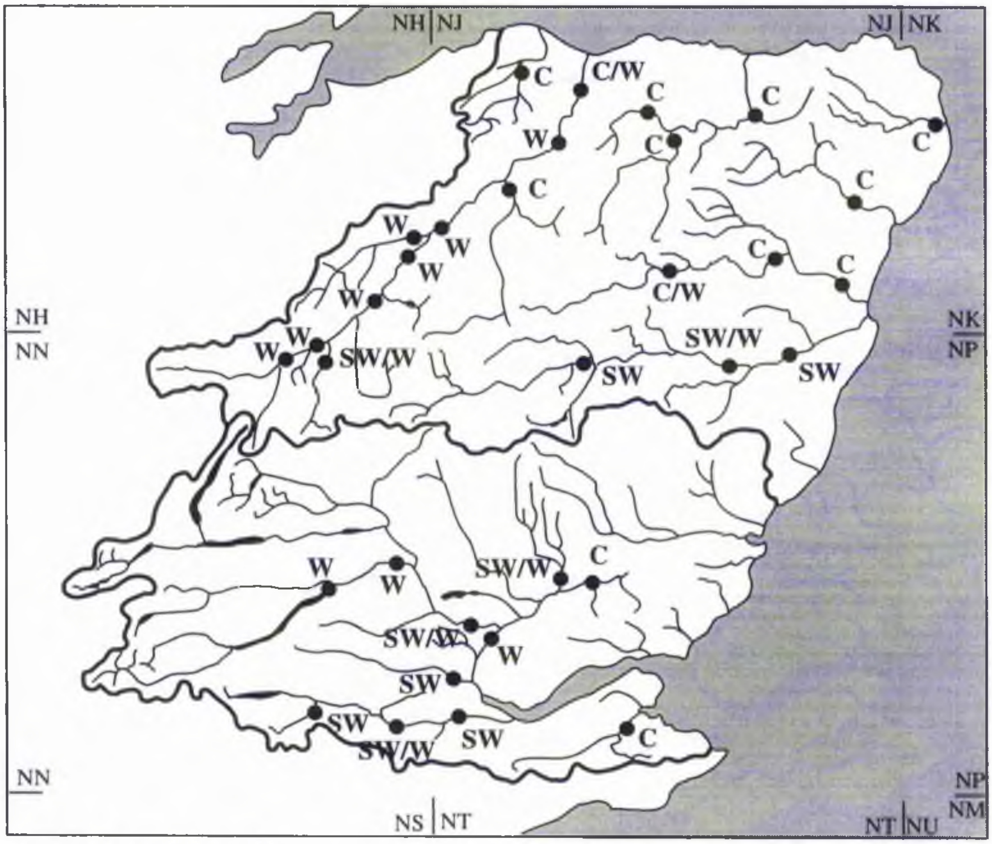


AREA 23,110 KM²

RPB BOUNDARIES	
PRIMARY WEATHER TYPE	W

BASED ON: HYDROLOGICAL DATA UK - HYDROMETRIC REGISTER AND STATISTICS 1986-1990 (NERC, 1993)

Map 6.2: North-East and Tay RPBs: Primary Mayes Weather Type on the 'Day of Flood'

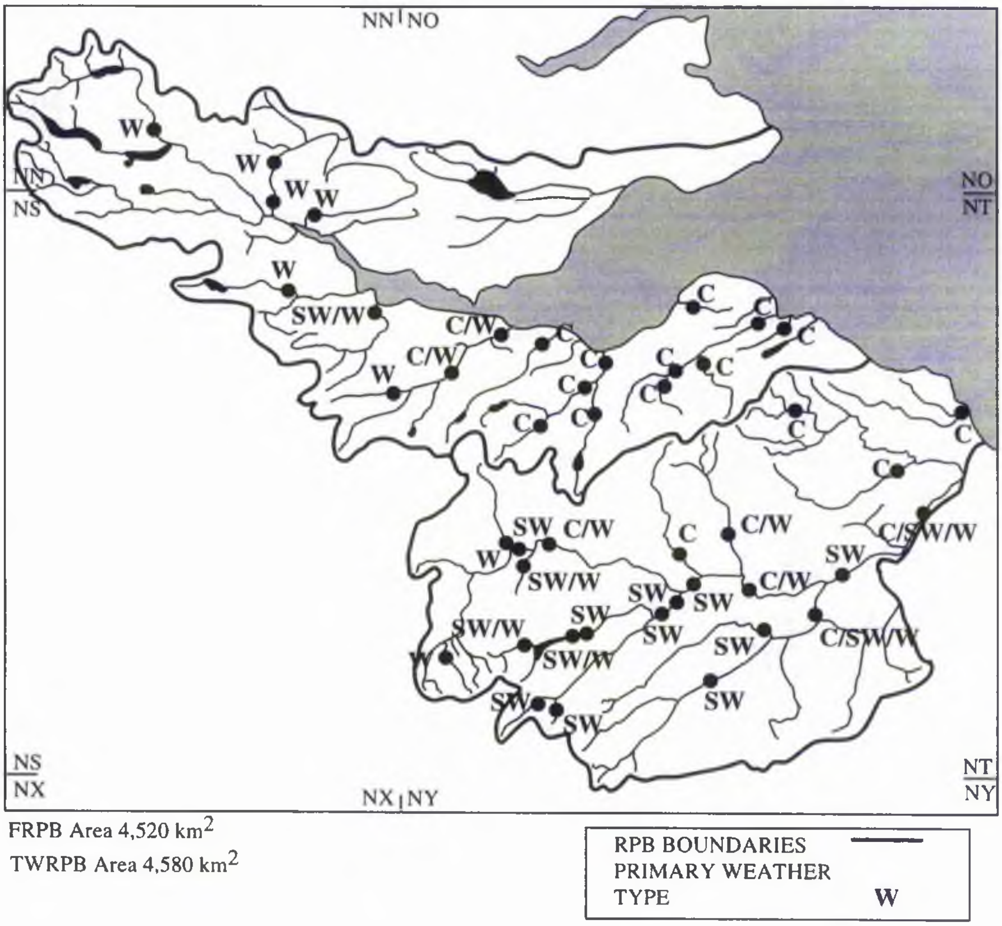


NERPB Area 10,420 km^2
TPRB Area 8,710 km^2

RPB BOUNDARIES	———
PRIMARY WEATHER TYPE	W

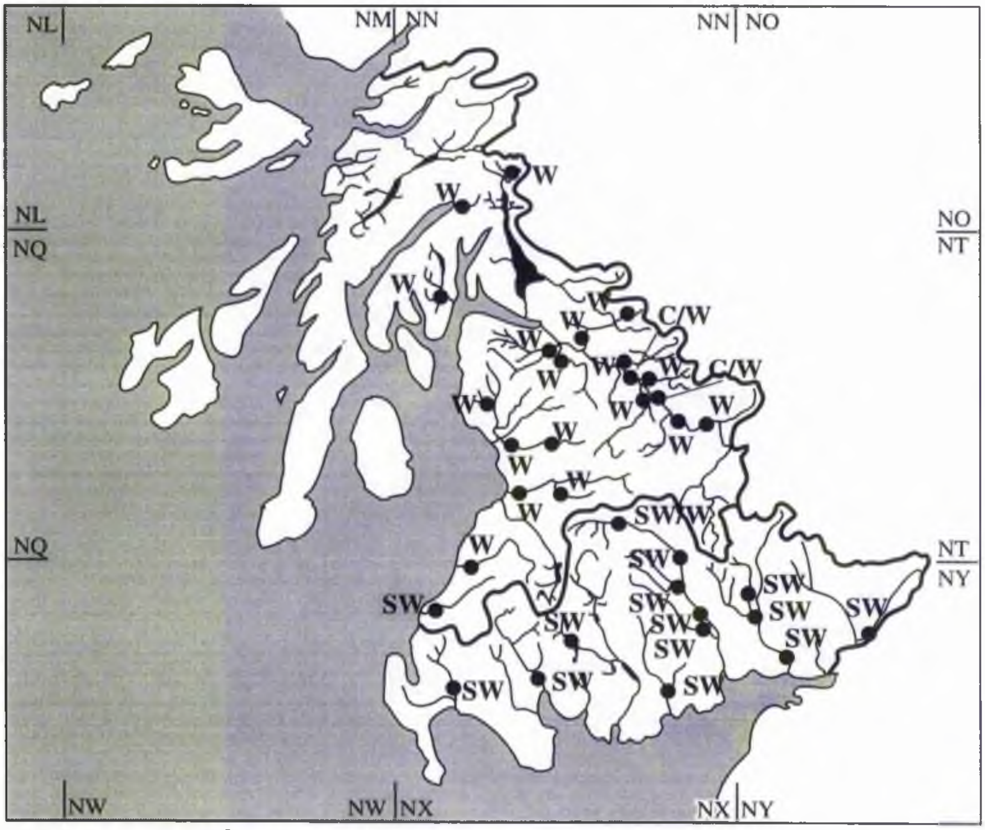
BASED ON: HYDROLOGICAL DATA UK - HYDROMETRIC REGISTER AND STATISTICS 1986-1990 (NERC, 1993)

Map 6.3: Forth and Tweed RPBs: Primary Mayes Weather Type on the 'Day of Flood'



BASED ON: HYDROLOGICAL DATA UK - HYDROMETRIC REGISTER AND STATISTICS 1986-1990 (NERC, 1993)

Map 6.4: Solway and Clyde RPBs: Primary Mayes Weather Type on the 'Day of Flood'

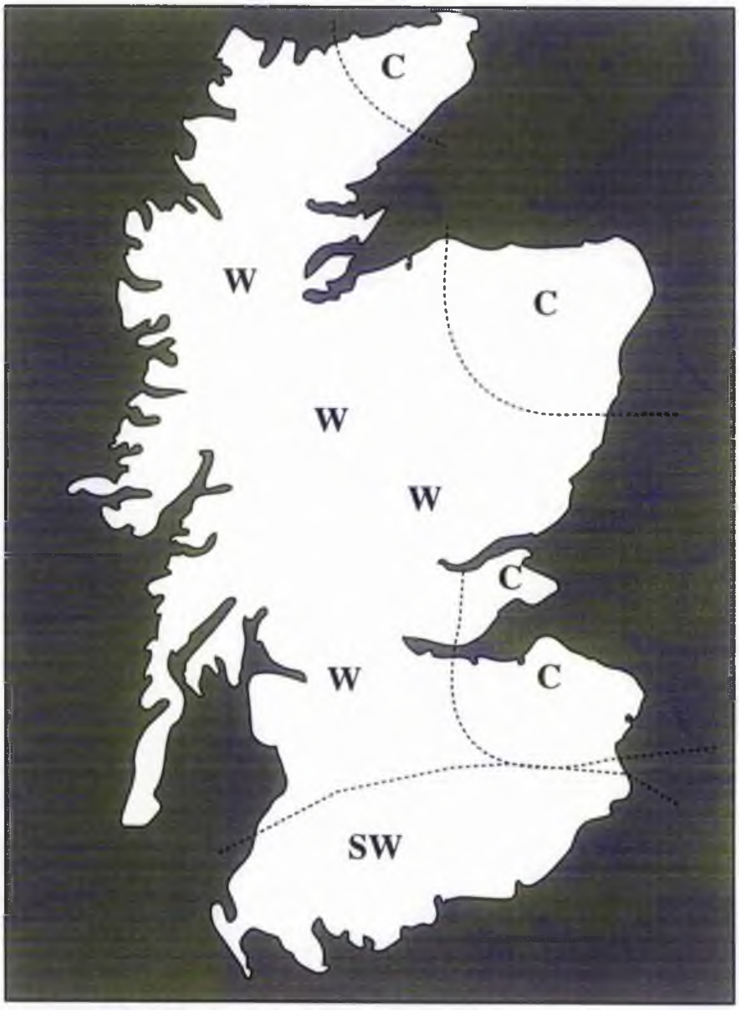


SRPB Area 6,790 km^2
CRPB Area 13,555 km^2

RPB BOUNDARIES	
PRIMARY WEATHER TYPE	**W**

BASED ON: HYDROLOGICAL DATA UK - HYDROMETRIC REGISTER AND STATISTICS 1986-90 (NERC, 1993)

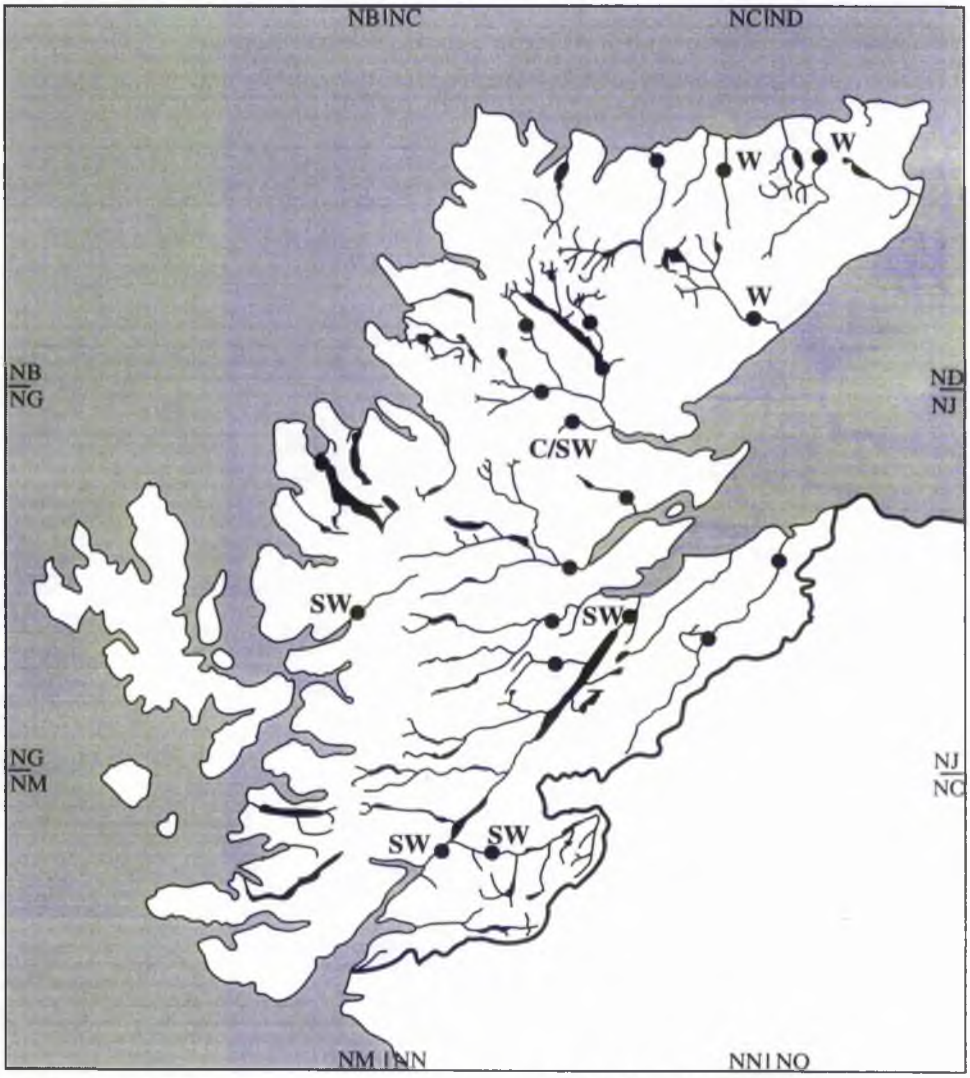
Map 6.5: A summary of the primary flood trigger weather types (Mayes record)



C	Cyclonic
W	Westerly
SW	South-Westerly

Appendix Three

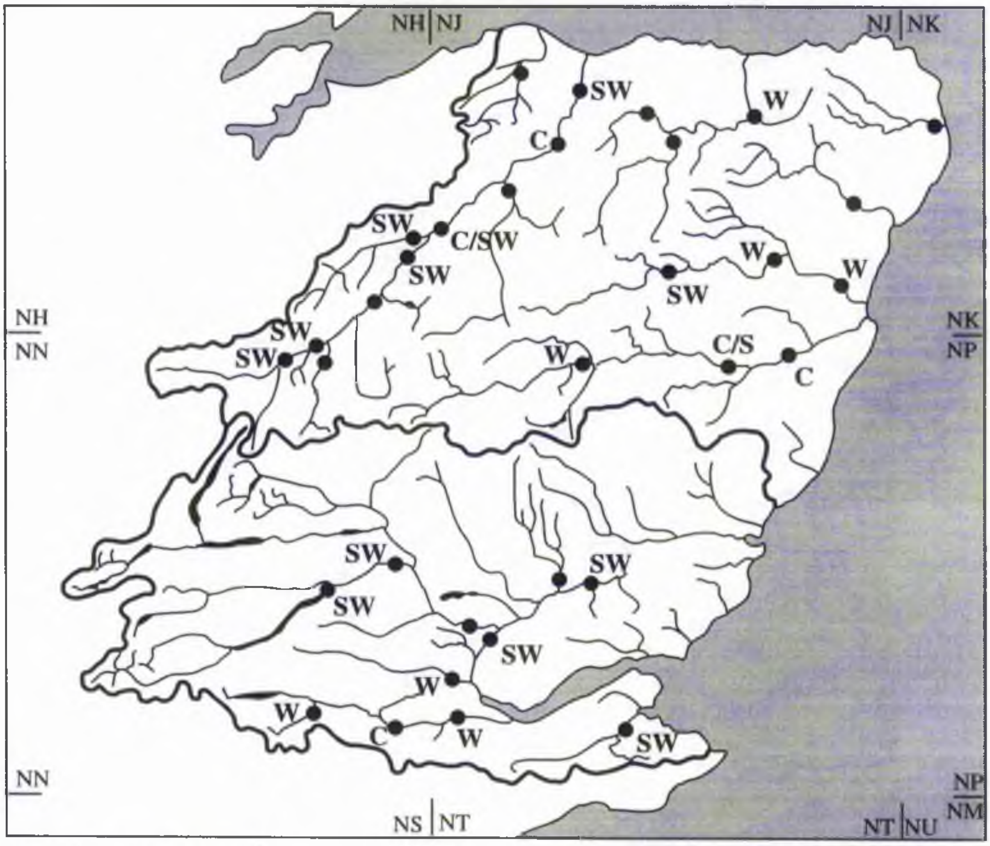
Map 6.6: Highland RPB: Secondary Mayes Weather Type on the 'Day of Flood'



AREA 23,110 KM^2

RPB BOUNDARIES
SECONDARY WEATHER TYPE **W**

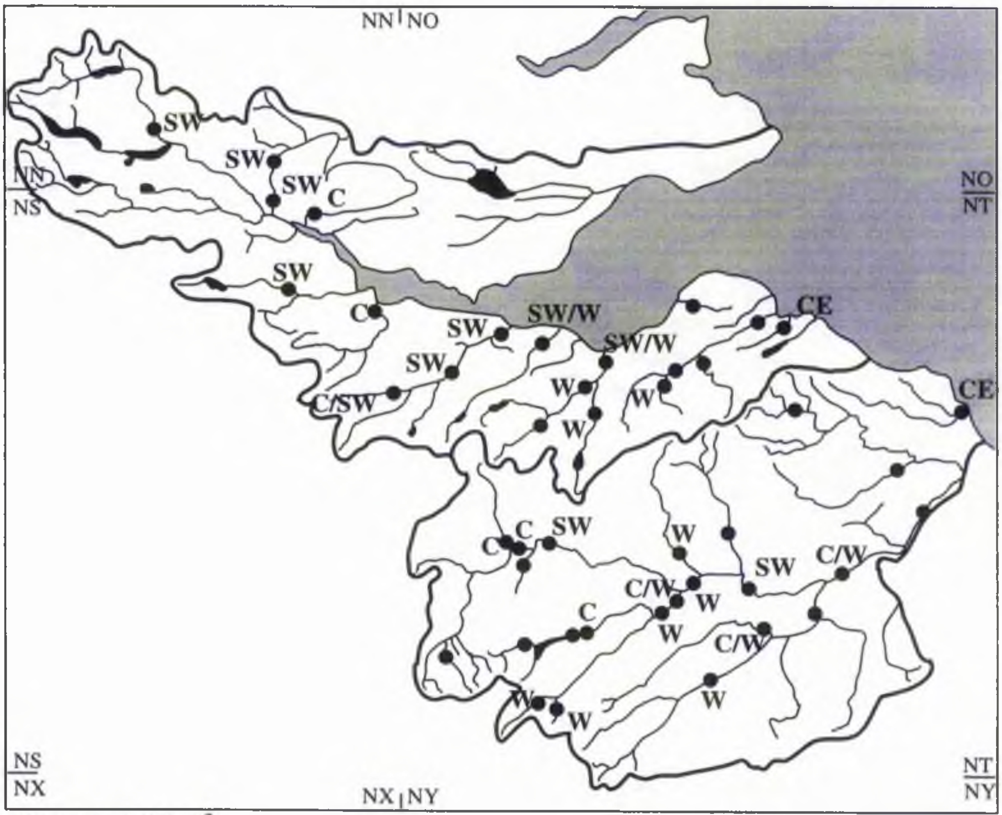
Map 6.7: North-East and Tay RPBs: Secondary Mayes Weather Type on the 'Day of Flood'



NERPB Area 10,420 km^2
TPRB Area 8,710 km^2

RPB BOUNDARIES	———
SECONDARY WEATHER TYPE	**W**

Map 6.8: Forth and Tweed RPBs: Secondary Mayes Weather Type on the 'Day of Flood'

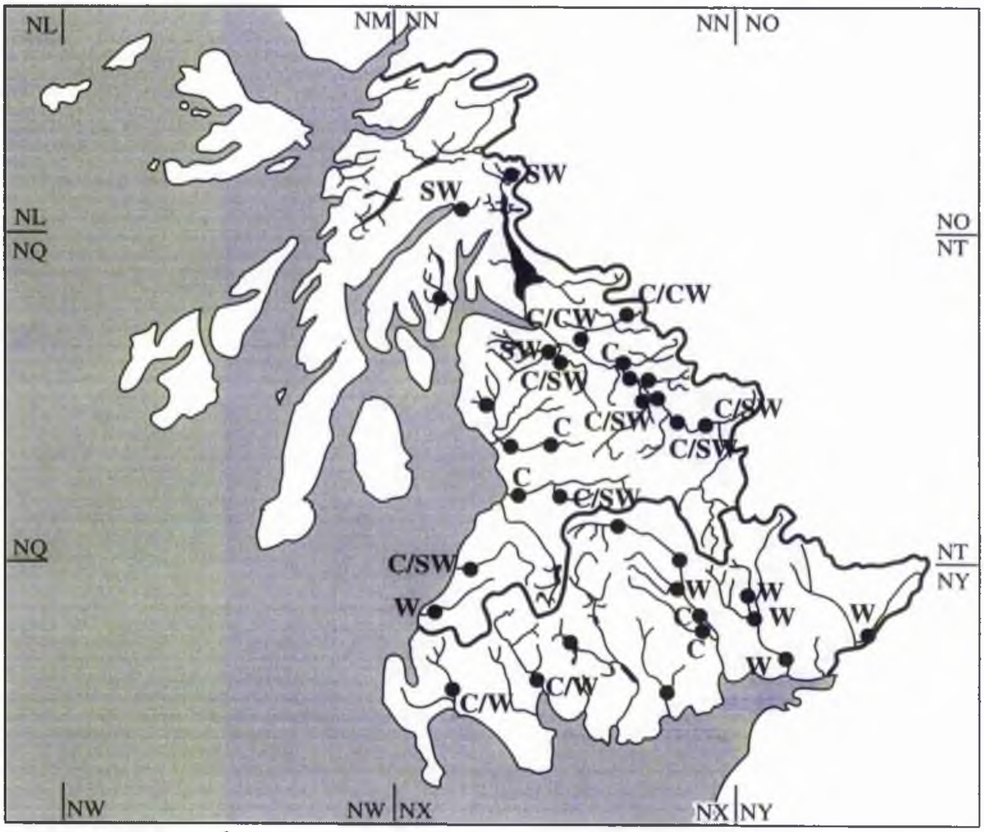


FRPB Area 4,520 km^2
TWRPB Area 4,580 km^2

RPB BOUNDARIES	
SECONDARY WEATHER TYPE	W

Appendix Three

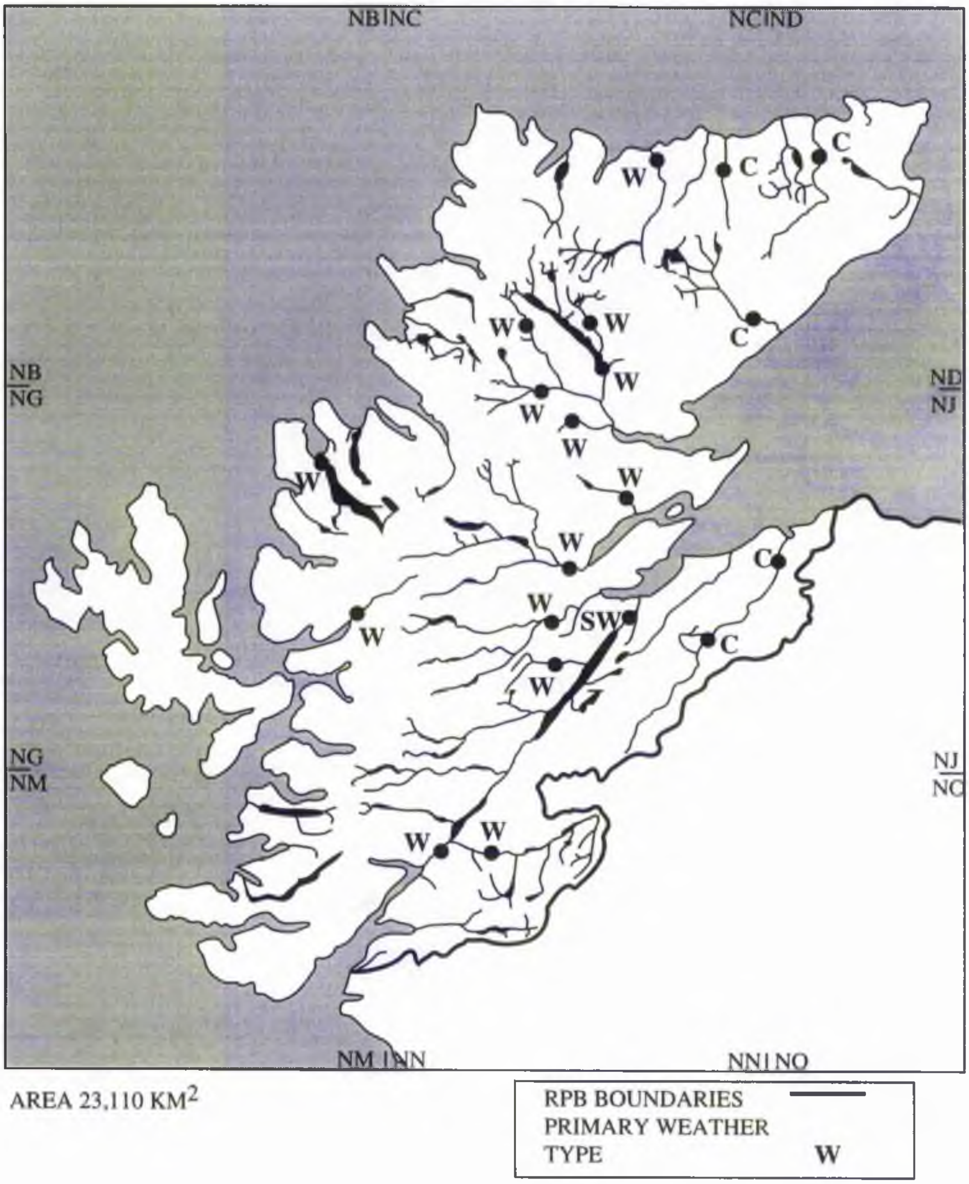
Map 6.9 Solway and Clyde RPBs: Secondary Mayes Weather Type on the 'Day of Flood'



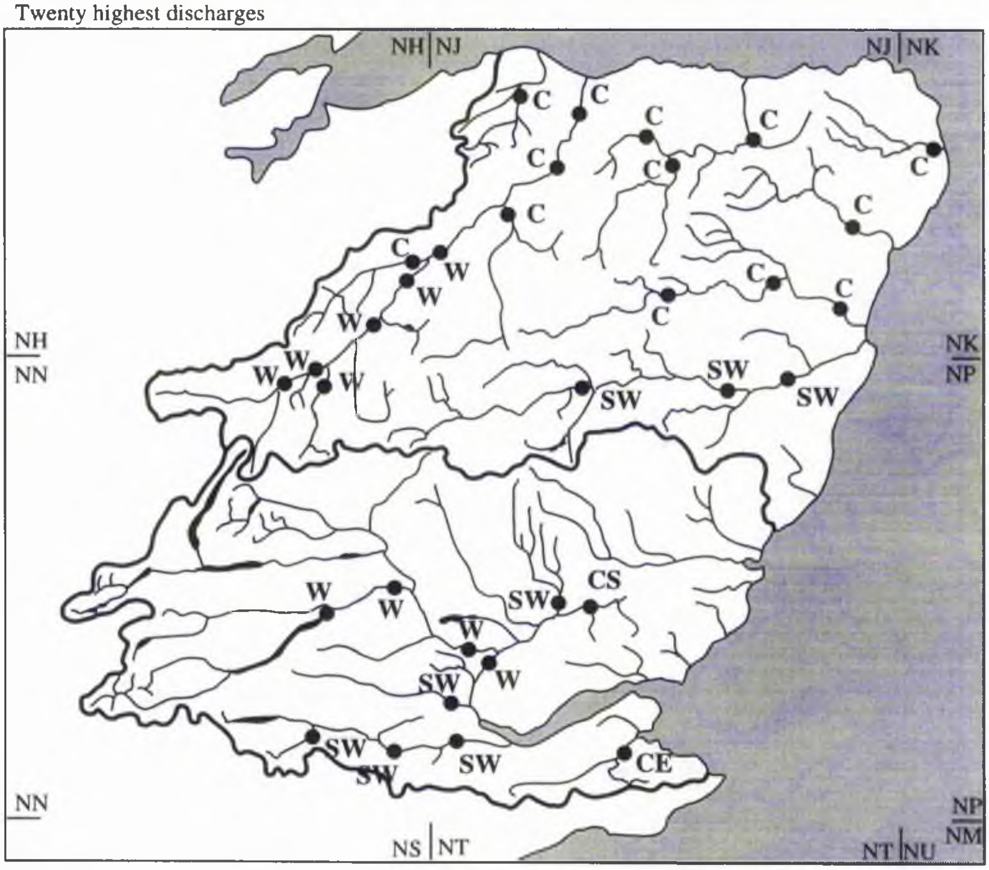
SRPB Area 6,790 km^2
CRPB Area 13,555 km^2

RPB BOUNDARIES	———
SECONDARY WEATHER TYPE	**W**

Map 6.10: Highland RPB: Primary Mayes Weather Type on the 'Day of Flood': Twenty highest discharges



Map 6.11: North-East and Tay RPBs: Primary Mayes Weather Type on the 'Day of Flood': Twenty highest discharges

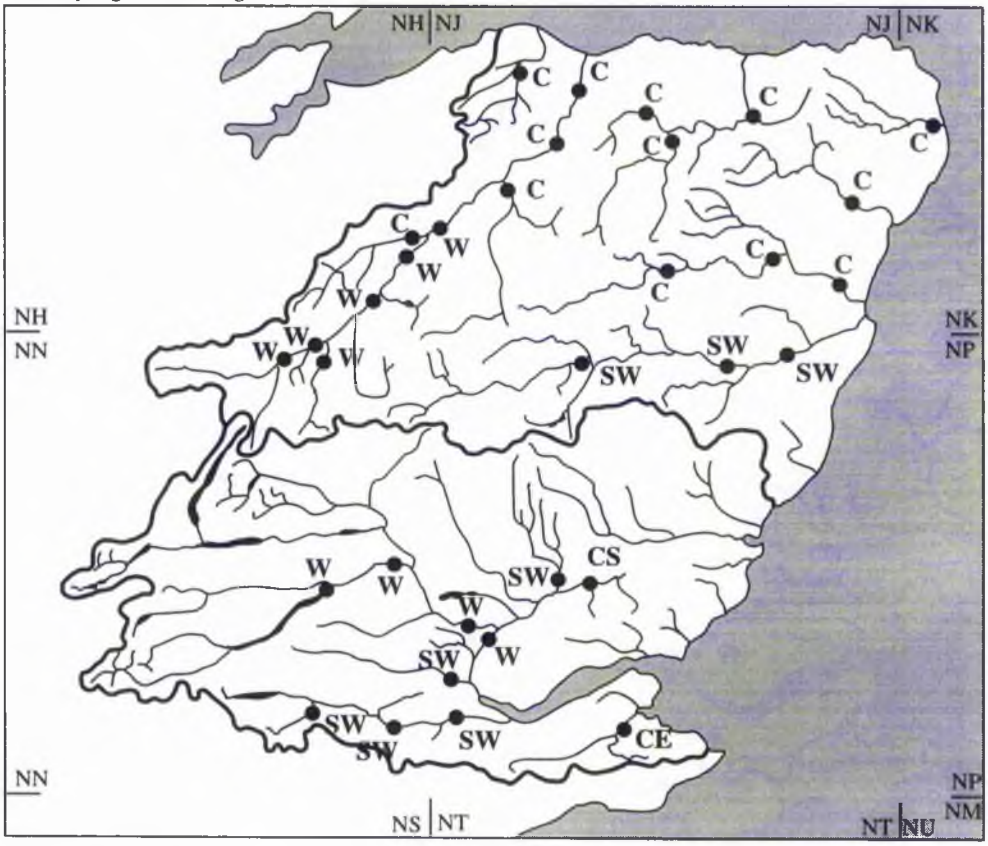


NERPB Area 10,420 km^2

TPRB Area 8,710 km^2

RPB BOUNDARIES	———
PRIMARY WEATHER TYPE	**W**

Map 6.11: North-East and Tay RPBs: Primary Mayes Weather Type on the 'Day of Flood': Twenty highest discharges

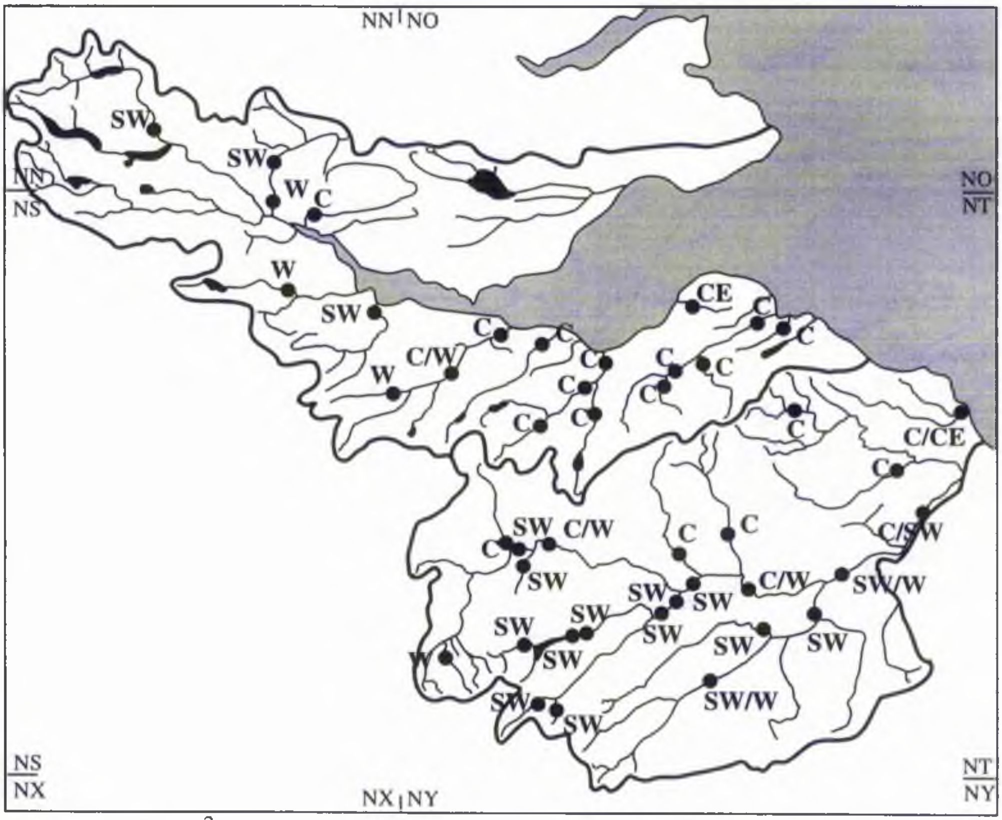


NERPB Area 10,420 km^2

TPRB Area 8,710 km^2

RPB BOUNDARIES	
PRIMARY WEATHER TYPE	W

Map 6.12: Forth and Tweed RPBs: Primary Mayes Weather Type on the 'Day of Flood': Twenty highest discharges

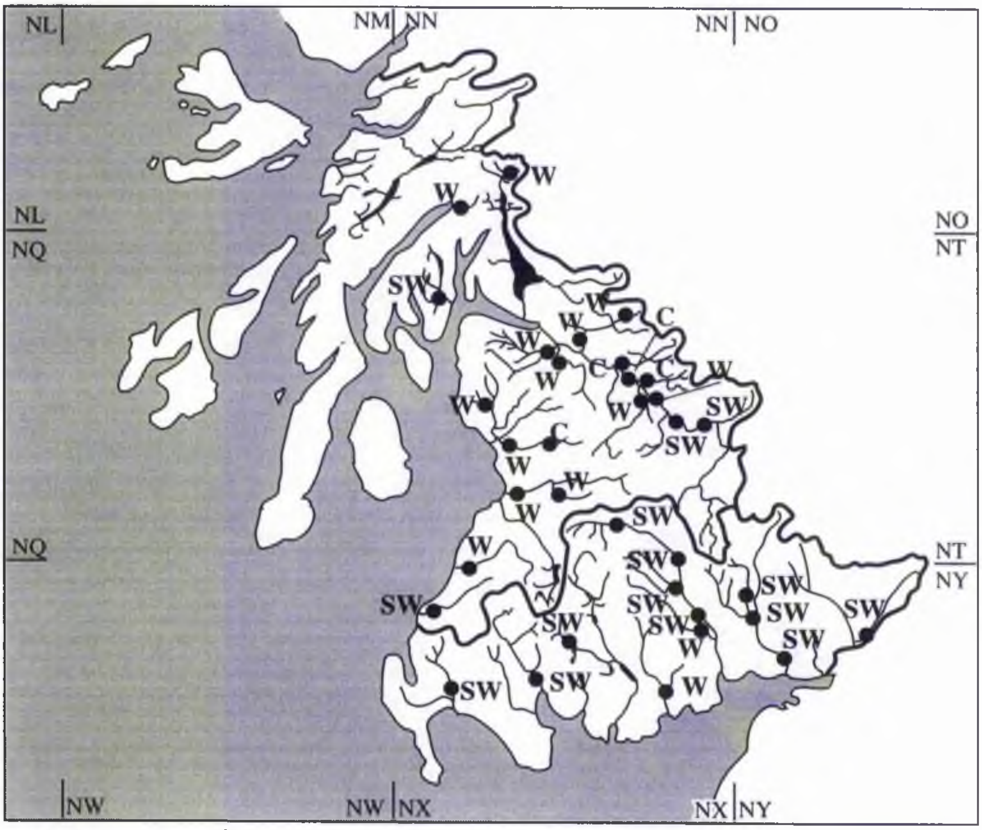


FRPB Area 4,520 km^2

TWRPB Area 4,580 km^2

RPB BOUNDARIES	
PRIMARY WEATHER TYPE	**W**

Map 6.13: Solway and Clyde RPBs: Primary Mayes Weather Type on the 'Day of Flood': Twenty highest discharges



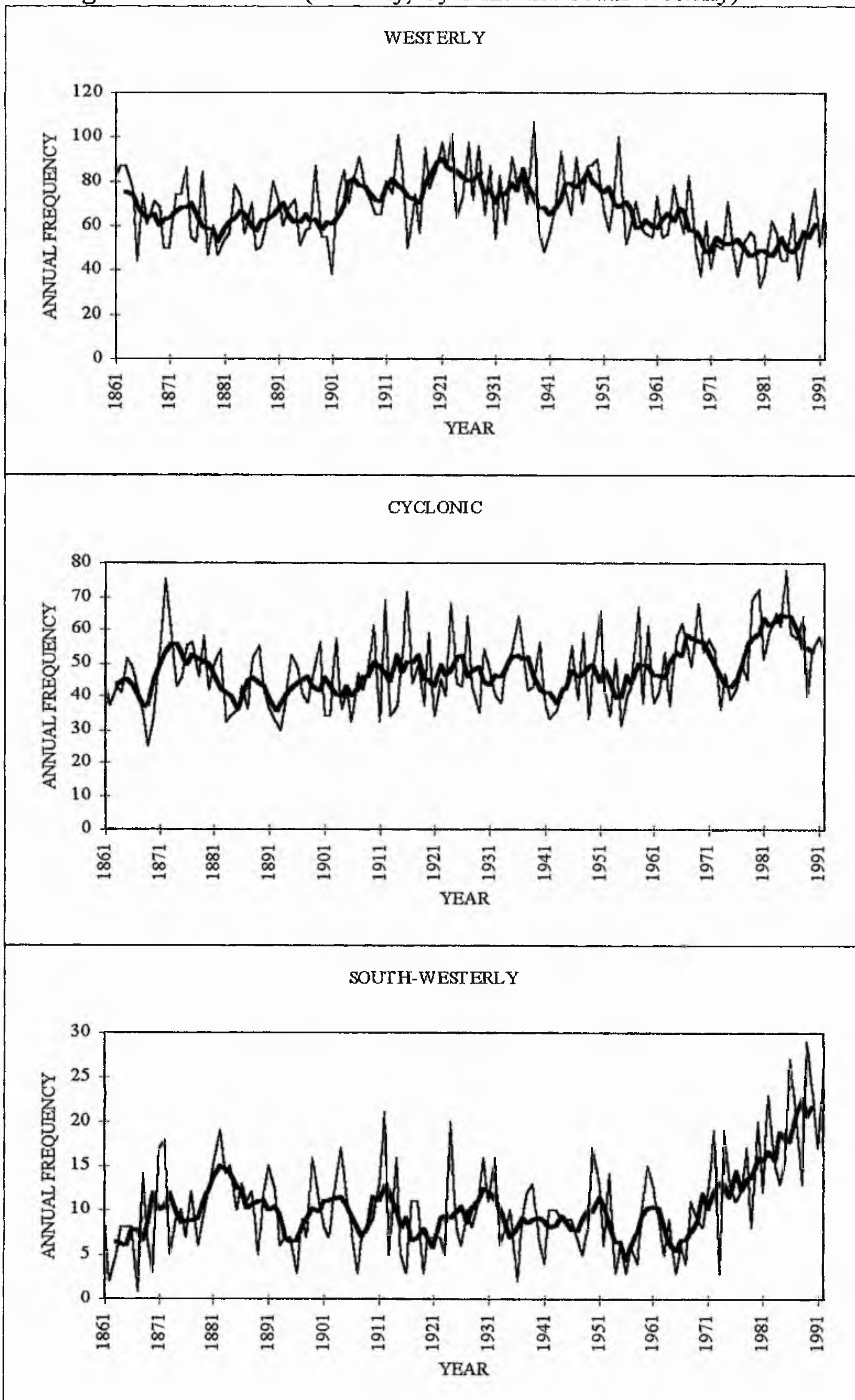
SRPB Area 6,790 km^2
CRPB Area 13,555 km^2

RPB BOUNDARIES	——
PRIMARY WEATHER TYPE	**W**

APPENDIX FOUR

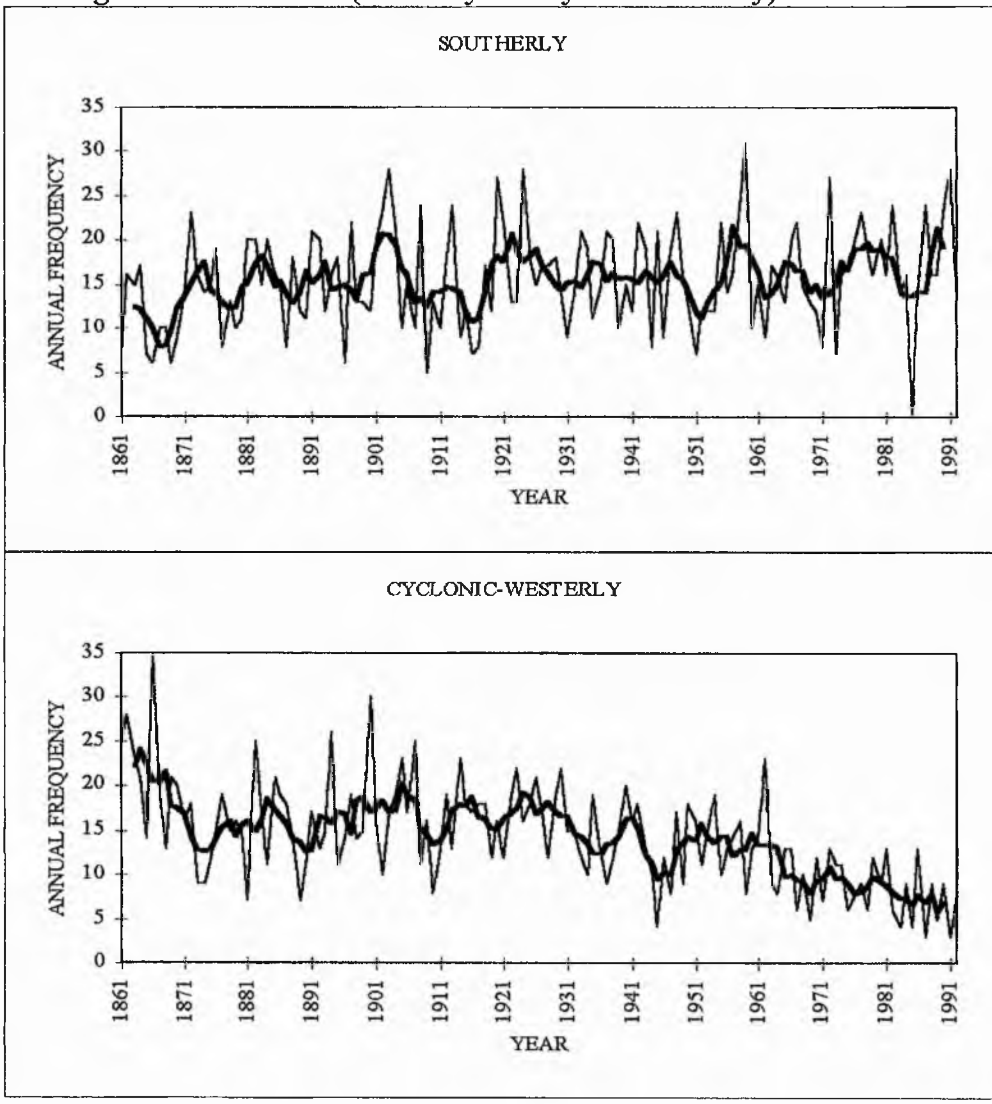
Appendix Four

Figure 6.1(a)-(c): Annual Frequencies of Lamb Weather Types and Five-Year Running Means 1861-1992 (Westerly, Cyclonic and South-Westerly)



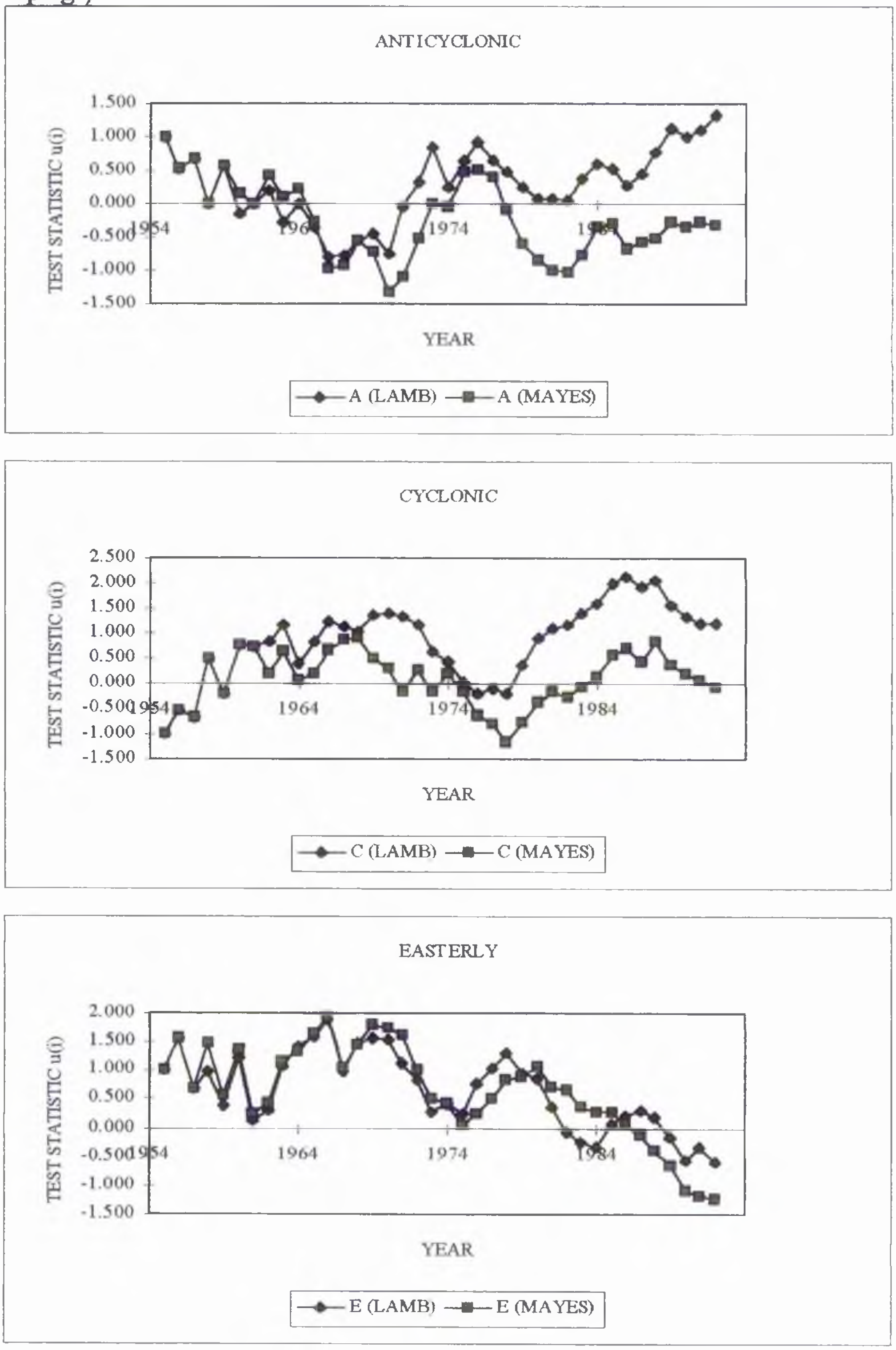
Appendix Four

Figure 6.1(d)-(e): Annual Frequencies of Lamb Weather Types and Five-Year Running Means 1861-1992 (Southerly and Cyclonic-Westerly)



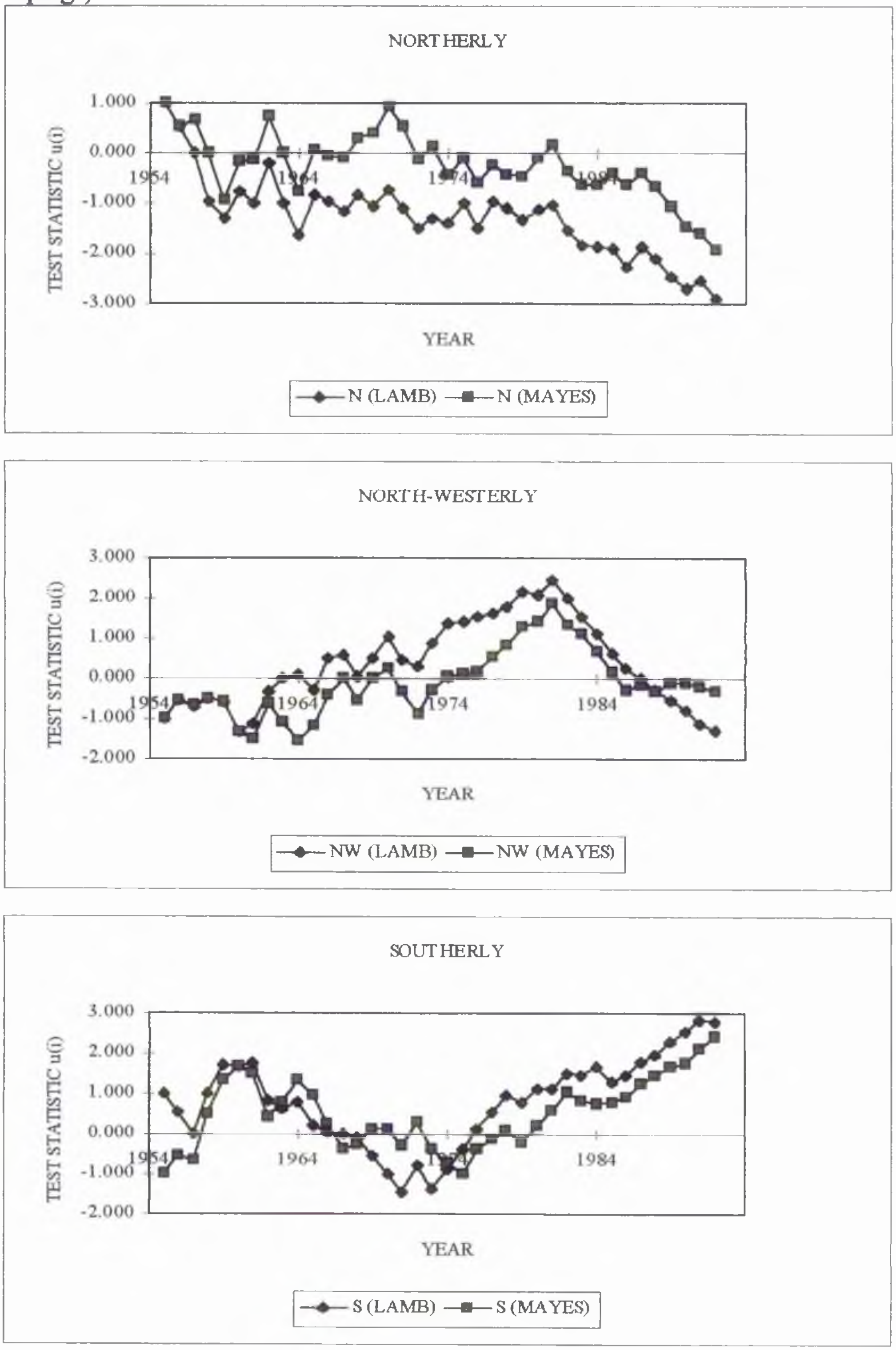
Appendix Four

Figure 6.2(a)-(c): Lamb and Mayes Weather Types - Mann's Test for Trend in the Mean (Annual Frequency Series) 1954-92 (Anticyclonic, Cyclonic and Easterly Groupings)



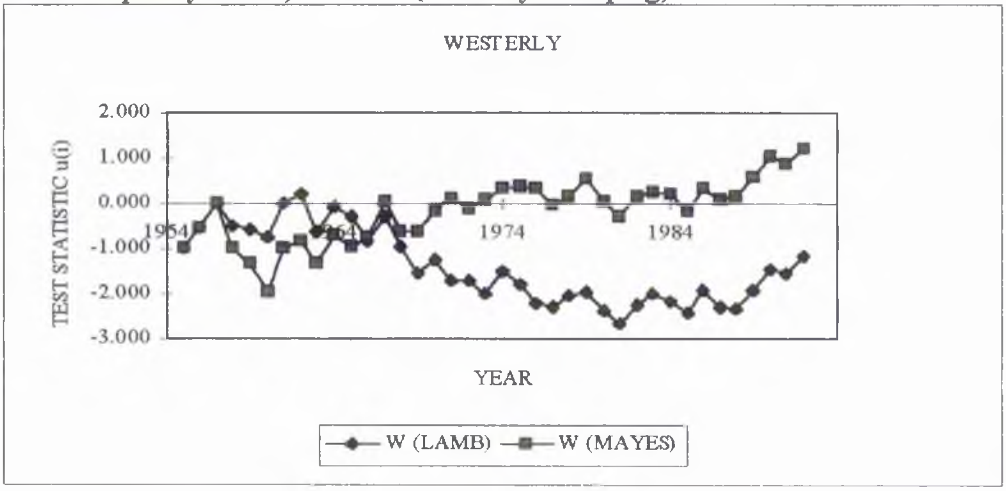
Appendix Four

Figure 6.2(d)-(f): Lamb and Mayes Weather Types - Mann's Test for Trend in the Mean (Annual Frequency Series) 1954-92 (Northerly, North-Westerly and Southerly Groupings)



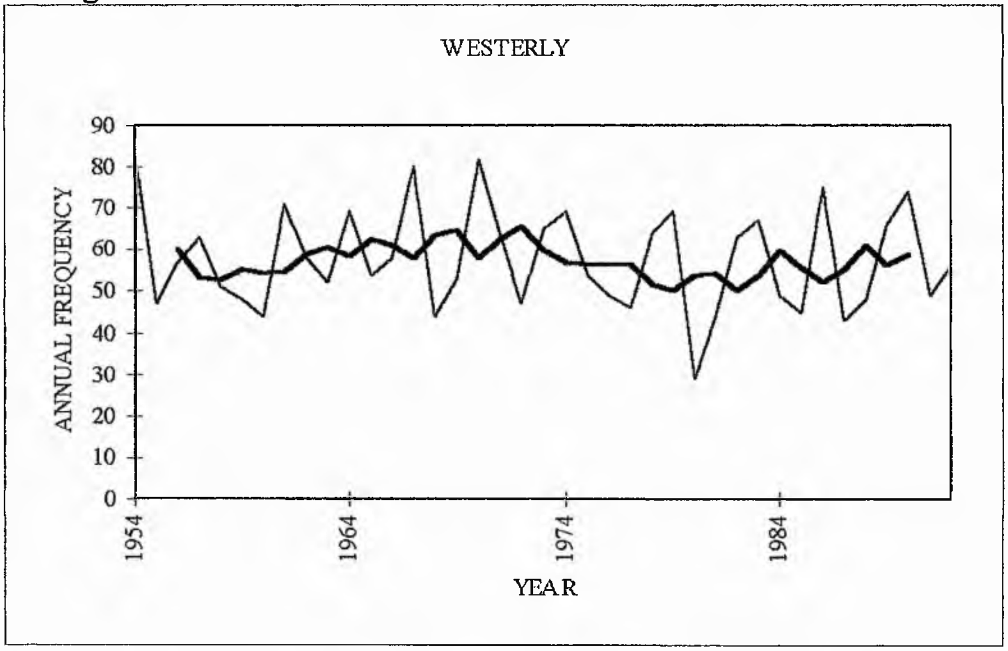
Appendix Four

Figure 6.2(g): Lamb and Mayes Weather Types - Mann's Test for Trend in the Mean (Annual Frequency Series) 1954-92 (Westerly Grouping)

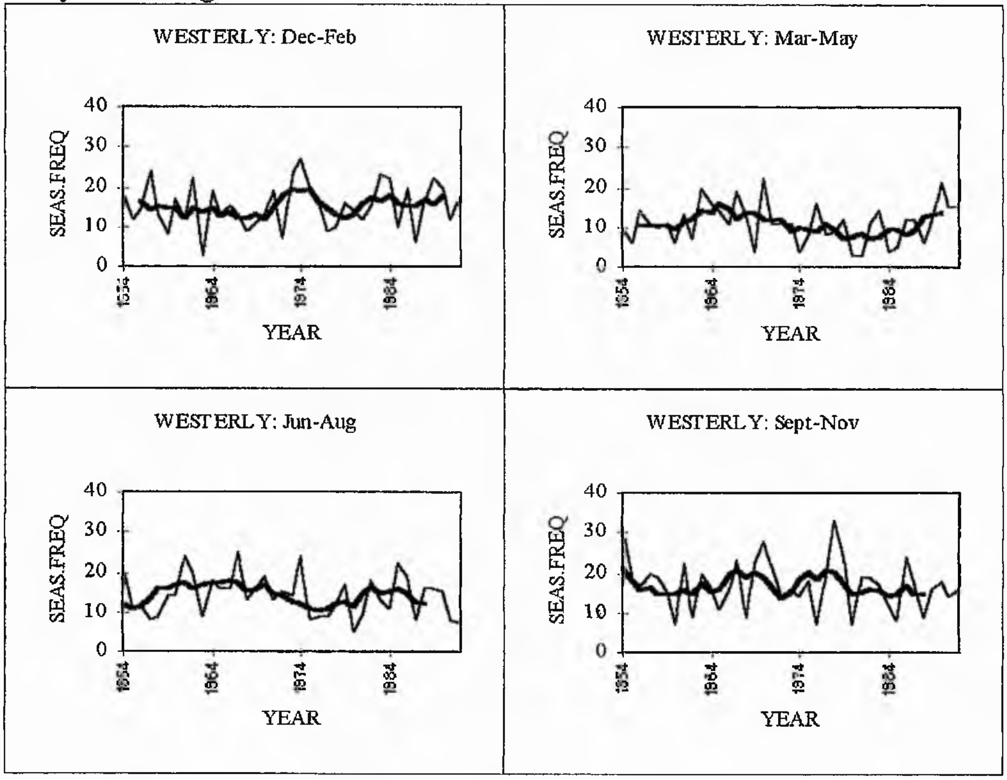


Appendix Four

Figure 6.3(a): Westerly weather type 1954-92: Annual frequencies and a five-year running mean

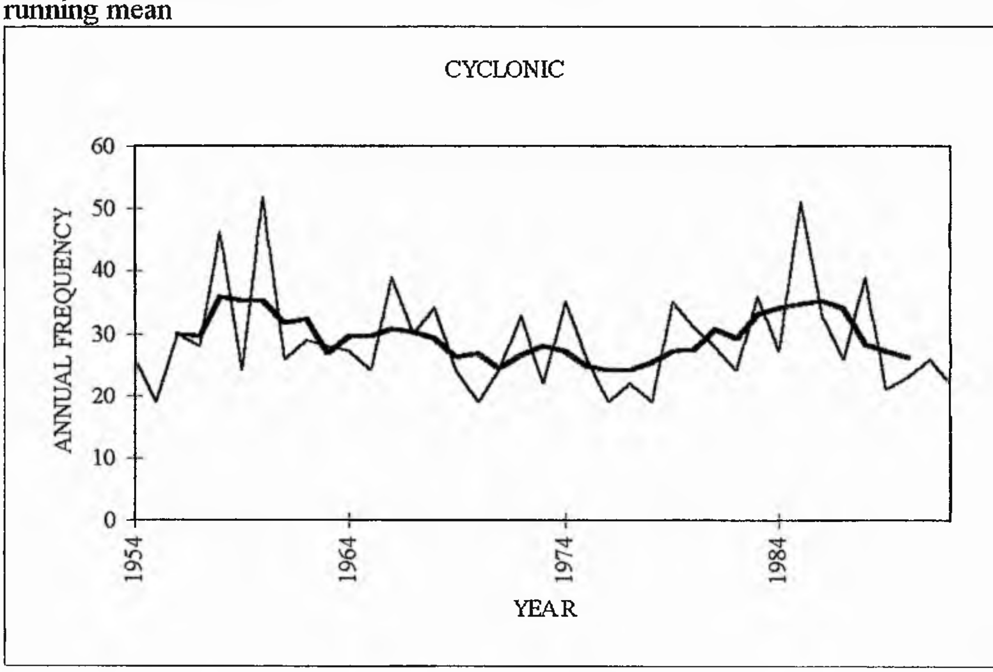


Figures 6.3(b)-6.3(e): Westerly weather type 1954-92: Seasonal frequencies and five-year running means

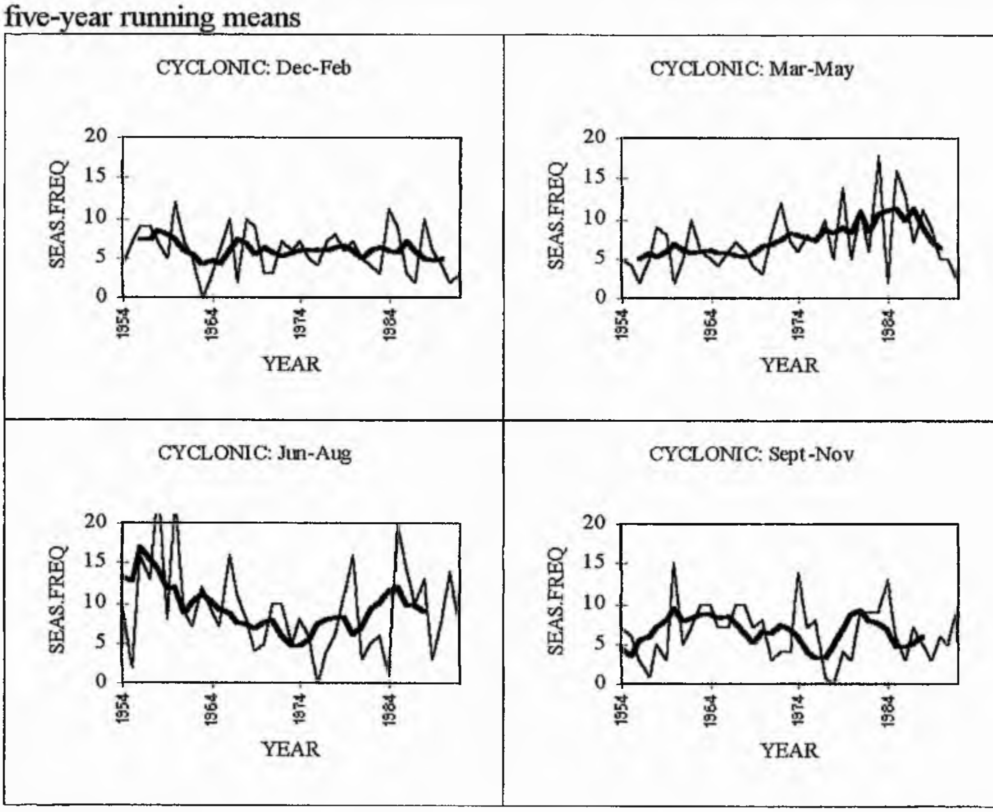


Appendix Four

Figure 6.4(a): Cyclonic weather type 1954-92: Annual frequencies and a five-year running mean

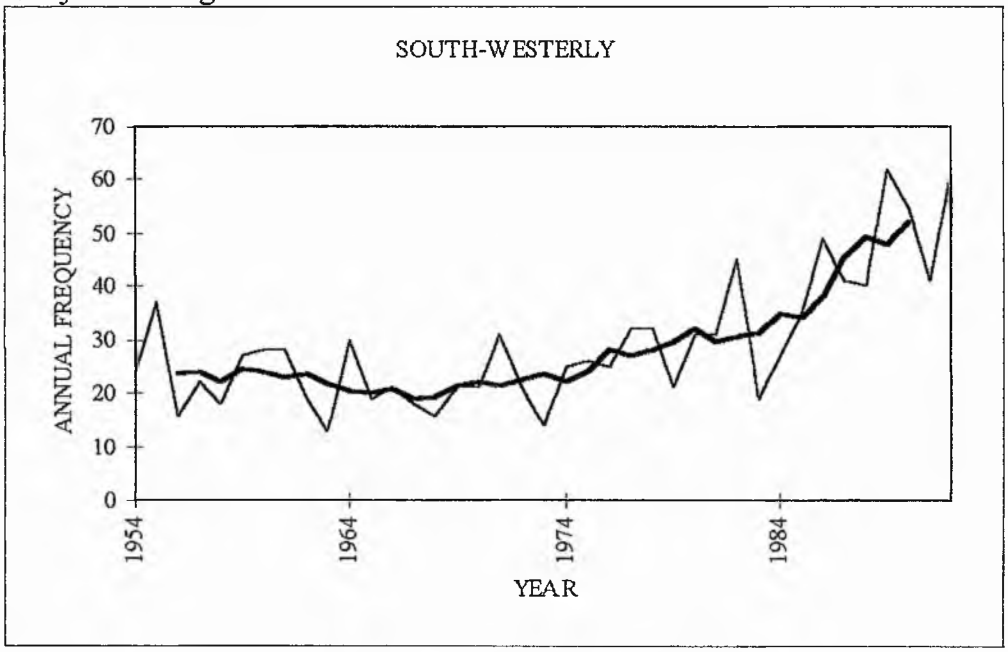


Figures 6.4(b)-6.4(e): Cyclonic weather type 1954-92: Seasonal frequencies and five-year running means

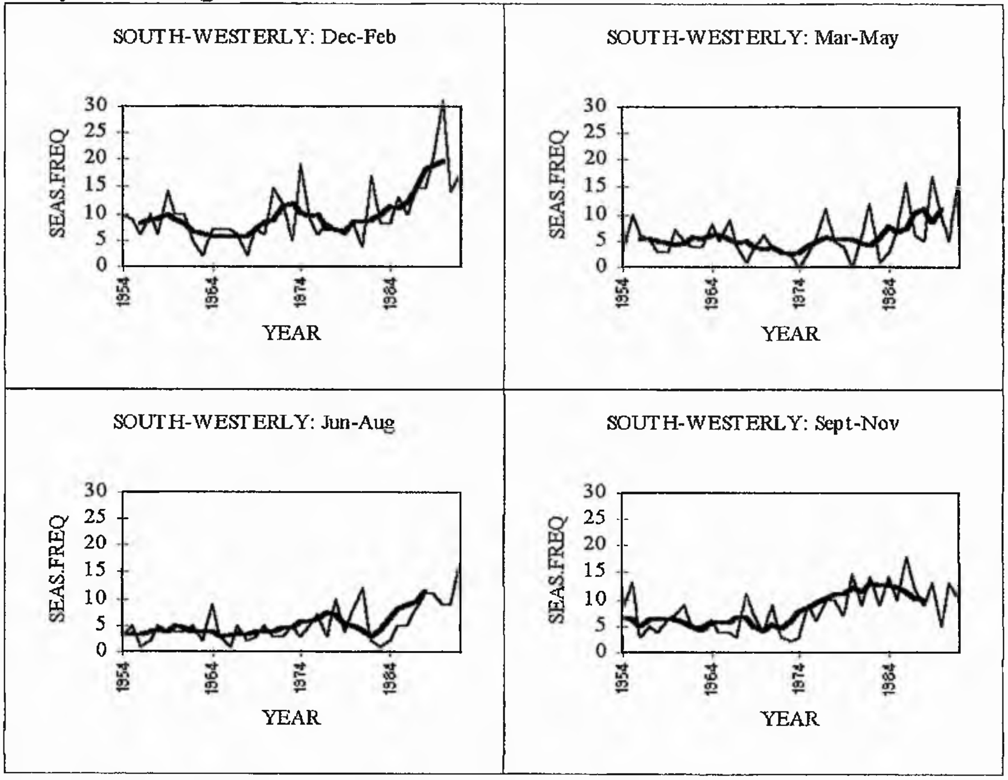


Appendix Four

Figure 6.5(a): South-Westerly weather type 1954-92: Annual frequencies and a five-year running mean

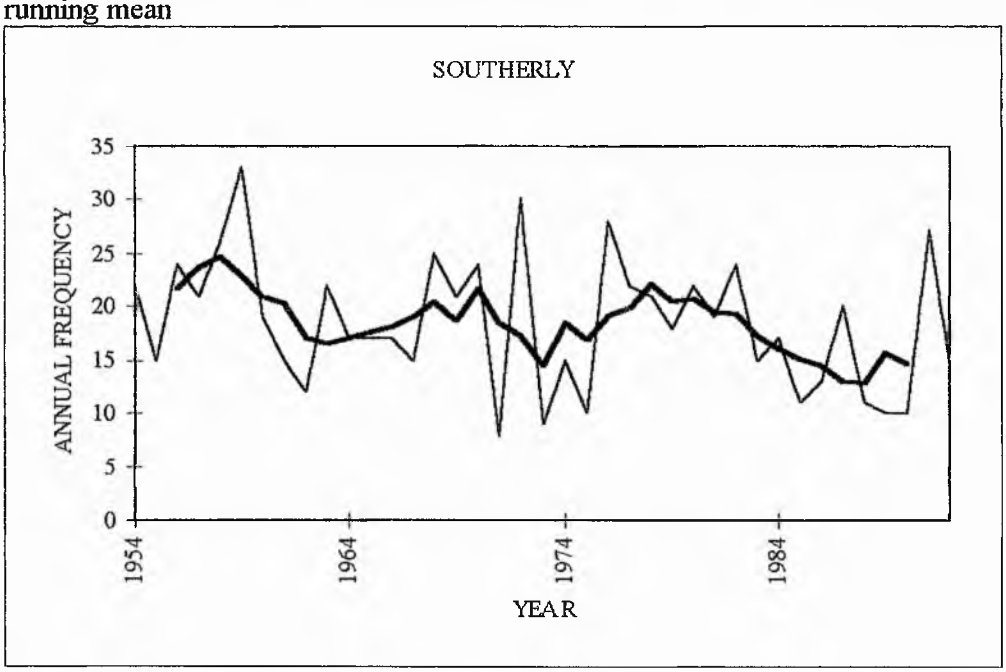


Figures 6.5(b)-6.5(e): South-Westerly weather type 1954-92: Seasonal frequencies five-year running means

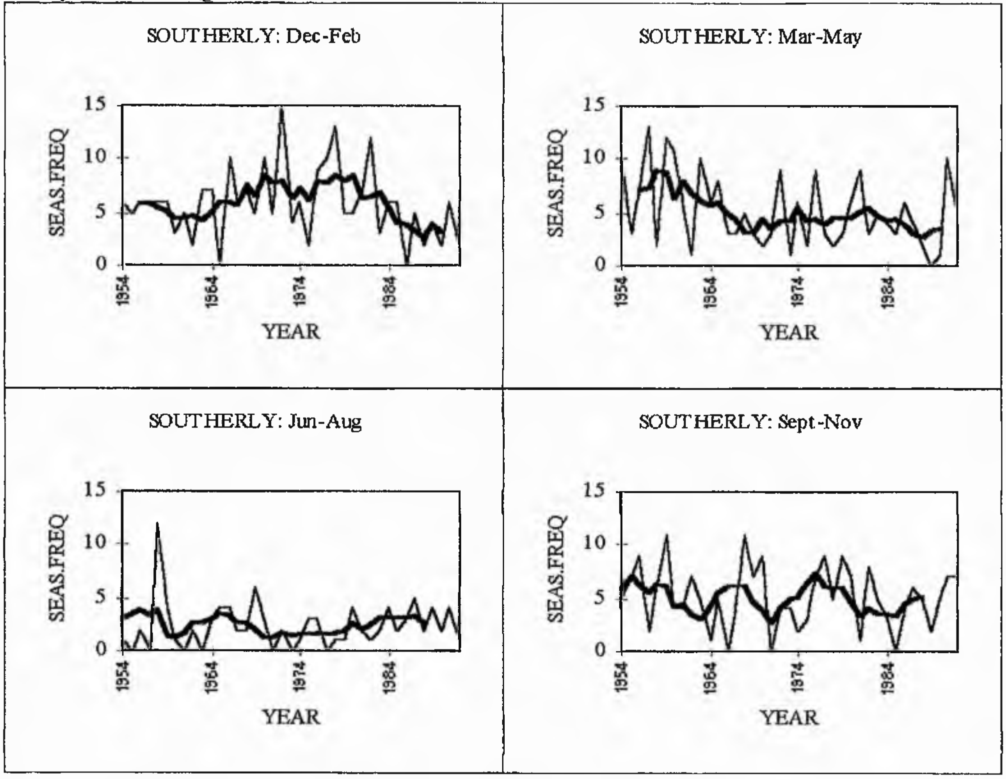


Appendix Four

Figure 6.6(a): Southerly weather type 1954-92: Annual frequencies and a five-year running mean

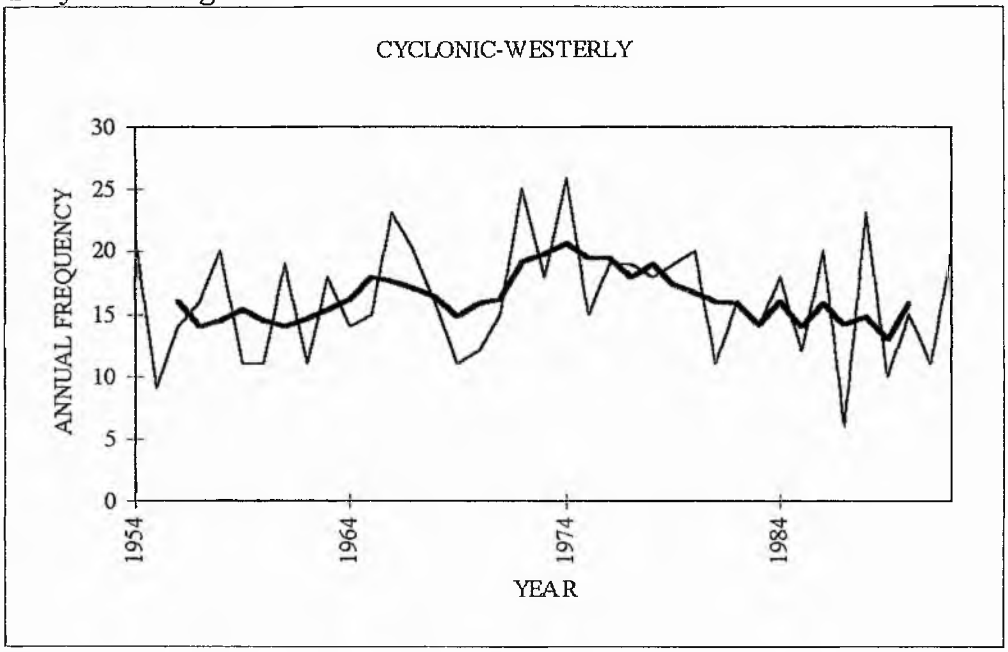


Figures 6.6(b)-6.6(e): Southerly weather type 1954-92: Seasonal frequencies and five-year running means

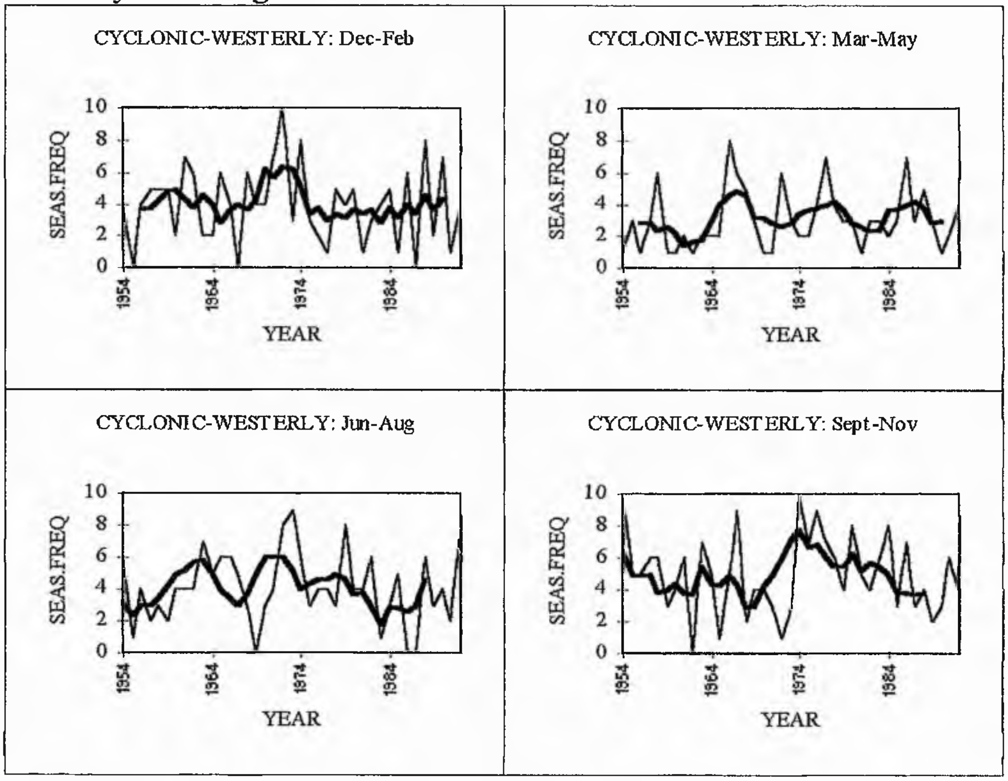


Appendix Four

Figure 6.7(a): Cyclonic-Westerly weather type 1954-92: Annual frequencies and a five-year running mean

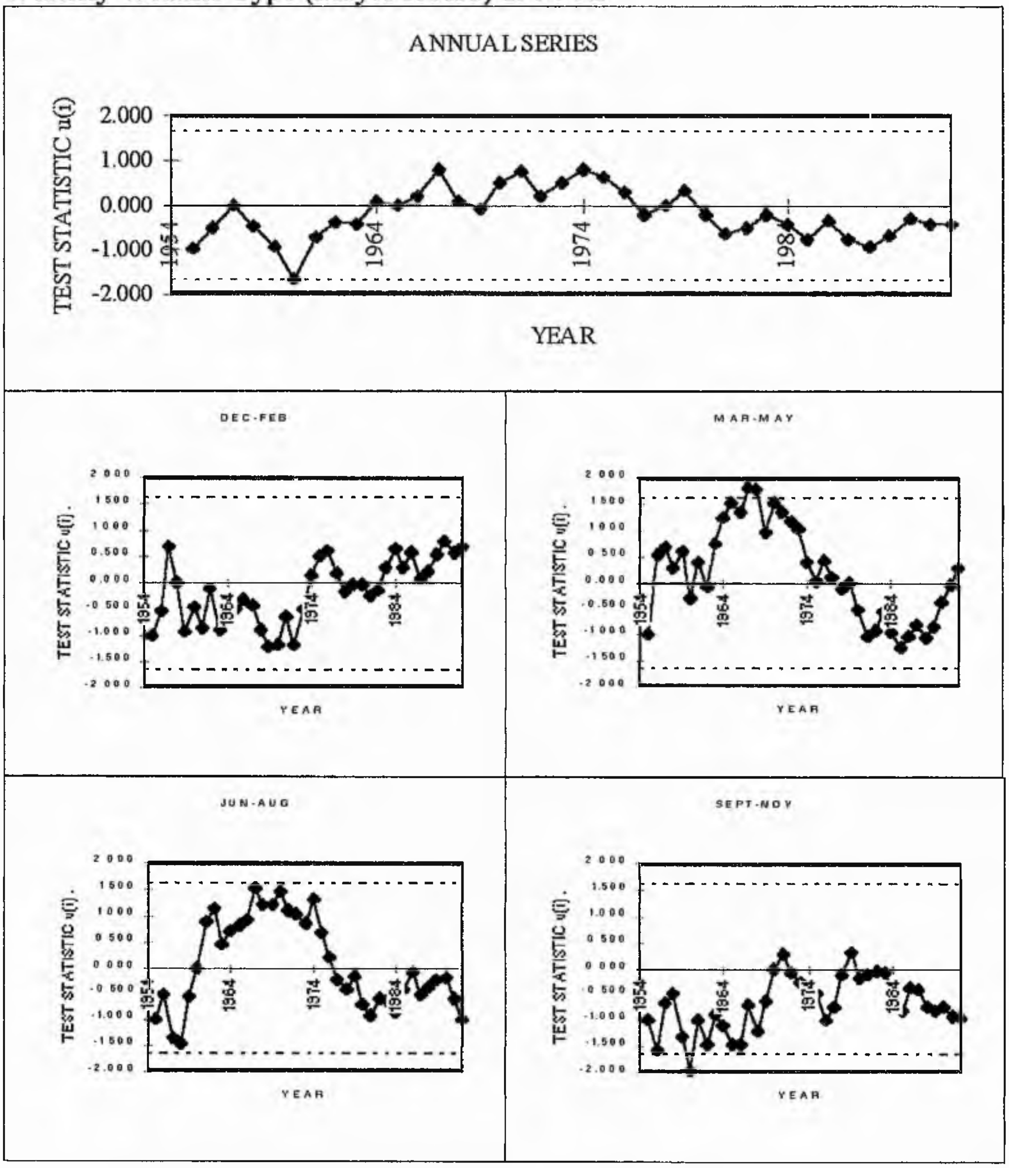


Figures 6.7(b)-6.7(e): Cyclonic-Westerly weather type 1954-92: Seasonal frequencies and five-year running means



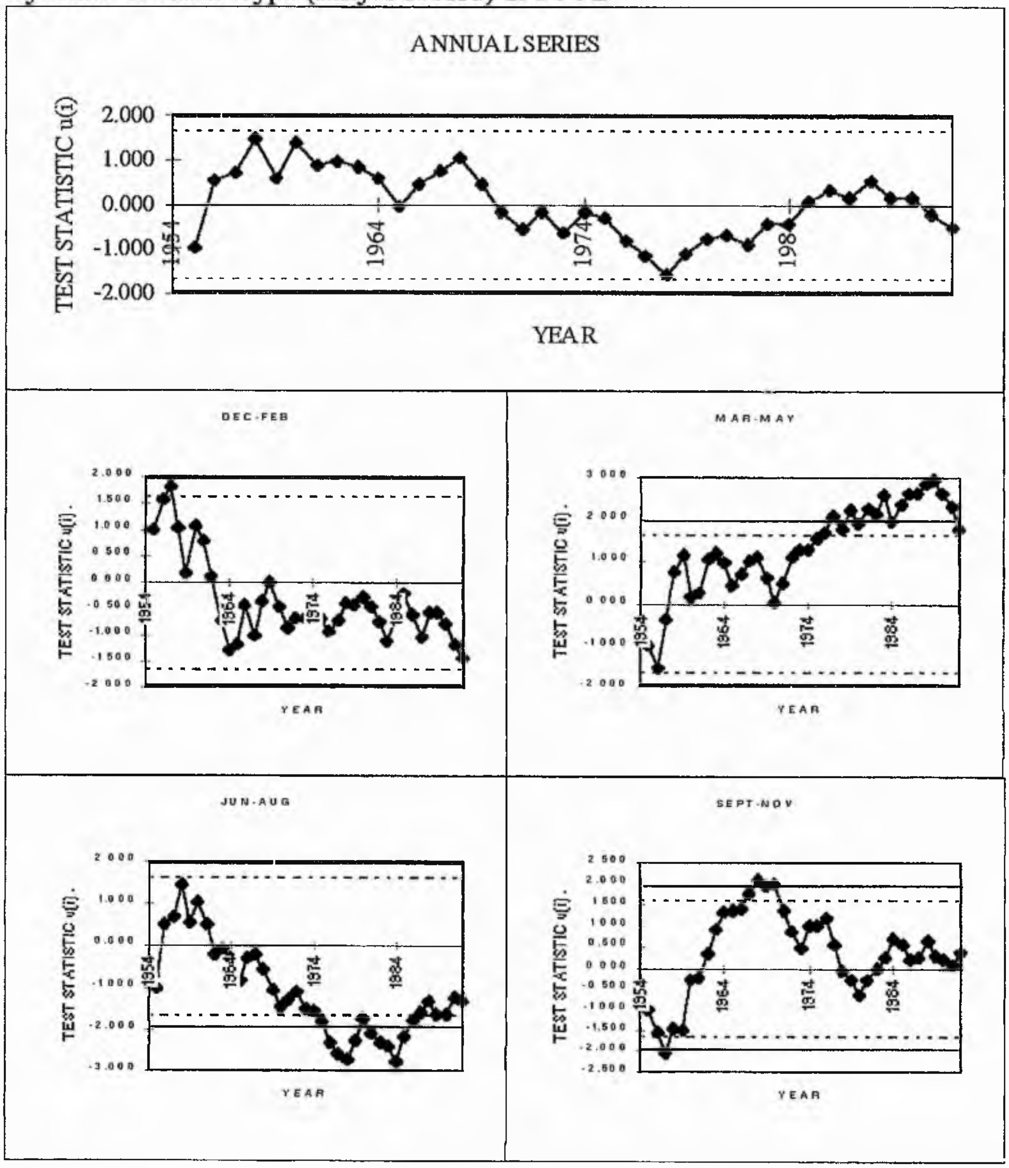
Appendix Four

Figures 6.8(a)-6.8(e): Mann's Test for Trend in the Mean: Frequencies of the Westerly Weather Type (Mayes record) 1954-92



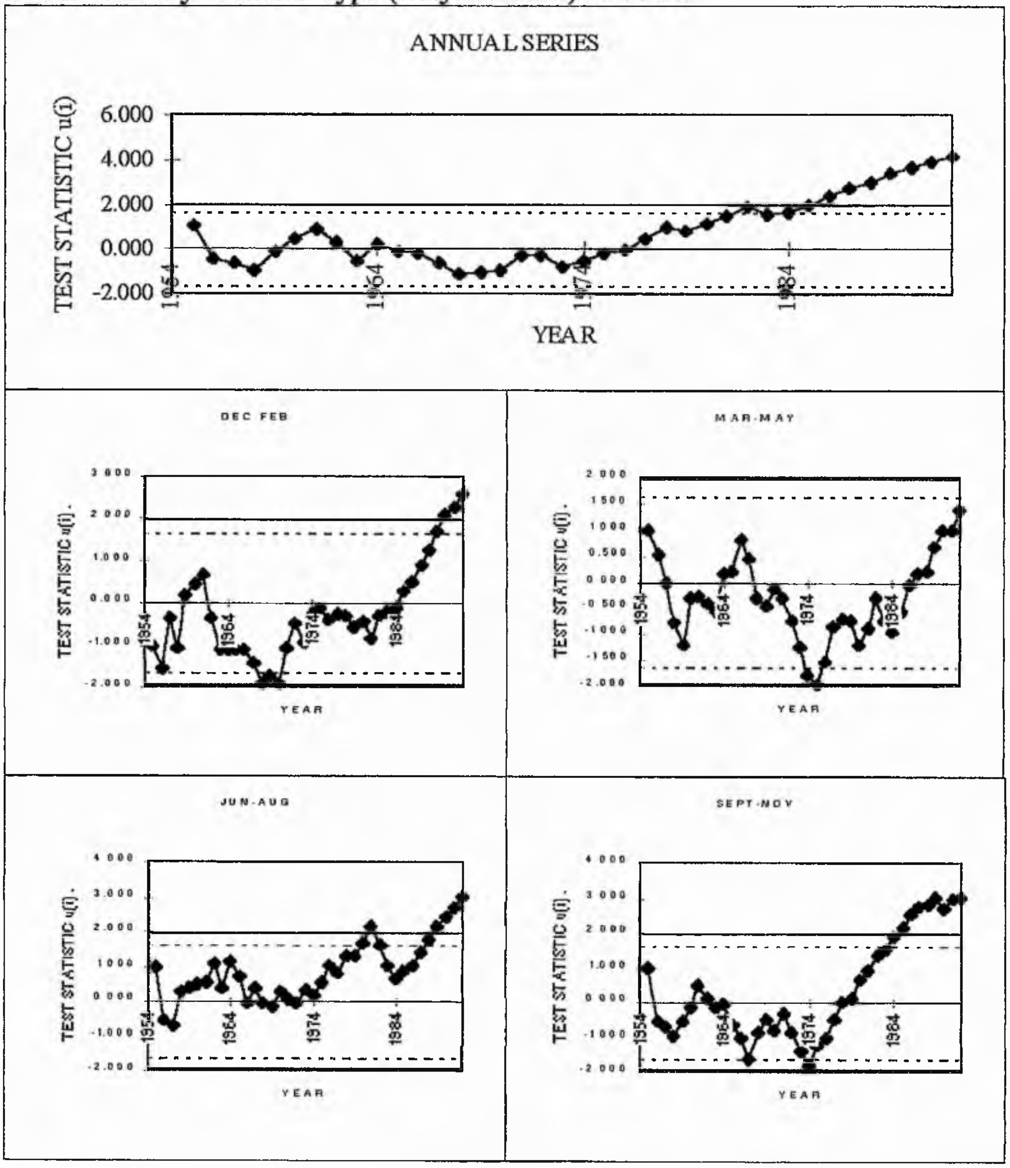
Appendix Four

Figures 6.9(a)-6.9(e): Mann's Test for Trend in the Mean: Frequencies of the Cyclonic Weather Type (Mayes record) 1954-92



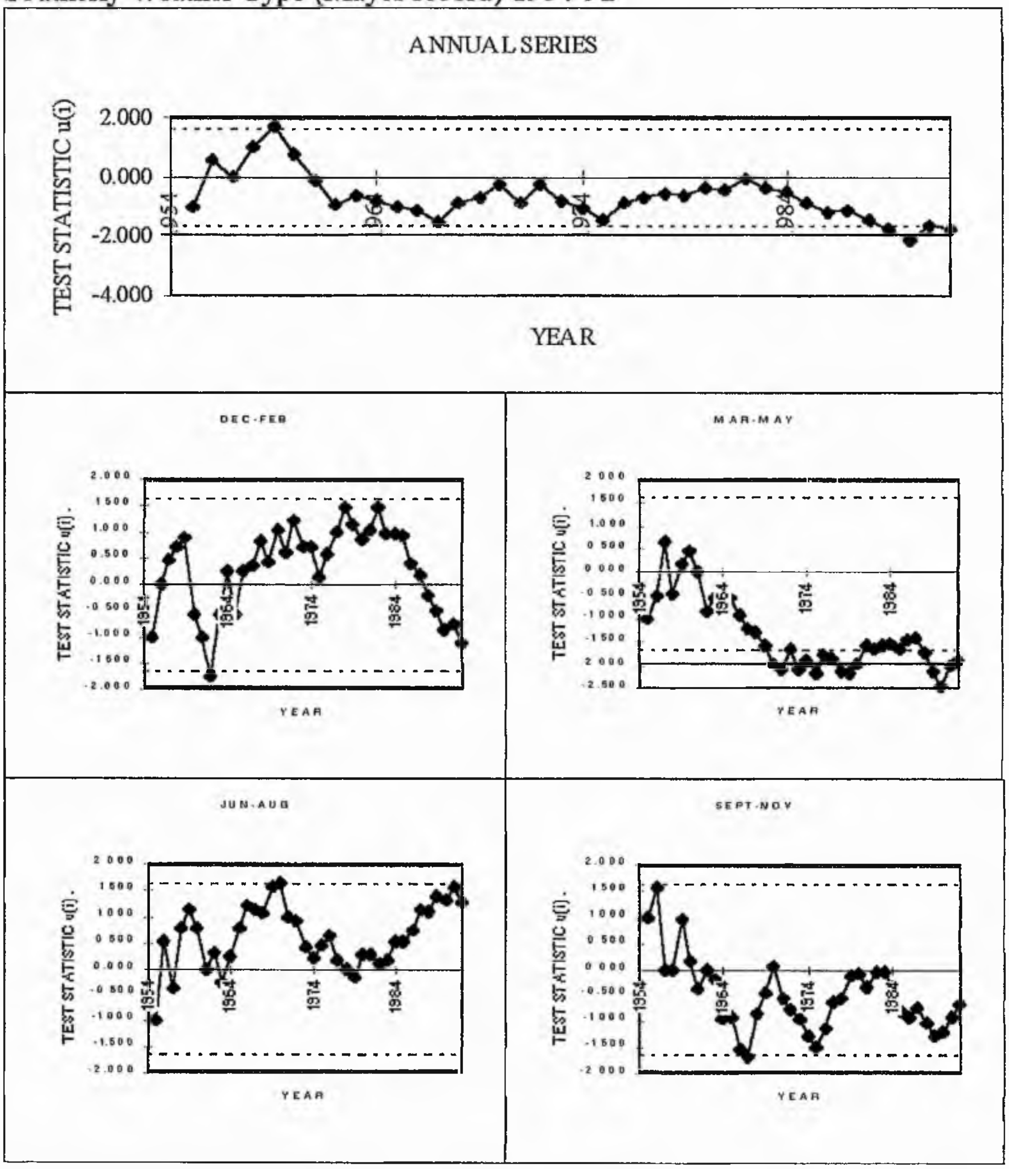
Appendix Four

Figures 6.10(a)-6.10(e): Mann's Test for Trend in the Mean: Frequencies of the South-Westerly Weather Type (Mayes record) 1954-92



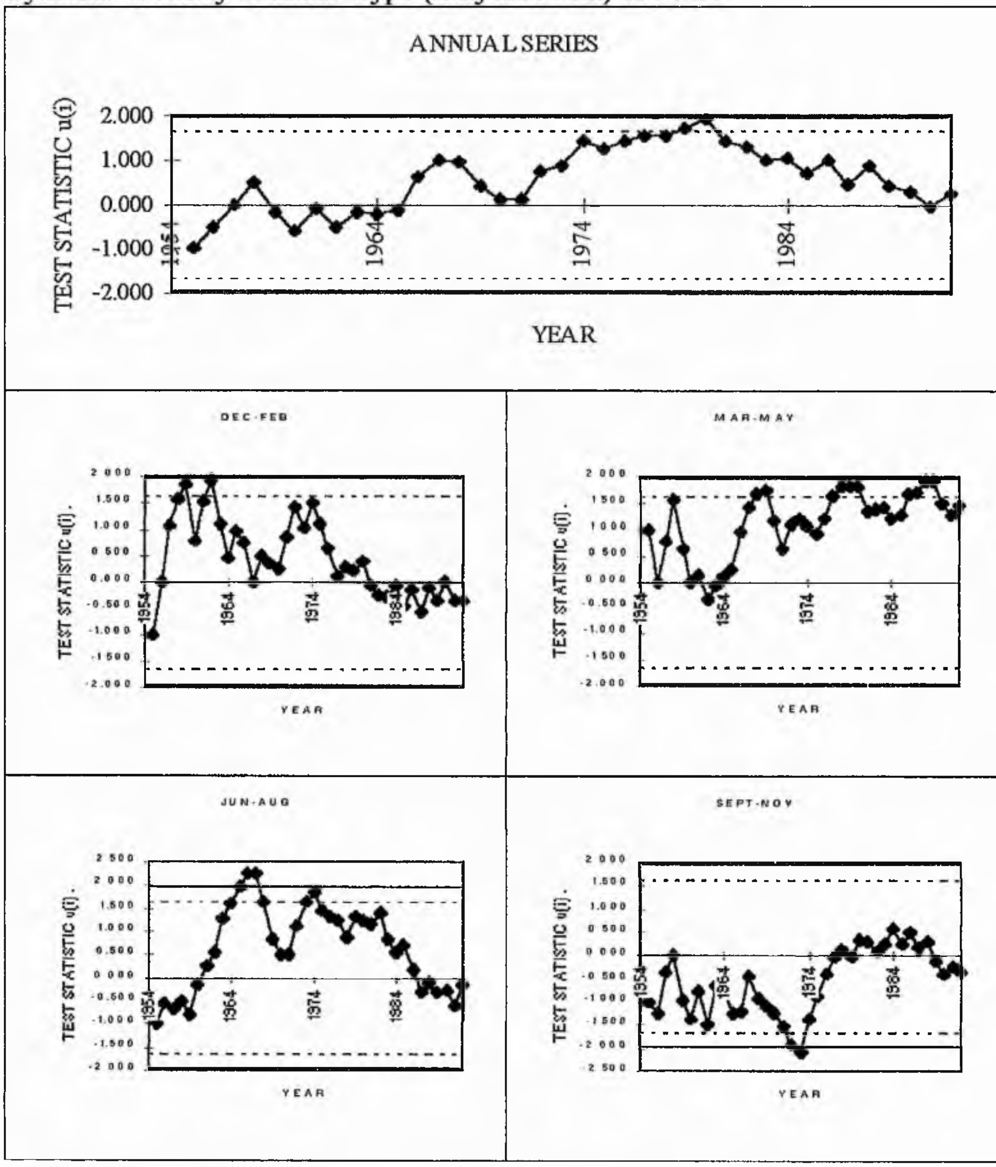
Appendix Four

Figures 6.11(a)-6.11(e): Mann's Test for Trend in the Mean: Frequencies of the Southerly Weather Type (Mayes record) 1954-92



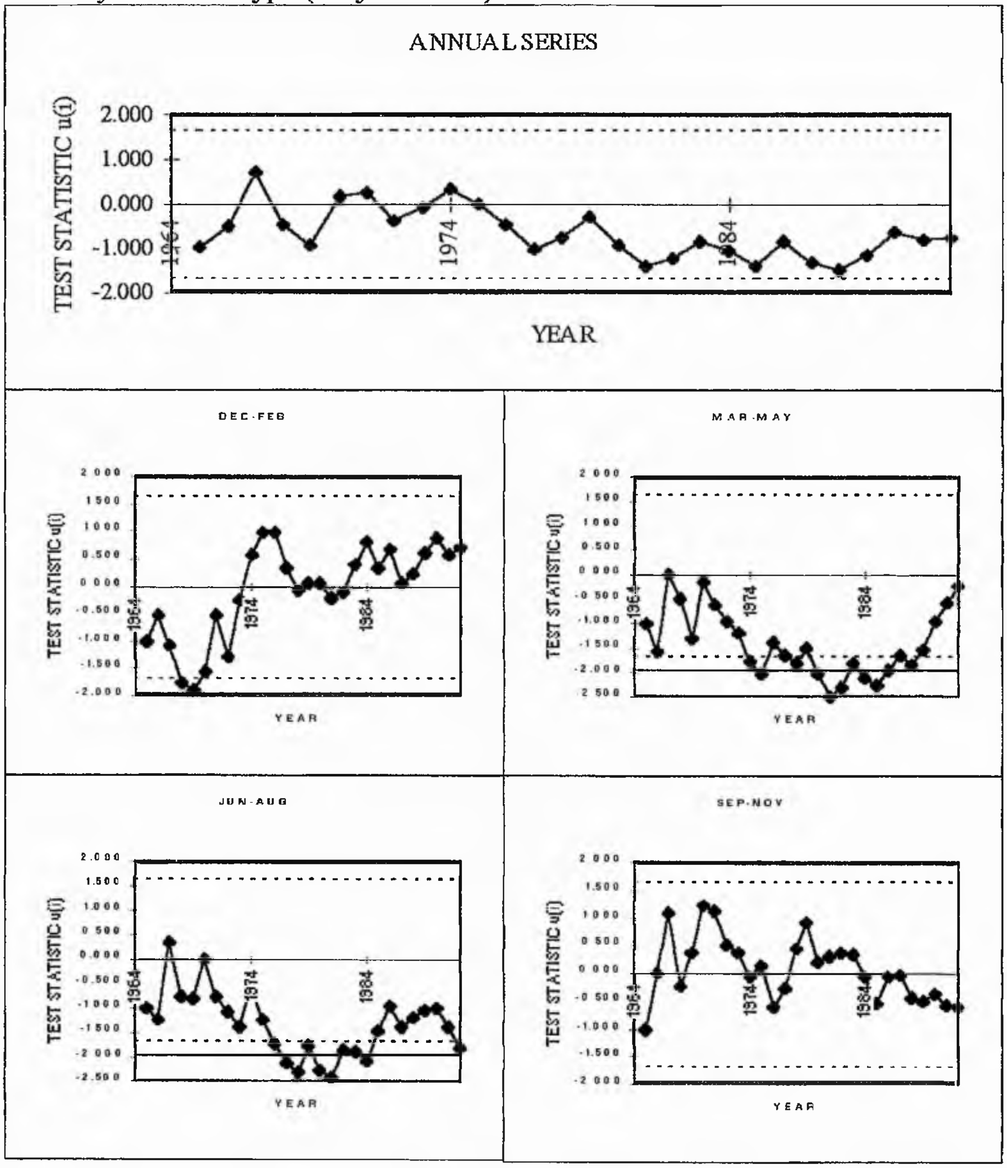
Appendix Four

Figures 6.12(a)-6.12(e): Mann's Test for Trend in the Mean: Frequencies of the Cyclonic-Westerly Weather Type (Mayes record) 1954-92



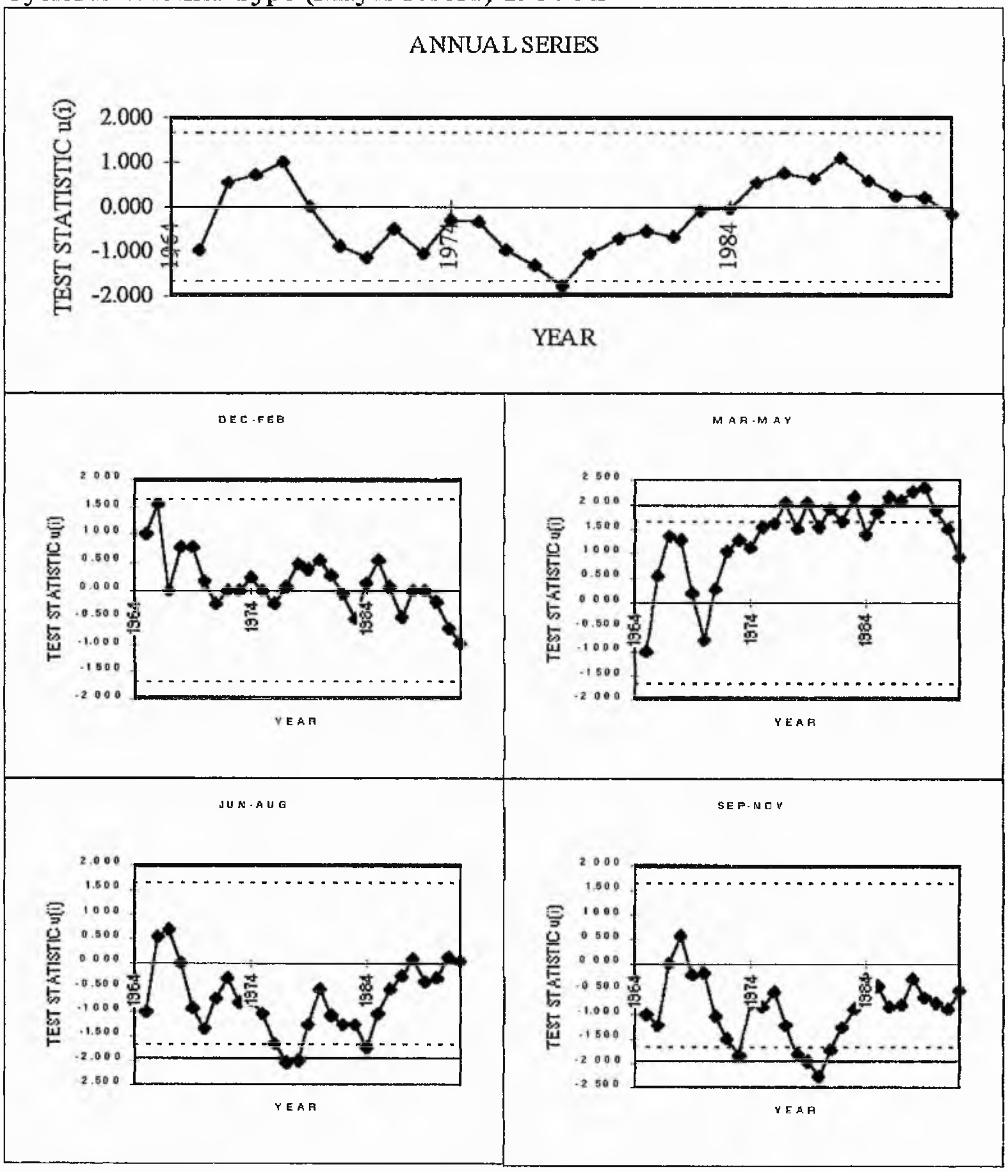
Appendix Four

Figures 6.13(a)-6.13(e): Mann's Test for Trend in the Mean: Frequencies of the Westerly Weather Type (Mayes record) 1964-92



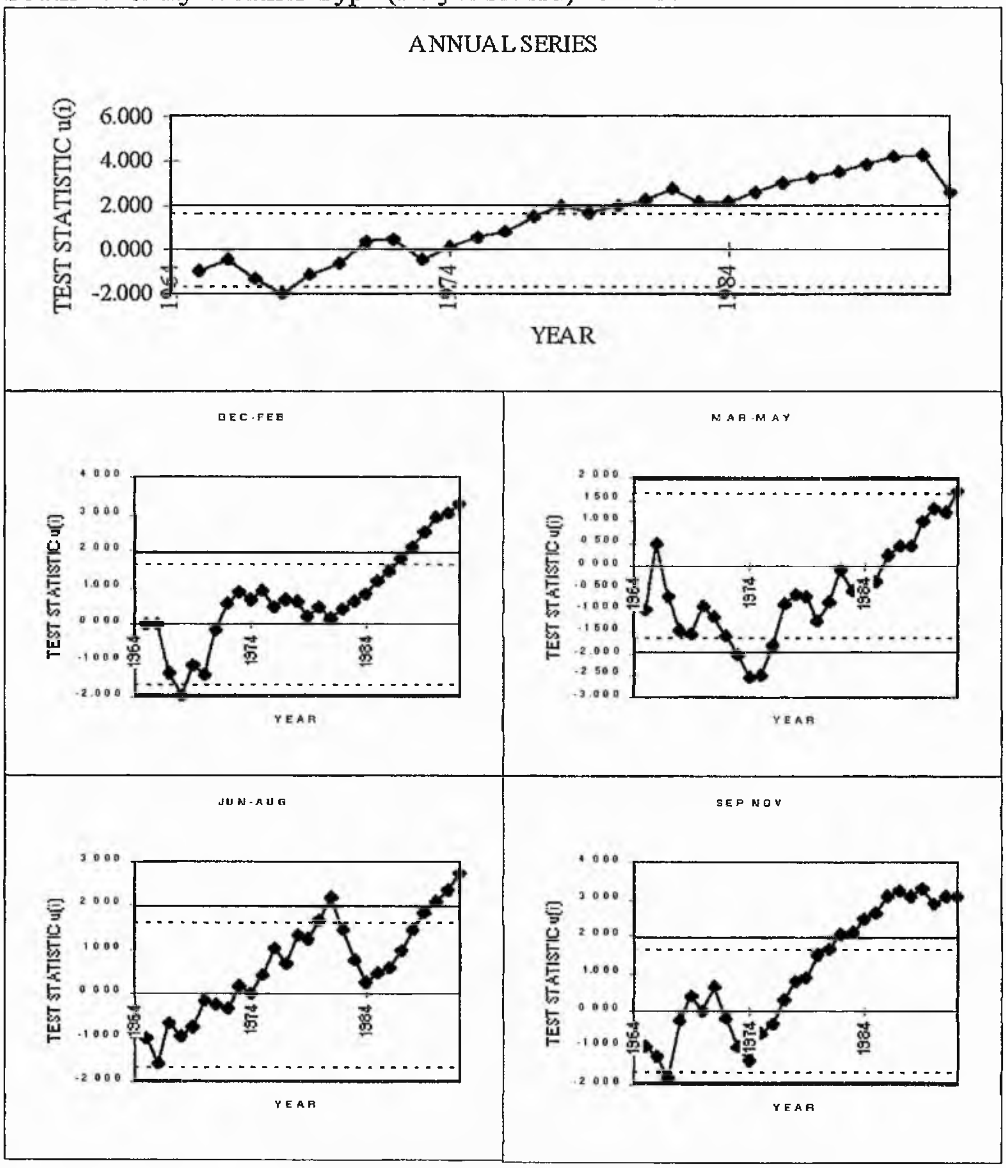
Appendix Four

Figures 6.14(a)-6.14(e): Mann's Test for Trend in the Mean: Frequencies of the Cyclonic Weather Type (Mayes record) 1964-92



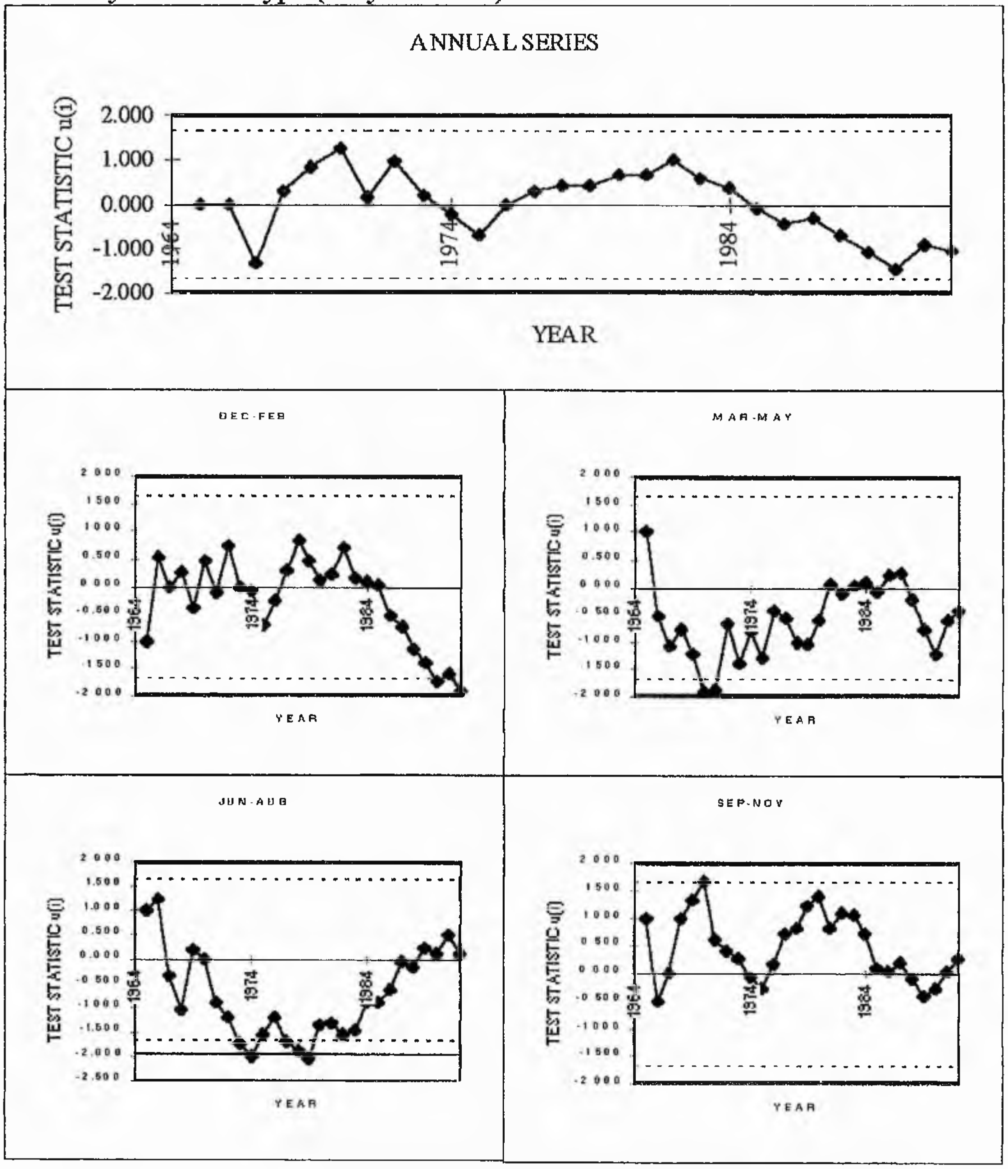
Appendix Four

Figures 6.15(a)-6.15(e): Mann's Test for Trend in the Mean: Frequencies of the South-Westerly Weather Type (Mayes record) 1964-92



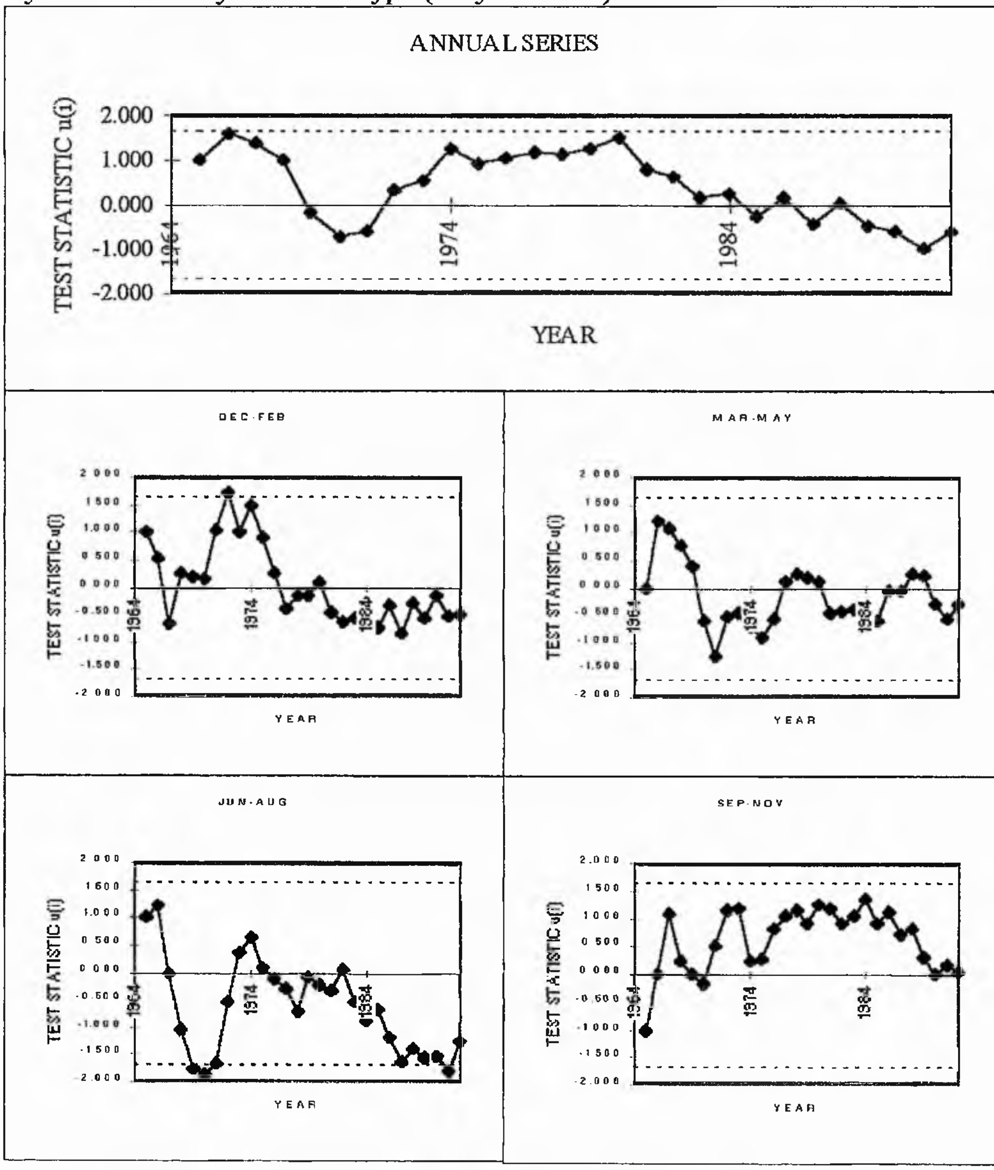
Appendix Four

Figures 6.16(a)-6.16(e): Mann's Test for Trend in the Mean: Frequencies of the Southerly Weather Type (Mayes record) 1964-92



Appendix Four

Figures 6.17(a)-6.17(e): Mann's Test for Trend in the Mean: Frequencies of the Cyclonic-Westerly Weather Type (Mayes record) 1964-92



APPENDIX FIVE

Appendix Five

Table 7.1: Records used in Flood Frequency Analysis, with complete and split periods of record used

GAUGING STATION RECORD	LENGTH OF RECORD ANALYSED	SPLITS BASED ON FLOOD FREQUENCY SERIES	SPLITS BASED ON FLOOD MAGNITUDE SERIES
Dee at Woodend (12001)	1934 - 92	1934 - 62; 1963 - 82; 1983 - 92	1934 - 62; 1963 - 92
Irvine at Kilmarnock (83802)	1914 -18	1914 - 28; 1929 - 51; 1952 - 77; 1978 - 88	1914 - 46; 1947 - 88
Allt Leachdach at Intake (91802)	1939-80	1939 - 49; 1950 - 80	1939 - 55; 1956 - 69; 1970 - 80
Dee at Woodend (12001)	1944 - 92	1944 - 62; 1963 - 92	1944 - 62; 1963 - 92
Avon at Delnashaugh (08004)	1954 - 92	1954 - 66; 1967 - 92	1954 - 65; 1966 - 92
Spey at Boat of Garten (08005)	1954 - 92	1954 - 80; 1981 - 92	1954 - 65; 1966 - 92
Spey at Boat of Brig (08006)	1954 - 92	1954 - 66; 1967 - 82; 1983 - 92	1954 - 77; 1978 - 92
Spey at Invertruim (08007)	1954 - 92	1954 - 77; 1978 - 92	1954 - 60; 1961 - 92
Dulnain at Balnaan Bridge (08009)	1954 - 92	1954 - 77; 1978 - 92	1954 - 77; 1978 - 92
Spey at Grantown (08010)	1954 - 92	1954 - 80; 1981 - 92	1954 - 65; 1966 - 92
Dee at Woodend (12001)	1954 - 92	1954 - 73; 1974 - 92	1954 - 73; 1974 - 92
Tay at Caputh (15003)	1954 - 92	1954 - 73; 1974 - 92	no splits possible
Tay at Ballathie (15006)	1954 - 92	1954 - 73; 1974 - 92	1954 - 73; 1974 - 92
Tay at Pitnacree (15007)	1954 - 92	1954 - 73; 1974 - 92	1954 - 65; 1966 - 92
Dean Water at Cookston (15008)	1954 - 92	1954 - 73; 1974 - 92	1954 - 73; 1974 - 92
Earn at Kinkell (16001)	1954 - 92	1954 - 76; 1977 - 92	no splits possible
Tweed at Peebles (21003)	1954 - 92	1954 - 73; 1974 - 92	no splits possible
Kelvin at Killermont (84001)	1954 - 92	1954 - 77; 1978 - 92	1954 - 73; 1974 - 92
Findhorn at Shenachie (07001)	1964 - 92	1964 - 73; 1974 - 92	1964 - 77; 1978 - 92
Findhorn at Forres (07002)	1964 - 92	1964 - 77; 1978 - 92	1964 - 77; 1978 - 92
Lossie at Sherrifmills (07003)	1964 - 92	1964 - 75; 1976 - 92	1964 - 80; 1981 - 92
Avon at Delnashaugh (08004)	1964 - 92	1964 - 73; 1974 - 92	1964 - 79; 1980-92
Spey at Boat of Garten (08005)	1964 - 92	1964 - 80; 1981 - 92	1964 - 73; 1974 - 92
Spey at Boat o'Brig (08006)	1964 - 92	1964 - 77; 1978 - 92	1964 - 77; 1978 - 92
Spey at Invertruim (08007)	1964 - 92	1964 - 74; 1975 - 92	1964 - 73; 1974 - 92
Dulnain at Balnaan Bridge (08009)	1964 - 92	1964 - 78; 1979 - 92	1964 - 72; 1973 - 92
Spey at Grantown (08010)	1964 - 92	1964 - 78; 1979 - 92	1964 - 73; 1974 - 92
Deveron at Avochie (09001)	1964 - 92	1964 - 74; 1975 - 92	1964 - 75; 1976 - 92
Deveron at Muiresk (09002)	1964 - 92	1964 - 74; 1975 - 92	1964 - 75; 1976 - 92
Isla at Grange (09003)	1964 - 92	1964 - 73; 1974 - 92	1964 - 73; 1974 - 92
Dee at Woodend (12001)	1964 - 92	1964 - 73; 1974 - 92	1964 - 73; 1974 - 92
Tay at Caputh (15003)	1964 - 92	1964 - 73; 1974 - 92	1964 - 73; 1974 - 92
Tay at Ballathie (15006)	1964 - 92	1964 - 80; 1981 - 92	1964 - 73; 1974 - 92
Tay at Pitnacree (15007)	1964 - 92	1964 - 73; 1974 - 92	1964 - 73; 1974 - 92

Appendix Five

Table 7.1 (cont): Records used in Flood Frequency Analysis, with complete and split periods of record used

Dean Water at Cookston (15008)	1964 - 92	1964 - 75; 1976 - 92	1964 - 75; 1976 - 85; 1986 - 92
Earn at Kinkell (16001)	1964 - 92	1964 - 76; 1977 - 92	1964 - 83; 1984 - 92
Ruchill Water at Cultybraggan (16003)	1964 - 92	1964 - 72; 1973 - 92	1964 - 75; 1976 - 92
Almond at Craigiehall (19001)	1964 - 92	1964 - 74; 1975 - 92	1964 - 75; 1976 - 92
Almond at Almond Weir (19002)	1964 - 92	1964 - 76; 1977 - 92	1964 - 75; 1976 - 92
N.Esk at Dalmore Weir (19004)	1964 - 92	1964 - 74; 1975 - 92	1964 - 69; 1970 - 85; 1986 - 92
Water of Leith at Murrayfield (19006)	1964 - 92	1964 - 73; 1974 - 92	1964 - 73; 1974 - 92
Esk at Musselburgh (19007)	1964 - 92	1964 - 74; 1975 - 92	1964 - 73; 1974 - 92
N.Esk at Dalkeith Palace (19011)	1964 - 92	1964 - 74; 1975 - 92	1964 - 73; 1974 - 92
Tyne at East Linton (20001)	1964 - 92	1964 - 74; 1975 - 92	1964 - 73; 1974 - 92
Tyne at Spilmersford (20003)	1964 - 92	1964 - 74; 1975 - 92	1964 - 74; 1975 - 92
Birns Water at Saltoun Hall (20005)	1964 - 92	1964 - 76; 1977 - 92	1964 - 73; 1974 - 92
Tweed at Peebles (21003)	1964 - 92	1964 - 73; 1974 - 92	1964 - 76; 1977 - 92
Tweed at Lyne Ford (21005)	1964 - 92	1964 - 80; 1981 - 92	1964 - 73; 1974 - 92
Tweed at Boleside (21006)	1964 - 92	1964 - 73; 1974 - 92	1964 - 70; 1971 - 92
Ettrick Water at Lindean (21007)	1964 - 92	1964 - 73; 1974 - 92	1964 - 78; 1979 - 92
Teviot at Ormiston Mill (21008)	1964 - 92	1964 - 73; 1974 - 92	1964 - 76; 1977 - 92
Tweed at Norham (21009)	1964 - 92	1964 - 77; 1978 - 92	1964 - 77; 1978 - 92
Yarrow Water at Philiphaugh (21011)	1964 - 92	1964 - 73; 1974 - 92	1964 - 71; 1972 - 92
Teviot at Hawick (21012)	1964 - 92	1964 - 73; 1974 - 92	1964 - 77; 1978 - 92
Gala Water at Galashiels (21013)	1964 - 92	1964 - 73; 1974 - 92	1964 - 74; 1975 - 92
Nith at Friars Carse (79002)	1964 - 92	1964 - 73; 1974 - 92	no splits possible
Nith at Hallbridge (79003)	1964 - 92	1964 - 80; 1981 - 92	1964 - 73; 1974 - 92
Scar Water at Capenoch (79004)	1964 - 92	1964 - 73; 1974 - 92	1964 - 73; 1974 - 92
Cluden Water at Fiddler's Ford (79005)	1964 - 92	1964 - 73; 1974 - 92	no splits possible
Urr at Dalbeattie (80001)	1964 - 92	1964 - 73; 1974 - 92	no splits possible
Cree at Newton Stewart (81002)	1964 - 92	1964 - 71; 1972 - 92	1964 - 70; 1971 - 92
Girvan at Robstone (82001)	1964 - 92	1964 - 72; 1973 - 92	1964 - 82; 1983 - 92
Kelvin at Killermont (84001)	1964 - 92	1964 - 73; 1974 - 92	1964 - 73; 1974 - 92
Clyde at Hazelbank (84003)	1964 - 92	1964 - 73; 1974 - 92	1964 - 76; 1977 - 92
Clyde at Sills (84004)	1964 - 92	1964 - 73; 1974 - 92	1964 - 76; 1977 - 92
Clyde at Blairston (84005)	1964 - 92	1964 - 73; 1974 - 92	1964 - 76; 1977 - 92
Gryfe at Craigend (84011)	1964 - 92	1964 - 74; 1975 - 92	1964 - 73; 1974 - 86; 1987 - 92

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Table 7.5 (cont): Magnitude of One-Hundred Year Flood for Complete and Split Series - 1964-92 records

STATION RECORD	**MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100)** **Periods defined by flood frequency series**			
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Clyde @ Hazelbank (84003)	533.4	459.4 *(-13.9)*	564.1 *(+5.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Clyde @ Sills (84004)	398.0	395.2 *(-0.7)*	396.7 *(-0.3)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Clyde @ Blairston (84005)	776.1	709.5 *(-8.6)*	789.8 *(+1.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
Gryfe (84011)	98.4	101.7 *(+3.4)*	103.2 *(+4.9)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
W.Cart Water (84012)	211.0	235.6 *(+11.3)*	218.4 *(+3.2)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
N.Calder Water (84019)	93.4	76.5 *(-18.1)*	105.5 *(+13.0)*	

Table 7.1 (cont): Records used in Flood Frequency Analysis, with complete and split periods of record used

White Cart Water at Hawkhead (84012)	1964 - 92	1964 - 75; 1976 - 92	1964 - 73; 1974 -92
Calder Water at Calderpark (84019)	1964 - 92	1964 - 75; 1976 - 92	1964 - 73; 1974 - 92

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Table 7.2: Magnitude of One-Hundred Year Flood for Complete and Split Series - Long POT records

STATION RECORD	MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by flood frequency series				
RECORD / SPLIT PERIOD	**1934 - 92**	**1934 - 62**	**1963 - 82**	**1983 - 92**	
Dee at Woodend (12001)	938 m^3s^{-1}	910 *(-3.0%)*	977 *(+4.2%)*	751 *(-19.9%)*	
RECORD / SPLIT PERIOD	**1914 - 88**	**1914 - 28**	**1929 - 51**	**1952-77**	**1978-88**
Irvine at Kilmarnock (83802)	146 m^3s^{-1}	101 *(-31.0%)*	119 *(-18.0%)*	163 *(+11.0%)*	160 *(+9.9%)*
RECORD / SPLIT PERIOD	**1939 - 80**	**1939 - 49**	**1950 - 80**		
Allt Leachdach at Intake (91802)	11.7 m^3s^{-1}	11.2 *(-4.3%)*	11.5 *(-1.7%)*		
STATION RECORD	**MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by mean exceedance series**				
RECORD / SPLIT PERIOD	**1934 - 92**	**1934 - 62**	**1963 - 92**		
Dee at Woodend (12001)	938 m^3s^{-1}	910 *(-3.0%)*	894 *(-4.4%)*		
RECORD / SPLIT PERIOD	**1914 - 88**	**1914 - 46**	**1947 - 88**		
Irvine at Kilmarnock (83802)	146 m^3s^{-1}	101 *(-31.0%)*	160 *(+9.9%)*		
RECORD / SPLIT PERIOD	**1939 - 80**	**1939 - 55**	**1956 - 69**	**1970 - 80**	
Allt Leachdach at Intake (91802)	11.7 m^3s^{-1}	13.4 *(+14.5%)*	11.5 *(-1.7%)*	9.1 *(-22.2%)*	

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Table 7.3: Magnitude of One-Hundred Year Flood for Complete and Split Series - 1944-92 records

STATION RECORD	MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by flood frequency series		
RECORD / SPLIT PERIOD	1944 - 92	1944 - 62	1963 - 92
Dee at Woodend (12001)	893 m^3s^{-1}	826 *(-7.6%)*	894 *(+0.1%)*
STATION RECORD	**MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by mean exceedance series**		
RECORD / SPLIT PERIOD	**1944 - 92**	**1944 - 62**	**1963 - 92**
Dee at Woodend (12001)	893 m^3s^{-1}	826 *(-7.6%)*	894 *(+0.1%)*

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Table 7.4: Magnitude of One-Hundred Year Flood for Complete and Split Series - 1954-92 records

STATION RECORD	**MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100)** **Periods defined by flood frequency series**			
RECORD / SPLIT PERIOD	**1954-92**	**1954-66**	**1967-92**	
Avon (08004)	551.2	665.1 *(+20.7)*	478.2 *(-13.2)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-80**	**1981-92**	
Spey @ Boat of Garten (08005)	393.6	365.1 *(-7.2)*	476.3 *(+21.0)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-66**	**1967-82**	**1983-92**
Spey @ Boat of Brig (08006)	1203.4	1469.9 *(+22.1)*	1091.1 *(-9.3)*	1005.4 *(-16.5)*
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**	
Spey @ Invertruim (08007)	269.0	233.7 *(-13.1)*	340.5 *(+26.6)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**	
Dulnain (08009)	218.6	202.1 *(-7.5)*	210.6 *(-3.7)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-80**	**1981-92**	
Spey @ Grantown (08010)	518.7	528.3 *(+1.9)*	531.0 *(+2.4)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Dee (12001)	892.0	825.0 *(-7.5)*	932.6 *(+4.4)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tay @ Caputh (15003)	1485.4	1301.4 *(-12.4)*	1562.4 *(+5.2)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tay @ Ballathie (15006)	1727.3	1613.5 *(-6.6)*	1784.2 *(+3.3)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tay @ Pitnacree (15007)	741.3	637.2 *(-14.0)*	823.6 *(+11.1)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Dean Water (15008)	52.9	52.8 *(-0.2)*	51.2 *(-3.2)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-76**	**1977-92**	
Earn (16001)	299.7	312.1 *(+4.1)*	299.1 *(-0.2)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tweed @ Peebles (21003)	338.1	376.5 *(+11.4)*	291.2 *(-13.9)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**	
Kelvin (84001)	146.4	163.2 *(+11.5)*	119.2 *(-18.6)*	

Table 7.4 (cont): Magnitude of One-Hundred Year Flood for Complete and Split Series - 1954-92 records

STATION RECORD	**MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by mean exceedance series**			
RECORD / SPLIT PERIOD	**1954-92**	**1954-65**	**1966-92**	
Avon (08004)	551.2	625.9 *(+13.6)*	468.1 *(-15.1)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-65**	**1966-92**	
Spey @ Boat of Garten (08005)	393.6	315.0 *(-20.0)*	426.1 *(+8.3)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**	
Spey @ Boat of Brig (08006)	1203.4	1323.4 *(+10.0)*	1020.4 *(-15.2)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-60**	**1961-92**	
Spey @ Invertruim (08007)	269.0	155.8 *(-42.1)*	278.2 *(+3.4)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**	
Dulnain (08009)	218.6	202.1 *(-7.5)*	210.6 *(-3.7)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-65**	**1966-92**	
Spey @ Grantown (08010)	518.7	483.5 *(-6.8)*	522.9 *(+0.8)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Dee (12001)	892.0	825.0 *(-7.6)*	932.6 *(+4.4)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tay @ Caputh (15003)	1485.4	1301.4 *(-12.4)*	1562.4 *(+5.2)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tay @ Ballathie (15006)	1727.3	1613.5 *(-6.6)*	1784.2 *(+3.3)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-65**	**1966-92**	
Tay @ Pitnacree (15007)	741.3	733.7 *(-1.0)*	758.6 *(+2.3)*	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Dean Water (15008)	52.9	52.8 *(-0.2)*	51.2 *(-3.2)*	
RECORD / SPLIT PERIOD	**1954-92**			
Earn (16001)	299.7			
RECORD / SPLIT PERIOD	**1954-92**			
Tweed @ Peebles (21003)	338.1			
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Kelvin (84001)	146.4	165.8 *(13.3)*	124.2 *(-15.2)*	

Appendix Five

Table 7.5: Magnitude of One-Hundred Year Flood for Complete and Split Series - 1964-92 records

STATION RECORD	MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by flood frequency series			
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Findhorn @ Shenachie (07001)	514.5	455.9 *(-11.4)*	514.5 *(0.0)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Findhorn @ Forres (07002)	1108.2	1051.7 *(-5.1)*	1151.5 *(+3.9)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Lossie (07003)	109.0	137.3 *(+26.0)*	89.3 *(-18.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Avon (08004)	471.9	545.5 *(+15.6)*	468.1 *(-0.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-80**	**1981-92**	
Spey @ Boat of Garten (08005)	413.6	351.8 *(-14.9)*	476.3 *(+15.2)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Spey @ Boat of Brig (08006)	1058.7	1159.8 *(+9.5)*	1020.4 *(-3.6)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
Spey @ Invertruim (08007)	279.3	263.4 *(-5.7)*	312.5 *(+11.9)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-78**	**1979-92**	
Dulnain (08009)	213.5	197.1 *(-7.7)*	204.5 *(-4.2)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-78**	**1979-92**	
Spey @ Grantown (08010)	522.7	520.5 *(-0.4)*	518.7 *(-0.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
Deveron @ Avochie (09001)	241.5	289.2 *(+19.8)*	228.6 *(-5.3)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
Deveron @ Muiresk (09002)	516.4	589.2 *(+14.1)*	468.4 *(-9.3)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Isla (09003)	92.0	93.7 *(+1.8)*	98.2 *(+6.7)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Dee (12001)	902.7	508.0 *(-43.7)*	991.3 *(+9.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tay @ Caputh (15003)	1529.7	1295.7 *(-15.3)*	1562.4 *(+2.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-80**	**1981-92**	
Tay @ Ballathie (15006)	1717.3	1780.2 *(+3.7)*	1607.4 *(-6.4)*	

Appendix Five

Table 7.5 (cont): Magnitude of One-Hundred Year Flood for Complete and Split Series - 1964-92 records

STATION RECORD	**MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100)** Periods defined by flood frequency series			
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tay @ Pitnacree (15007)	738.9	484.7 *(-34.4)*	823.6 *(+11.5)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Dean Water (15008)	50.2	45.0 *(-10.4)*	52.4 *(+4.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Earn (16001)	300.2	293.7 *(-2.2)*	299.1 *(-0.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-72**	**1973-92**	
Ruchill Water (16003)	334.8	268.2 *(-19.9)*	346.7 *(+3.6)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
Almond @ Craigiehall (19001)	231.8	227.6 *(-1.8)*	259.0 *(+11.7)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Almond @ Almond Weir (19002)	44.9	30.3 *(-32.5)*	50.9 *(+13.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
N.Esk @ Dalmore Weir (19004)	49.8	46.3 *(-7.0)*	51.5 *(+3.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Water of Leith (19006)	58.5	49.2 *(-15.9)*	61.7 *(+5.5)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
Esk @ Musselburgh (19007)	208.2	163.3 *(-21.6)*	226.8 *(+8.9)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
N.Esk @ Dalkeith Palace (19011)	87.8	71.8 *(-18.2)*	95.8 *(+9.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
Tyne @E.Linton (20001)	146.7	148.4 *(+1.2)*	151.7 *(+3.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-95**	
Tyne @ Spilmersford (20003)	113.5	109.8 *(-3.3)*	121.1 *(+6.7)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Birns Water (20005)				
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tweed @ Peebles (21003)	307.8	273.6 *(-11.1)*	291.2 *(-5.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-80**	**1981-92**	
Tweed @ Lyne Ford (21005)	230.2	227.8 *(-1.0)*	233.1 *(+1.3)*	

Table 7.5 (cont): Magnitude of One-Hundred Year Flood for Complete and Split Series - 1964-92 records

STATION RECORD	MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by flood frequency series			
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tweed @ Boleside (21006)	795.8	787.3 *(-1.1)*	872.6 *(+9.7)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Ettrick Water (21007)	490.2	472.0 *(-3.7)*	517.3 *(+5.5)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Teviot @ Ormiston Mill (21008)	652.4	586.3 *(-10.1)*	672.5 *(+3.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Tweed @ Norham (21009)	1750.4	1273.9 *(-27.2)*	2105.7 *(+20.3)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Yarrow Water (21011)	169.2	134.7 *(-20.4)*	185.3 *(+9.5)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Teviot @Hawick (21012)	310.3	345.0 *(+11.2)*	301.4 *(-2.9)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Gala Water (21013)	118.9	79.7 *(-33.0)*	138.4 *(+16.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Nith @ Friar's Carse (79002)	894.3	805.8 *(-9.9)*	907.1 *(+1.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-80**	**1981-92**	
Nith @ Hall Bridge (79003)	140.0	137.0 *(-2.7)*	151.3 *(+8.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Scar Water (79004)	280.6	258.5 *(-7.9)*	294.7 *(+5.0)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Cluden Water (79005)	235.4	194.3 *(-17.9)*	250.3 *(+6.3)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Urr (80001)	184.7	160.7 *(-13.0)*	197.7 *(+7.0)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-71**	**1972-92**	
Cree (81002)	450.7	397.0 *(-11.9)*	482.6 *(+7.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-72**	**1973-92**	
Girvan (82001)	135.5	135.4 *(-0.1)*	140.6 *(+3.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Kelvin (84001)	130.5	136.7 *(+4.8)*	124.2 *(-4.8)*	

Table 7.5 (cont): Magnitude of One-Hundred Year Flood for Complete and Split Series - 1964-92 records

STATION RECORD	MAGNITUDE OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by mean exceedance series			
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Findhorn @ Shenachie (07001)	514.5	405.1 *(-21.3)*	531.9 *(+3.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Findhorn @ Forres (07002)	1108.2	1051.7 *(-5.1)*	1151.5 *(+3.9)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-80**	**1981-92**	
Lossie (07003)	109.0	116.1 *(+6.5)*	104.2 *(-4.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-79**	**1980-92**	
Avon (08004)	471.9	484.3 *(+2.6)*	482.6 *(+2.3)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Spey @ Boat of Garten (08005)	413.6	315.4 *(-23.7)*	442.8 *(+7.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Spey @ Boat of Brig (08006)	1058.7	1159.8 *(+9.5)*	1020.4 *(-3.6)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Spey @ Invertruim (08007)	279.3	234.6 *(-16.0)*	311.8 *(+11.6)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-72**	**1973-92**	
Dulnain (08009)	213.5	222.2 *(+4.1)*	205.4 *(-3.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Spey @ Grantown (08010)	522.7	492.7 *(-5.7)*	516.7 *(-1.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Deveron @ Avochie (09001)	241.5	281.6 *(+16.6)*	231.7 *(-4.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Deveron @ Muiresk (09002)	516.4	570.5 *(+10.5)*	471.6 *(-8.7)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Isla (09003)	92.0	93.7 *(+1.8)*	98.2 *(+6.7)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Dee (12001)	902.7	508.0 *(-43.7)*	991.3 *(+9.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tay @ Caputh (15003)	1529.7	1295.7 *(-15.3)*	1562.4 *(+2.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tay @ Ballathie (15006)	1717.3	1448.8 *(-15.6)*	1784.1 *(+3.9)*	

Table 7.5 (cont): Magnitude of One-Hundred Year Flood for Complete and Split Series - 1964-92 records

STATION RECORD	MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by mean exceedance series			
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tay @ Pitnacree (15007)	738.9	484.7 *(-34.4)*	823.6 *(+11.5)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-85**	**1986-92**
Dean Water (15008)	50.2	45.0 *(-10.4)*	56.8 *(+13.1)*	49.2 *(-2.0)*
RECORD / SPLIT PERIOD	**1964-92**	**1964-83**	**1984-92**	
Earn (16001)	300.2	288.8 *(-3.8)*	306.4 *(+2.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Ruchill Water (16003)	334.8	334.0 *(-0.2)*	325.1 *(-2.9)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Almond @ Craigiehall (19001)	231.8	220.0 *(-5.1)*	260.8 *(+12.5)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Almond @ Almond Weir (19002)	44.9	31.0 *(-31.0)*	50.1 *(+11.6)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-69**	**1970-85**	**1986-92**
N.Esk @ Dalmore Weir (19004)	49.8	53.6 *(+7.6)*	43.2 *(-13.3)*	58.7 *(+17.9)*
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Water of Leith (19006)	58.5	49.2 *(-15.9)*	61.7 *(+5.5)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Esk @ Musselburgh (19007)	208.2	175.1 *(-15.9)*	218.9 *(+5.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
N.Esk @ Dalkeith Palace (19011)	87.8	76.6 *(-12.8)*	95.3 *(+8.5)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tyne @E.Linton (20001)	146.7	155.4 *(+5.9)*	148.3 *(+1.1)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tyne @ Spilmersford (20003)	113.5	109.8 *(-3.3)*	121.1 *(+6.7)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Birns Water (20005)				
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Tweed @ Peebles (21003)	307.8	272.9 *(-11.3)*	279.5 *(-9.2)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tweed @ Lyne Ford (21005)	230.2	198.0 *(-14.0)*	226.4 *(-1.7)*	

Appendix Five

Table 7.5 (cont): Magnitude of One-Hundred Year Flood for Complete and Split Series - 1964-92 records

STATION RECORD	MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by mean exceedance series			
RECORD / SPLIT PERIOD	**1964-92**	**1964-70**	**1971-92**	
Tweed @ Boleside (21006)	795.8	747.1 *(-6.1)*	814.4 *(+2.3)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-78**	**1979-92**	
Ettrick Water (21007)	490.2	533.5 *(+8.8)*	449.9 *(-8.2)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Teviot @ Ormiston Mill (21008)	652.4	525.1 *(-19.5)*	708.4 *(+8.6)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Tweed @ Norham (21009)	1750.4	1273.9 *(-27.2)*	2105.7 *(+20.3)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-71**	**1972-92**	
Yarrow Water (21011)	169.2	141.2 *(-16.5)*	181.4 *(+7.2)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Teviot @Hawick (21012)	310.3	320.7 *(+3.4)*	304.8 *(-1.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
Gala Water (21013)	118.9	84.8 *(-28.7)*	140.8 *(+18.4)*	
RECORD / SPLIT PERIOD	**1964-92**			
Nith @ Friar's Carse (79002)	894.3			
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Nith @ Hall Bridge (79003)	140.0	109.3 *(-21.9)*	154.5 *(+10.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Scar Water (79004)	280.6	258.5 *(-7.9)*	294.7 *(+5.0)*	
RECORD / SPLIT PERIOD	**1964-92**			
Cluden Water (79005)	235.4			
RECORD / SPLIT PERIOD	**1964-92**			
Urr (80001)	184.7			
RECORD / SPLIT PERIOD	**1964-92**	**1964-70**	**1971-92**	
Cree (81002)	450.7	366.7 *(-18.6)*	477.1 *(+5.9)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-82**	**1983-92**	
Girvan (82001)	135.5	138.6 *(+2.3)*	129.4 *(-4.5)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Kelvin (84001)	130.5	136.7 *(+4.8)*	124.2 *(-4.8)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	

Clyde @ Hazelbank (84003)	533.4	442.2 *(-17.1)*	579.7 *(+8.7)*	

Table 7.5 (cont): Magnitude of One-Hundred Year Flood for Complete and Split Series - 1964-92 records

STATION RECORD	**MAGNITUDE (m^3s^{-1}) OF Q100 (AND % DIFFERENCE FROM COMPLETE SERIES Q100) Periods defined by mean exceedance series**			
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Clyde @ Sills (84004)	398.0	371.9 *(-6.6)*	413.8 *(+4.0)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Clyde @ Blairston (84005)	776.1	666.9 *(-14.1)*	833.8 *(+7.4)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-86**	**1987-92**
Gryfe (84011)	98.4	98.2 *(-0.2)*	103.7 *(+5.4)*	100.8 *(+2.4)*
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
W.Cart Water (84012)	211.0	218.2 *(+3.1)*	220.1 *(+4.0)*	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
N.Calder Water (84019)	93.4	76.1 *(-18.5)*	101.7 *(+8.9)*	

Appendix Five

Table 7.6: Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - Long POT Records

STATION RECORD	GROWTH FACTOR Q100/Q5: Frequency Splits				
RECORD / SPLIT PERIOD	**1934 - 92**	**1934 - 62**	**1963 - 82**	**1983 - 92**	
Dee (12001)	1.645	1.572	1.725	1.593	
RECORD / SPLIT PERIOD	**1914 - 88**	**1914 - 28**	**1929 - 51**	**1952-77**	**1978-88**
Irvine (83802)	1.466	1.300	1.381	1.587	1.377
RECORD / SPLIT PERIOD	**1939 - 80**	**1939 - 49**	**1950 - 80**		
Allt Leachdach (91802)	1.444	1.383	1.456		
STATION RECORD	**GROWTH FACTOR Q100/Q5: Magnitude Splits**				
RECORD / SPLIT PERIOD	**1934 - 92**	**1934 - 62**	**1963 - 92**		
Dee (12001)	1.645	1.572	1.680		
RECORD / SPLIT PERIOD	**1914 - 88**	**1914 - 46**	**1947 - 88**		
Irvine (83802)	1.466	1.301	1.465		
RECORD / SPLIT PERIOD	**1939 - 80**	**1939 - 55**	**1956 - 69**	**1970 - 80**	
Allt Leachdach (91802)	1.444	1.540	1.438	1.264	

Table 7.7: Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - 1944-92 POT records

STATION RECORD	GROWTH FACTOR Q100/Q5: Frequency Splits		
RECORD / SPLIT PERIOD	**1944 - 92**	**1944 - 62**	**1963 - 92**
Dee (12001)	1.626	1.517	1.680
STATION RECORD	**GROWTH FACTOR Q100/Q5: Magnitude Splits**		
RECORD / SPLIT PERIOD	**1944 - 92**	**1944 - 62**	**1963 - 92**
Dee (12001)	1.626	1.517	1.680

Table 7.8: Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - 1954-92 POT Records

STATION RECORD	**GROWTH FACTOR Q100/Q5: Frequency Splits**			
RECORD / SPLIT PERIOD	**1954-92**	**1954-66**	**1967-92**	
Avon (08004)	1.723	1.725	1.714	
RECORD / SPLIT PERIOD	**1954-92**	**1954-80**	**1981-92**	
Spey @ Boat of Garten (08005)	1.616	1.612	1.672	
RECORD / SPLIT PERIOD	**1954-92**	**1954-66**	**1967-82**	**1983-92**
Spey @ Boat of Brig (08006)	1.683	1.726	1.670	1.641
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**	
Spey @ Invertruim (08007)	1.673	1.708	1.717	
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**	
Dulnain (08009)	1.592	1.595	1.495	
RECORD / SPLIT PERIOD	**1954-92**	**1954-80**	**1981-92**	
Spey @ Grantown (08010)	1.539	1.569	1.528	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Dee (12001)	1.635	1.625	1.623	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tay @ Caputh (15003)	1.457	1.397	1.455	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tay @ Ballathie (15006)	1.396	1.366	1.399	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tay @ Pitnacree (15007)	1.570	1.528	1.589	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Dean Water (15008)	1.469	1.479	1.430	
RECORD / SPLIT PERIOD	**1954-92**	**1954-76**	**1977-92**	
Earn (16001)	1.347	1.379	1.348	
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**	
Tweed at Peebles (21003)	1.512	1.569	1.425	
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**	
Kelvin (84001)	1.317	1.413	1.161	

Appendix Five

Table 7.8 (cont): Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - 1954-92 POT Records

STATION RECORD	GROWTH FACTOR Q100/Q5: Magnitude splits		
RECORD / SPLIT PERIOD	**1954-92**	**1954-65**	**1966-92**
Avon (08004)	1.723	1.737	1.709
RECORD / SPLIT PERIOD	**1954-92**	**1954-65**	**1966-92**
Spey @ Boat of Garten (08005)	1.616	1.489	1.658
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**
Spey @ Boat of Brig (08006)	1.683	1.722	1.615
RECORD / SPLIT PERIOD	**1954-92**	**1954-60**	**1961-92**
Spey @ Invertruim (08007)	1.673	1.540	1.661
RECORD / SPLIT PERIOD	**1954-92**	**1954-77**	**1978-92**
Dulnain (08009)	1.592	1.595	1.495
RECORD / SPLIT PERIOD	**1954-92**	**1954-65**	**1966-92**
Spey @ Grantown (08010)	1.539	1.472	1.550
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**
Dee (12001)	1.635	1.625	1.623
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**
Tay @ Caputh (15003)	1.457	1.397	1.455
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**
Tay @ Ballathie (15006)	1.396	1.366	1.399
RECORD / SPLIT PERIOD	**1954-92**	**1954-65**	**1966-92**
Tay @ Pitnacree (15007)	1.570	1.578	1.582
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**
Dean Water (15008)	1.469	1.479	1.430
RECORD / SPLIT PERIOD	**1954-92**		
Earn (16001)	1.347		
RECORD / SPLIT PERIOD	**1954-92**		
Tweed at Peebles (21003)	1.512		
RECORD / SPLIT PERIOD	**1954-92**	**1954-73**	**1974-92**
Kelvin (84001)	1.317	1.417	1.197

Appendix Five

Table 7.9: Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - 1964-92 POT records

STATION RECORD	GROWTH FACTOR Q100/Q5: Frequency Splits		
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**
Findhorn @ Shenachie (07001)	1.572	1.647	1.531
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**
Findhorn @ Forres (07002)	1.812	1.855	1.792
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**
Lossie (07003)	1.799	1.878	1.724
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**
Avon (08004)	1.673	1.726	1.709
RECORD / SPLIT PERIOD	**1964-92**	**1964-80**	**1981-92**
Spey @ Boat of Garten (08005)	1.650	1.614	1.672
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**
Spey @ Boat of Brig (08006)	1.641	1.716	1.615
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**
Spey @ Invertruim (08007)	1.661	1.751	1.692
RECORD / SPLIT PERIOD	**1964-92**	**1964-78**	**1979-92**
Dulnain (08009)	1.568	1.600	1.474
RECORD / SPLIT PERIOD	**1964-92**	**1964-78**	**1979-92**
Spey @ Grantown (08010)	1.564	1.592	1.534
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**
Deveron @ Avochie (09001)	1.612	1.685	1.619
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**
Deveron @ Muiresk (09002)	1.680	1.722	1.643
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**
Isla (09003)	1.589	1.691	1.607
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**
Dee (12001)	1.684	1.533	1.672
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**
Tay @ Caputh (15003)	1.484	1.474	1.455
RECORD / SPLIT PERIOD	**1964-92**	**1964-80**	**1981-92**
Tay @ Ballathie (15006)	1.410	1.477	1.330
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**
Tay @ Pitnacree (15007)	1.573	1.475	1.589
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**
Dean Water (15008)	1.447	1.438	1.440

Appendix Five

Table 7.9 (cont): Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - 1964-92 POT records

STATION RECORD	GROWTH FACTOR Q100/Q5: Frequency Splits		
RECORD / SPLIT PERIOD	1964-92	1964-76	1977-92
Earn (16001)	1.370	1.386	1.348
RECORD / SPLIT PERIOD	1964-92	1964-72	1973-92
Ruchill Water (16003)	1.609	1.676	1.579
RECORD / SPLIT PERIOD	1964-92	1964-74	1975-92
Almond @ Craigiehall (19001)	1.539	1.605	1.590
RECORD / SPLIT PERIOD	1964-92	1964-76	1977-92
Almond @ Almond Weir (19002)	1.682	1.538	1.674
RECORD / SPLIT PERIOD	1964-92	1964-74	1975-92
N.Esk @ Dalmore Weir (19004)	1.677	1.636	1.694
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Water of Leith (19006)	1.612	1.582	1.603
RECORD / SPLIT PERIOD	1964-92	1964-74	1975-92
Esk @ Musselburgh (19007)	1.770	1.714	1.772
RECORD / SPLIT PERIOD	1964-92	1964-74	1975-92
N.Esk @ Dalkeith Palace (19011)	1.725	1.662	1.742
RECORD / SPLIT PERIOD	1964-92	1964-74	1975-92
Tyne @E.Linton (20001)	1.778	1.837	1.783
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-95
Tyne @ Spilmersford (20003)	1.911	1.896	1.956
RECORD / SPLIT PERIOD	1964-92	1964-76	1977-92
Birns Water (20005)	1.773	1.857	1.787
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Tweed @ Peebles (21003)	1.501	1.477	1.425
RECORD / SPLIT PERIOD	1964-92	1964-80	1981-92
Tweed @ Lyne Ford (21005)	1.550	1.646	1.486
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Tweed @ Boleside (21006)	1.560	1.635	1.603
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Ettrick Water (21007)	1.607	1.639	1.623
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Teviot @ Ormiston Mill (21008)	1.584	1.561	1.583
RECORD / SPLIT PERIOD	1964-92	1964-77	1978-92
Tweed @ Norham (21009)	1.575	1.504	1.608

Appendix Five

Table 7.9 (cont): Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - 1964-92 POT records

STATION RECORD	GROWTH FACTOR Q100/Q5: Frequency Splits		
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Yarrow Water (21011)	1.667	1.609	1.686
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Teviot @Hawick (21012)	1.433	1.586	1.388
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Gala Water (21013)	1.689	1.495	1.750
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Nith @ Friar's Carse (79002)	1.560	1.559	1.537
RECORD / SPLIT PERIOD	1964-92	1964-80	1981-92
Nith @ Hall Bridge (79003)	1.507	1.515	1.539
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Scar Water (79004)	1.529	1.517	1.543
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Cluden Water (79005)	1.544	1.484	1.550
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Urr (80001)	1.505	1.478	1.524
RECORD / SPLIT PERIOD	1964-92	1964-71	1972-92
Cree (81002)	1.520	1.572	1.534
RECORD / SPLIT PERIOD	1964-92	1964-72	1973-92
Girvan (82001)	1.374	1.406	1.391
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Kelvin (84001)	1.246	1.328	1.197
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Clyde @ Hazelbank (84003)	1.524	1.463	1.541
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Clyde @ Sills (84004)	1.527	1.560	1.508
RECORD / SPLIT PERIOD	1964-92	1964-73	1974-92
Clyde @ Blairston (84005)	1.517	1.499	1.509
RECORD / SPLIT PERIOD	1964-92	1964-74	1975-92
Gryfe (84011)	1.359	1.426	1.380
RECORD / SPLIT PERIOD	1964-92	1964-75	1976-92
W.Cart Water (84012)	1.377	1.604	1.366
RECORD / SPLIT PERIOD	1964-92	1964-75	1976-92
N.Calder Water (84019)	1.674	1.723	1.688

Appendix Five

Table 7.9 (cont): Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - 1964-92 POT records

STATION RECORD	**GROWTH FACTOR Q100/Q5: Magnitude Splits**			
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Findhorn @ Shenachie (07001)	1.572	1.599	1.515	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Findhorn @ Forres (07002)	1.812	1.855	1.792	
RECORD / SPLIT PERIOD	**1964-92**	**1964-80**	**1981-92**	
Lossie (07003)	1.799	1.834	1.787	
RECORD / SPLIT PERIOD	**1964-92**	**1964-79**	**1980-92**	
Avon (08004)	1.673	1.698	1.689	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Spey @ Boat of Garten (08005)	1.650	1.571	1.653	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Spey @ Boat of Brig (08006)	1.641	1.716	1.615	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Spey @ Invertruim (08007)	1.661	1.751	1.683	
RECORD / SPLIT PERIOD	**1964-92**	**1964-72**	**1973-92**	
Dulnain (08009)	1.568	1.662	1.521	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Spey @ Grantown (08010)	1.564	1.567	1.528	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Deveron @ Avochie (09001)	1.612	1.678	1.626	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Deveron @ Muiresk (09002)	1.680	1.707	1.647	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Isla (09003)	1.589	1.691	1.607	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Dee (12001)	1.684	1.533	1.672	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tay @ Caputh (15003)	1.484	1.474	1.455	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tay @ Ballathie (15006)	1.410	1.399	1.399	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tay @ Pitnacree (15007)	1.573	1.475	1.589	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-85**	**1986-92**
Dean Water (15008)	1.447	1.438	1.456	1.519

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Table 7.9 (cont): Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - 1964-92 POT records

STATION RECORD	GROWTH FACTOR Q100/Q5: Magnitude Splits			
RECORD / SPLIT PERIOD	**1964-92**	**1964-83**	**1984-92**	
Earn (16001)	1.370	1.371	1.339	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Ruchill Water (16003)	1.609	1.719	1.542	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Almond @ Craigiehall (19001)	1.539	1.595	1.583	
RECORD / SPLIT PERIOD	**1964-92**	**1964-75**	**1976-92**	
Almond @ Almond Weir (19002)	1.682	1.550	1.676	
RECORD / SPLIT PERIOD	**1964-92**	**1964-69**	**1970-85**	**1986-92**
N.Esk @ Dalmore Weir (19004)	1.677	1.654	1.630	1.763
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Water of Leith (19006)	1.612	1.582	1.603	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Esk @ Musselburgh (19007)	1.770	1.746	1.760	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-95**	
N.Esk @ Dalkeith Palace (19011)	1.725	1.695	1.755	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-95**	
Tyne @E.Linton (20001)	1.778	1.841	1.780	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-95**	
Tyne @ Spilmersford (20003)	1.911	1.896	1.956	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Birns Water (20005)	1.773	1.873	1.759	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Tweed @ Peebles (21003)	1.501	1.474	1.378	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Tweed @ Lyne Ford (21005)	1.550	1.566	1.492	
RECORD / SPLIT PERIOD	**1964-92**	**1964-70**	**1971-92**	
Tweed @ Boleside (21006)	1.560	1.528	1.573	
RECORD / SPLIT PERIOD	**1964-92**	**1964-78**	**1979-92**	
Ettrick Water (21007)	1.607	1.683	1.529	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Teviot @ Ormiston Mill (21008)	1.584	1.501	1.592	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Tweed @ Norham (21009)	1.575	1.504	1.608	

Appendix Five

Table 7.9 (cont): Growth Factors of Frequency-Magnitude Relationships, based on 2.0 peaks per year - 1964-92 POT records

STATION RECORD	GROWTH FACTOR Q100/Q5: Magnitude Splits			
RECORD / SPLIT PERIOD	**1964-92**	**1964-71**	**1972-92**	
Yarrow Water (21011)	1.667	1.616	1.692	
RECORD / SPLIT PERIOD	**1964-92**	**1964-77**	**1978-92**	
Teviot @Hawick (21012)	1.433	1.501	1.391	
RECORD / SPLIT PERIOD	**1964-92**	**1964-74**	**1975-92**	
Gala Water (21013)	1.689	1.565	1.747	
RECORD / SPLIT PERIOD	**1964-92**			
Nith @ Friar's Carse (79002)	1.560			
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Nith @ Hall Bridge (79003)	1.507	1.396	1.548	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Scar Water (79004)	1.529	1.517	1.543	
RECORD / SPLIT PERIOD	**1964-92**			
Cluden Water (79005)	1.544			
RECORD / SPLIT PERIOD	**1964-92**			
Urr (80001)	1.505			
RECORD / SPLIT PERIOD	**1964-92**	**1964-70**	**1971-92**	
Cree (81002)	1.520	1.480	1.534	
RECORD / SPLIT PERIOD	**1964-92**	**1964-82**	**1983-92**	
Girvan (82001)	1.374	1.378	1.369	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
Kelvin (84001)	1.246	1.328	1.197	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Clyde @ Hazelbank (84003)	1.524	1.440	1.543	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Clyde @ Sills (84004)	1.527	1.527	1.525	
RECORD / SPLIT PERIOD	**1964-92**	**1964-76**	**1977-92**	
Clyde @ Blairston (84005)	1.517	1.472	1.527	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-86**	**1987-92**
Gryfe (84011)	1.359	1.407	1.370	1.398
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
W.Cart Water (84012)	1.377	1.571	1.372	
RECORD / SPLIT PERIOD	**1964-92**	**1964-73**	**1974-92**	
N.Calder Water (84019)	1.674	1.695	1.681	

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Table 7.10: Changes in the Return Period for a flood of fixed discharge for selected records only

RECORD	FIXED DISCHARGE	PERIOD OF RECORD	RETURN PERIOD
• Dee at Woodend	750 cumecs	1934 - 92	20 - 25 years
(12001)		1934 - 62	20 - 25 years
		1963 - 82	20 years
		1983 - 92	90 - 100 years
• Irvine at Kilmarnock	100 cumecs	1914 - 88	5 years
(83802)		1914 - 28	90 - 100 years
		1929 - 51	20 years
		1952 - 77	5 years
		1978 - 88	2 years
• Avon at Delnashaugh	500 cumecs	1954 - 92	50 years
(08004)		1954 - 66	20 years
		1967 - 92	> 100 years
• Spey at Boat of Garten	400 cumecs	1954 - 92	100 years
(08005)		1954 - 80	> 100 years
		1981 - 92	30 - 40 years
• Spey at Boat of Brig	1000 cumecs	1954 - 92	30 - 40 years
(08006)		1954 - 66	10 years
		1967 - 82	50 years
		1983 - 92	100 years
• Spey at Invertruim	250 cumecs	1954 - 92	50 - 60 years
(08007)		1954 - 77	> 100 years
		1978 - 92	10 - 20 years
• Findhorn at Shenachie	400 cumecs	1964 - 92	15 - 18 years
(07001)		1964 - 77	100 years
		1978 - 92	10 years
• Lossie at Sheriffmills	75 cumecs	1964 - 92	12 years
(07003)		1964 - 75	5 years
		1976 - 92	30 - 40 years
• Spey at Boat of Garten	300 cumecs	1964 - 92	10 - 12 years
(08005)		1964 - 73	60 - 70 years
		1974 - 92	10 years
• Deveron at Avochie	200 cumecs	1964 - 92	30 years
(09001)		1964 - 74	10 years
		1975 - 92	40 - 50 years
• Dee at Woodend	750 cumecs	1964 - 92	30 - 40 years
(12001)		1964 - 73	> 100 years
		1974 - 92	20 years
• Tay at Pitnacree	600 cumecs	1964 - 92	20 years
(15007)		1964 - 73	> 100 years
		1974 - 92	10 - 15 years
• Ruchill Water at	250 cumecs	1964 - 92	15 - 20 years
Cultybraggan (16003)		1964 - 72	50 - 60 years
		1973 - 92	10 years
• Almond at Almond	30 cumecs	1964 - 92	10 years
Weir (19002)		1964 - 76	90 - 100 years
		1977 - 92	5 years
• Esk at Musselburgh	150 cumecs	1964 - 92	15 years
(19007)		1964 - 74	50 years
		1975 - 92	10 years

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Table 7.10(cont): Changes in the Return Period for a flood of fixed discharge for selected records only

RECORD	FIXED DISCHARGE	PERIOD OF RECORD	RETURN PERIOD
• Teviot at Ormiston Mill	500 cumecs	1964 - 92	15 years
(21008)		1964 - 76	60 - 70 years
		1977 - 92	10 - 15 years
• Tweed at Norham	1500 cumecs	1964 - 92	30 years
(21009)		1964 - 77	> 100 years
		1978 - 92	10 years

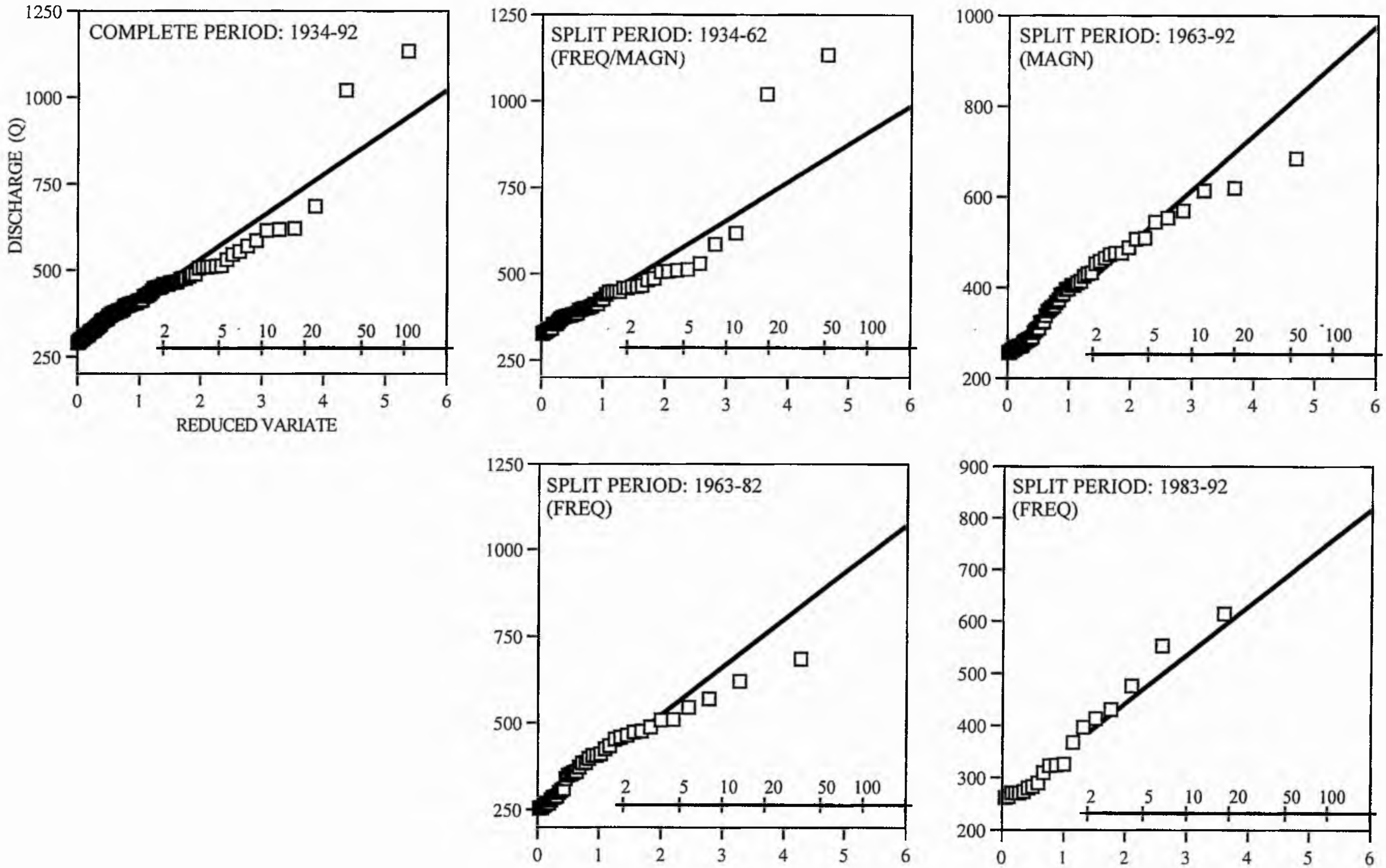

Figure 7.3: Flood frequency curves for complete and split periods of record
Dee at Woodend (12001) 1934-92

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Figure 7.4: Flood frequency curves for complete and split periods of record
Irvine at Kilmarnock (83802) 1914-88

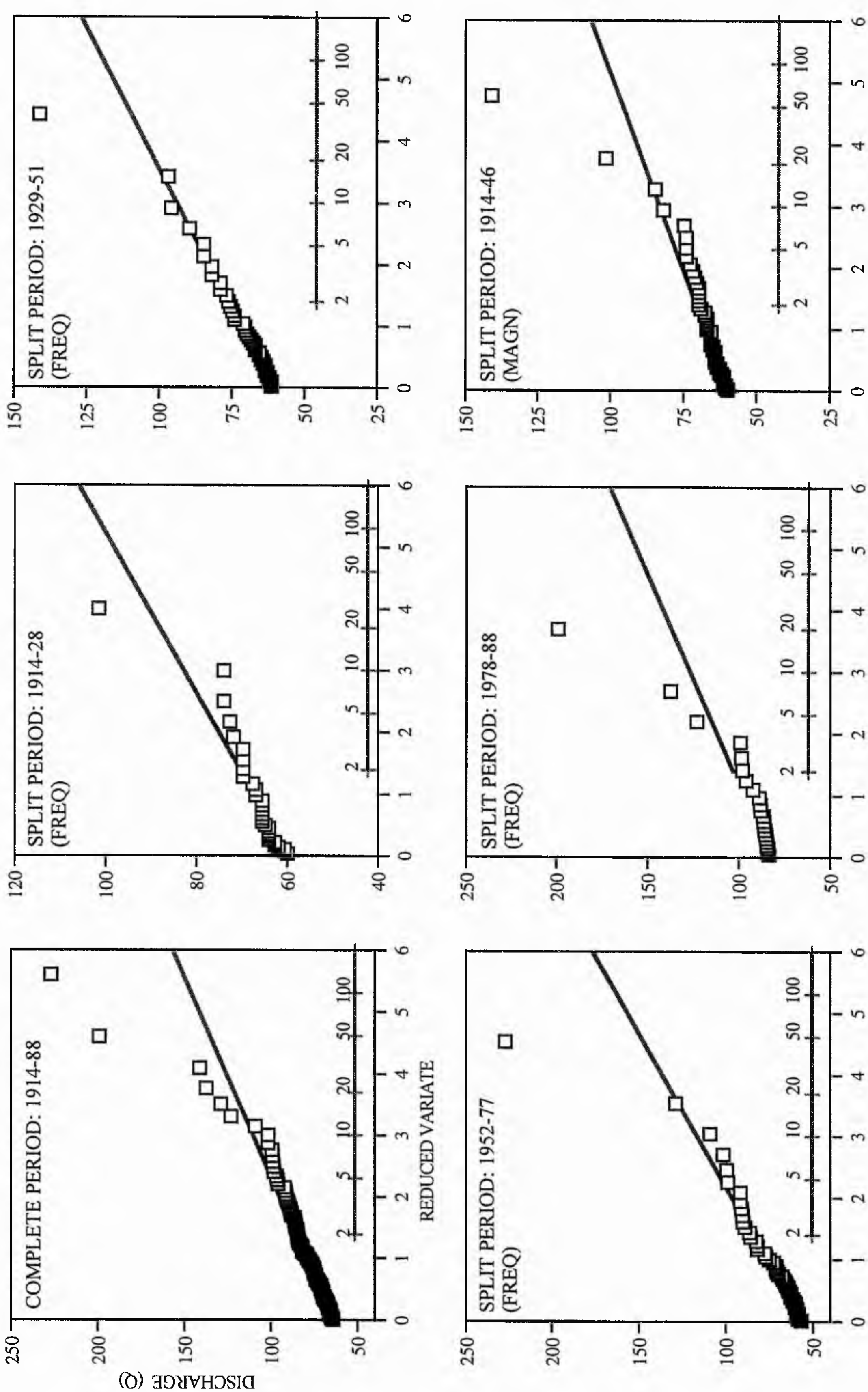

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Figure 7.4 (cont): Flood frequency curves for complete and split periods of record
Irvine at Kilmarnock (83802) 1914-88

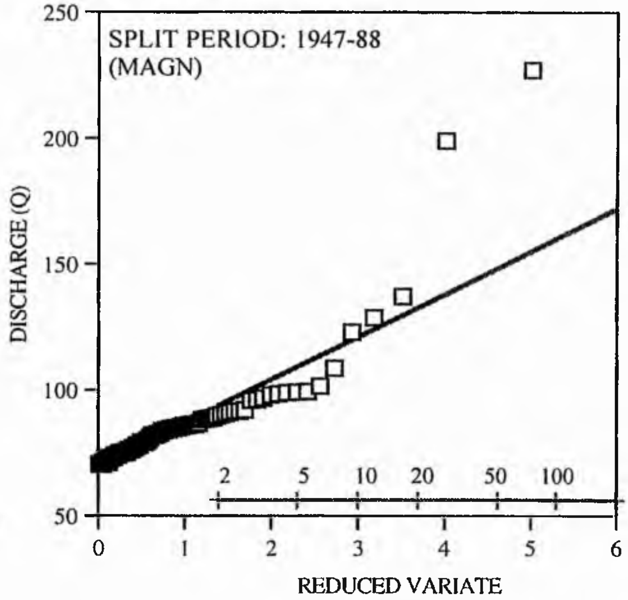

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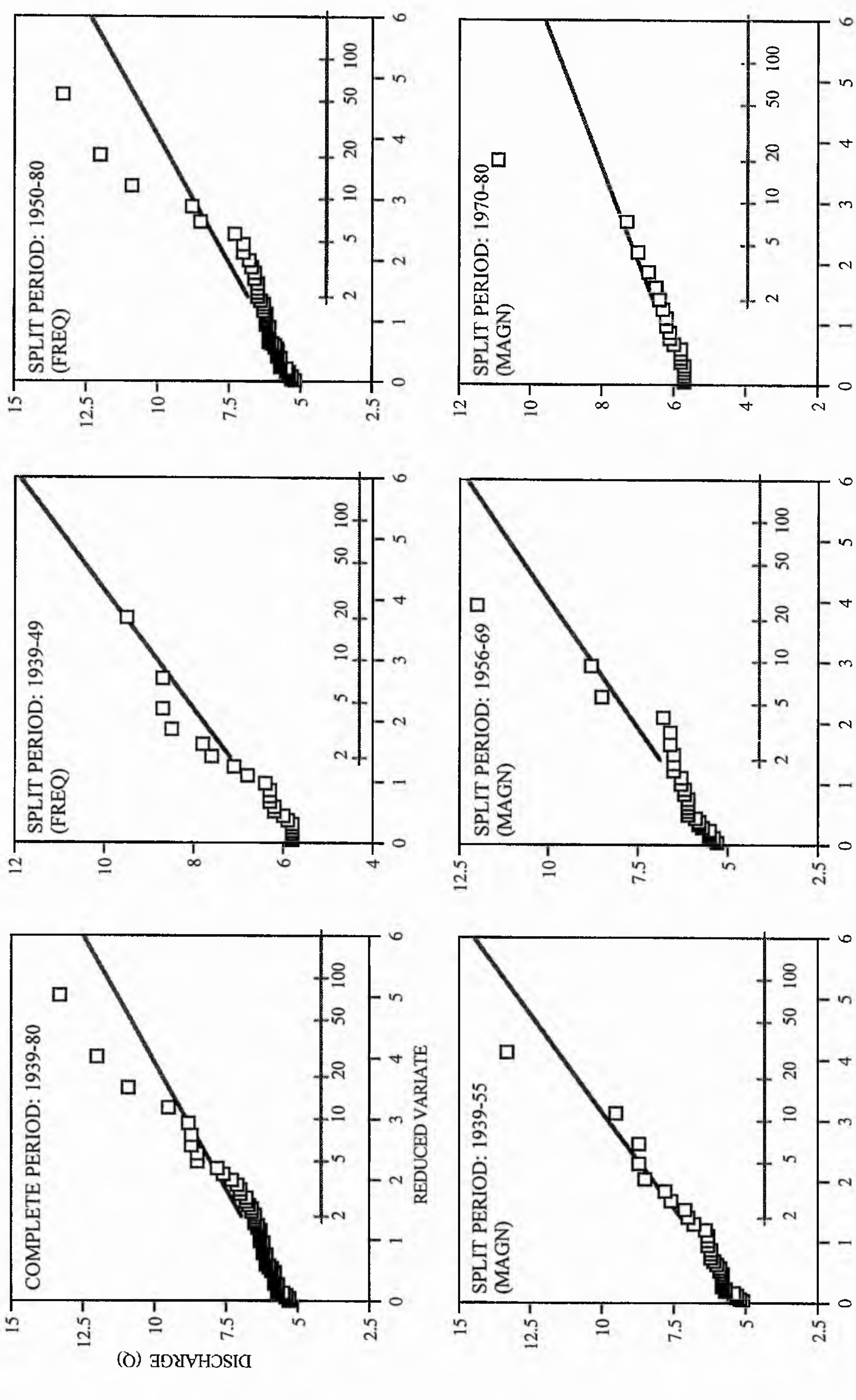
Figure 7.5: Flood frequency curves for complete and split periods of record
Allt Leachdach at Intake (91802) 1939-80



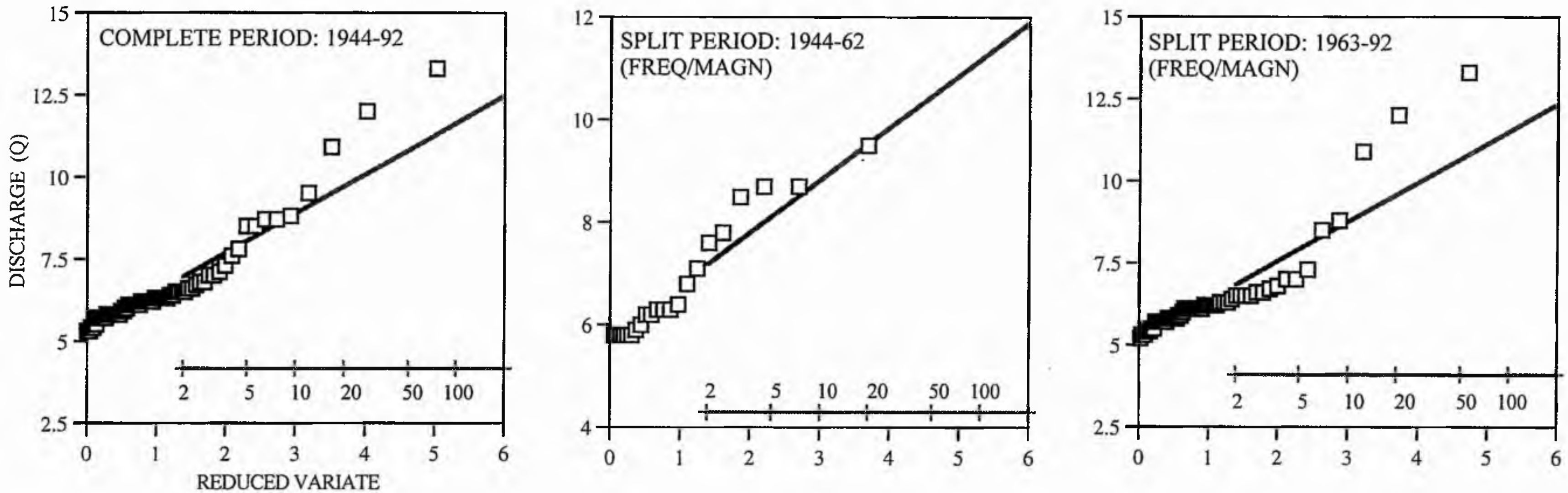


Figure 7.6: Flood frequency curves for complete and split periods of record
Dee at Woodend (12001) 1944-92

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Figure 7.7: Flood frequency curves for complete and split periods of record
Avon at Delnashaugh (08004) 1954-92

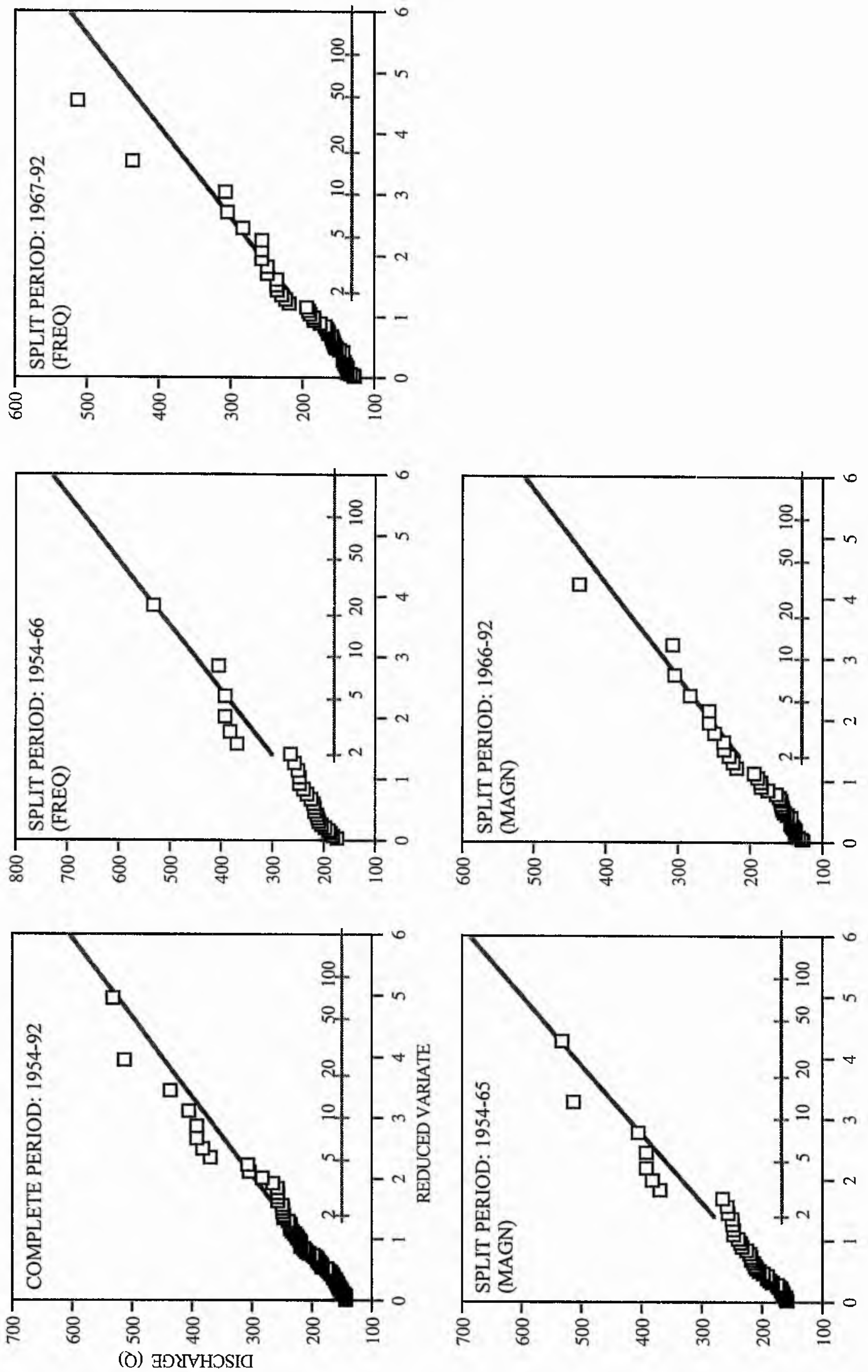

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Figure 7.8: Flood frequency curves for complete and split periods of record
Spey at Boat of Garten (08005) 1954-92

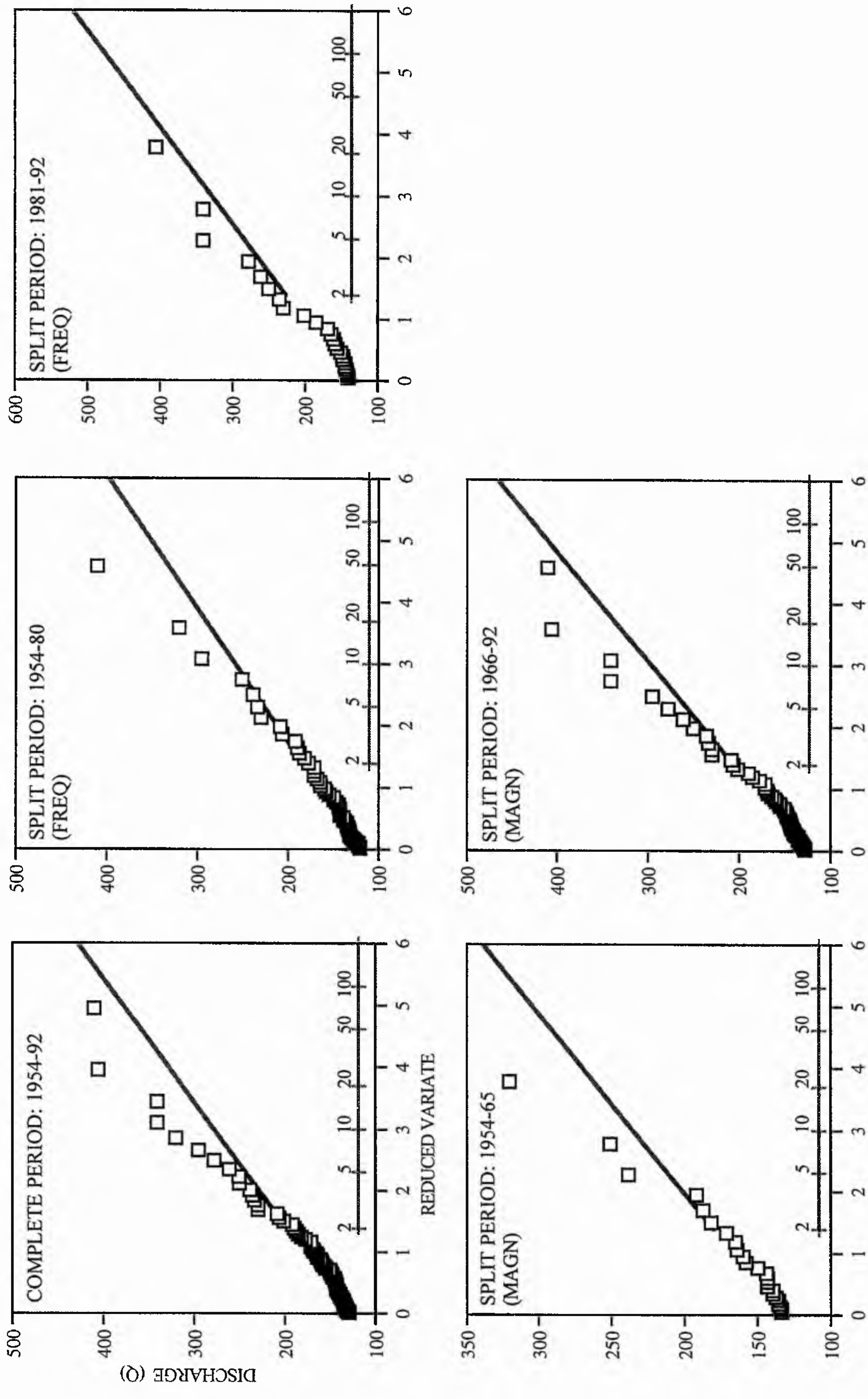

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Figure 7.9: Flood frequency curves for complete and split periods of record
Spey at Boat of Brig (08006) 1954-92

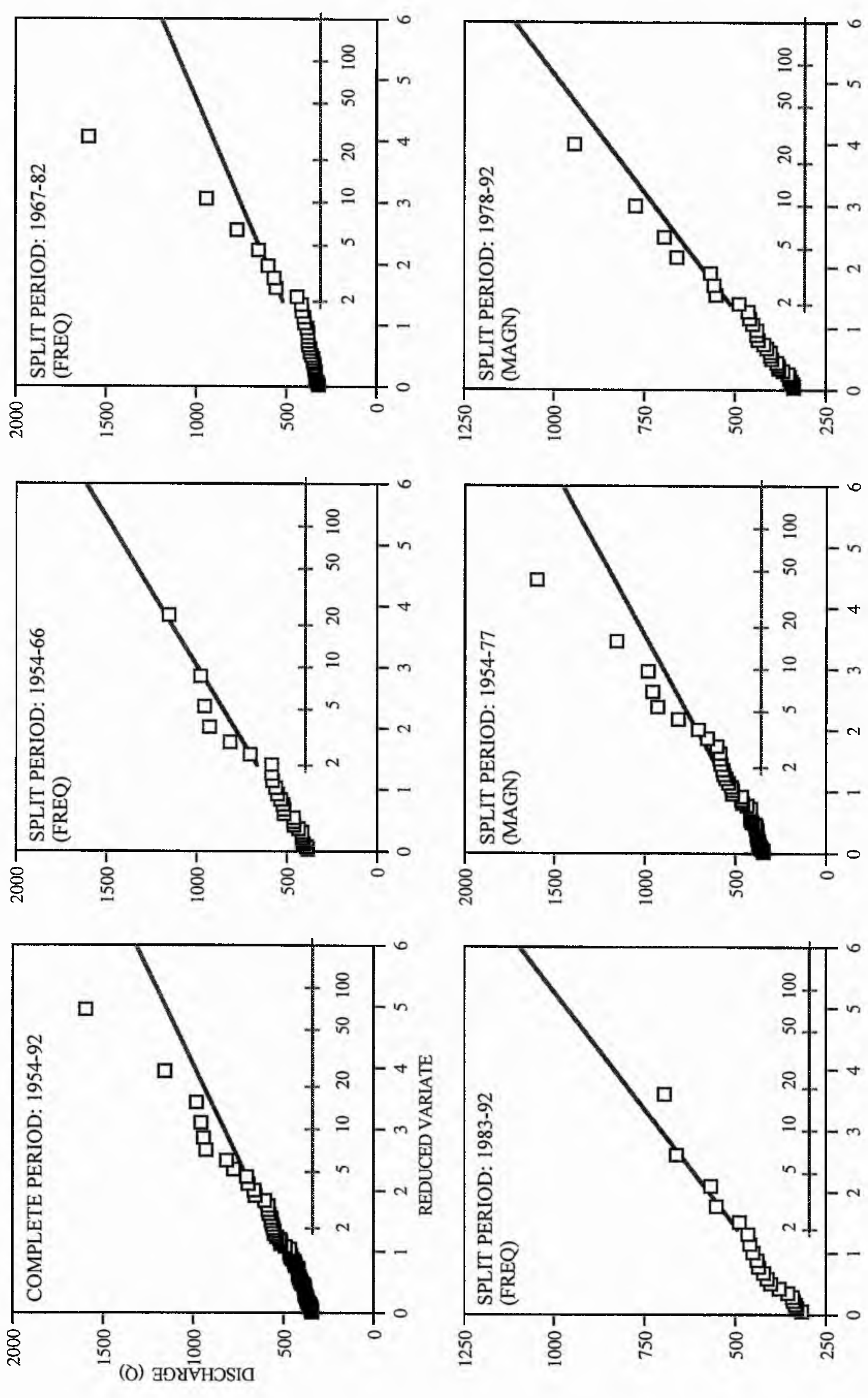

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Figure 7.10: Flood frequency curves for complete and split periods of record
Spey at Invertruim (08007) 1954-92

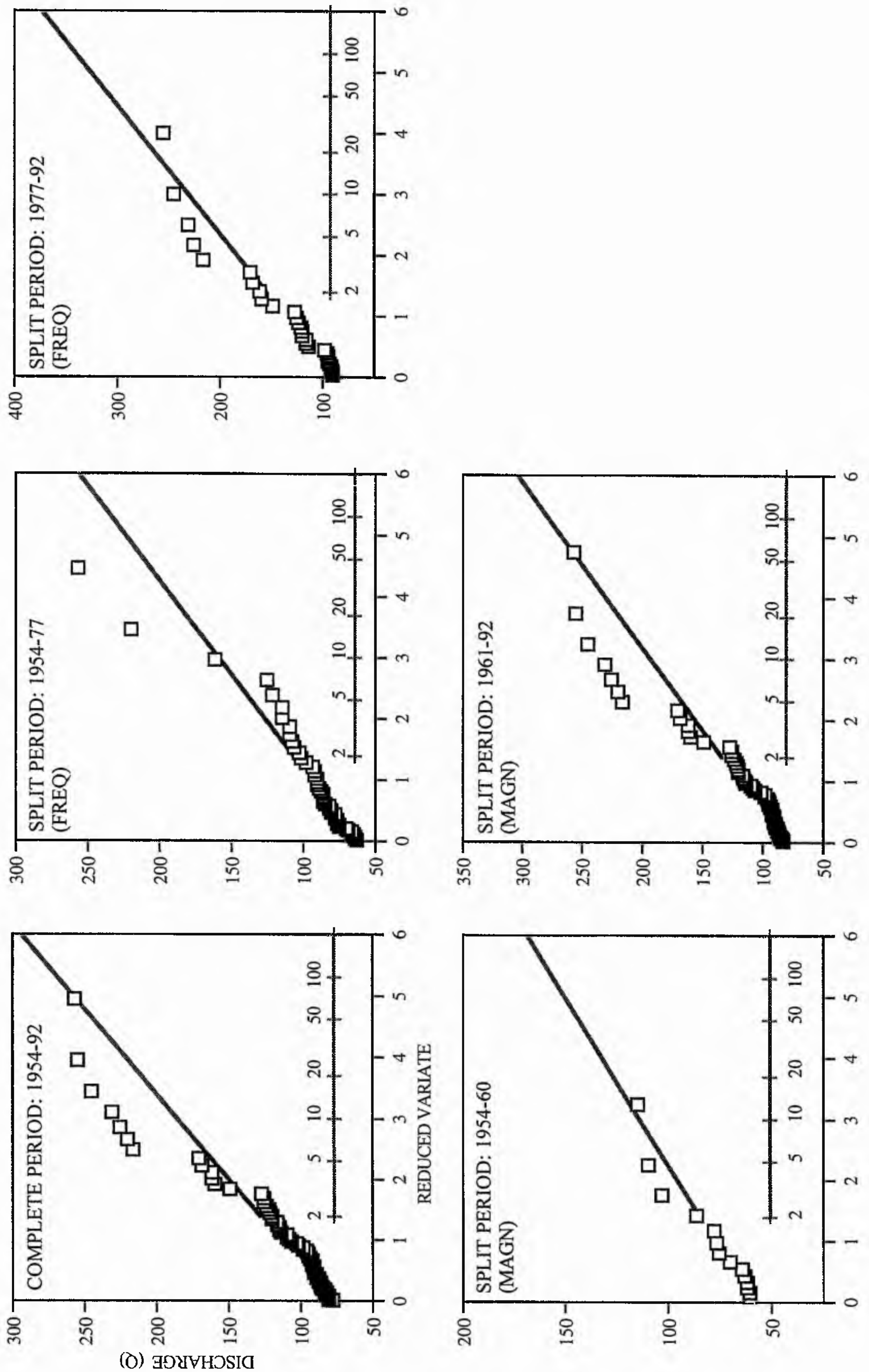

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Figure 7.11: Flood frequency curves for complete and split periods of record
Dulnain at Balnaan Bridge (08009) 1954-92

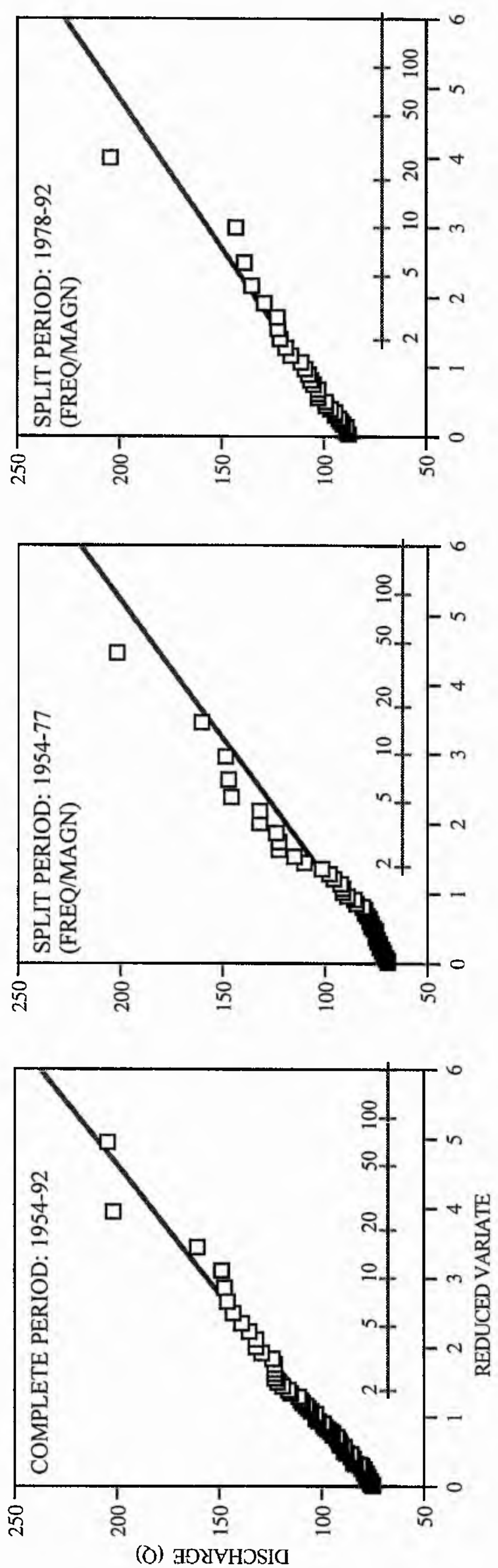

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Figure 7.12: Flood frequency curves for complete and split periods of record
Spey at Grantown (08010) 1954-92

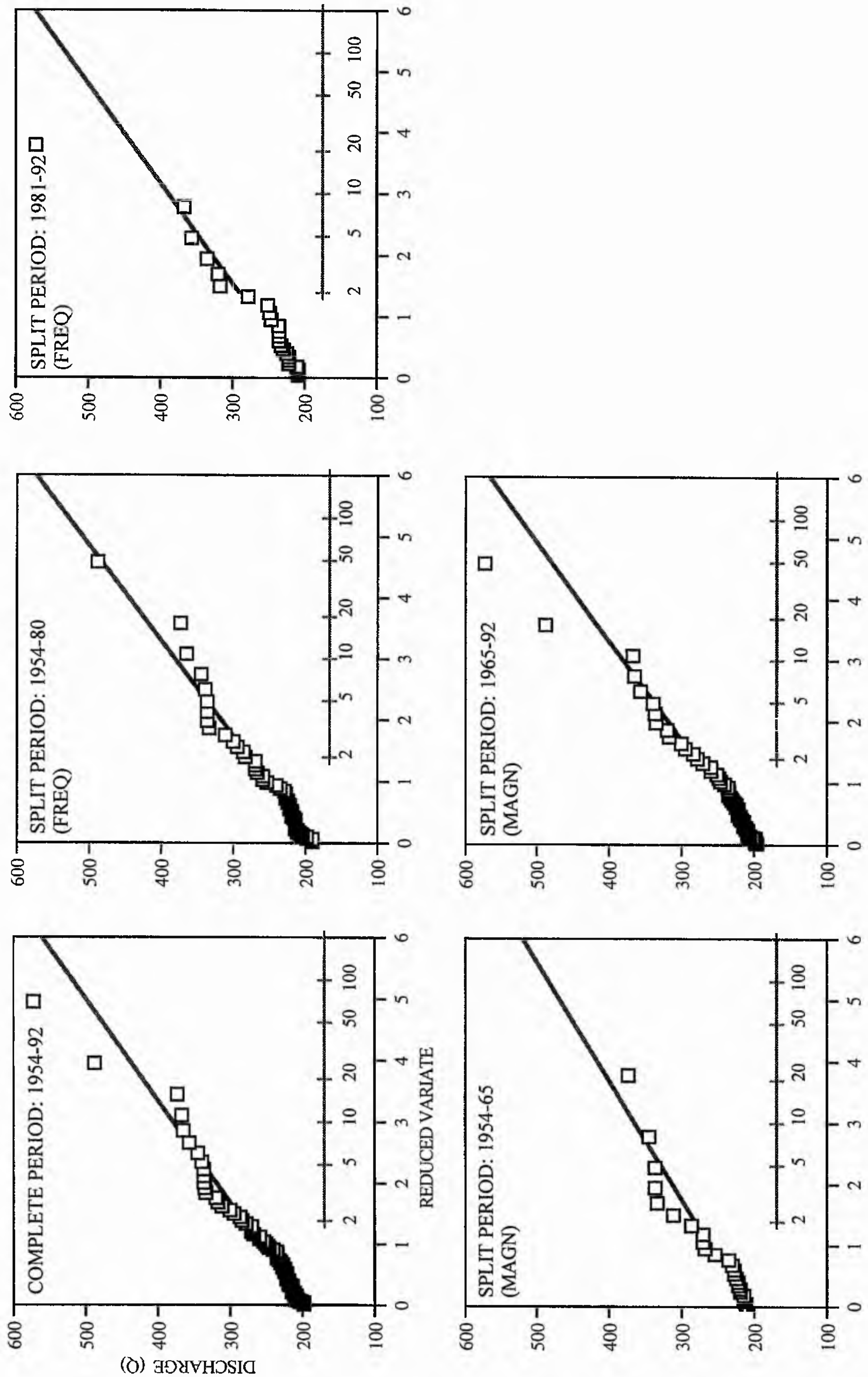

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Figure 7.13: Flood frequency curves for complete and split periods of record
Dee at Woodend (12001) 1954-92

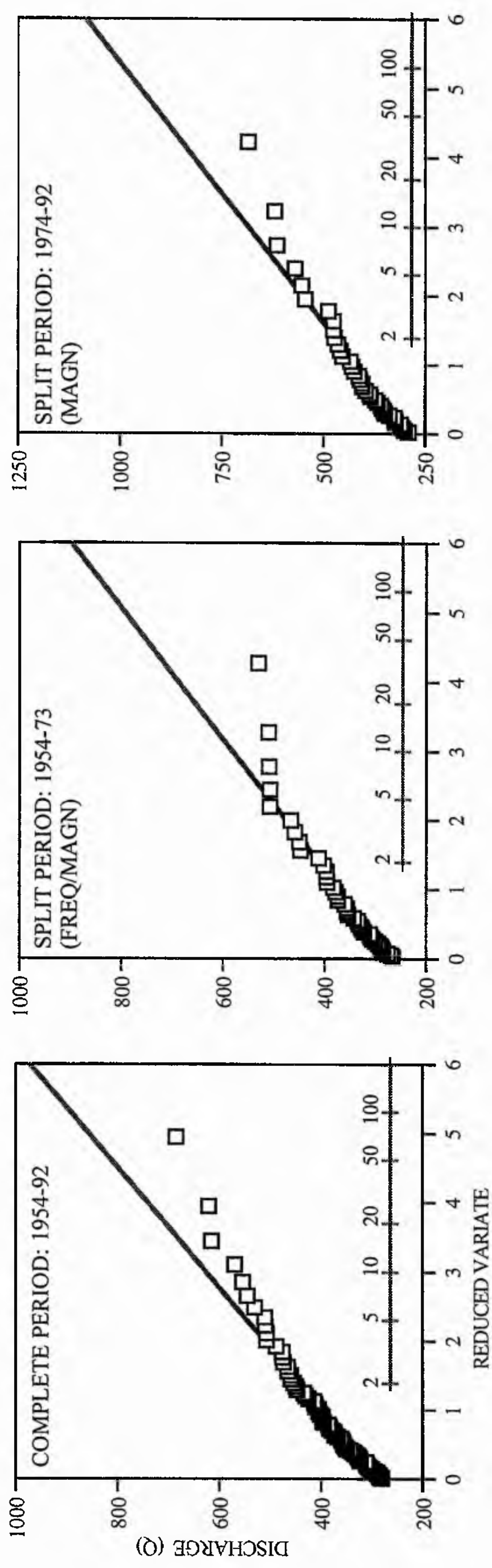

Figure 7.14: Flood frequency curves for complete and split periods of record
Tay at Caputh (15003) 1954-92

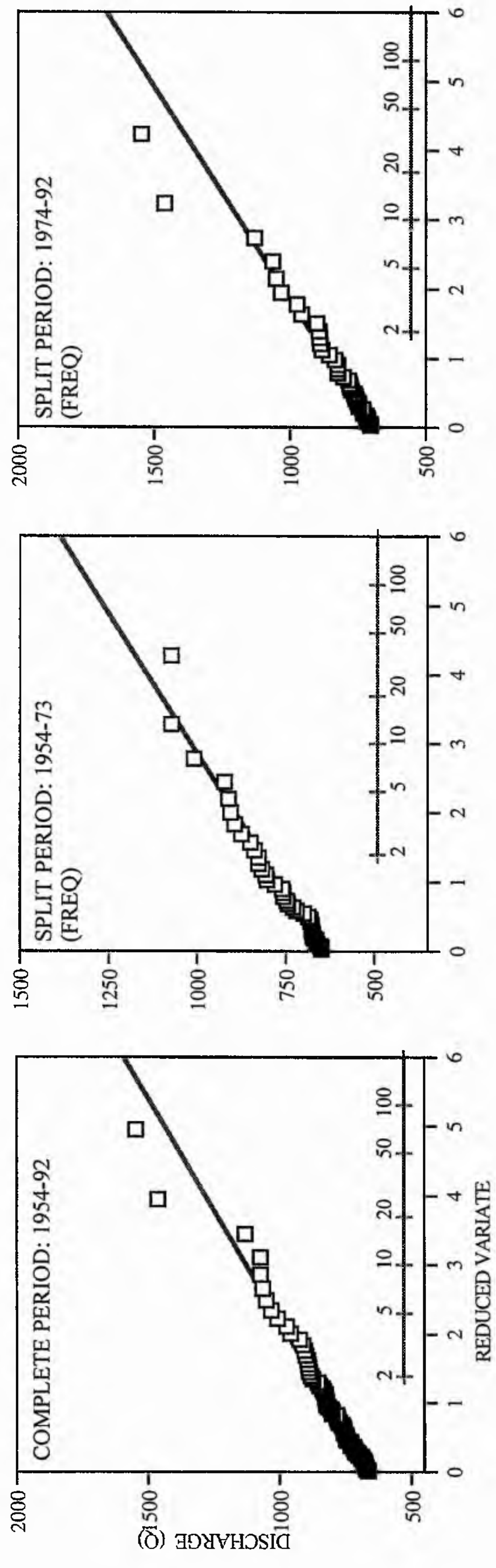

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Figure 7.15: Flood frequency curves for complete and split periods of record
Tay at Ballathie (15006) 1954-92

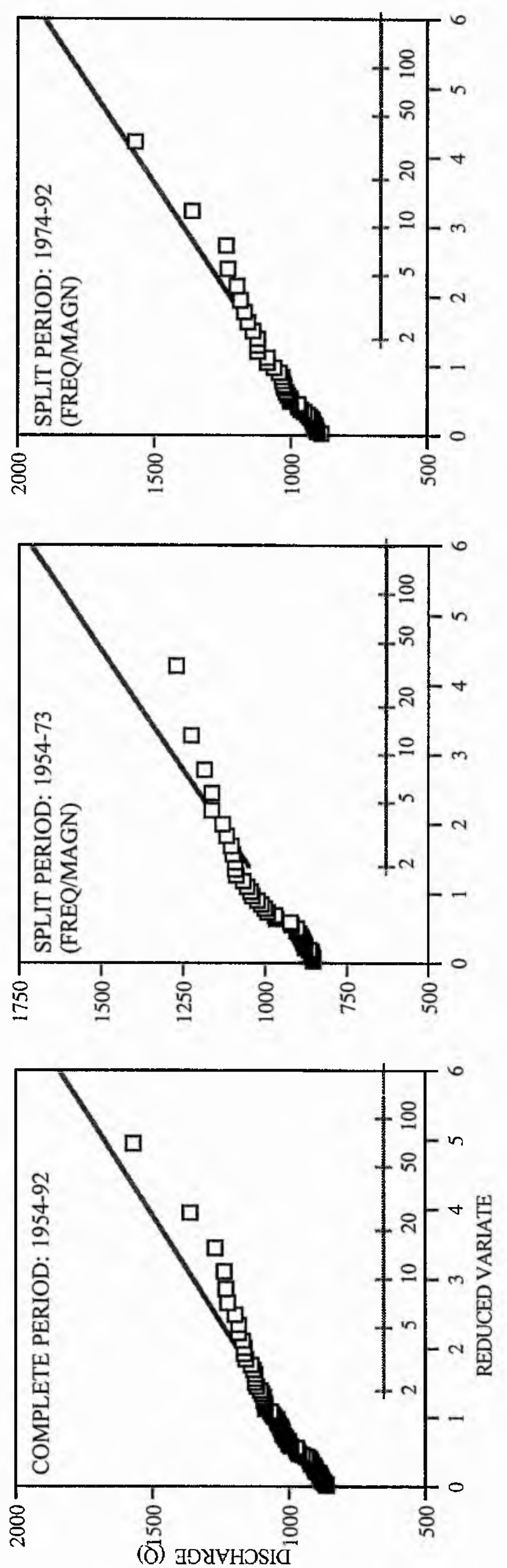

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Figure 7.16: Flood frequency curves for complete and split periods of record
Tay at Pitnacree (15007) 1954-92

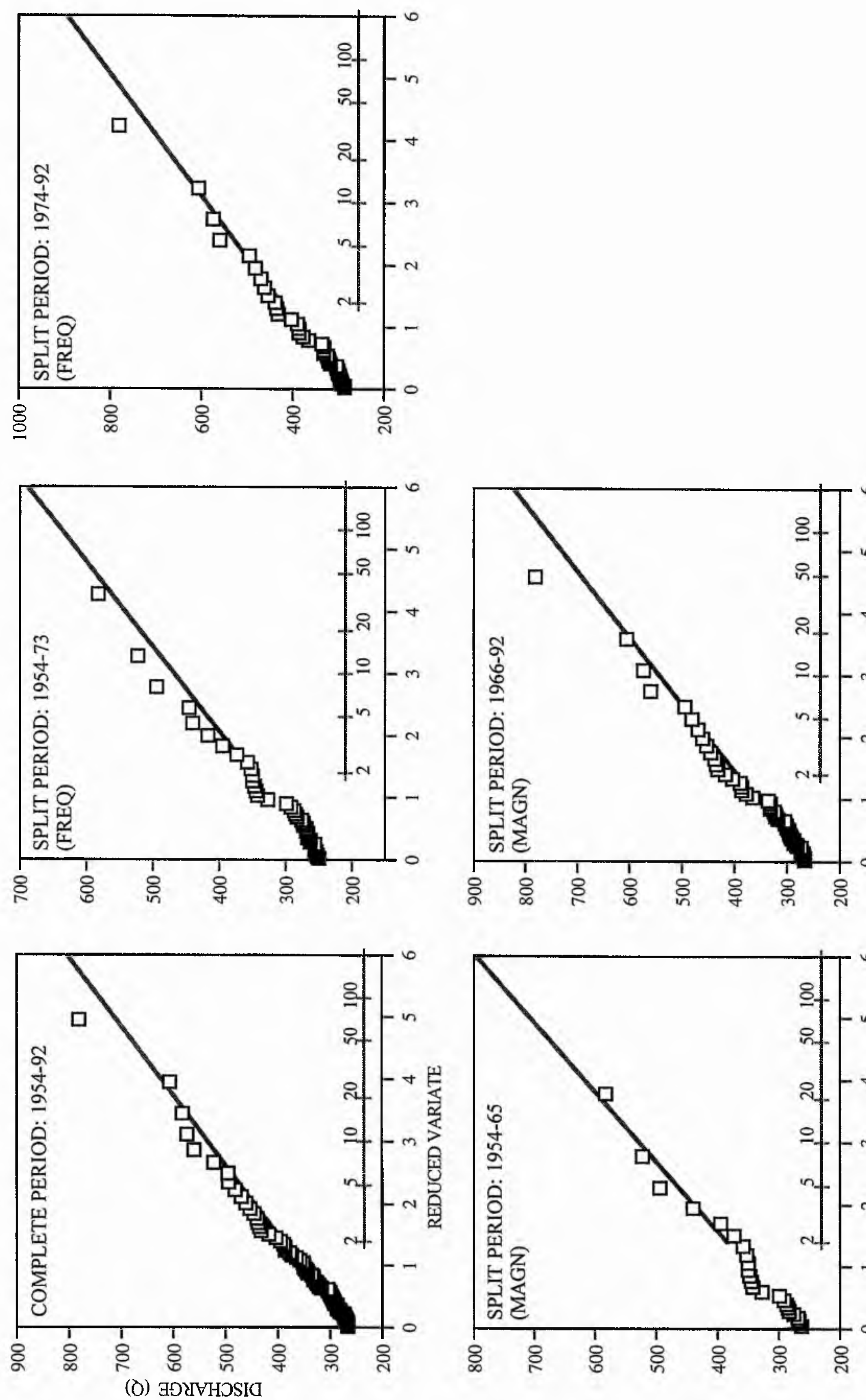

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Figure 7.17: Flood frequency curves for complete and split periods of record
Dean Water at Cookston (15008) 1954-92

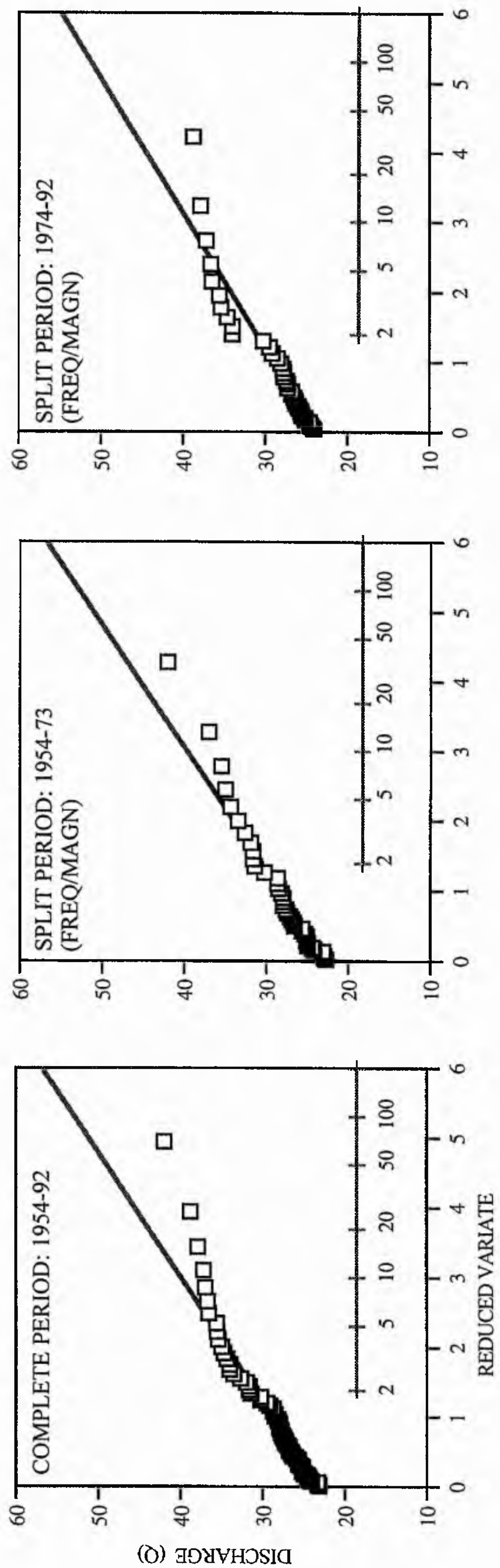

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Figure 7.18: Flood frequency curves for complete and split periods of record
Earn at Kinkell (16001) 1954-92

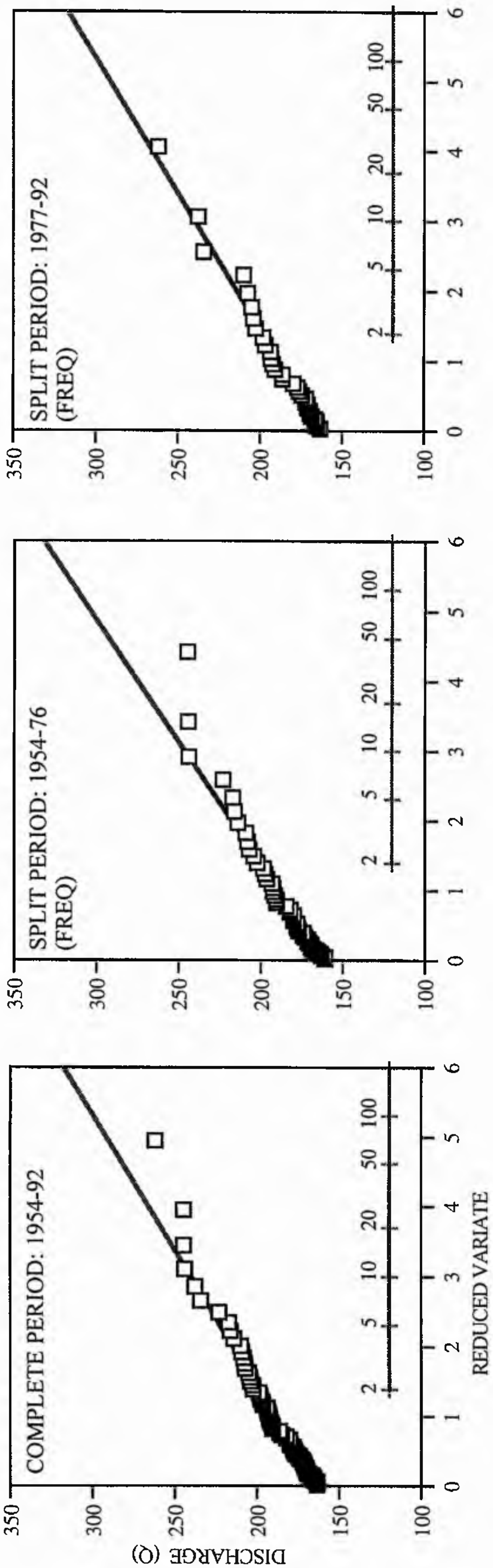

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Figure 7.19: Flood frequency curves for complete and split periods of record
Tweed at Peebles (21003) 1954-92

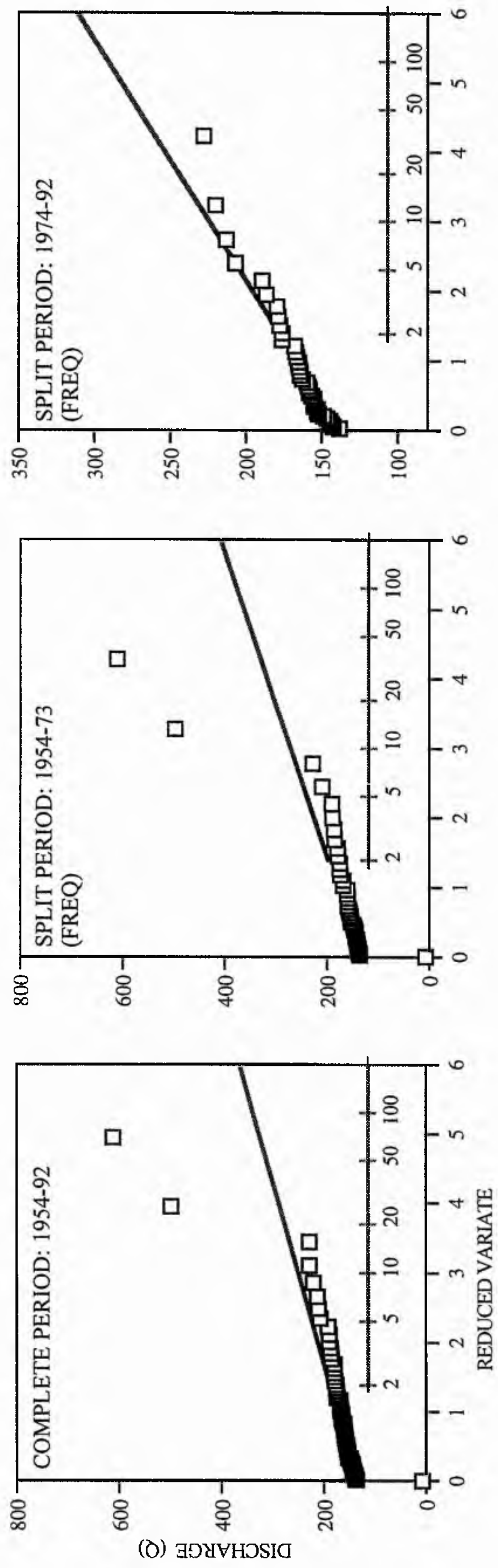

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Figure 7.20: Flood frequency curves for complete and split periods of record
Kelvin at Killermont (84001) 1954-92

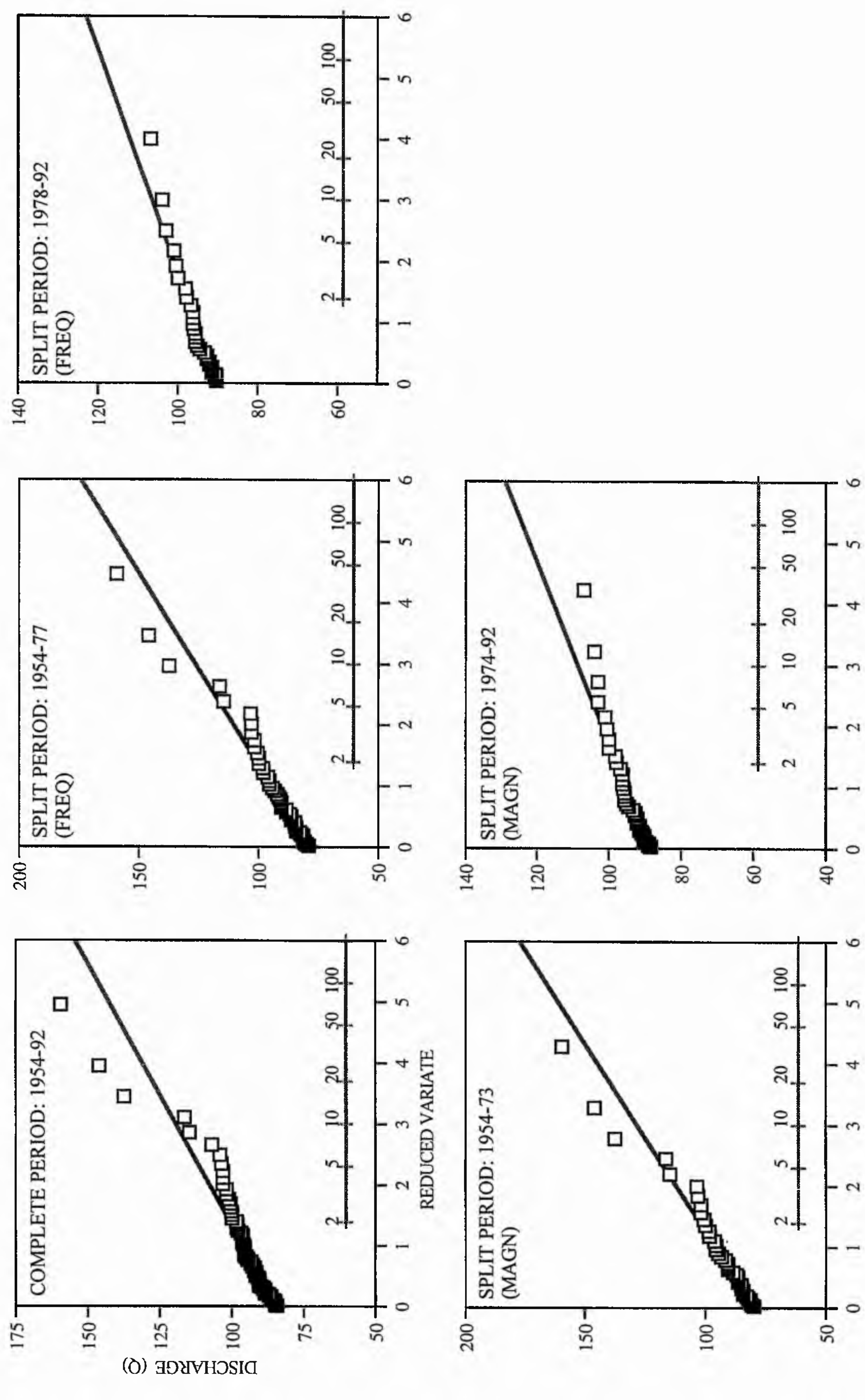

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Figure 7.21: Flood frequency curves for complete and split periods of record
Findhorn at Shenachie (07001) 1964-92

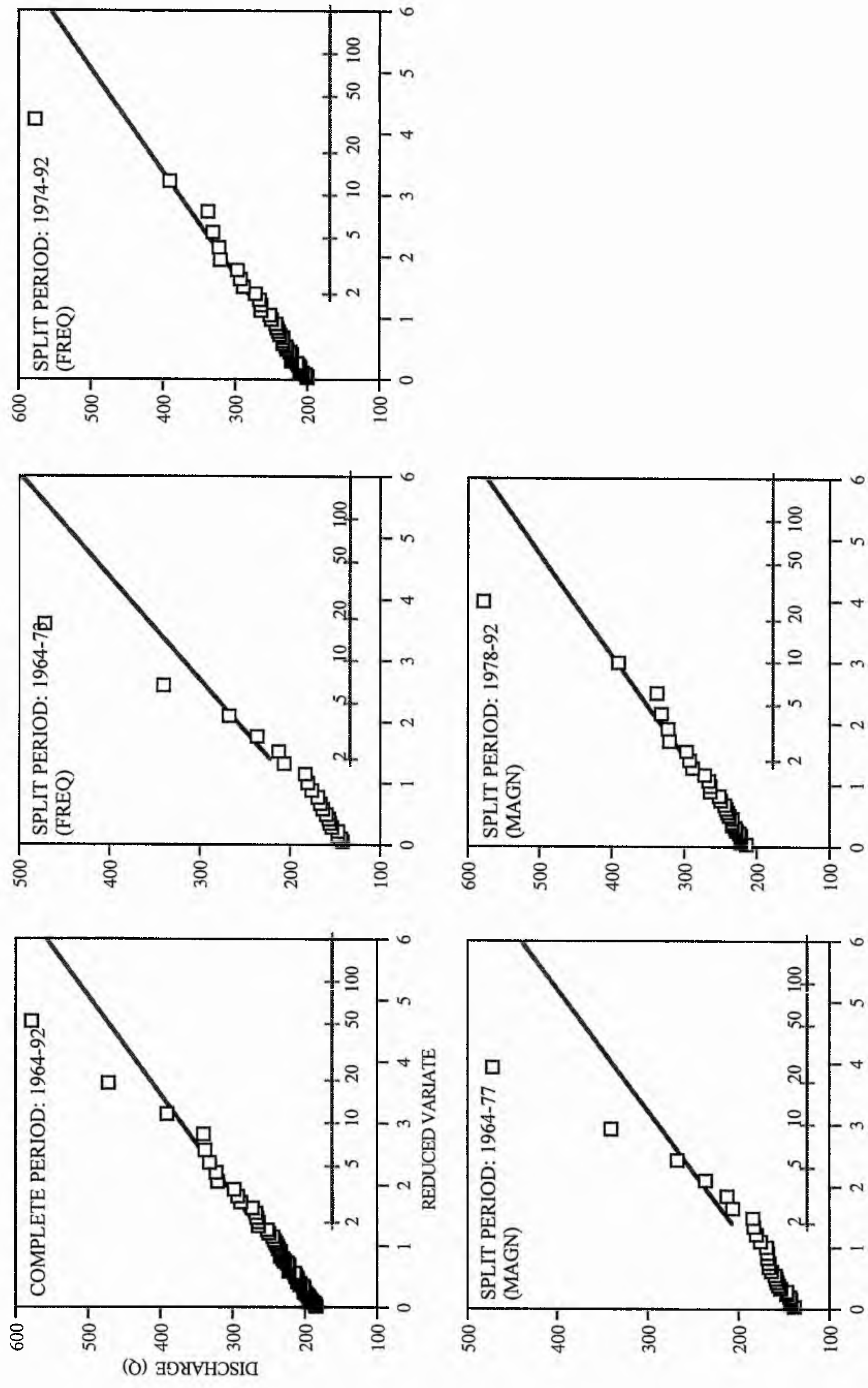

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Figure 7.22: Flood frequency curves for complete and split periods of record
Findhorn at Forres (07002) 1964-92

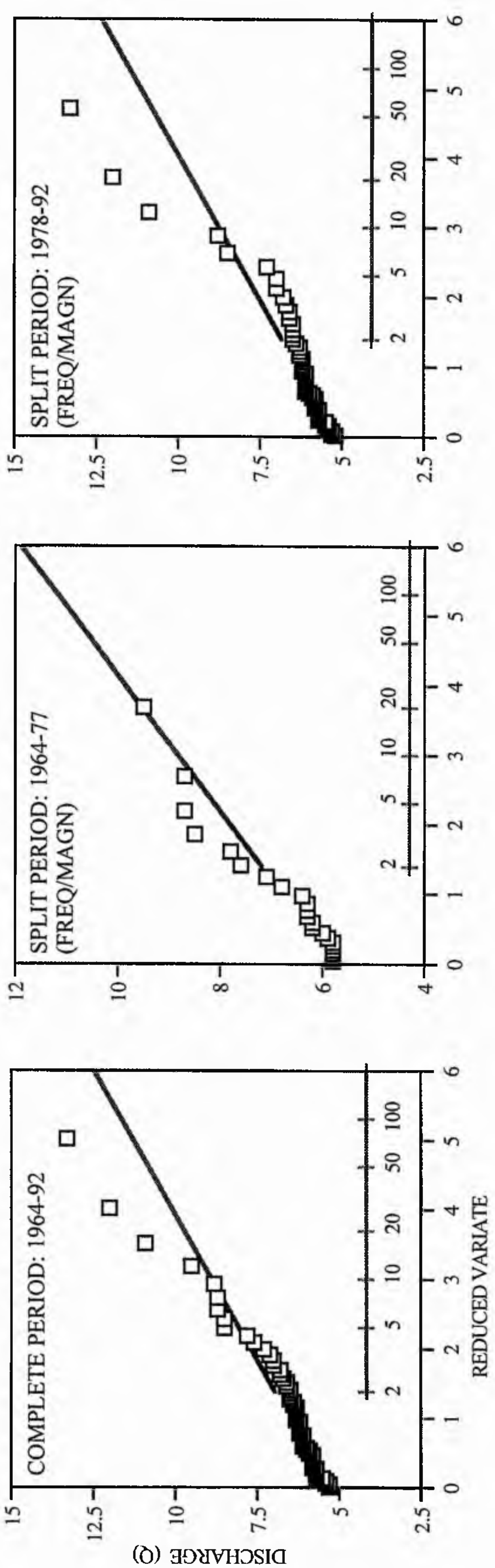

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Figure 7.23: Flood frequency curves for complete and split periods of record
Lossie at Sheriffmills (07003) 1964-92

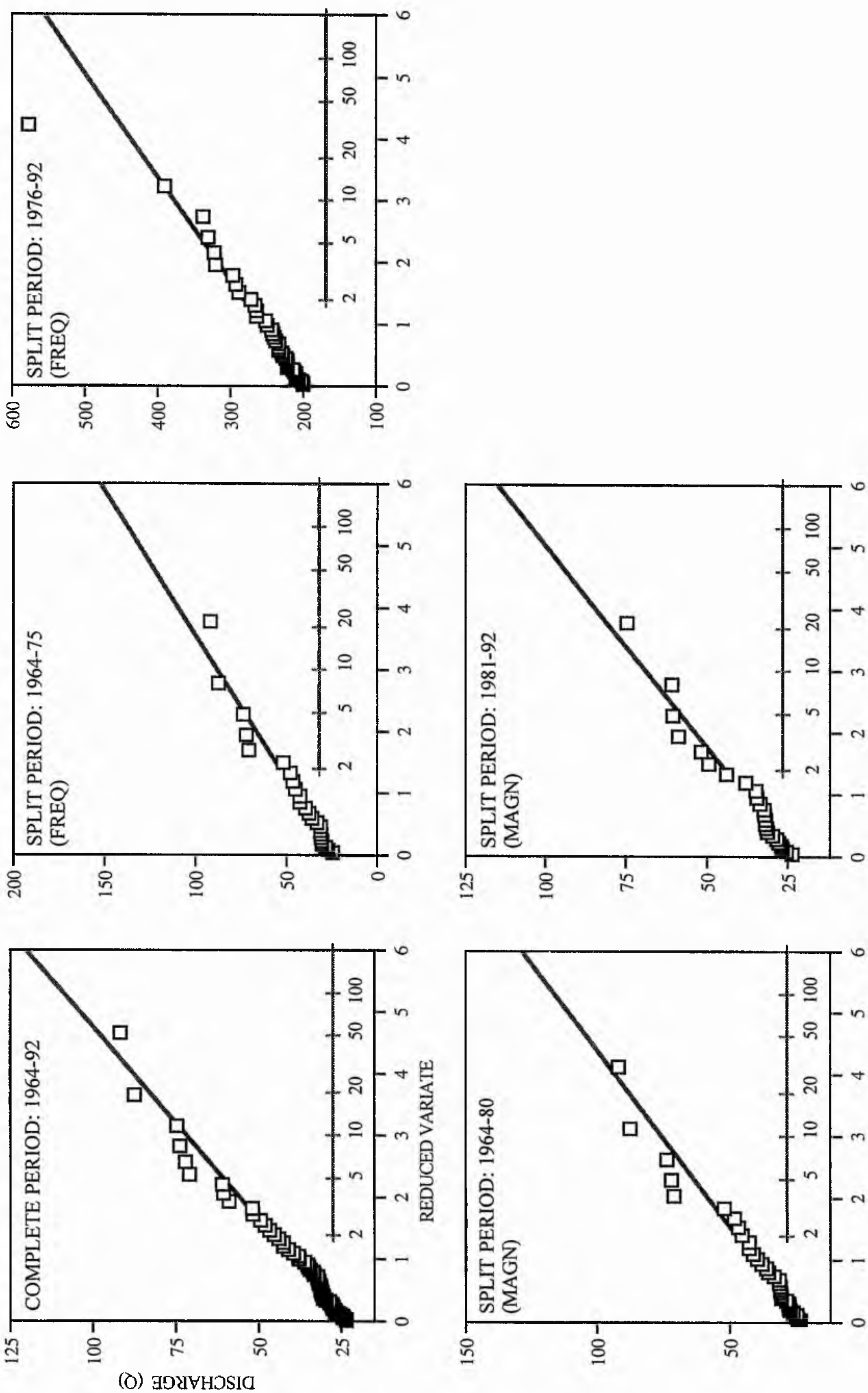

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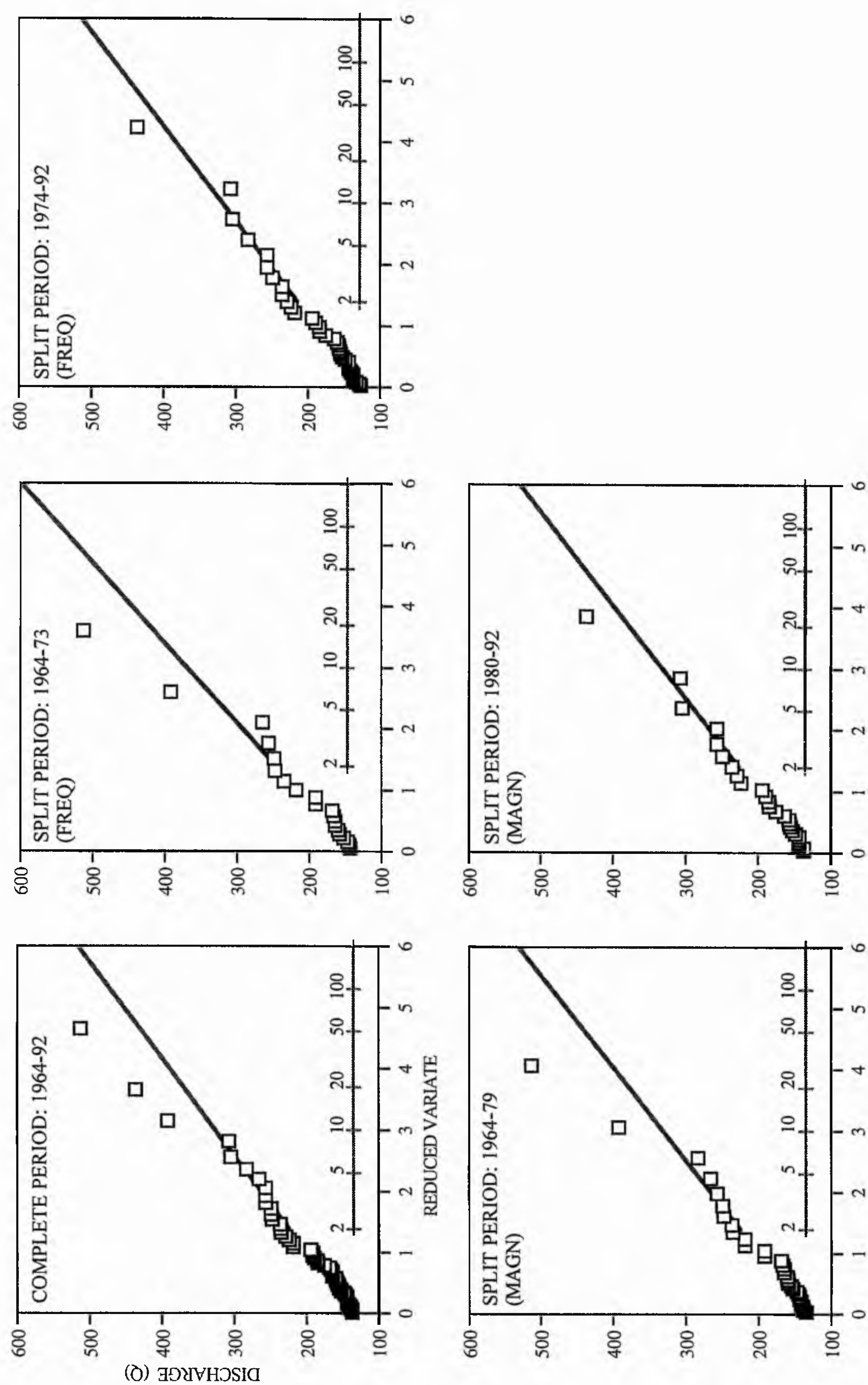
Figure 7.24: Flood frequency curves for complete and split periods of record
Avon at Delnashaugh (08004) 1964-92



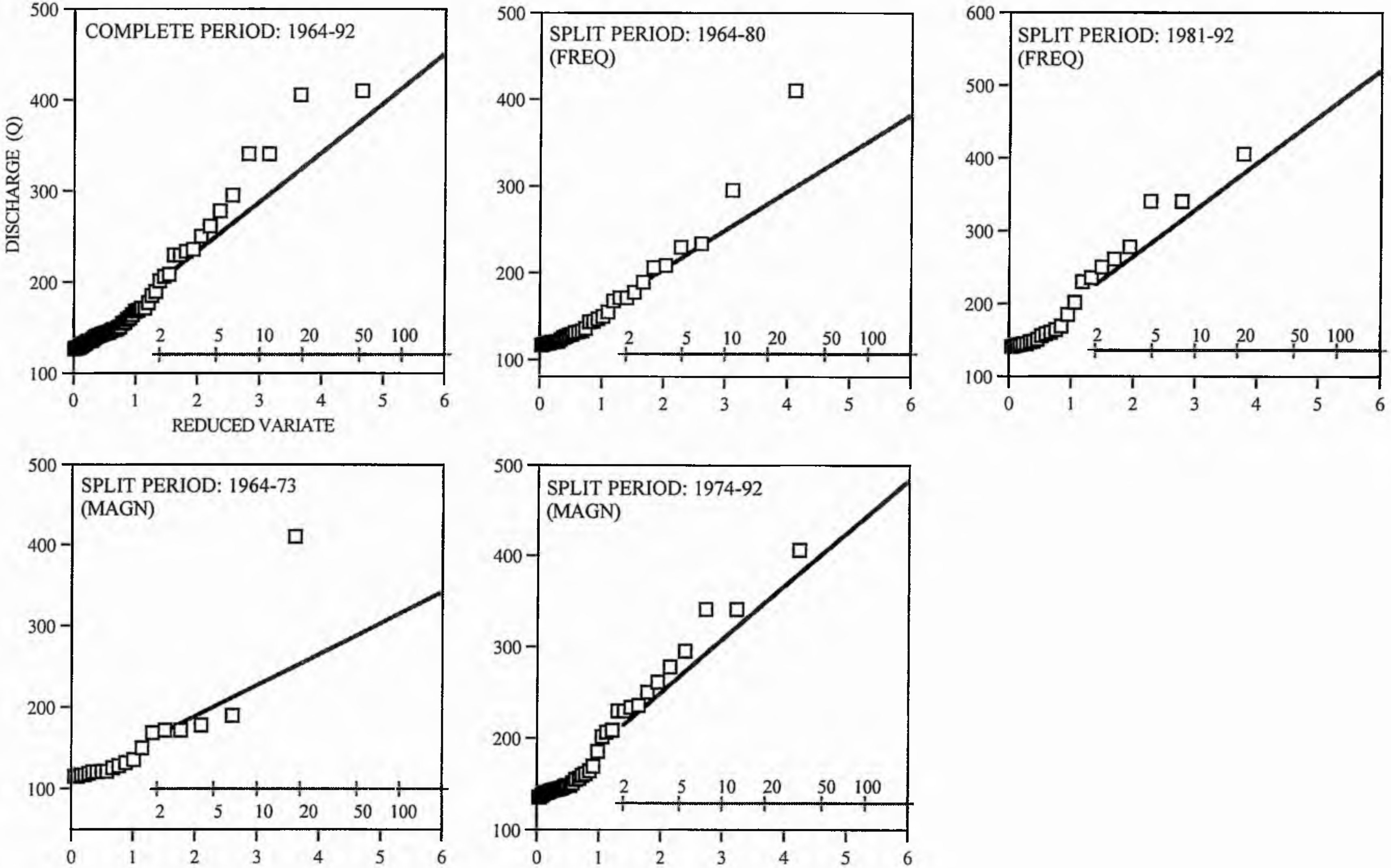


Figure 7.25: Flood frequency curves for complete and split periods of record
Spey at Boat of Garten (08005) 1964-92

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Figure 7.26: Flood frequency curves for complete and split periods of record
Spey at Boat of Brig (08006) 1964-92

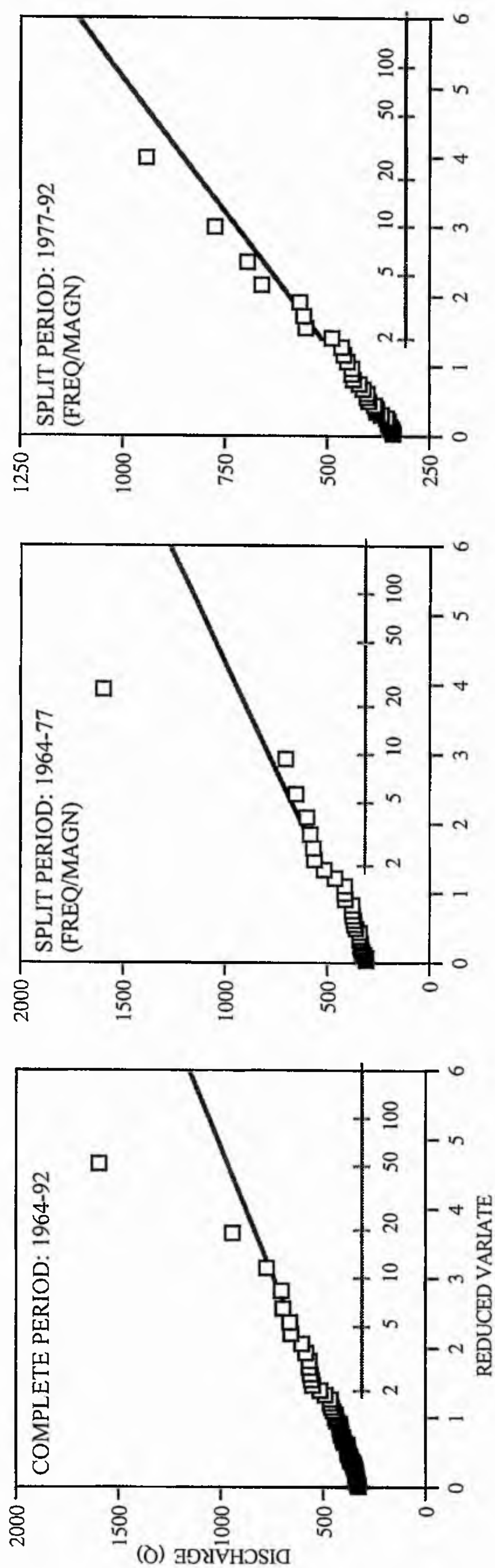

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Figure 7.27: Flood frequency curves for complete and split periods of record
Spey at Invertruim (08007) 1964-92

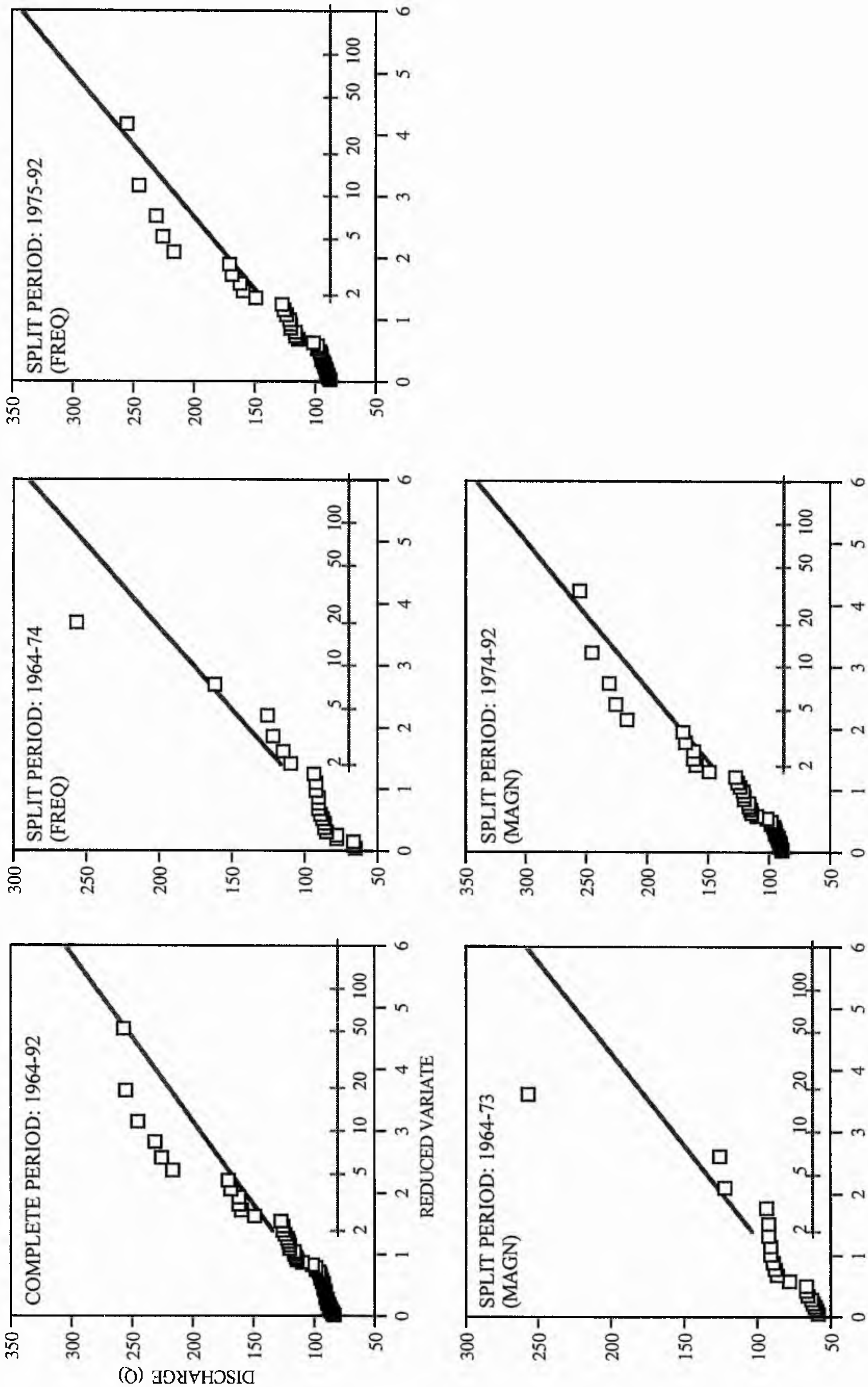

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Figure 7.28: Flood frequency curves for complete and split periods of record
Dulnain at Balnaan Bridge (08009) 1964-92

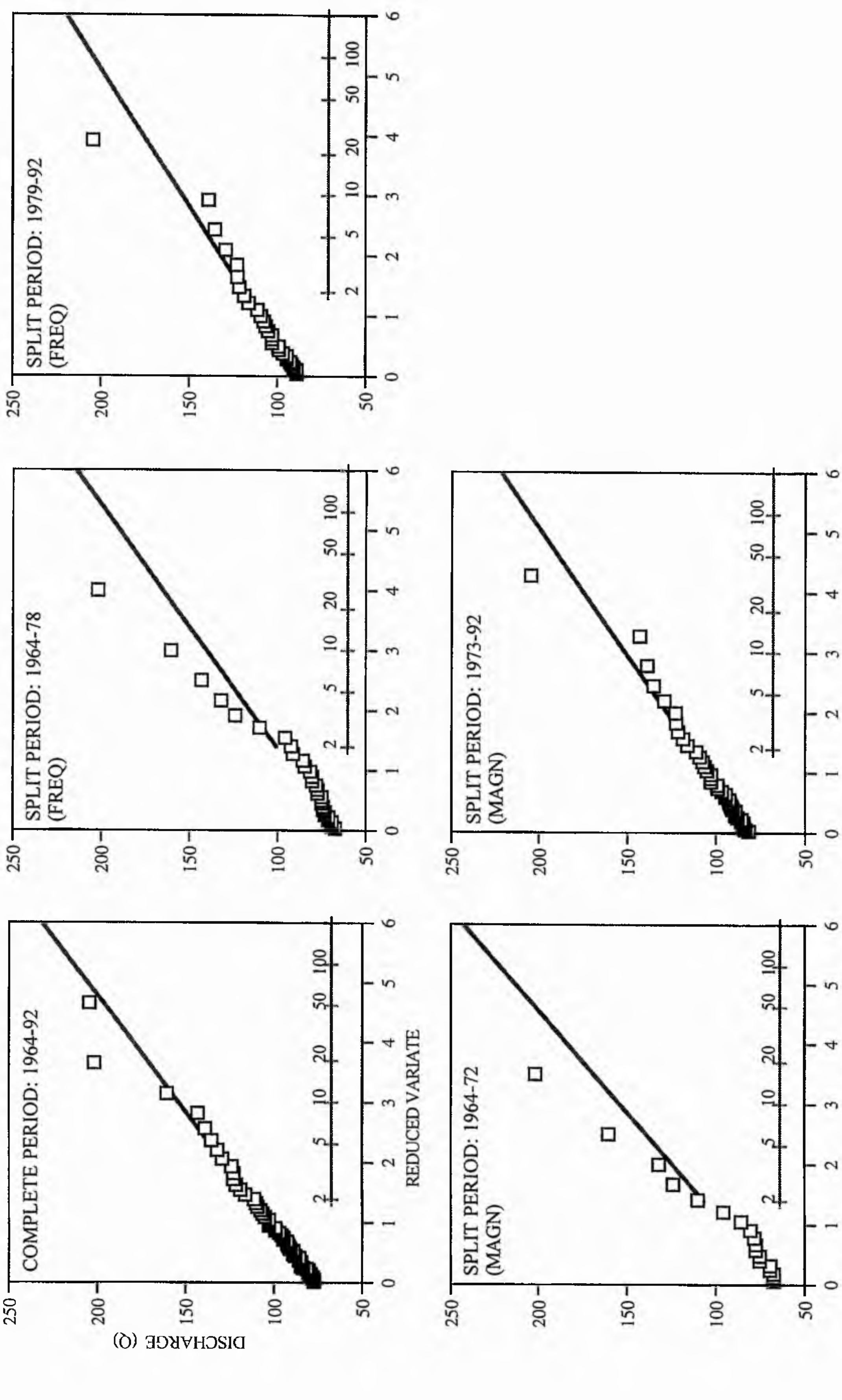

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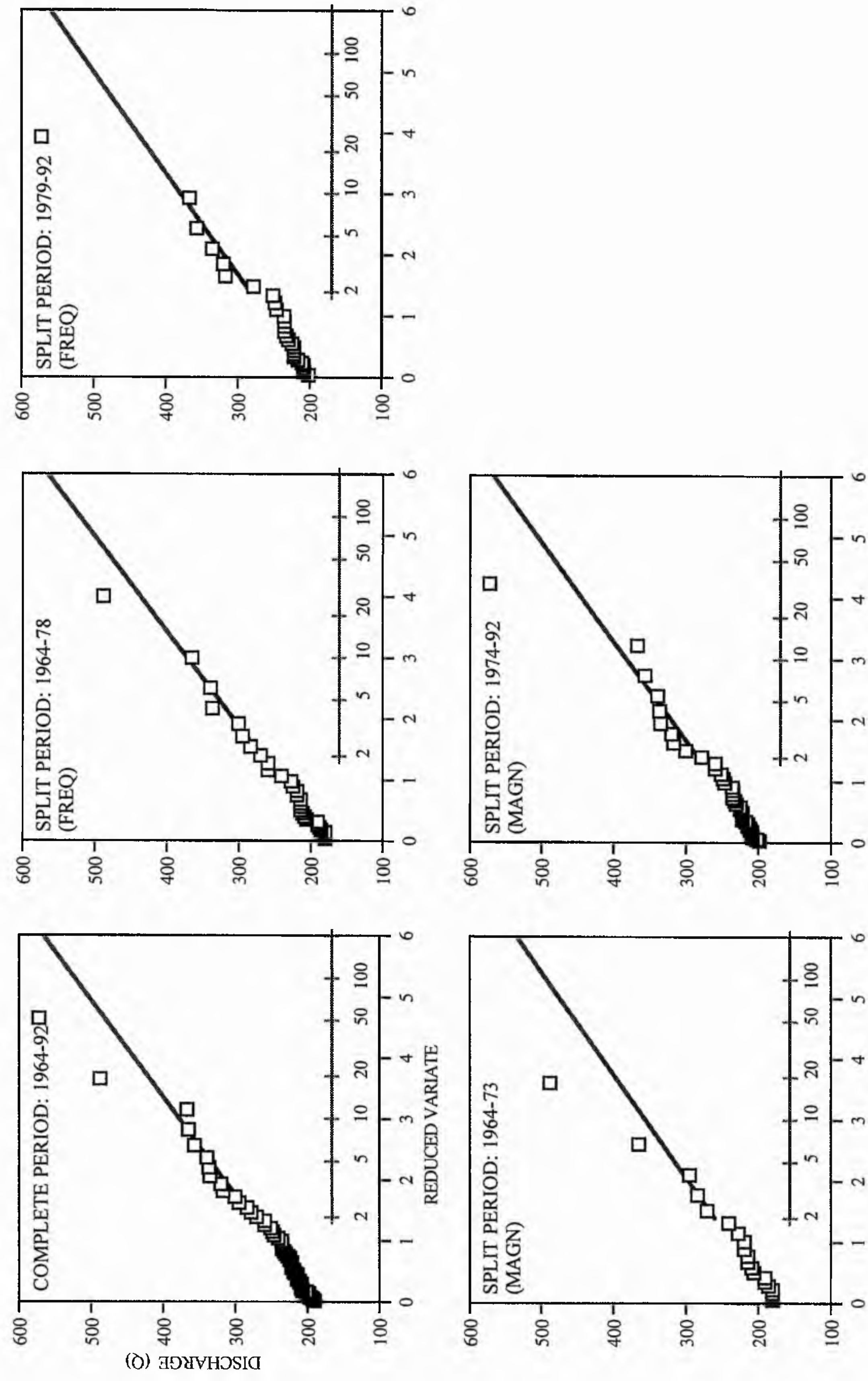
Figure 7.29: Flood frequency curves for complete and split periods of record
Spey at Grantown (08010) 1964-92



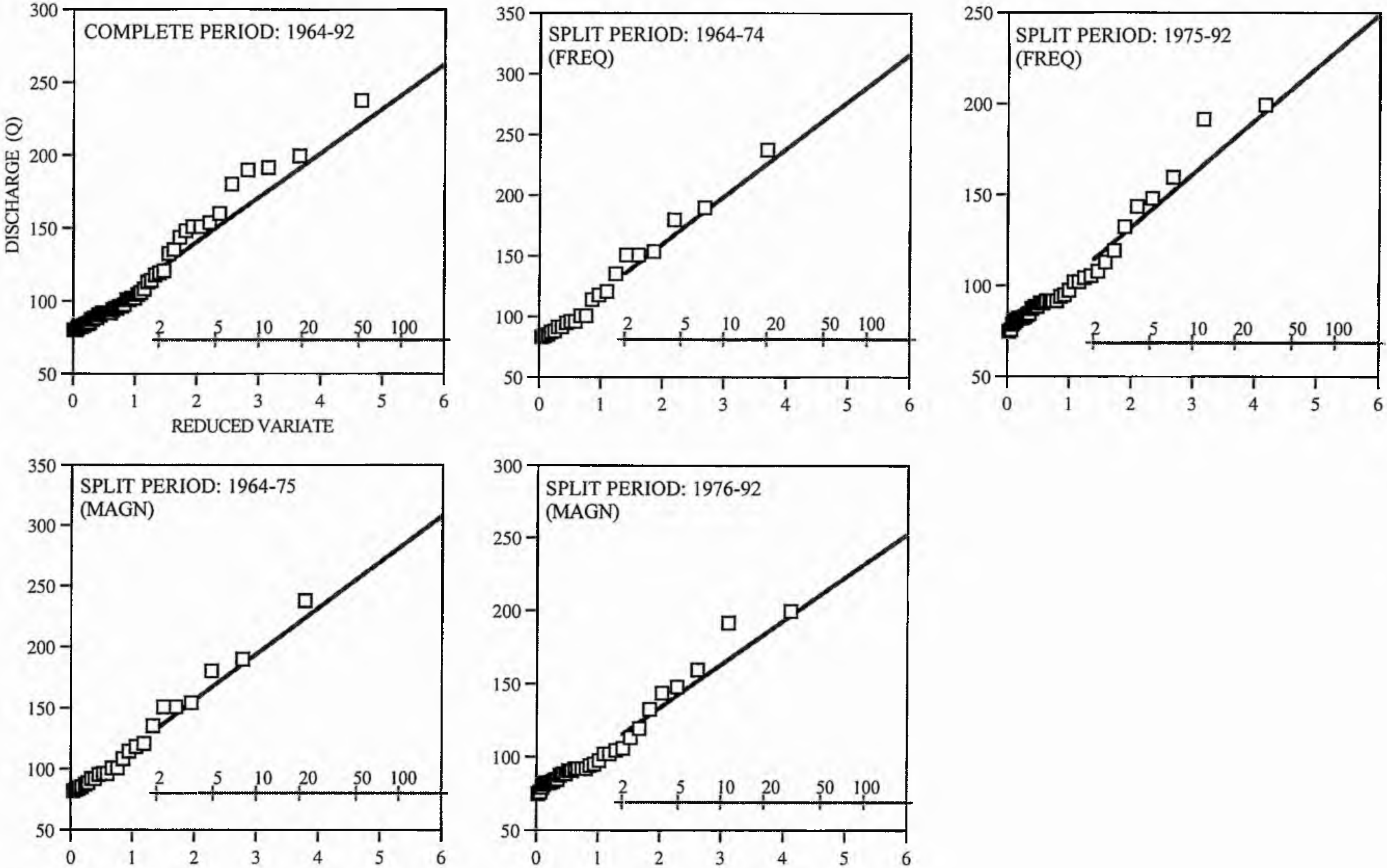


Figure 7.30: Flood frequency curves for complete and split periods of record
Deveron at Avochie (09001) 1964-92

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Figure 7.31: Flood frequency curves for complete and split periods of record
Deveron at Muiresk (09002) 1964-92

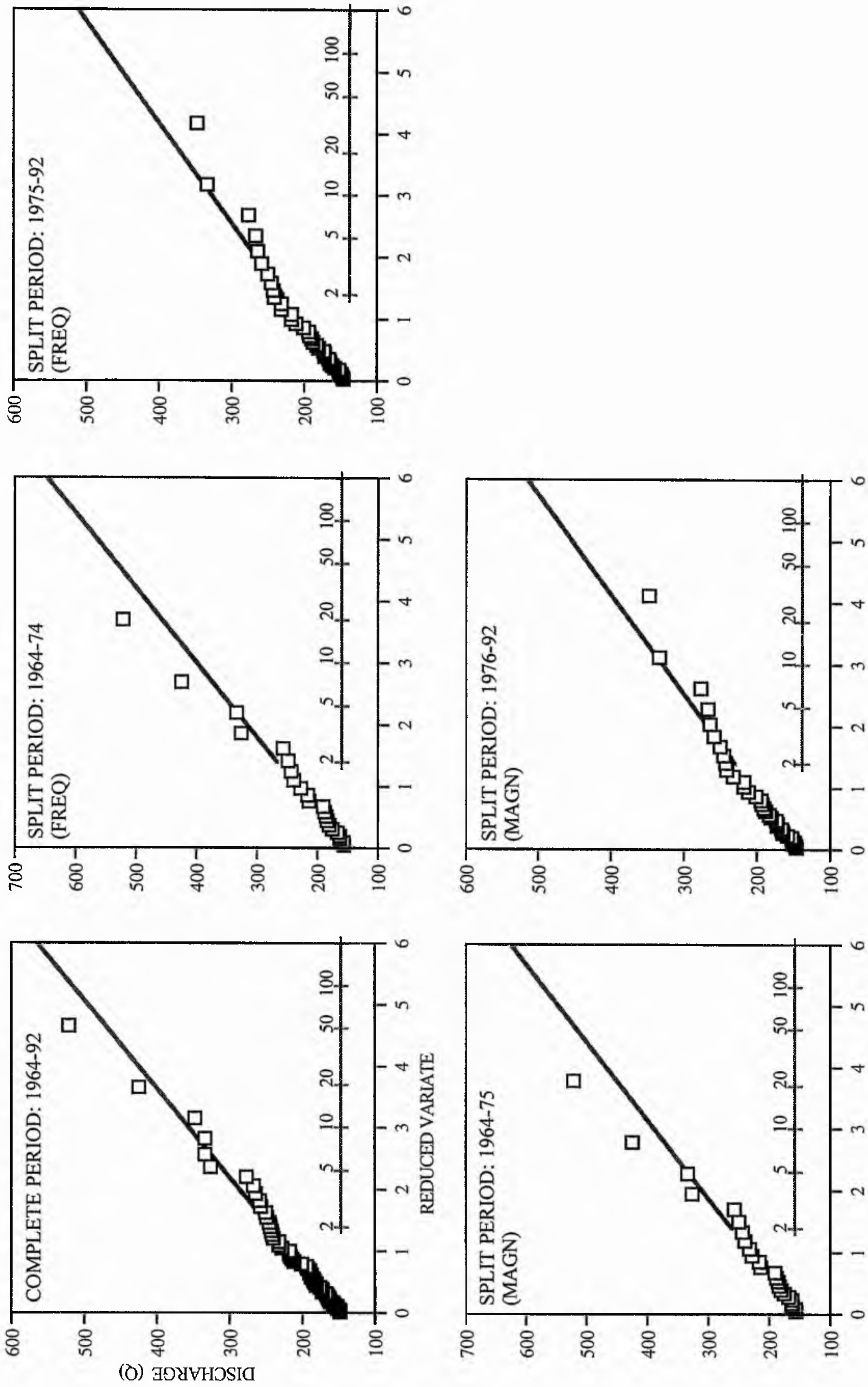

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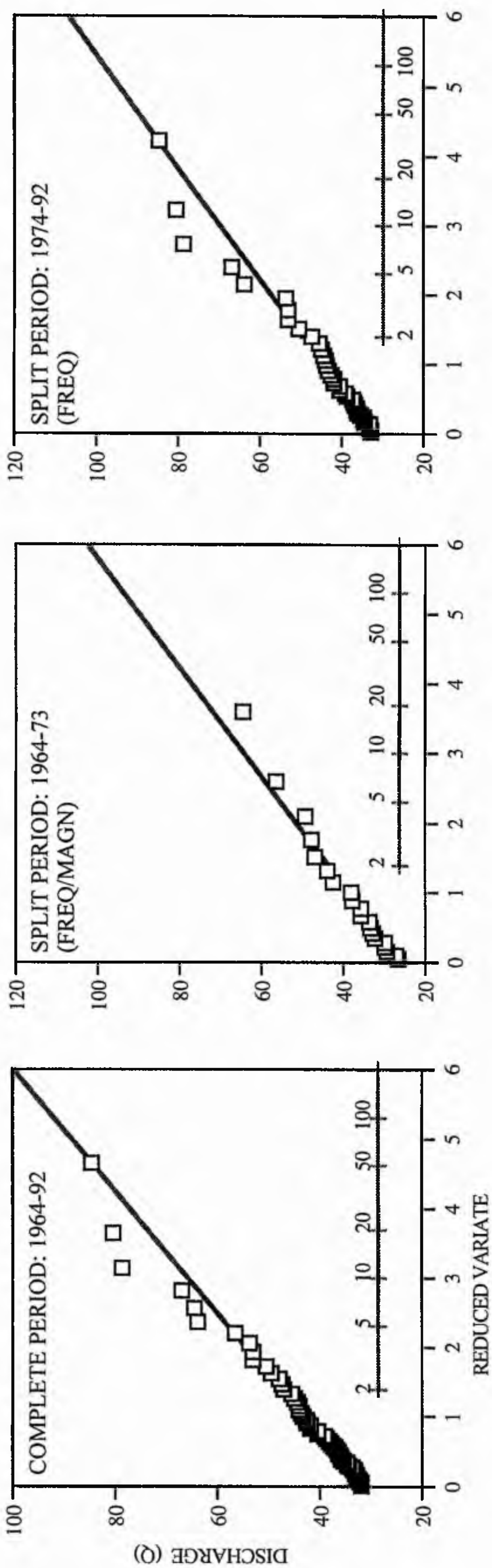
Figure 7.32: Flood frequency curves for complete and split periods of record
Isla at Grange (09003) 1964-92



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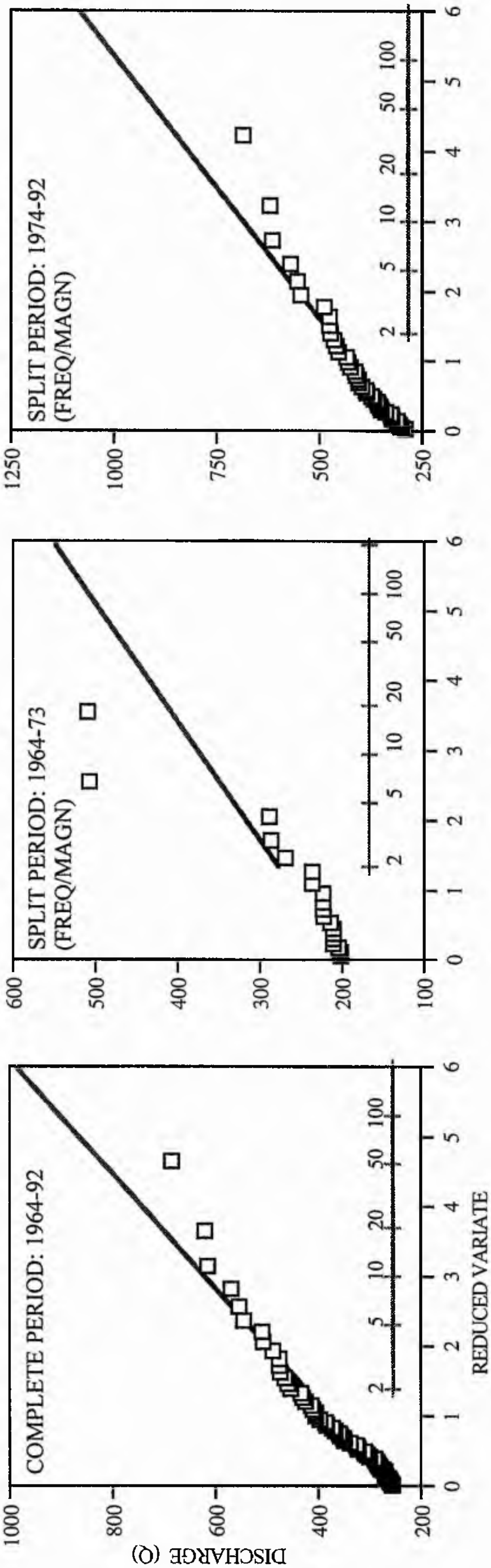

Figure 7.33: Flood frequency curves for complete and split periods of record
Dee at Woodend (12001) 1964-92

Figure 7.34: Flood frequency curves for complete and split periods of record
Tay at Caputh (15003) 1964-92

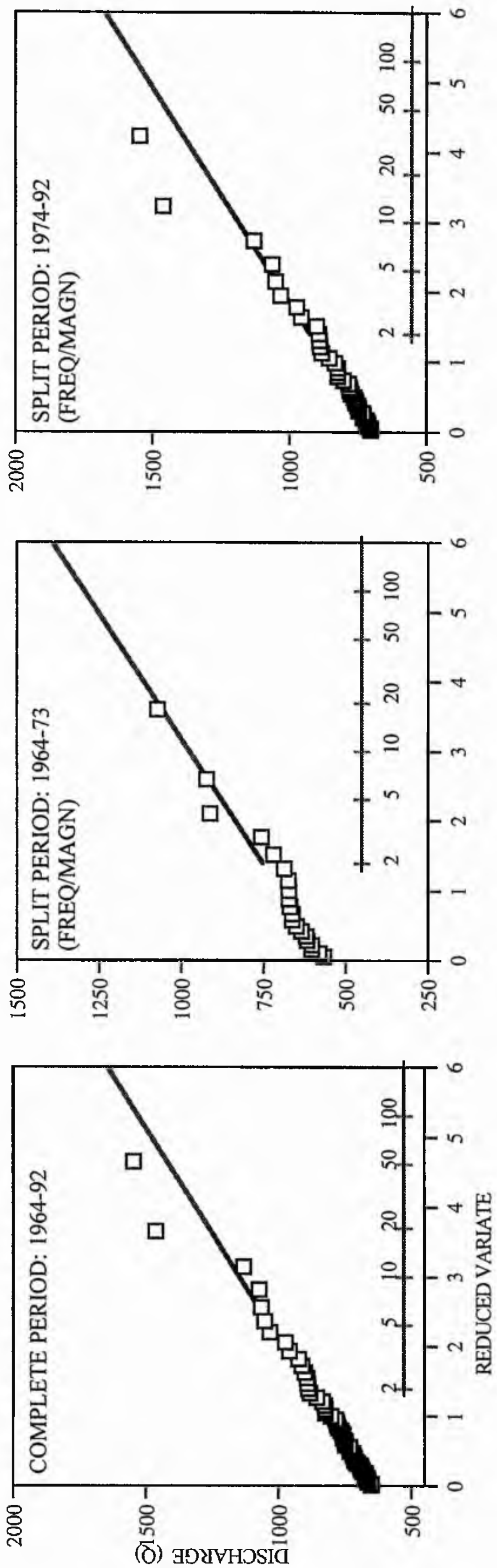

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Figure 7.35: Flood frequency curves for complete and split periods of record
Tay at Ballathie (15006) 1964-92

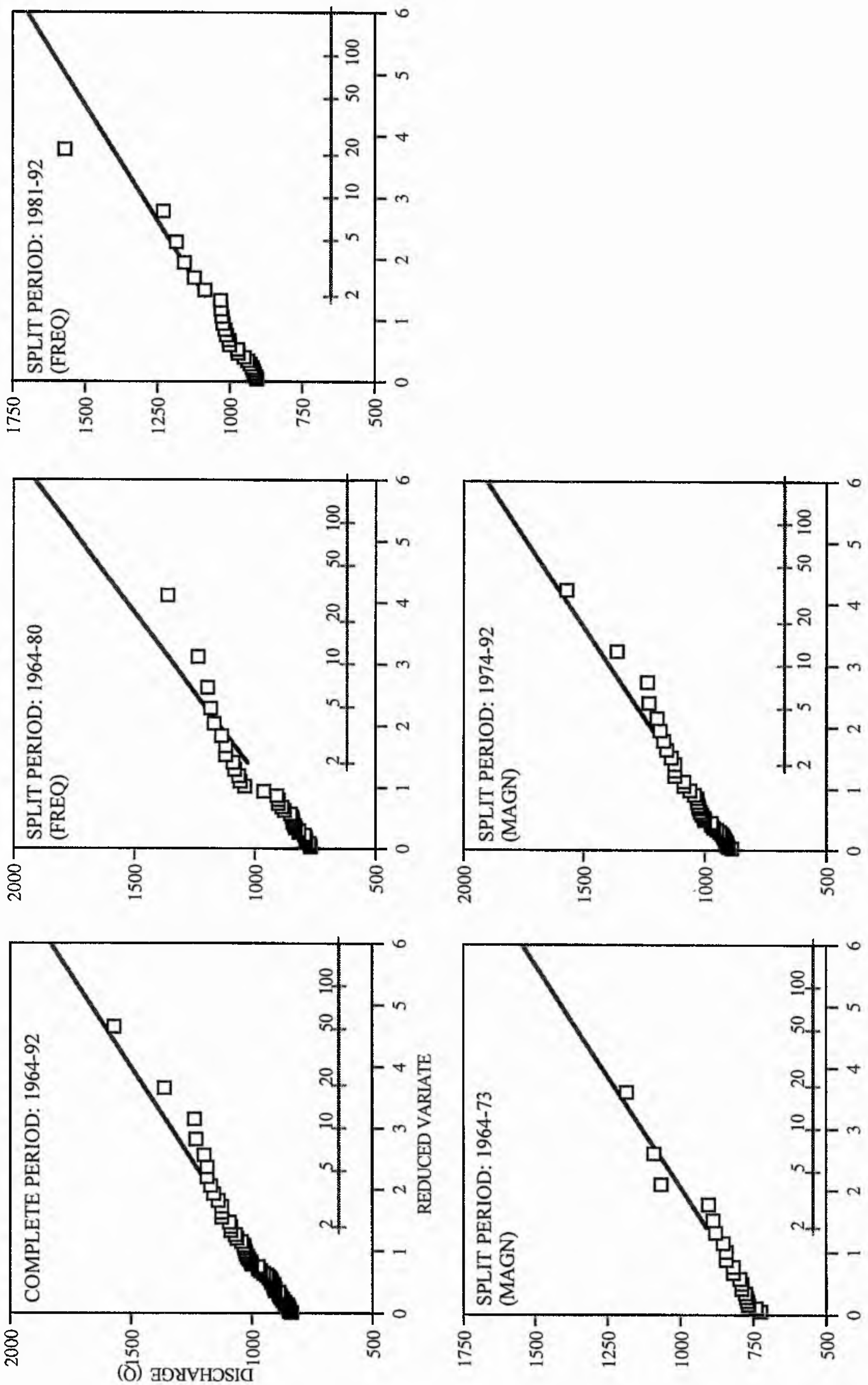

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Figure 7.36: Flood frequency curves for complete and split periods of record
Tay at Pitnacree (15007) 1964-92

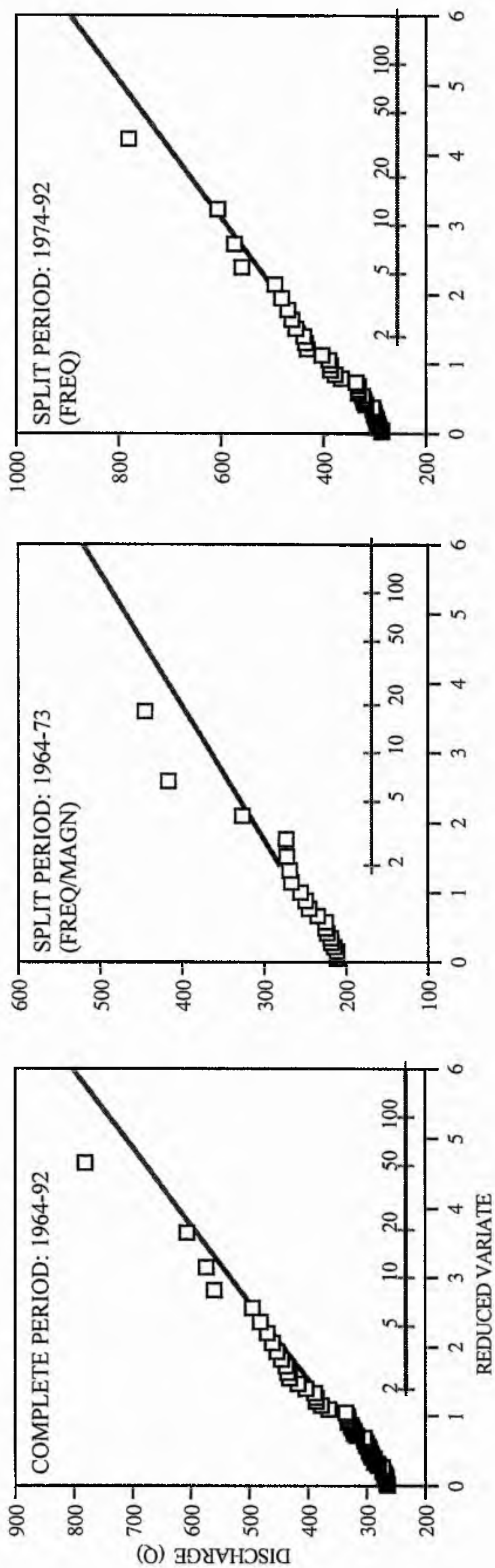

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Figure 7.37: Flood frequency curves for complete and split periods of record
Dean Water at Cookston (15008) 1964-92

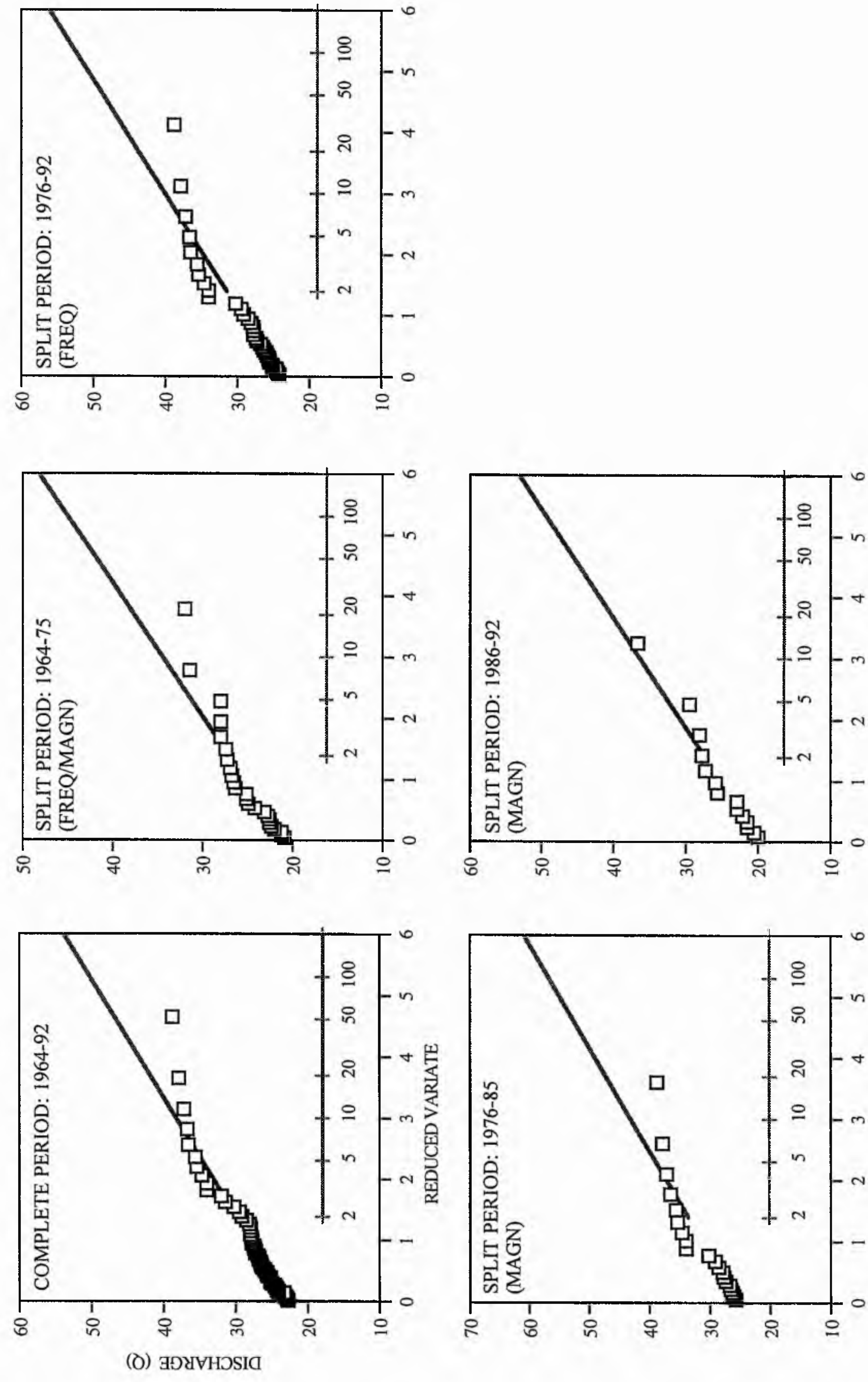

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Figure 7.38: Flood frequency curves for complete and split periods of record
Earn at Kinkell (16001) 1964-92

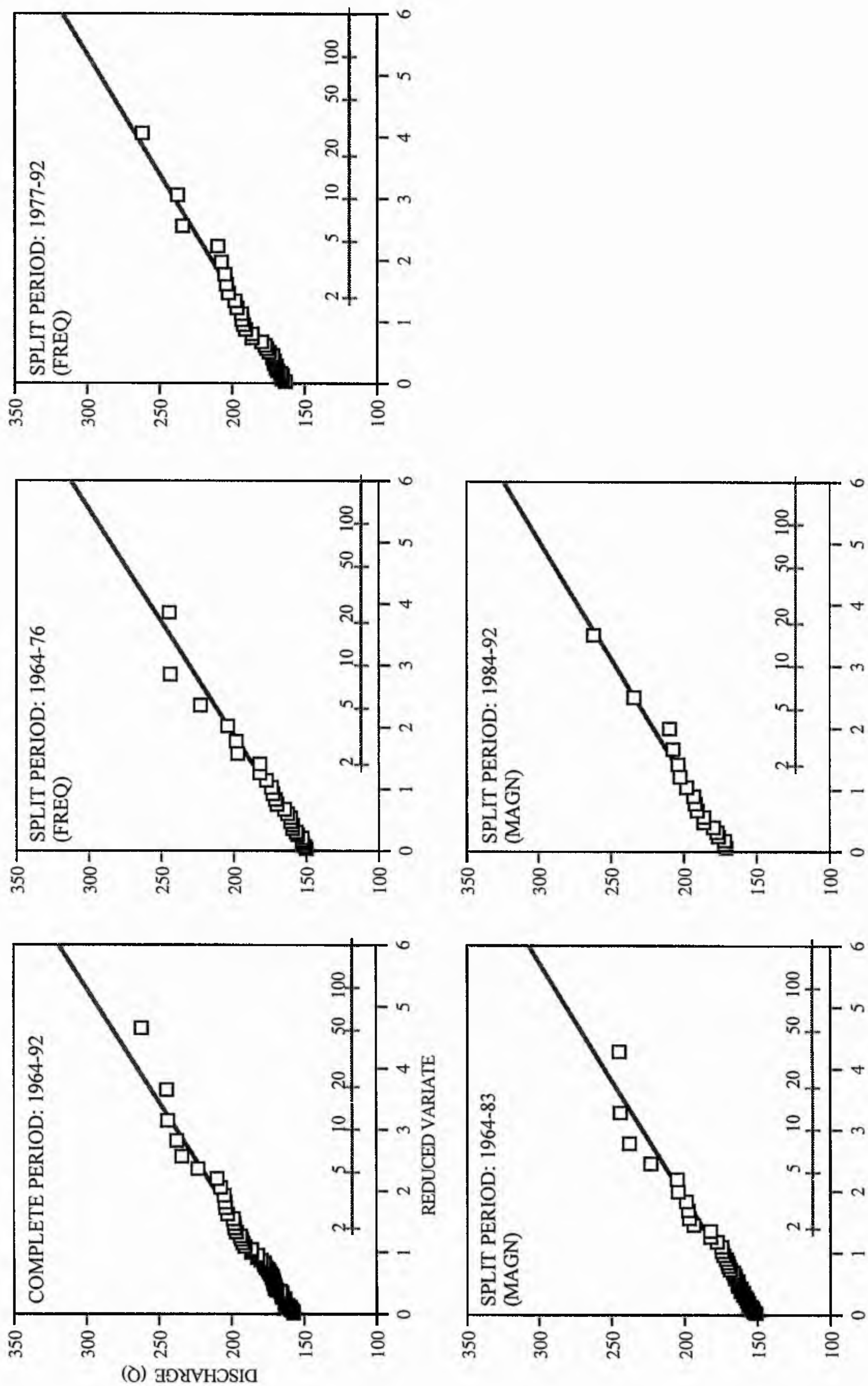

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Figure 7.39: Flood frequency curves for complete and split periods of record
Ruchill Water at Cultybraggan (16003) 1964-92

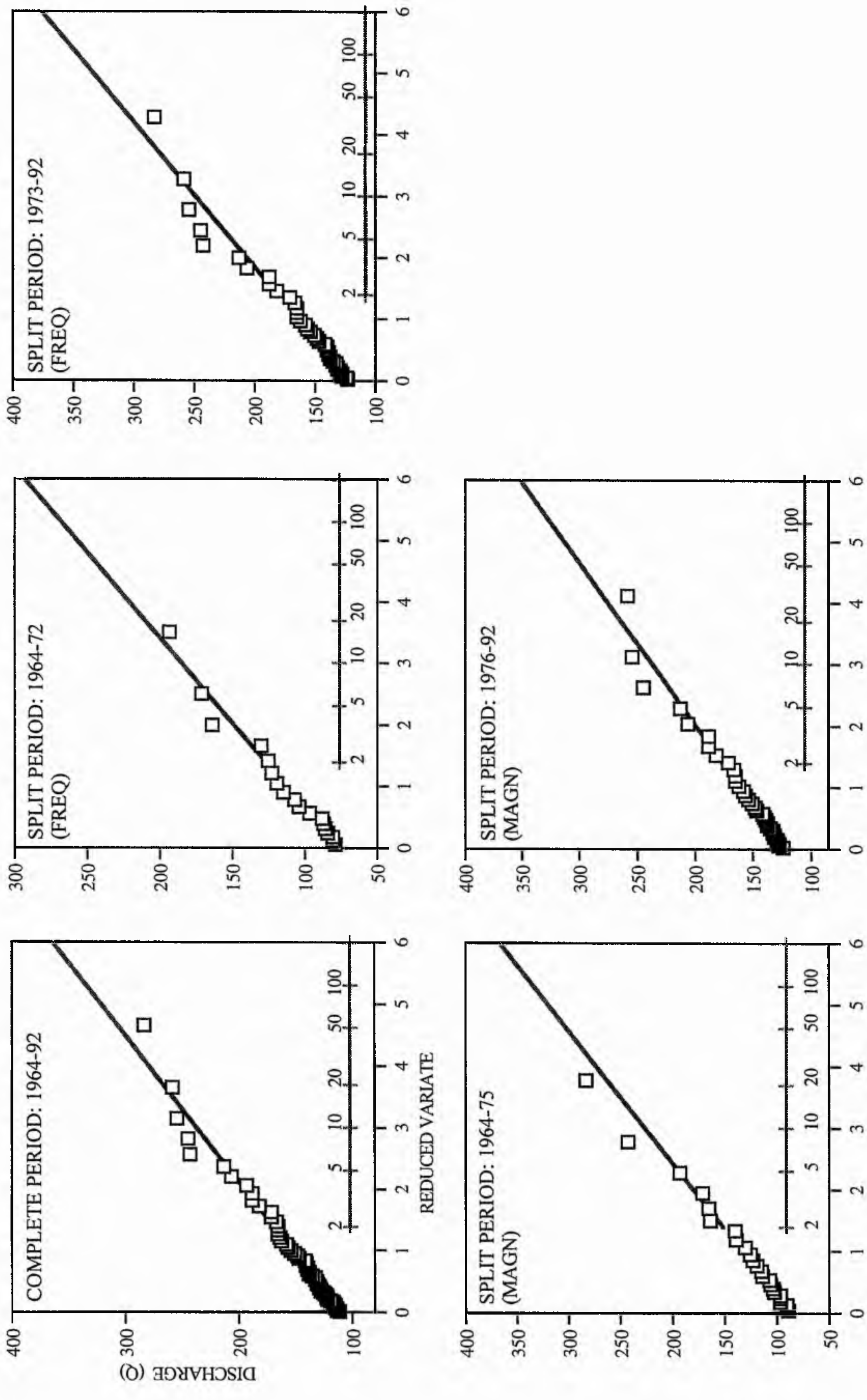

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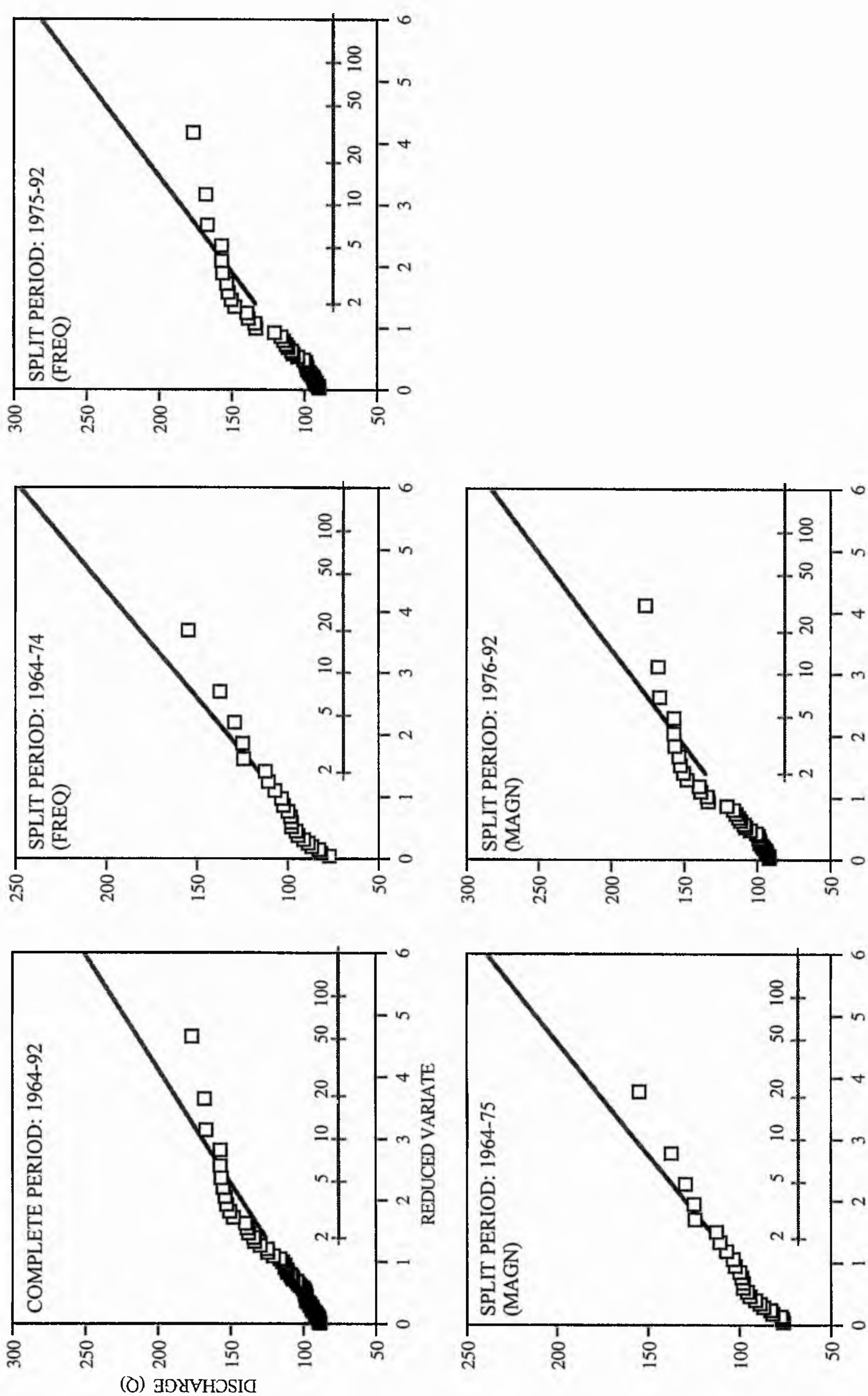
Figure 7.40: Flood frequency curves for complete and split periods of record
Almond at Craigiehall (19001) 1964-92



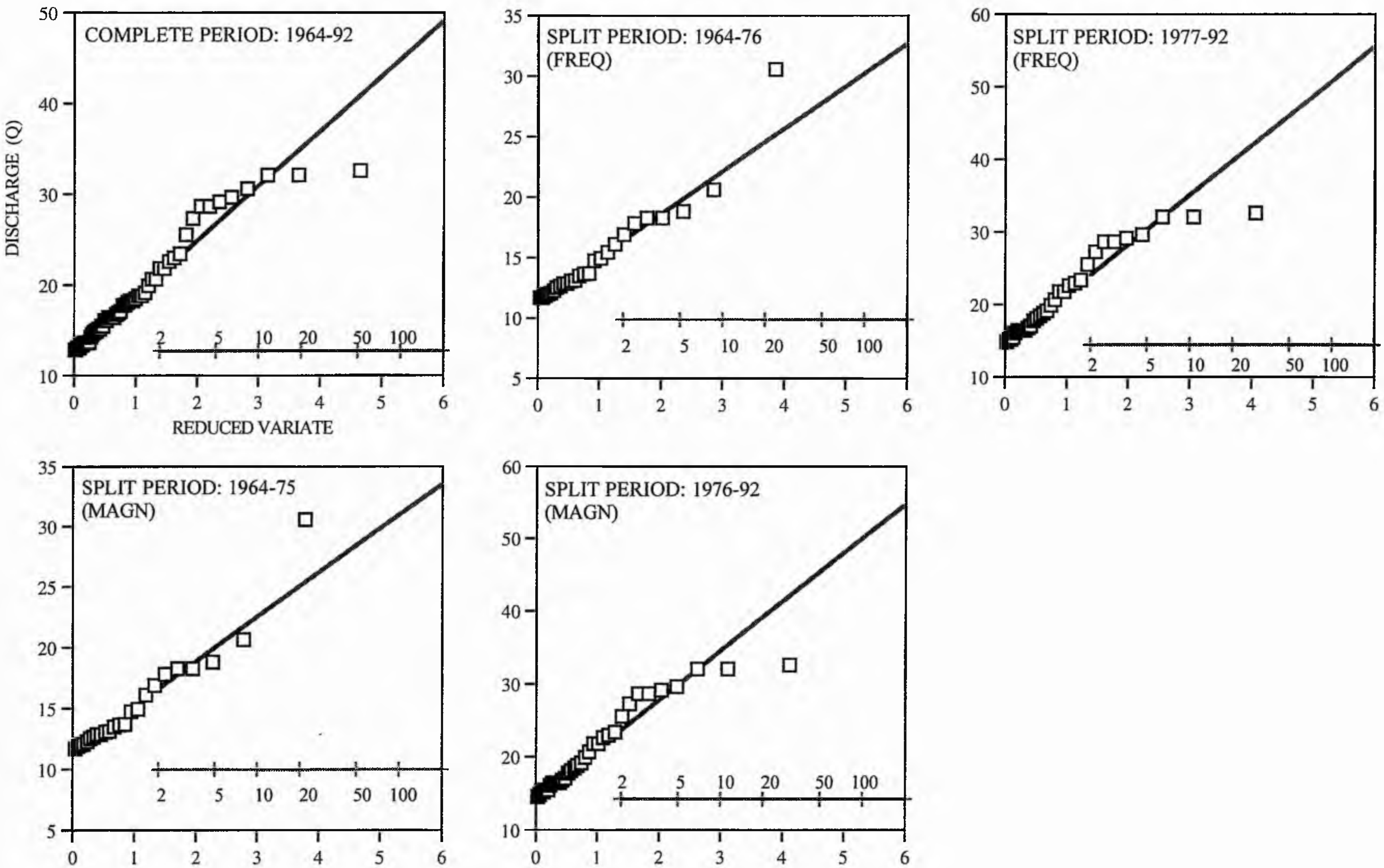


Figure 7.41: Flood frequency curves for complete and split periods of record Almond at Almond Weir (19002) 1964-92

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Figure 7.42: Flood frequency curves for complete and split periods of record
North Esk at Dalmore Weir (19004) 1964-92

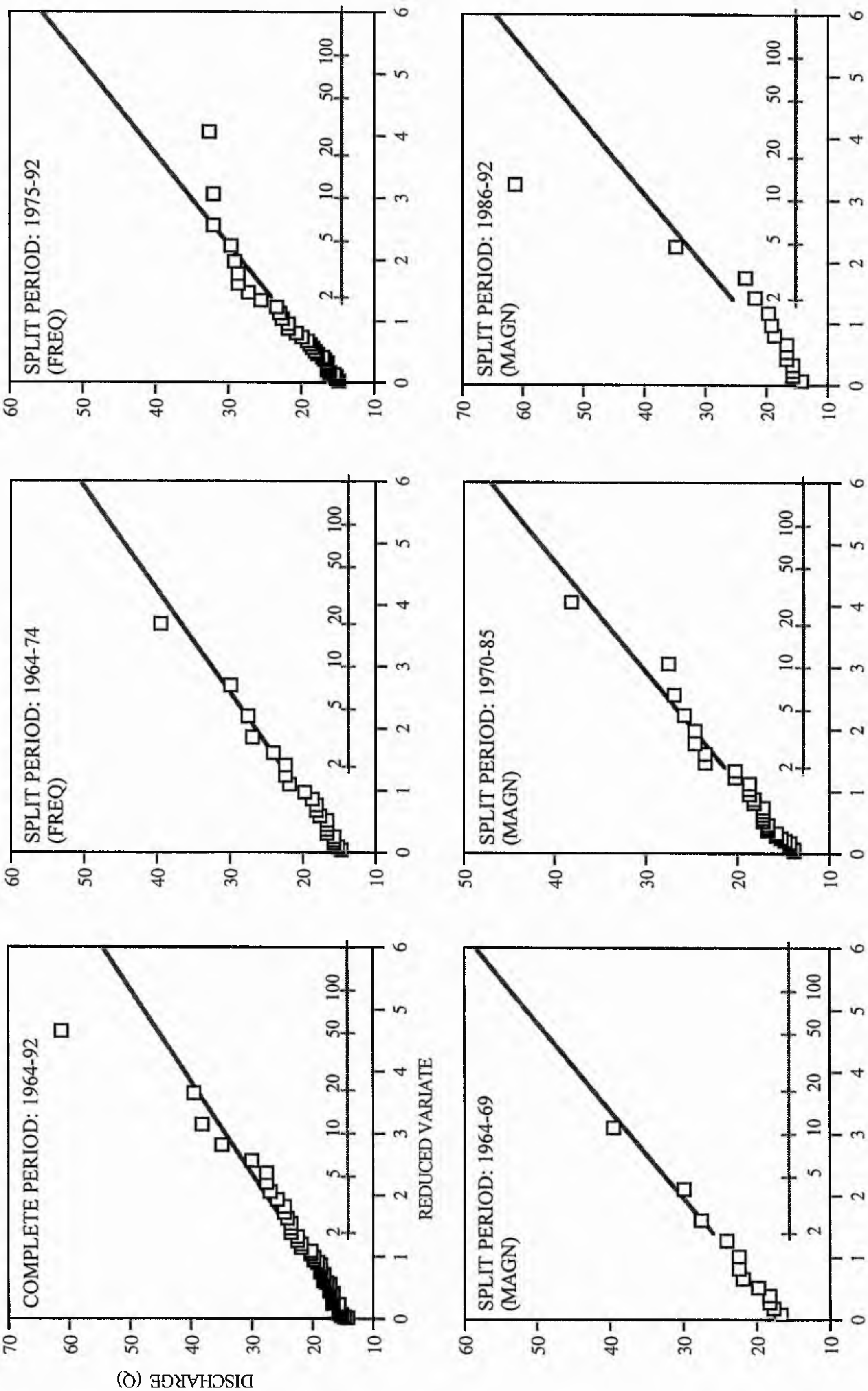

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Figure 7.43: Flood frequency curves for complete and split periods of record
Water of Leith at Murrayfield (19006) 1964-92

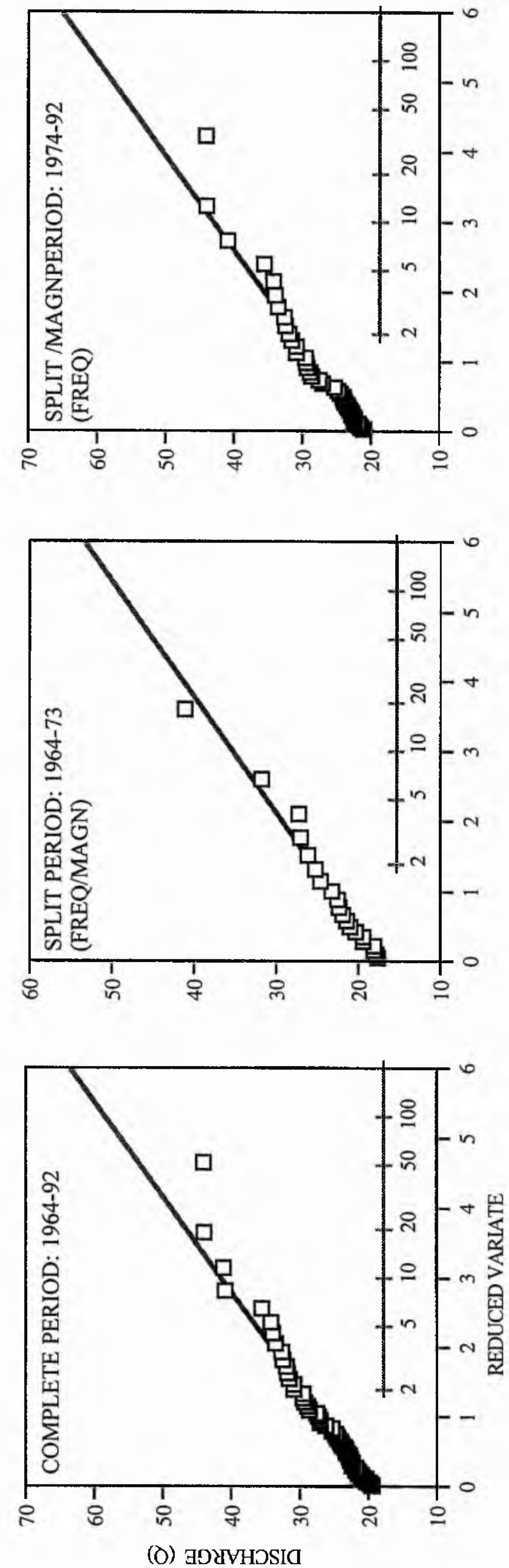

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Figure 7.44: Flood frequency curves for complete and split periods of record
Esk at Musselburgh (19007) 1964-92

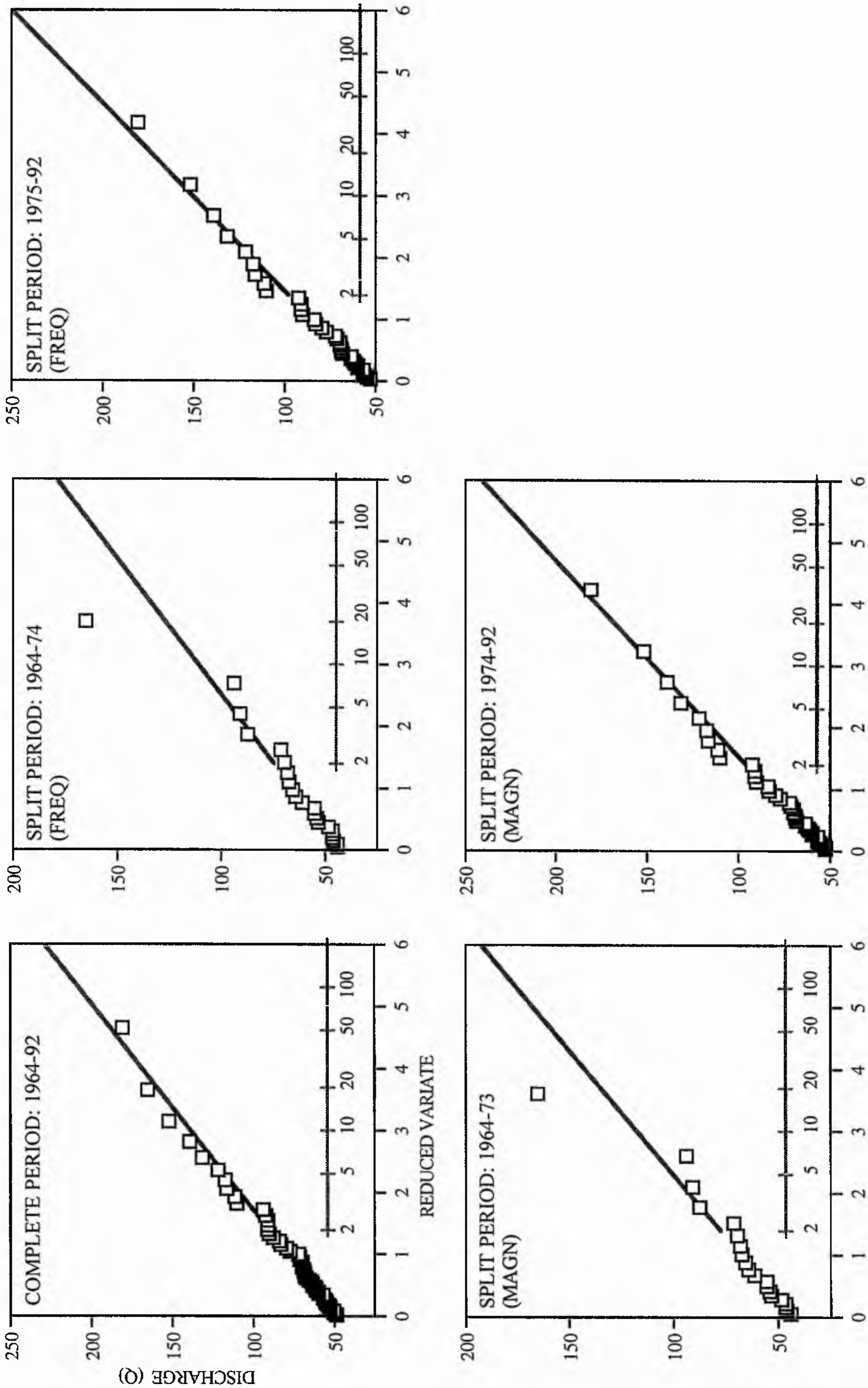

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Figure 7.45: Flood frequency curves for complete and split periods of record
North Esk at Dalkeith Palace (19011) 1964-92

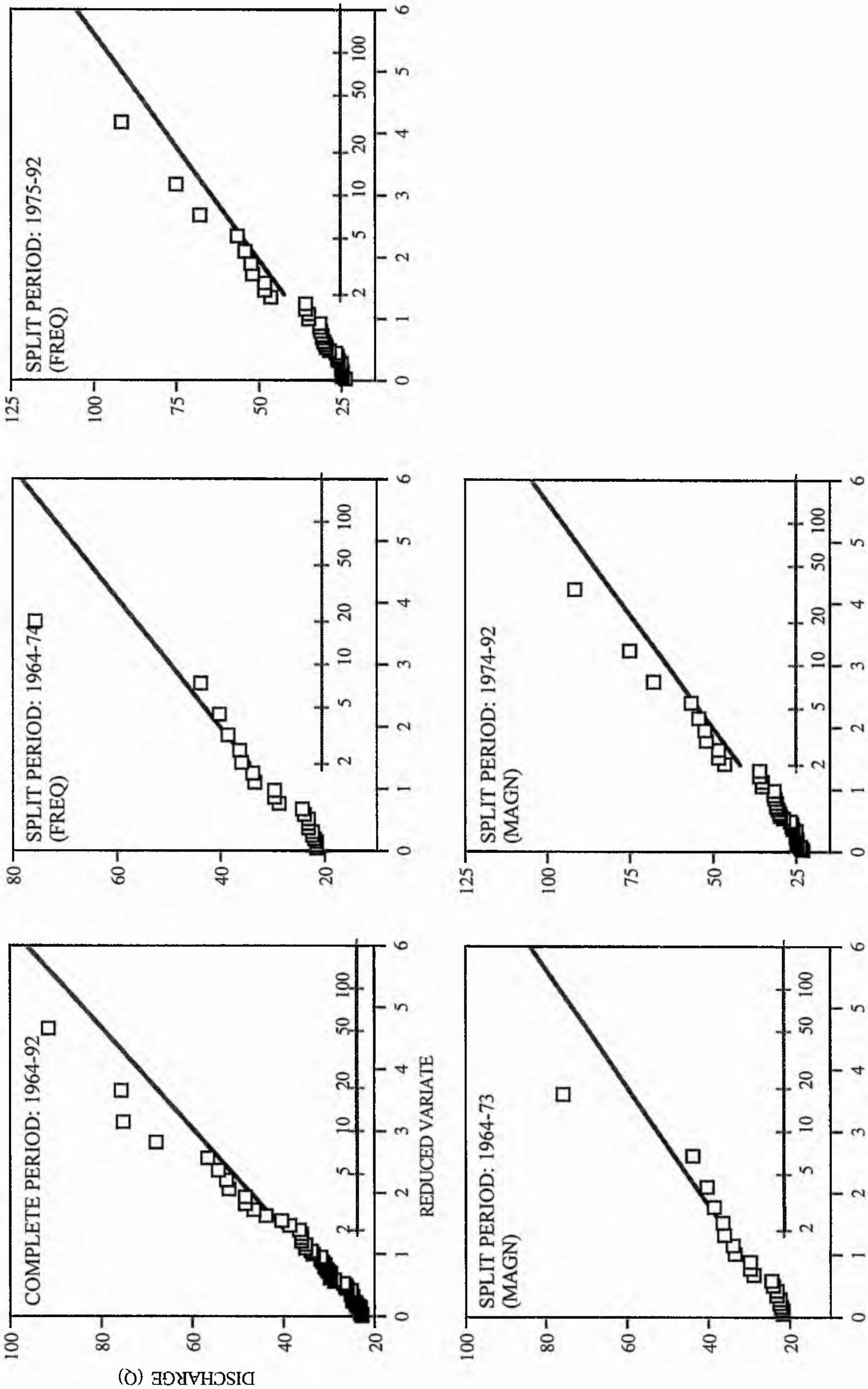

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Figure 7.46: Flood frequency curves for complete and split periods of record
Tyne at East Linton (20001) 1964-92

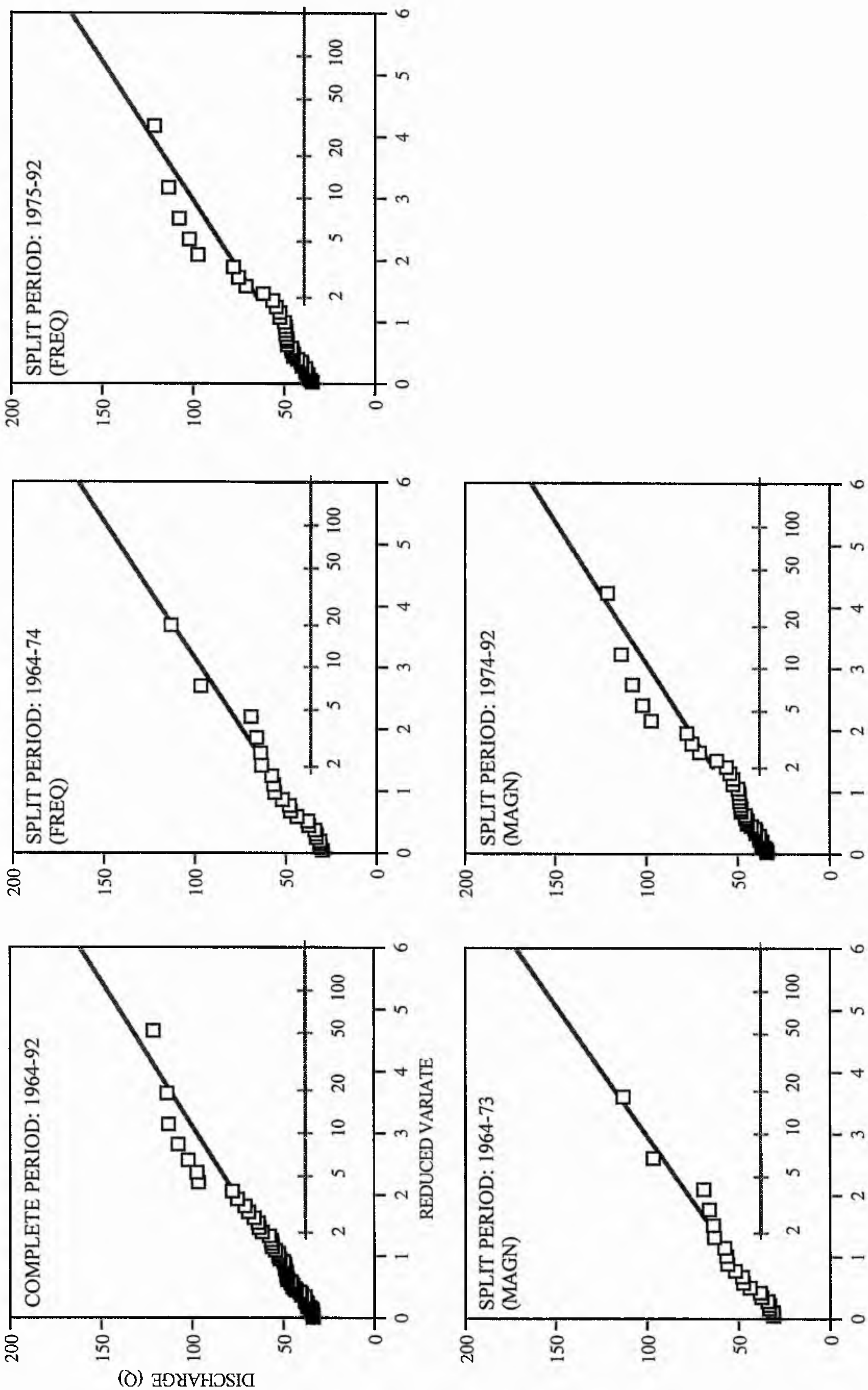

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Figure 7.47: Flood frequency curves for complete and split periods of record
Tyne at Spilmersford (20003) 1964-92

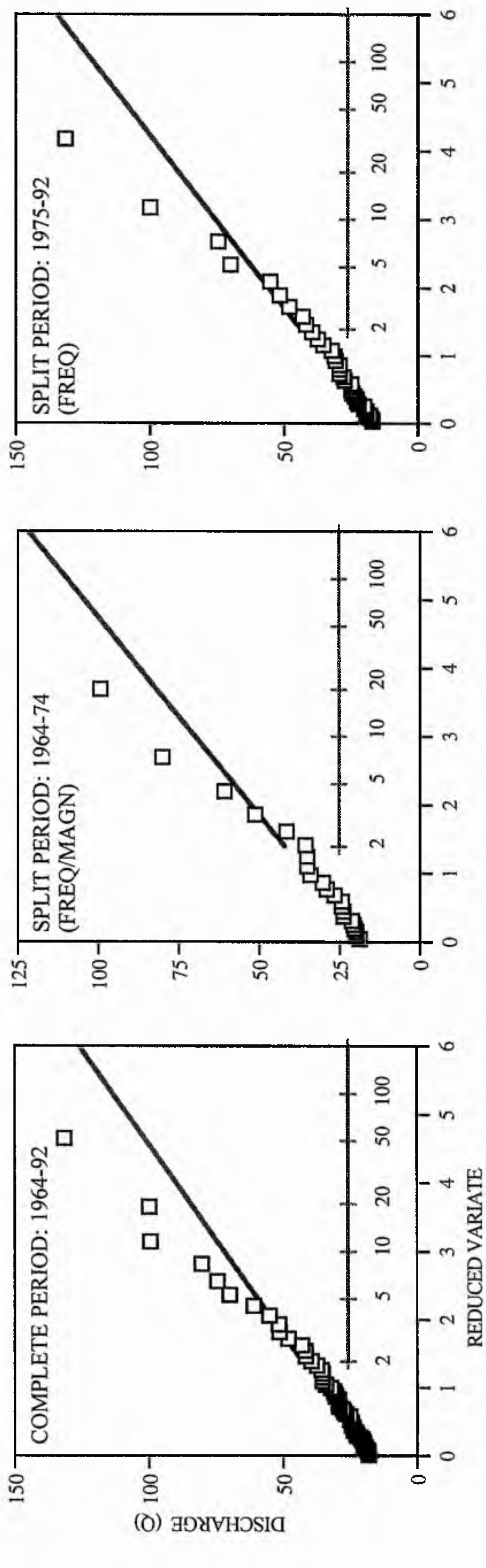

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Figure 7.48: Flood frequency curves for complete and split periods of record
Birns Water at Saltoun Hall (20005) 1964-92

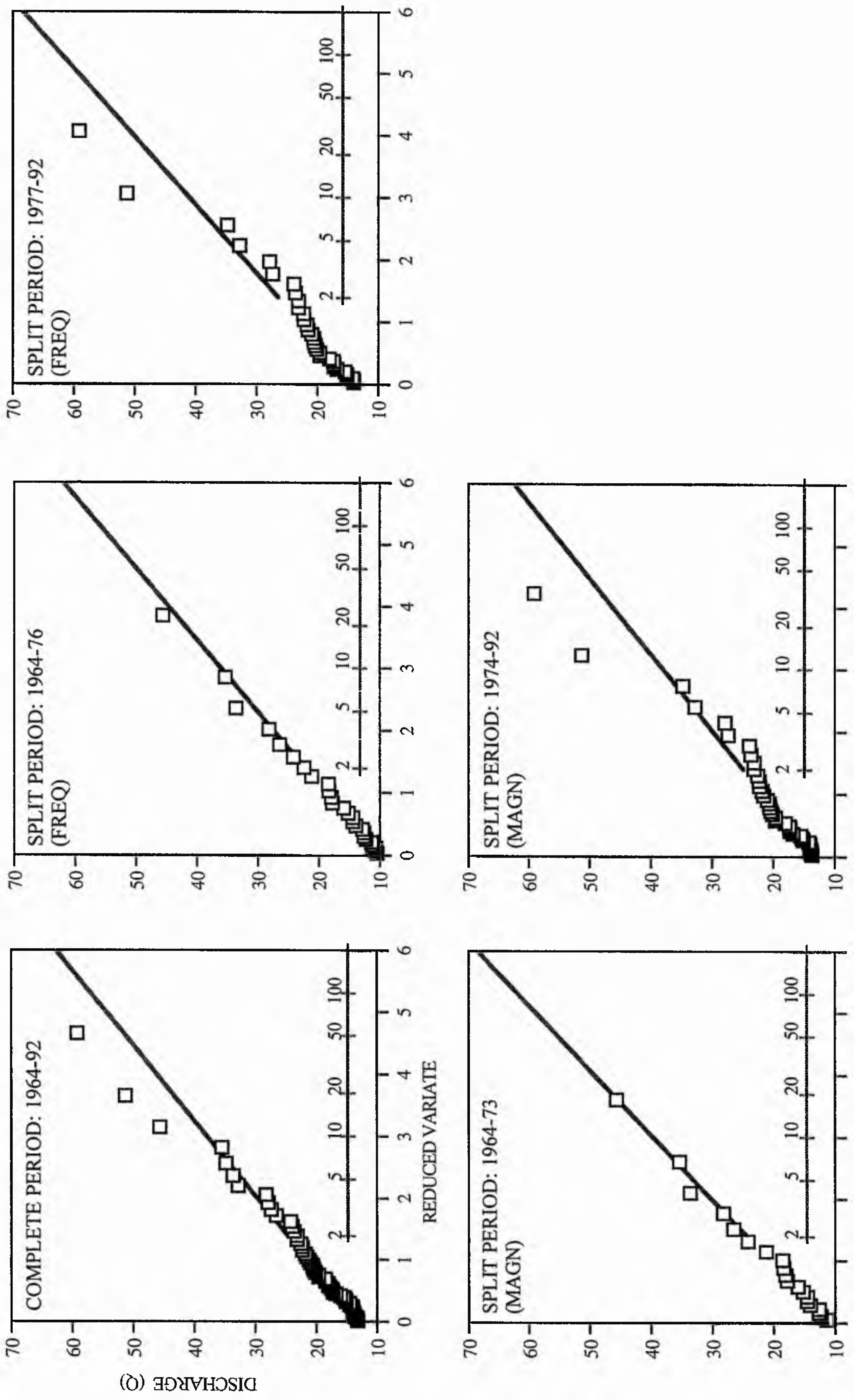

Figure 7.49: Flood frequency curves for complete and split periods of record
Tweed at Peebles (21003) 1964-92

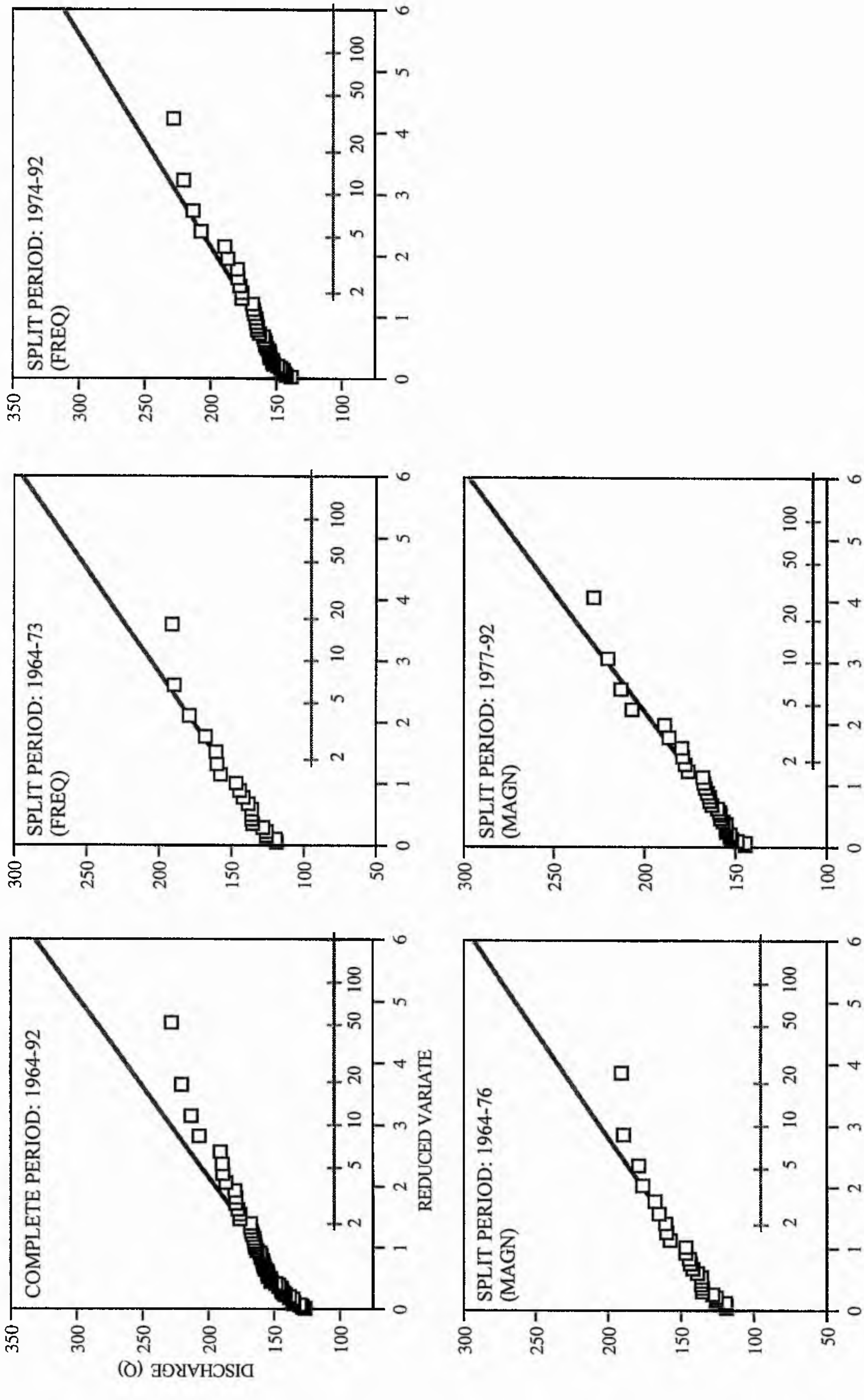

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Figure 7.50: Flood frequency curves for complete and split periods of record
Tweed at Lyne Ford (21005) 1964-92

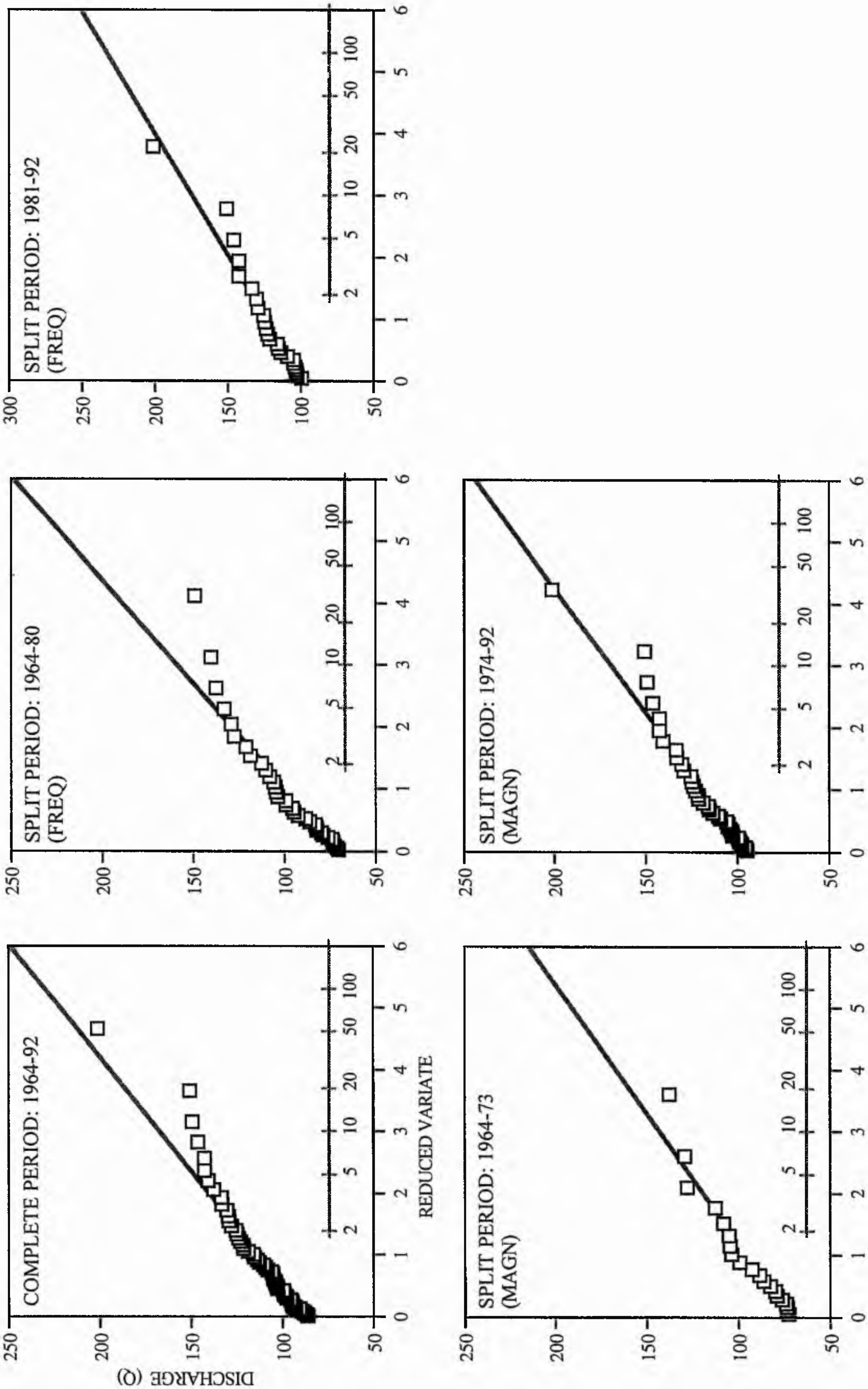

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Figure 7.51: Flood frequency curves for complete and split periods of record
Tweed at Boleside (21006) 1964-92

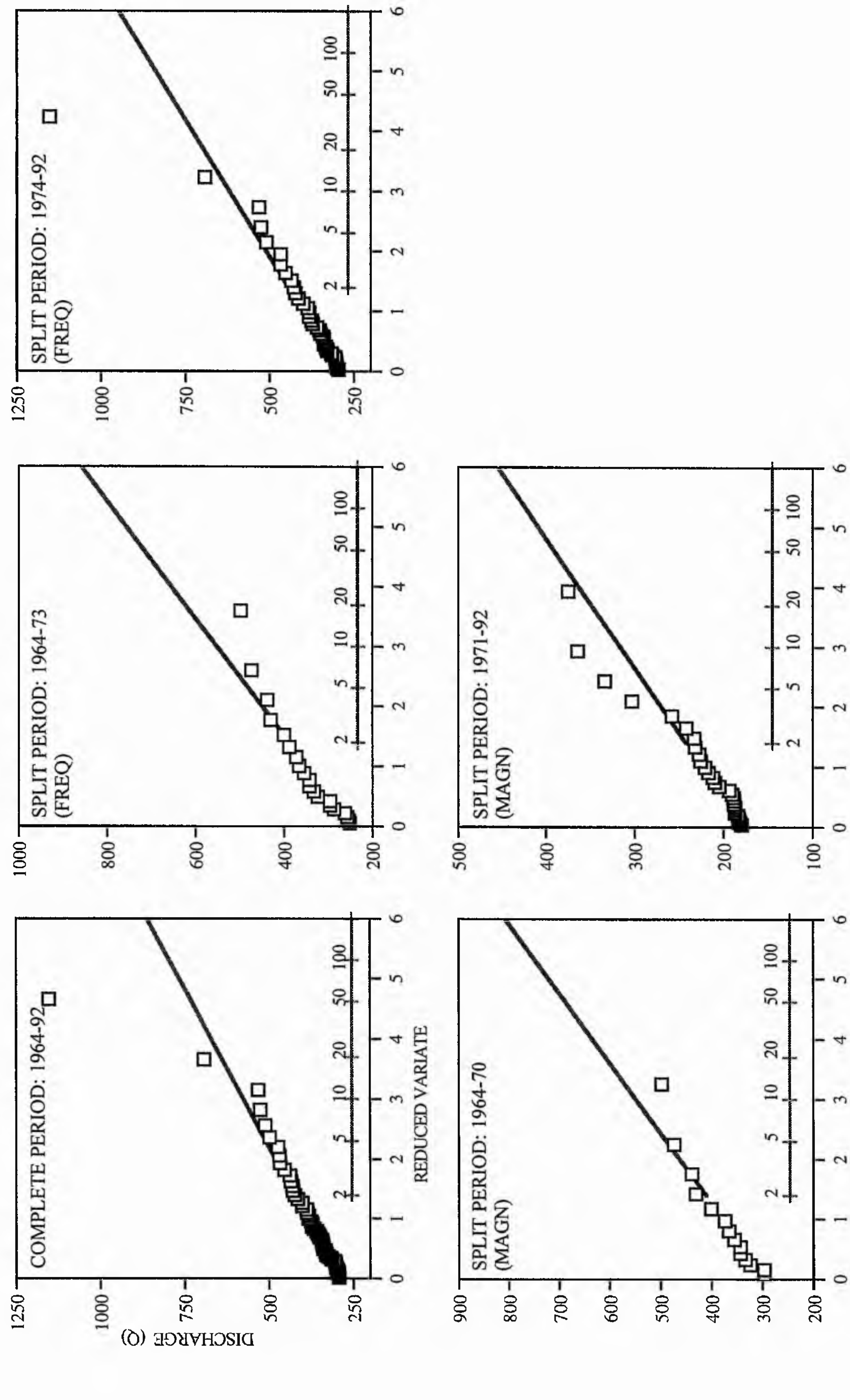

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Figure 7.52: Flood frequency curves for complete and split periods of record
Ettrick Water at Lindean (21007) 1964-92

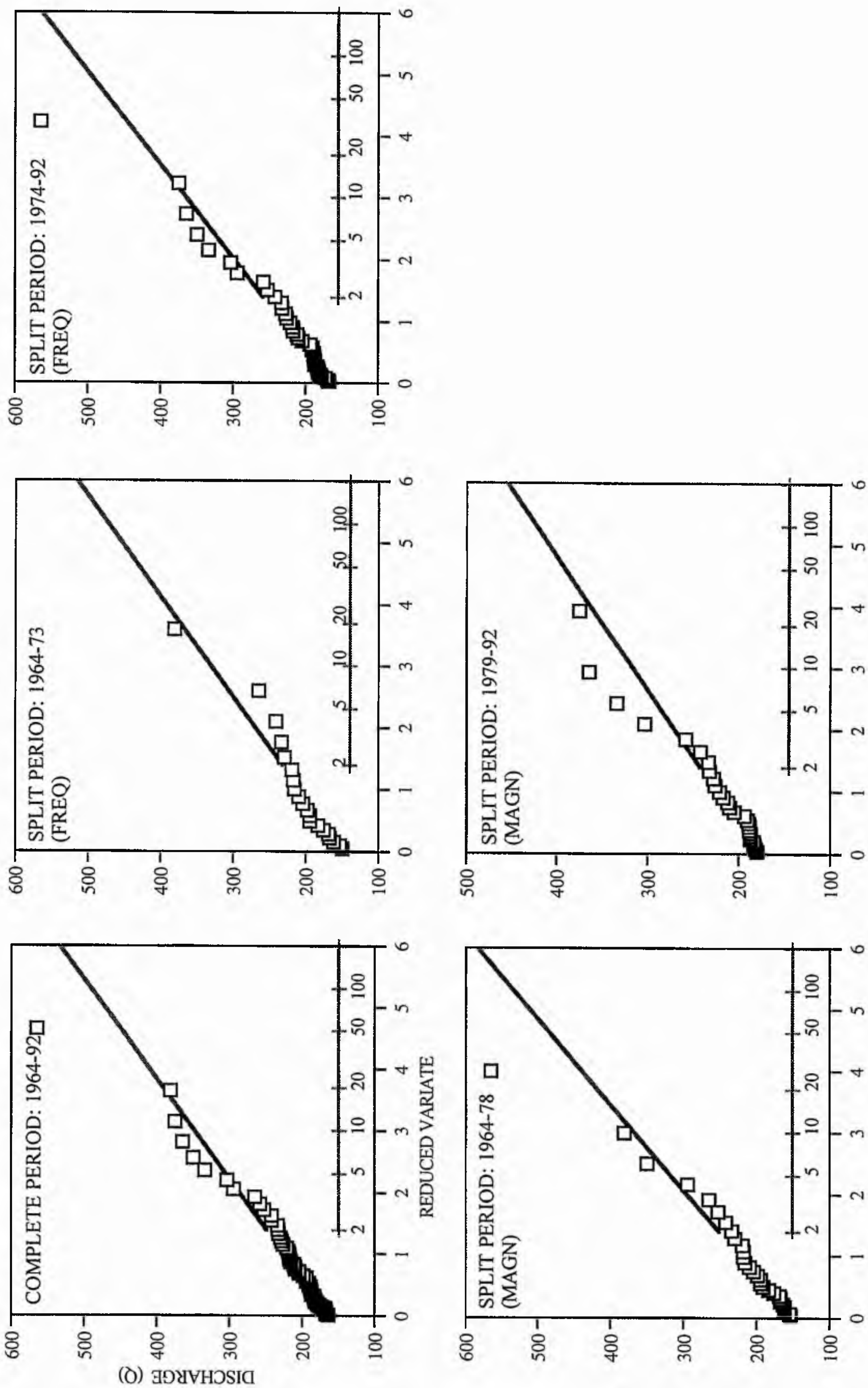

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Figure 7.53: Flood frequency curves for complete and split periods of record
Teviot at Ormiston Mill (21008) 1964-92

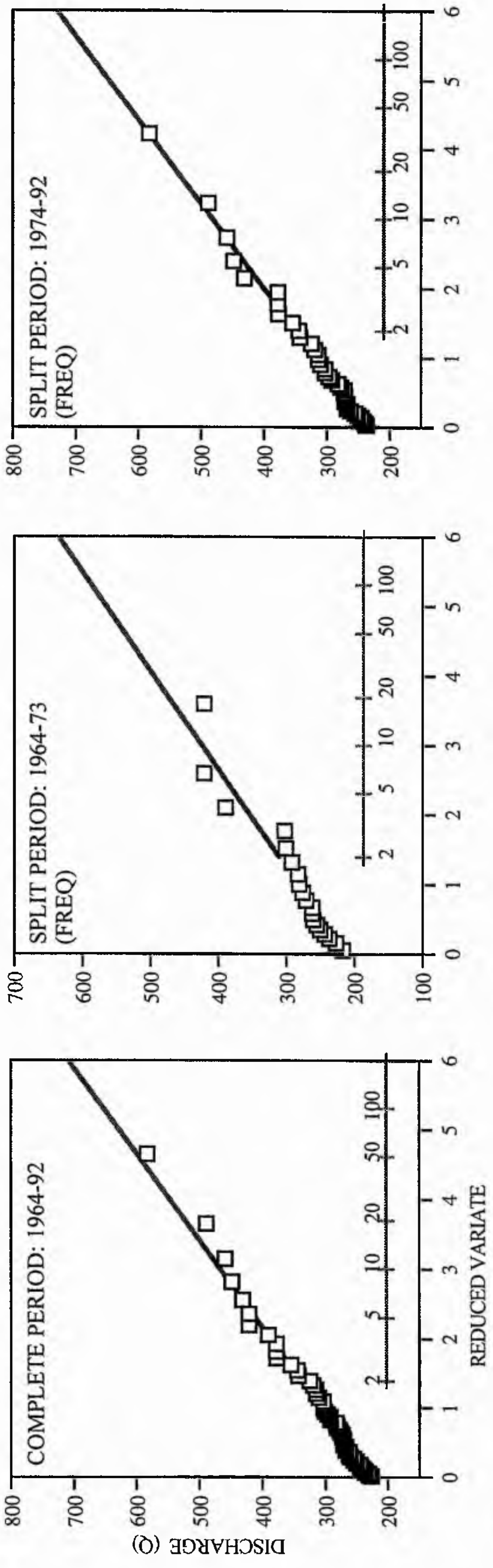

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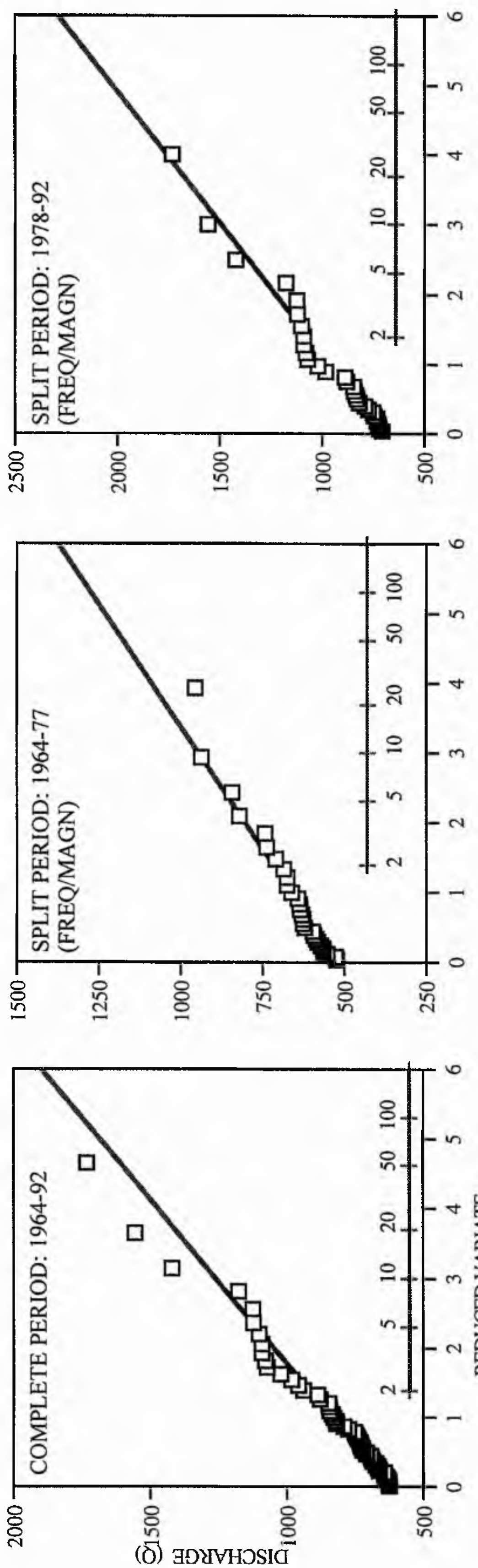
Figure 7.54: Flood frequency curves for complete and split periods of record
Tweed at Norham (21009) 1964-92



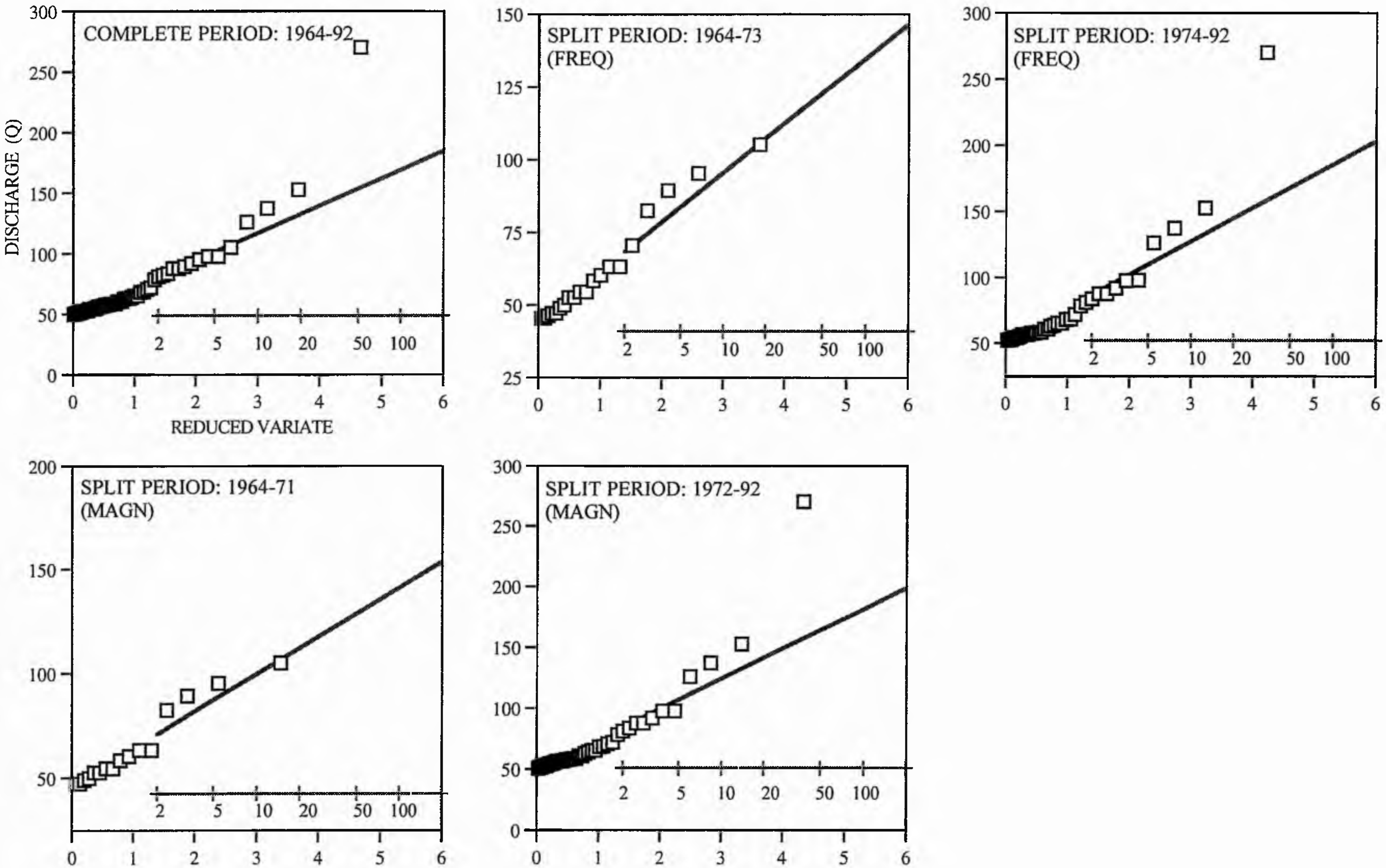


Figure 7.55: Flood frequency curves for complete and split periods of record Yarrow Water at Philiphaugh (21011) 1964-92

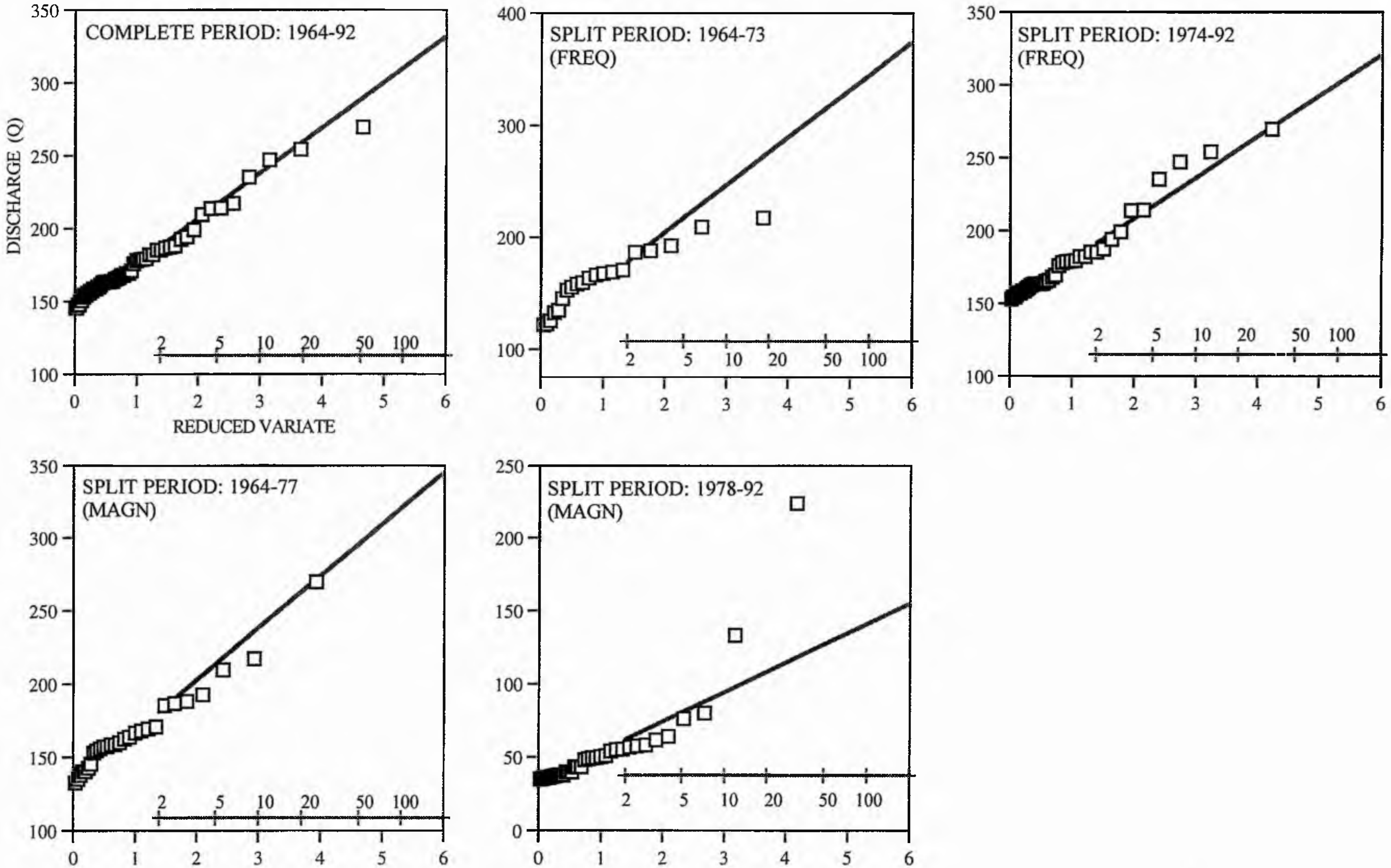


Figure 7.56: Flood frequency curves for complete and split periods of record Teviot at Hawick (21012) 1964-92

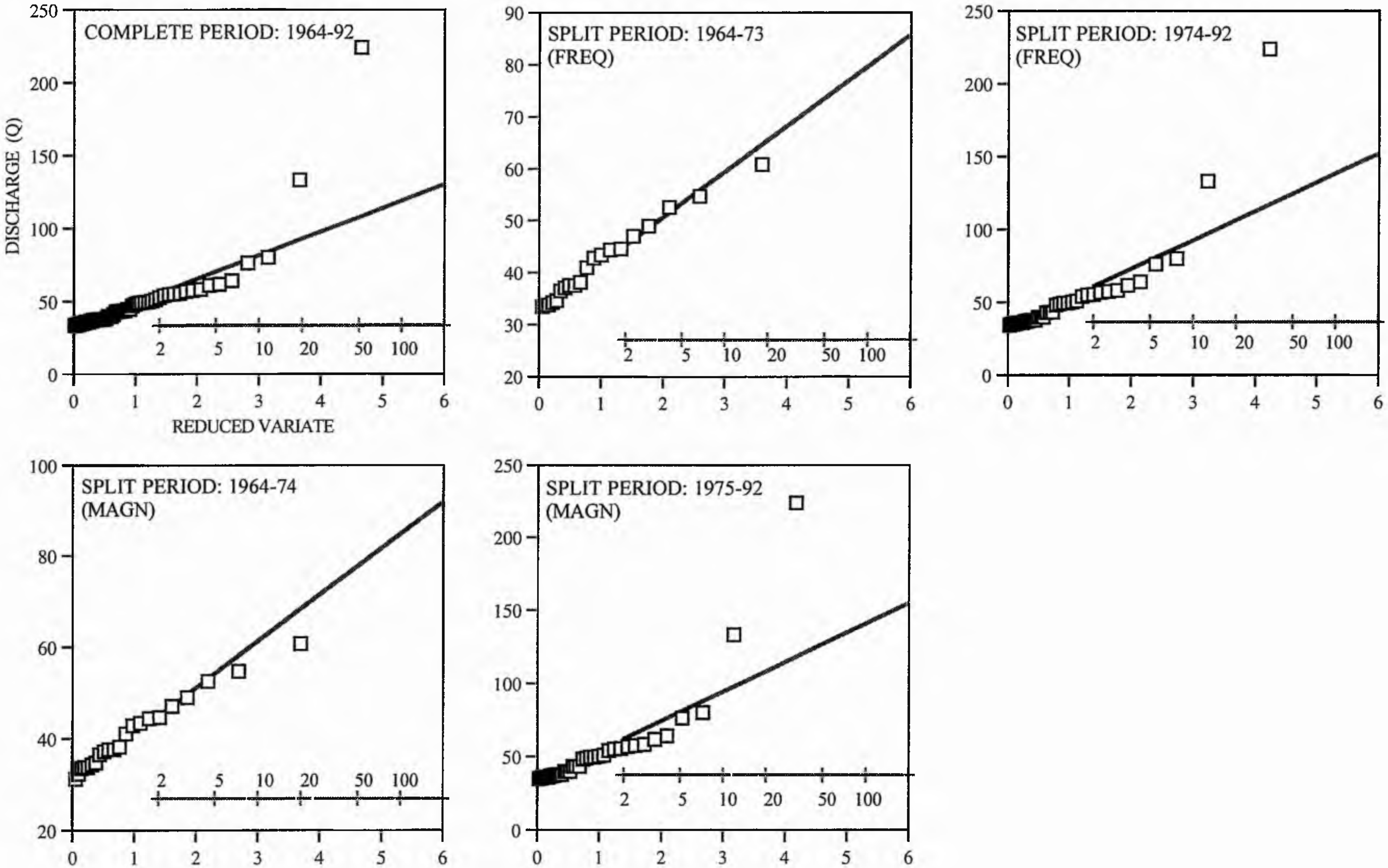


Figure 7.57: Flood frequency curves for complete and split periods of record Gala Water at Galashiels (21013) 1964-92

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Figure 7.58: Flood frequency curves for complete and split periods of record
Nith at Friars Carse (79002) 1964-92

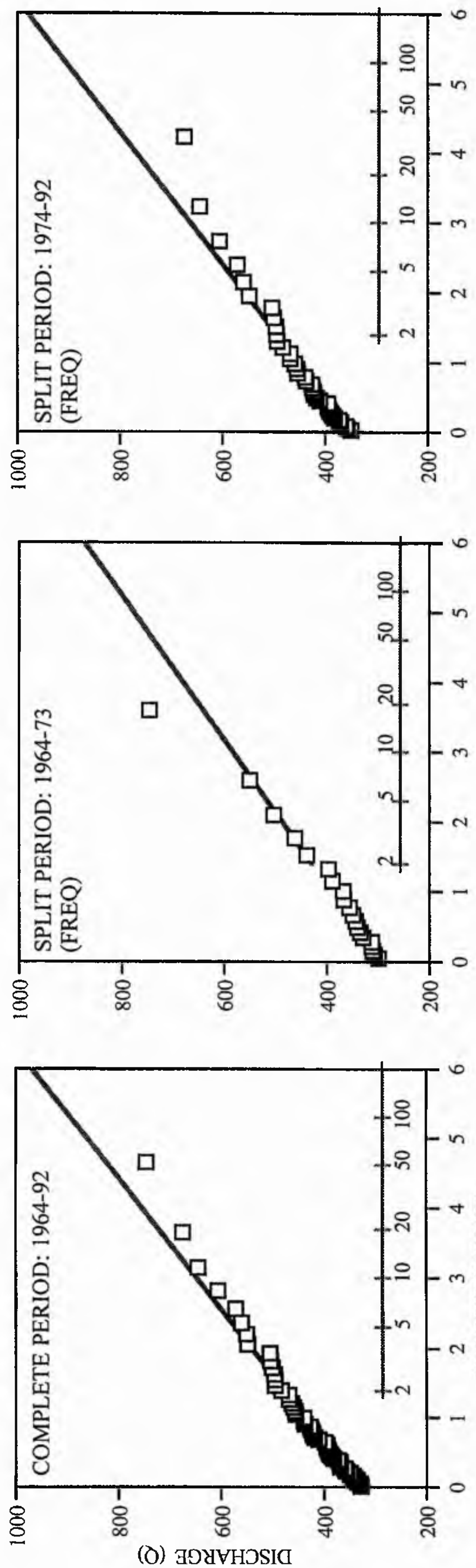

Figure 7.59: Flood frequency curves for complete and split periods of record
Nith at Hallbridge (79003) 1964-92

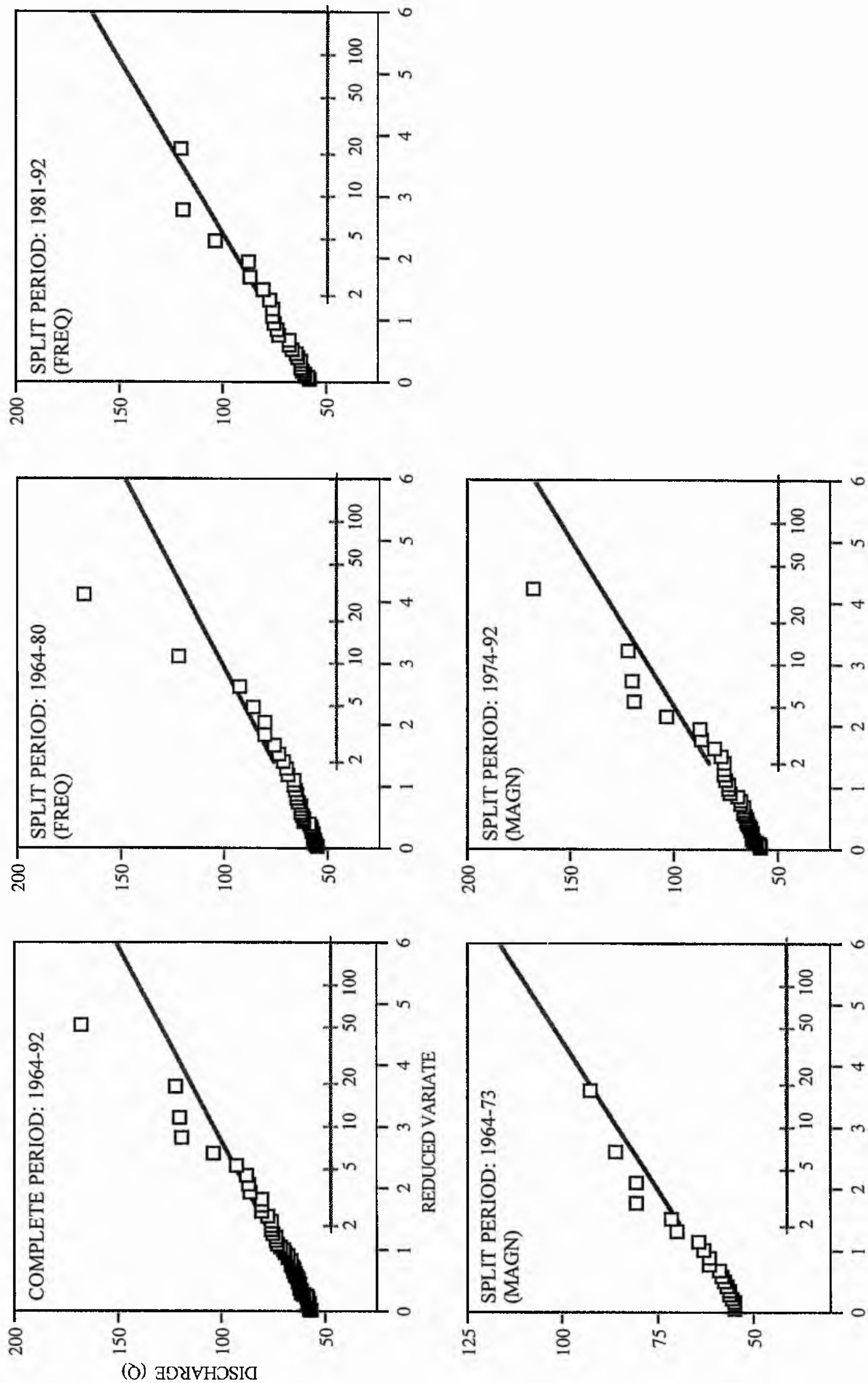

Figure 7.60: Flood frequency curves for complete and split periods of record
Scar Water at Capenoch (79004) 1964-92

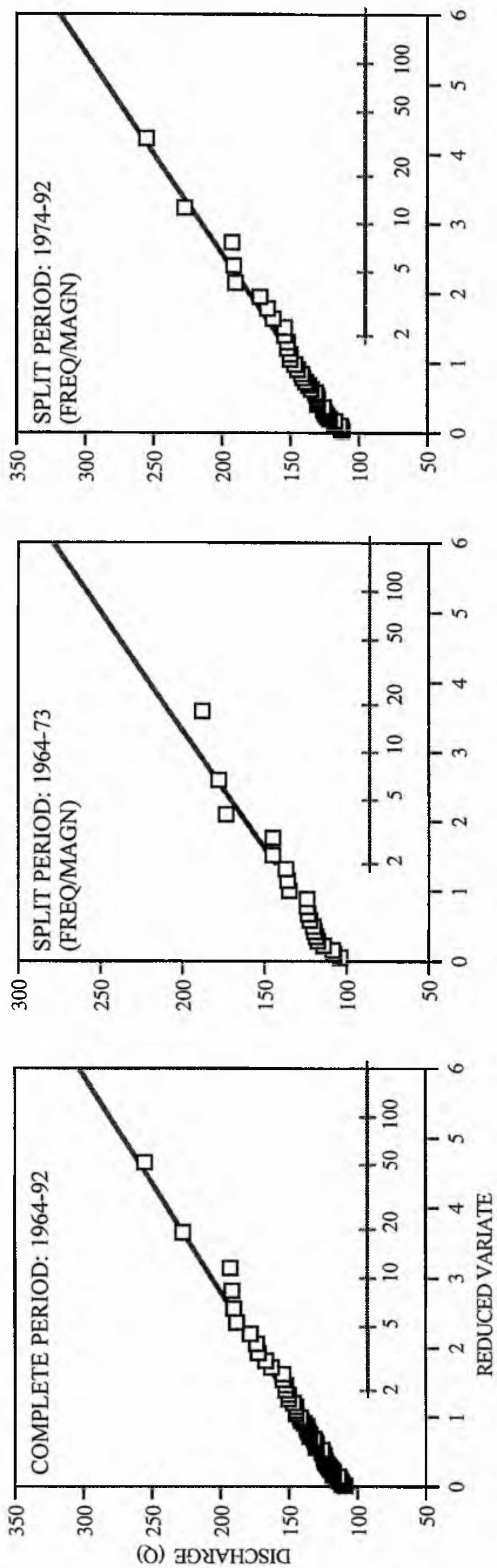

Figure 7.61: Flood frequency curves for complete and split periods of record
Cluden Water at Fiddler's Ford (79005) 1964-92

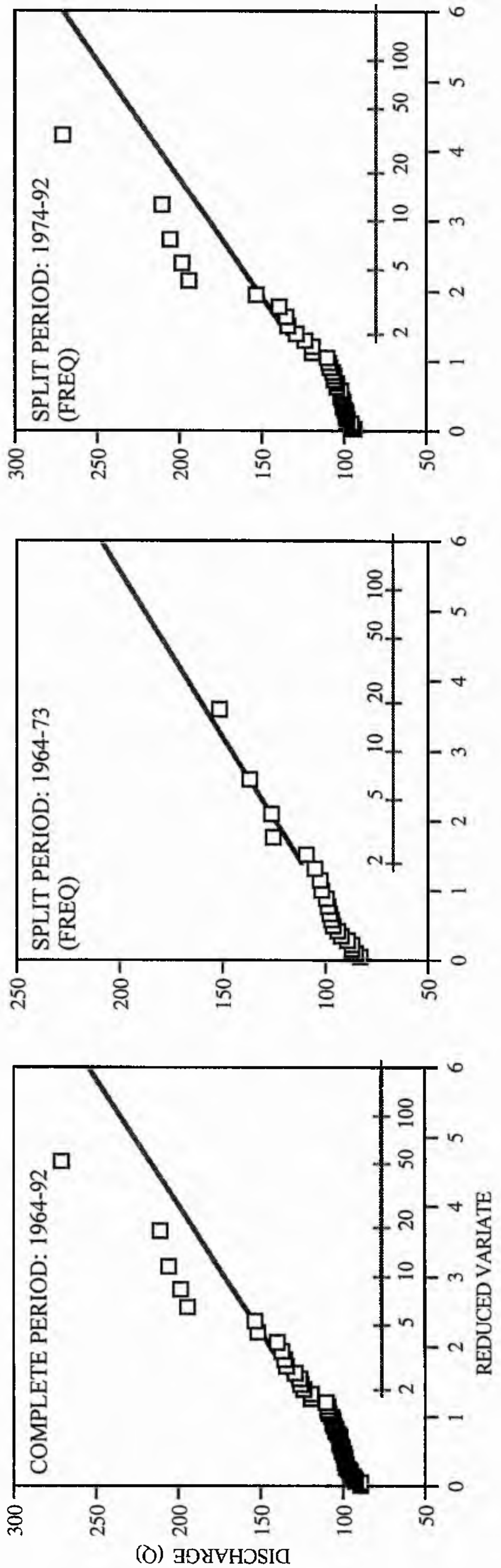

Figure 7.62: Flood frequency curves for complete and split periods of record
Urr at Dalbeattie (80001) 1964-92

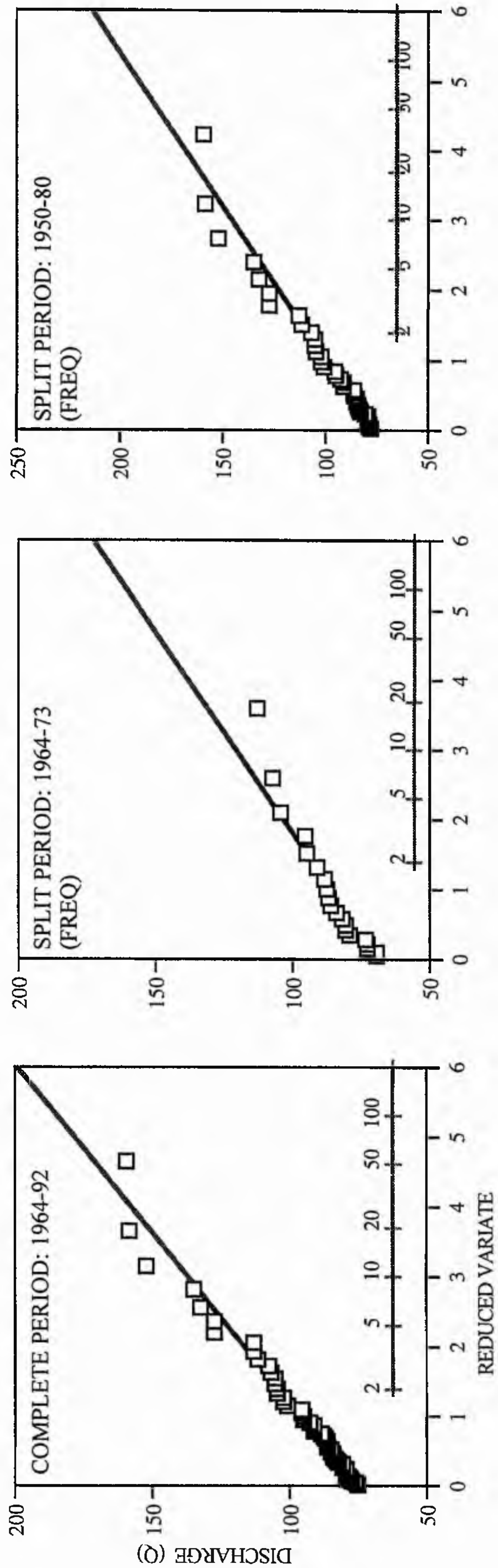

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Figure 7.63: Flood frequency curves for complete and split periods of record
Cree at Newton Stewart (81002) 1964-92

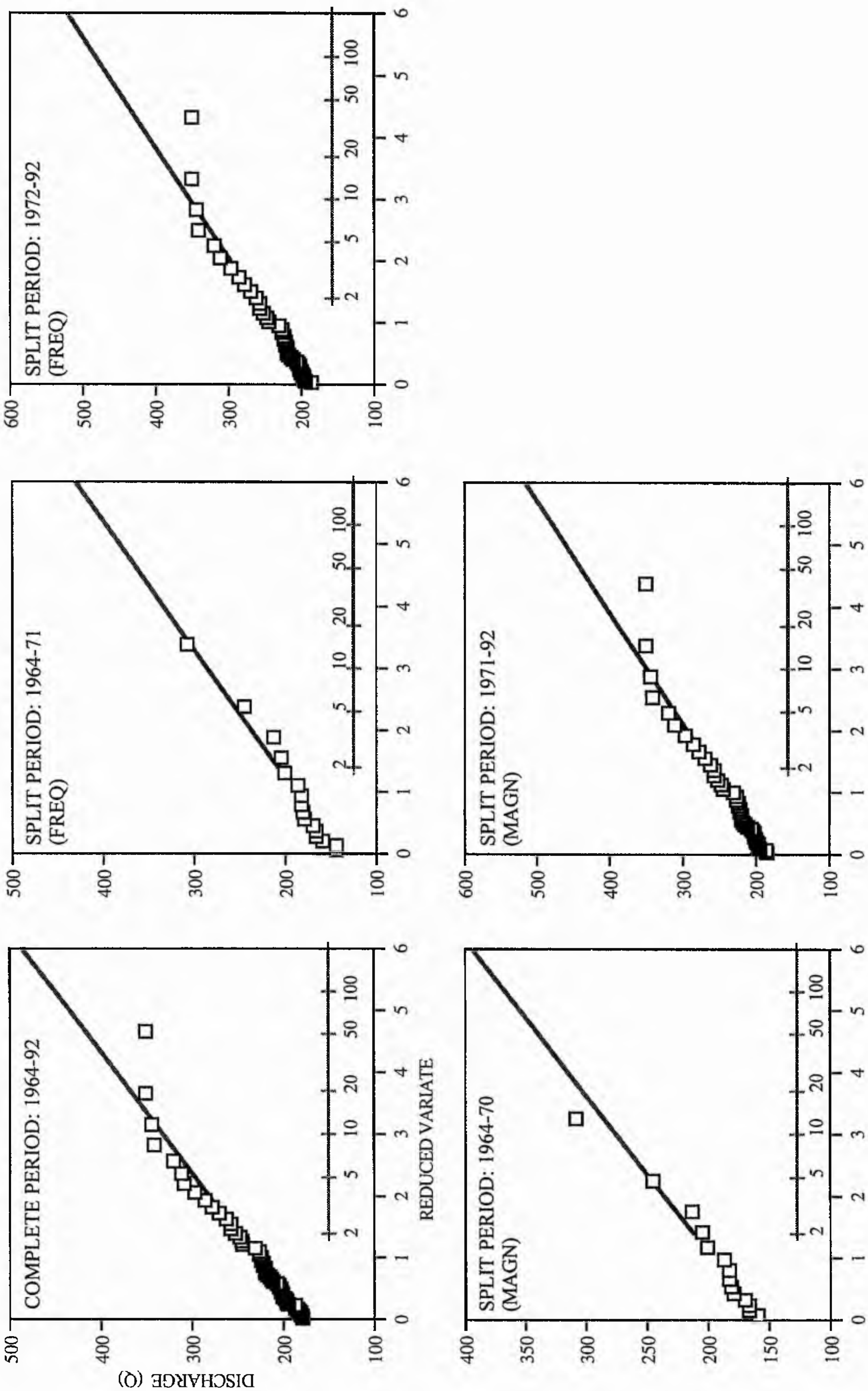

Figure 7.64: Flood frequency curves for complete and split periods of record
Girvan at Robstone (82001) 1964-92

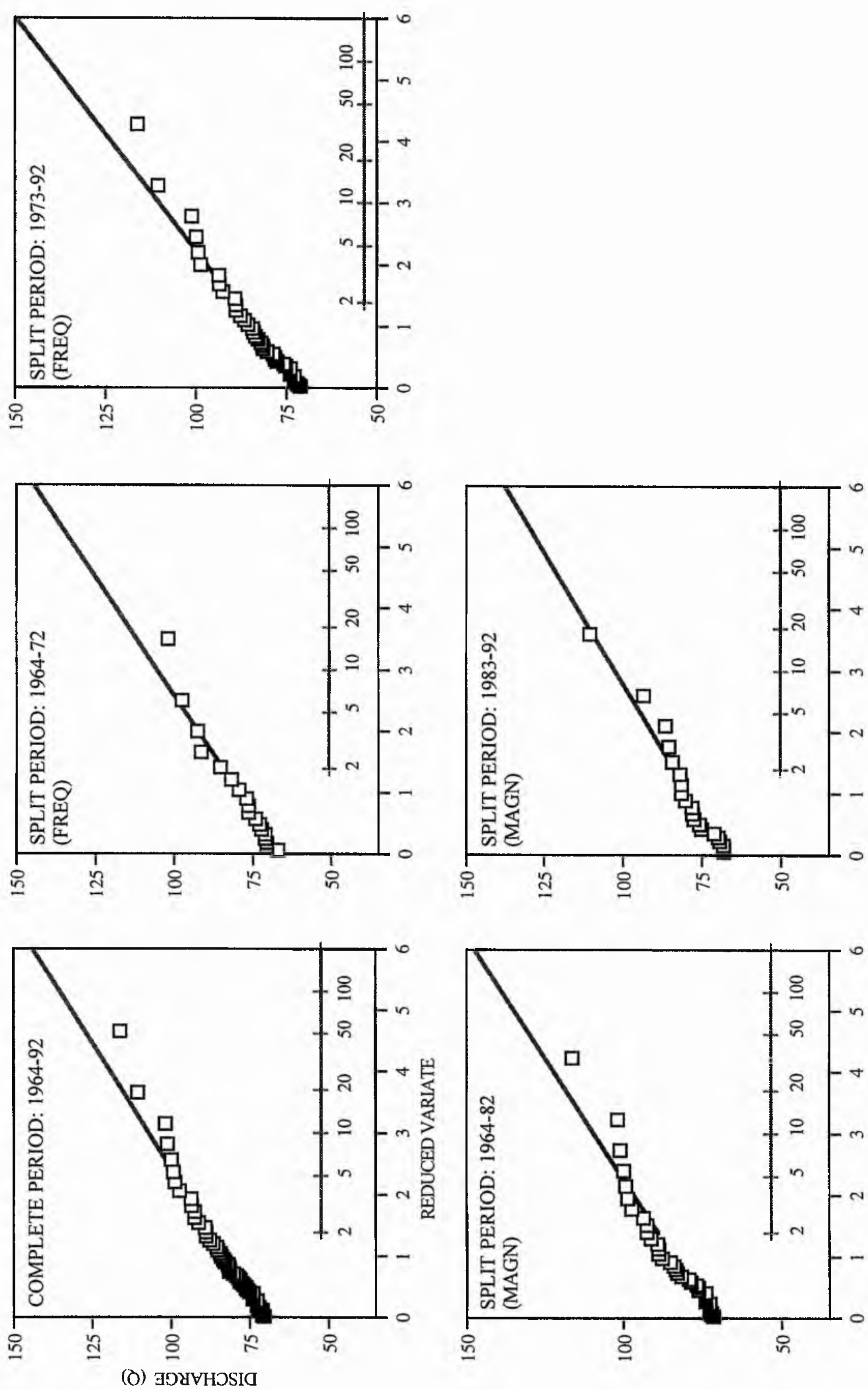

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Figure 7.65: Flood frequency curves for complete and split periods of record
Kelvin at Killermont (84001) 1964-92

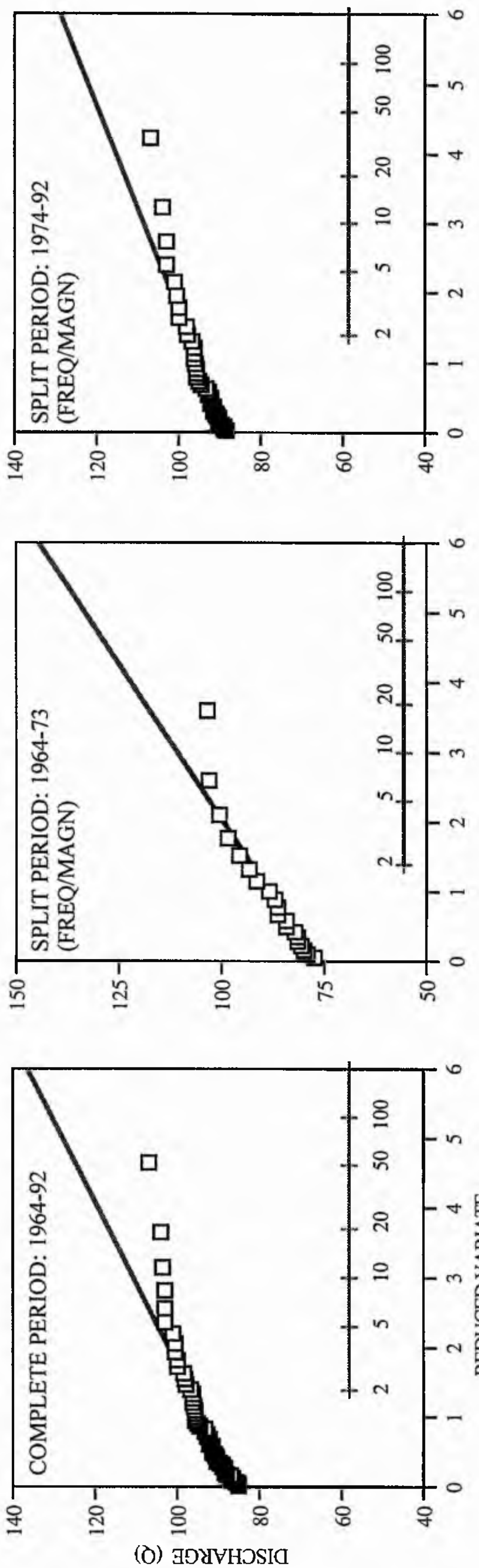

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Figure 7.66: Flood frequency curves for complete and split periods of record
Clyde at Hazelbank (84003) 1964-92

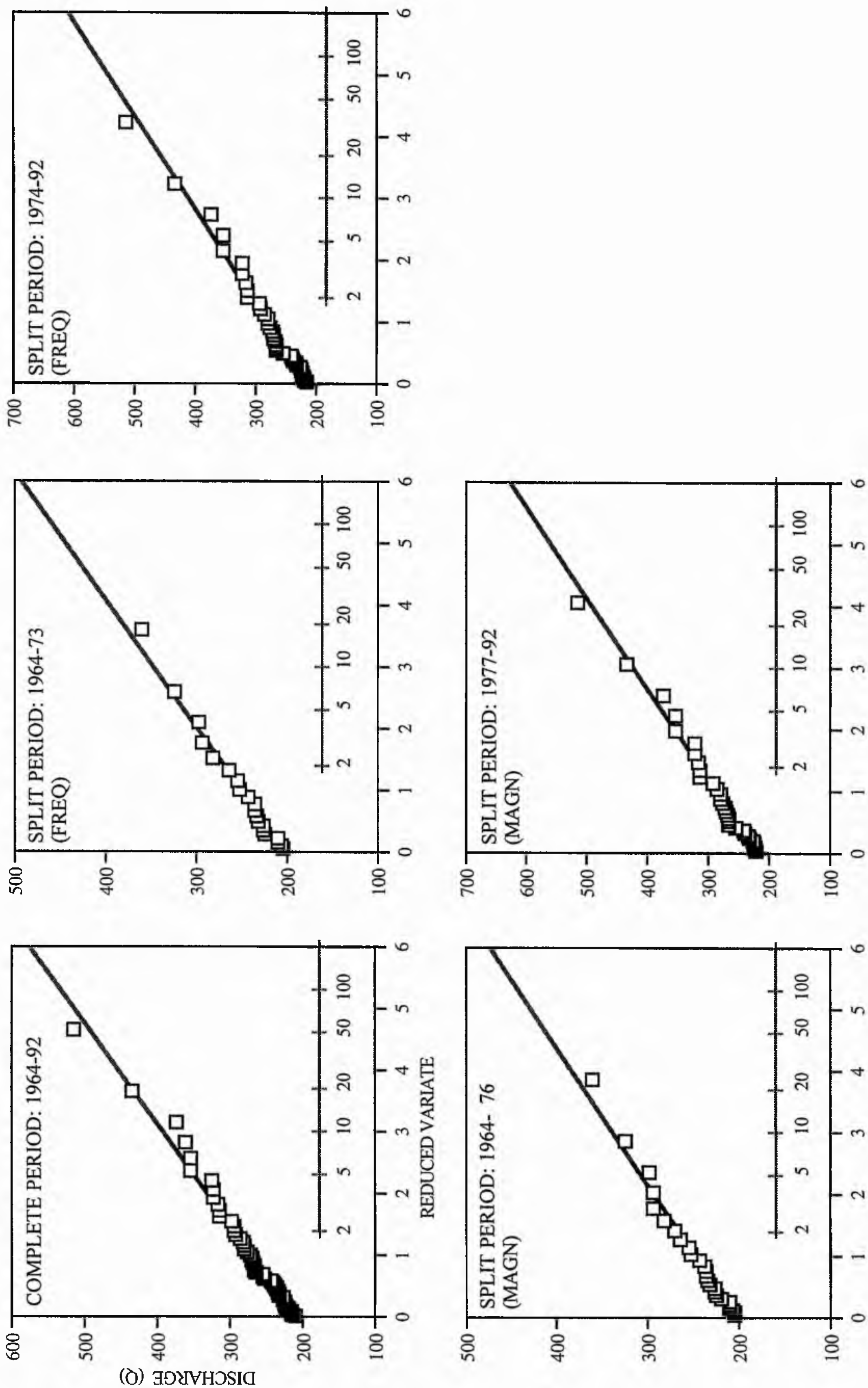

Figure 7.67: Flood frequency curves for complete and split periods of record
Clyde at Sills (84004) 1964-92

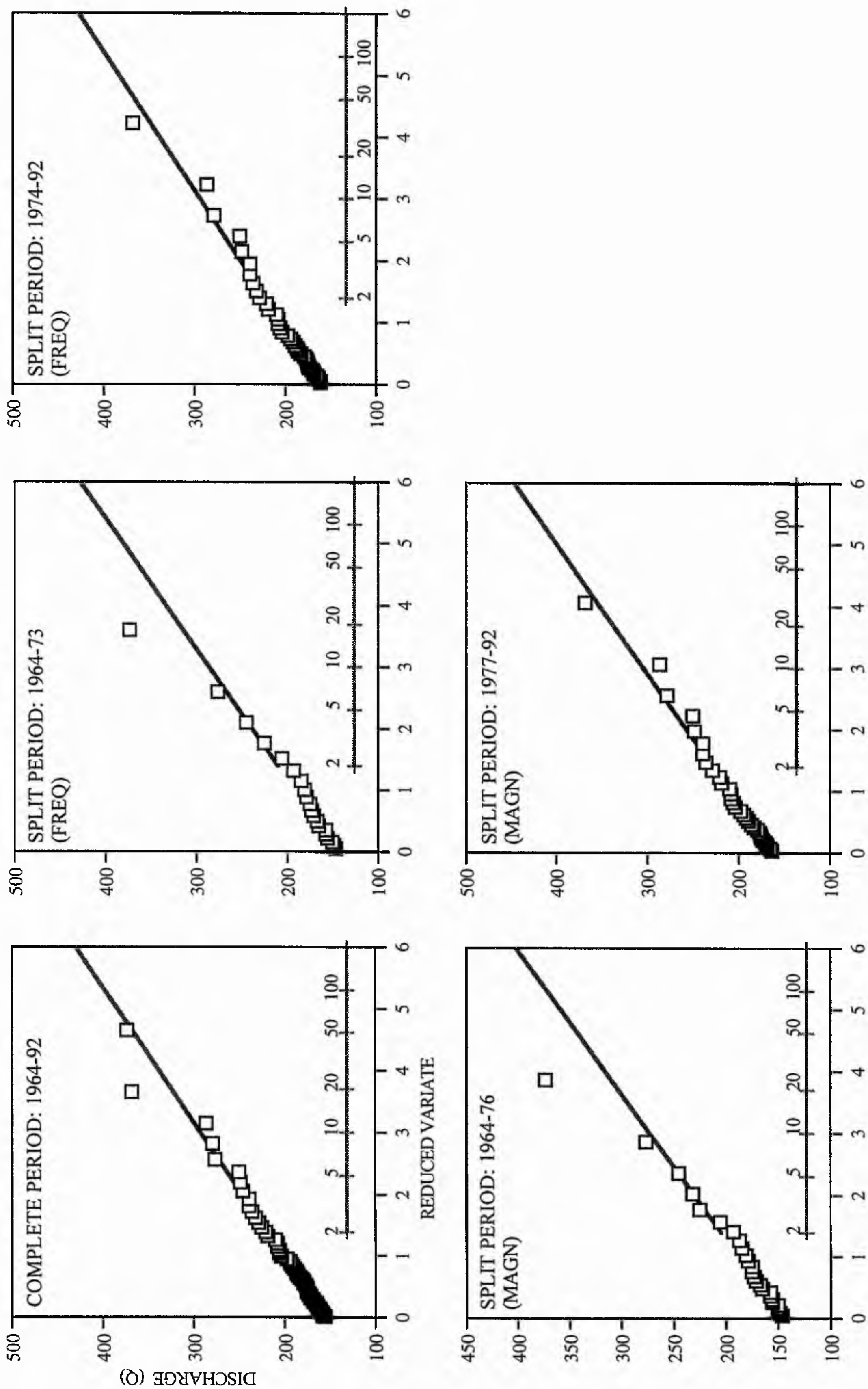

Figure 7.68: Flood frequency curves for complete and split periods of record
Clyde at Blairston (84005) 1964-92

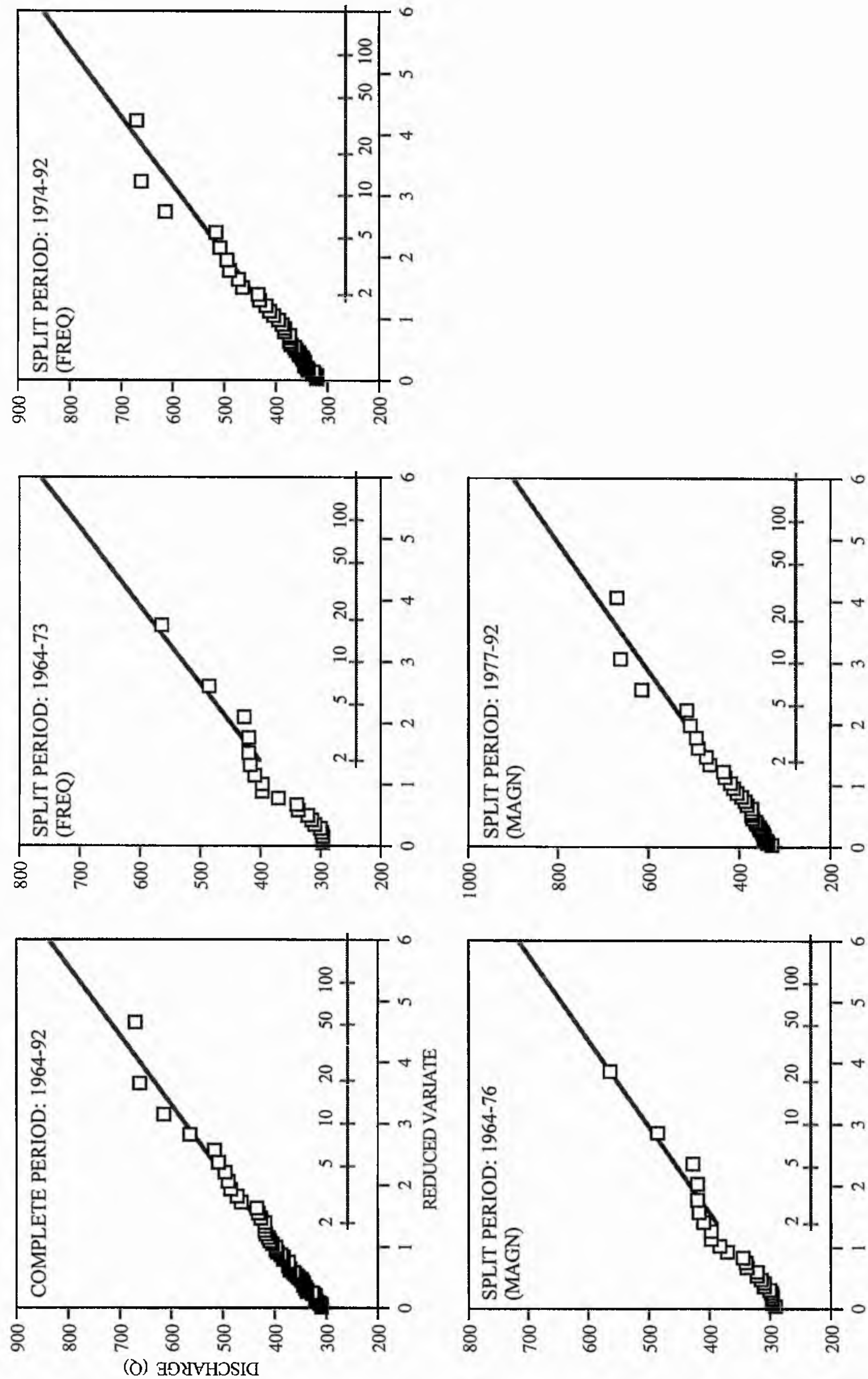

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Figure 7.69: Flood frequency curves for complete and split periods of record
Gryfe at Craigend (84011) 1964-92

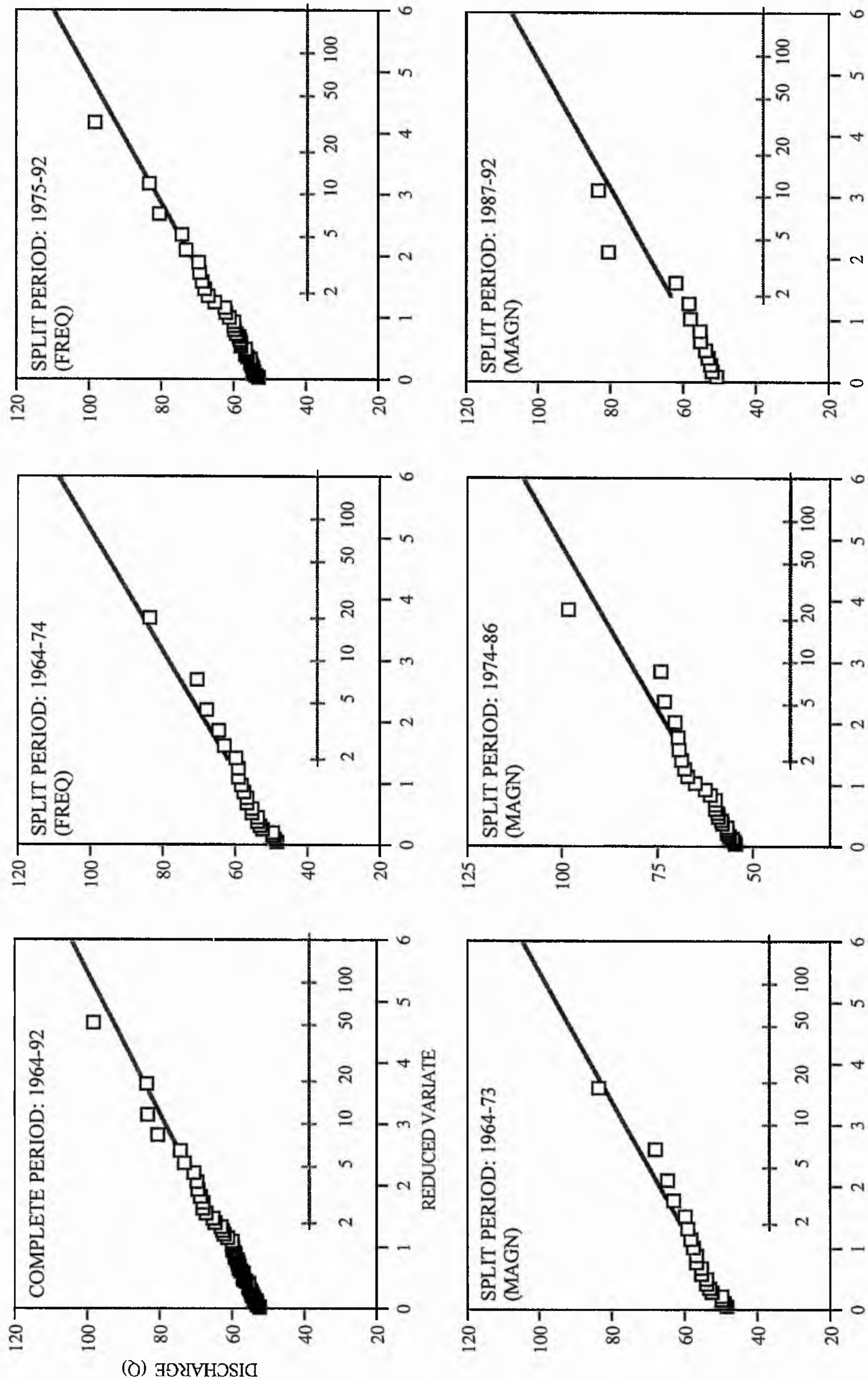

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Figure 7.70: Flood frequency curves for complete and split periods of record
White Cart Water at Hawkhead (84012) 1964-92

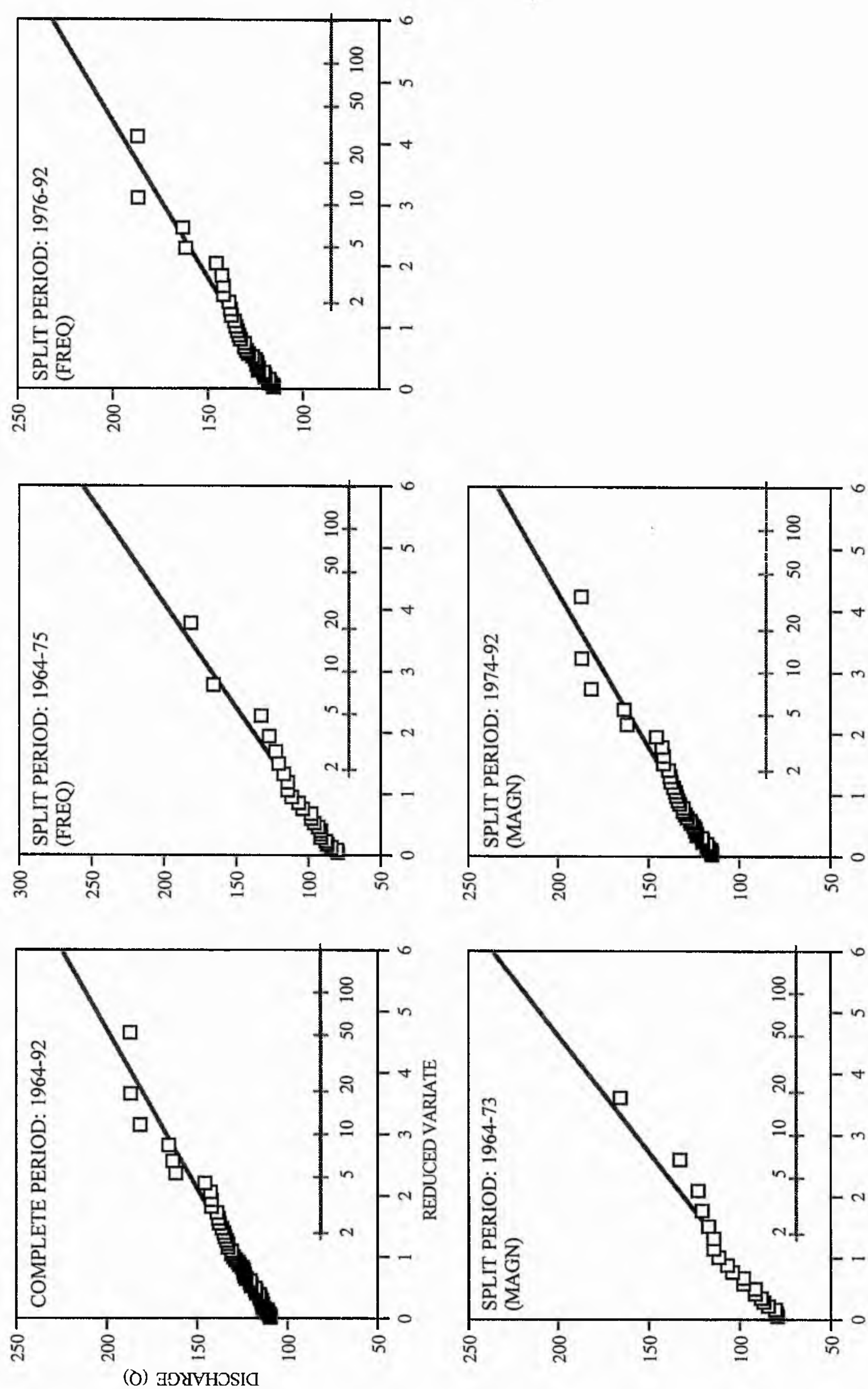

Figure 7.71: Flood frequency curves for complete and split periods of record
Calder Water at Calderpark (84019) 1964-92