A MULTI-SCALE INVESTIGATION INTO THE EFFECTS OF AGRICULTURE ON FLOOD HYDROLOGY IN SOUTHWEST ENGLAND

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by

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Abstract

In the UK, perceived increases in high impact flood events over the last decade and broad scale recognition of the enhanced flood risks associated with future climate change predictions, have reinforced the need for improved understanding and management of processes governing peak flow responses. This thesis investigates the effects of agricultural land uses on the hydrology of rural areas at a range of spatial and temporal scales.

At the catchment scale, 48 catchments and subcatchments distributed across the south western counties of Cornwall, Devon, Somerset and Dorset were investigated. A suite of multivariate statistical techniques, including Direct (Redundancy Analysis) and Indirect (Principal Components Analysis) Ordination were used to explore catchment responses to four major storm events, selected from the wet autumn/winter of 2000-2001. A Geographic Information System (GIS) incorporating the Hydrology of Soil Types (HOST) soil classification system and Land Cover Map 2000 satellite imagery data was developed to parameterise catchment physiographic variables and calculate the extent of 27 land use classes.

Analysis of regional trends in environmental variables and two multivariate runoff datasets (R1 and R2) identified land use as the principal control of streamflow responses to extreme storm events. Land use, soil and geology parameters together explained 84% (R1) and 78% (R2) of the variance in runoff for the same four storms. Grassland and improved grassland were consistent characteristics of catchments generating higher runoff volumes per unit area. Similarities in the hydrological behaviours of the Camel catchment and the De Lank subcatchment supported a dominant control on peak flows by runoff from grazed upland areas.

A longer-term study of the River Camel catchment (1965-2000) revealed a 20% increase in the magnitude of the one in 25 year flow. Daily rainfall totals aggregated at monthly, seasonal and annual timescales and agricultural census data for the years 1969, 1979, 1988, 1997 and 2000 were examined to determine the influence of climate and land use changes on the enhanced streamflow response. Increases in the frequency and magnitude of peak flows were attributed to the cumulative impacts of a subtle, long-term rise in October rainfall totals, coupled with local urban development, the expansion of arable cultivation on highly connected slopes in the lower catchment and a rise in the intensity of grazing in the upper catchment.

At the field scale, characterisation of the textural, structural and hydraulic properties of soils subject to different land managements, including continuous cereal cultivation (CC), semi permanent pasture (SPP), permanent pasture (PP) and farm woodland (FW), identified a link between land use and the structural stability of the surface horizon. Marked differences in the percentage of water stable aggregates (WSA>2.8mm) between the topsoils of FW (66%) and PP (71%), SPP (11%) and CC (6%) helped to

explain differences in saturated hydraulic conductivity that were in the order FW>PP>SPP>CC. Laboratory rainfall simulations revealed slower wetting rates and higher average soil moisture percentages at near-saturation in FW and PP soil plots compared to SPP and CC soil plots that resulted from higher total porosities under FW and PP.

Agricultural management systems are therefore capable of playing an important role in attenuating peak flow responses to storm events through considered land management which ameliorates or prevents soil structural deterioration and encourages the movement of water into storages within the hillslope. The adoption of specific measures, such as the introduction of buffer strips, widening of hedgerows or the introduction of forested areas to act as sinks, may serve to disconnect hydrological pathways from the main channel by providing a barrier to runoff, thereby reducing the upslope contributing area.

Author's Declaration

At no time during the registration for the Degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee.

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May 2004	Agriculture and Flooding in the SW. Chartered Institute for Water and Environmental Management (CIWEM) and the Institute for Chartered Engineers, Exeter, UK. Poster presentation.
Nov 2001	Flooding in a changing climate. Royal Society, London, UK. Oral and poster presentation.

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Oct 2002	Water-what should be done? Royal Geographical Society (RGS) and the Institute of British Geographers (IBG), London, UK.
Sept 2002	British Society of Soil Science (BSSS) and the Institute of Professional Soil Scientists (IPSS): Annual General Meeting, Seale Hayne, UK.
June 2002	Catchment Flood Management Plans (CFMP). Chartered Institute for Water and Environmental Management (CIWEM) and the Institute for Chartered Engineers (ICE), Exminster, UK.
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Thesis introduction (Part I)

1.1 Introduction

The research presented in this thesis encompasses 48 catchments and subcatchments distributed across the southwestern counties of Cornwall, Devon, Somerset and Dorset, and represents an investigation into the effects of agricultural land use on the hydrological functioning of rural land. Primarily, this study sets out to explore the relationship between the generation of peak flows and climate, spatial patterns of land use and physical catchment parameters.

To this end the project takes a multi-stage approach, combining field and laboratory soil testing with a Geographic Information System (GIS) and a suite of multivariate statistical techniques, to explore the impact of land use on fast response runoff across a range of spatial and temporal scales.

1.2 Research Context

During an era when the concept of sustainability is paramount in international political decisions, human impacts on natural systems are becoming increasingly manifest as extreme natural disasters. In the UK, perceived increases in the frequency and magnitude of flooding events have become the focus of mounting concern, attracting considerable publicity, particularly over the last five years.

> "A major flooding incident is one involving the flooding (fluvial or coastal) of a significant number of properties, or significant disruption to key parts of the country's infrastructure" (Environment Agency, 2001, p8).

A flood event may have severe socioeconomic repercussions that are compounded by the effects of high peak flows on the environment through soil erosion (Evans, 1990b), river sedimentation (Allan *et al*, 1997) and diffuse pollution (Dunn *et al*, 1998). Siltation processes and the erosion of channel beds and banks may significantly reduce ecological diversity and threaten the integrity of riverine and wetland habitats (Allan *et al*, 1997; Bhaduri *et al*, 2000; Halcrow, 2000b). Damage to property and the degradation of agricultural land and water quality incur substantial economic costs that are borne chiefly by local authorities, individual home owners and their insurance companies (Boardman, 1995).

River	Gauging station	Median annual maximum flood (m^3/s)	Date of peak	Peak flow (m^3/s)	Estimated return period (years)
Whiteadder	Hutton Castle	117	7/11/2000	285	15–20
Wharfe	Flint Mill	231	31/10/2000	415	20–35
Derwent	Buttercrambe	82	9/11/2000	172	60–80
Trent	Colwick	447	8/11/2000	1019	50–80
Mimram	Panshanger+	0.8	24/3/2001	1.97	>150
Thames	Kingston	308	7/11/2000	440	10
Lambourn	Shaw+	2.77	23/2/2001	6.14	80–120
Ewelme Bk	Ewelme≠	0.08	27/3/2001	0.202	100–150
Uck	Isfield	32.1	12/10/2000	113	80–120
Itchen	Allbrook	8.82	12/12/2000	22	>150
Taw	Umberleigh	219	30/10/2000	618	70–100
Severn	Bewdley	357	2/11/2000	556	20–30*
Meese	Tibberton	5.35	6/11/2000	9.6	40–50
Teifi	Glan Teifi	190	30/10/2000	310	5–10
Dee	Manley Hall	217	30/10/2000	467	30–50
Cree	Newton Stewart	225	25/10/2000	370	20–30
Enler	Comber	22.9	8/12/2000	60	>50

Pooled group analyses(10) used except in the case of the Mimram
*The corresponding peak level was the third highest in a series from 1921.
+Based on 5-day maxima
≠Based on highest daily mean flows

Table 1.1 Distribution of flooded rivers across England and Wales following autumn 2000 storms (Marsh and Dale, 2002, pg 182 and 184).

In 1998, flooding in the UK, including low lying areas of central Scotland and the English Midlands (Mance *et al*, 2002), caused the deaths of five people and over £350million worth of damage to property (Bye and Horner, 1998). In the autumn and winter of 2000-2001, the country experienced the wettest autumn for 270 years, which resulted in areas of southern England being affected by extensive and prolonged flooding (table 1.1). Flood waters inundated more than 10,000 homes and businesses and generated costs due to damages which have surmounted £1billion (ICE, 2001).

Major catchments, including the Severn, the Yorkshire Ouse and Medway, responded with a one in 100-year flow having been previously saturated by earlier October rainstorms (Holman *et al*, 2000). According to Marsh and Dale (2002) a large number of catchments across the southeast approached saturation two months earlier than the average for the preceding ten years. Studies undertaken by Robson (2002) and Marsh and Dale (2002), support a trend towards increasing peak flows over the last 30-50 years for many parts of the UK. Locally, flash flooding has become a regular problem affecting many communities in southwest England (Sonia Thurley, Environment Agency 2003, *pers comm.*), including the Boscastle in August 2004.

Flooding is not a modern-day phenomenon (Mance *et al*, 2002). However, a postulated increase in flood frequency and severity is a testament to human activities customarily placing vast pressures on natural resources. The potential effects of climate change on increased flood risk may be exacerbated by the incapacity of catchment, riparian and wetland systems to naturally buffer the impacts of episodes of extreme weather due to land cover changes such as urbanisation, deforestation and cultivation (Mance *et al*, 2002; Tollan, 2002).

It is widely acknowledged that urban areas play an important role in enhancing peak discharges as a result of increased runoff production and transport over impervious surfaces and through engineered drainage systems (Hollis, 1979). A comprehensive body of evidence also exists to support the supposition that in predominantly rural regions, agricultural land use changes, specifically enhanced grazing pressure, under drainage and intensive cultivation practices, have repeatedly led to soil compaction, reduced infiltration and groundwater recharge and rapid and excessive runoff (De Roo, 1993; Boardman, 1995; Evans, 1998; Holman *et al*, 2000; Fohrer *et al*, 2001; Mance *et al*, 2002; Tollan, 2002).

The estimated value of properties and agricultural land at risk from fluvial or tidal flooding in England and Wales presently exceeds £200billion. The cost of building and maintaining protective flood defenses equates to £400million (Defra, 2001). In the past, river managers have historically rejected a holistic approach to flood alleviation in favour of the control offered by traditional engineering techniques. Conventional approaches have been typically reactive and myopic in nature, involving the channelisation of lowland river corridors, designed to control the natural dynamics of fluvial systems (Newson, 1997). Through canalisation, channelisation and regulation, human impacts have extended on a huge scale to river morphology and have served to enhance the sensitivity and power of river discharges (Newson, 1997). Encouraged by the encroachment of development onto floodplains, technocentric approaches to river management have tended to concentrate on alleviating the local symptoms of flooding that are evident in particular reaches (Newson and Lewin, 1991).

Catchment systems are extremely complex and exhibit considerable spatial variability which is manifest at a range of scales (Blöschl and Sivapalan, 1995). The ubiquitous nature of patterns of variability in physiographic features and climate, within catchment systems and between them, creates huge differences between the response patterns of individual catchments. A poor appreciation of the scale and temporal and spatial heterogeneity of functional catchment processes has caused decision-makers to frequently underestimate the long-term variability of hydraulic systems and misjudge the off-site impacts of local flood prevention schemes on riparian habitats (Dollar, 2000). In many cases, there is an insufficient understanding of the principal causes of flood peaks, which may often originate in the high-energy environments of upland headwater areas (Dollar, 2000).

Historically, resources have been managed independently and simplistically in relation to agency-specific interests, due to a paucity of cross-disciplinary information and an inadequate understanding of terrestrial and aquatic systems (Stanford and Ward, 1992). By their nature, river systems are fundamentally variable. Piece-meal methodologies for river basin management may not fully appreciate the interdependencies among elements of the river basin.

More recently through expanded knowledge, the sustainable use and restoration of degraded systems has become a central feature on the agendas of decision-makers concerned with the future impacts of environmental change and the development of policy that fulfils the production and service requirements of the world's burgeoning population (Chapin *et al*, 1996). In conjunction to this, there has been an obvious shift in the philosophy and practice of ecosystem management. Narrow sectoral progammes are gradually being replaced by a more holistic approach that regards the river basin as a common conceptual and physical framework for interdisciplinary research and management. An integrative scientific approach is essential to the formation of realistic policy objectives that observe the general threshold levels of regionally variable river basin ecosystems (Naiman, 1992).

Over the last decade, water management in the UK has undergone a significant transition, from operating at a municipal level towards the widespread adoption of a catchment level approach (Williams, 2001). In a desire to embrace sustainability at a regional level, this evolution of policy practice has fostered an integrated approach to river management, involving a move away from exclusive reliance on structural flood alleviation measures and the promotion of a strategic approach to flood management (Tollan, 2002; Defra, 2004).

Integrated catchment management (ICM) aims to balance long-term ecological, economic and social sustainability with progressive environmental change by incorporating multi-sectoral interests into comprehensive management strategies (Van Zyl, 1995). In Europe, the proposed Water Framework Directive aims to encapsulate the core principles of ICM in international policy by demanding that all member states assign their land area to 'River Basin Districts' (RBD) (Williams, 2001).

The Water Framework Directive represents a significant driver for a fully integrated flood management strategy that is based on a greater recognition of the complexity and connectivity of hydrological processes operating across whole catchments. This is particularly fundamental given the current atmosphere of mounting international fears over the environmental impacts of global climate change.

1.3 Aims and Objectives

The damaging and wide-felt consequences of recent flooding events in the UK have highlighted the fact that there currently exists a national dearth of information relating to the catchment scale impacts of land use change on peak flows. The significant impacts that could potentially arise with the reoccurrence of large scale flooding in the future necessitates an enhanced scientific understanding of the effects of specific management decisions on the hydrological processes controlling peak flows. The latter is essential to the provision of evidence for the promotion of sustainable flood alleviation strategies as part of a holistic catchment management approach.

The management of environmental resources within a regional framework, such as the river basin, will facilitate the development of proactive flood alleviation strategies through multiple agency cooperation between public and private sectors and scientists that collectively, will help to aid interpretation and present a clearer picture of the natural processes operating within it (Burton, 1995). In terms of the level of EU water policy and regional water management implementation, it is vital that hydrological research efforts are targeted towards same-scale studies.

Hydrological theories and conceptualizations have been and are currently being developed at small scales in space and time (Sivapalan and Kalma, 1995). However, the extrapolation of small scale observations of non-linear processes including infiltration-excess overland flow and throughflow, to large scale natural systems such as the drainage basin, the level at which land management strategies are applied, carries with it a number of problems (Sivapalan and Kalma, 1995). The river basin represents the definitive unit of land for calculating water budgets, as means to quantify one element of the hydrological cycle through the exchanges that take place at the interface between the atmosphere and land (Newson, 1997). However, these estimations are associated with wide margins of error that advocate the adoption of smaller, plot-scale experiments (Newson, 1997).

The proposed project therefore employs a multi-scale approach to investigate the importance of climate, and surface and topographic catchment parameters, on hydrological response characteristics. Primarily, the thesis aims to elucidate the level of control that catchment scale patterns of land use exert on peak flow responses, and the nature and significance of land management impacts on smaller, field-scale hydrological processes in relation to local environmental conditions. Moreover, by encompassing both small and large spatial and temporal scales, the research presented aims to provide a better understanding of the effectiveness of adopting land use changes to reduce flood incidence by dampening peak flow responses, through specific land management options that enhance the movement of water into and through storages in the hillslope.

The following objectives were devised to address these aims:

Objective i: To investigate the factors influencing regional catchment responses to extreme storm events.

A GIS was developed to derive topographic features such as slope and channel network, and calculate soil, geology and land cover information for 48 catchments across southwest England. In addition to rainfall characteristics, catchment data were analysed using a suite of multivariate statistical techniques to identify the variables controlling the total volume of quickflow generated by catchments in response to the same four selected storm events.

Objective ii: To investigate the impacts of land use change on long-term hydrological response in the Camel catchment, north Cornwall.

Hydrometric and land use data for the River Camel catchment over the period 1965-2000, were investigated using spatial and temporal approaches to identify factors controlling trends in the hydrological response, namely increases in peak flows. The impacts of upland land uses were distinguished through a comparison of the Camel catchment with the De Lank headwater subcatchment.

Objective iii: To explore whether the effects of land management on soil hydrology can be identified by characterising the textural, structural and hydraulic properties of soils subject to different land management activities.

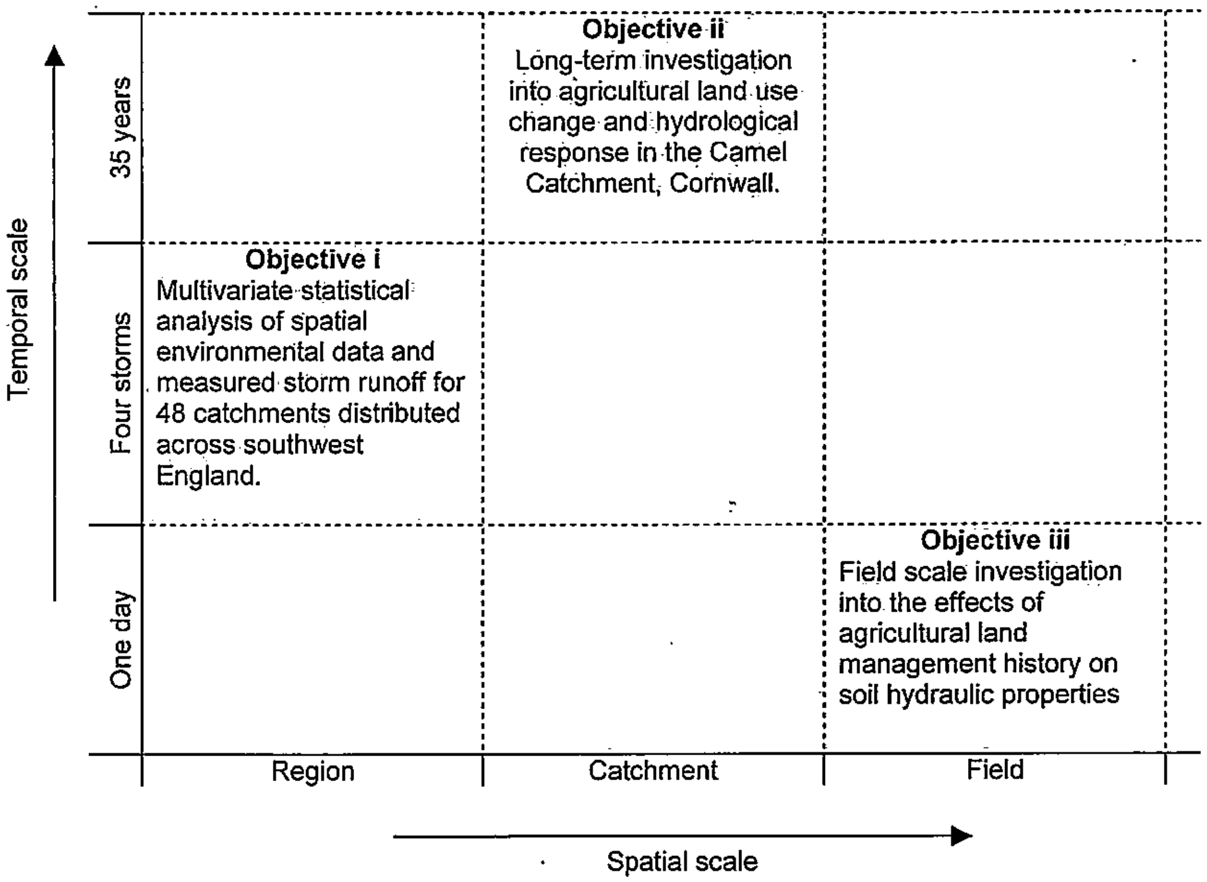
Field and laboratory testing was undertaken on surface and subsurface soils under four comparative land cover types, in order to investigate the influence of long-term (30 years) land management activities on the soil hydraulic processes controlling the generation of runoff.

1.4 Thesis structure

1.4.1 Introduction

This thesis adopted a multi-scale approach which explored both spatial and temporal trends in environment data to investigate the impacts of agricultural land use change on flood hydrology in catchments and subcatchments located across southwest England. Southwest England was selected as the study region due to the high interest generated from reported flooding in recent years that has been particularly prevalent in this area (Hall *et al*, 2005). Little research has been undertaken in this part of the country to try to establish the effects of rural land uses on peak flow responses.

The thesis structure was underpinned by three complementary investigations, directly relating to each of the three key objectives (section 1.3). These were undertaken at different spatial scales, encompassing regional, catchment and field spatial scales and timescales ranging from individual storm events to a 35-year hydrometric record. Details of the three-staged analysis are presented in figure 1.1.



Temporal scale	Region	Catchment	Field
35 years		**Objective ii** Long-term investigation into agricultural land use change and hydrological response in the Camel Catchment, Cornwall.	
Four storms	**Objective i** Multivariate statistical analysis of spatial environmental data and measured storm runoff for 48 catchments distributed across southwest England.		
One day			**Objective iii** Field scale investigation into the effects of agricultural land management history on soil hydraulic properties

Figure 1.1 The range of spatial and temporal scales encompassed in the three-stage methodological approach.

The thesis structure is divided into 5 parts (figure 1.2), each focusing on a specific element of the study and incorporating the three objectives of the methodology (figure 1.1):

PART I: Chapter 1 presents a general introduction to the subject area and provides wider contextual information relating to research and management of flood issues. It establishes the relevance of the thesis and defines the specific aims and objectives of the study. Chapter 2 reviews current understanding of the factors affecting hydrological processes and response at field, hillslope and catchment scales, including the impacts of climate and land use changes. In particular, chapter 2 presents and reviews literature that addresses the effects of changes in agricultural land use on hydrological processes.

PART II: Part 2 addresses objective 1 of the three-stage methodological approach (figure 1.1). In part 2, chapter 3 presents and reviews the techniques adopted firstly to parameterise 48 study catchments and secondly, to statistically analyse them. The environmental characteristics of the 48 catchments are subsequently described in chapter 4, whilst chapter 5 presents the results of a series of statistical analyses performed on the environmental data.

PART III: Part 3 refers to objective 2 of the investigation, a long-term study of the Camel catchment that was undertaken at an early stage of the investigation and published in the journal of Applied Geography (Sullivan *et al*, 2004). In view of the need to set this longer term discussion within the wider structure of the thesis, chapter 6 provides more comprehensive details of the characteristics of the River Camel catchment and sets the context for the methodology, results and discussion presented in the Applied Geography paper (Appendix I).

PART IV: Objective 3 of the methodological approach is addressed in part 4 (figure 1.1). Chapter 7 presents a field scale investigation of the textural, structural and hydraulic properties of soils subject to different 30-year histories of land management. The processes of site selection and field and laboratory testing are described and reviewed. The results are presented and discussed in relation to the effects of land use on soil hydrological properties and the usefulness of field techniques to improving knowledge of land management impacts on processes of runoff generation.

PART V: In the final part of the thesis, chapter 8 provides an overall discussion and synthesis of the results of all three objectives (parts 2-4). Key findings are reviewed in relation to contemporary research and understanding of the effects of land use change on peak flows at multiple scales. The potential for future land use changes and specific management options to dampen peak flows and alleviate flooding are assessed. Chapter 9 summarises the most salient findings from each stage in the investigation and makes recommendations for catchment flood management.

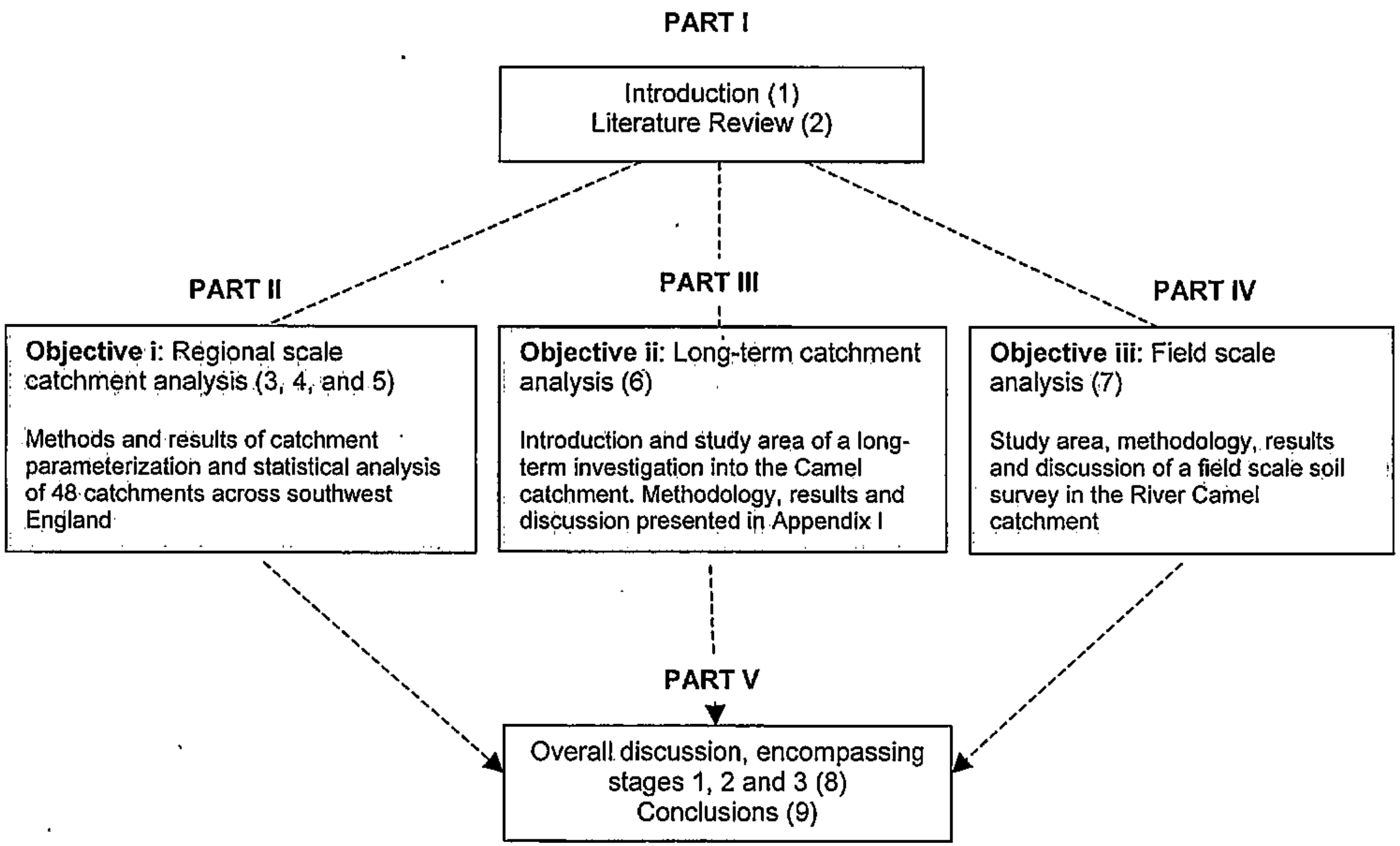


Figure 1.2 Overview of the thesis structure with chapter numbers between brackets.

Chapter 2

Factors affecting hydrological processes and response at field, hillslope and catchment scales (Part I)

2.1 Introduction

Such was the magnitude of the flood problem in autumn 2000, that it raised public, political and scientific awareness of the large-scale consequences of further increases in the frequency and magnitude of peak flows. It highlighted the urgency of improving knowledge of the significant system changes that drive these events. In response, the need for a sustainable solution to flooding has been publicly emphasised by the recent production by the Institute of Civil Engineers, of a report entitled 'Learning to live with rivers,' which joins together technical aspects of flood risk management with long-term solutions (ICE, 2001). Flooding represents the dynamic interplay of a range of interrelated environmental, economic and social conditions, and policy decisions, illustrated schematically in figure 2.1. Achieving a sustainable solution therefore requires that greater communication between policy-makers, hydrologists, planners, ecologists and engineers, goes hand in hand with a sufficient understanding of the key flood producing mechanisms operating within a catchment.

Endeavors to elucidate the principal variables governing peak flows, or the volume of quickflow produced in response to extreme rainfall events, are complicated by the complexity and unpredictability of hydrological systems. Catchments respond to rainfall in a variety of ways depending on numerous physical components, including drainage basin shape and density (Newson, 1997), geomorphology and terrain (Kirkby and Chorley, 1967; Grayson *et al*, 1997; Woods *et al*, 1997), soil characteristics (Horton, 1933) and vegetation cover or land use (Hollis, 1979; Robinson, 1990). Sullivan *et al* (2004) highlighted the inherent difficulties of attempting to disentangle the precise impacts of individual land uses on flood flows. This was compounded by a paucity of useful data on land use, physical catchment parameters and climate, at adequate spatial and temporal scales.

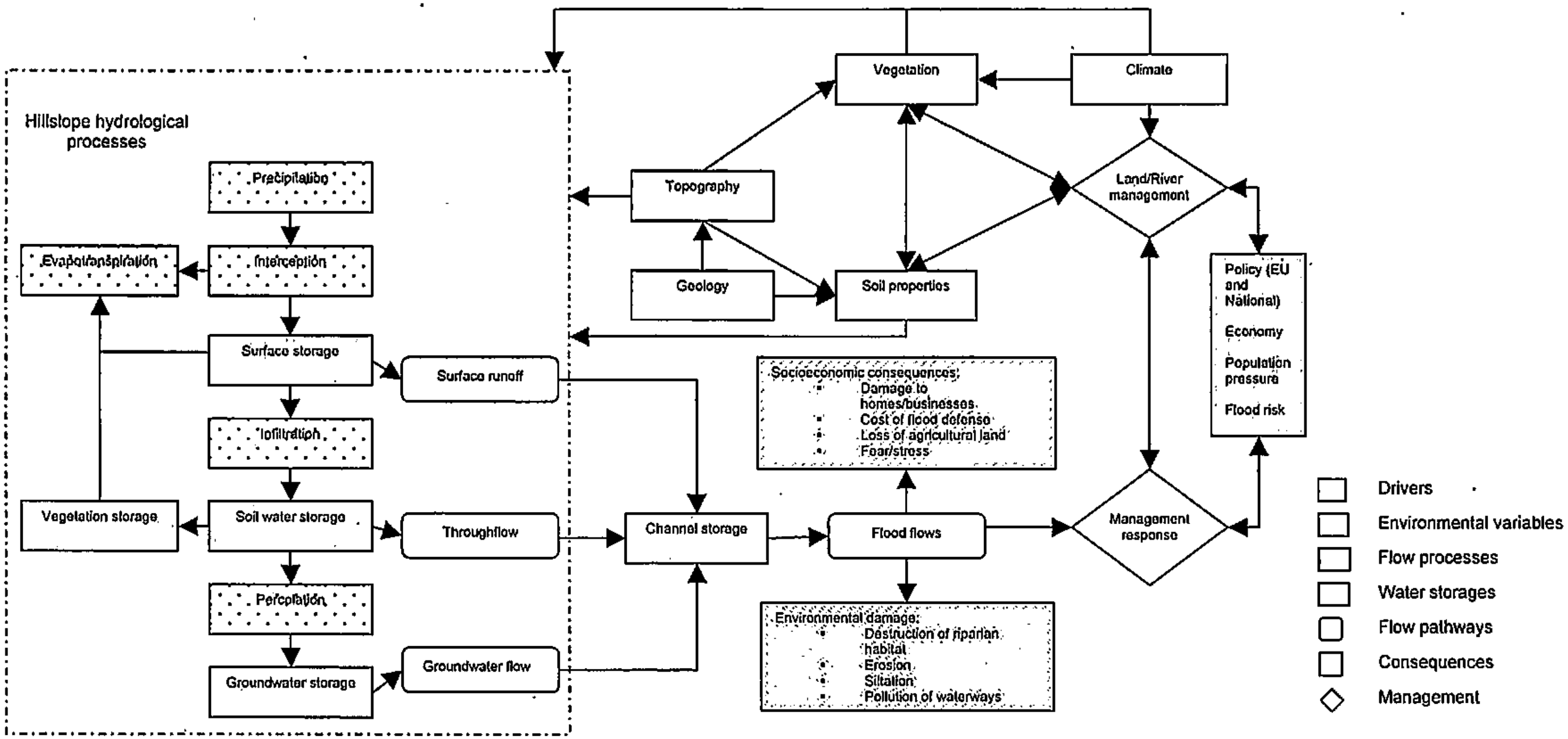


Figure 2.1 A schematic representation of the interplay between the social, economic and environmental factors associated with flooding.

Catchments are nested systems, the processes driving hydrological systems involve feedback mechanisms operating across a range of overlapping scales (figure 2.2). Hydrological processes are believed to span approximately eight orders of magnitude from local, hillslope, catchment and regional spatial scales through event, seasonal and long-term time-scales (Klemeš, 1983). For example, hydrological processes range from unsaturated flow in a 1 m soil profile to floods in a river system of a million kilometers squared, and from a surface runoff event that lasts second or minutes, to baseflow in an aquifer over hundreds of years (Blöschl and Sivapalan, 1995).

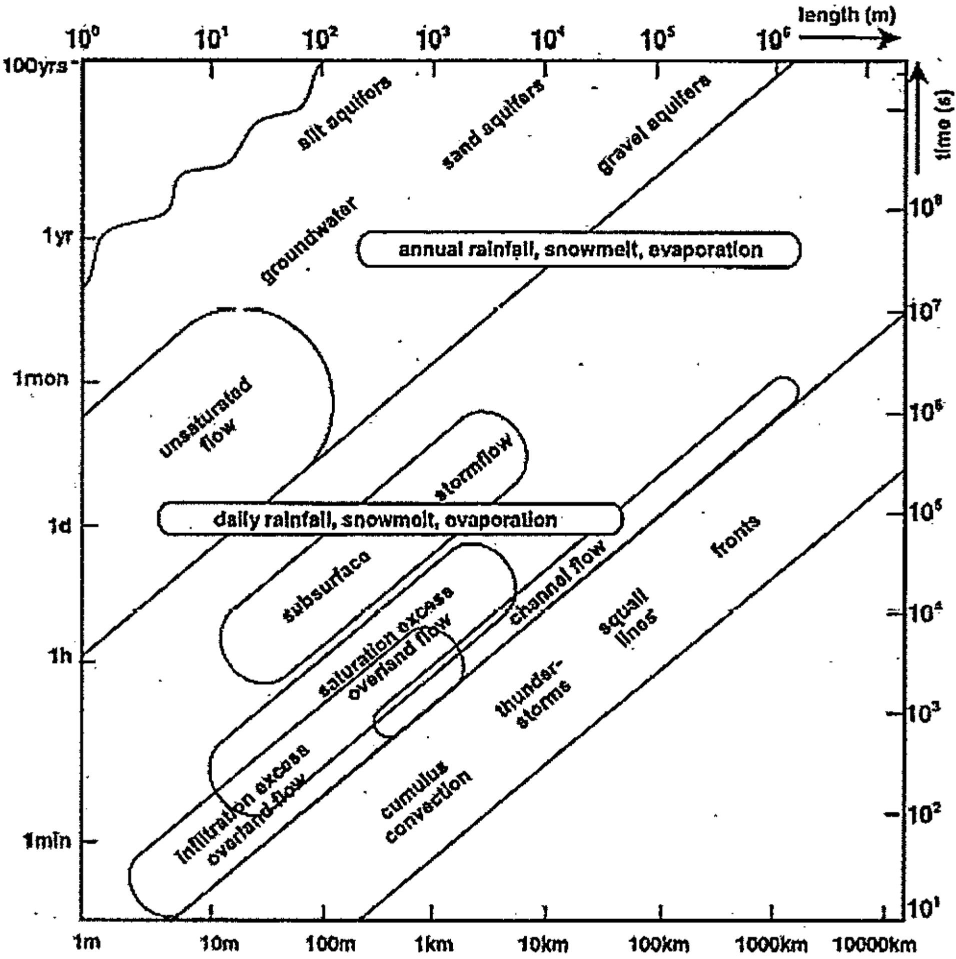


Figure 2.2 Space and time interrelationships of processes relevant in hydrology (Schulze, 2000, pg 192).

There is also often a variable time delay between the responses of many hydrological processes to precipitation, which is governed by the dominant runoff mechanism (Blöschl and Sivapalan, 1995). Infiltration-excess runoff will be faster (<30minutes) than saturation-excess runoff, as the latter requires an initial period for the development of a layer of saturation (Blöschl and Sivapalan, 1995). Subsurface flow or throughflow will be slower again, with a response time of approximately a day or so, whilst the response time of groundwater may range from months to hundreds of years (figure 2.2) (Anderson and Burt, 1990).

Integrated catchment behaviour, including lateral water flow, is contingent upon systematic behavior at the small scale (Robinson and Sivapalan, 1997). Runoff is therefore dependent upon both small and large-scale components of variable soil, vegetation, topography and rainfall parameters (Wood *et al*, 1988; Blöschl and Sivapalan, 1997). Given that the magnitude of land use effects will be dictated by the nature and scale of the land use change and is intimately linked to the climatic and physical characteristics of the catchment (Dunn and Mackay, 1995), establishing clear linkages between specific land use changes and changes to extreme hydrological responses at the catchment scale poses a formidable problem in hydrological studies.

This chapter provides an introduction to current understanding of the factors affecting the hydrological processes driving enhanced peak flows, and the role of land use on hydrological functioning at the level of the field, hillslope and catchment.

2.2 Climate change

The distribution and seasonality of river flooding is fundamentally symptomatic of variability in aspects of the regional climate (Newson and Lewin, 1991; Black and Werritty, 1997; Longfield and Macklin, 1999). Cyclonicity in the north and west and convection cell activity in the south and east are characteristics of the present climate which drive regional patterns of flood incidence (Newson and Lewin, 1991). Extreme peak flows are generally produced by winter frontal systems that yield regular, high magnitude, long duration storm events and by summer convective rainstorms that are typically high intensity and low frequency (Beven, 1993).

Against this background of extreme regional climate effects, policy-makers have become increasingly concerned about the possible implications of much larger-scale climatic changes on enhanced flood risk (Pielke, 1999). There has been growing support for the theory that climate changes over the twentieth century, due to the impacts of anthropogenically increased concentrations of greenhouse gases on global warming, have exerted a major influence on hydrological processes and regimes (Sansom, 1996).

Research undertaken in Australia (Smith, 1993), Britain (Beven, 1993) and the USA (Milly *et al*, 2002) strongly advocate that climate change is associated with marked changes in flood frequency and magnitude. Knox (1993) presents evidence from a 7,000 year geological record of over-bank floods for the Mississippi river, which demonstrates a high sensitivity of flood occurrence and magnitude to climatic changes over a time frame of several hundred years (Knox, 1993). Flow simulation studies by Reynard *et al* (2001) predict for the year 2050 that climate change scenarios will engender an increase in the frequency and severity of flooding events, in both the Thames and Severn rivers.

A review of relevant literature undertaken by Robson (2002) shows some grounds to suggest that the intensity and frequency of intense rainfall events has increased in many areas, including the UK (Easterling *et al*, 2000; Osborn *et al*, 2000). Nonetheless, following a statistical analysis of UK hydrometerological records, Robson (2002) maintained that there was insufficient evidence to substantiate a relationship between climate change and flood behaviour. Equally, the study was also unable to dismiss the possibility of a link between trends in climate and increased flooding (Robson, 2002).

The general consensus among climate change scenarios is that a warmer Britain will experience increased precipitation, particularly in winter (Arnell, 1990). Hence it is reasonable to assume that a postulated rise in storminess and flood producing rainfalls would make a warmer Britain increasingly prone to flooding, with a greater frequency and higher magnitude of extreme peak flows (Longfield and Macklin, 1999). However, as a result of the very coarse spatial and temporal scales involved in global circulation modeling, the projected consequences of a rise in greenhouse gases are often inconclusive and open to considerable scepticism (Arnell, 1990; Reynard *et al*, 2001). There is insufficient evidence to support a direct link between changes in climate with global warming and recent increases in the number of episodes of flooding, due to the paucity of flow records that encompass the huge timescales involved (Sefton and Boorman, 1997).

Scenarios derived from global circulation models are generally concerned with predicting mean flows and fail to adequately explore the repercussions of potential climate changes on peak discharges. Beven (1993) has warned of the uncertainties inherent in predicting the effects of global climate change on fluvial flooding. Such uncertainties are associated with the difficulties of attempting to disentangle the effects of climate change from the impacts of changes in land use, given that most climate change research has been undertaken on catchments that have previously been subject to extensive modification by man's actions.

The movement of global warming to the forefront of international political agenda and the centre of scientific research has encouraged the media and public to ascribe virtually all episodes of extreme weather to climate change (Pielke, 1999). The shortage of reliable long-term quantification of temperatures prevents the identification of a trend in regional rainfalls or flooding that can be attributed to global warming. Hence, it is essentially impossible to associate global warming to any single weather event (Peilke, 1999; Reynard *et al,* 2001). A preoccupation with global warming impacts on flooding carries with it a risk of devaluing the importance of additional complex flood producing mechanisms, such as land use change.

2:3 Land use change

An investigation into the relative impacts of climate change and land use change on the history of flooding and channel stability in the river Dee over the last 200 years was undertaken by McEwen (1989). The impacts of three major land use factors were found to be directly responsible for modifications to flooding and channel stability, including tree cover on the floodplain, abstraction for milling and the construction of flood embankments (McEwen (1989), in Newson and Lewin, 1991).

Results of catchment simulation modeling undertaken by Reynard *et al* (2001), suggested that best guess land use changes had little impact on flood response. However, a 50% increase in forest cover was shown to counteract the impact of climate change. Moreover, a large change in the urban cover of the catchments had a large impact on the frequency and magnitude of flooding, beyond the changes due to climate alone (Reynard *et al,* 2001).

Land use change represents another system disturbance which can influence many hydrological processes both directly, through the link with the evapotranspiration regime and indirectly, by impacting upon soil properties controlling the generation of runoff, such as infiltration and soil moisture (Dunn and Mackay 1995; Lahmer *et al*, 2001). The cumulative effects of progressive changes in land use within a catchment may profoundly change the volume and velocity of runoff and subsequent streamflow regime (Flemming, 2002).

Early hydrological studies in the UK, which first demonstrated the sensitivity of catchment responses to land cover change, were initially concerned with single land use functions including lowland urbanisation (Hollis, 1979), upland afforestation (Calder and Newson, 1979; Bosch and Hewlett, 1982 and Calder, 1986) and land drainage (Baily and Bree, 1981; Newson and Robinson, 1983; Robinson, 1990). Land use impacts on hydrological functioning are generally most pronounced at the small scale, such as the patch, field or hillslope (Tollan, 2002). At this level, field studies can identify the relative impacts of specific land uses, for example, impervious surfaces associated with urbanisation or the effects of compaction from over grazing, on runoff generation and localised flooding. At larger scales, the impact of land use changes have routinely been considered to exert a comparatively minor influence on flood responses, as a result of the compensating effects of complex water storage and release mechanisms (Fohrer *et al*, 2001).

In the absence of scientific 'proof' of catchment-scale land use change effects on peak flows, the speed and complexity of developments in resource use has not been matched by an adequate consideration of the consequences of these changes on the wider environment (Burt, 2001). It is only recently, with the threat of potential future increases in flooding, that greater attention is being paid to the roles of multiple catchment uses to the generation of downstream flooding.

2.4 Agricultural land use change

Integration into the European Union in 1973 brought about the phased replacement of UK agricultural policy with the productionist regulations of the Common Agricultural Policy (CAP) (Bowler, 2000). The CAP has exerted a massive influence on agricultural land use in the last 30 years. A succession of policy changes affecting 75% of the land area of the UK, translated into conspicuous shifts in farming practice and countryside management, which were made possible by modernisation and technological improvements (Robinson and Sutherland, 2002). Political devices such as capital incentives and taxation relief have engendered the formation of spatially distinctive changes in agriculture, namely specialisation by farm and by area, the regional concentration of farming units and dramatically enhanced levels of production (Lowe *et al*, 1994).

Regard for the importance of changes in agricultural land management in rural catchments and particularly, the cumulative impacts of intensive farming on flow processes started to become more widespread in the late 1970's and the 1980's and was borne primarily out of concerns for water quality and land degradation (Newson and Lewin, 1991). The enlargement of farming units, reduction in mixed farming enterprises, increased pesticide and fertilizer use, higher stocking densities and a dramatic decline in semi-natural habitat have imposed far-reaching consequences on numerous landscape functions, including nutrient cycling and species biodiversity; not least the character of the country's rivers (Newson, 1997; Jones and Essex, 1999; Fohrer *et al*, 2001).

The precise nature of the impacts of agricultural intensification on the active elements of hydrological systems is difficult to distinguish. The potential ramifications of land use changes in rural landscapes transcend scales in space and time. At regional and large catchment scales, catchment runoff and response may be determined by channel geomorphology and the nature and form of hydrological reservoirs. By increasing the density of ephemeral streams and enhancing surface water runoff through soil compaction, it is argued that recent changes in agricultural practices, namely the cultivation of winter cereals and the construction of drainage ditches, have exerted a major impact on streamflow in catchments across southwest England (L. Jenkins, Environment Agency 2003, *pers comm.*).

In smaller catchments, variability in soil and land use parameters and slope steepness, which organise patterns of soil moisture on the hillslope, may be more important than network response (Robinson and Sivapalan, 1997; Fitzjohn *et al*, 1998; Schulze, 2000). Land management may alter hydraulic characteristics of the hillslope, such as soil hydraulic conductivity, porosity and antecedent moisture, which determine sources of spatial or temporal variability in the nature and rate of runoff generation through various different flow routes (Fu and Chen, 2001).

At the field scale, a range of studies have documented the impact of agricultural land management practices on soil hydraulic processes, establishing a direct relationship between increased agricultural intensity and higher runoff rates (Reed, 1979; De Roo, 1993; Sansom, 1996; Fohrer *et al*, 2001; JNCC, 2002). Soil structural deterioration leading to surface crusting or reduced soil porosity and storage, has been shown to magnify the volume of fast response runoff, through infiltration-excess or saturation-excess mechanisms of overland flow generation (Beven and Wood, 1983; Burt and Butcher, 1985).

2.4.1 The effects of agricultural land management change on hydrological processes at the field scale

i. Infiltration-excess overland flow

The rate at which water moves vertically into the soil is closely controlled by the soil structure. A well structured soil will exhibit good internal drainage (De Roo, 1993). Agricultural developments have led to a widespread deterioration in soil structures, a process which favours soil sealing and crusting, and heightened runoff production due to reduced rates of infiltration (De Roo, 1993). Key land management activities, namely winter cereal production, are thought to have accelerated this process.

Soil exposure during vulnerable periods

Of the most prominent agricultural land use changes in the UK has been the substitution of spring sown cereals for autumn-sown 'winter cereals' in order to achieve maximum yields, together with an increase in the intensive production of late harvested crops such as maize, for use as animal fodder on dairy farms (Boardman and Favis-Mortlock, 1993; Boardman, 1995; Fohrer *et al*, 2001; JNCC, 2002). During the period 1939 to 1997, national yields of winter wheat increased by threefold and yields of barley and oats were more than doubled (Bowler, 2000; Robinson and Sutherland, 2002). Figure 2.3 shows patterns of changing arable production across the UK, over the period 1960-2000.

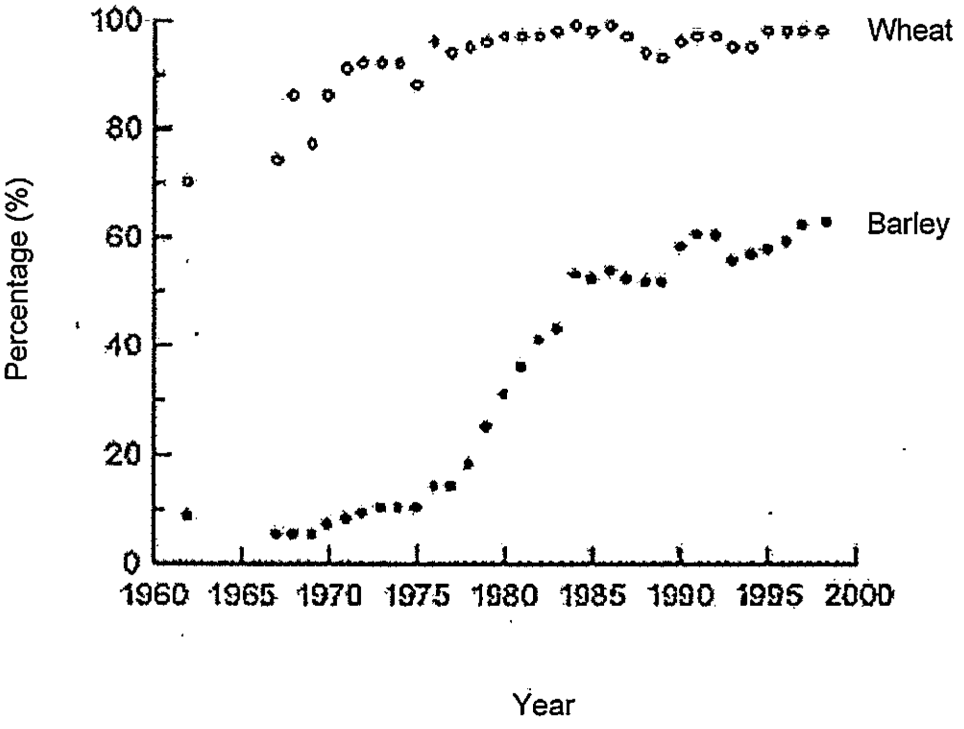


Figure 2.3 Changes in the proportion of total UK wheat and barley production, sown in winter between 1960 and 2000 (Robinson and Sutherland, 2002, pg 162).

It has been argued that infiltration-excess overland flow is generally less common than saturation-excess runoff and is restricted to steep slopes next to streams or impervious surfaces (Hewlett and Hibbert, 1967; Beven and Wood, 1983; Jordan 1994). However, there is evidence to suggest that in agricultural areas under arable management, infiltration-excess overland flow is the dominant process of runoff production. Torri *et al* (1999) have shown that even in dry antecedent conditions, raindrop impacts may considerably enhance surface runoff, as a result of the deleterious impacts of raindrop forces on rates of infiltration and hydraulic conductivity, through the development of surface seals and crusts, and the decay of soil microtopography (Tisdall and Oades, 1982; Slattery and Bryan, 1992; Slattery and Bryan, 1994).

The widespread production of winter cereals has been accountable for 40% of all water erosion in England and Wales (Evans, 1988) and 65% of erosion problems in Scotland (Spiers and Frost 1985). Accelerated erosion by water reduces the depth of topsoil, thereby removing nutrients and organic matter that are essential for maintaining crop yield and quality (Chow *et al*, 1990). Regionally runoff induced soil erosion has tended to concentrate in areas of eastern England where autumn-sown cereals have been grown in heavy textured soils and in wetter western areas, such as Gwent, Dorset and Herefordshire (Evans, 1988). By the late 1980's, many areas of the South Downs had greater than 60% of the landscape under cereals (Boardman, 1995). Considerable damage to properties resulted from soil erosion and serious flooding in this area that had been triggered by enhanced runoff from agricultural land under autumn-sown crops (Boardman, 1995).

Reduced soil organic matter

Organic matter acts as a binding agent which stabilizes soil aggregates and is important for maintaining soil structures (Curtis *et al*, 1976). Reductions in the organic matter content of soils can exert a major effect on infiltration rates by reducing soil resistance to surface sealing (Slattery and Bryan, 1994). Reduced infiltration is thought to have developed as a result of lowered levels of organic matter associated with a dependency on inorganic fertilizer with continued intensification and consequently, the reduced resistance of exposed soil surfaces to raindrop and rainsplash forces (Reed, 1979; JNCC, 2002).

ii. Saturation-excess overland flow

Saturation-excess overland flow is liable to arise in areas of the catchment where the water table is high, in areas of thinner soils, where soil storage is reduced, in topographic hollows at the base of slopes and on shallow slopes, since subsurface runoff is limited by a low hydraulic gradient (Kirkby and Chorley, 1967). Beven and German (1982) postulated that in saturated conditions water could move rapidly downslope through subsurface pathways due to the presence of well connected macropores, thereby bypassing slower flow pathways through smaller pores within the soil matrix.

Runoff generated through a saturation mechanism will be strongly related to antecedent soil moisture condition (Hoeg *et al*, 2000). At both the storm event and in the long term, soil moisture greatly influences the nature of a catchment response through its role in the separation of precipitation into infiltration and runoff (Grayson *et al*, 1997). Under conditions of limited soil water storage following prolonged, high frequency rainfall, the soil will quickly become saturated. Zones of saturation form source areas for saturation-excess overland flow and consequently, will generate surface water runoff with further rainfall (Burt and Butcher, 1985). Saturation-excess runoff may become an increasingly dominant control on streamflow in areas experiencing high frequency, long duration rainstorms. This is a result of the lateral expansion of contributing areas across the catchment with increasing wetness (Anderson and Burt, 1990).

Many workers have advocated enhanced runoff production in response to the impacts of agricultural practices on the soil characteristics controlling spatial patterns of soil moisture, including soil structure and vegetation cover (Meyles *et al*, 2003). Lowered soil porosity and reduced saturated hydraulic conductivity are typical with a breakdown of soil aggregates that can result from compaction. Combined with the effects of reduced soil permeability, a limited storage capacity heightens the potential for saturation-excess overland flow (Kirkby and Chorley, 1967). Boardman (1995), for example, observed erosion on fields sown to winter cereals initiated by low rainfall volumes of 30mm in 2 days at a rate of 0.6mmhr^{-1}.

Trampling by grazing animals

In the 1940's the numbers of sheep in the UK approximated to 12million, by 1996 this figure exceeded 43million (Sansom, 1996). Headage payments have encouraged farmers to increase stocking densities to a level which habitually transcends the carrying capacity of the farm (JNCC, 2002). Evans (1998) and Sansom (1996) have noted a significant increase in the frequency and volume of runoff and sediment yields from heavily grazed areas that are largely the result of alterations to patterns of soil moisture.

These changes can result from soil exposure and reduced rates of evapotranspiration that arise with a loss of vegetative cover, as well as poaching and compaction of the soil surface by animal hooves. Trampling destabilizes soil aggregates and gradually leads to the destruction of the soil structure. Increased soil bulk densities resulting from animal-induced compaction increases total runoff amounts and the number of runoff events, as a result of lowered soil surface porosity and storage (Owens *et al*, 1997; Meyles *et al*, 2003).

Soil compaction by machinery

Holman *et al* (2000) have demonstrated strong evidence for enhanced soil degradation in the UK as a result of cropping and management practices being undertaken during poor conditions. In support of the findings of de Roo (1993), the soil degradation reported by Holman *et al* (2000) was largely associated with the late harvesting of crops such as maize, sugar beet and main crop potatoes (Holman *et al*, 2000).

This practice is regularly undertaken when the soil moisture is often at or near field capacity and therefore less resistant to the compactive forces of farm machinery. As a result soils are often heavily compacted and rutted. Reed (1979) carried out an extensive study of water erosion at 600 sites in the West Midlands during the years 1967 to 1976. In over 95% of the cases, the extent of soil compaction by heavy farm machinery and down-slope drainage lines exacerbated problems of accelerated runoff and erosion (Reed, 1979). This process is often enhanced by intensive tillage practices and a notable decline in the time fields are left fallow.

The prevailing mechanism of runoff generation is not exclusive to specific land management practices. For example, soil surface compaction resulting from the trampling effects of grazing animals or farm machinery may also lead to runoff as a result of infiltration-excess overland flow. In addition, in any given situation it is possible that both mechanisms of saturation-excess and infiltration-excess overland flow may operate, but with a strong seasonal control.

2.4.2 The effects of agricultural land management change on hydrological processes at the hillslope and catchment scales

Horton's (1933) early model of infiltration-excess overland flow described runoff as a catchment-wide process, whereby every part of the river basin is thought to contribute to runoff during rainfall conditions of a critical intensity at which the infiltration capacity of the soil is exceeded (Newson, 1997). However, anthropogenic landscapes are similar to natural ones in the way that they exhibit considerable patchiness. This variability influences the types of processes that dominate and the rates at which they occur, and can result in complex, event dependent behaviour (Merz and Plate, 1997; Schulze, 2000).

Beston (1964) and Dunne and Black (1970) were among the first workers to observe the spatial heterogeneity inherent in runoff production and advocated that during any given storm event surface runoff would only be produced in parts of the catchment (Beven *et al*, 1988; Burt, 2001). According to Chorley (1978), these spatially distinct runoff producing zones, termed Partially Contributing Areas (PCA), control the overall volumes of runoff from the basin and by a saturation-excess rather than an infiltration-excess process (Newson, 1997). Rapid stormflow in a catchment is thought to be produced from transient areas at the base of slopes or adjacent to the stream (O'Loughlin, 1986). These source areas expand and contract seasonally and within individual storm events (Beven and Wood, 1983).

Throughflow is thought to be produced from saturated or near saturated variable contributing areas at the base of slopes (Hewlett and Hibbert, 1967; Hewlett, 1974; Burt and Butcher, 1985). Moreover, the presence of a low permeability or impermeable horizon at depth has been shown to limit the storage capacity of a soil profile and engender the development of a significant subsurface flow (Whipkey, 1965; Weyman, 1974; Burt *et al*, 1983; Anderson and Burt, 1990).

Partial area, saturation-excess runoff has been attributed by many contemporary workers to the organisation of spatial variations in soil moisture into topographically defined areas of saturation, or source areas (O'Loughlin, 1986; Grayson *et al*, 1997; Western *et al*, 1999). The nature of the partial organisation of soil moisture has three main aspects, which are fundamental to catchment hydrological response (Merz and Plate, 1997). These features comprise the continuity of source areas and the connectivity and convergence of flow paths or drainage lines, each of which influence the potential for and rate of water transfer to the channel.

Depending upon the prevailing climate conditions, the connectivity of defined flow paths can significantly enhance fast response runoff by enlarging the contributing area (Meyles *et al*, 2003). In dry periods, when evapotranspiration exceeds rainfall intensity, soil moisture exhibits little topographic organization and discontinuities exist in catchment hydrological pathways (Fitzjohn *et al*, 2002; Meyles *et al*, 2003). As maintained by Grayson *et al* (1997), under these conditions, the runoff which is produced is highly localized and water flows are dominated by vertical fluxes. The runoff is restricted to convergent areas governed by soil and terrain; there is no connection between a source and its upslope area (Grayson *et al*, 1997).

Alternatively, during periods of prolonged, heavy rainfall the catchment may become highly connected and subsurface and surface lateral flows predominate (Grayson *et al*, 1997). Soil moisture patterns become increasingly homogenous and are organized along topographically defined drainage lines. Hence, patches become interconnected and non-local runoff is able to contribute to streamflow (Grayson *et al*, 1997; Meyles *et al*, 2003). The impact of catchment connectivity on runoff will be contingent upon rainfall intensity in relation to hydraulic conductivity (Woolhieser *et al*, 1996; Merz and Plate, 1997).

According to Fitzjohn *et al* (1998), the connectivity and continuity of runoff producing areas is strongly dependent upon the wetness threshold of a catchment (Fitzjohn *et al*, 1998). The catchment wetness threshold is determined by various runoff-generating parameters, including rainfall intensity and soil hydraulic and physical characteristics such as infiltration capacity, hydraulic conductivity, soil structure, texture, and antecedent soil moisture (Fitzjohn *et al*, 2002).

Above a threshold value, also identified by Imeson *et al* (1992) and Meyles *et al* (2003), extensive saturation enhances the continuity and connectivity of hillslope pathways and storages and as a result, produces widespread runoff and erosion (Fitzjohn *et al*, 2002). Grayson *et al* (1997) have demonstrated a high degree of variability between discharges resulting from connected and disconnected patterns of antecedent soil moisture. Patterns of high connectivity have been shown to produce greater runoff in terms of peak flows and the total volume of discharge, for relatively small rainstorm events (Western *et al*, 2001). It is important to recognize the distribution of processes such as lateral, surface or subsurface flows, in relation to their degree of connectivity to the channel. Changes to streamflow regimes may not require large-scale, catchment-wide shifts in land management. By modifying flow pathways and spatial and temporal patterns of surface water runoff, intensive land uses may increase channel flow by enhancing the degree to which source areas become connected (Fitzjohn *et al*, 2002).

Specific agricultural management activities, such as cultivation during wet conditions and overgrazing, may play a major role in controlling the wetness thresholds that determine the connectivity of a catchment, due to the effects on interception and evapotranspiration rate, and on soil compaction and storage capacity. Such land management activities have the potential to considerably alter the hydrological attributes of the land surface by changing the hydraulic properties of the soil, causing a lowering of the wetness threshold of a catchment and a change to the distribution and continuity of areas with high soil moisture in relation to the channel.

Where infiltration-excess runoff operates, maximum rainfall intensities and soil infiltration characteristics can exert a profound bearing upon runoff coefficients of catchments (Kang *et al*, 2001). In this situation, regional climate characteristics, such as summer convective storms or winter frontal rainstorms, can form a key parameter governing patterns of streamflow and are especially important in areas with fine texture, low permeability soils, or soils with low organic matter that are susceptible to surface sealing or crusting, such as exposed arable soils (Tisdall and Oades, 1982; Martinez-Mena *et al*, 1998; Perrin *et al*, 2001). Lowered rates of infiltration in the presence of soil surface crusts, may also serve to enhance catchment connectivity. By discouraging spatial heterogeneity in soil properties, farmers may have improved the continuity of sources of runoff and heightened the potential for surface water to bypass hillslope storages, so preventing the reabsorption of water into the soil before reaching the river channel (Fitzjohn *et al*, 2002). Other farming changes, such as the removal of hedgerows or the installation of artificial drainages have been subtler in their effects on the connectivity of the landscape, but the result is no less important.

Hedgerow removal

The structure of the CAP has generated a proliferation of single-crop production enterprises, or monocultures, for example, cereals, oilseeds or potatoes (JNCC, 2002). Monocultures have no practical requirement for field boundaries and hedgerow removal allows better access for farm machinery (JNCC, 2002). Moreover, the Annual Area Payment Scheme introduced as part of the MacSharry Reforms in 1992, excludes wide field margins from area calculations and further promotes boundary removal (CEC, 2002). In 1996, a survey by the Countryside Commission estimated that approximately 22% of hedgerows in England and Wales had been lost between the years 1947 and 1985 (Whitby, 1994).

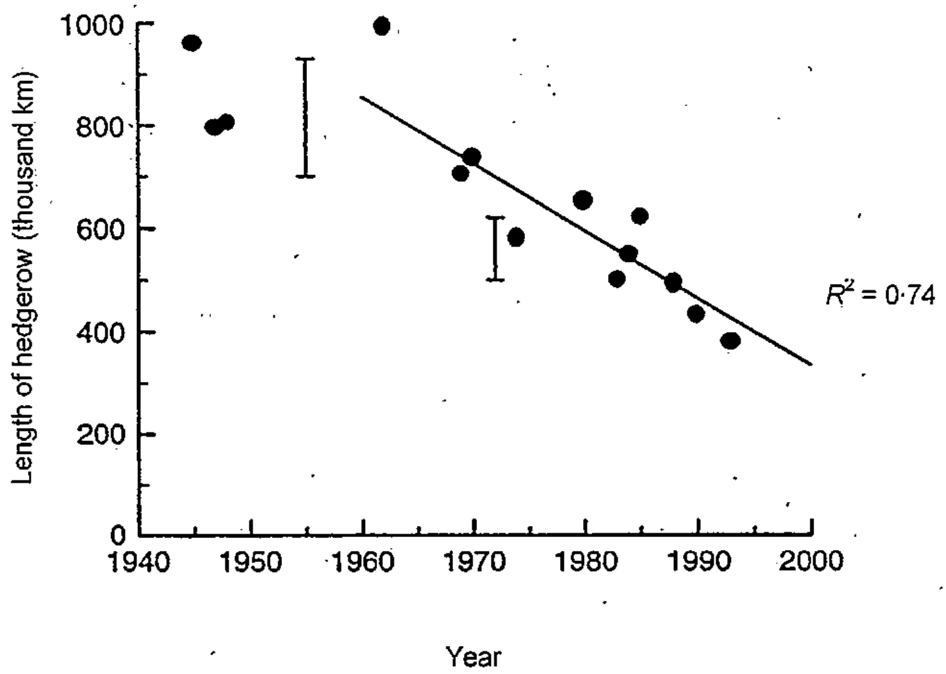


Figure 2.4 Estimates of hedgerow length in England and Wales; dots indicate mean estimates, bars represent ranges (Robinson and Sutherland, 2002, p162).

During the 1980's hedgerows suffered intensive management (Robinson and Sutherland, 2002). According to figures presented by Robinson and Sutherland (2002), average field size in Somerset and Dorset increased from 5.5 ha to 9.5 ha between 1945 and 1994. Figure 2.4 clearly illustrates the propensity for farmers across the UK to remove hedgerows over that time. The widespread removal of hedgerows and farm woodland to increase the area under tillage, together with an increase in the area of under drained land, has also affected catchment hydrology (Boardman and Favis-Mortlock, 1993). The elimination of hedgerow boundaries that lie cross-slope connects previously discrete components of the landscape (Evans, 1990b). The contributing area at the base of slopes is effectively increased, thus heightening the potential for downstream flooding

(Boardman, 1995). The development of large blocks of land with long, steep slopes under intensive agriculture, may have served to increase peak flows by reducing the potential for the infiltration of surface water and by enhancing the connectivity of hydrological reservoirs in the catchment (Blöschl and Sivapalan, 1997).

Increased under drainage

Stimulated by the high rates of grant under the governments mandate of agricultural support, the area of drained agricultural land rose considerably over the post war period (figure 2.5) (Robinson, 1990). In high rainfall regions, such as the southwest, field drainage is often required to increase the cultivation period. The effects of land drainage on river discharges have been widely debated and are comprehensively reviewed by Robinson (1990). It is commonly perceived that the installation of artificial drainage ditches will reduce peak flows by lowering the groundwater table enough to enhance the storage capacity of the soil (Tollan, 2002).

The impacts of drainage on streamflow response will vary locally, depending on the conditions of the soil, for example whether it is compacted or has a high clay content, and the location, distribution, and condition of the ditches within the catchment (Tollan, 2002). Drainage ditches can amplify peak flows by creating shorter flow paths, enhancing catchment drainage density and removing the storage capacity of former wetlands (Tollan, 2002). Surface water is transported directly to the channel via ephemeral streams which avoid natural obstacles and inhibit water flow and storage within the soil matrix (Howe *et al*, 1967; Robinson, 1990; Moussa *et al*, 2002).

Land use change impacts will be crucially dependent upon the scale of the disturbance and their location within the catchment. In addition to the connectivity and continuity of drainage lines, the complexity, distribution and disposition of different land uses may hugely influence catchment response (Schulze, 2000). Patterns of increased runoff and peak flows may be symptomatic of highly connected, localized runoff that is able to contribute to peak flows due to the disposition of source areas within the catchment, such as cultivated floodplain areas. For example, where intensive maize production is situated in flat, low lying areas adjacent to the channel, runoff from these slopes may have a dramatic effect upon river discharges as a result of their high degree of connectivity to the river and because these areas are prone to saturation.

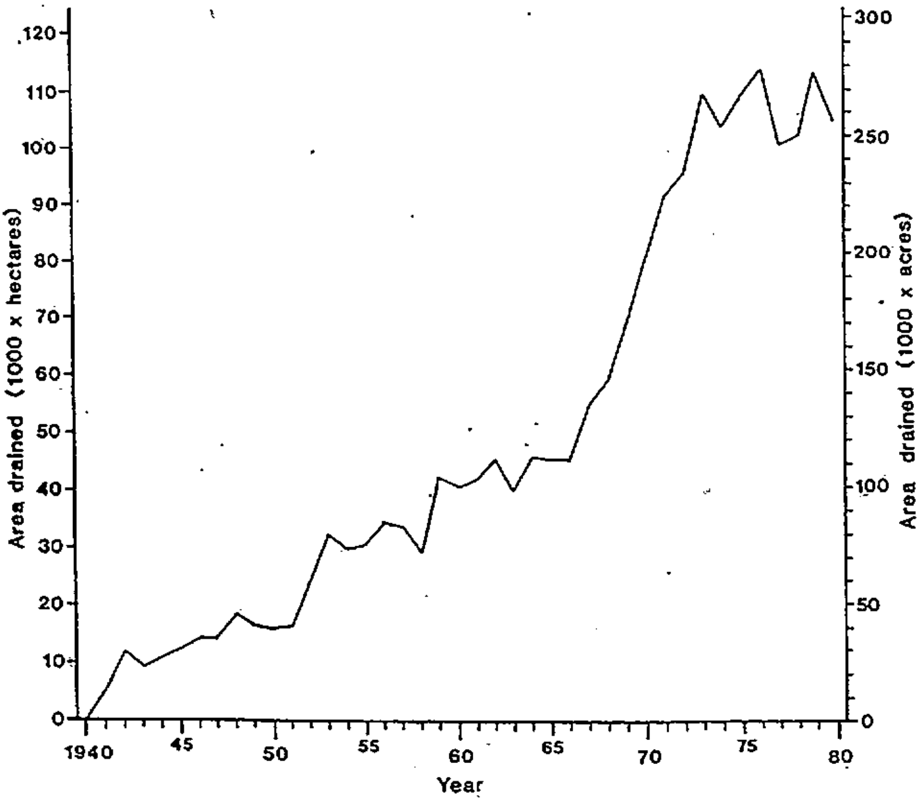


Figure 2.5: Increase in area of land with under drainage between 1940 and 1980 (Robinson, 1990; p16).

Summary

- This chapter has introduced and reviewed current understanding of the factors affecting peak hydrological responses at field, hillslope and catchment scales. It has highlighted the need for improved understanding of the role of climate changes (section 2.2) and changes in land use (section 2.3) on the processes controlling peak flow propagation.

- Section 2.4 discusses the extent to which shifts in agricultural policy since UK integration into the EU in 1973, have driven changes in farming practice. The CAP resulted in discrete changes in the management of the countryside, namely specialisation by farm and by area, the regional concentration of farming units and the intensification of production.

- At the field scale, many workers have identified an enhanced agricultural land management impact on the generation of runoff, as a result of soil structural deterioration leading to surface crusting or reduced soil porosity and storage (section 2.4.1).

- Section 2.4.2 introduces the difficulties of determining the influence of agricultural land management practices on the mechanisms governing hydrological response pathways at hillslope and catchment scales, due to the inherent spatial and temporal variability of catchment systems.

The following chapter details the methods used in Chapter 5, to statistically investigate the influence of spatial patterns of land management on peak flow responses at the catchment scale.

Chapter 3

Techniques of catchment characterisation and multivariate statistical analysis of spatial environmental data and measured storm runoff for 48 catchments distributed across southwest England (Part II).

3.1 Introduction

Chapter 3 describes and assesses the techniques employed to develop a multivariate database of catchment characteristics (chapter 4), and the methods employed for statistical analysis (chapter 5), to satisfy the first objective of this thesis (section 1.3);

'To investigate the factors influencing regional catchment responses to extreme storm events.'

This chapter details the processes through which hydrometric, environmental and spatial data were derived and collated. In order to achieve a satisfactory sample size for analysis of statistical significance, 48 watersheds were chosen. These were selected on the basis of available and complete rainfall and river flow data, and with the aim of establishing a diverse range of basin size, shape, topography, geology and soil type (section 4.2).

Trends and relationships between catchment environmental parameters and measured runoff characteristics (total volume of quickflow, peak discharge, time to peak) for the same four selected storm events were explored using a combination of univariate and multivariate statistical techniques, these are also reviewed here. Ordination and classification techniques, including principal components analysis (PCA) and cluster analysis, were employed to uncover relationships between environmental variables and to establish the significant factors driving observed environmental gradients. A suite of complimentary statistical techniques were used, including both indirect (detrended correspondence analysis (DCA)/PCA) and direct (redundancy analysis (RDA)) ordination methods, with the aim of refining the analysis and explaining patterns in measured runoff data from distributions in the environmental data.

3.2 Hydrometric characteristics

Tipping bucket rainfall (TBR) gauge data and 15-minute interval river discharge measurements for each catchment, for the period autumn-winter 2000-2001, were obtained from regional Environment Agency archives. This period was selected because it was recorded as the wettest autumn for 270years (ICE 2001). A computer programme was developed in Excel to convert TBR rainfall information into 15 minute totals. Data were screened for potential errors and inconsistencies. Daily and annual rainfall and discharge readings were compared in order to identify inaccurate readings or missing data due over bank river flows or poorly positioned or malfunctioning gauges. Information relating to the reliability of gauges was obtained from the Environment Agency. Four rain storms displaying the largest volume of rainfall per event over the winter period 2001-2002, were traced in each rainfall data set. These are presented below in order of decreasing magnitude:

- Storm 1: 07/10/2001
- Storm 2: 25/10/2001
- Storm 3: 25/01/2002
- Storm 4: 30/11/2001.

The ensuing river responses were characterised through hydrograph analysis of storm runoff.

3.2.1 Hydrograph separation

Characterisation of catchment runoff responses to the precipitation falling during the four selected storm events was fundamental to better understand the relative impacts of environmental parameters and land use changes on peak flows. Runoff is described as the proportion of rainfall over a catchment area which becomes streamflow (Weyman, 1975). Rainfall may contribute to streamflow either directly by falling on the open channel, or indirectly, as runoff that is produced on the hillslopes and is transported to the river outlet via the channel network (Beven, 2000). Several mechanisms for generating runoff at the hillslope have been identified and are reviewed in chapter 2 (Hewlett, 1974; Dunne, 1983).

The routing of rainwater as surface or subsurface runoff by hillslope processes is governed by topography, and soil and vegetation characteristics controlling infiltration capacity, which demonstrate tremendous heterogeneity at various scales in space and time (Gupta *et al*, 1986). During the course of a storm event, the nature of a streamflow response will be differentially influenced by runoff inputs from temporally variable runoff generating mechanisms that are spatially distributed across the catchment.

The complex nature of water movement within a catchment prevents hydrologists from replicating the intricacies of the processes which determine the stream response (Beven, 2000). The limitations of runoff measurement are such that in order to investigate spatially variable patterns of response and assess the potential consequences of hydrological change at the catchment scale, extrapolation from available rainfall and flow data must be undertaken (Beven, 2000).

Streamflow was characterised using three key parameters, including the total volume of quickflow, peak discharge and time to peak (figure 3.1).

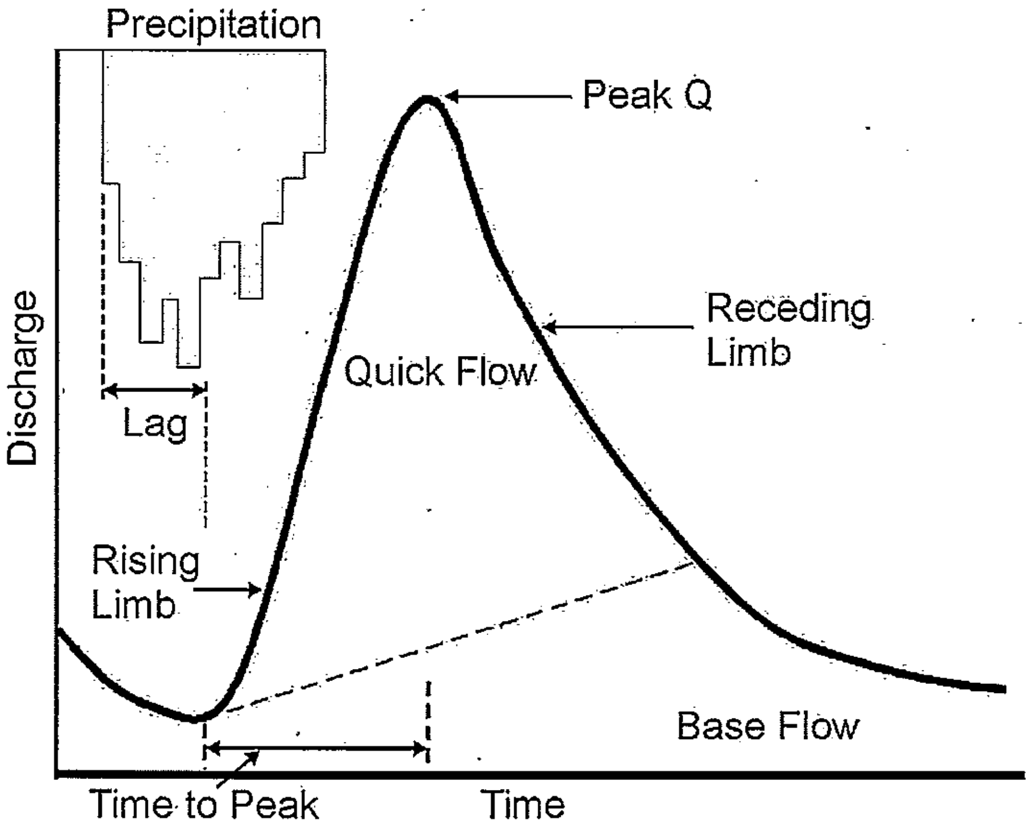


Figure 3.1 Key parameters of a flood hydrograph.

Peak discharge and time to peak were read directly from individual flood hydrographs, plotted for each catchment and the four individual events. A number of methods have been developed to identify the different stage relationships of the hydrograph components. For example, specific conductance has been used as an index for solute concentration to identify processes of water runoff (Anderson and Burt, 1990), whilst isotopic tracers including oxygen-18 (^{18}O), have been applied to investigate old water, new water concepts (Ward and Robinson, 1990; Beven, 2000). Due to the large number of analyses required in this thesis (48 catchments and four storms), hydrograph separation offered the only practical approach for estimating the total volume of quickflow produced by each catchment in response to the four storms.

The application of hydrograph separation techniques are well established in practical hydrology (Beven, 1991). The separation of hydrographs into stormflow and baseflow, or quickflow and delayed flow components has long been used to estimate the volume of direct runoff generated in a given storm event (figure 3.1). Traditionally, hydrograph analysis techniques have been applied in flood hydrograph studies with the assumption that it is possible to distinguish the various flow components on the basis that overland flow would be most rapid and arrive at the stream channel before throughflow, with groundwater exhibiting the slowest response rate (Ward and Robinson, 1990).

The majority of hydrograph separation techniques separate quickflow and baseflow by connecting the point at the initial break of slope when stream discharge begins to rise, to an arbitrarily predetermined part on the recession limb (Ward and Robinson, 1990). An array of hydrograph separation techniques have been developed, ranging from the simple method (Linsley *et al*, 1982), which involves drawing a straight horizontal line from the point at which the hydrograph begins to rise to its intersection with the recession limb (line 4, figure 3.2), to approaches based on catchment area and those which incorporate a given time interval following peak discharge. Linsley *et al* (1982) proposed an empirical equation to determine the inflection point,

$$N = A^{0.2}$$

Equation 3.1

where N is the number of days and A represents the drainage area in square miles (line 2, figure 3:2).

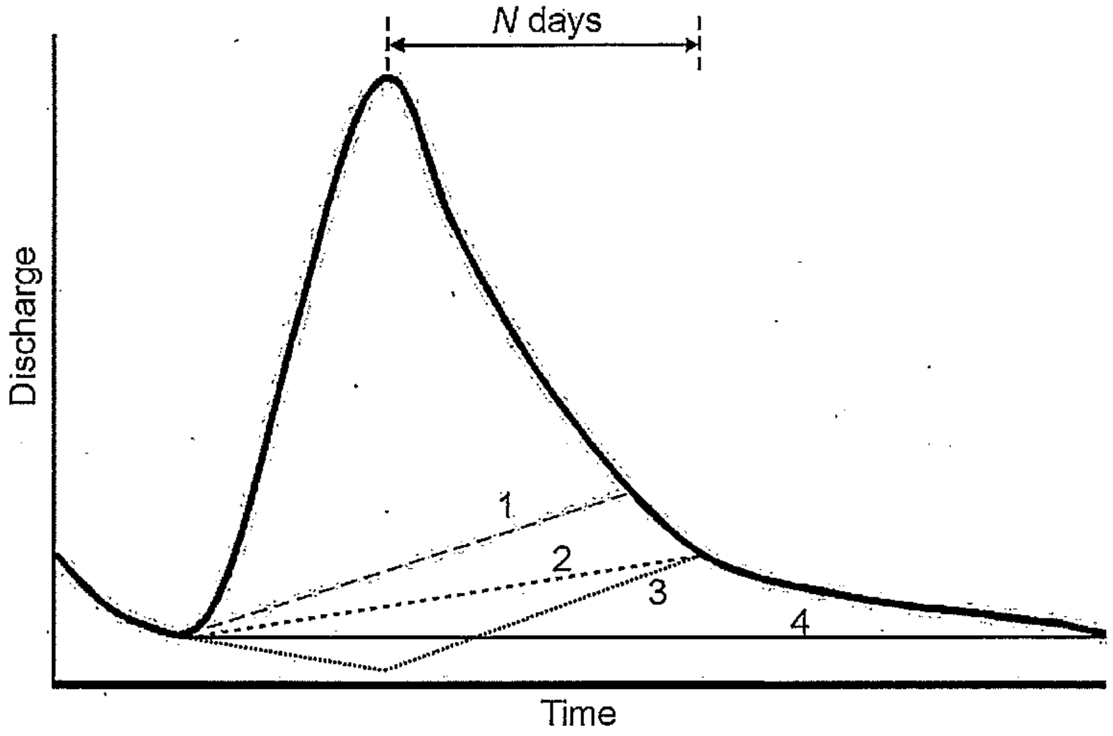


Figure 3.2 Four popular methods of hydrograph separation, where 1=Tani (1997), 2=Linsley *et al* (1982), 3=Local Minimum Method and 4=Simple Method (Ward and Robinson, 1990, pg236)

Linsley and Ackerman (1942) had previously advocated the importance of the area of the watershed as a function of the baseflow (Beven, 1991). Alternatively, the inflection point on the recession limb may simply comprise the point of the greatest curvature (line 1, figure 3.2) (Ward and Robinson, 1990). The inflection point can also be indicated by the point on the recession limb at which it is assumed to become exponential (Tani, 1997). This point represents baseflow under natural conditions. At the inflection point, the curve becomes fixed on a semi-logarithmic graph scale.

A widely used separation procedure is that put forward by Hewlett and Hibbert (1967), derived from work undertaken in small forested catchments in humid regions where a small amount of overland flow was expected (Hewlett and Hibbert, 1967). This technique separates quickflow from delayed flow by a line of constant slope, from the point of rise on the hydrograph, to where it intercepts on the falling limb. The baseflow during a storm is assumed to be increasing at a constant rate of 0.55 ls^{-1} km^{-2} hr^{-1} (Hewlett and Hibbert, 1967).

Hewlett and Hibbert (1967) chose this particular value as it was observed to be higher than the diurnal fluctuation of flow (Ward and Robinson, 1990). In addition, it provided a comparatively short time base to the largest single-peaked hydrographs in the study area and enabled large storms occurring within three days of each other to be treated as individual events (Ward and Robinson, 1990).

Such techniques have long been the subject of considerable discourse (Beven, 2000). Hewlett and Hibbert (1967) describe hydrograph separation as,

> "One of the most desperate techniques in use in hydrology."

Moreover, Beven (2000) has suggested that,

> "The only physically justifiable technique for hydrograph separation is to try to estimate the flow occurring if the storm had not happened."

The majority of methodologies currently available for hydrograph separation are to a large degree arbitrary (Beven, 2000). Interpreting the different physical elements of the response hydrograph often generates a large amount of contention owing to the inherent complexity of flow in natural catchments. The ambiguity lies predominantly in the synthetic sorting of the flow into either baseflow or stormflow components. Overland flow may reach the channel rapidly through both surface and subsurface pathways. In addition, baseflow may contain water which has travelled as throughflow through the soil profile and from deeper, groundwater sources (Ward and Robinson, 1990). The routing of water through variable flow pathways is very much interconnected and change in very non-linear fashions in relation to flow rates and antecedent conditions. Hence they are seldom detectable in the hydrograph trace (Hewlett and Hibbert, 1967; Beven, 2000).

Despite these inherent shortcomings, it was necessary to undertake separation of response hydrographs as a consistent tool for simple comparative analysis of the responses of 48 catchments. In support of this approach, Hewlett and Hibbert (1967) maintained the argument that,

> "since an arbitrary separation must be made in any single case, why not base the classification on a single arbitrary decision such as a fixed, universal method for separating hydrographs on all small watersheds?" (Hewlett and Hibbert, 1967, p280)

Using a 15-minute time step, the storm hydrograph was delineated for each of the four events and for each catchment. Hydrograph separation was undertaken for each hydrograph in order to quantify the total volume of quickflow generated following every storm event. The Hewlett and Hibbert (1967) hydrograph separation technique was initially tested on a small (16km^2) and large (323.7km^2) catchment from the study set. This technique was developed for small watersheds and thus worked well for the smaller catchment, predicting consistent quickflow volumes for consecutive storms. However, the upward gradient of 0.55 ls^{-1} km^{-2} hr^{-1} was found to provide an unnaturally steep baseflow curve for the large catchment and considerably underestimated the quickflow volume.

The technique proposed by Linsley *et al* (1982), which is also incorporated into the US Geological Surveys' (USGS) local minimum method (Pettyjohn *et al*, 1979), was subsequently tested. This method has also been termed the fixed base-length separation technique and assumes that surface runoff finishes a fixed time after the peak of the flood hydrograph (Linsley *et al*, 1982). Surface runoff duration following a precipitation event is calculated using equation 3.1, whereby the fixed time (N) after the peak is a function of basin area.

The baseflow before the start of surface runoff is projected ahead to the time of the peak (Linsley *et al*, 1982). Regression analysis was performed on declining baseflow values prior to the storm, against time. This provided the predicted y values as a trend line with points. The difference between two adjacent points is then used to predict the line forward to the point under the peak discharge. The gradient of the line is tested against the equation given following the automatic calculation of the trend line. A straight line is then drawn to the point on the recession limb N days after the peak (line 3, figure 3.2).

The application of this method to calculate the incline from the baseflow discharge under the peak provided a more realistic gradient for the large catchment. On the hydrographs for the smaller catchment, it gave only a slight deviation from previous quickflow volumes predicted using the Hewlett and Hibbert (1967) hydrograph separation technique. Based on these findings, the second method was employed to separate the baseflow component from the total volume of quickflow on event hydrographs for all 48 study catchments. The total volume of quickflow represented the area under the hydrograph curve, minus the baseflow component.

The fixed base-length separation technique is thought to provide the most consistent results in the analysis of many different floods (Schulz, 1973; Sinclair and Pitts, 1999). Arguably, by projecting forward the trend in baseflow to the hydrograph peak and incorporating basin area, this technique offers a more realistic prediction of process than other techniques that directly connect the point of the start of the response on the rising limb to the intersection on the recession limb (lines 1, 2 and 4, figure 3.2). Despite the large uncertainty that is inherent in all hydrograph separation techniques, the improved results that were obtained using this technique were considered to warrant the extra computational work involved.

3.2.2 Storm rainfall characteristics

Each rainfall event was characterised using three key parameters namely, the total volume of rainfall, and the average and maximum rainfall intensities. Rainfall intensity was calculated every 15 minutes for the duration of each storm. In many instances, the start of the storm event was unclear and difficult to determine relatively accurately. A consistent and much less subjective approach for establishing the beginning of each event was adopted. This involved calculating the average time period (hours) between the start of rain falling on a catchment and its corresponding streamflow response, indicated by a distinct rise on the hydrograph, for five randomly selected rainfall events per catchment. This average time taken (lag) for each catchment to respond to rainfall was then calculated backwards from the initial start of rise on the hydrograph, to provide the starting point of the event rainfall for the four selected storms (figure 3.1). The end of the rainfall event was artificially defined by the inflection point on the recession limb of the hydrograph.

Antecedent wetness influences catchment response by effecting soil storage capacity and time to saturation (Grayson *et al*, 1997). Antecedent precipitation indices are frequently used to provide an indication of the wetness condition of catchments (Linsley *et al*, 1982; Shaw 1997; Houghton-Carr, 1999; Meyles, 2002; Sullivan *et al*, 2004). In addition to the three rainfall parameters, a seven day antecedent precipitation index (API^7) was used to provide a crude estimation of the wetness condition of the study catchments prior to each storm event. API^7 was calculated from daily rainfall totals using equation 3.2 (Weyman, 1975; Houghton-Carr, 1999).

Characterising antecedent catchment wetness using API^7 does not incorporate the effects of potential evaporation, soil moisture or the physical characteristics of the basin. API^7 is a coarse, catchment-based parameter and does not characterise variability in catchment parameters over smaller spatial scales. Similarly, variability in rainfall that can occur over shorter timescales is not represented.

$$API^7 = \sum \frac{(P_t + P_{t+n} + P_{t+2n} \ldots\ldots P_{t+7n})}{t \quad t+n \quad t+2n \quad t+7n}$$

Where:

API^7= Antecedent Precipitation Index over seven days

P_t = precipitation on day t

n = number of days prior to the event

Equation 3.2

3.2.3 Hydrometric data limitations

Characterising the hydrometric parameters of a catchment based upon 'at-site' measurements of flow and rainfall data entail the simplification of natural processes (Davis *et al*, 1999). Point data conceals spatial and temporal variability in soil, topography and climate parameters, which differentially influence river discharge at various scales within the catchment (Jordan, 1994). The scaling up of research and aggregation of data to represent whole basins may artificially homogenize spatial variations or conceal patterns in processes that are manifest locally (Griffith *et al*, 1999). Large catchments may attenuate the intricacies and dynamics of local patterns of runoff production, which can become insensitive to changes in rainfall intensity that are recorded at individual gauges (Wood *et al*, 1988).

Storm energy and rainfall intensity may dissipate as a frontal system passes over the region. Storm runoff generation may vary considerably both along a slope length and between any two slopes in a catchment. Moreover the runoff generated from a single hillslope will be very different from the collective generation of runoff from a basin (Gupta *et al*, 1986). Hydrological theories that have been developed from small-scale empirical observations cannot simply be used to quantify or infer basin scale processes or relationships (Gupta *et al*, 1986). In addition, the quality of the flow gauge and positioning of a TBR gauge will be fundamentally important to the accuracy and reliability of the data. Hence, the identification and quantification of relationships at a level where predictions are required and management strategies applied will inevitably involve some degree of misrepresentation, assumptions and averaging out.

3.3 Parameterisation of catchment characteristics

Geographic Information Systems (GIS) are currently being used for managing and displaying spatially distributed catchment data (Grayson *et al*, 1993). As a result of the benefit of linking process-based distributed models with the spatial data representation capabilities of GIS systems, hydrological modelling over the last couple of decades has progressively introduced applications of GIS (Gurnell and Montgomery, 2000). These developments have coincided with an improvement in the availability and manipulation of high resolution digital elevation models (DEM) (Meijerink *et al*, 1993).

3.3.1 *Parameterisation of catchment topographic characteristics*

The processing of a DEM to delineate and measure terrain characteristics, such as slope gradient, drainage basin area and drainage network has been previously described in the literature (Goodchild *et al*, 1993; Maidment, 1993; Gurnell and Montgomery, 2000). A range of algorithms have been developed to provide automatic procedures with which the characteristics of a river basin may be extracted from the topological data contained within a DEM (Gurnell and Montgomery, 2000).

i. Slope

In order to characterise the steepness of slopes within study catchments and hence create a measure for assessing the role of topography in driving catchment responses to storm events, catchment slope factors were parameterised following the calculation of slope gradient (degrees) from DEMs (50m by 50m), using ESRI ArcGIS software (ESRI, 2004). DEMs were downloaded from Edina Digimap services in order to characterise the land surface terrain of each catchment (Edina Digimap, 2004). Slope consists of two components, namely gradient and maximum rate of change of altitude (Burrough and McDonnell, 1998). It is computed through the automatic investigation of the DEM matrix by means of a small window or 3x3 kernel of cells, which moves progressively across the map (Peuker and Douglas, 1985; Burrough and McDonnell, 1998).

Hodgson (1995) and Jones (1998) have both undertaken a review of the variety of methods currently available for estimating slope (Burrough and McDonnell, 1998). The key difference between the majority of slope algorithms is the number of grid cells used and the weightings assigned to each cell value (Jones (1998), in Burrough and McDonnell, 1998). A grid of slope can be generated simply by assigning each cell a value that is representative of the maximum downward gradient. This is referred to as the

Simple Method (Burrough and McDonnell, 1998) and was adopted in this thesis to provide a measure of the steepest gradient of each grid square on the DEM.

Using GIS, the number of grid squares in each catchment was calculated from the slope grid and a delineated catchment boundary map. This information was subsequently used to determine the average slope gradient of each catchment. In addition, the gradients of grid squares were subdivided into eight slope frequency classes (table 3.1) to provide a more detailed assessment of the steepness of catchments. These frequency class boundaries represented a normal distribution in the data.

1	No. of grid squares 0-6° steep
2	No. of grid squares 7-12° steep
3	No. of grid squares 13-18° steep
4	No. of grid squares 19-24° steep
5	No. of grid squares 25-30° steep
6	No. of grid squares 31-35° steep
7	No. of grid squares 36-40° steep
8	No. of grid squares 41-45° steep

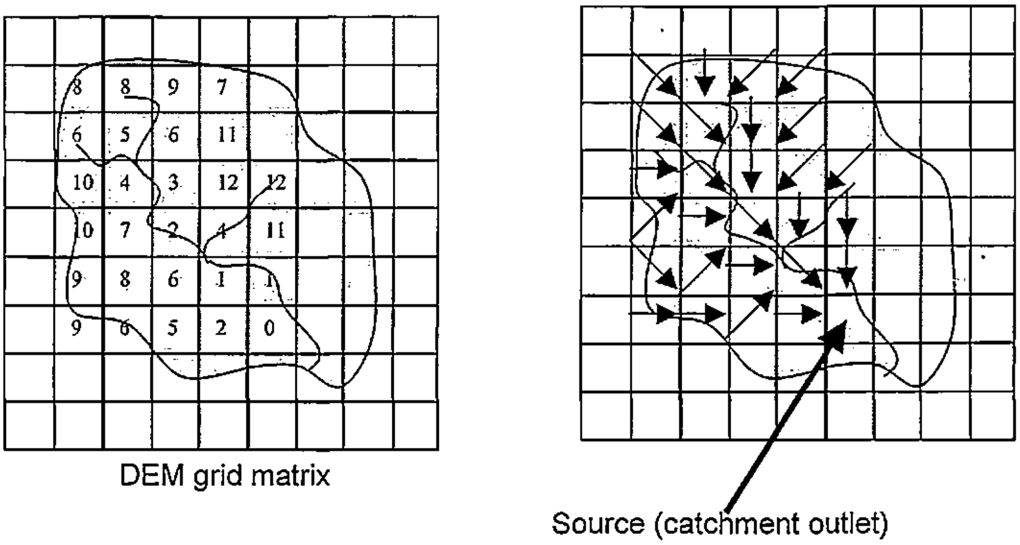
Table 3.1 Eight slope frequency classes used to characterise catchment steepness.

ii. Delineation of catchment hydraulic characteristics using GIS

Drainage basin area and the length and density of drainage channels, exert a fundamental influence on the response of catchments to storm events. A land surface DEM has become essential for the detection and delineation of watershed boundaries and the stream network. The flow direction concept represents the direction of outflow from a cell (Marks *et al*, 1984; Jenson and Domingue, 1988). The simplest algorithm available for identifying the direction of flow of water over a gridded surface is one which allows water to flow from each grid cell to one of four neighbouring cells. Each cell in the new grid of flow direction has a direction which represents the direction of steepest downward decent from the choice of cells (Maidment, 1993).

Peuker and Douglas (1985) implemented the first method to delineate the drainage network using a kernel of four adjacent cells and located river channels and ridge points by identifying convex and concave configurations (Broder and Sperling, 1993; Maidment, 1993). A fundamental flaw associated with this technique is that it is only capable of generating discontinuous networks and thus requires some degree of post-processing in order to manually complete the network (Broder and Sperling, 1993). In addition, the method is limited when applied to surfaces with complex morphologies and low resolution DEMs.

An algorithm which estimates the direction of flow using the direction of steepest slope but with a 3x3 cell window is the D8 deterministic method (Burrough and McDonnell, 1998). Water on a grid is able to flow to any one of eight adjoining cells. Consequently, flow direction becomes automatically separated into 45° units (figure 3.3) (Burrough and McDonnell, 1998).



DEM grid matrix

Source (catchment outlet)

Figure 3.3 Calculation of flow direction based on the steepest downward slope algorithm.

This procedure was adopted to create a grid of FLOWDIRECTION that was necessary for delineation of watershed boundaries and drainage networks for each catchment flow gauge, or source areas (Eastman, 1999) (figure 3.4). The creation of a watershed boundary and stream network was accomplished by calculation of the flow accumulation from the flow direction matrix. This involves computing the number of upstream cells from which runoff flows through each downstream cell (Maidment, 1993). This is effectively, a simulation of the contributing area for every cell in the network. Rows of cells which have no other cells flowing through them comprise watershed divides (Maidment, 1993).

Stream channels were denoted by lines of cells which exceeded a threshold contributing area, or through which flowed greater than a threshold number of upstream cells (Maidment, 1993). A threshold was determined on the basis of a comparison between automatically and cartographically produced stream networks. Blue lines, representing stream channels on Ordnance Survey (OS) maps were compared on screen by overlaying the scanned OS map on top of the grid of FLOWACCUMULATION. A threshold level was applied which facilitated delineation of unmapped, topographically defined channels that were likely flow during a storm event. A grid of stream network was created following application of the threshold to the results of the FLOWACCUMULATION. For each catchment, the final FLOWACCUMULATION grid was clipped using the catchment boundary map and the total stream length determined from the grid summary statistics.

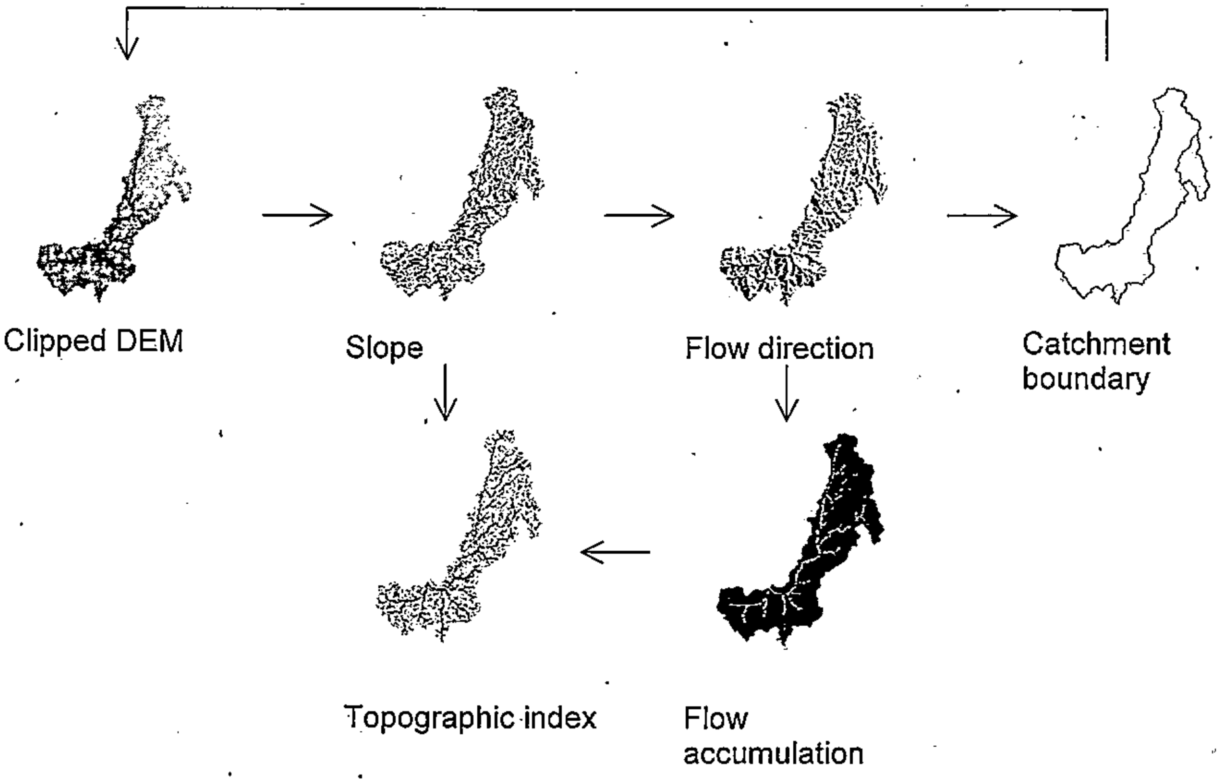


Figure 3.4 GIS procedure for the calculation of catchment parameters from a DEM.

The flow accumulation matrix can form an important tool for more complex hydrological interpretations and modelling. In addition to terrain, the estimation of flows of water over a landscape is contingent upon spatial variability in soil moisture. Beven *et al* (1984) integrated flow accumulation into an index of catchment wetness, or a topographic index, $\ln (a/\tan \beta)$, where A is the upslope contributing area as determined from the DEM at any location and β is the slope at that location (Meijerink *et al*, 1993). Characterisation of spatial soil moisture patterns, represented by the number of grid squares within catchments that were prone to saturation or exhibited a higher wetness index, was undertaken by applying the topographic index (TI) algorithm of Beven *et al* (1984) to grids of SLOPE and FLOWACCUMULATION (figure 3.4). The topographic indices of grid cells were classified according to five frequency classes (table 3.2) to distinguish the extent of areas with higher or lower risk of saturation within catchments, whereby a TI of 30 represented the highest risk of saturation.

1	No. of grid squares TI 0-10
2	No. of grid squares TI 11-15
3	No. of grid squares TI 16-20
4	No. of grid squares TI 21-25
5	No. of grid squares TI 26-30

Table 3.2 Five topographic index frequency classes used to characterise catchment wetness.

a) Sink areas

When working with grids it is imperative that the DEM is error-free. Some cells in a raster will frequently become surrounded by cells having higher elevations (Burrough and McDonnell, 1998). These depressions are termed pits or sinks (ESRI, 2004). Mark (1988) and Jenson and Domingue (1988) have both claimed that pits are commonly the symptom of data errors, or artefacts, in the DEM matrix. Artefact pits are generated at all levels of resolution, often where the width of narrow valley bottoms is smaller than the cell size (Burrough and McDonnell, 1998). Chorowicz *et al* (1992) and Martz and De Jong (1988) argue that pits are not simply data errors but in addition, may comprise real features of the topography and should therefore be treated as ponds or reservoirs. However, pits disrupt the drainage topology and it is important that hydrological processing is undertaken using a depressionless DEM.

DEMs incorporated into the GIS in this thesis were first corrected to create depressionless grids of terrain. Sinks were identified and filled automatically using an iterative process in ArcGIS, which involved raising the elevation of the sink cell to equal the elevation of one or more adjacent cells (Burrough and McDonnell, 1998). Adjacent cells were hydrologically linked with another cell (Burrough and McDonnell, 1998).

b) Drainage density

Catchment drainage density strongly influences the time taken for water to reach a given point on a stream (Gordan *et al*, 1992). For example, a catchment with a well developed drainage system will exhibit a shorter time of concentration, than one containing a greater number of surface depression storages (Petts and Foster, 1985). Drainage density (R_D) was calculated for each catchment using total stream length (ΣL) and drainage basin area (A), in equation 3.3.

$$R_D = \frac{\Sigma L}{A}$$

(after Gordan *et al*, 1992, pg 107)

Equation 3.3

c) Limitations

DEMs will inevitably contain errors that are particularly related to the differentiation of specific landforms. Slope steepness and length characteristics are assumed to be constant across each cell (Meijerink *et al*, 1993). The DEM is unable to accurately depict variable elevations over shorter distances. Natural channel width may vary over the course of a stream. However, in a DEM-derived stream network the channel width is consistently one cell wide (Burrough and McDonnell, 1998). In situations where wide channel floodplains are present, cells sharing the same elevation may occur adjacent to each other. The direction of flow or channel network may be incorrectly simulated over this area of the catchment. Likewise, cell size will also affect estimates of watershed boundaries. Hence, for practical reasons, the resolution of a DEM cannot be too small (Meijerink *et al*, 1993).

Automatic derivation of the drainage network also has a number of problems associated with it. Firstly, determining a threshold flow accumulation for determination of stream network using OS data, assumes that a blue line on a map represents a channel. Due to time and resource constraints the thesis was unable to incorporate the ground-truthing required to validate this assumption. Moreover, channel shape and length is a dynamic geomorphological feature, the approach adopted could not accurately replicate natural temporal variability in channel form. Errors in the delineation of the stream network will subsequently affect calculation of catchment drainage density.

The modelling of dispersion and diffusion is decidedly problematic (Burrough and McDonnell, 1998). Flow modelling using any of these techniques is limited by the fact that in reality, water draining a catchment will flow stochastically in any downward direction (Maidment, 1993). Burrough and McDonnell (1998) point out that flow accumulation assumes simple gravity-driven processes and fails to take account of the measured response of some water flow through subsurface pathways that need to be dealt with using kinematic wave equations. Without a basic understanding of the dominant flow processes in a given management situation, it is highly possible that the assumption that all flow processes are topographically driven, will result in an unjustified confidence in the model output and significant misinterpretation of the results (Grayson *et al*, 1993).

iii. Soils

Soil type exerts a major influence on river hydrology. However, analysing the hydrological influence of soils at the catchment scale is made difficult by the fact that soil classification systems generally do not directly relate to soil hydrological properties (Dunn and Lily, 2000). In the UK, the Hydrology of soil types (HOST) system (Boorman *et al*, 1995) represents a classification of all soil types delineated on the 1:250 000 scale soil map according to their hydrological response. The HOST classification was developed using pedotransfer rules and functions to derive a set of semi-quantified soil attributes from existing soil morphological information, as surrogates for the missing hydraulic data (Lilly *et al*, 1998). All soil types are grouped into one of 29 classes on the basis of soil attributes and the dominant pathways of water movement through the soil and substrate (Boorman *et al*, 1995; Maréchal and Holman, 2005).

Eleven conceptual hydrological response models describe the pattern of flow through the soil. This is dependent upon the presence of slowly permeable layers that restrict the downward movement of water and by seasonal saturation within the soil profile (Dunn and Lily, 2000). The eleven response models are allocated to one of three physical settings relating to the presence and likely depth to groundwater, including groundwater present at a depth greater than 2m, a shallow water table generally within 2m and no significant groundwater, or aquifer. Finally, some of the response models are sub-divided according to the rate of response and the water storage within the soil profile (Maréchal and Holman, 2005), resulting in a 29-class system (Boorman *et al*, 1995).

HOST has wide application in hydrological studies (Boorman *et al*, 1995; Lilly *et al*, 1998; Maréchal and Holman, 2005). Boorman *et al* (1995) for example, demonstrated how the HOST classification could be used to derive hydrological catchment indices, using multiple linear regression performed between the proportion of each hydrological response model in each catchment and the catchment's Base Flow Index (BFI) and Standard Percentage Runoff (SPR), for a range of UK catchments. BFI is the long-term average proportion of flow that comes from stored sources and SPR is the percentage runoff derived from event data (Maréchal and Holman, 2005). The coefficients derived from these analyses provide a methodology for calculating BFI and SPR for ungauged catchments using the distribution of HOST classes within them. HOST can readily be incorporated into a GIS framework, for example Dunn and Lily (2000).

Distributed digital data on soils was required for investigation of the effects of soil type on streamflow responses to storm events at the catchment scale. However, characterising the soil types of all 48 study catchments was not possible through field experimentation or examination of paper soil maps. Using the 1:250 000 scale soil map, the hydrological characteristics of the soil types distributed within each of the study catchments, was determined by applying the HOST classification system (Boorman *et. al*, 1995). Soil maps were scanned, registered and rectified using ArcTools GIS software (ESRI, 2004) and soil series boundaries digitised using on-screen digitising methods in ArcMap editor. Manual derivation of the HOST classes was undertaken using the procedure outlined in the Flood Estimation Handbook (FEH) (Houghton-Carr, 1999). The result was a digital polygon vector coverage of soil HOST classes, distributed across each catchment.

Fundamentally, the HOST classification is based on assumptions about soil hydrological functioning. It involves the grouping together of soils that are expected to share similar flow paths and hydrological mechanisms (Dunn and Lily, 2000). In reality, it is likely that there is huge variability between the properties of soils within the different groups. In addition to the assumptions inherent in the HOST system, the method and application of HOST in this study is limited by errors that can be introduced during the processes of registering and rectifying. Images can become distorted as a result of several factors, including differences in the scale of the image and the base coverage, the quality of the image and the inaccuracies associated with onscreen digitising methods.

iv. Geology

Geology affects streamflow response through the influence of the porosity and permeability of bedrock on the movement and storage of water as groundwater, and through its influence on overlying soil properties such as texture. Representing the hydrology of the underlying geology and substrate of study catchments was very difficult due to the paucity of available data. Unlike soil data, which were represented in terms of their modelled hydrological behaviour through the HOST classification, an equivalent classification of rock types according to their hydrological characteristics was not available. Hence, the extent of different geology classes underlying study catchments was determined following GIS analysis of digital geology maps obtained from Geological Survey (British Geological Survey, 2004). Bedrock types were categorised into 14 sub-groups on the basis of broadly similar permeability and porosity characteristics, in order to refine the number of parameters (M. Gipson, University of Plymouth 2004, *pers comm.*). Limited information on substrates was incorporated within the HOST classification of soil types. The nature of the datasets prevents a direct comparison between catchment soil and geology characteristics.

v. Land Use

In order to assess the hydrological impacts of land use on catchment response, characterisation of the land cover of each catchment was essential. Digital land use data derived from processing and classification of satellite imagery was acquired from the Land Cover Map 2000 data set (LCM2000), which is held at the Centre of Ecology and Hydrology (CEH) (Fuller *et al*, 1994). The LCM2000 data represent information collated from 80 satellites that has been used to create a vector data base of the whole of the UK, and displays areas of different land uses as polygons or parcels of land (Fuller *et al*, 1994). Sixteen land cover types with 27 subclasses have been identified through the automatic grouping of image pixels, or cells, on a 25mx25m grid before undergoing vectorisation. Pixels traversing more than one land cover type were classified according to the dominant cover. LCM2000 data are compatible with broad-ranging contextual catchment data on terrain, soils and geology that are also incorporated in this study.

LCM2000 data have been calibrated using field maps on broad habitats collected during the extensive Countryside Survey 2000 (CS2000) for 1km squares. The field data are not ground truth but used solely for the process of intercalibration. The accuracy of the data has undergone testing through the construction of correspondence matrices, which demonstrated a basic correspondence of 66% (Fuller *et al*, 2003). Errors were explained by differences in the timing, scale and approach of the surveys. For example, the detail is affected by the lower spatial resolution of the LCM2000 (Fuller *et al*, 2003).

The problems of cross-calibrating two land use data sets, created using different methodologies, has been highlighted and reviewed by Comber *et al* (2003). They observed inconsistencies between the parcel and land cover target class and the broad habitat class in 1990 and 2000 respectively. Following correction of the dataset, to account for such differences, the accuracy of the LCM2000 was calculated as 85% (Centre for Ecology and Hydrology, 2000). The LCM2000 dataset is not simply supported by information on broad habitats but is also developed on the basis of subclasses, class variants and spectral subclasses; probability estimates, and information on parcel-size and neighbourhood.

Fuller *et al* (2003), argue that the measurement of small to medium scale land use changes over large areas requires levels of precision in mapping which are almost impossible to achieve with satellite image classifications alone. These limitations may not be so problematic when the data are applied to a spatial study of land use, which does not require measurement of changes through time. Nonetheless, the results of area measurements of catchment-scale land use cover, calculated using such maps, will need to be interpreted in the context of the potential inaccuracies associated with the data.

3.4 Multivariate statistical analysis

The complicated nature of water movement over and through the soil and rocks within a catchment is such that contemporary measurement techniques are not capable of providing the data necessary to replicate the details of the flow processes that govern the nature of peak flows (Beven, 2000). Notwithstanding this, the need to understand the functioning and response characteristics of catchments, in order to underpin decision making for water resource management and flood prevention has fostered the development of a plethora of rainfall – runoff models.

Hydrological models represent tools for extrapolating data, either temporarily to alternative periods in time, or spatially to different catchments (Beven, 2000). Ranging in complexity and computational requirement, models exist which help hydrologists gain differing degrees of understanding of hydrological processes operating across entire catchments and in spatially distributed elements (grid squares) within them (Beven, 2000). Major modelling techniques are summarised in figure 3.5.

At the most basic level the catchment is viewed as a single unit and catchment data are lumped together. The catchment is essentially treated as a 'black box' and modelling is undertaken on observations of inputs and outputs alone; no inferences are made regarding the internal flow processes translating rainfall into runoff (Beven, 2000). Occupying the other extreme of model complexity are distributed and physically based models (figure 3.5). Such models are used to make predictions that are spatially distributed by discretizing or pixelating catchments into numbers of grid squares. Local hydraulic conditions are derived through the application of equations to parameters which are averaged for each grid square.

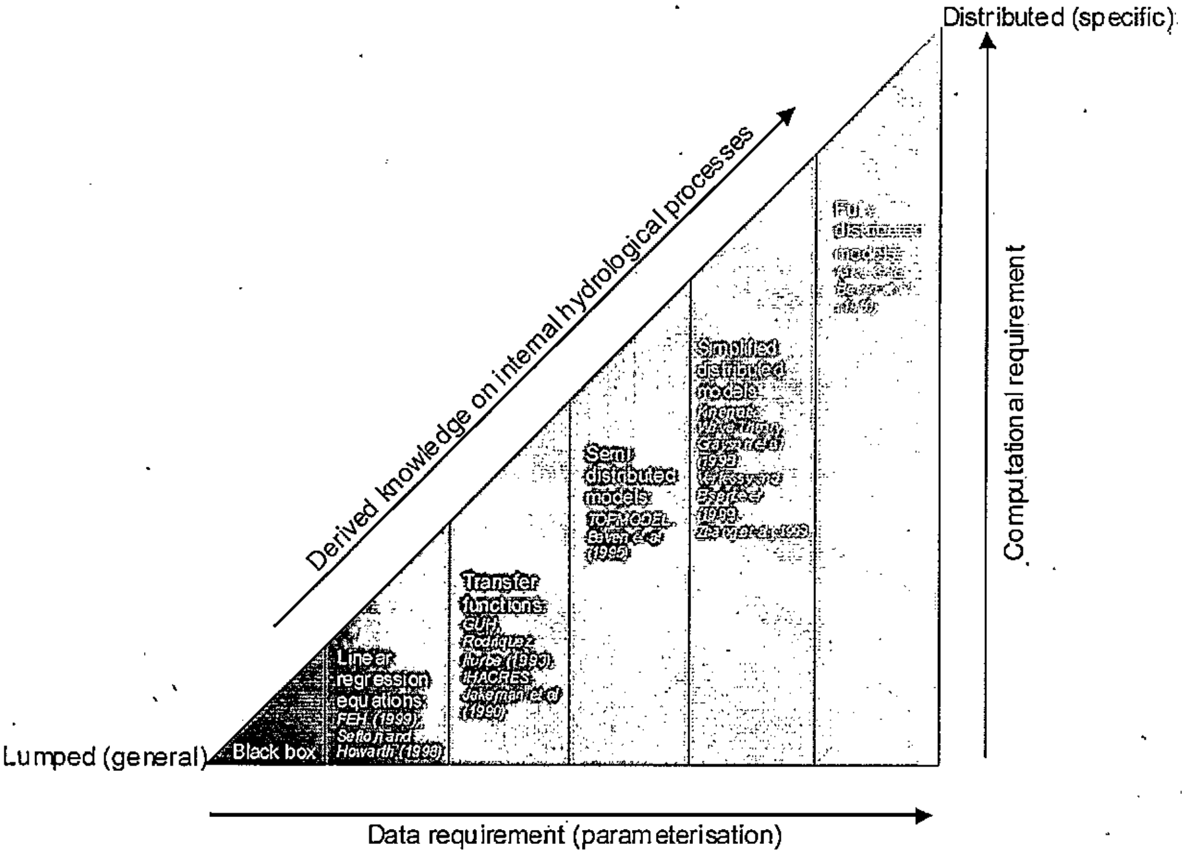


Figure 3.5 The range of techniques available to increase understanding of the hydrological functioning of catchments.

The predictive shortcomings of the black box approach are clear. In contrast, distributed models have the advantage of being able to generate predictions of flow pathways that are spatially distributed within catchments and based on physical theory (Beven, 2000). This has significant benefits to investigations into the impacts of land use change, since the effects on hydrology are often restricted to particular areas of a catchment, namely upland headwaters or highly connected flood plains.

Despite their obvious advantages, distributed models remain largely computationally and parametrically demanding (Beven, 2000). The inherent difficulties of determining the effective values of parameters at the grid scale, weakens their capacity to examine the effects of the characteristics of a catchment, by altering the physically based parameter values (Beven, 2000). Moreover, the descriptions of the process upon which the models are founded are fundamentally only mathematical simplifications of reality. As a result of the scale of parameterisation associated with complex models, it is arguable that they do not necessarily engender improved hydrological predictions. This is principally due to the enhanced predictive uncertainty related to increases in calibration problems.

The approach adopted in this thesis was constrained or guided by the need to address a number of important research problems, outlined below, which relate to the first aim of the thesis; to investigate the factors influencing regional catchment responses to extreme storm events (section 1.3). Achieving this aim required characterisation of a large number of catchments across south west England, which range in size, geology, soil type and morphological attributes. Hence, the approach adopted was very much constrained by available data.

1) Catchments are naturally complex systems, with many environmental attributes, including soils, geology and land use that are strongly interrelated. Consequently, as explanatory variables, these characteristics may never be completely independent of one another. This represents a statistical problem in terms of dealing with the effects of multicollinearity. However, measurement of the combined influence of two or more variables on runoff may contribute to understanding the effects of their interactions on the nature of storm flow.

2) Environmental variables are highly spatially heterogeneous. For example, particular land uses or soil types that are common to a catchment may not be

present or equally represented in another catchment, especially given the relatively wide distribution of the large number of catchments involved in the study. Final modelled outputs which describe the relationships between a few reduced soil or land use types and runoff is therefore not necessarily spatially transferable. An approach is required that is not only capable of modelling the discrete effects of individual environmental variables but in addition, can be used to explore the collective effects of several similar variables grouped together into statistical subsets.

3) Spatial structuring is implicit in environmental phenomena at a range of scales (Borecard *et al*, 1992; Kent and Coker, 1992) and is detectable in environmental data as spatial autocorrelation (Legendre and Legendre, 1998). It is symptomatic of the relationships between points in space, namely their geographic proximity (Kent and Coker, 1992) and may be identified as ecological patches, environmental gradients or geographic trends such as climatic variability.

Figure 3.6 shows the results of interpolation performed on gauged annual total rainfalls (mm) and annual total river discharges (m^3 s^{-1} km^{-2}) for the 48 study catchments. A distinct west-east trend is apparent in both annual rainfall and river flow data. Hence, catchments may demonstrate similar streamflow response characteristics because of their proximity to each other and as a result of their location across the region, in relation to spatial structuring in climatic drivers. It is therefore essential that measurement of the extent of spatial autocorrelation in environmental data is undertaken in order to minimise the potential for spatial structuring to act as an artificial variable for the original processes, which ultimately created it (Borecard *et al*, 1992). Spatial patterning may exert a significant and noteworthy control on event-scale runoff characteristics, which will have implications on regional catchment management strategies.

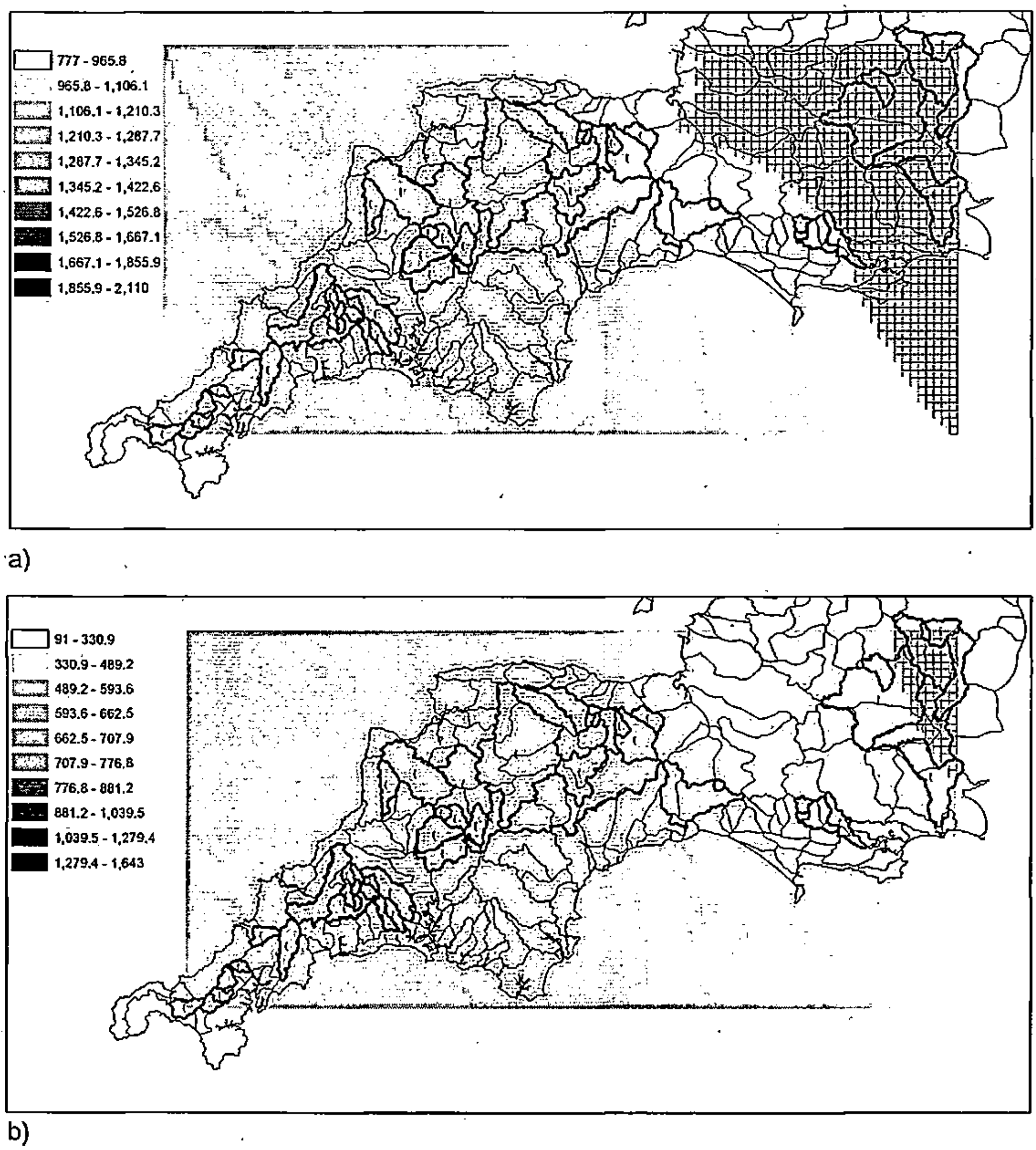


Figure 3.6 Results of interpolation performed on a) average annual rainfall (mm) and b) average annual runoff ($m^3\ s^{-1}\ km^{-2}$).

3.4.1. Derivation of spatial variables

In order to assess the amount of explained variance in runoff and environmental data accountable to spatial structuring, a matrix of spatial variables was incorporated into all multivariate statistical procedures. The geographical coordinates of the centre of gravity of each catchment in the study were determined using the CENTROID grid function in ArcGIS software (ESRI, 2004). The coordinates were centred on their means to reduce colinearity.

The northings (y) and eastings (x) of each catchment centroid were used to calculate a matrix of spatial variables by including the following nine terms for a cubic trend surface regression, x, y, x^2, xy, y^2, x^3, x^2y, xy^2, y^3, after Legendre (1990). The nine terms were entered into the process of variable reduction (Borcard *et al*, 1992; Anderson and Gribble, 1998).

3.4.2. Statistical modelling approach

In this instance the potential predictive advantages of semi and fully distributed modelling approaches are overshadowed by the unfeasibility of satisfactorily parameterising the large number of catchments involved. Statistical modelling based upon empirical regression analyses were applied on the basis that they made efficient use of the available data, in terms of balancing computational requirement with predictive capability. In the case of flooding, the nature of the problem is a multifaceted one involving a plethora of interacting variables. Multivariate statistical techniques allow the simultaneous analysis of several independent and dependent variables which are all correlated with each other to varying degrees (Tabachnick and Fidel, 1989).

A suite of multivariate approaches were adopted including cluster analysis, factor analysis, and direct and indirect gradient analyses, which fully satisfied the stated methodological requirements by facilitating data reduction, the exploration of underlying environmental gradients in regional catchment data and measurement of the amount of variability in runoff attributable to both individual and sets of environmental variables.

a) Cluster Analysis

Cluster analysis is one of a number of numerical classification techniques which apply a range of algorithms to derive groups of samples that are internally homogenous and distinct from other groups (Kent and Coker, 1992). The process of numerical clustering highlights order in the data set and allows clear interpretations to be made regarding the characteristics of the shared attributes of samples that are driving the groupings. In conjunction to its usefulness in revealing the relationships among catchments and environmental variables, clustering is valuable to the process of data reduction by aiding the detection of outliers and redundancies in the data set.

Hierarchical agglomerative clustering using Primer software (6th Edition), developed by the Plymouth Maine Laboratory, was performed to a) identify groups of catchments on the basis of shared environmental characteristics and b) identify outlying catchments. Similarity matrices of standardised data were generated using the Bray-Curtis coefficient calculated between samples. Manual determination of the numbers and structures of groupings were undertaken through visual interpretation of cluster dendrograms. Classification methods are objective in terms of repeatability and will produce consistent results. However, interpretation of the groupings from dendrograms is open to subjectivity. Results of the classifications were interpreted to determine the final number of groups, with reference to a consistent similarity cut-off level where possible to minimise bias.

b) Ordination

Ordination techniques were developed to help biologists and ecologists infer relationships between plant and animal communities and their environments, thereby providing an insight into the impacts of environmental changes on biological assemblages (ter Braak and Šmilauer, 2002). The value of ordination techniques in hydrological investigations, which frequently involve large multivariate datasets, has until now gone relatively unnoticed. The core principles of data reduction and exploration upon which ordination is based, are readily transferable to hydrological studies into the impacts of particular catchment characteristics, such as land use, on stormflow. In a hydrological context, catchments are the quadrats, runoff measurements represent the species and catchment attributes are the environmental variables.

Table 3.3 Presents the three main types of ordination and summarises their application to this study. The ordination techniques employed in this thesis included Multiple Dimensional Scaling (non-metric) (MDS), Principal Components Analysis (PCA) and Redundancy Analysis (RDA). The program CANOCO for windows version 4.5 (ter Braak and Šmilauer, 1998a; ter Braak and Šmilauer, 2002) was used to perform PCA and RDA ordinations. Ordination diagrams were plotted using CANODRAW version 4.5 (Šmilauer, 1992a). MDS was undertaken using PRIMER 6th edition statistical software, developed at Plymouth Marine Laboratory (PML).

Method	Objective	Application
INDIRECT GRADIENT ANALYSIS	To summarise dataset variation, i.e. the correlation structure of a set of environmental variables.	1. To characterise pattern in catchments and highlight the significant environmental variability driving this pattern.
		2. To indicate redundant variables, not influencing structure in catchment variability.
		3. To highlight and examine outlying samples or catchments.
DIRECT GRADIENT ANALYSIS	To predict, explain and display the response of species (runoff) to environmental data (catchment characteristics)	To measure and characterise the amount of variability in runoff determined by environmental factors.
PARTIAL CANONICAL ORDINATION	To explain species abundance data (runoff data) from environmental data, after removing the variation explained by a third data set.	To facilitate the examination of the discrete variation in runoff explained by subsets of environmental variables once the effects of additional subsets are removed, i.e. allows removal and measurement of spatial structuring in environmental data.

Table 3.3 Summary of the ordination techniques applied during multivariate statistical analyses.

For each ordination analysis, the eigenvalues and the percentage cumulative variance explained were presented. Eigenvalues measure the contribution of each of the ordination axes (components) to explaining the total variation in the dataset (Kent and Coker, 1992). The size of the eigenvalue, ranging between 0 and 1, is a measure of its importance (ter Braak and Šmilauer, 2002). The percentage of variance of the data explained by the axis is given cumulatively and is the amount of variation in the data that is explained by the ordination axes (ter Braak and Šmilauer, 2002). Each axis explains a proportion of the total variance of the fitted values, which is the sum of all eigenvalues (ter Braak and Šmilauer, 2002).

3.4.3. Data reduction

Indirect ordination techniques examine and summarise the internal variability in a multivariate data set. They offer a means of objectively screening both runoff and environmental datasets for extreme or superfluous data, which were subsequently removed from the analysis. These data comprised:

a) Outlier catchments exhibiting extreme runoff and/or environmental characteristics.

b) Redundant environmental variables which exhibited little influence on catchment groupings and/or an insignificant relationship with runoff.

c) Environmental variables demonstrating strong intercorrelation with other variables.

It was essential that the data reduction procedure established specific, representative variables for general catchment attributes (i.e. slate and granite to represent geology), to enable testing of the relative importance of catchment attributes in explaining variability in runoff using direct gradient analysis. For this end, the environmental data set was subdivided according to six attribute types, including rainfall, land use, geology, soil, topography and spatial characteristics.

Both parametric, Principal Components Analysis (PCA) (Orloci, 1966) and non-metric multidimensional scaling (MDS) (Fasham, 1977; Clarke, 1993), were applied to maximise exploration of the data using complimentary linear and non-linear approaches. PCA and MDS were undertaken consecutively on each group of variables. With reference to a Spearman's rank correlation matrix, which tested the intercorrelation of variables within each attribute class, and the results of replicate MDS and PCA analyses, environmental variables which exerted a minimal impact upon structuring in each of the environmental datasets and/or were shown to be strongly intercorrelated were omitted. This procedure was undertaken in order to refine the explanatory dataset.

Factor analysis: Multidimensional Scaling (MDS)

Non-metric multidimensional scaling (MDS) was performed on the entire environmental dataset (48 catchments and 92 environmental variables) following the derivation of a similarity matrix, to identify the key environmental gradients controlling observed catchment groupings. MDS plots were generated using an iterative technique to find the best display of the multivariate data in two-dimensions. Stress values indicated how well the data were displayed, a low stress value is less than 0.2 (Clarke, 1993). The existence of relationships between environmental gradients and runoff were tested for visually by overlaying catchment runoff data as a bubble plot on top of the MDS plot. This facilitated the identification of catchments with extreme runoff values or environmental characteristics.

Indirect gradient analysis: Principal Components Analysis (PCA)

Principal Components Analysis (PCA) was also employed on the entire environmental dataset for the same purpose of identifying environmental gradients most strongly governing observed structuring in the data. PCA was performed on a correlation matrix with centring and standardisation of the environmental data. Ordination plots were examined for outlying catchments. Subsequent PCA's were performed on reduced environmental sets. Key ordination axes were correlated with runoff in order to provide an indication of the relative importance of ordination axes that represented detected environmental gradients, in controlling variability runoff (Borecard *et al*, 1992).

Direct gradient analysis

Direct, or constrained, ordination is a method for examining the relationships between species (runoff) distributions and the distribution of environmental factors and gradients (Lepš and Šmilauer, 2003). In direct ordination, the ordination axes are constrained to be linear combinations of the environmental variables (Legendre and Legendre, 1998). Redundancy analysis (RDA) is a constrained form of the linear ordination method of PCA and is essentially a multiple regression of all runoff data simultaneously (ter Braak and Šmilauer, 2002).

The use of RDA facilitates the measurement of variation (sum of eigenvalues) in runoff that can be explained by the environmental variables. Hence, unlike its unimodal counterpart, Canonical Correspondence Analysis (CCA), RDA makes the distinction between the responses (runoff measurements) and the explanatory variables (environmental data) (ter Braak and Šmilauer, 2002). RDA is the more appropriate direct ordination method to employ when a Detrended Correspondence Analysis (DCA) of runoff data indicates short species gradients (<3) and therefore, relatively low heterogeneity (Lepš and Šmilauer, 2003). Following testing of the data using DCA, RDA was applied to examine the percentage variation in runoff explained by environmental gradients, and by the interactions of these gradients (partial ordination).

It is recommended that a few carefully selected environmental variables are favourable to the inclusion of a larger number of poorly chosen ones (ter Braak and Šmilauer, 2002). In addition to the screening exercise undertaken using indirect ordination, further data reduction was required to remove environmental variables and erroneous catchments which contributed little to determining the distribution of runoff and added unnecessary noise to the analysis. Prior to undertaking the final RDA, a sequence of analyses was exercised (steps a-e) in order to inspect the environmental and runoff datasets. Catchments which demonstrated unusual environmental attributes and/or uncharacteristic runoff values were examined and removed where necessary. A series of RDAs were performed to derive a subset of environmental variables that explained both a significant ($p<0.05$) and partially independent amount of variation in the runoff data.

Monte Carlo permutation tests were used to measure the statistical significance of the runoff–environment relationships derived through RDAs. In ordination analysis, a Monte Carlo test randomly shuffles (or permutes) the samples before calculating the test statistic (Lepš and Šmilauer, 2003). The null hypothesis (H_o) states that the response (runoff) is independent of the explanatory (environmental) variables. The alternative hypothesis (H_1) states that runoff will respond to the environmental variables. Variables that were not found to exert statistically significant independent control on runoff distributions ($p>0.05$) were removed from further analyses.

a) Spearman's rank (r_s) correlation matrix

Initially, the strength of intercorrelation between pairs of environmental variables was examined using a matrix Spearman's rank correlation coefficients (r_s). Spearman's rank was selected over Pearson's correlation coefficient as the most appropriate analysis of correlation, on account of evidence of skew in the raw data. The correlation coefficients were presented with their associated tests of significance. Variables which demonstrated strong multicollinearity and therefore, no independent contribution to the ordination, were identified. The results of the correlation matrix provided additional evidence to support decisions made regarding the removal of variables during data reduction exercises, thereby minimising the subjectivity of the selection process.

b) Constrained redundancy analyses (RDA)

In order to establish whether environmental variables were able to explain a satisfactorily significant amount of variance in the runoff data, a series of constrained RDAs were run for each variable in turn (ter Braak and Šmilauer, 2002). The closer the total explained variance (sum of all canoncial eigenvalues) to one, the greater the importance of environmental variable in explaining the distribution in the runoff data (ter Braak and Šmilauer, 2002). Those data that exhibited a low explained variance and no unique influence over the variability in runoff ($p > 0.05$), using 999 Monte Carlo permutations, were eliminated.

c) Examination of inter-set correlations

Inter-set correlations are the correlation coefficients between environmental variables and the ordination axes. More specifically, the correlations are weighted linear correlation coefficients between sample scores on the ordination axis (obtained from the runoff scores) and the values of the particular environmental variable (ter Braak and Šmilauer, 2002). Contrary to regression and canonical coefficients, which become unstable in the presence of multicollinearity, inter-set correlations remain stable when environmental variables are strongly correlated with each other (ter Braak and Šmilauer, 2002). In light of this, inter-set correlations were examined to establish the significance of correlations between individual environmental variables and the ordination axes generated by the RDAs. Variables which demonstrated low inter-set correlations (<0.2) were removed from subsequent analyses (ter Braak and Šmilauer, 1998).

d) Manual forward selection of environmental variables.

RDAs were performed on each of the six catchment attribute subsets. Forward selection was used to derive further reduced sets, containing variables that independently explained a significant proportion of variance in runoff data (Anderson and Gribble, 1998). Manual forward selection is a stepwise process that facilitates testing of the marginal effects of each variable. This is the amount of variability in the runoff explained by a partially constrained ordination, where that variable is the only explanatory variable (Lepš and Šmilauer, 2003). Testing of the statistical significance of each variable in each subset was undertaken separately using 999 Monte Carlo permutations. A variable which contributed significantly was included in one of the final model subsets on the condition that its p value was ≤ 0.05.

e) Examination of variance inflation factors.

Variance Inflation Factors (VIF) indicate the independence of each variable to the ordination (ter Braak and Šmilauer, 2002). High VIFs denote multicollinearity among environmental variables which destabilise the canonical coefficient, causing spurious results if interpreted incorrectly (ter Braak and Šmilauer, 2002). According to ter Braak and Šmilauer (2002), variables with VIFs greater than 20 are strongly correlated with other variables and should be removed from the analysis in turn (largest first) until all VIFs are below 20.

RDA was employed on all environmental variables in all six subsets to assess the interactions of variables both within and between sets. Variables displaying the highest degree of colinearity (VIFs >20) were successively removed and the RDA re-run until all remaining environmental variables exhibited VIFs <20.

3.4.4. Variance Partitioning

The variance in runoff explained by the selected subsets of environmental variables may not be completely free from the impacts of intercorrelation. Moreover, an analysis of spatial patterns in both total annual rainfalls and total annual river discharges (figure 3.6), demonstrated a clear regional trend. Observed relationships between event-scale runoff and catchment parameters may simply represent symptoms of spatial structuring in the data (Legendre and Legendre, 1998). Borcard *et al* (1992) proposed the use of partial canonical correspondence analysis (CCA) to partition the variation in a species dataset, into different portions corresponding to spatial and environmental descriptors. This technique is referred to as variance partitioning and is one of very few procedures available that specifically incorporate spatial structuring into environmental modelling (Méot *et al*, 1998).

Variance partitioning with RDA was employed to isolate the portions of total variance in runoff explained by each of the six environmental subsets, and by interactions among them. This enabled quantification of the strength of the interaction (overlap) between spatial parameters and the environment (Cushman and Wallin, 2002). Furthermore, the spatial component of runoff was partialled out of the runoff-environment relationship. The process involved performing a series of both constrained and partially constrained RDAs.

In the partial ordination model, the influence of covariables is factored out. For example, as illustrated in figure 3.7, it is possible to distinguish a) the non-spatial environmental variation in the runoff data or the independent environmental contribution, b) the spatial structuring in the runoff data that is shared by the environmental data, c) the spatial structuring in the runoff data that is not shared by the environmental data, or the independent spatial contribution, and d) the proportion of the variation in runoff which is not explained by neither the spatial or environmental data (Borcard *et al*, 1992).

Subsets of data to be partialled out of the analysis were entered into the ordination as covariables (Anderson and Gribble, 1998). For each step in the analysis, the value of the sum of canonical eigenvalues was recorded. Monte Carlo permutation tests with 999 permutations were also undertaken to measure the significance of the effects of the constraining variables on the runoff data, minus the effects of the covariables if present (Anderson and Gribble, 1998).

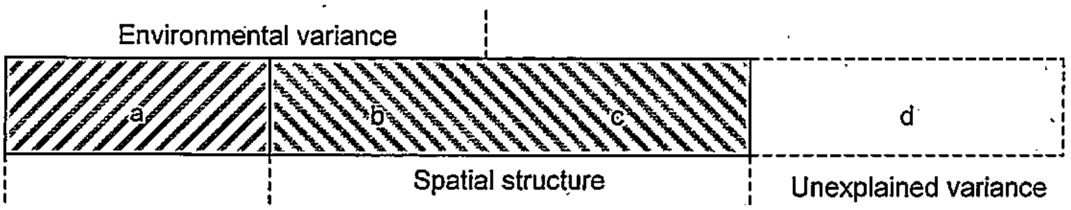


Figure 3.7 The explained variance in runoff distinguished by variance partitioning, adapted from Borcard *et al* (1992).

Variance partitioning is commonly applied to three variable sets (Borcard *et al*, 1992; Anderson and Gribble, 1998 and Cushman and Wallin, 2002). It is generally not recommended that the technique be used on more than three sets (Økland, 2003). This is principally the result of the practical problems and potential for error that is associated with calculating the variation controlled by large numbers of variation components. For example, there are 63 permutations involved in a six-set analysis (Økland, 2003). To avoid such problems, many studies have successfully broken down complex partitioning problems into a number of more simple equations (Økland, 2003).

Environmental component	Covariables
All components	none
Land surface component	none spatial component hydraulic component hydraulic component + spatial component
Hydraulic component	none spatial component land surface component land surface component + spatial component
Spatial component	none land surface hydraulic component hydraulic component + land surface component

Table 3.4 Series of ordinations run during level one variance partitioning

In light of this, variance partitioning was undertaken at two levels. Firstly, variance partitioning was run on three environmental components, a hydraulic set comprising topographic and rainfall subsets, a land surface component, including land use, soil and geology subsets, and finally a spatial set (table 3.4). Secondly, the overlap between subsets within the hydraulic (topography and rainfall) and land surface components (land use soil and geology) were quantified. At both levels, variance partitioning enabled measurement of the percentage of total variability in runoff explained by i) each environmental component and/or subset, i.e. its independent or marginal effect, and ii) the combined effects of two or more environmental components and/or subsets, i.e. their conditional effects. A series of overlapping Venn diagrams were generated to illustrate the results.

3.4.5. Runoff datasets

a) Four storms

In order to thoroughly examine the relationships between environmental variables and runoff, thereby fully investigating the impacts of land use, the statistical approach was repeated on two separate multivariate runoff datasets. The first dataset comprised runoff volumes calculated from the total river discharges of the 48 catchments for four separate storm events. The methodology for calculating the volume of catchment runoff and for selecting the four storm events were discussed in section 3.2.1 of this chapter.

Measured rainfall data are exclusive to individual events and their associated catchment responses. Therefore, in addition to the four existing rainfall parameters, including the total volume of rainfall, the maximum and average rainfall intensity, and API[7] (section 3.2.2), two additional variables representing the average rainfall total (mm) and the standard deviation of rainfall for the four storms, were calculated and included in the environmental data matrix as part of the rainfall subset.

b) Bin class runoff

The second runoff dataset was created by assigning the entire dataset of total runoff volumes, including all 48 catchments and four storm events, to one of five frequency, or bin classes. These classes were determined following a detailed examination of the distribution in runoff data through a series of frequency histograms that were derived using different ranges and numbers of bin classes. This process resulted in five runoff classes (section 5.7.2, table 5.7). For each catchment, the percentage occurrence of the runoff volumes in each class was given for each event.

3.4.6. Assumptions of statistical analysis

i. Linearity

Many of the multivariate statistical techniques employed are strongly founded upon the assumption of linearity. However, like most natural phenomenon, the characteristics of water movement and catchment response change in a very non-linear way depending upon flow rate and depth, and the antecedent state of the catchment (Grayson *et.al*, 1997; Beven, 2000). In hydrological modelling, lumped linear routing methods have been shown to work very well and numerous examples of their application exist in the literature. For example, the national Flood Studies Report (FSR) (1975) and more recent Flood Estimation Handbook (FEH) (Houghton-Carr, 1999), demonstrate the usefulness of the technique in calculations of peak flow, time to peak and estimations of effective runoff that are required for the production of a unit hydrograph (Beven, 2000).

Other examples use linear methods to model parameters or discharge characteristics for ungauged catchments (Beven, 2000). Sefton and Howarth (1998) applied a multiple linear regression to ascertain the relationship between physical catchment descriptor variables (independents) and a parameter of the IHACRES model (dependent). According to Beven (2000), when routing runoff, the inaccuracies that are introduced in estimations of the effective rainfall or runoff coefficient are generally greater than the errors associated with the assumption of linearity.

Moreover, non-linear relationships can be examined by transformation of the data. Transformation assists with normalising skewed variables, thereby bringing the data closer to the assumption of normality of linear models (Shaw and Wheeler, 1997; Sefton and Howarth, 1998). Where linear combinations of components in statistical tests are observed, the distribution of the data will be normal. A great number of multivariate techniques are based on the assumption that the variables' frequency distributions are approximately normal. Chatfield and Collins (1980) argue that most multivariate statistical methods are fairly reliable under conditions of departure from normality (Shaw and Wheeler, 1997).

The quality of the inferences made using parametric tests such as PCA and RDA will be highly dependent upon how closely the population resembles the normal distribution. Prior to analysis, using Minitab^{TM} Release 13.31 (Minitab^{TM}, 2000), environment and runoff data underwent a two-stage process of examination in order to check for normality. Firstly, the frequency distributions of all variables were plotted and examined for evidence of skew. Secondly, all variables were tested for normality using the Anderson-Darling normality test, which statistically tests the null hypothesis that the data should follow a normal distribution. The distribution is not normal where the p value of the test is lower than a rejection level of 0.05 (95% confidence level).

Variables that demonstrated skewed distributions and failed to satisfy the assumption of normality were transformed using either a $\log_{10}$ or square root transformation before being re-tested. Much of the skew in the frequency distributions of the environmental data represented an artefact of the influence of catchment area. Standardising these parameters by the basin area reduced this affect. Moreover, the creation of a second multivariate runoff dataset through the classification of storm runoff volumes into one of five frequency classes, served to enhance the linearity of the dataset.

ii. Multicollinearity

One of the main problems associated with multivariate statistics is the complex nature of environmental data. A specific hydrological response is related to many explanatory variables that are regularly highly intercorrelated (Graham, 2003). Problems associated with linear regression techniques are regularly related to multicollinearity between variables.

When two or more independent variables are linear combinations of each other, they are said to be multicollinear. In the presence of multicollinearity, the analysis of the influence of explanatory variables is hindered because the effects on the response may simply comprise an artefact of the effect of another explanatory variable. Hence the correlation may be spurious (Graham, 2003). Steps must be taken to remove, minimise or control the effects of multicollinearity, and the results interpreted appropriately. Furthermore, outputs from statistical models should always be accompanied by some expression of predictive uncertainty (Beven, 2000).

Much of the process of variable reduction adopted was centred upon minimising multicollinearity through the removal of highly collinear variables. The collinearity of variables was examined using a number of techniques such as, Spearman's rank correlation matrices, analysis of the direction of arrows on ordination bi-plots and through the calculation of variance inflation factors. Remaining intercorrelation between variables and subsets of variables was quantified through variance partitioning.

Summary

- This chapter presents and reviews the methods employed to parameterise 48 southwestern study catchments and to statistically explore their environmental and runoff characteristics in response to the same four storm events.

- Section 3.2 details the techniques adopted to derive the flow response (time to peak, peak discharge and the total volume of runoff) and rainfall (maximum and average rainfall intensity, total volume of rainfall and a 7-day antecedent precipitation index (API)) characteristics of each catchment for four selected storm events, occurring over the period 2001-2002, using 15-minute interval river discharge and tipping bucket rainfall (TBR) gauge data.

- Sections 3.3.1i-ii describe the development of a GIS, which facilitated the delineation and measurement of catchment terrain characteristics, such as slope gradient, drainage basin, drainage network and a topographic index (TI) using a digital elevation model (DEM) (50x50m).

- The classification of catchment soil types on the basis of shared hydrological characteristics using the HOST system is presented in section 3.3.1iii.

- Measurement of the spatial extent of geological (section 3.3.1iv) and land use (section 3.3.1v) classes is undertaken through manipulation of existing digital information within the GIS.

- Statistical testing of the effects of spatial autocorrelation in chapter 5 is made possible through calculation of the x and y coordinates of the centre of gravity, or CENTROID (section 3.4.1), of each catchment using GIS.

- Sections 3.4.2 to 3.4.6 explain the sequence of multivariate statistical techniques, including clustering, factor analysis, and indirect, direct and partial ordinations, which is employed in Chapter 5 to refine and explore the derived catchment variables, described in Chapter 4.

The following chapter (4) presents and describes measured hydrometric, environmental and spatial catchment attributes of the 48 study catchments and four selected storm events. This dataset forms the basis for statistical testing of the affects of land use on peak flow responses at the catchment scale, undertaken in Chapter 5.

Chapter 4

Characteristics of 48 study catchments distributed across southwest England

(Part II)

4.1 Introduction

This chapter presents and describes the characteristics of the 48 study catchments located across southwest England, derived using the procedures outlined in chapter 3. The database of catchment characteristics was required for multivariate statistical analyses (chapter 5) to fulfil objective one of the thesis (section 1.3);

'To investigate the factors influencing regional catchment responses to extreme storm events.'

The nature and rate of runoff movement to a stream will be affected by a wide range of strongly inter-dependent factors. These include storm patterns, catchment area, basin shape, the length and steepness of slopes and drainage density, in addition to geology, soil characteristics and vegetation cover. This section describes catchment scale patterns in environmental data. GIS is used to illustrate the geographical distribution, morphometric characteristics and environmental attributes of the 48 study catchments.

4.2 Catchment selection

Catchments were selected on the basis of a number of predetermined criteria.

i. The project was primarily concerned with the effects of rural land management practices on peak flow generation. Hence, catchments sited in the southwest were chosen on account of the predominance of farming land uses in the region. In addition, the catchments were selected to avoid bias towards a single county. Catchments were also selected to encompass the wide range of environmental variability found in the southwest.

ii. Only the catchments of gauged rivers were selected. Moreover, it was essential that the discharge data derived from gauging stations were accurate, reliable, consistent or uninterrupted, and recorded at a suitable time interval.

iii. Catchments also required at least one rainfall station to be sited in close proximity, with rainfall data meeting the same quality requirements as river flow data.

iv. Catchments were selected to encompass a diversity of soil type, land use, geology and relief in order to investigate the peak flow responses of catchments to the same four rainfall events.

v. Catchments that contained several flow gauges were also selected to facilitate a comparison of the whole catchment response with their associated subcatchments.

4.3 Catchment environmental and hydrometerological characteristics

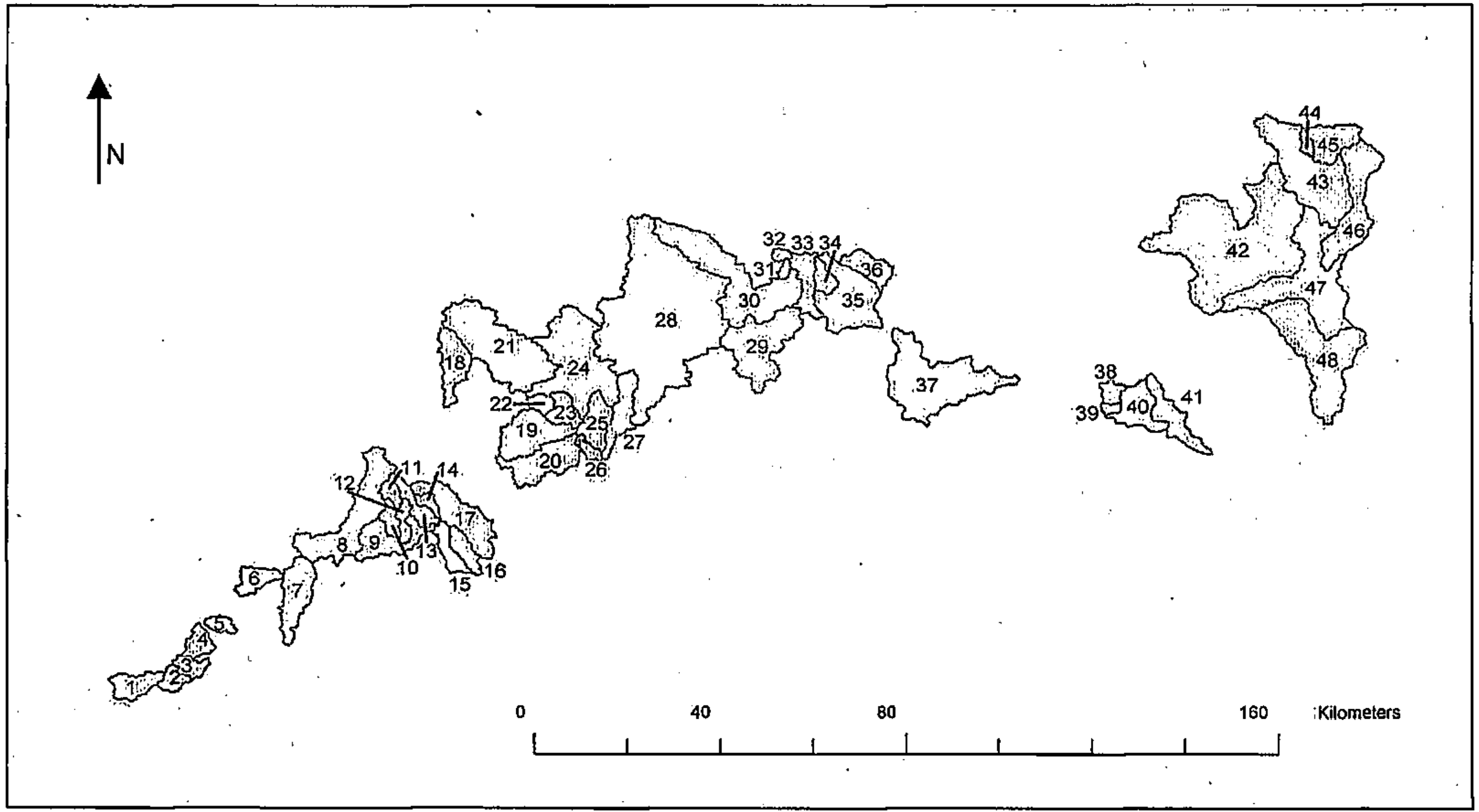
Data for a total of 94 environmental parameters, together with climatological data for four storm events, were collated for all 48 study catchments (figure 4.1). These data were collated from a range of sources including soil and geological maps, hydrometerological records, GIS analysis of digital relief information and existing digital databases.

4.3.1. Basin morphometry

Variable	Acronym	Units	Minimum	Maximum	Median	Mean	Standard Dev.
Area of catchment	AREA	Km^2	8.73	1716.55	59.50	200.05	346.91
Catchment easting	X	metres	160075.00	421775.00	256500.00	278139.58	78335.94
Catchment northing	Y	metres	32575.00	160825.00	97550.00	96363.54	33599.80
Average slope steepness	SLOPE	Degrees	2.27	7.83	4.70	4.84	1.43
Total stream length	STRM_L	Km	9.06	2415.69	79.68	268.56	475.15
Drainage density	DD	$Kmkm^2$	0.87	1.41	1.24	1.24	0.10
No. of grid squares 0-6° steep	SLOPE<6	Frequency	1358.00	586826.00	18224.00	61715.50	113334.68
No. of grid squares 7-12° steep	SLOPE<12	Frequency	472.00	91372.00	5414.00	16040.58	23548.86
No. of grid squares 13-18° steep	SLOPE<18	Frequency	24.00	28248.00	1146.50	3517.42	6018.08
No. of grid squares 19-24° steep	SLOPE<24	Frequency	0.00	9870.00	167.50	965.54	2001.54
No. of grid squares 25-30° steep	SLOPE<30	Frequency	0.00	2317.00	7.50	167.69	455.80
No. of grid squares 31-35° steep	SLOPE<35	Frequency	0.00	233.00	0.00	14.67	46.84
No. of grid squares 36-40° steep	SLOPE<40	Frequency	0.00	18.00	0.00	1.29	4.36
No. of grid squares 41-45° steep	SLOPE<45	Frequency	0.00	5.00	0.00	0.21	1.00
No. of grid squares with TI 0-10	TI<10	Frequency	15.00	194811.00	2621.50	12580.35	31714.19
No. of grid squares with TI 11-15	TI<15	Frequency	2086.00	360737.00	13956.50	39487.52	69907.23
No. of grid squares with TI 16-20	TI<20	Frequency	169.00	64660.00	1439.50	5523.90	11569.03
No. of grid squares with TI 21-25	TI<25	Frequency	0.00	10730.00	250.50	892.25	1933.86
No. of grid squares with TI 26-30	TI<30	Frequency	0.00	1263.00	7.00	72.25	214.76

Table 4.1 Descriptive statistics of catchment morphological and relief characteristics.

A subset of six environmental variables described the size, relief and drainage characteristics of catchments. These were basin area, drainage density, stream length, average slope, and the frequency of slope and topographic index (TI) classes. The slope steepness and topographic indices (TI) of digital elevation model (DEM) grid squares (50m by 50m), were calculated using GIS and subdivided into eight and five frequency classes (table 4.1). The coordinates of the centre of gravity (centroid) of each catchment were determined through GIS processing of catchment boundary polygons, using the CENTROID function. The northing (y) and easting (X) of each centroid were required to investigate spatial structuring in the environmental dataset.



1	St Erth	11	De Lank	21	Rockhay Bridge	31	Upton	41	Baggs Mill
2	Trenear Intake	12	Craigshill Wood	22	Norley Bridge	32	Bessom Bridge	42	Wilton
3	Ponsanooth	13	Trekeivesteps	23	Gribbleford Bridge	33	Greenham	43	Amesbury
4	Bissoe	14	Bastreet	24	Torrington	34	Milverton	44	North Newnton
5	Truro	15	Trebrownbridge	25	Jacobstowe	35	Bishops Hull	45	Up Avon West
6	Gwills	16	Tideford	26	Vellake	36	Halsewater	46	Laverstock
7	Tregony	17	Pillaton Mill	27	Taw Bridge	37	Whitford	47	East Mills Weir
8	Denby	18	Crowford Bridge	28	Umberleigh	38	South House	48	Knapp Mill
9	Restormal	19	Tinhay	29	Thorverton	39	Little Puddle		
10	Trengoffe	20	Lifton Park	30	Stoodleigh	40	Briants Puddle		

Figure 4.1 Distribution of 48 study catchments across southwest England.

Basin area: Table 4.1 presents the descriptive statistics for all 17 morphological catchment parameters and the coordinates of catchment centroids. Area minima and maxima figures in table 4.1 illustrate the extremes of basin scale that were encompassed within the 48 catchment sample set, ranging from 8.73km^2 (Upton – catchment 31) to Knapp Mill (1717km^2), the catchment of the River Avon (catchment 42-48). Denby (210km^2) is approximately average in size and discharges into the River Camel, north Cornwall (figure 4.2).

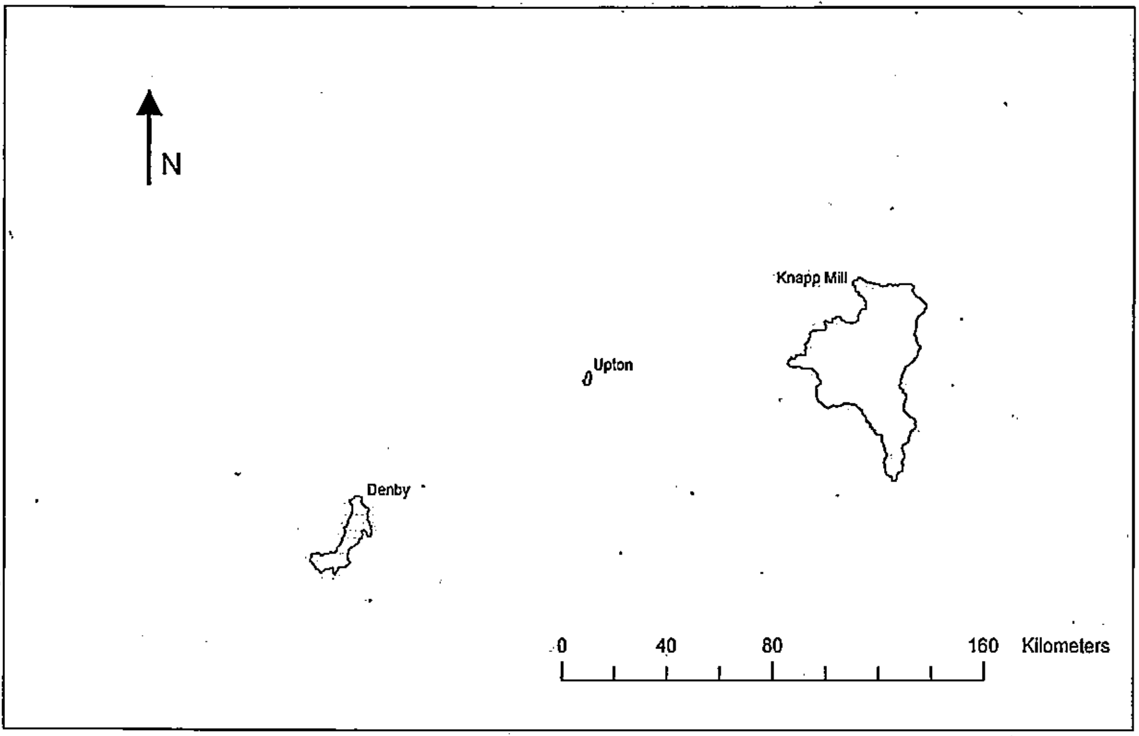


Figure 4.2 Map illustrating the range in catchment areas encompassed in the study.

Basin Shape: It is widely acknowledged that differences in catchment hydrological response characteristics will be significantly influenced by the shape of a basin. Related to topography, the 48 catchments exhibit a range of basin shapes. Unlike longer, narrower catchments such as Baggs Mill, shorter, wider catchments including Wayford may produce a peakier hydrograph due to a faster streamflow rise and fall. This principally arises because of the shorter travel time to the main channel (Gordan *et al*, 1992).

Basin relief: A stream with a steeper longitudinal profile may show a more rapid response and produce higher peak discharges than one which is less steep. Overall, Vellake is the steepest catchment with 19% of slopes over 18°. The shallowest catchment is Crowford, possessing 95% of slopes less than 6°. Shallow catchments are generally located in low lying coastal areas, upstream of estuaries or coastal inlets. Alternatively, steeply sloping catchments are typically sited in areas of higher elevation, where river valleys have been deeply incised.

Basin drainage density: Drainage density represents the length of channel length per unit area and was calculated following the creation of a stream network using a 50m by 50m grid scale digital elevation model. The density of a channel network reflects relief, in addition to climate patterns, geology, soils and vegetation cover (Gordan *et al*, 1992).

Catchments with predominantly gentle relief tend to have a high drainage density. This is supported by a significant positive correlation recorded between drainage density and slopes <6° (r=0.415, p<0.01), and a significant negative correlation with average slope (r= -0.314, p<0.05). Figure 4.3 illustrates the effect of relief on drainage density. Vellake (26) catchment displayed the lowest drainage density at 0.87km km^{-2} and the highest average slope steepness at 7.8° (figure 4.3). In steep catchments, water that flows down slope will be highly concentrated into fewer, better defined channels.

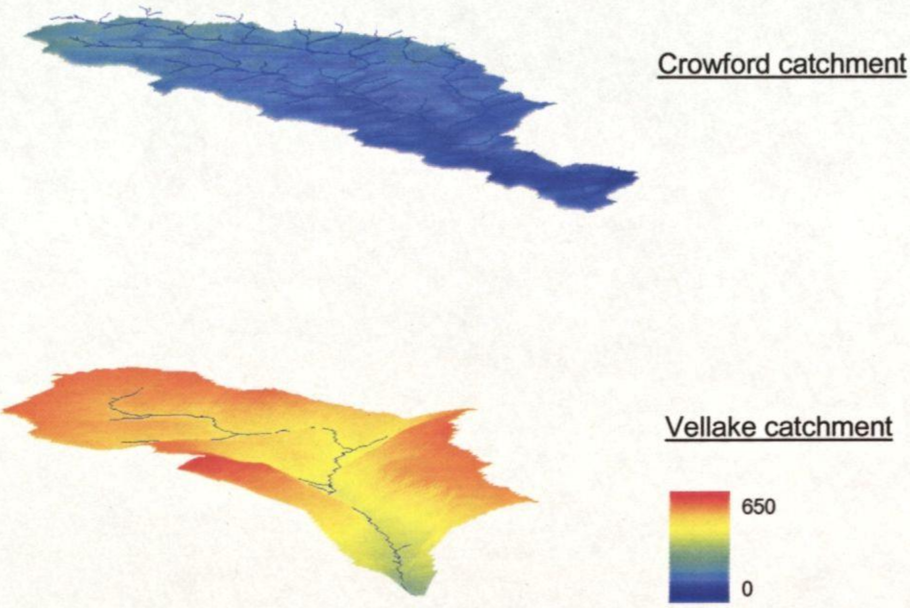


Figure 4.3 Three dimensional relief (m) maps of Vellake (26) and Crowford (18) catchments, illustrating the effect on drainage density.

Figure 4.4 illustrates the distribution of drainage density across the southwest. There is a noticeable eastwards trend, confirmed by a significant correlation between drainage density and the easting (x) of the centroid coordinate for each catchment (r=0.501, p<0.05). It has been established that slope steepness imposes a significant control on channel network patterns. Catchments with high drainage densities are located further east as the land becomes progressively more gentle in relief.

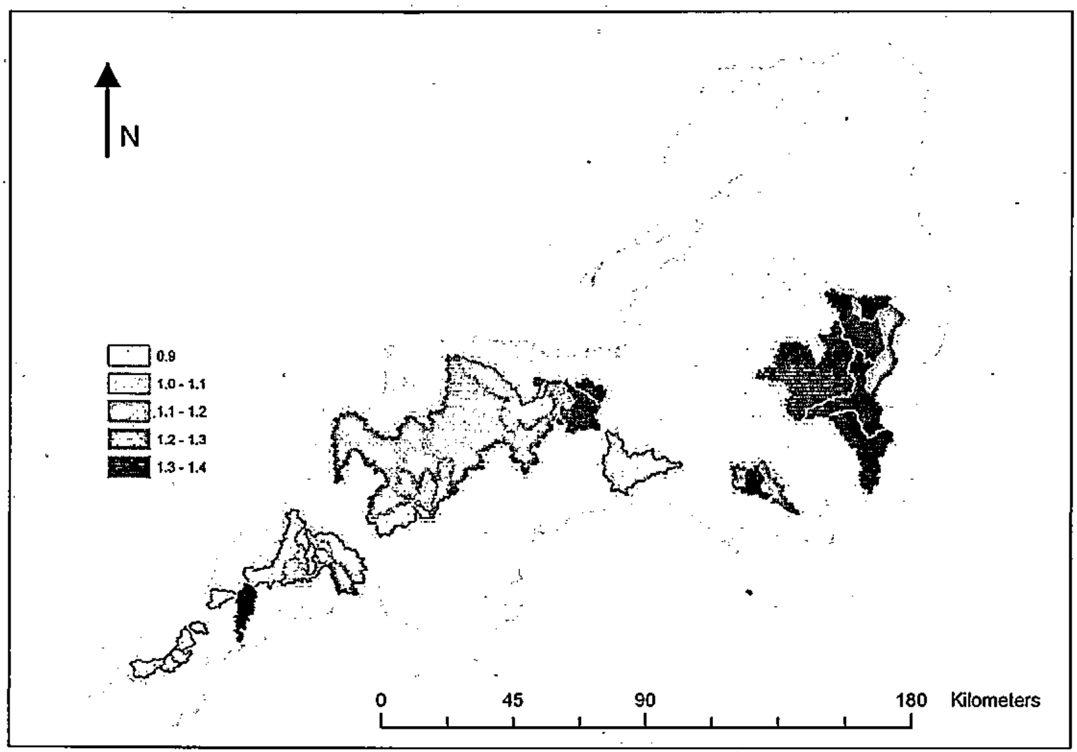


Figure 4.4 The distribution of catchment drainage density (km km^{-2}) across southwest England.

4.3.2. Basin land surface characteristics

Three subsets of land use, soil and geology data were parameterised for each catchment in order to examine the relationships between catchment attributes at the land surface.

Land Use: Firstly, calculation of the areas land use classes was undertaken using GIS analysis of digital satellite imagery data derived from the Centre for Ecology and Hydrology (CEH) Land cover Map 2000 (Fuller *et al*, 1994). Initially this provided multiple woodland, grassland and developed area classes. These were grouped together to reduce the number of variables. The final 17 land use classes and basic statistics of land use areas are presented in table 4.2.

Variable	Acronym	Units	Minimum	Maximum	Median	Mean	Standard Dev.
Woodland (conif/broad/mixed)	WOOD	Km^2	0.39	221.94	6.72	25.19	43.17
Arable cereals	AR_CER	Km^2	0.00	380.20	8.67	34.43	73.90
Arable horticulture	AR_HORT	Km^2	0.01	238.46	6.74	24.93	47.27
Arable non-rotational	AR_NONR	Km^2	0.00	22.14	0.00	1.52	4.28
Improved grassland	I_GRS	Km^2	0.04	489.48	24.12	80.93	121.38
Set Aside	SET_A	Km^2	0.00	4.08	0.00	0.28	0.91
Grassland (acid/calcareous/neutral)	GRS	Km^2	0.28	187.45	7.55	23.65	39.75
Dense dwarf shrub heath and bracken	DDSH	Km^2	0.00	18.52	0.07	0.92	2.89
Open dwarf shrub heath	ODSH	Km^2	0.00	11.57	0.01	1.57	2.89
Fen marsh swamp	FMS	Km^2	0.00	0.62	0.00	0.03	0.11
Bog deep peat	BDP	Km^2	0.00	6.70	0.00	0.75	1.61
Inland bare ground	IBG	Km^2	0.00	67.08	0.17	4.68	13.98
Suburban/rural development	DEV	Km^2	0.00	60.64	1.82	5.48	10.96
Continuous urban	C_URB	Km^2	0.00	10.86	0.38	1.20	2.15
Littoral sediment	L_SED	Km^2	0.00	0.01	0.00	0.00	0.00
Water body	WATER	Km^2	0.00	4.03	0.05	0.55	1.02
Road network density	ROAD_D	Km km^{-2}	0.00	0.01	0.00	0.00	0.00

Table 4.2 Descriptive statistics of catchment land cover characteristics.

Improved grassland represents the most important land use in the region, occupying on average 81km^2 of the catchment areas (table 4.2), ranging from 28.5% (Knapp Mill, 48) to 77.6% (Bessom Bridge, 32) (table 4.3). On average, arable cereal production is the second most extensive land use (34.4km^2), followed by woodland, horticulture and grassland (unimproved) (25km^2) (table 4.3).

Cereal production is extensive in Little Puddle (32.7%), Briants Puddle (31.7%) and Up Avon West (27.9%) (table 4.3). Bastreet (24.1%) and Restormal (18.3%) support significant stands of woodland, whilst horticulture is most prevalent in North Newton (20.8%). The percentage cover of grassland in the De Lank catchment is approximately four times the average percentage cover of 14.5% (table 4.3). Major urban or unvegetated areas cover no greater than an average 5km^2 of catchments (table 4.2). Tregony (19.5%), Bissoe (11.1%) and Laverstock (10.6%) share the highest percentages of bare or developed land (table 4.3).

		Woodland	Arable cereals	Arable horticulture	Arable non-rotational	Improved grassland	Set Aside	Grassland	Dense dwarf shrub heath and bracken	Open dwarf shrub heath	Fen marsh swamp	Bog deep peat	Inland bare ground	Suburban/rural development	Continuous urban	Littoral sediment	Water body
43	Amesbury	9.1	18.6	14.4	0.0	33.2	0.0	15.9	0.0	0.0	0.0	0.0	5.3	2.9	0.5	0.0	0.0
41	Baggs Mill	8.9	27.4	19.8	3.3	29.0	1.0	3.9	1.2	0.9	0.0	0.0	2.5	1.5	0.4	0.0	0.1
14	Bastreet	24.1	0.6	1.4	0.0	8.0	0.0	54.4	0.2	4.2	0.0	4.8	0.0	2.1	0.2	0.0	0.0
32	Bessom Bridge	5.7	0.3	9.0	0.0	77.6	0.0	5.4	0.0	0.0	0.0	0.0	0.7	0.5	0.8	0.0	0.0
35	Bishops Hull	9.5	18.8	15.6	0.7	43.2	0.0	5.4	0.2	0.0	0.0	0.0	0.4	4.8	1.0	0.0	0.2
4	Bissoe	5.7	4.0	15.4	0.0	38.7	0.0	25.0	0.1	0.0	0.0	0.0	0.4	9.5	1.2	0.0	0.0
40	Briants Puddle	5.1	31.7	21.1	3.1	31.4	0.7	3.1	0.1	0.1	0.0	0.0	2.2	0.9	0.3	0.0	0.0
12	Craigshill Wood	12.0	3.6	4.2	0.0	39.9	0.0	19.8	0.2	0.3	0.0	2.3	0.0	2.7	1.1	0.0	14.0
18	Crowford Bridge	7.5	13.5	9.4	0.0	61.7	0.0	5.3	0.0	0.0	0.0	0.0	0.0	1.5	0.6	0.0	0.4
11	De Lank	10.1	0.1	1.8	0.0	15.9	0.0	59.0	0.0	4.1	0.0	7.5	0.0	1.3	0.2	0.0	0.0
8	Denby	13.0	6.1	8.8	0.0	46.6	0.0	18.1	0.1	0.6	0.0	1.2	0.7	3.4	1.1	0.0	0.2
47	East Mills Weir	10.5	22.8	15.0	1.0	29.8	0.3	11.8	0.2	0.2	0.0	0.0	4.5	3.2	0.6	0.0	0.1
33	Greenham	13.7	6.5	9.9	1.4	61.3	0.0	4.9	0.2	0.0	0.0	0.0	0.1	1.1	0.2	0.0	0.8
23	Gribbleford Bridge	15.3	12.9	5.0	0.0	60.6	0.0	4.5	0.1	0.0	0.0	0.0	0.0	1.2	0.5	0.0	0.0
6	Gwills	9.2	16.0	24.3	0.0	31.4	0.0	13.3	0.3	1.4	0.0	0.0	1.1	2.4	0.6	0.0	0.0
36	Halsewater	11.4	21.0	22.6	0.0	30.6	0.0	7.5	0.3	0.0	0.0	0.0	0.6	4.9	1.1	0.0	0.0
25	Jacobstowe	13.3	6.2	4.2	0.0	26.6	0.0	28.5	0.2	8.4	0.0	8.4	0.4	3.1	0.5	0.0	0.3
48	Knapp Mill	12.9	22.1	13.9	1.3	28.5	0.2	10.9	1.1	0.7	0.0	0.0	3.9	3.5	0.6	0.0	0.2
46	Laverstock	10.1	25.9	14.2	0.4	30.5	0.0	8.2	0.0	0.0	0.0	0.0	6.6	3.7	0.4	0.0	0.0
20	Lifton Park	15.0	8.2	6.2	0.0	55.9	0.0	9.8	0.1	1.6	0.0	0.0	0.1	1.6	0.3	0.0	1.3
39	Little Puddle	4.1	32.7	15.7	4.4	37.4	0.2	3.4	0.0	0.0	0.0	0.0	0.9	1.0	0.0	0.0	0.2
34	Milverton	12.3	20.4	12.8	0.0	43.4	0.0	5.7	0.0	0.0	0.0	0.0	0.2	4.4	0.7	0.0	0.0
22	Norley Bridge	9.0	19.3	5.6	0.0	60.3	0.0	4.6	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0
44	North Newnton	11.0	20.8	27.9	0.0	28.2	0.0	2.3	0.0	0.0	0.0	0.0	1.3	6.2	2.3	0.0	0.1
17	Pillaton Mill	14.2	9.0	10.7	0.0	42.5	0.0	18.3	0.1	1.3	0.0	0.6	0.1	2.8	0.5	0.0	0.0
3	Ponsanooth	7.7	6.9	14.1	0.0	43.7	0.0	19.7	0.0	0.0	0.0	0.0	0.0	4.2	0.5	0.0	3.1
9	Restormal	18.3	4.2	6.5	0.0	39.7	0.0	23.9	0.4	0.7	0.0	1.1	0.4	1.9	0.7	0.0	2.4
21	Rockhay Bridge	13.0	18.3	12.6	0.0	45.9	0.0	7.4	0.1	0.0	0.0	0.0	0.1	1.5	1.2	0.0	0.0
38	South House	5.7	25.8	15.4	3.6	43.2	0.3	4.2	0.0	0.0	0.0	0.0	0.6	0.9	0.1	0.0	0.2
1	St Erth	8.7	12.4	27.5	0.0	29.1	0.0	16.0	0.3	0.0	0.0	0.0	0.0	3.8	2.1	0.0	0.1
30	Stoodleigh	16.4	2.7	5.2	0.1	53.2	0.0	16.9	1.4	2.2	0.0	0.2	0.1	1.0	0.2	0.0	0.3
27	Taw Bridge	10.6	18.7	8.4	0.0	33.9	0.0	13.9	1.1	5.9	0.0	5.0	0.0	2.0	0.4	0.0	0.0
29	Thorverton	15.2	5.5	6.8	0.1	51.6	0.0	15.3	1.0	1.6	0.0	0.2	0.1	2.0	0.3	0.0	0.2
16	Tideford	9.7	20.2	14.4	0.0	45.3	0.0	5.5	0.0	0.0	0.0	0.0	0.2	3.9	0.8	0.0	0.0
19	Tinhay	14.6	9.9	5.5	0.0	60.3	0.0	5.3	0.0	0.0	0.0	0.0	0.1	1.5	0.3	0.0	2.5
24	Torrington	13.9	16.0	9.8	0.0	46.2	0.0	9.3	0.1	0.9	0.0	1.0	0.3	1.6	0.8	0.0	0.0
15	Trebrownbridge	7.0	15.7	15.7	0.0	45.0	0.0	9.5	0.1	0.1	0.0	0.0	0.4	5.3	1.0	0.0	0.0
7	Tregony	15.4	9.9	13.0	0.0	35.5	0.0	6.4	0.2	0.0	0.0	0.0	14.7	3.5	1.3	0.0	0.1
13	Trekeivesteps	10.9	0.6	3.4	0.0	35.2	0.0	41.2	0.1	3.0	0.0	2.5	0.1	1.6	0.2	0.0	1.3
2	Trenear Intake	6.5	5.1	16.2	0.0	46.6	0.0	23.6	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0
10	Trengoffe	12.8	1.3	6.0	0.0	32.7	0.0	41.8	0.7	0.0	0.0	0.9	0.1	2.3	0.4	0.0	1.0
5	Truro	6.2	17.2	22.6	0.0	36.4	0.0	10.1	0.0	0.0	0.0	0.0	0.0	6.2	1.2	0.0	0.0
28	Umberleigh	13.0	13.4	9.2	0.0	53.4	0.0	6.7	0.4	1.0	0.0	0.4	0.1	2.0	0.4	0.0	0.0
45	Up Avon West	11.3	27.9	22.6	0.0	28.1	0.0	3.4	0.0	0.0	0.0	0.0	2.1	3.6	1.0	0.0	0.0
31	Upton	14.7	0.4	9.1	0.0	67.8	0.0	6.3	0.3	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0
26	Vellake	2.9	0.0	0.1	0.0	0.3	0.0	45.2	0.0	17.9	0.0	33.6	0.0	0.0	0.0	0.0	0.0
37	Whitford	9.4	15.9	10.0	4.8	53.6	0.0	2.8	0.0	0.0	0.0	0.0	0.1	3.0	0.3	0.0	0.0
42	Wilton	11.4	21.2	14.8	1.1	29.6	0.4	13.4	0.2	0.2	0.0	0.0	4.5	2.5	0.4	0.0	0.2
	Average	11.0	13.3	12.0	0.5	40.6	0.1	14.5	0.2	1.2	0.0	1.5	1.2	2.7	0.6	0.0	0.6

Table 4.3 Percentage cover of land use types in sampled catchments (%). Percentage cover totals may have small percentage errors due to limitations associated with calculating from electronic land use data in a GIS.

Soil Hydrology: Hydrology of soil types (HOST) is a soil classification system (Boorman *et al*, 1995) and was adopted to provide information on the hydrological characteristics of the soils and underlying substrates (section 3.3.1iii). A digital soil map of the southwest was incorporated into a GIS system and the percentage cover of HOST classes per catchment calculated manually.

Variable	Acronym	Units	Minimum	Maximum	Median	Mean	Standard Dev.
Host class 1	HA	%	0.00	85.43	0.00	13.56	26.03
Host class 2	HB	%	0.00	13.62	0.00	0.63	2.10
Host class 3	HC	%	0.00	31.46	0.00	3.21	6.28
Host class 4	HD	%	0.00	79.36	2.25	11.59	20.00
Host class 5	HE	%	0.00	13.16	0.00	1.23	3.24
Host class 6	HF	%	0.00	13.15	1.12	3.11	3.62
Host class 7	HG	%	0.00	4.44	0.00	0.20	0.75
Host class 8	HH	%	0.00	13.38	0.96	2.06	2.92
Host class 9	HI	%	0.00	18.80	0.79	2.81	4.28
Host class 10	HJ	%	0.00	15.83	0.00	1.81	3.80
Host class 11	HK	%	0.00	0.46	0.00	0.03	0.09
Host class 12	HL	%	0.00	5.54	0.00	0.36	1.05
Host class 13	HM	%	0.00	11.22	0.00	0.71	1.83
Host class 15	HO	%	0.00	85.33	0.51	9.86	20.11
Host class 16	HP	%	0.00	59.21	0.00	2.53	9.73
Host class 17	HQ	%	0.00	71.07	12.20	19.02	20.47
Host class 18	HR	%	0.00	21.95	4.50	5.16	5.12
Host class 19	HS	%	0.00	0.04	0.00	0.00	0.01
Host class 20	HT	%	0.00	4.27	0.00	0.14	0.64
Host class 21	HU	%	0.00	29.88	0.17	5.95	9.02
Host class 22	HV	%	0.00	13.57	0.88	2.56	3.71
Host class 23	HW	%	0.00	2.86	0.00	0.09	0.43
Host class 24	HX	%	0.00	62.14	1.18	8.63	14.43
Host class 25	HY	%	0.00	16.81	0.00	0.97	3.38
Host class 26	HZ	%	0.00	7.51	0.00	0.45	1.37
Host class 27	HAC	%	0.00	42.44	0.00	2.37	6.85
Water	HAD	%	0.00	4.95	0.00	0.21	0.78

Table 4.4 Descriptive statistics of catchment soil characteristics.

Table 4.4 presents the descriptive statistics of the percentage cover of soil HOST classes within the catchments that are detailed in table 4.5. The soil types covering the largest proportion of catchments were HA, HD and HQ, which covered 13.6%, 11.6% and 19%. These soil types corresponded to HOST classes 1, 4 and 17 (table 4.5). Classes 1 and 4 are free draining soils with porous or permeable substrates, good predicted rates of permeability and a low risk of runoff (table 4.5). Host class 1 was found to be most extensive in Laverstock (85.4%) and Little Puddle (83.8%) catchments.

HOST class 4 covered the greatest percentage area of Ponsanooth and Craigshill Wood catchments, encompassing 79.4% and 73.8% respectively. HOST class 17 overlies impermeable substrates and has a relatively high risk of runoff generation, with a Standard Percentage Runoff (SPR) value of 29.2% (table 4.5). In Bessom Bridge catchment soils categorised as HOST class 17 cover 71.7%, the largest proportion of basin area for the region.

Soil type	Substrate Permeability	Substrate hydrogeology	Groundwater or aquifer	Mineral soils	Flow processes	SPR* (%)
HA	Permeable vertical K_{sat} >10cm day-1	a)Weekly consolidated, microporous, by-pass flow uncommon Chalk, chalk rubble, clay, chalky drift	Normally present and at >2m	No impermeable or gleyed layer within 100cm	Surface runoff possible Vertical unsaturated flow	2.0
HB	Permeable vertical K_{sat} >10cm day	b)Weekly consolidated, microporous, by-pass flow uncommon Limestone: Soft Magnesian, brashy or Oolitic limestone and Ironstone	Normally present and at >2m	No impermeable or gleyed layer within 100cm	Surface runoff possible	2.0
HC	Permeable vertical K_{sat} >10cm day	c)Weekly consolidated, macroporous, by-pass flow uncommon Soft sandstone, weakly consolidated sand	Normally present and at >2m	No impermeable or gleyed layer within 100cm	Vertical unsaturated flow	14.5
HD	Permeable vertical K_{sat} >10cm day	d) Strongly consolidated, non or slightly porous. By-pass flow common Weathered metamorphic rock, hard fissured limestone or sandstone	Normally present and at >2m	No impermeable or gleyed layer within 100cm	Surface runoff possible Vertical unsaturated flow	2.0
HE	Permeable vertical K_{sat} >10cm day	e)Unconsolidated, macroporous, by-pass flow very uncommon Blown sand, sand, gravel	Normally present and at >2m	No impermeable or gleyed layer within 100cm	Surface runoff possible Vertical unsaturated flow	14.5
HF	Permeable vertical K_{sat} >10cm day	f)Unconsolidated, microporous, by-pass flow common Colluvium, cover loam, loamy drift	Normally present and at >2m	No impermeable or gleyed layer within 100cm	Surface runoff possible Vertical unsaturated flow	33.8
HG		e)Unconsolidated, macroporous, by-pass flow very uncommon Blown sand, sand, gravel	Normally present and at ≤2m	Impermeable layer within 100cm or gleyed layer at 40-100cm	Surface runoff possible	44.3
HH		f)Unconsolidated, microporous, by-pass flow common Colluvium, cover loam, loamy drift	Normally present and at ≤2m	Impermeable layer within 100cm or gleyed layer at 40-100cm	Surface runoff possible	44.3
HI		f)Unconsolidated, microporous, by-pass flow common Colluvium, cover loam, loamy drift	Normally present and at ≤2m	Gleyed layer within 40cm. Ksat <1m per day-^{1}	Prolonged saturated subsoil flow	25.3
HJ		f)Unconsolidated, microporous, by-pass flow common Colluvium, cover loam, loamy drift	Normally present and at ≤2m	Gleyed layer within 40cm. Ksat ≥1m per day-^{1}	Prolonged saturated subsoil flow	25.3
HK		f)Unconsolidated, microporous, by-pass flow common Colluvium, cover loam, loamy drift	Normally present and at ≤2m	Peat soils. Drained	Surface runoff likely Saturated soil flow	2.0
HL		f)Unconsolidated, microporous, by-pass flow common Colluvium, cover loam, loamy drift	Normally present and at ≤2m	Peat Soils (Undrained)	Surface runoff likely Saturated soil flow	60.0
HM		a) to f)	Normally present and at >2m	Impermeable layer within 100cm or gleyed layer at 40-100cm	Surface runoff possible Seasonal saturated flow Mainly vertical unsaturated flow	2.0
HO		a) to f)	Normally present and at >2m	Peat Soils	Surface runoff likely Saturated soil flow Leakage to substrate	48.4
HP	Slowly permeable vertical K_{sat} 0.10-10cm day-1	Soft shales with subordinate mudstones and siltstones Very soft reddish blocky mudstones (Marls) Very soft bedded loams, clays and sands Very soft bedded loams/clay/sand with subordinate sandstone Glaciolacustrine clays and silts Till, compact head Clay with flints or plateau drift	No significant groundwater or aquifer	No impermeable or gleyed layer within 100cm	Surface runoff likely Vertical unsaturated and "by-pass" flow	29.2
HQ	Impermeable (hard)	Hard Coherent Rocks	No significant groundwater or aquifer	No impermeable or gleyed layer within 100cm	Surface runoff likely Vertical unsaturated and 'By-pass' flow	29.2
HR	Slowly permeable vertical K_{sat} 0.10-10cm day-1		No significant groundwater or aquifer	Impermeable layer within 100cm or gleyed layer at 40cm. Integrated Air Capacity > 7.5	Surface runoff likely Seasonal saturated flow Some seasonal unsaturated and 'By-pass' flow to substrate	47.2

				%		
HS	Impermeable (hard)	Hard Coherent Rocks	No significant groundwater or aquifer	Impermeable layer within 100cm or gleyed layer at 40cm. Integrated Air Capacity >7.5 %	Surface runoff likely Seasonal saturated flow Some seasonal unsaturated and 'By-pass' flow to substrate	60.0
HT	Impermeable (soft)	Very soft massive clays	No significant groundwater or aquifer	Impermeable layer within 100cm or gleyed layer at 40. Integrated Air Capacity >7.5 %	Surface runoff likely Seasonal saturated flow Some seasonal unsaturated and 'By-pass' flow to substrate	60.0
HU	Slowly permeable vertical K_{sat} 0.10-10cm day-1	Soft shales with subordinate mudstones and siltstones Very soft reddish blocky mudstones (Marls) Very soft bedded loams, clays and sands Very soft bedded loams/clay/sand with subordinate sandstone Glaciolacustrine clays and silts Till, compact head Clay with flints or plateau drift	No significant groundwater or aquifer	Impermeable layer within 100cm or gleyed layer at 40. Integrated Air Capacity ≤7.5 %	Surface runoff likely Seasonal saturated flow Some seasonal unsaturated and 'By-pass' flow to substrate	47.2
HV	Impermeable (hard)	Hard Coherent Rocks	No significant groundwater or aquifer	Impermeable layer within 100cm or gleyed layer at 40cm. Integrated Air Capacity ≤7.5 %	Surface runoff likely Seasonal saturated flow Some seasonal unsaturated and 'By-pass' flow to substrate	60.0
HW	Impermeable (soft)	Very soft massive clays	No significant groundwater or aquifer	Impermeable layer within 100cm or gleyed layer at 40cm. Integrated Air Capacity ≤7.5 %	Surface runoff likely Seasonal saturated flow Some seasonal unsaturated and 'By-pass' flow to substrate	60.0
HX	Slowly permeable vertical K_{sat} 0.10-10cm day-1	Soft shales with subordinate mudstones and siltstones Very soft reddish blocky mudstones (Marls) Very soft bedded loams, clays and sands Very soft bedded loams/clay/sand with subordinate sandstone Glaciolacustrine clays and silts Till, compact head Clay with flints or plateau drift	No significant groundwater or aquifer	Gleyed layer within 40cm	Surface runoff likely Prolonged seasonal saturated flow Short seasonal unsaturated and 'By-pass' flow to substrate	39.7
HY	Impermeable (soft)	Very soft massive clays	No significant groundwater or aquifer	Gleyed layer within 40cm	Surface runoff likely Prolonged seasonal saturated flow Short seasonal unsaturated and 'By-pass' flow to substrate	49.6
HZ	Slowly permeable vertical K_{sat} 0.10-10cm day-1	Soft shales with subordinate mudstones and siltstones Very soft reddish blocky mudstones (Marls) Very soft bedded loams, clays and sands Very soft bedded loams/clay/sand with subordinate sandstone Glaciolacustrine clays and silts Till, compact head Clay with flints or plateau drift	No significant groundwater or aquifer	Peat Soils	Surface runoff likely Saturated soil flow	58.7
HAC	Impermeable (hard)	Hard Coherent Rocks	No significant groundwater or aquifer	Peat Soils	Surface runoff likely Saturated soil flow	60.0

*Standard percentage runoff

Table 4.5 Hydrological characteristics of HOST classifications (Boorman *et al*, 1995).

The Standard Percentage Runoff (SPR) measure in the HOST classification description facilitates identification of catchments that may be highly susceptible to runoff generation, on the basis of the characteristics of dominant soil types and underlying substrates. Table 4.6 presents the percentage of each catchment that is underlain with soils that exhibit low runoff risk (SPR <2%) or moderate to high runoff risk (SPR 14.5-60%).

Flow gauge		SPR 2.0%	SPR 14.5-60%	Flow gauge		SPR 2.0%	SPR 14.5-60%	Flow gauge		SPR 2.0%	SPR 14.5-60%
43	Amesbury	76.4	22.1	25	Jacobstowe	18.0	82.0	29	Thorverton	4.8	93.7
41	Baggs Mill	52.5	47.5	48	Knapp Mill	30.3	67.4	16	Tideford	18.0	82.1
14	Bastreet	0.2	99.8	46	Laverstock	87.0	13.0	19	Tinhay	3.0	97.0
32	Bessom Bridge	8.0	92.0	20	Lifton Park	15.8	84.2	24	Torrington	0.7	98.8
35	Bishops Hull	4.8	94.0	39	Little Puddle	83.9	16.1	15	Trebrownbridge	16.5	82.8
4	Bissoe	20.8	79.1	34	Milverton	7.1	93.0	7	Tregony	4.8	79.3
40	Briants Puddle	51.8	48.3	22	Norley Bridge	0.0	100.0	13	Trekeivesteps	18.0	80.2
12	Craigshill Wood	73.8	26.3	44	North Newnton	53.5	46.5	2	Trenear Intake	63.5	36.6
18	Crowford Bridge	0.8	98.1	17	Pillaton Mill	18.1	81.9	10	Trengoffe	47.5	52.5
11	De Lank	5.8	94.2	3	Ponsanooth	79.4	15.7	5	Truro	2.4	92.7
8	Denby	12.8	84.7	9	Restormal	66.4	33.6	28	Umberleigh	2.8	97.3
47	East Mills Weir	66.5	28.8	21	Rockhay Bridge	1.6	98.4	45	Up Avon West	40.1	60.0
33	Greenham	2.9	95.6	38	South House	69.7	30.3	31	Upton	13.6	86.4
23	Gribbleford Bridge	0.0	100.0	1	St Erth	14.0	85.9	26	Vellake	11.2	88.8
6	Gwills	2.1	98.5	30	Stoodleigh	2.3	97.7	37	Whitford	8.7	90.8
36	Halsewater	5.5	94.5	27	Taw Bridge	15.6	84.7	42	Wilton	70.2	28.9

Table 4.6 Percentage of soils with a low (<2.0%) and moderate to high (14.5-60%) SPR

Geology: Unlike soil HOST data, hydrological classifications of geology types or information relating to the hydrological characteristics of overlying regolith are not available. Hence, a digital map of the geology of southwest England, obtained from the British Geological Survey (BGS) provided data on the basic rock types underlying catchments. Bedrock types were categorised into 14 sub-groups on the basis of broadly similar permeability and porosity characteristics (section 3.3.1.iv), in order to refine the number of parameters (table 4.7). The geological information was incorporated into a GIS to enable calculation of the extent of rock classes within each catchment.

Geology class	Rock type	
Basalts	BASALT BASALTIC LAVA BASALTIC TUFF HYALOCLASTITE BASALTIC PYROCLASTIC ROCKS	MAFIC LAVA AND MAFIC TUFF MAFIC TUFF METABASALT METABASALTIC ROCK METAMAFIC ROCK
Granites	FELSITE GRANITE GRANITE, COARSE-GRAINED GRANITE, MEDIUM-GRAINED METADOLERITE	
Chert	CHERT CHERT AND SLATE CHERT, LIMESTONE AND MUDSTONE METACHERT	
Breccias and conglomerate	BRECCIA BRECCIA AND SANDSTONE, INTERBEDDED CONGLOMERATE AGGLOMERATE	
Sandstones	SANDSTONE SANDSTONE AND [SUBEQUAL /SUBORDINATE] ARGILLACEOUS ROCKS, INTERBEDDED	UP/MID SANDSTONE AND LIMESTONE QUARTZITE
Mudstones and Sandstones	METAMUDSTONE AND METASANDSTONE METASANDSTONE AND METAMUDSTONE MUDSTONE AND SANDSTONE MUDSTONE AND SANDSTONE, INTERBEDDED	MIDDLE LIAS SANDSTONE, SILTSTONE AND MUDSTONE
Mudstones and Silts	METAMUDSTONE METAMUDSTONE AND METASILTSTONE METASILTSTONE AND METAMUDSTONE MUDSTONE MUDSTONE AND SILTSTONE MUDSTONE, SILTSTONE AND SANDSTONE	SILTSTONE SILTSTONE AND MUDSTONE, INTERBEDDED SILTY MUDSTONE SLATE CLAY LOWER LIAS
Limestone and Oolite	GREAT OOLITE LIMESTONE METALIMESTONE METAMORPHOSED LIMESTONE AND PELITE	CHALK
Basic Igneous	PERIDOTITE PICRITE ULTRAMAFIC-ROCK BASIC ROCK, UNDIFFERENTIATED, FINE-GRAINED	DOLERITE
Fine grained acidic igneous	GRANITE, FINE-GRAINED IGNEOUS ROCK LAMPROPHYRE GROUP LAVA AND TUFF, UNDIFFERENTIATED METAMORPHOSED TUFF	RHYOLITE TUFF MICROGRANITE
Unconsolidated <64mm in diameter	PEBBLE BED CLAYEY GRAVEL GRAVEL, SILT AND CLAY	
Unknown geology type	UNKNOWN	
Mudstone and limestone	METAMUDSTONE AND METALIMESTONE MUDSTONE AND LIMESTONE, INTERBEDDED	
Upper Lias	UPPER LIAS	
Clay, sand and silt	CLAY, SILT AND SAND	

Table 4.7 Classification of rock types into geology classes.

The geological sub-groups and basic statistics of geology area data are displayed in table 4.8, including mean, minimum and maximum areas of bedrock classes.

Variable	Acronym	Units	Minimum	Maximum	Median	Mean	Standard Dev.
Basalts	BAS	Km^2	0.00	4.40	0.00	0.19	0.70
Granites	GRAN	Km^2	0.00	84.46	0.00	9.14	15.48
Chert	CHER	Km^2	0.00	16.48	0.00	1.28	3.81
Breccias and conglomerate	BREC_C	Km^2	0.00	40.71	0.00	1.70	6.54
Sandstones	SST	Km^2	0.00	368.57	3.51	44.50	85.02
Mudstones and Sandstones	MU_SST	Km^2	0.00	153.35	0.00	11.63	31.11
Mudstones and Silts	MU_SLT	Km^2	0.00	297.18	20.65	51.29	78.22
Limestone and Oolite	LST_O	Km^2	0.00	1242.50	0.01	77.49	251.41
Basic Igneous	BAS_IG	Km^2	0.00	2.38	0.00	0.24	0.55
Fine grained acidic igneous	FGAIG	Km^2	0.00	3.23	0.00	0.35	0.78
Unconsolidated <64mm in diameter	UNCON	Km^2	0.00	15.05	0.00	0.46	2.22
Unknown geology type	U	Km^2	0.00	1.60	0.00	0.08	0.32
Mudstone and limestone	MU_LST	Km^2	0.00	37.06	0.00	0.77	5.31
Upper Lias	UP_L	Km^2	0.00	15.85	0.00	0.33	2.27
Clay, sand and silt	CL_S_S	Km^2	0.00	108.64	0.00	3.06	15.77

Table 4.8 Descriptive statistics of catchment geological characteristics.

Mudstones and siltstones occur in most catchments and have an average catchment area of 51.3km^2. They predominantly underlie Truro, Norley Bridge and Bessom Bridge (table 4.9). Limestone and Oolite (chalk) has a mean area of 77.5km^2. It is most widespread in Laverstock (96.7%), Briants Puddle (91.4%) and Little Puddle (90.4%) catchments (table 4.9). Sandstones also make-up a substantial proportion of the underlying regional geology, with the average catchment coverage at 44.5km^2 (table 4.8).

Mudstones and sandstones, and granite are the only other rock types of considerable extent in the region. Mudstones and sandstones cover an average catchment area of 11.6km^2 and are most prevalent in Tregony (44%) and Denby (34.3%) (table 4.9). Granite is limited to a few geographically limited outcrops on Bodmin moor, Dartmoor and Exmoor, accounting for an average 9.4km^2 of catchments. Bastreet, Trenear, Vellake and De Lank are all granite catchments.

Flow gauge		BAS	GRAN	CHER	BREC_C	SST	MU_SST	MU_SLT	LST_O	BAS_IG	FGAIG	UNCON	U	MU_LST	UP_L	CL_S_S
43	Amesbury	-	-	-	-	25.4	-	0.2	74.4	-	-	-	-	-	-	-
41	Baggs Mill	-	-	-	-	-	-	20.0	80.0	-	-	-	-	-	-	-
14	Bastreet	-	100.0	-	-	-	-	-	-	-	-	-	-	-	-	-
32	Bessom Bridge	-	-	-	-	3.0	-	97.0	-	-	-	-	-	-	-	-
35	Bishops Hull	-	-	-	-	34.7	-	56.4	2.7	-	-	6.2	-	-	-	-
4	Bissoe	-	16.5	-	-	83.5	-	-	-	-	-	-	-	-	-	-
40	Briants Puddle	-	-	-	-	7.7	-	1.0	91.4	-	-	-	-	-	-	-
12	Craigshill Wood	-	68.5	-	-	-	-	27.7	-	0.1	3.7	-	-	-	-	-
18	Crowford Bridge	-	-	-	-	71.9	-	28.1	-	-	-	-	-	-	-	-
11	De Lank	-	87.4	-	-	-	-	-	-	-	12.6	-	-	-	-	-
8	Denby	0.1	22.5	-	-	-	34.3	38.7	3.5	0.7	0.2	-	-	-	-	-
47	East Mills Weir	-	-	-	-	13.8	-	5.2	80.9	-	-	-	0.1	-	-	-
33	Greenham	-	-	-	-	56.5	-	32.1	11.4	-	-	-	-	-	-	-
23	Gribbleford Bridge	-	-	-	-	9.8	-	90.1	-	-	0.1	-	-	-	-	-
6	Gwills	-	1.3	-	-	-	3.9	4.8	-	-	-	-	-	90.0	-	-
36	Halsewater	-	-	-	-	52.8	-	42.7	-	-	-	4.6	-	-	-	-
25	Jacobstowe	-	21.8	2.5	2.7	5.7	-	63.4	-	1.7	2.1	-	-	-	-	-
48	Knapp Mill	-	-	-	-	12.0	-	15.6	72.4	-	-	-	-	-	-	-
46	Laverstock	-	-	-	-	3.3	-	-	96.7	-	-	-	-	-	-	-
20	Lifton Park	1.5	7.3	14.3	-	11.9	8.0	55.3	0.1	1.4	0.4	-	-	-	-	-
39	Little Puddle	-	-	-	-	9.6	-	-	90.4	-	-	-	-	-	-	-
34	Milverton	-	-	-	-	41.7	-	50.3	-	-	-	2.6	5.4	-	-	-
22	Norley Bridge	-	-	-	-	2.5	-	97.3	-	-	0.1	-	-	-	-	-
44	North Newnton	-	-	-	-	52.6	-	-	47.4	-	-	-	-	-	-	-
17	Pillaton Mill	3.7	18.2	7.7	-	2.9	34.1	31.5	-	2.0	-	-	-	-	-	-
3	Ponsanooth	-	94.7	-	-	-	4.5	0.8	-	-	-	-	-	-	-	-
9	Restormal	-	50.5	-	-	0.7	9.7	37.2	0.2	0.2	1.5	-	-	-	-	-
21	Rockhay Bridge	-	-	-	-	74.9	-	25.0	-	-	-	-	-	-	-	-
38	South House	-	-	-	-	13.8	-	-	85.7	-	-	-	0.6	-	-	-
1	St Erth	0.4	21.4	-	-	-	-	76.8	-	1.0	0.3	-	-	-	-	-
30	Stoodleigh	-	-	3.1	0.7	30.0	15.0	51.0	0.2	-	-	-	-	-	-	-
27	Taw Bridge	0.2	21.2	1.8	9.4	13.5	-	52.5	0.4	0.6	0.4	-	-	-	-	-
29	Thorverton	-	-	2.7	6.8	23.9	25.5	40.7	0.2	-	0.2	-	-	-	-	-
16	Tideford	3.9	-	-	-	7.0	4.6	82.1	-	1.3	-	-	1.1	-	-	-
19	Tinhay	-	-	0.8	-	6.9	1.3	91.1	-	-	-	-	-	-	-	-
24	Torrington	-	4.3	0.3	1.7	50.1	-	41.9	-	0.2	0.3	0.1	-	-	-	1.2
15	Trebrownbridge	0.5	9.2	0.4	-	-	22.0	62.7	-	5.2	-	-	-	-	-	-
7	Tregony	-	20.9	-	-	-	44.0	14.4	2.2	0.2	3.4	-	-	-	-	15.0
13	Trekeivesteps	-	95.4	-	-	-	-	-	-	-	4.6	-	-	-	-	-
2	Trenear Intake	-	100.0	-	-	-	-	-	-	-	-	-	-	-	-	-
10	Trengoffe	-	75.7	-	-	-	-	24.2	-	0.1	-	-	-	-	-	-
5	Truro	-	-	-	-	-	-	99.9	-	-	0.1	-	-	-	-	-
28	Umberleigh	0.1	1.8	0.2	2.2	44.3	15.4	35.7	0.1	-	-	-	-	-	-	-
45	Up Avon West	-	-	-	-	58.8	-	0.8	40.4	-	-	-	-	-	-	-
31	Upton	-	-	-	-	17.1	-	82.9	-	-	-	-	-	-	-	-
26	Vellake	-	99.4	-	-	-	-	0.6	-	-	-	-	-	-	-	-
37	Whitford	-	-	-	-	39.1	8.9	30.1	10.3	-	-	1.2	-	-	5.2	5.2
42	Wilton	-	-	-	-	-	-	7.2	76.6	-	-	-	-	-	-	16.3

Table 4.9. Percentage cover (%) of geology class in 48 study catchments across southwest England.

4.3.3. Rainfall and discharge characteristics

Hydrometerological data for each catchment were extracted from Environment Agency archives. Both rainfall and discharge data were recorded at 15 minute intervals. Rainfall data measured using tipping bucket rainfall (TBR) gauges were converted to a 15 minute time step in Excel. In addition to quality assessments undertaken by the Environment Agency, data were manually screened for potential errors and inconsistencies through exploration of annual, winter and seasonal aggregations, and through the calculation of a series of correlations with indicator variables such as basin area. Moreover, information relating to the reliability of gauges was obtained from the Environment Agency.

Four of the largest storm events over the winter period 2001-2002 were selected, based upon the maximum volume of rainfall. Storms falling on the following dates were distinguished,

- Storm 1: 7/10/2001
- Storm 2: 25/10/2001
- Storm 3: 25/1/2002
- Storm 4: 30/11/2001

Using the methodology outlined in section (3.2.2), the rainfall was characterised for each event using four key attributes namely, the maximum and average rainfall intensity (using precipitation data at 15 minute intervals), the total volume of rainfall and the antecedent precipitation index (API^7). API^7 was determined for the start of each event to indicate the prevailing wetness condition of the catchments.

Three variables were used to characterise the streamflow responses to the four storm events. These were calculated from storm hydrographs, separated into quickflow and baseflow components, using the technique described in section 3.2.1. They included time to peak, peak discharge and the total volume of runoff or quickflow (figure 3.1).

Table 4.10 displays the descriptive statistics of rainfall and runoff data for four storms and all 48 study catchments.

Variable	Acronym	Units	Minimum	Maximum	Median	Mean	Standard Dev.
Time to peak	MAXQT	Hrs	1.25	147.25	13.75	17.05	13.75
Peak Discharge	MAXQ	$m^3 s^{-1} km^{-2}$	0.091	207.56	4.32	17.92	36.29
Total volume of runoff per event	RO	$m^3 s^{-1} km^{-2}$	0.61	5133.51	45.11	256.31	664.80
Antecedent Precipitation Index	API	Na	0.47	464.19	15.96	36.27	70.80
Total rainfall per event	RF_T	mm	2.60	523.58	25.30	51.99	89.02
Average rainfall intensity	RF_AV	mmhr-^{1}	0.02	59.04	2.48	4.92	6.86
Maximum rainfall intensity	RF_MAX	mmhr-^{1}	0.09	400.00	12.00	24.17	41.63

Table 4.10 Descriptive statistics of rainfall and discharge characteristics for all four events.

Storm rainfall characteristics: Both between storm and within storm characteristics are highly variable. Hydrometric data presented in table 4.11 show a notable difference between the maximum total volume of rain falling in storm one (55.2mm) and storm three (523.6mm). This pattern is mirrored in average total rainfall figures, which show storm one as the smallest event overall, with an average total rainfall of 27.4mm. Storm three is the largest event and has an average total volume of rainfall of 75.2mm (table 4.11).

Considerable variability is also apparent in the characteristics of rain falling in catchments during a single storm event. Wide deviations from the mean are presented for both storms two (105mm) and storm three (118.2mm). Storm three has the maximum range in total runoff figures, at 520mm. The most consistent figures for the total volume of rain falling in an individual event are shown for storm one, which range by just 49.2mm, between 6mm and 55.2mm. Storm one exhibited the highest average rainfall intensity at 59mmhr-^{1} and storm three, the lowest at 18.4mmhr-^{1}.

Storm	Rainfall variable	Minimum	Maximum	Median	Mean	Standard Dev.
1	Total rainfall per event	6.00	55.20	25.00	27.44	11.21
	Average rainfall intensity	0.02	59.04	2.21	4.27	9.23
	Maximum rainfall intensity	0.09	400.00	12.00	24.75	62.25
2	Total rainfall per event	6.60	482.34	29.00	68.89	105.02
	Average rainfall intensity	0.69	23.89	3.83	7.44	7.46
	Maximum rainfall intensity	4.80	136.00	16.00	37.44	43.26
3	Total rainfall per event	3.20	523.58	33.30	75.22	118.21
	Average rainfall intensity	0.56	18.29	2.61	4.75	5.23
	Maximum rainfall intensity	1.60	128.00	10.00	22.77	27.77
4	Total rainfall per event	2.60	462.37	17.10	36.40	73.29
	Average rainfall intensity	0.95	18.39	1.67	3.23	3.60
	Maximum rainfall intensity	3.20	48.00	4.80	11.73	13.56

Table 4.11 Descriptive statistics of rainfall characteristics for four storm events.

The average total volume of rainfall for all four storms (table 4.12) shows that Trekievesteps, Denby and De Lank catchments were the wettest catchments overall.

Catchment	Maximum average total rainfall (mm)	Catchment	Minimum average total rainfall (mm)
Trekievesteps	377	Upton	14
Denby	250	Little Puddle	15
De Lank	220	Gwills	17
Jacobstowe	149	Milverton	17
Gribbleford Bridge	128	Laverstock	18
Norley Bridge	122	Bessom Bridge	18
Craigshill Wood	112	Stoodleigh	18
Vellake	89	Bishops Hull	18
Tregony	49	North Newnton	18

Table 4.12 Catchments showing the highest and lowest average total rainfall volumes for the 4 storm events.

The smallest individual storm events affected Wilton, Bishops Hull, Upton, Stoodleigh and Laverstock catchments, which each received less than 6mm of rainfall. For the four storms combined, Upton is the driest catchment, receiving just 14mm of rainfall on average (table 4.12). The consistently high precipitation received in Trekievesteps, Denby and De Lank catchments is primarily due to their location. All three catchments lie adjacent to one another in north Cornwall, on or in close proximity to the exposed, high relief area of Bodmin Moor (figures 4.1 and 4.5). In contrast, catchments exposed to comparatively small rainfall volumes are located in lower relief areas, and towards the east of the region where they are less exposed to frontal systems moving in from the southwest (figure 4.5).

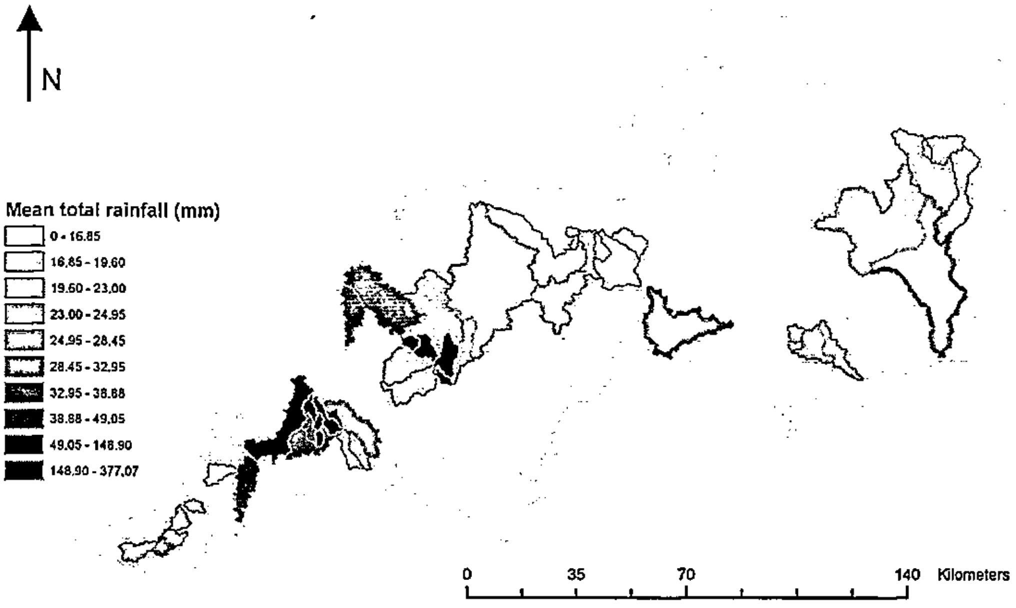


Figure 4.5 The distribution of mean total rainfall volumes over the four storms across southwest England.

Storm runoff characteristics: To facilitate a direct comparison between catchments, runoff data are presented per unit area (km^2). The average total volume of runoff for the sampled catchments and four storm events ranged from 0.76 m^3 s-^{1} km^{-2} (Wilton) to 4.78 m^3 s-^{1} km^{-2} (Norley Bridge) (table 4.13). Little Puddle demonstrated the lowest average peak flow of 0.004 m^3 s-^{1} km^{-2}, which contrasted the highest average peak flow of 1.04 m^3 s-^{1} km^{-2}, recorded at Vellake (table 4.13).

The response characteristics of sampled catchments are markedly diverse. On average, the responses of Craigshill wood, Upton and Bissoe are particularly flashy, taking under eight hours to reach peak discharge (table 4.13). Tregony (47hrs), Amesbury (44hrs) and Crowford bridge (34hrs) exhibit relatively damped responses.

High runoff generating catchments included Pillaton Mill, Baggs Mill, De Lank, Gwills, Craigshill Wood, which all produced greater than 7 m^3 s^{-1} km^{-2} in a single response. For a single event, Pillaton Mill, Jacobstowe, De Lank and Ponsanooth engendered the smallest volumes of runoff, each generating less than 0.04m^3 s^{-1} km^{-2}.

	Average time to peak (hrs)		Average peak discharge (m^3 s^{-1} km^{-2})		Average total volume of runoff (m^3 s^{-1} km^{-2})	
Lowest	Craigshill Wood	6.06	Little Puddle	0.004	Wilton	0.76
	Upton	7.63	East Mills Weir	0.005	Little Puddle	0.86
	Bissoe	8.00	Laverstock	0.005	East Mills Weir	0.97
	Bessom Bridge	9.81	South House	0.008	Trengoffe	0.98
	South House	10.00	Wilton	0.011	Amesbury	1.00
	Truro	10.69	Amesbury	0.012	Gwills	1.03
	Trenear Intake	11.00	St Erth	0.013	Trekeivesteps	1.04
	Milverton	11.13	Briants Puddle	0.015	Restormal	1.05
	Taw Bridge	11.13	Knapp Mill	0.016	North Newnton	1.07
	Gwills	11.25	Baggs Mill	0.019	South House	1.26
Highest	Wilton	21.75	Upton	0.194	Bishops Hull	2.36
	Baggs Mill	23.38	Rockhay Bridge	0.198	Halsewater	2.36
	Denby	23.38	Torrington	0.199	Trenear Intake	2.44
	Up Avon West	27.25	De Lank	0.204	St Erth	2.62
	Knapp Mill	27.88	Gribbleford Bridge	0.217	Crowford Bridge	2.80
	East Mills Weir	29.19	Norley Bridge	0.241	Gribbleford Bridge	2.81
	Briants Puddle	32.25	Bastreet	0.335	Umberleigh	2.89
	Crowford Bridge	34.06	Taw Bridge	0.340	Craigshill Wood	3.55
	Amesbury	44.44	Jacobstowe	0.382	Tregony	3.69
	Tregony	47.19	Vellake	1.035	Norley Bridge	4.78

Table 4.13 Average catchment response characteristics over the four storm events.

Umberleigh, Torrington, Stoodleigh, Whitford and Rockhay Bridge catchments are among the largest catchments in the sampled set, with areas greater than 259km^2. The responses of large catchments to storm events are normally damped and characterised by longer lag times as a result of longer travel times to the main channel. With time to peak values less than 19 hours, the response times of these relatively large catchments are approximately equal to or less than the average response time for the 48 catchments and four storm events analysed. Hence these catchments are distinctively flashy in comparison to other catchments in the study. In contrast, Tregony, Amesbury, North Newton and Briants Puddle display higher than average response times, indicated by average times to peak presented in table 4.13. The responses of these catchments are damped in comparison to other sampled catchments.

Summary

- This chapter presents the results of catchment parameterisation using the GIS procedures and data outlined in Chapter 3.
- Catchments displayed wide variability in terms of physiographic and terrain characteristics (section 4.3.1), and the attributes of the land surface (section 4.3.2), including geology, soil HOST classes and land use.
- The land use of all 48 study catchments was predominantly agricultural and dominated by grassland, cereal cultivation and horticultural production; major urban or uncultivated land covered just 4.5% of catchments on average.
- Hydrometric data presented in section 4.3.3, exhibited high variability both spatially between catchments and temporally, between the four storms for each individual catchment.

Against this background of extreme variability in catchment environmental and runoff characteristics, the following chapter (5) applies a statistical approach to the presented catchment database, to explore whether it is possible to distinguish the dominant factors controlling regional hydrological responses to large storm events.

Chapter 5

The effects of environmental variables on runoff at the catchment scale: I. Indirect ordination and classification using environmental data (Part II)

5.1 Introduction

Chapter 5 analyses the environmental characteristics of the 48 study catchments (chapter 4) using a series of multivariate statistical techniques (chapter 3) to satisfy objective one of the thesis;

'To investigate the factors influencing regional catchment responses to extreme storm events.'

A wide range of strongly independent factors will affect the nature and rate of runoff movement to a stream. These include storm patterns, catchment area, basin shape, the length and steepness of slopes and drainage density, in addition to subsurface geology, soil permeability and moisture content, vegetation cover and land use.

This chapter examines the key factors driving patterns in catchment scale environmental data and the volume of runoff produced during four storm events. Hence, the data are unstandardised by area. A combination of classification and indirect ordination approaches are employed to examine relationships between the environmental variables, investigate catchment groupings and identify the significant factors driving environmental gradients. Clustering is used to classify the 48 sampled catchments based on shared environmental characteristics. A non-parametric analysis provides a display of the similarity or dissimilarity of the catchments, positioned in relation to axes of variation within the environmental data.

Both nMDS (non-linear) and PCA (linear) ordination techniques (section 3.4.2) are used to detect the key environmental gradients constraining observed groupings, and to reduce the environmental dataset by highlighting redundant variables and outlying catchments with extreme or unusual environmental characteristics (ter Braak and Šmilauer, 2002). The distributions of measured environmental variables are examined and data are transformed where necessary.

The percentage of variability in runoff explained by primary environmental drivers at the catchment scale is tested indirectly by a regression analysis between the principal components (axes) and measured runoff volumes.

5.2 Ordination of the full environmental data set

As the first stage, ordination was performed on the entire environmental data set, comprising 83 environmental variables and 48 catchments. This initial analysis was undertaken primarily to explore the data. Using PRIMER software (Plymouth Marine Laboratory), non-metric multidimensional scaling (nMDS) was performed on a Bray-Curtis similarity matrix with unstandardised and untransformed data. In the resultant MDS plot there was a marked horizontal gradient in the distribution of catchments according to the volume of runoff they produced.

The apparent trend in catchment runoff data was further examined through the classification of catchments using hierarchical clustering. The similarity level was determined subjectively based on observation of distinct groups in the dendrogram. Clustering of catchments at the 30% similarity level identified two catchment groups with an almost even split in the sampled set. The cluster dendrogram is displayed in figure 5.1).

The catchment groups identified using classification were subsequently investigated using factor analysis to establish the environmental parameters driving this patterning. According to the output table, catchments in both groups one and two exhibit a relatively high percentage similarity at approximately 50% (table 5.1). Moreover, they are fundamentally constrained by catchment area, which is responsible for explaining 39% of the similarity in group one and 46% in group two. In addition, the land use type I_GRS (improved grassland) is also important and explains 18% of the similarity between catchments in group one and 17% in group two.

a)

Variables	Contribution to percentage variance explained (%)	Cumulative percentage variance explained (%)
Area	**39.21**	**39.21**
I_GRS	18.07	57.27
MU_SLT	9.37	66.64
AR_CER	5.54	72.19
WOOD	5.28	77.47
SST	4.72	82.19
AR_HORT	4.71	86.89
LST_O	4.44	91.33

Group 1 average similarity: 47.31%

b)

Variables	Contribution to percentage variance explained%	Cumulative percentage variance explained (%)
Area	**45.83**	**45.83**
I_GRS	16.55	62.38
MU_SLT	8.75	71.13
GRAN	5.88	77.01
GRS	5.59	82.60
AR_HORT	4.37	86.98
WOOD	4.07	91.05

Group 2 average similarity: 49.57%

Table 5.1 Results of factor analysis of the entire data set, including 83 variables and 48 catchments. Factors controlling the similarities in catchments are presented for a) group 1 and b) group 2.

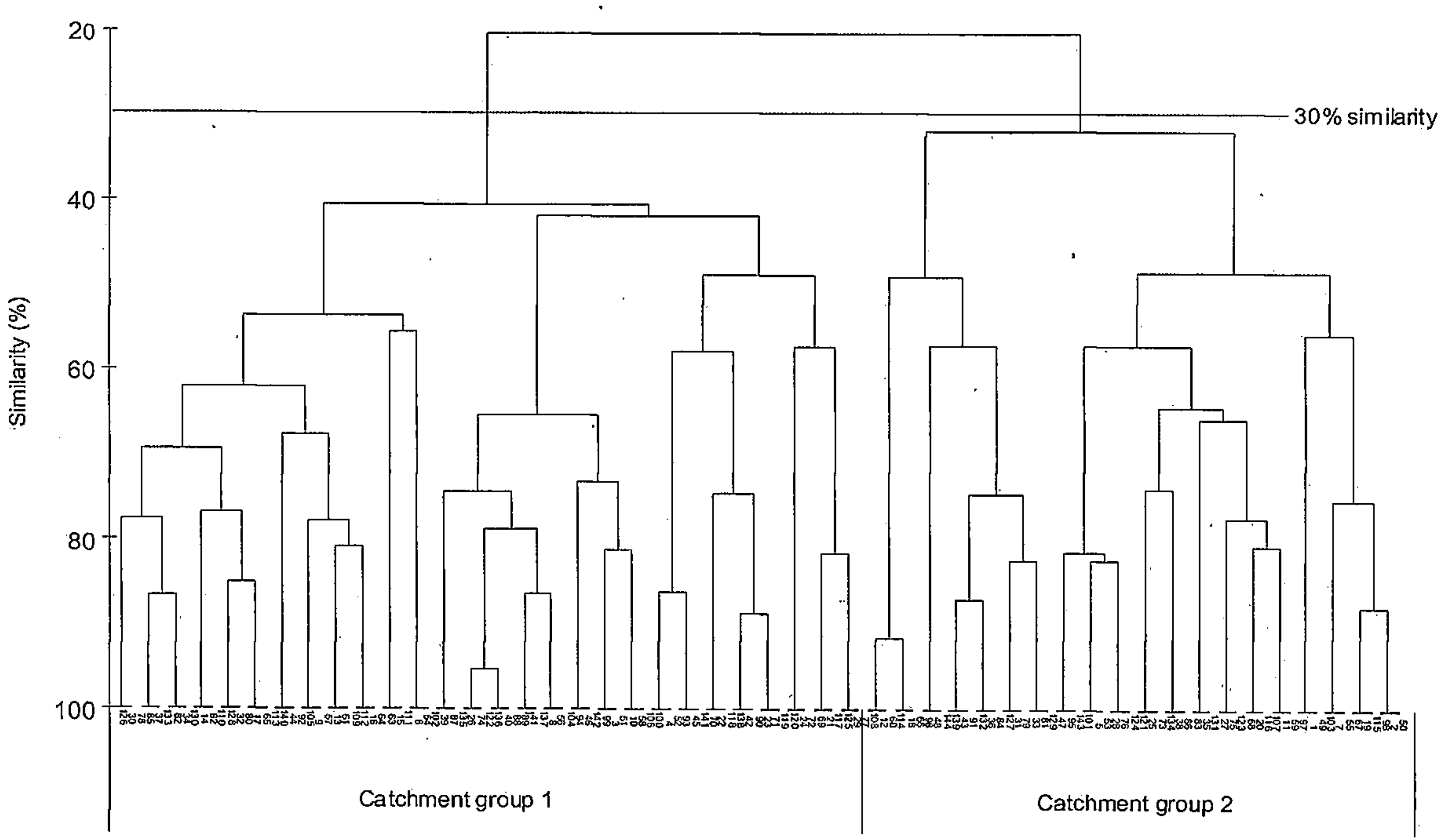


Figure 5.1 Dendrogram of cluster analysis performed on the entire environmental dataset.

Catchments in group one have smaller basin areas and range from Upton, with an area of 8.7km², to Up Avon West catchment which is 85km². In group two, catchment areas range from 95km² at Tregony, to the largest catchment at Knapp Mill, which measures 1717km².

5.3 Normality testing of the environmental data

The apparent split in the sampled catchments implies that the data set is not normal. Statistical testing that incorporates assumptions of normality or linearity should not be applied without first investigating this. Hence, selection of the most appropriate statistical methodology necessitated a thorough examination of distributions in the data. Two complementary procedures were performed to examine whether data were normally distributed. Firstly, plotting the frequency distribution of each of the environmental variables enabled a visual investigation of the degree of skew in each of the environmental data sets. Drainage density (DD), SLOPE and X and Y coordinates exhibited a near-normal distribution, all other data were skewed.

Data therefore underwent a second process of statistical testing of normality in Minitab™ Release 13.31 (Minitab Inc™, 2000), using the Anderson-Darling normality test. This statistically tests the null hypothesis that the data should follow a normal distribution. If the *p*-value of the test is lower than a rejection level of 0.05 (95% confidence level), then the null hypothesis is rejected and the distribution of the data is not normal.

The physiographic variables SLOPE<6, SLOPE<12, TI<25 and DD, spatial variable Y, and land use types WOOD, AR_CER, AR_HORT and I_GRS all displayed significant normal distributions. Nonetheless, the majority of the environmental variables failed to satisfy the normality assumption. In order to reduce their apparent skew, these data were subsequently transformed using either a $\log_{10}$ or square root transformation before being re-tested. Variables that failed to statistically normalise despite various attempts at transformation, were incorporated into the analysis following a $\log_{10}$ transformation, after Burgess (2004). Having transformed the data where necessary, both nMDS ordination and hierarchical clustering were repeated. The results of MDS again revealed a gradient in the data, but an improved stress tolerance at 0.13.

The clustering dendrogram is presented in figure 5.2 and as before, shows two distinct groups that become partitioned on this occasion at the higher, 70% similarity level. The results of factor analysis performed on the grouped catchments are presented in table 5.2. The catchment group statistics mirror those generated from the first set of analyses performed on untransformed data, with two groups exhibiting approximately 50% similarity. Correspondingly, the analysis distinguishes area as the primary environmental driver. Area accounts for 40% of the similarity in group one and 46% in group two (table 5.2).

The presence of two distinct groups in the data set has important implications on the methodology adopted since the data violate the assumption of linearity, which is intrinsic to parametric statistical techniques. An alternative approach, which improves the linearity of the data set, involves the development of two statistical models, for large and small catchments. A second option involves the use of higher order, non-linear statistical approaches that do not require data to fulfil assumptions of normality or linearity.

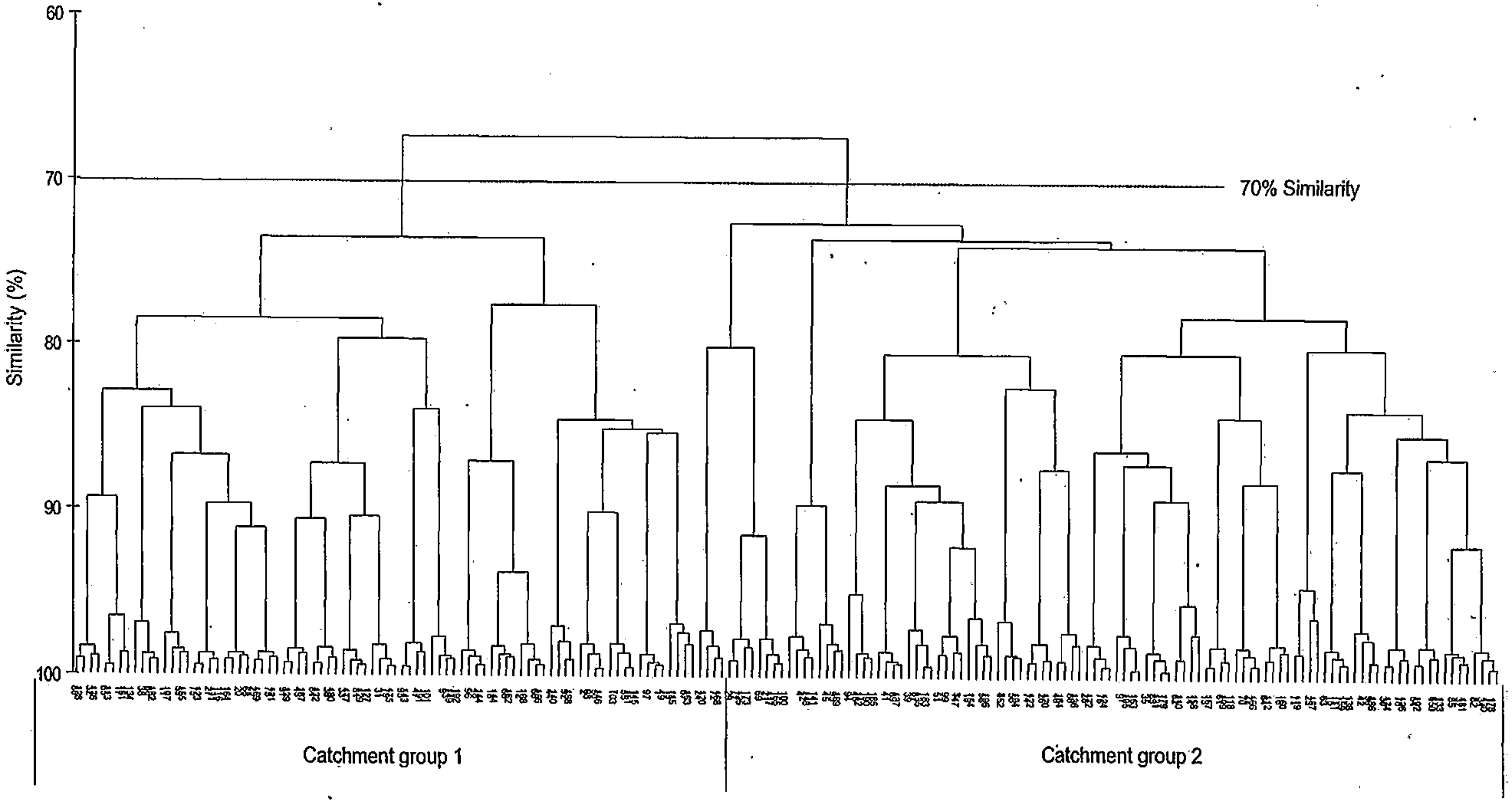


Figure 5.2 Dendrogram of cluster analysis performed on the entire environmental dataset.

a)

Variables	Contribution to percentage variance explained (%)	Cumulative percentage variance explained (%)
Area	**39.68**	**39.68**
I_GRS	18.27	57.95
MU_SLT	9.45	67.39
AR_CER	5.61	73.00
WOOD	5.34	78.35
AR_HORT	4.77	83.11
SST	4.73	92.36
LST_O	4.51	87.85

Group 1 average similarity: 48.17%

b)

Variables	Contribution to percentage variance explained (%)	Cumulative percentage variance explained (%)
Area	**46.12**	**46.12**
I_GRS	16.62	62.75
MU_SLT	8.69	71.43
GRAN	5.90	77.33
GRS	4.10	82.99
AR_HORT	4.41	87.39
WOOD	5.66	91.49

Group 1 average similarity: 50.94%

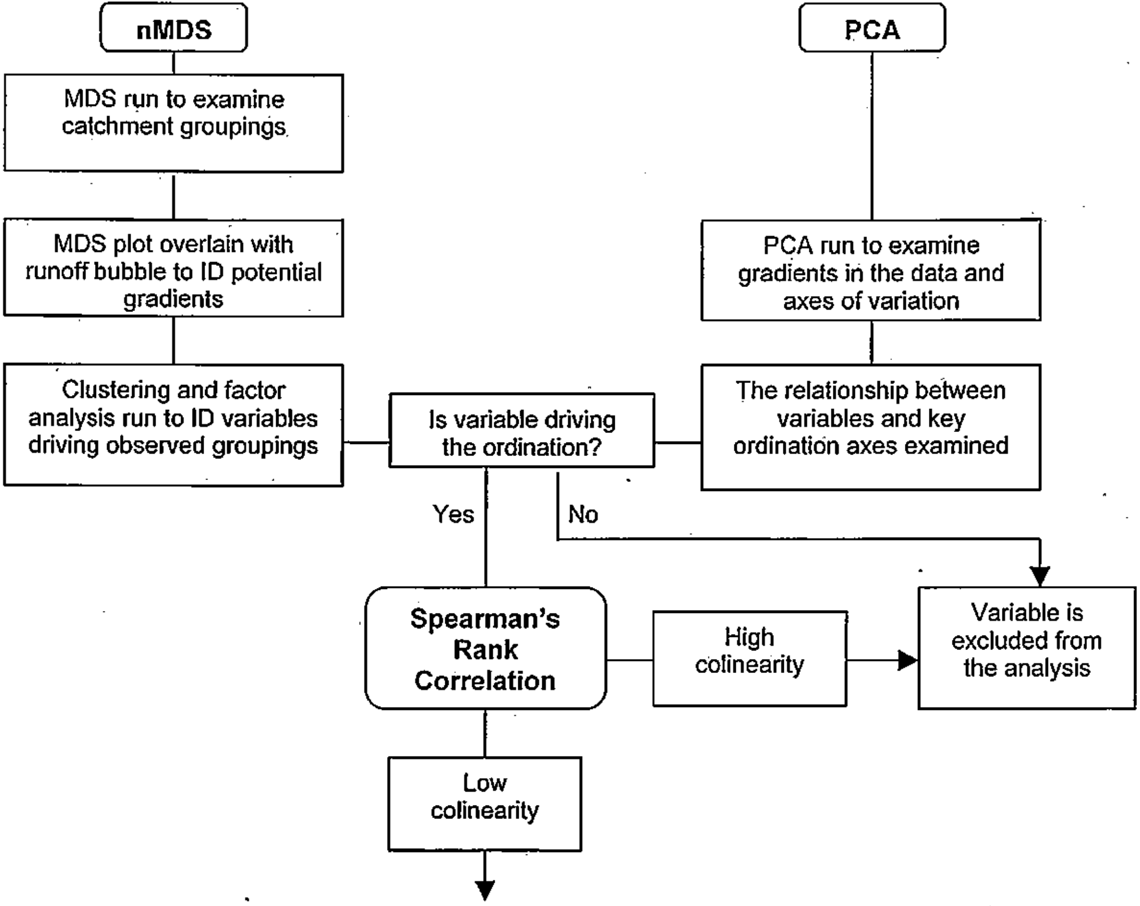
Table 5.2 Results of factor analysis of the entire data set, including 83 variables and 48 catchments. Factors controlling the similarities in catchments are presented for a) group 1 and b) group 2.

The overriding significance of area warrants careful consideration. In conjunction to the effects on catchment clustering, area is inevitably incorporated into the calculations of several other environmental variables, causing observed skew in their distributions. The following set of ordinations investigates the influence of environmental parameters on runoff at the catchment scale. This process examines more closely the influence of area on the overall analysis and the nature of the model applied.

5.4 Data Reduction

Large datasets often contain redundancies that contribute little to the analysis and are usually removed (Burgess, 2004). Screening of the environmental data for redundant variables using both nMDS (non-linear) and PCA (linear) ordination methods refined the data set to a smaller number of important environmental parameters, which could better explain the variability in catchment runoff. It was essential that environmental variables were included in the final set which were representative of all major catchment characteristics, namely land use, soils, geology, topography and drainage, and rainfall. Corresponding subsets of environmental data were consecutively analysed to establish the significant variables in each set that were constraining the key ordination axes (figure 5.3).

Figure 5.3 summarises the systematic process of testing undertaken on environmental subsets, incorporating ordinations with clustering to identify the key variables forcing environmental gradients in each of the datasets. Redundant variables or unusual catchments were excluded. Variables found to be driving catchment groupings within subsets were subsequently tested for colinearity using matrices of Spearman's Rank correlation coefficients (r_s) in Minitab 13^{TM}. Highly collinear variables were excluded from the final reduced set. Between-set intercorrelations were examined at a later stage in the analysis.



Reduced environmental parameter subsets						
Geology	Spatial	Soil		Topography	Rainfall	Land Use
LST_O	XY	HA	HU	AREA	RF_T	I_GRS
GRAN		HA	HD	SLOPE	RF_AV	AR_CER
MU_SLT		C	HF	STRM_L	RF_MAX	AR_HORT
SST		HO	HX	DD		GRS
BREC_C		HR		SLOPE<6		WOOD
MU_SST		HQ		SLOPE<12		BDP
				TI<10		DEV
				TI<15		C_URB

Figure 5.3 Methodology for the selection of environmental variables to be included in the final ordination.

5.5 Ordination (PCA) of the reduced dataset

Using CANOCO for windows version 4 (ter Braak and Šmilauer, 1998), a standard PCA was run to distinguish the significant environmental gradients and identify outlier sites with extreme or unusual environmental characteristics. PCA was performed on a correlation matrix with centring and standardisation of the environmental data. Standardisation to unit variance brings all means to zero and the variances to one (Lepš and Šmilauer, 2003).

Axis	Eigenvalue	Cumulative % variance
1	0.426	42.6
2	0.162	58.8 (16.2)
3	0.117	70.5 (11.7)
4	0.065	77.0 (6.5)

Table 5.3 Results of PCA analysis on the 48 catchments and 35 environmental variables. (Numbers in parentheses indicate individual axes contributions).

Table 5.3 presents the eigenvalues and cumulative variance attributable to the first four ordination axes. The results indicate that the reduced set of 35 environmental variables explain a significant proportion of the variance in the data. The total percentage of variance in the data that is accounted for by the first four axes is relatively high at 77%. A comparison of the proprtion of variance explained by each of the axes individually suggests that axis one represents the principal gradient of variation in the environmental dataset. There is a large difference between the percentage variance explained by axis one (43%), and axes two (16.2%), three (11.7%) and four (6.5%). A regression analysis tested the ability of axis one factor scores to predict the variability in runoff for 48 catchments and four storm events. Despite the huge temporal variability in runoff volumes between individual storm events, axis one demonstrated a fairly strong positive relationship with runoff (logged and standardised to unit variance) ($r^2 = 0.43$, $r = 0.66$, $p<0.05$) (figure 5.4).

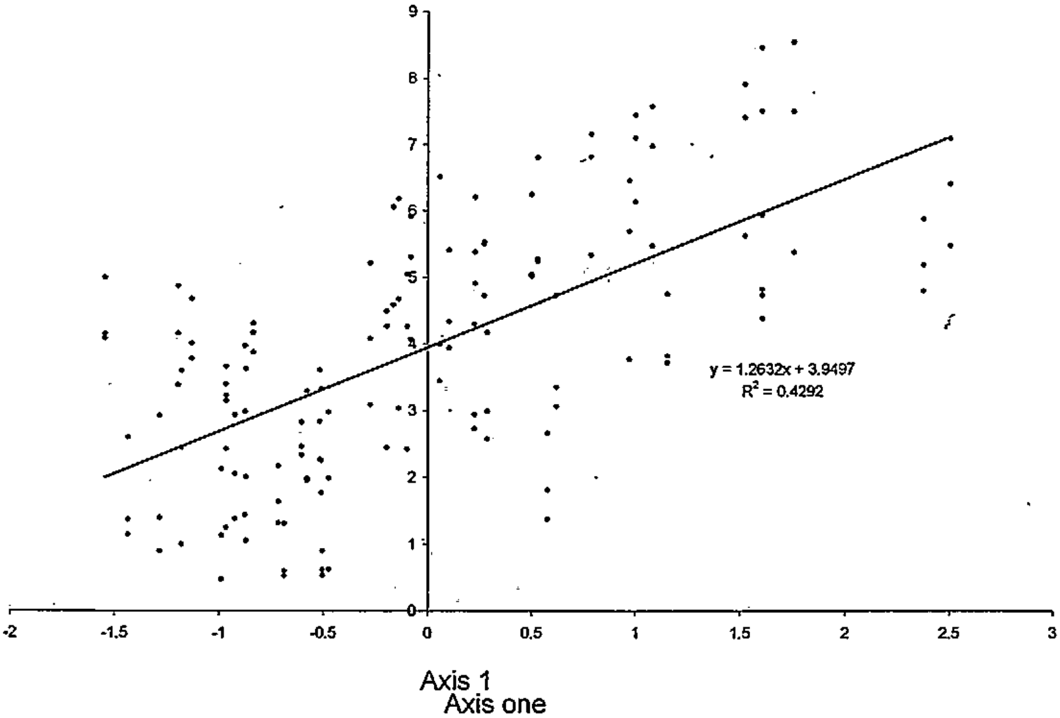


Figure 5.4 Scatter plot displaying the relationship between total runoff volumes and principal component axis one.

Of all environmental variables tested, those most closely related to axis one will exert a stronger influence on catchment runoff volumes. This is detectable through an examination of the interset correlations of the environmental variables versus the first four ordination axes, listed in table 5.4. For each variable, the axis it is most significantly correlated with is highlighted. Axis one is driven by a number of factors, but is most strongly governed (in order of importance) by STRM _L, AREA, AR_CER, SLOPE<6, I_GRS, AR_HORT, WOOD, TI<15, DEV, SLOPE<12, C_URB, TI<10, GRS, SST and MU_SLT. Almost perfect relationships exist between physiographic and land use characteristics, and the major ordination axis. This infers that these catchment attributes are fundamentally controlling the variability in the dataset. Axis one is negatively correlated with HOST classes HD, HO and HAC.

Interestingly, climatic characteristics RF_T, RF_AV and RF_MAX are most strongly correlated with axis four, which accounts for a comparatively small amount percentage of the variability in the data (6.5%), see table 5.4. By the same token, soil variables relate to axes two and three, which together explain less variability (27.9%) in the dataset than axis one alone (42.6%).

Environmental Variable	**Ordination Axes**			
	1	**2**	**3**	**4**
AREA	0.97			
HA		-0.80		
HD	-0.50			
HF		-0.51		
HO			0.64	
HQ		0.60	-0.47	
HR			-0.57	
HU			-0.65	
HX			-0.57	
HAC			0.61	
SLOPE		0.47		
RF_T				0.57
RF_AV				0.54
RF_MAX				0.58
STRM_L	0.98			
DD	0.53			
WOOD	0.95			
AR_CER	0.96			
AR_HORT	0.95			
I_GRS	0.95			
GRS	0.75			
BDP		0.69		
DEV	0.92			
C_URB	0.89			
GRAN		0.61		
BREC_C		0.58		
SST	0.75	0.07		
MU_SST		0.58		
MU_SLT	0.69	0.48		
LST_O		-0.68		
SLOPE.6	0.95			
SLOPE.12	0.91			
TI.10	0.85			
TI.15	0.94			
XY		-0.52		

Table 5.4 Interset correlations between 35 environmental variables and first four axes of ordination.

The small angles between arrows in the bi-plot are symptomatic of high correlation between these variables. Indeed many of the more significant variables are closely aligned to stream length and area.

5.6 Spearman's Rank correlation: testing colinearity

It is extremely difficult to elucidate the individual impacts of catchment attributes on peak flows when area is implicit in calculations of many of the measured environmental variables. For example the areas of land use and geology classes, the frequencies of slope and topographic index classes, and rainfall characteristics. This is particularly discernable in this instance, where a series of clustering and ordination analyses have demonstrated that area is underpinning the prinipal ordination axis, explaining a significant proportion of the variability in runoff.

Spearman's Rank correlation coefficients were thus employed to examine the colinearity of area by statistically testing the relationships between catchment area and key environmental variables using the original data (untransformed). Table 5.5 presents the resultant Spearman's Rank correlation coefficients (r_s>0.6, p<0.01) between AREA and environmental variables. As predicted, area is highly multicolinear and strongly intercorrelated with a range of land use, geology, topographic variables and runoff, including near pefect correlations with STRM_L, SLOPE_6, TI_15, L_GRS, TI_20 and WOOD (table 5.6).

A regression analysis was undertaken to further test the importance of basin area (independent) on total runoff volume (dependent) at the catchment scale. Figure 5.6 presents results of a regression analysis between catchment area (logged) and runoff (logged and standardised to unit variance) for 48 catchments and four storm events. Area is responsible for explaining approximately 50% of the variability in total runoff volumes ($r^2 = 0.48$, $p<0.05$).

Environmental variable	Spearman's Rank Correlation
STRM_L	0.998
SLOPE6	0.987
TI15	0.986
I_GRS	0.979
TI20	0.966
WOOD	0.962
TI25	0.936
AR_HORT	0.924
AR_CER	0.914
SLOPE12	0.914
DEV	0.911
TI30	0.908
TI10	0.903
C_URB	0.901
SLOPE18	0.805
IBG	0.779
GRS	0.764
RO	0.743
MU_SLT	0.739
SLOPE24	0.736
DDSH	0.723
MAXQ	0.649
SLOPE30	0.645
LST_O	0.633
SST	0.612

Table 5.6. Spearman's Rank Correlation coefficients (r_s) between AREA and environmental variables, where $r_s>0.6$.

Where environmental attributes are intercorrelated with area, it is quite possible that any measured influence they appear to have on runoff volume at the catchment scale may largely be explained by the relationship between area and runoff volumes. Failure to acknowledge this in the analysis will generate erroneous results that are wholly misleading. Unless the effects of area are removed from the analysis, it will be impossible to accurately ascertain the impacts of intercorrelated variables on runoff volumes.

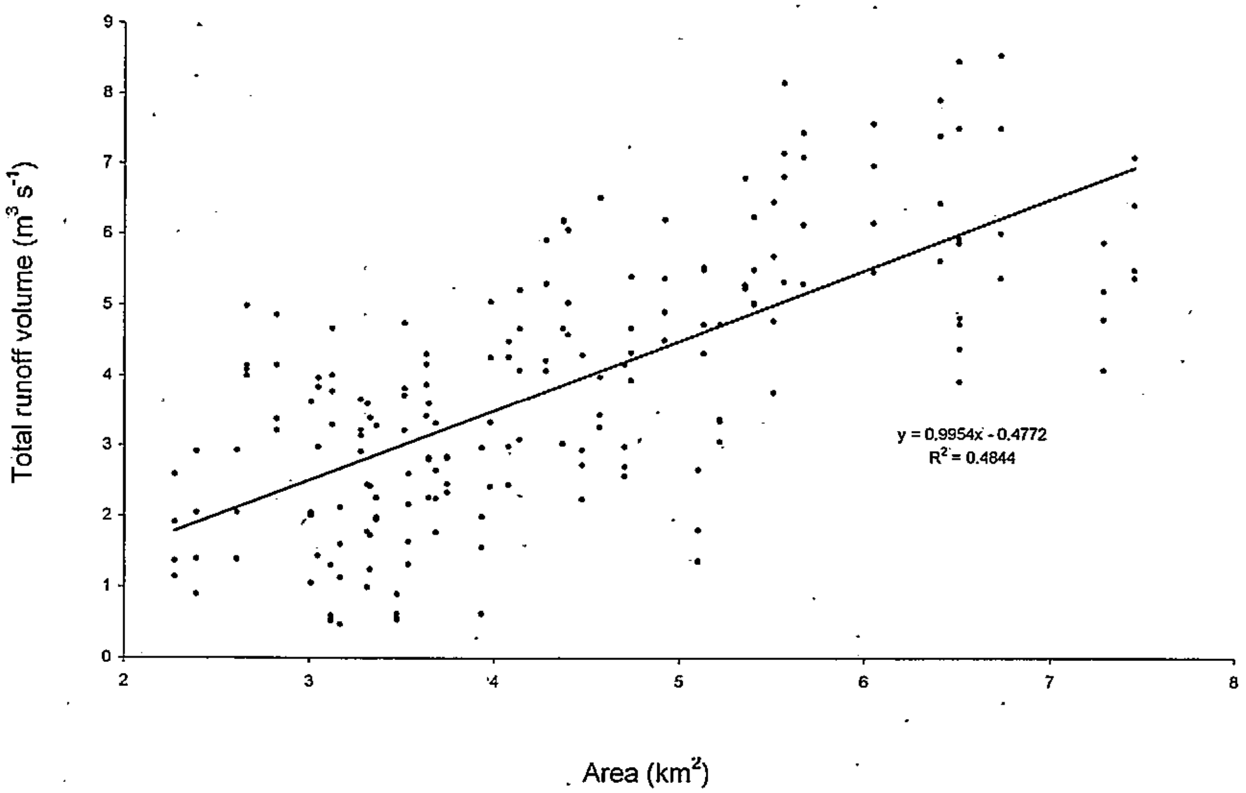


Figure 5.6 Relationship between area (logged) and total runoff volumes (logged and standardised to unit variance) for 48 catchments and four storm events.

5.7 The effects of environmental variables on runoff at the catchment scale: II. Catchment data standardised per unit area (km^2)

5.7.1 Introduction

Area is of foremost importance in explaining variability in catchment runoff volumes. Ordination and clustering have identified area as the key environmental gradient governing patterns in total runoff at the catchment scale. Even so, it is also apparent at this scale that the individual impacts of catchment parameters, including slope steepness, land use and soil type, are impossible to clearly distinguish due to their high colinearity with area. The inherent difficulties of disentangling the effects of catchment area from the results of ordinations at the catchment scale have necessitated the standardisation of area-dependent catchment parameters to represent values per unit area (km^2).

Essentially, this involves identifying all measured catchment parameters that are influenced by the size of the river basin and dividing (or standardising) the data by the catchment area (this should not be confused with standardisation per unit variance in previous sections, which refers to division by the standard deviation). Using area-standardised data reduces the influence of catchment area, thereby helping to elucidate the effects of additional environmental parameters, and the interactions between them, on patterns of variability in measured volumes of runoff.

The following sections investigate the effects of environmental parameters on volumes of runoff per km^2, using catchment data that are standardised by area and transformed. A suite of complementary statistical techniques is used, including both indirect (DCA/PCA) and direct (RDA) ordination methods with the aim of explaining patterns in runoff data from distributions in the environmental data.

5.7.2 Ordination

Detrended Correspondence Analysis (DCA) and Principal Components Analysis (PCA) are also used to examine trends in the runoff and environment data. Redundancy Analysis (RDA) is subsequently adopted to test the statistical significance of environment-runoff relationships, thereby facilitating the identification of the environmental parameters that are most strongly correlated with distributions of measured runoff volumes. The statistical approach follows a step-by-step process, which is repeated on two multivariate runoff datasets, including five runoff frequency classes and four individual storm events.

Direct gradient analysis is a multivariate statistical analysis. Unlike other multivariate techniques, such as multiple linear regression which examines the ability for a number of independent variables to explain the variability in a single, dependent variable, gradient analysis can be used to investigate the relationships between two sets of multivariate data. This characteristic of gradient analysis facilitates simultaneous investigation of the degree of similarity between individual samples (catchments) and species (runoff measurements), and how the order of the individuals is correlated with underlying environmental controls (Kent and Coker, 1992).

In order to thoroughly examine the relationships between environmental variables and runoff, gradient analysis was undertaken using environmental data and two separate runoff datasets. Runoff volume per unit area is a single variable and hence, is not multivariate. Two approaches were adopted to derive multivariate runoff datasets from a univariate one. In the first instance, the runoff dataset comprised four sets of runoff volumes (m^3 s^{-1} km^{-2}) calculated from the river discharges (per unit area) of the 48 catchments following four separate storm events. These events represented the four largest storms, by volume of rainfall, occurring during the period autumn/winter 2000-2001. In this manner, each storm event is treated as an individual component (species).

It is acknowledged that measured rainfall data are exclusive to individual events and their associated catchment responses. Therefore, in addition to the four sets of storm rainfall characteristics, variables representing average rainfall figures and the standard deviation of total rainfall volume were calculated and included in the environmental data matrix as part of the rainfall subset.

In the second analysis, the entire dataset of runoff volumes ($m^3 s^{-1} km^{-2}$), including all 48 catchments and all four storms, was assigned to one of five frequency classes or bin classes. These classes were determined following a detailed examination of the distribution in runoff data. A series of frequency histograms were derived from different ranges and numbers of runoff bin classes. Runoff classes range from one to five with class one representing low volumes and five, high volumes. The precise class distinctions are presented in table 5.7. For each catchment, the percentage occurrence of the storms in each class is calculated. All runoff data were standardised by area and logged prior to categorisation and analysis.

Bin Class	Storm runoff volume ($m^3 s^{-1} km^{-2}$)
1	< or = 0.26
2	< or = 0.44
3	< or = 3.5
4	< or = 6.3
5	< or = 14

Table 5.7The upper limits of the five runoff bin classes used in direct ordinations.

The following statistical analysis is repeated on each of the two runoff datasets. At each stage in the analysis, the procedure is outlined and the results of ordinations on each set consecutively presented. Thus, for every sub-section there will be two sets of results.

5.7.2i Detrended Correspondence Analysis (DCA): Linear or unimodal methods?

Ordination methods are available that are based upon linear species responses to environmental gradients, such as PCA (indirect) and RDA (direct), or those that use weighted averaging methods which correspond to unimodal species response models, such as Canonical Correspondence Analysis (CCA) (Lepš and Šmilauer, 2003). The most appropriate technique will be dictated by the nature and distribution of the data. According to Lepš and Šmilauer (2003), the lengths of gradients following Detrended Correspondence Analysis (DCA) measure the diversity in composition of the data (or turnover) along the ordination axes, and indicate the most appropriate model.

Runoff data were examined using a DCA, with detrending by segments, on both runoff datasets and all 48 catchments. The longest gradient length for the bin class runoff set was 2.53 standard deviation units. The corresponding figure for the storm set measured 0.27 standard deviation units. Linear ordination methods are recommended where the longest gradient is less than 3.0 standard deviation units, since the data are deemed not to be too heterogeneous (Lepš and Šmilauer, 2003). Hence, environment-runoff relationships were investigated using linear ordination techniques for direct gradient analysis, namely RDA.

5.7.2ii Indirect gradient analysis (PCA): All catchments and all runoff data

PCA undertaken on runoff data for all 48 catchments enabled underlying trends or gradients to be examined and facilitated identification of unusual catchments. The characteristically extreme values of erroneous catchments on ordination axes may act to compress the remaining catchments into a smaller area of the ordination plot, resulting in an insufficient explanation of the total variability within the dataset (Burgess, 2004).

Results: Four storm runoff dataset

Table 5.8 presents the results of PCA performed on the storm runoff dataset for all 48 catchments. The high percentage variance explained by axis one (81%) and overall percentage explained by all four axes (100%) illustrates the lack of noise in the data and supports the choice of linear ordination methods.

Axis	Eigenvalue	Cumulative % variance of runoff data represented
1	0.808	80.8
2	0.086	89.4 (8.6)
3	0.080	97.4 (8.0)
4	0.026	100.0 (2.6)

Table 5.8 Results of PCA performed using storm runoff data for 48 catchments four storms.

Figure 5.7 displays the ordination bi-plot of PCA undertaken using the entire storm runoff dataset. The importance of axis one in representing variability in storm runoff is demonstrated by the horizontal direction and angle of the arrows. Principally, storm one is most strongly correlated with axis one, whilst storms two and four are most similar in terms of variability. Catchment 38 (South House) appears to be dissimilar to other catchments in terms of runoff volume for the four storm events.

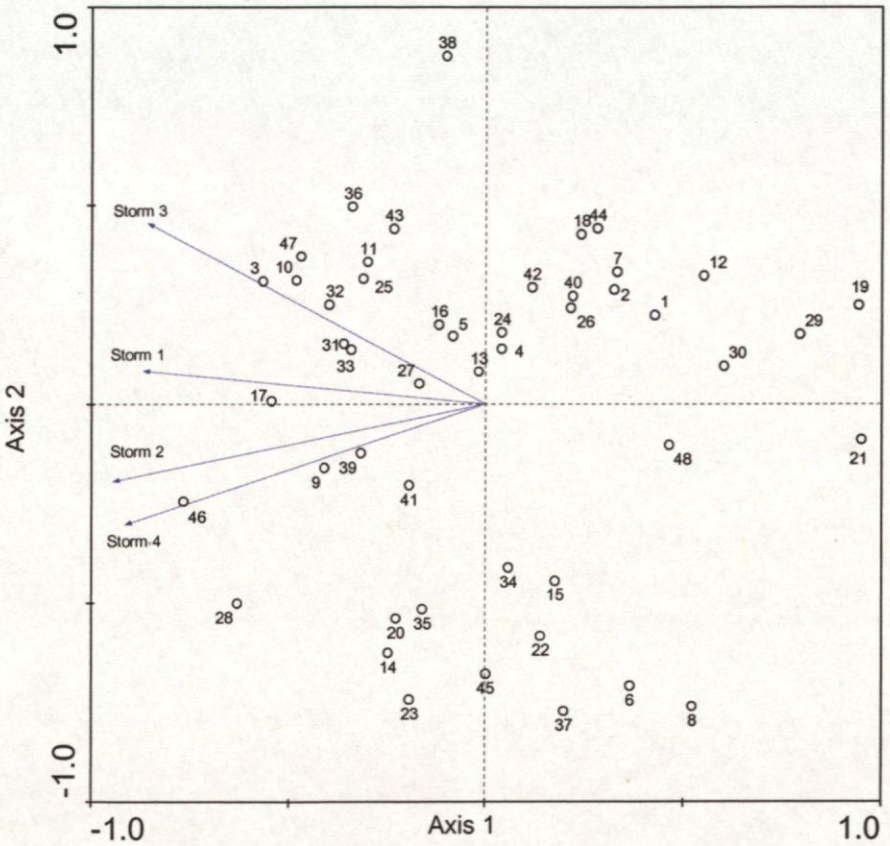


Figure 5.7 Ordination bi-plot (axis 1 vs. 2) illustrating the results of PCA on the full storm runoff dataset (four storms and 48 catchments).

Removal of outliers: Four storm runoff dataset

In order to establish groupings in the data and fully examine the presence of outlying catchments, MDS and cluster analyses were also undertaken. Figure 5.8 presents the resulting dendrogram of cluster analysis performed on the full storm runoff dataset. At the 50% similarity level four catchment groups were identified and two outliers, catchments 24 (Torrington) and 39 (Little Puddle) are circled in red. Catchment 38 (South House) was incorporated into the largest group, represented by a green circle in figure 5.9, which displays the catchment groupings applied to the PCA ordination diagram.

to low runoff volumes. At the 60% division on the cluster dendrogram this group would be sub-divided into three groups. However, at this stage in the analysis this was not deemed necessary.

Group 3 Group three catchments are situated in the lower left hand quadrant and are characterised by average runoff volumes, most closely related to storm four.

Group 4 Group four is the smallest group, comprising of catchments 27 (Taw Bridge) and 41 (Baggs Mill). These are both located towards the middle to left of the diagram and are characterised by average runoff.

The MDS plot is presented in figure 5.10 and is overlain with a runoff bubble plot, which shows a slight horizontal gradient right to left of the diagram. As with the results of cluster analysis, it does not show catchment 38 (South House) as distinct from other catchments. However, catchment 24 (Torrington) is usual in the context that it exhibits relatively high runoff (donated by a large bubble), yet is positioned to the right of the diagram. The unusual nature of catchment 24 (Torrington) is acknowledged but at this stage it is not removed from the analysis. This is due to the fact that it does not appear to be distinct from other catchments on observation of the ordination diagram. Conversely, the removal of catchment 38 (South House), which does appear to be dissimilar, reduces the sample set to 47 catchments.

The results of a PCA analysis performed on the reduced set are displayed in table 5.9. Removal of catchment 38 (South House) makes no change to the overall percentage of total variance explained by the first four axes (100%). However, it slightly improves the explanatory power of axis one, from 80.8% to 81.5% and axis two, from 89.4% to 89.6%.

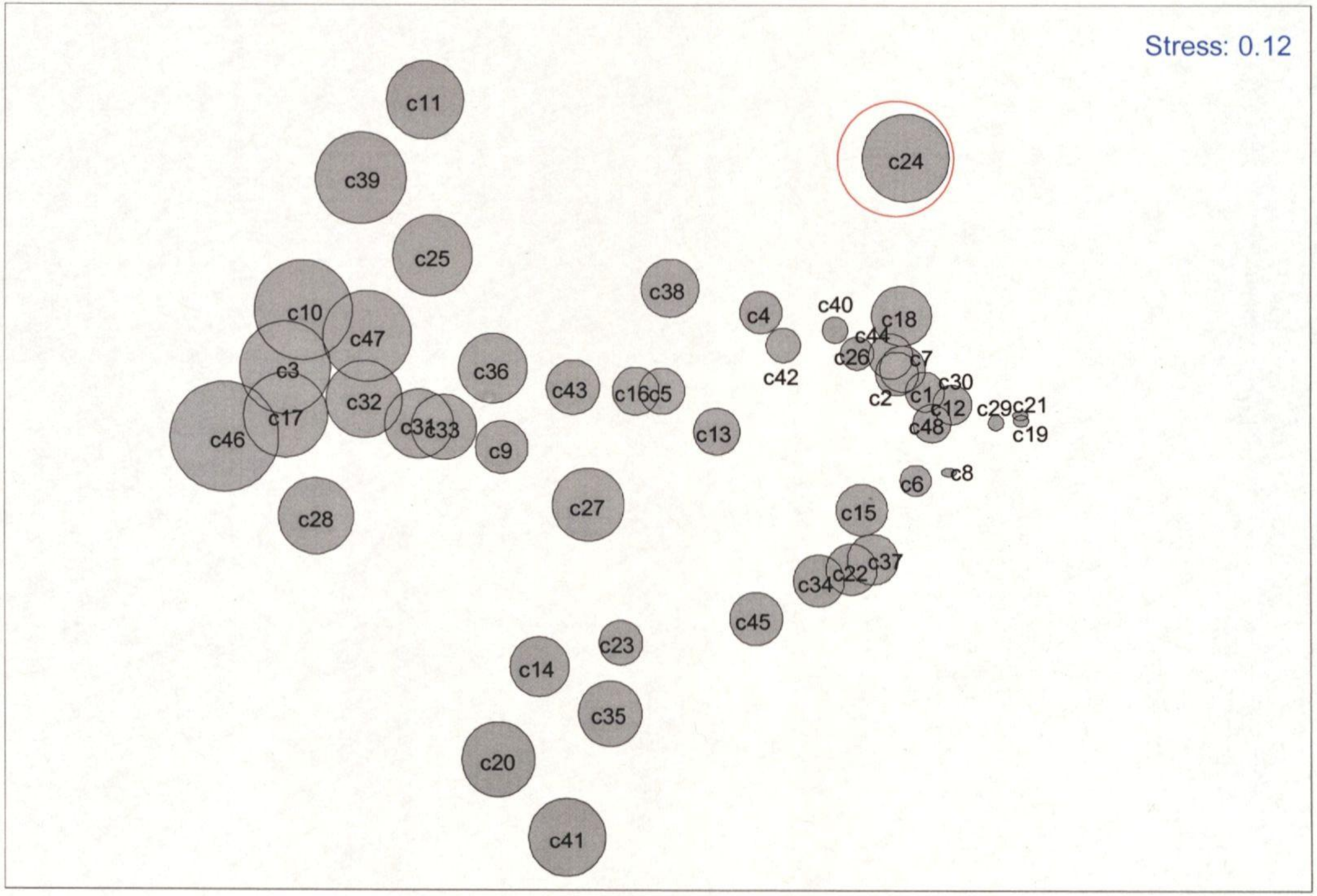


Figure 5.10 Results of MDS undertaken on all 48 catchments with runoff overlain as a bubble plot.

Results: Five bin class runoff dataset

The tabulated results of a PCA run using the bin class runoff dataset for all 48 catchments is presented in table 5.10.

Axis	Eigenvalue	Cumulative % variance of runoff data represented
1	0.472	47.2
2	0.215	68.7 (21.5)
3	0.185	87.2 (18.5)
4	0.127	100.0 (12.7)

Table 5.10 Results of PCA performed using five runoff bin classes and 48 catchments.

The first four axes explain 100% of the variability in runoff. The majority of the variability is explained by axis one (47%), with axes two and three explaining 22% and 19% respectively.

The resultant ordination bi-plot for the PCA is illustrated in figure 5.12. Bin classes one (RO_1), three (RO_3) and four (RO_4) are most strongly correlated with axis one, as indicated by the horizontal direction of the arrows. The highest runoff, bin class 5 (RO_5), is most strongly correlated with axis two. In general, catchments are distributed towards the centre of the ordination plot, with the exception of a cluster of catchments along bin class five that exhibit high runoff volumes. Catchment 38 (South House) at the top of axis two is exposed as an outlying catchment.

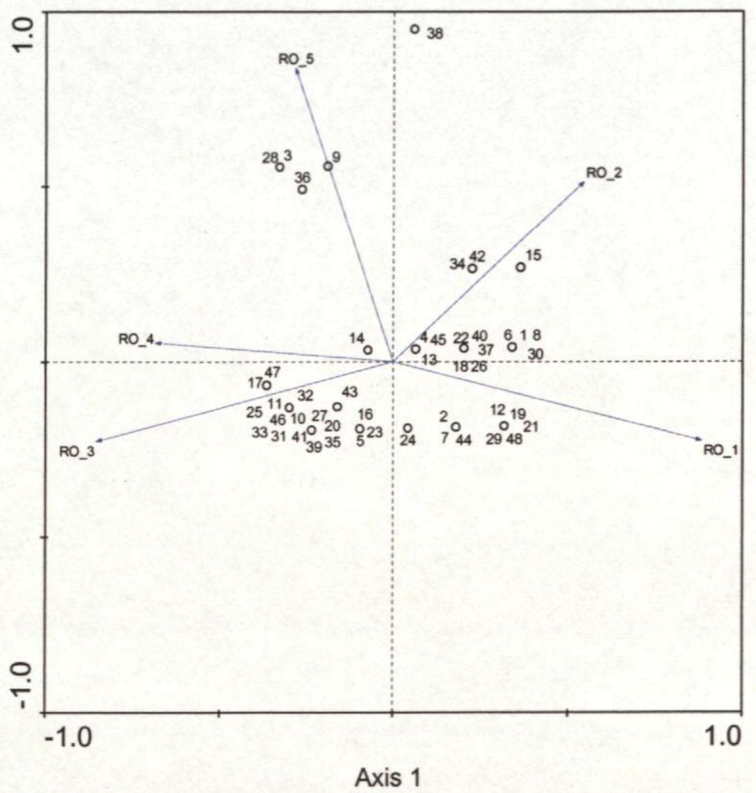


Figure 5.12 PCA ordination bi-plot (axis 1 vs. 2) for five runoff bin classes and 48 catchments.

Removal of outliers: Five bin class runoff dataset

In order to investigate similarity or dissimilarity of catchments in terms of the volume of runoff they produce, MDS and cluster analyses were performed on runoff data. The results of the cluster analysis are illustrated in the dendrogram in figure 5.13. At the 60% similarity level four catchment groups were identified and one outlier, 38 (South House). The catchment groupings are presented in the ordination bi-plot in figure 5.14.

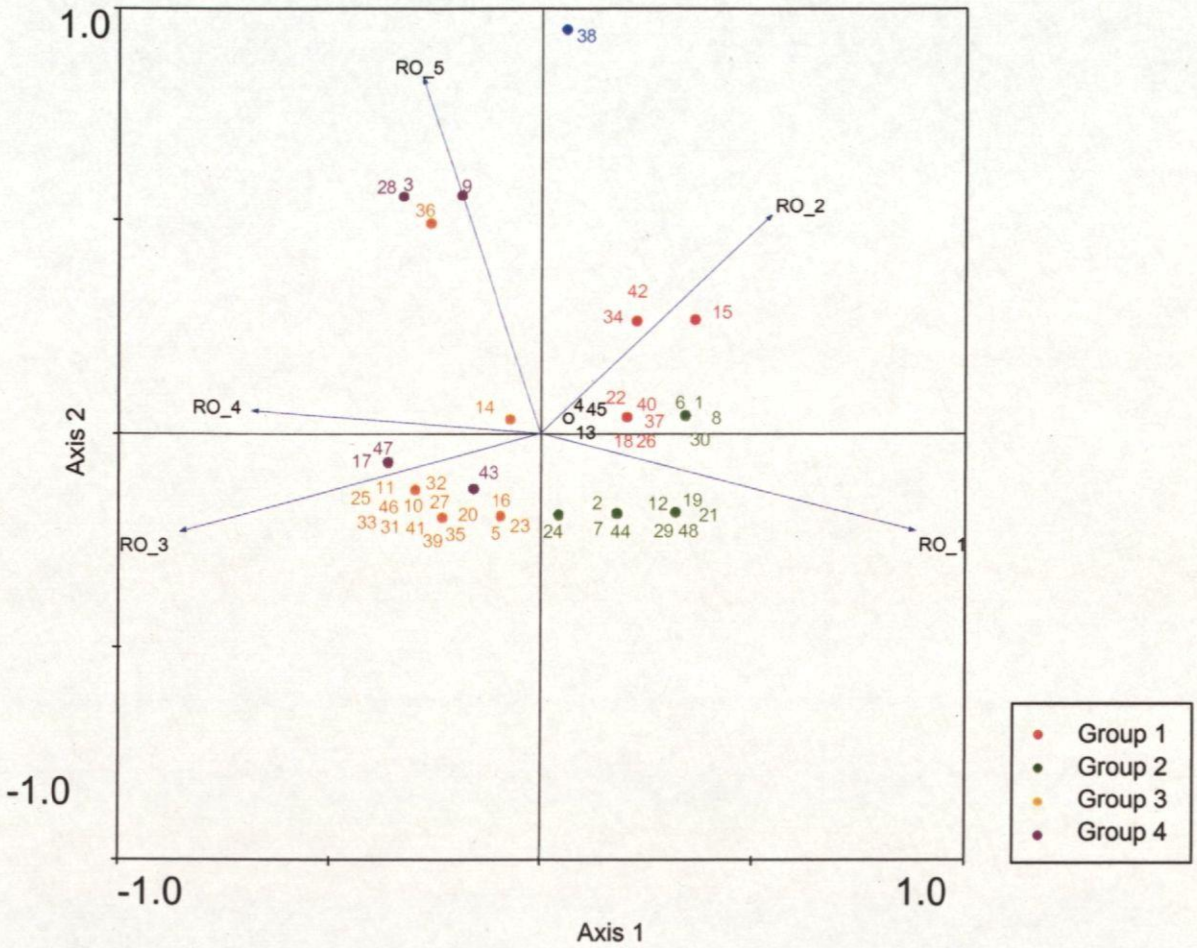


Figure 5.14 PCA ordination bi-plot (axis 1 vs. 2) for five runoff bin classes and 48 catchments. Catchments are grouped according to the results of cluster analysis.

Group 1 The catchments in group one are located in the upper right hand quadrant of the ordination diagram. They are characterised by runoff volumes in bin class two.

Group 2 Group two catchments are distributed towards the lower right hand quadrant of the ordination plot. This group of catchments are characterised by low runoff volumes that are typical of bin class one.

Group 3 Group three catchments are generally situated in the lower left hand quadrant and are characterised by average runoff volumes. They are most closely related to bin class three.

Group 4 Group four catchments are located in the middle to upper left of the ordination plot. Although fairly dispersed, the runoff from this group of catchments is characteristically relatively high; being positioned near to bin classes three, four and five.

The distribution of catchments is displayed in the MDS plot presented in figure 5.15. In support of the findings of the cluster analysis, catchment 38 (South House) is clearly distinct from other catchments. The results of a PCA performed on a reduced dataset of 47 catchments, following the removal of catchment 38, are displayed in table 5.11.

Axis	Eigenvalue	Cumulative % variance of runoff data represented
1	0.490	49.0
2	0.209	69.9 (20.9)
3	0.167	86.6 (16.7)
4	0.134	100.0 (13.4)

Table 5.11 Results of PCA performed using five runoff bin classes and for 47 catchments, catchment 38 is removed.

The overall percentage of total variance explained by the first four axes remains the same at 100% with the reduced sample size. Notable changes are observed in the percentage of variability in runoff explained by axes one, two and three. For axis one there is an observed increase from 47.2% to 49%. Similarly, the variability in runoff explained by axis two improves by 1.2% to 69.9%, whilst the explanatory power of axis three declines slightly to 86.6% from 87.2%.

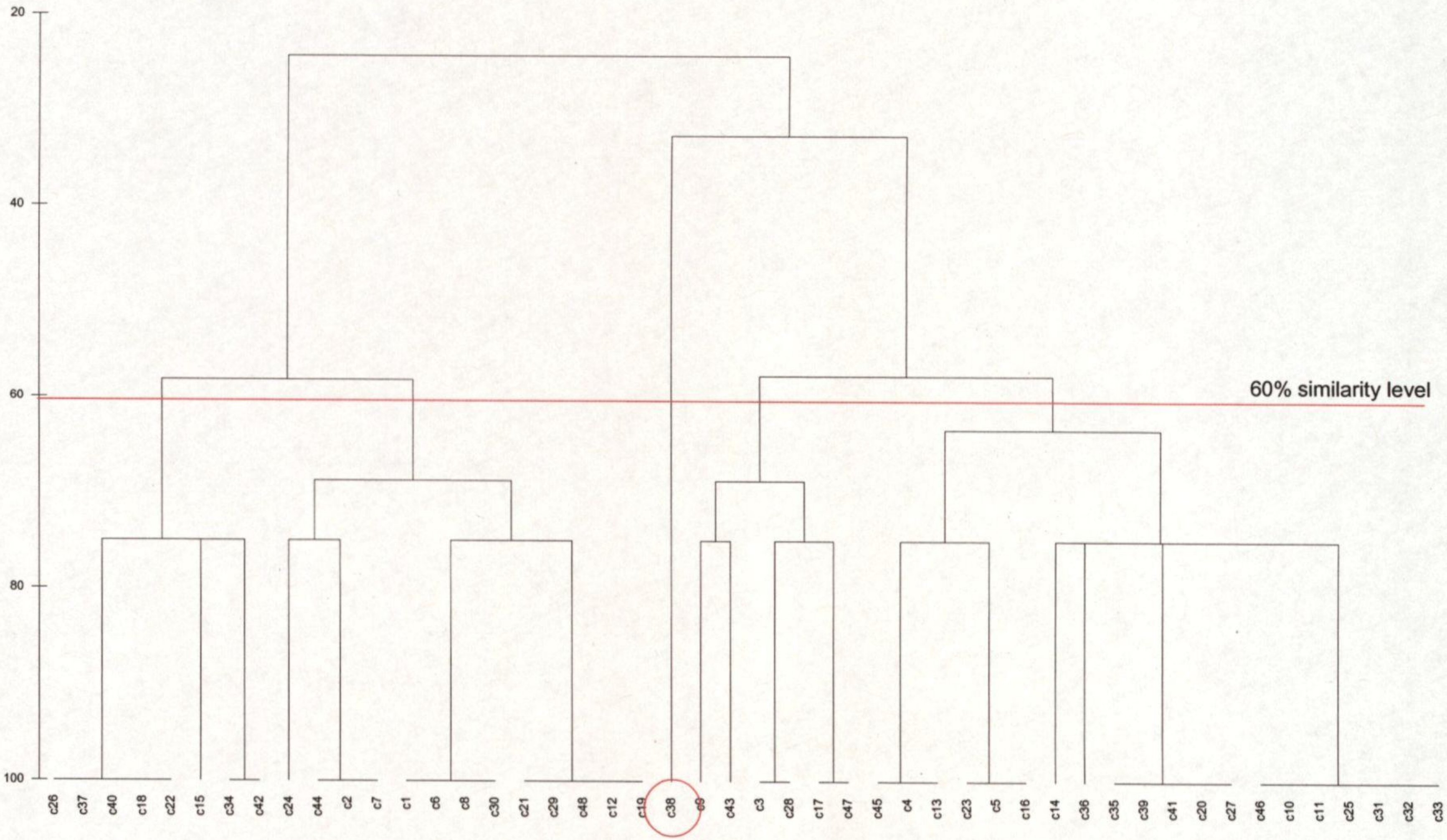


Figure 5.13 Dendrogram of cluster analysis performed using the five runoff bin classes and 48 catchments.

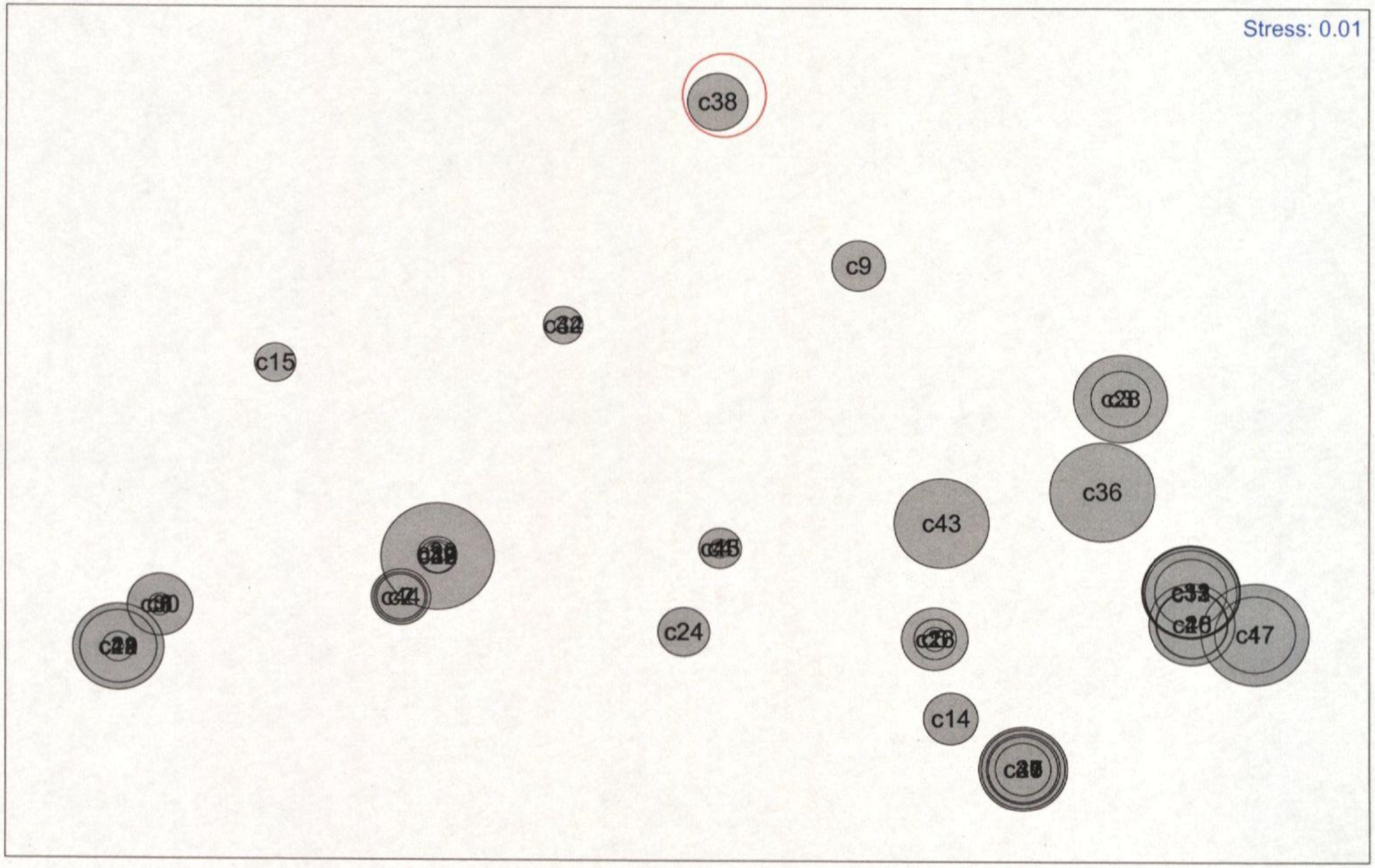


Figure 5.15 Results of MDS undertaken using all 48 catchments with runoff overlain as a bubble plot.

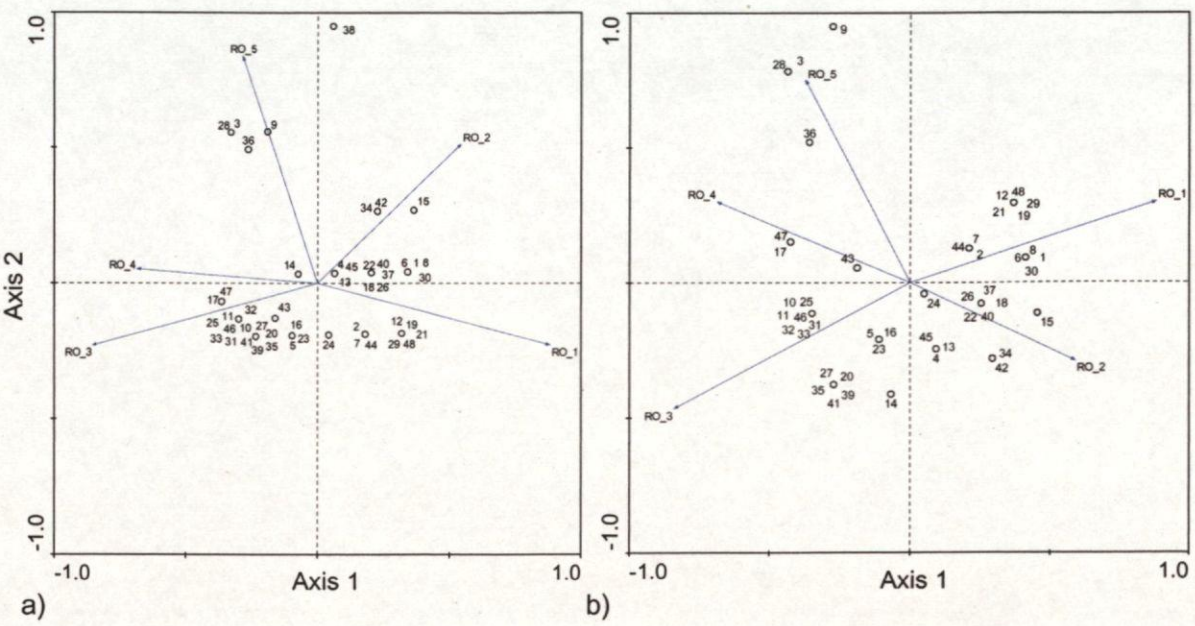


Figure 5.16 PCA ordination bi-plots (axis 1 vs. 2) for five runoff bin classes, a) 48 catchments and b) with catchment 38 removed.

The representation of variability in runoff by ordination axes is slightly improved through the removal of catchment 38 (South House) from the analysis, the before (figure 5.16a) and after (figure 5.16b) ordination bi-plots of the PCA's demonstrate the effect of catchment 38 (South House) on the scaling of the ordination. Catchments in figure 5.16a are observably better spread. The force of catchment 38 (South House) on axis two concentrated the other catchments into a tighter cluster on the ordination plot, leading to a misrepresentation of the variability in the data.

Summary points

Storm runoff dataset

- The results of PCA ordination revealed axis one as the key gradient of variation in the storm runoff dataset, accounting for 80.8% of the explained variance.

- Catchment 38 (South House) was identified as a clear outlier through observation of the ordination plot. South House exhibits low to average runoff for storms one, two and four, but relatively high runoff for storm three. Hence it was subsequently removed.
- Cluster analysis identified four catchment groups at the 50% similarity level. Catchments 24 (Torrington) and 39 (Little Puddle) were found to be dissimilar in this analysis. However, these catchments\were not removed at this stage.
- Removal of 38 (South House) catchment improved the percentage of variance explained by axis one to 81.5%. The plotted distribution of catchments also notably improved.
- All four storms are correlated with axis one.

Bin class runoff dataset

- PCA ordination undertaken on the bin class runoff dataset showed axis one as explaining 47.2% of variance. Axes two and three explain 22% and 19% respectfully.
- As with the PCA using storm runoff data, catchment 38 (South House) was found to be outlying on the ordination plot. Cluster analysis and MDS ordination also identified catchment 38 as dissimilar from other catchments. Catchments 24 (Torrington) and 39 (Little Puddle) were not found to be dissimilar.
- Cluster analysis identified four catchment groups at the 60% similarity level.
- Following the removal of South House catchment, the percentage of variance explained by axis one increased to 49.0%. Moreover the percentage explained by axis two rose by 1.2%. Catchments were observably better distributed on the ordination-bi-plot.

- Bin classes one, three and four are most strongly correlated with axis one, as indicated by the horizontal direction of the arrows. Bin class 5 is most strongly correlated with axis two.

5.7.2iii Indirect gradient analysis (PCA): All catchments and all environmental variables

A PCA analysis was employed to explore key environmental gradients and identify catchments with extreme environmental characteristics. Primarily, the analysis was performed using all 48 catchments and 92 environmental variables. Table 5.12 displays the eigenvalues and cumulative variance explained by axes one to four.

Axis	Eigenvalue	Cumulative % variance
1	0.170	17.0
2	0.090	26.1 (9.1)
3	0.086	34.7 (8.6)
4	0.081	42.8 (8.1)

Table 5.12 Results of PCA performed using all 92 environmental variables and 48 catchments.

The results indicate that the environmental parameters explain less than half of the variability in the data, with the first four axes accounting for 43%. The difference between the variability explained by axis one (17.0%) and axes two (9.1%), three (8.6%) and four (8.1%) is relatively large, suggesting that axis one corresponds to the most significant gradient of variability. The low overall percentages and even spread of variation explained by axes two, three and four is indicative of a large amount of noise in the dataset. This is most likely due to the huge number of environmental variables incorporated in the analysis.

The ordination bi-plots of axis one versus axis two and axis one against axis three are displayed in figures 5.17a and b. Axis one is most significantly correlated with and driven by variability in ODSH, GRS and GRAN. It is strongly negatively correlated with spatial variables and AR_CER. Topographic parameters, including SLOPE_30, SLOPE_35 and SLOPE_40 are strongly influencing axis two. In figure 5.17a, catchment 24 (Torrington) is exposed as an outlying catchment. Catchment 46 (Laverstock) appears to be markedly dissimilar to other catchments in figure 5.17b.

To further explore the nature of potentially outlying catchments, MDS and cluster analysis were performed on the full dataset, including all 48 catchments and 92 environmental variables. The resulting MDS plot with runoff bubble plot is presented in figure 5.18. In support of the PCA analysis, catchment 24 is again shown to be different from other catchments and is positioned some distance away from the remaining samples. Notably, catchment 46 does not appear to be unusual but does exhibit high runoff.

Classification of catchments into groups at the 50% similarity level was undertaken using cluster analysis. The final catchment groupings have been added to the PCA ordination bi-plot and can be observed in figure 5.19. As a result of the dissimilarity of catchment 24 it is not incorporated into any catchment groups. Catchment 46 shares characteristics that are similar to catchments in group three.

In conjunction with PCA and MDS ordinations, cluster analysis has highlighted catchment 24 as an outlier. The tabulated results of a PCA performed on 47 catchments, with catchment 24 removed, shows improvement in the overall variance in the data explained by the first four axes. The total cumulative percentage variance explained is 43.5% as compared to 42.8% in the initial analysis (table 5.13). The percentage of variability in the data accounted for by each of the axes individually has risen very slightly, with the exception of axis four which has fallen by 0.1%. For axis one the increase is by 0.3% and for axes two and three the increases are 0.1% and 0.4%.

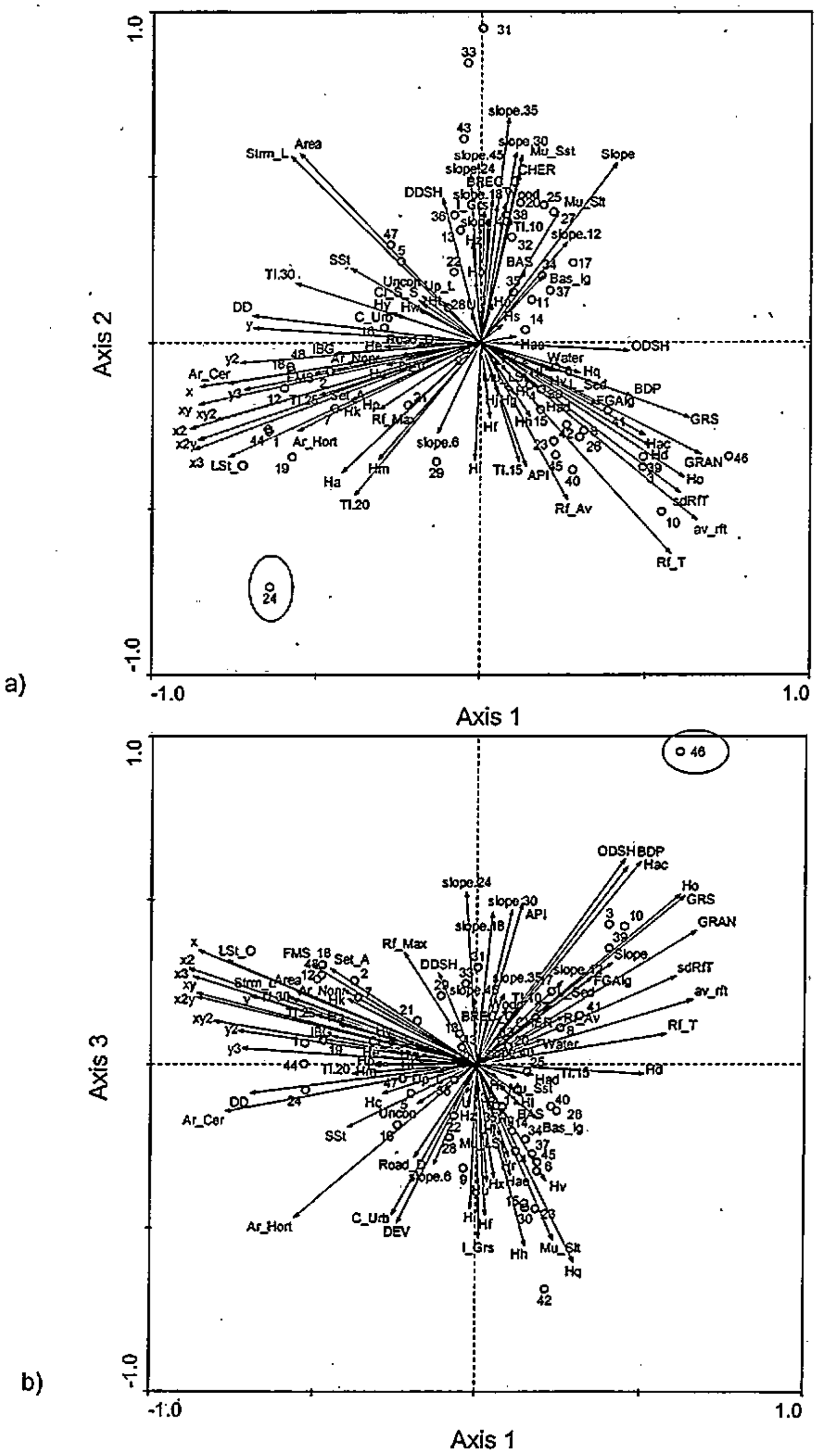


Figure 5.17 PCA ordination bi-plots performed using all 48 catchments and 92 environmental variables a) axis 1 vs. 2 and b) axis 1vs 3.

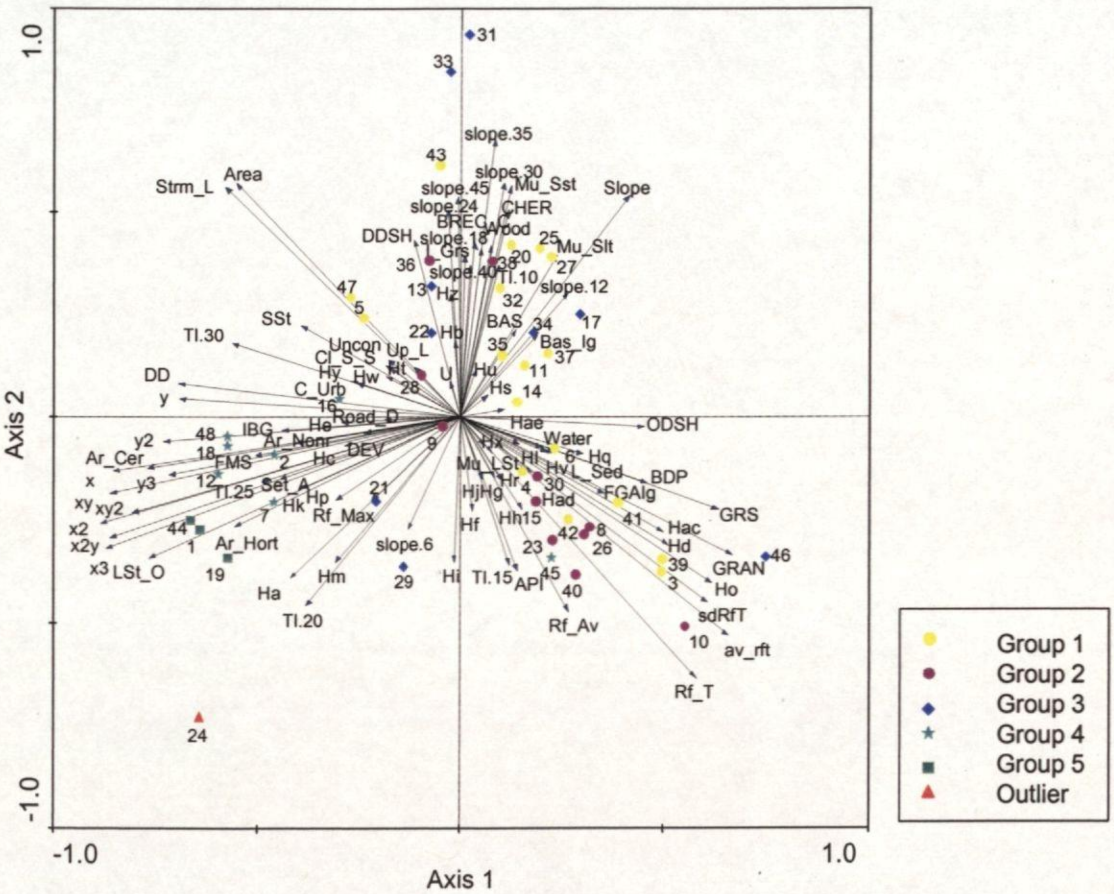


Figure 5.19 PCA ordination bi-plot (axis 1 vs. 2) for all 92 environmental variables and 48 catchments. Catchments are grouped according to the results of cluster analysis.

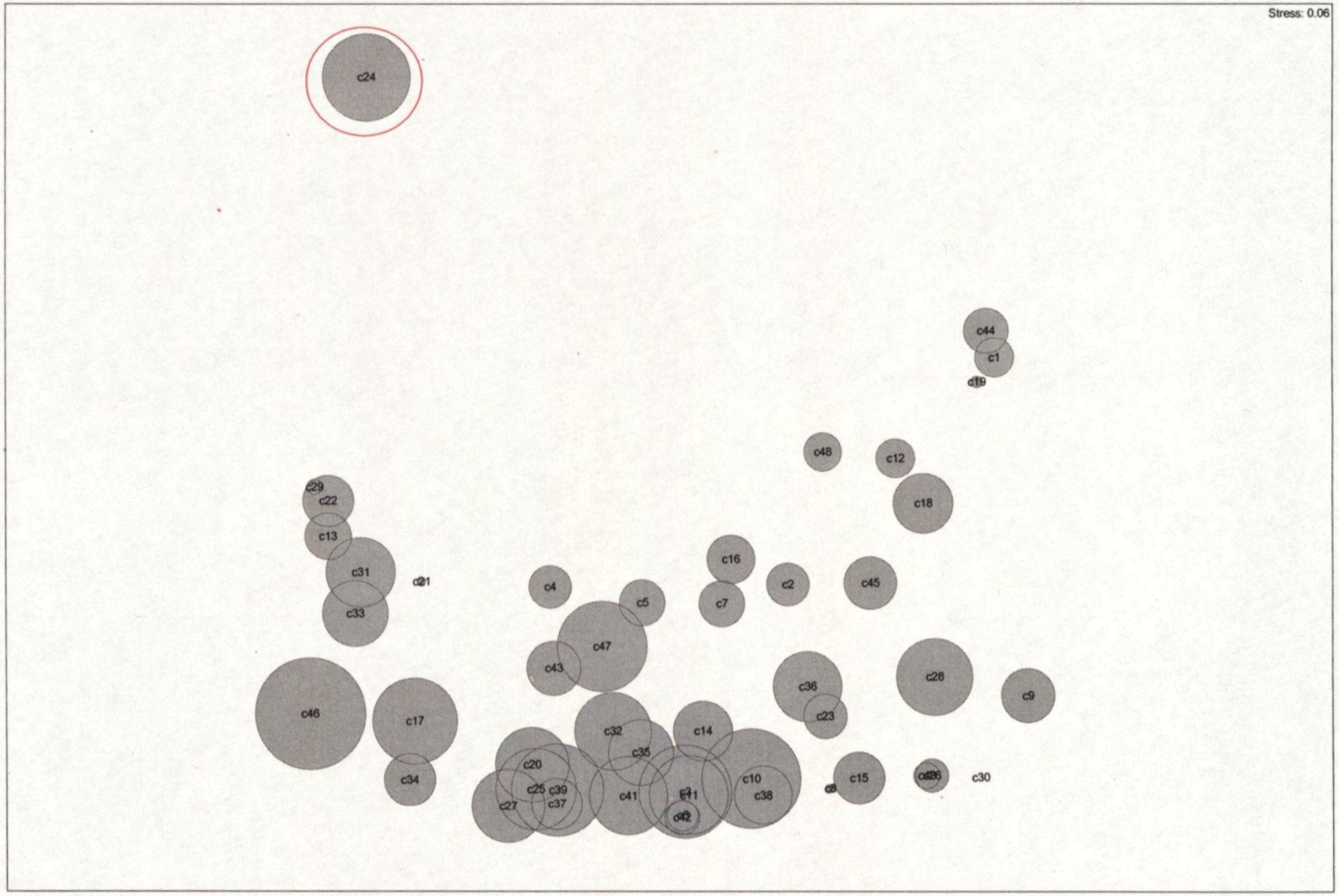


Figure 5.18 Results of MDS undertaken using all 92 environmental variables and 48 catchments.

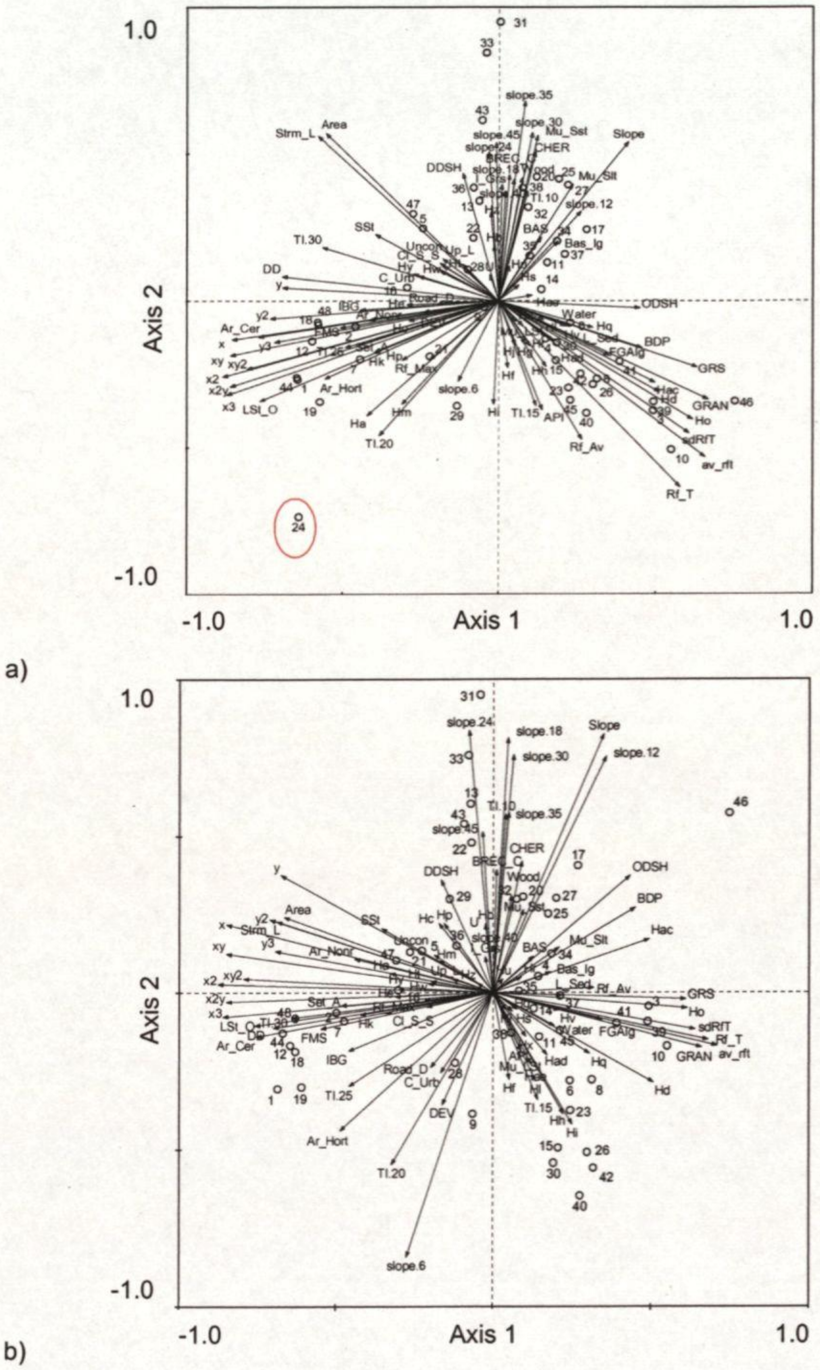


Figure 5.20 PCA ordination bi-plots (axis 1 vs. 2) performed using all 92 environmental variables and a) 48 catchments and b) with catchment 24 removed.

Graphically, removal of catchment 24 has altered the scaling of the ordination bi-plot. Figures 5.20a and 5.20b demonstrate the differences in the distribution of catchments and

major environmental gradients between ordinations undertaken on the full and reduced sample sets. The most prominent changes are the increased dispersion of catchments and differences in the angles of gradient arrows with respect to ordination axes. For example, it is now evident that spatial factors, LST_O, STREAM_L and AREA are strongly negatively correlated with axis one. Moreover, axis one is positively correlated with rainfall parameters, and HO, GRAN and GRS. In addition, topographic factors, such as SLOPE, SLOPE_6 and SLOPE_12 are clearly highly significant environmental controls on variability in the catchment environmental data, due to the comparatively long length of arrows; these are most strongly related to axis two.

Axis	Eigenvalue	Cumulative % variance
1	0.173	17.3
2	0.092	26.4 (9.2)
3	0.090	35.4 (9.0)
4	0.080	43.5 (8.0)

Table 5.13 Results of PCA performed using all 92 environmental variables and 47 catchments, catchment 24 is removed.

Summary points

- PCA ordination has highlighted considerable noise in the analysis as a result of incorporating a large number of environmental variables, many of which are strongly intercorrelated.
- The first four axes explain less than half of the total variability in the dataset (42.8%). Axis one is the strongest gradient and accounts for 17.0% of the variance.
- Clustering has identified five catchment groups at the 50% similarity level.
- The PCA ordination, MDS ordination and cluster analysis all distinguish catchment 24 (Torrington) as outlying. This is additional to catchment 38 (South House),

which was consistently identified as an outlier in analyses undertaken on runoff data. Laverstock (46) catchment is similar to catchments in group three.

- Removal of catchment 24 increases the overall percentage of variance explained by the first four axes to 43.5%. Catchments appear more spread on the ordination plot as a result.

5.7.2iv Direct gradient analysis (RDA): Examination of environment-runoff relations

Initial RDA performed on the full, screened dataset

Using indirect ordination techniques it is possible to begin to identify the major environmental gradients driving variability in the catchment dataset. Moreover, they provide useful information on interrelationships between environmental variables. However, the primary aim of the investigation is to explore the influence of key environmental gradients on variability in runoff. PCA, MDS and clustering have been used to screen both runoff and environmental datasets for unusual samples.

In the following section, direct ordination is employed to investigate environment-runoff relationships using the screened datasets. An initial RDA is performed on a reduced set of 46 catchments; catchments 38 and 24 are removed from the analysis from this point forward. The large number of environmental variables included in the analysis at this stage makes it difficult to interpret underlying trends and relationships from ordination diagrams. The results of the RDA are therefore graphed with only one environmental subset of variables visible per plot.

Results: Four storm runoff dataset

The results of an exploratory RDA undertaken using the full screened sample set of 92 environmental variables, four storms and 46 catchments, are presented in table 5.14. The total cumulative percentage variance of runoff data explained by the first four ordination axes is high at 64.9%. Of this figure, 53.8% is attributed to axis one, with axes two, three and four contributing comparatively little and explaining a total of 11.4% of the variability in runoff. Moreover, the correlation between runoff and environmental variables is high for axis one, at 0.808, indicating a strong relationship between key environmental gradients and runoff. Significance testing using 999 Monte Carlo permutations confirmed that the analysis was significant at the 95% confidence level ($T = 0.649$, $p < 0.05$).

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.538	0.809	53.8	83.0		
2	0.056	0.888	59.5 (5.7)	91.7 (8.7)		
3	0.045	0.759	64.0 (4.5)	98.6 (6.9)		
4	0.009	0.565	64.9 (0.9)	100.0(1.4)	1.000	0.649 (64.9%)

Test of significance of all canonical axes : Trace = 0.649
P-value = 0.024

Table 5.14 Results of RDA on the 92 environmental variables, four storms and 46 catchments (numbers in parentheses are the contributions made by individual axes).

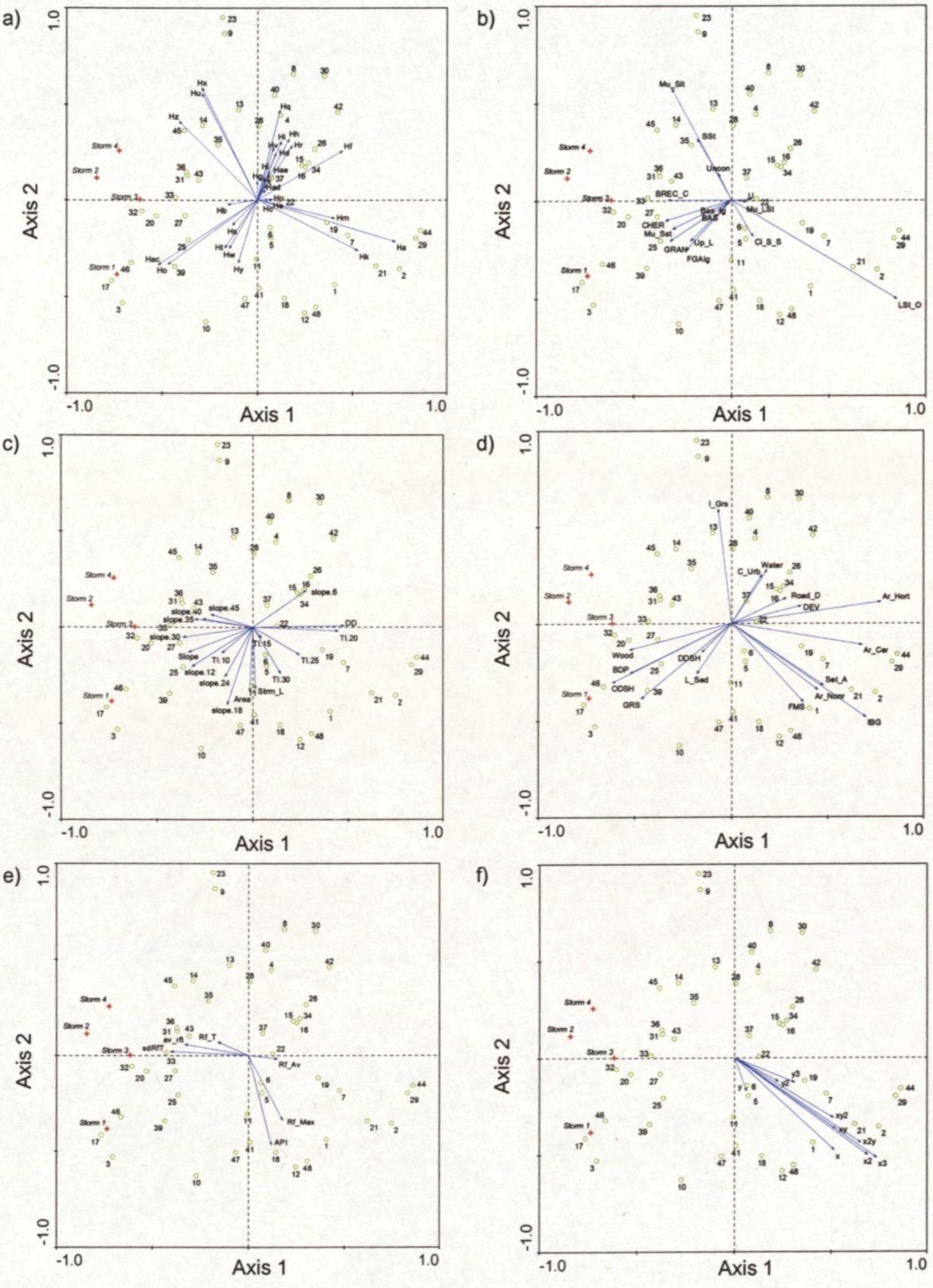
The results of the RDA are also displayed graphically in a series of tri-plots presenting the catchments, the storm event runoff and individual subsets of environmental data (figure 21a-f). Analysis of the variables, which show a strong relationship with axis one, provides evidence of clear patterns and potential interrelationships between environmental parameters.

Two sets of dominant catchment conditions are emerging. The first is characterised by HA and HF soils that are typically free draining brown earths overlying chalk (LST_O). The arrows pertaining to soil types HA and HF, in figure 5.21a and LST_O in figure 5.21b, show a strong positive relationship with axis one. The soils in these catchments support arable production and horticulture land uses that are generally restricted to shallow slopes. In addition to AR_CER and AR_HORT, TI<20, SLOPE<6 and DD were also found to be related to axis one. Higher drainage densities are characteristic of low-lying catchments.

In the second set of catchment conditions, HO and HAC soils dominate. These are poor draining peat soils that are limited geographically to steeply sloping upland areas. The unproductive nature of these soils causes them to support stands of woodland, grassland, shrub land and bog. In the ordination plots this pattern is evident through observation of environmental parameters negatively correlated with axis one, namely soils HO and HA, topographic parameters SLOPE<30, SLOPE<35 and SLOPE<45, and the land use classes WOOD, GRS, ODSH and BDP (figures 5.21a,c and d). Exposed upland catchments typically receive higher amounts of precipitation. In figure 5.21e both SD_RFT and AV_RFT are also negatively related to the first axis.

Spatial variables are positively correlated to axis one. The latter may be indicative of a transition further north and east towards more gentle relief, lower rainfall and a predominance of arable land uses (figure 5.21f). All storm events are distributed in the left hand quadrants of the ordination plot. Higher runoff may be produced in catchments that are governed by environmental variables which exhibit a negative relationship with axis one. Although the findings are tentative at this stage, it is apparent that higher runoff producing catchments may be increasingly characterised by environmental parameters creating conditions pertaining to scenario two above.

Also of interest in figure 5.21f is the positioning of spatial variable vectors, which lie in close proximity to one another on the ordination plot. This is symptomatic of high colinearity between the measured parameters. Some degree of inter-correlation between individual environmental variables is detectable within all subset plots and is pronounced between them. This is examined in more detail at subsequent stages in the analysis.



<u>Figure 5.21 RDA ordination tri-plots (axis1 vs. axis2) performed on 46 catchments, four storms and full a) soil, b) geology, c) topography, d) land use, e) rainfall and f) spatial environmental datasets.</u>

Results: Five bin class runoff dataset

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.356	0.851	35.6	57.9		
2	0.131	0.829	48.7 (13.1)	79.2 (21.3)		
3	0.074	0.644	56.1 (7.4)	91.3 (12.1)		
4	0.054	0.620	61.5 (5.4)	100.0 (8.7)	1.000	0.615 (61.5%)
Test of significance of all canonical axes :				Trace = 0.615 P-value = 0.018		

Table 5.15 Results of RDA on the 92 environmental variables, five runoff bin classes and 46 catchments (numbers in parentheses are the contributions made by individual axes).

Table 5.15 presents the results of an initial RDA performed on the entire screened sample set of 92 environmental variables, five runoff bin classes and 46 catchments. The first four ordination axes together explain 61.5% of the total cumulative percentage variance in runoff data. Axis one is responsible for controlling 35.6% of this variation. Axis two explains just 13.1%, whilst axes three and four explain 7.4% and 5.4% respectively. There is a strong relationship between the environmental parameters and runoff, as demonstrated by a high correlation (0.851) between runoff and environmental variables. The analysis tested statistically significant (*p*<0.05) (999 Monte Carlo permutations).

The resulting tri-plots from the RDA on runoff bin class data are displayed graphically in figures to 5.22a to f. As with the first RDA using storm runoff data, it was the focus of the analysis to identify the variables most strongly related to the main gradient of ordination, axis one. The patterns displayed duplicate those revealed in the storm runoff set RDA (page 158).

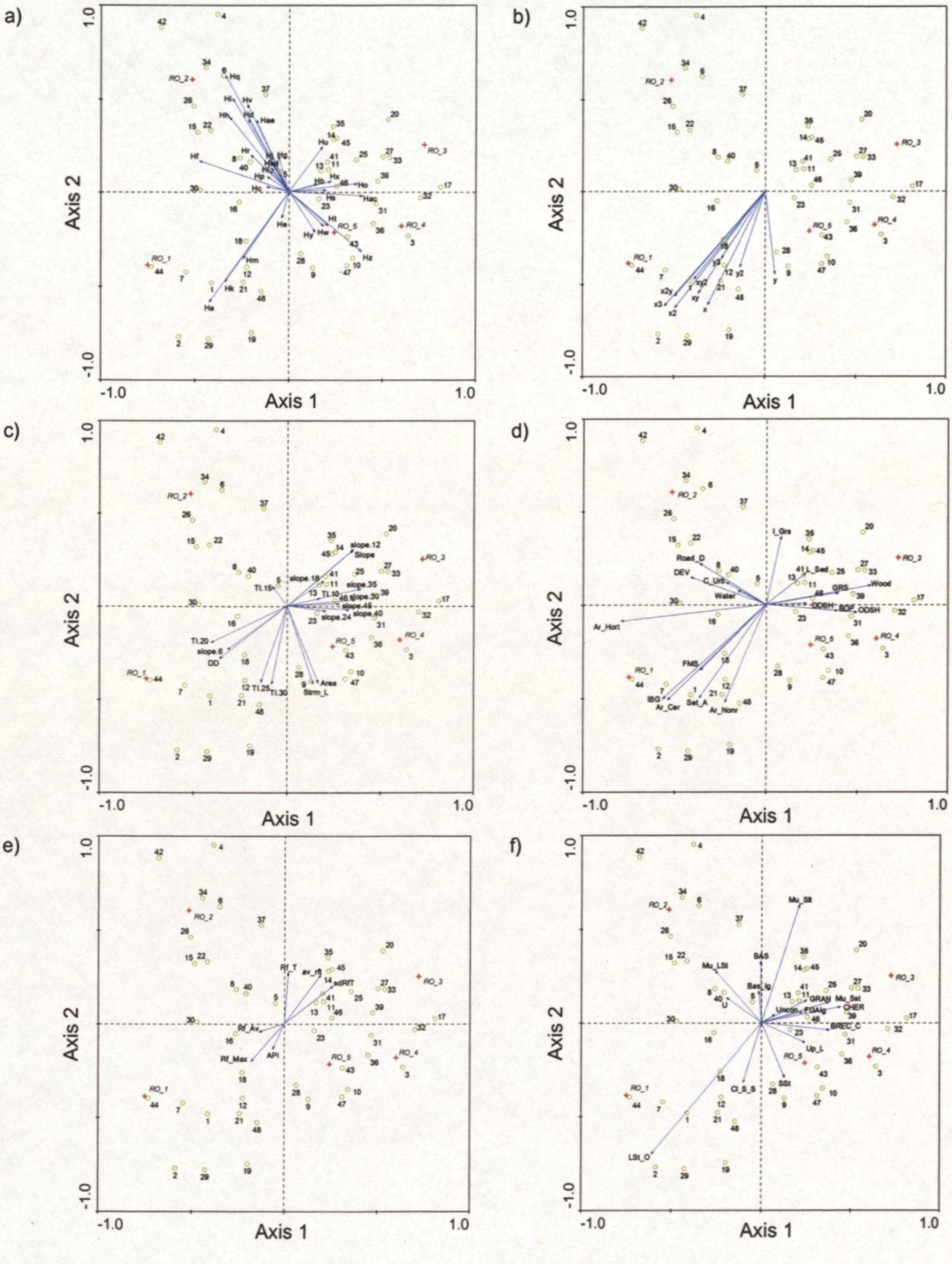


Figure 5.22 RDA ordination tri-plots (axis1 vs. axis2) performed on 46 catchments, five runoff bin classes and full a) soil, b) geology, c) topography, d) land use, e) rainfall and f) spatial environmental datasets.

In addition to the soil types HO and HAC, steep topographic indicators SLOPE<30, SLOPE<35, SLOPE<40 and SLOPE<45, rainfall characteristics SD_RFT and AV_RFT, and land uses WOOD, BDP, ODSH, and DDSH, the geology types BREC_C, MU_SST, CHERT and GRAN are all positively related to axis one. Environmental variables which are negatively related to axis one include HA, HF and HK soils, rock types LST_O and MU_LST, topographic factors indicative of shallow relief such as DD, SLOPE<6, TI<15 and TI<20, and the land use classes AR_HORT, AR_CER, IBG, DEV and ROAD_D.

The runoff bin classes are distributed across the plot. However, the low runoff classes RO_1 and RO_2 are notably positioned in the left hand quadrants and are negatively related to axis one. Conversely, bin classes representing high runoff volumes, including RO_4 and RO_5, demonstrate a positive relationship with axis one and are located on the right hand side of the diagram. The same is true of RO_3 which represents medium runoff. The distribution of the bin classes in the ordination plot supports the findings of the first RDA and the assumption that environmental characteristics that are typical of upland catchments may generate higher volumes of runoff during extreme storm events.

In terms of land use, this supposition questions the importance of land uses that are traditionally considered hydrologically intensive, such as cereal production and urbanisation, in generating high volumes of runoff at the catchment scale. Pasture, rough grazing, shrub land and bog generally dominate upland catchments. These trends may be pointing towards a topographic or hydraulic driver. Notwithstanding this, high runoff may be being strongly influenced by overgrazing, where improved grassland (I_GRS) or grassland (GRS) predominate.

Summary points

- A pattern of two sets of variables is observed in the catchment environmental data. These groups of variables are characteristic of upland and lowland areas.
- Environmental characteristics broadly associated with upland catchments include steep slopes, high rainfall, unproductive land uses (GRS, ODSH, WOOD, BDP), geology types GRAN, CHERT, BREC_C and MU_SLT, and typically poor draining soils (HO and HAC).
- The attributes that are thought to be characteristic of lowland catchments include, freely draining soil classes (HA, HF), arable (AR_CER, AR_HORT) and urbanised (DEV and ROAD_D) land uses, shallow slopes, high drainage densities, and the geology types LST_O and MU_LST.
- The positive relationship between spatial parameters and axis one in the storm runoff RDA, and negative relationship between spatial parameters and axis one in the bin class runoff RDA, suggests a northeastern trend in catchments towards 'lowland' type characteristics.
- The closeness of vector arrows in the ordination plots is symptomatic of high multicolinearity in the environmental data.

Storm runoff data

- RDA performed using the storm runoff data, and with all 92 environmental variables and 47 catchments, showed that the first four ordination axes significantly explained 64.9% of the total variability in runoff.
- Axis one formed the main gradient of variation in the dataset, explaining 53.8% of the variance.

Bin class runoff data

- RDA employed on the bin class runoff dataset, using all 92 environmental variables and 47 catchments, revealed that the first four ordination axes significantly explained 61.5% of the total variance in the in runoff data.
- Collectively, axes one (35.6%) and two (13.1%) explained almost half of the total variability in runoff.

5.7.3 Selection of environmental variables for inclusion within final RDA

Due to the large number of environmental variables incorporated in the analysis, the results of RDA are generally noisy. Many variables may contribute very little to the ordination. Moreover, it is not easy to distinguish the key environmental parameters that are driving the ordination, especially when all six subsets are plotted together. In addition, a large proportion of the variables are strongly intercorrelated. Colinearity exists both within and between environmental subsets.

In light of these problems, it is necessary to refine the range of environmental parameters to a smaller number of carefully selected variables. According to ter Braak and Šmilauer (1998), this is preferential to the inclusion of a large number of poorly selected ones. A series of data screening techniques were therefore employed to identify and eliminate environmental redundancies and variables explaining an insignificant proportion of the variability in runoff.

5.7.3i Intercorrelation between environmental variables

Environmental variables that demonstrated a high degree of intercorrelation during earlier analyses were noted at this stage. Further testing was required to compare the colinearity of the variables with the percentage variance in runoff explained. Variables which showed high colinearity and explained an insignificant proportion of the variability in runoff were eliminated first.

5.7.3ii Constrained RDA's

Environmental variables were tested individually using constrained RDA's (ter Braak and Šmilauer, 1998). This process determined the capacity for the variable to explain a statistically significant amount of variability in the runoff data and involved constraining runoff to each environmental variable in turn.

Results: Four storm runoff dataset

Table 5.16 displays the results of constrained RDA's performed on the entire environmental dataset, including all six subsets.

No.	**Environmental variable**	**Percentage explained (%)**	***p* value**	**No.**	**Environmental variable**	**Percentage explained (%)**	***p* value**
1.	LST_O	39.6	0.002	47.	HQ	2.6	0.244
2.	X^3	28.8	0.002	48.	SLOPE<45	2.8	0.262
3.	AR_HORT	28.7	0.002	49.	HR	2.7	0.270
4.	X^2	25.5	0.002	50.	TI<30	2.5	0.274
5.	AR_CER	24.5	0.002	51.	HM	2.4	0.274
6.	X^2Y	21.8	0.002	52.	RF_MAX	2.7	0.278
7.	HA	20.6	0.002	53.	SLOPE<18	2.2	0.280
8.	ODSH	20.1	0.002	54.	I_GRS	2.6	0.282
9.	BDP	14.7	0.002	55.	UP_L	2.7	0.292
10.	HK	15.3	0.004	56.	L_SED	2.2	0.298
11.	SET_A	12.8	0.004	57.	SLOPE<40	2.3	0.300
12.	AR_NONR	11.3	0.004	58.	SST	1.9	0.344
13.	X	15.3	0.006	59.	HT	2	0.348
14.	WOOD	14.9	0.006	60.	API	2.1	0.352
15.	HF	11	0.006	61.	RF_T	2.1	0.354
16.	HAC	14.7	0.008	62.	HH	1.9	0.362
17.	DD	12.2	0.008	63.	SLOPE<24	1.7	0.374
18.	IBG	10.5	0.008	64.	TI<10	1.7	0.410
19.	XY	14.5	0.010	65.	HW	1.6	0.432
20.	HO	12	0.010	66.	DDSH	1.7	0.444
21.	HZ	10.9	0.010	67.	HD	1.5	0.454
22.	XY^2	13	0.012	68.	RF_AV	1.6	0.456
23.	GRS	11.6	0.014	69.	C_URB	1.3	0.480
24.	TI<20	9.9	0.018	70.	HB	1.4	0.494
25.	SD_RFT	9.1	0.024	71.	HL	1.3	0.518
26.	FMS	8.3	0.028	72.	U	1.2	0.524
27.	SLOPE≤30	7.6	0.032	73.	STRM_L	1.2	0.528
28.	MU_SLT	7.2	0.049	74.	AREA	1.2	0.530

29.	DEV	6.5	0.052	75.	HY	1.2	0.544
30.	AV_RFT	6.3	0.054	76.	HS	1.2	0.546
31.	BREC_C	6.1	0.068	77.	HV	1.2	0.550
32.	HU	6.5	0.072	78.	HAE	1	0.612
33.	SLOPE<12	5.7	0.074	79.	TI<15	0.9	0.640
34.	HX	6.1	0.078	80.	HP	0.9	0.644
35.	GRAN	5.5	0.078	81.	HI	0.8	0.698
36.	SLOPE	5.8	0.08	82.	HE	0.7	0.700
37.	CHER	6	0.086	83.	Y	0.7	0.710
38.	SLOPE<35	5.4	0.106	84.	HC	0.7	0.724
39.	Y^3	5.1	0.112	85.	BAS_IG	0.7	0.740
40.	MU_SST	4.8	0.116	86.	UNCON	0.7	0.742
41.	ROAD_D	4.5	0.118	87.	CL_S_S	0.7	0.762
42.	SLOPE<6	4.2	0.118	88.	HJ	0.6	0.818
43.	TI<25	3.5	0.152	89.	MU_LST	0.6	0.836
44.	FGAIG	3.3	0.162	90.	BAS	0.4	0.880
45.	Y^2	3.1	0.212	91.	HG	0.5	0.882
46.	WATER	2.9	0.226	92.	HAD	0.3	0.960

Table 5.16 Results of constrained RDA analyses undertaken on environmental variables and the four storm runoff dataset. Shaded variables independently explained a significant percentage of the variance in runoff data.

Using 999 Monte Carlo permutations, 28 of the 92 original variables were highlighted as explaining a statistically significant percentage of the variance in storm runoff data ($p<0.05$) and individually explained between 7.2% and 39.6% of the total variance in runoff. High contributions were observed from LST_O, X^3, AR_HORT, X^2, AR_CER, HA and ODSH, which all explained over 20% of variability in runoff. The remaining 64 were found to each explain a statistically insignificant proportion of the variability in runoff and were removed from the following analysis.

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.764	0.962	76.4	85.2		
2	0.060	0.921	82.4 (6.0)	91.9 (6.7)		
3	0.053	0.815	87.7 (5.3)	97.8 (5.9)		
4	0.020	0.901	89.7 (2.0)	100.0(2.2)	1.000	0.897 (89.7%)
Test of significance of all canonical axes :				Trace = 0.897 P-value = 0.002		

Table 5.17 Results of RDA undertaken on the reduced set of 28 environmental variables, four storms and 46 catchments.

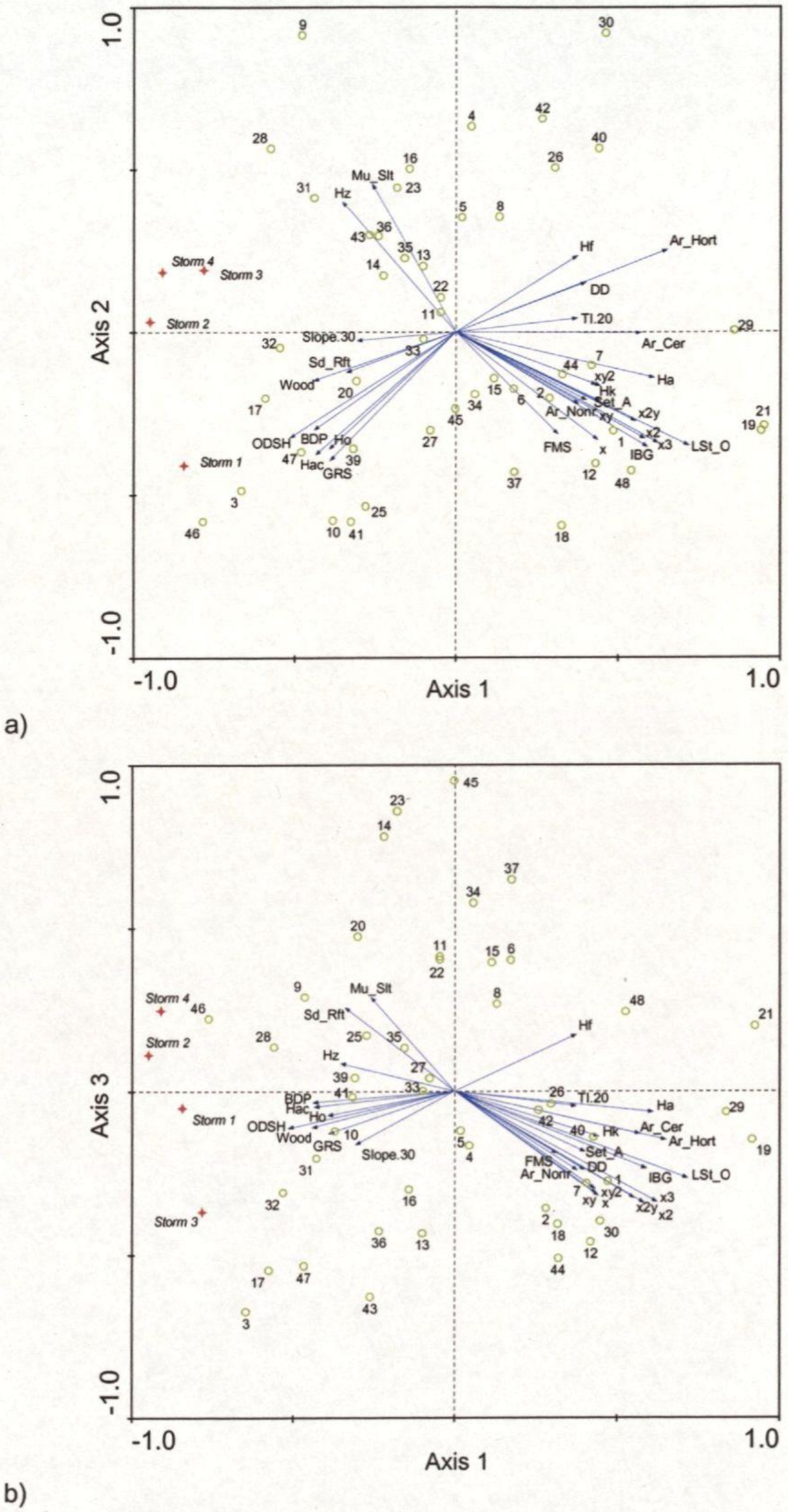


Figure 5.23 RDA ordination tri-plots performed on 46 catchments (less 24 and 38), four storms and 28 environmental variables a) axis 1 vs. 2 b) 1 vs. 3.

Table 5.17 presents the results of RDA analysis undertaken using the reduced set of 28 environmental variables. The total percentage variance in storm runoff data explained by the first four axes is very high. At 89.7% it is an improvement of 24.8% on the results of RDA analysis using the full environmental set (table 5.17). The analysis tested significant at the 99% confidence level using 999 Monte Carlo permutations. Moreover, the high runoff-environment correlations for all four axes (1= 0.962, 2=0.921, 3=0.815 and 4=0.901) demonstrate the strong relationships that exist between environmental data and runoff.

Having reduced the environmental set, the most marked change is the importance of axis one. Axis one now accounts for over two thirds of the variance (76.4%) as compared to the original RDA, where it was found to explain approximately half (53.8%). The explanatory power of the ordination has dramatically improved. Figure 5.23a and b demonstrate the importance of axis one to the ordination. The majority of the vectors for the remaining environmental variables are pointing in the direction of this axis.

Results: Five bin class runoff dataset

No.	Environmental variable	Percentage explained (%)	*p* value	No.	Environmental variable	Percentage explained (%)	*p* value
1.	AR_CER	13.8	0.002	47.	Y^2	4	0.140
2.	AR_HORT	19.9	0.002	48.	L_SED	3.9	0.144
3.	ODSH	10	0.002	49.	HU	3.9	0.146
4.	X	10.7	0.002	50.	HR	4	0.152
5.	X^2	15.1	0.002	51.	C_URB	3.3	0.158
6.	X^3	16.3	0.002	52.	UNCON	3.6	0.178
7.	X^2Y	13.1	0.002	53.	HB	3.2	0.196
8.	MU_SST	20.5	0.002	54.	HG	3.2	0.200
9.	UP_L	9.1	0.002	55.	SLOPE<45	3.3	0.204
10.	HX	11	0.002	56.	RF_MAX	3.1	0.204
11.	WOOD	1.2	0.004	57.	TI<25	2.7	0.220
12.	XY	10	0.004	58.	HW	3	0.256
13.	IBG	8	0.006	59.	CHER	2.7	0.258
14.	HD	8	0.006	60.	AREA	2.6	0.274
15.	HO	8.5	0.006	61.	SD_RFT	2.5	0.302
16.	SET_A	8.6	0.012	62.	MU_LST	2.5	0.314
17.	BDP	6.1	0.012	63.	STRM_L	2.4	0.318
18.	XY^2	8.8	0.012	64.	TI<30	2.3	0.356

19.	BAS	7.9	0.012	65.	DDSH	2.4	0.368
20.	HI	7.6	0.012	66.	HV	2.1	0.374
21.	DD	6.6	0.016	67.	HS	2.1	0.378
22.	TI<20	6.5	0.018	68.	I_GRS	2.1	0.392
23.	SLOPE<12	7	0.018	69.	LST_O	1.8	0.434
24.	HAC	6.7	0.018	70.	HP	1.7	0.492
25.	DEV	6.2	0.022	71.	HJ	1.7	0.520
26.	SLOPE	6.9	0.028	72.	HC	1.6	0.536
27.	SLOPE<40	6.2	0.028	73.	FGAIG	1.5	0.574
28.	AR_NONR	6.4	0.028	74.	HK	1.4	0.594
29.	FMS	6.4	0.030	75.	AV_RFT	1.4	0.604
30.	SST	6.3	0.030	76.	HAE	1	0.612
31.	GRS	5.7	0.040	77.	HQ	1.7	0.632
32.	GRAN	5.8	0.040	78.	TI<10	1.3	0.650
33.	HF	5.4	0.040	79.	CL_S_S	1.2	0.678
34.	HY	5.5	0.044	80.	BAS_IG	1	0.744
35.	ROAD_D	5.1	0.046	81.	WATER	1	0.762
36.	SLOPE<6	5.4	0.049	82.	HA	0.9	0.764
37.	SLOPE<30	5.1	0.060	83.	API	1	0.790
38.	SLOPE<35	5	0.070	84.	RF_AV	0.8	0.836
39.	SLOPE<18	4.6	0.074	85.	HH	0.7	0.854
40.	BREC_C	4.8	0.076	86.	RF_T	0.7	0.858
41.	HL	4.8	0.076	87.	HM	0.7	0.858
42.	Y^3	4.5	0.096	88.	MU_SLT	0.7	0.870
43.	HT	4.1	0.104	89.	HZ	0.5	0.938
44.	U	4.7	0.126	90.	HE	0.5	0.960
45.	Y	4	0.136	91.	HAD	0.3	0.960
46.	SLOPE<24	3.6	0.140	92.	TI<15	0.4	0.968

Table 5.18 Results of constrained RDA analyses undertaken using environmental variables and the five bin class runoff dataset. Shaded variables independently explained a significant percentage of the variance in runoff data.

The results of a series of constrained RDA's undertaken on all 92 environmental variables using the bin class runoff dataset are displayed in table 5.18. The process identified 36 environmental variables as accounting for a statistically significant proportion of variance in the runoff data ($p<0.05$). Over half of these variables were identified as significant using the four storm runoff dataset (table 5.17). 56 variables failed to individually contribute a significant percentage variance and were rejected from the analysis. MU_SST (20.5%) contributed the highest percentage explained by an individual variable. The lowest percentage variance explained of the selected variables is 5.1%. High contributions were also observed from AR_HORT, AR_CER X, X^3, X^2 and X^2Y, which each explained over 10% of variability in runoff.

RDA performed on the reduced set of 36 environmental variables shows a substantial increase in the total percentage variance of runoff data explained (table 5.19). The total percentage variance in bin class runoff data explained by the first four axes has increased from 61.5% to 91.3%. The analysis tested significant at the 99% confidence level using 999 Monte Carlo permutations ($p<0.01$). Near-perfect runoff-environment correlations exist for the first three axes and the correlation for axis four is high (1=0.969, 2=0.961, 3=0.984 and 4=0.857).

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.461	0.969	46.1	50.5		
2	0.194	0.961	65.5 (19.4)	71.7 (21.2)		
3	0.160	0.984	81.6 (16.0)	89.3 (17.6)		
4	0.098	0.857	91.3 (9.8)	100.0 (1.7)	1.000	0.913 (91.3%)
Test of significance of all canonical axes :				Trace = 0.913 P-value = 0.004		

Table 5.19 Results of RDA undertaken on the reduced set of 36 environmental variables, five bin classes and 46 catchments.

This indicates that environmental data exhibit very strong relationships with runoff. Almost half of the variance is now explained by axis one (46.1%). This represents an increase of 10.5% from the RDA performed on the full set. Similarly, the explanatory power of all other axes has increased. The ordination tri-plots of the reduced set of 36 environmental variables and 46 catchments are displayed in figures 5.24a and b. A large proportion of the vectors for the 36 environmental variables are pointing in the direction of axis one. Hence, axis one represents the strongest gradient (figure 5.24).

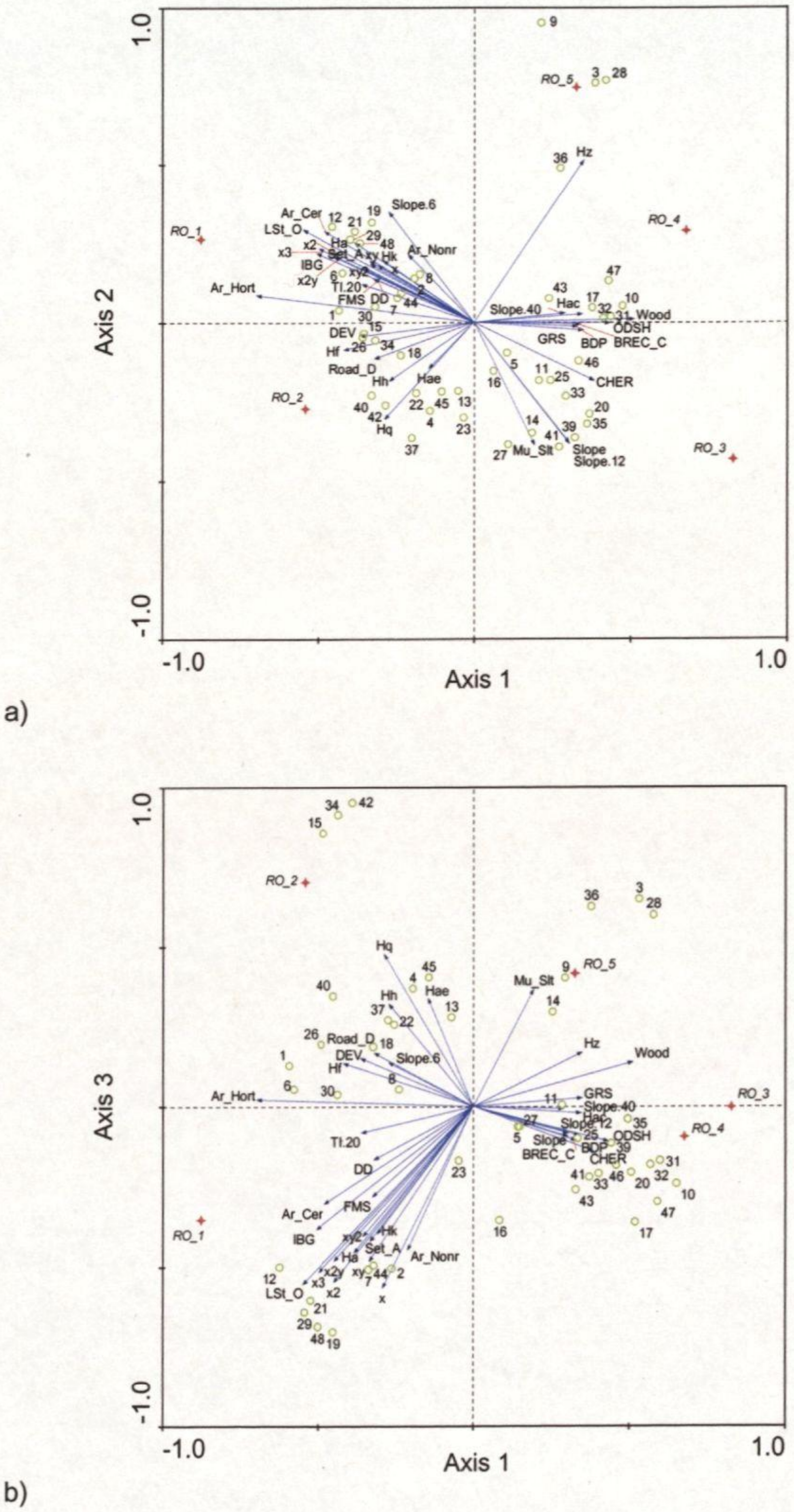


Figure 5.24 RDA ordination tri-plots performed on 46 catchments (less 24 and 38), five bin classes and 36 environmental variables a) axis 1 vs. 2 b) 1 vs. 3.

5.7.3iii Examination of inter-set correlations

Exploration of inter-set correlations is an additional mechanism for assessing the contribution of each variable to the explained variability in runoff data (ter Braak and Šmilauer, 1998). Examination of the correlations between the ordination axes and individual variables was undertaken to further test the proportion of variance in runoff explained by selected environmental parameters. Variables displaying correlations less than 0.2 were removed (Legendre and Legendre, 1998). The cut-off value was set relatively low at this point to maintain a sufficient number of variables in the analysis. True redundancies would be highlighted in subsequent testing.

Results: Four storm runoff dataset

The inter-set correlations of the reduced set of environmental variables are presented in table 5.20. All 28 contribute significantly to RDA axes one, two or four. Almost the entire set of variables exhibit correlations with this axis. MU_SLT is highly correlated with axis two and HZ with axis four. The close proximity of vectors on the ordination plots in figure 5.23 demonstrates that many of these variables are also highly intercorrelated. Hence, the contribution of a significant proportion may be superfluous.

Environmental Variable	Inter-set correlation Axis 1	Axis 2	Axis 3	Axis 4
LST_O	-0.6907	0.3856	0.0608	0.0540
AR_HORT	-0.5959	-0.0458	0.1024	0.0439
X^3	-0.5814	0.4360	0.0991	0.0141
AR_CER	-0.5513	0.0646	0.0385	0.0161
X^2	-0.5469	0.4195	0.0998	-0.0088
X^2Y	-0.5035	0.4009	0.0964	-0.0233
HA	-0.4944	0.3237	-0.0534	0.1197
HK	-0.4323	0.1473	0.0315	0.1346
X	-0.4163	0.4050	0.0784	-0.0286
XY	-0.4083	0.3455	0.0989	-0.0370
SET_A	-0.3922	0.1918	0.0598	0.1507
XY^2	-0.3880	0.3253	0.0942	-0.0362
DD	-0.3826	-0.0616	0.2178	-0.0467
AR_NONR	-0.3684	0.1968	0.0986	-0.0217
HF	-0.3589	-0.2528	-0.1113	0.0139
TI.20	-0.3481	0.0899	0.0365	0.1493
IBG	-0.3400	0.2208	0.3035	0.0440
FMS	-0.3082	0.2765	0.0525	0.0465
SLOPE.30	0.2978	0.0032	0.1799	-0.2509
SDRFT	0.3296	0.0773	-0.1844	0.0828
GRS	0.3674	0.2976	0.0242	0.0289
HO	0.3754	0.2943	0.0081	0.0513
HAC	0.4160	0.3163	-0.0166	0.0936
BDP	0.4204	0.2481	-0.0145	0.0549
WOOD	0.4244	0.1419	0.1362	-0.1519
ODSH	0.4925	0.2767	0.0389	0.0580
MU_SLT	0.2518	-0.4902	-0.1342	-0.1357
HZ	0.3370	-0.3182	0.0961	0.5669

Table 5.20 Inter-set correlations between the reduced set of 28 environmental variables, selected following constrained RDA's, and the first four ordination axes. Shaded variables exhibit a significant correlation ($p<0.05$).

Results: Five bin class runoff dataset

Of the 36 environmental variables examined, only 33 showed significant inter-set correlations with RDA axes (table 5.21). The inter-set correlations for X, X^2 and SLOPE<40 were weak and the variables were removed from the analysis. AR_HORT, LST_O and AR_CER have a dominant influence over the variability in the bin class runoff set, as highlighted by their large inter-set correlations with axis one. The high number of variables correlated to both axes one and two may represent the presence of multicolinearity and redundancies in the data.

Environmental Variable	Inter-set correlation			
	Axis 1	Axis 2	Axis 3	Axis 4
AR_HORT	-0.6492	-0.0774	-0.0145	0.0857
LST_O	-0.5372	-0.5469	0.1909	-0.0928
AR_CER	-0.4817	-0.3262	0.1757	-0.1124
HF	-0.3922	0.0622	-0.1119	0.1878
IBG	-0.3691	0.1894	0.1943	-0.1211
TI.20	-0.3610	-0.0732	0.0188	-0.1539
DEV	-0.3403	0.0969	-0.0396	0.2001
DD	-0.3393	-0.0996	0.0219	-0.2713
FMS	-0.3165	-0.2780	0.0822	-0.0422
ROAD_D	-0.2960	0.1056	-0.1169	0.2039
SLOPE.6	-0.2726	0.1666	0.2217	-0.1672
HH	-0.2494	0.2262	-0.1741	0.2491
SLOPE.12	0.3265	-0.1083	-0.2563	0.1992
SLOPE	0.3328	-0.0370	-0.2200	0.2462
BREC_C	0.3384	-0.0733	0.0926	0.1273
HAC	0.3384	0.0062	0.0722	-0.0393
BDP	0.3476	-0.0602	0.1021	0.1328
GRS	0.3491	0.0224	0.0368	0.0412
CHER	0.4000	-0.1021	-0.0920	0.0622
ODSH	0.4425	-0.0740	0.1364	0.1770
WOOD	0.4615	0.2586	0.0233	-0.2817
AR_NONR	-0.2710	-0.5757	0.1164	-0.0989
HA	-0.4656	-0.5295	0.1310	-0.0696
HAE	-0.3052	-0.5052	0.0949	-0.0990
HK	-0.3247	-0.4189	0.1155	-0.1325
HQ	-0.3272	-0.3914	0.1130	-0.1137
SET_A	0.2025	-0.2449	-0.1349	0.0962
X^2Y	-0.1610	0.2421	-0.2361	0.2175
X^3	-0.0962	0.2426	0.0004	0.0561
XY	-0.2016	0.2582	0.0463	-0.0271
XY^2	0.2552	0.2610	0.0650	0.1419
HZ	0.2668	0.3110	0.5020	-0.2554
MU_SLT	0.2198	0.2755	-0.3406	0.1454

Table 5.21 Inter-set correlations between the reduced set of 36 environmental variables, selected following constrained RDA's, and the first four ordination axes. Shaded variables exhibit a significant correlation (*p<0.05*).

Selection of representative rainfall characteristics

The process of screening of environmental variables using constrained RDA's eliminated all rainfall parameters. It is important to investigate the effects of rainfall on runoff variability in a final analysis using the bin class runoff dataset. A standard PCA carried out using the entire rainfall subset, informed the selection of a representative variable(s) for inclusion into the analysis. Examination of the inter-set correlations allowed variable(s) to be chosen which exhibited the strongest relationship with the key ordination axis.

Axis	Eigenvalue	Cumulative % variance
1	0.544	54.4
2	0.247	79.2 (24.7)
3	0.122	91.4 (12.2)
4	0.062	97.5 (6.2)

Table 5.22 Results of PCA performed using all rainfall variables and 46 catchments.

The tabulated results of the PCA are displayed in table 5.22. The total cumulative percentage variance in the data explained by the first four axes is very high at 97.5%. Axis one explains the greatest percentage of this (54.4%) and is the major axis of variation in the ordination. The variables most strongly inter-correlated with this axis are RF_T, RF_AV, AV_RFT and SD_RFT; the results are presented in table 5.23.

Rainfall Variable	Inter-set correlation			
	Axis 1	Axis 2	Axis 3	Axis 4
API	0.5389	0.6541	-0.3313	0.4134
RF_T	0.9067	-0.1834	0.2532	0.0905
RF_AV	0.7325	0.2058	0.6220	0.0205
RF_MAX	0.2855	0.8690	-0.0635	-0.3925
AV_RFT	0.9111	-0.3203	-0.2185	-0.0576
SDRFT	0.8399	-0.3492	-0.3447	-0.1850

Table 5.23 Inter-set correlations between rainfall variables and first four ordination axes. Shaded variables exhibit a strong significant correlation (*$p<0.05$*).

This is also visible graphically through the lengths and directions of the variables' vectors in the ordination plot in figure 5.25. RF_T, RF_AV, AV_RFT and SD_RFT are re-incorporated into the analysis, whilst the other rainfall variables remain excluded.

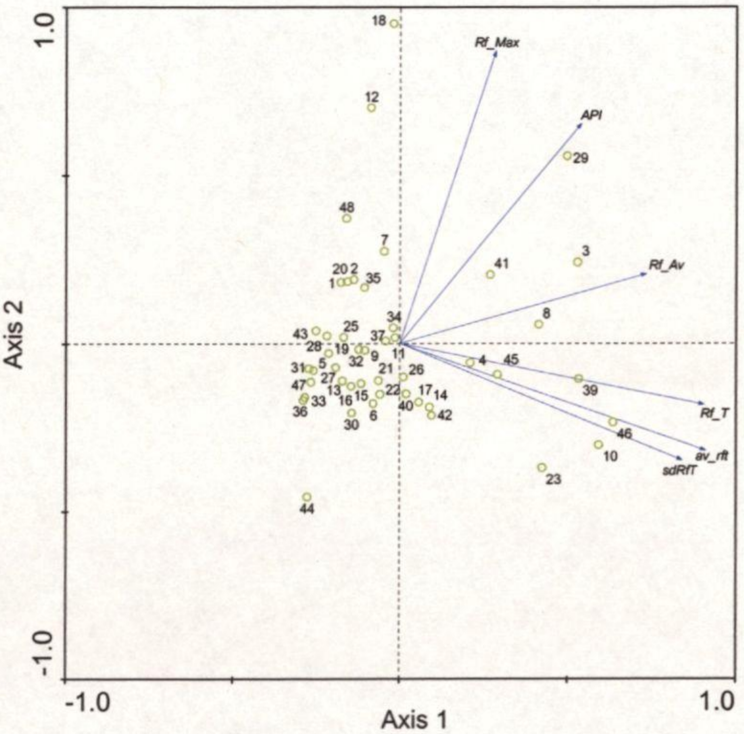


Figure 5.25 Ordination bi-plot (axis 1vs. axis 2) of PCA undertaken using rainfall variables and 46 catchments.

5.7.3iv Forward Selection of environmental variables

Forward selection uses a partial Monte Carlo permutation to test each variable separately in order to assess its independent or marginal effect on the distribution of runoff data (Lepš and Šmilauer, 1998). Essentially, this represents the amount of variability in the runoff data that can be explained by a constrained ordination model using that variable as the only explanatory variable (Lepš and Šmilauer, 1998). Manual forward selection was employed to establish the marginal influence of variables in the reduced environmental

sets on variance in runoff and test the statistical significance of the percent explained by each. Variables were rejected where results showed *p* values greater than 0.05.

Results: Four storm runoff dataset

Environmental variables	Percentage of runoff explained (%)	*P* value
LST_O	0.406	0.001
AR_HORT	0.330	0.001
X^3	0.311	0.001
HA	0.288	0.001
IBG	0.278	0.001
X^2	0.273	0.001
AR_CER	0.251	0.001
X2Y	0.245	0.001
ODSH	0.210	0.001
X	0.159	0.003
XY	0.159	0.002
HK	0.156	0.003
BDP	0.153	0.003
HAC	0.153	0.003
WOOD	0.152	0.001
XY2	0.150	0.006
SET_A	0.131	0.005
DD	0.128	0.009
GRS	0.126	0.008
HO	0.126	0.007
AR_NONR	0.117	0.012
HF	0.113	0.009
HZ	0.111	0.010
TI.20	0.109	0.020
SDRFT	0.093	0.032
FMS	0.085	0.027
SLOPE.30	0.076	0.047
MU_SLT	0.070	0.049

Table 5.24 Results of forward selection performed on the reduced set of 28 environmental variables, using the four storm runoff dataset.

The tabulated results of forward selection performed on the reduced set of 28 environmental variables using the storm runoff dataset, are displayed in table 5.24. All variables individually explained a statistically significant proportion of the variability in storm runoff data (p<0.05). Among the most important explanatory variables were LST_O, AR_HORT and X^3, which all individually explained over 30% of the variance. At the other extreme, variables such as SLOPE<30 (7.6%) and MU_SLT (7.0%) maybe considered for removal on account of their weak explanatory power. However, no variables were removed at this stage on account of the statistical significance of all of the tests.

Results: Five bin class runoff dataset

Environmental variables	Percentage of runoff explained (%)	*P* value
AR_HORT	0.227	0.001
LST_O	0.206	0.001
X3	0.169	0.001
IBG	0.151	0.002
AR_CER	0.139	0.001
X2Y	0.138	0.001
WOOD	0.129	0.002
HA	0.114	0.004
HZ	0.112	0.002
ODSH	0.101	0.002
XY	0.097	0.004
HQ	0.095	0.008
XY2	0.091	0.006
SET_A	0.088	0.011
HF	0.086	0.007
CHER	0.079	0.013
SLOPE	0.078	0.015
SLOPE.12	0.078	0.012
HK	0.077	0.015
DEV	0.069	0.016
MU_SLT	0.068	0.027
TI.20	0.067	0.019
DD	0.067	0.028
SLOPE.6	0.066	0.031
FMS	0.066	0.031
AR_NONR	0.064	0.033
BDP	0.062	0.026
HH	0.060	0.042
GRS	0.058	0.035
BREC_C	0.058	0.030
ROAD_D	0.056	0.040
HAC	0.056	0.041
HAE	0.035	0.178
SDRFT	0.032	0.204
AV_RFT	0.024	0.353
RF_T	0.011	0.722
RF_AV	0.008	0.830

Table 5.25 Results of forward selection performed on the reduced set of 33 environmental variables, using the five bin class runoff dataset.

The results of forward selection undertaken on the reduced set of 33 environmental variables, plus four rainfall variables, and using the bin class runoff dataset, show that five variables provide a statistically insignificant contribution to explaining the variability in runoff (table 5.25). HAE, SD_RFT, AV_RFT, RF_T and RF_AV individually explain between just 0.8% and 3.5% of the variance in runoff data. These variables are excluded from the analysis, and accordingly, all rainfall variables are removed.

RDA performed on the remaining 32 environmental variables showed a slight reduction in the total percentage variance in runoff data explained by the first four ordination axes, from 91.3% to 87.8%. This figure is still high and significant at the 99% confidence level using a Monte Carlo test with 999 permutations (tables 5.19 and 5.26). Environment-runoff correlations remain high, ranging between 0.819 and 0.963 (table 5.26). The individual percentage variance explained by all four axes decreases slightly but overall the distribution between them does not significantly change.

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.456	0.963	45.6	52.0		
2	0.179	0.929	63.5 (17.9)	72.4 (20.4)		
3	0.153	0.956	78.8 (15.3)	89.7 (17.3)		
4	0.090	0.819	87.8 (9.0)	100.0 (10.3)	1.000	0.878 (87.8%)
Test of significance of all canonical axes :				Trace = 0.878 P-value = 0.002		

Table 5.26 Results of RDA performed on 33 environmental variables, five bin classes and 46 catchments.

5.7.3v Examination of Variance Inflation Factors (VIF's)

Variance Inflation Factors (VIF's) indicate multicolinearity among the environmental variables. A variable is almost perfectly correlated with other variables if its VIF is greater than 20. In such cases, the variable makes no unique contribution to the regression equation and should be removed (ter Braak and Šmilauer, 1998). The reduced sets of environmental variables were tested to identify those with high VIF's (VIF>20). This process minimised multicolinearity among variables included in the final set and ensured that variables were selected that made an independent contribution to the ordination.

Results: Four storm runoff dataset

Variables that demonstrated high VIF's (VIF>20) are displayed in table 5.27. Extremely high values for spatial parameters were expected due to the consistently tight angles between spatial parameter arrows in the ordination plots of previous analyses (figure 5.21f). LST_O, in conjunction with several land use and soil classes also showed high values, in the range 21-196.

Environmental variables	Variance inflation factors >20
X^2	8529.2
X^3	3906.3
X^2Y	3496.1
XY^2	2800.1
XY	2782.3
X	488.2
LST_O	195.7
BDP	87.5
ODSH	41.2
IBG	37.2
HAC	36.0
HA	29.1
HO	21.0

Table 5.27 Variance inflation factors of environmental variables selected following analysis using the four storm runoff dataset.

A series of RDA's were subsequently performed to inform the selection of spatial parameters to be excluded from the final environmental set. Firstly, RDA's were performed with all except one spatial variable omitted from the ordination. Variables were tested consecutively and included or excluded following a comparison of the VIF's and the overall percentage variance in runoff explained by the first four axes. By retaining the spatial variable XY and removing all other spatial parameters, VIF's were minimised and the greatest total percentage variance in the runoff dataset explained.

Table 5.28 shows the total percentage variance in runoff data explained in RDA's performed with each of the intercorrelated variables removed sequentially, in the order of the value of their VIF, until all remaining VIF's are below 20. Removal of LST_O reduced the VIF of a number of other seemingly intercorrelated variables to below 20, thus they did not require further testing. Variables X^2, X^3, X^2Y, XY^2, X, LST_O, BDP and HO were removed.

Environmental variable removed	Total % variance of runoff data
LST_O	0.851
BDP	0.851
HO	0.837

Table 5.28 Total percentage variance in runoff data explained by selected environmental variables which exhibited high variance inflation factors.

Environmental variables	Variance inflation factors
AR_CER	10.4
GRS	8.3
SET_A	8.1
IBG	8.1
ODSH	7.9
AR_HORT	6.8
XY	6.5
FMS	6.0
DD	5.6
HAC	5.0
SD_RFT	4.6
HK	4.5
AR_NONR	4.0
HA	3.9
HF	3.4
MU_SLT	3.2
SLOPE.30	2.8
WOOD	2.7
TI.20	2.3
HZ	1.4

Table 5.29 Variance inflation factors of remaining environmental variables, following the removal of highly intercorrelated variables.

A final RDA performed on the refined set of 20 environmental variables showed VIF's in the range 1.4 to 10.4, indicating low correlation (table 5.29). The results of the final ordination are tabulated in table 5.30 and displayed graphically in figure 5.26.

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.742	0.948	74.2	88.6		
2	0.052	0.845	79.4 (5.2)	94.9 (6.3)		
3	0.027	0.595	82.1 (2.7)	98.1 (3.2)		
4	0.016	0.789	83.7 (1.6)	100.0 (1.9)	1.000	0.837 (83.7%)
Test of significance of all canonical axes :				Trace =	0.837	
				P-value =	0.002	

Table 5.30 Results of RDA performed on 20 environmental variables, four storms and 46 catchments.

The total percentage variance in storm runoff explained by the final environmental set is high at 83.7% and significant at the 99% significance level (using 999 Monte Carlo permutations). This is a small reduction of 6% from the set selected following constrained ordinations and examination of inter-set correlations. The majority of the variance is explained by axis one (74.2%), which represents the most important gradient in the ordination. The environment-runoff correlations are all high, showing 0.948 for axis one (table 5.30).

The tri-plots of the ordination performed using the final 20 environmental variables, 46 catchments and storm runoff data, are displayed in figure 5.26. Despite a reduction of 6% in the total percentage of runoff explained by the first four axes, comparison of figures 5.23 and 5.26 shows no change in the ordination bi-plots. Both the distribution of catchments and length and direction of environmental vectors remain the same. AR_HORT, HA and AR_CER are most strongly correlated with axis one. MU_SLT is most strongly correlated with axis two.

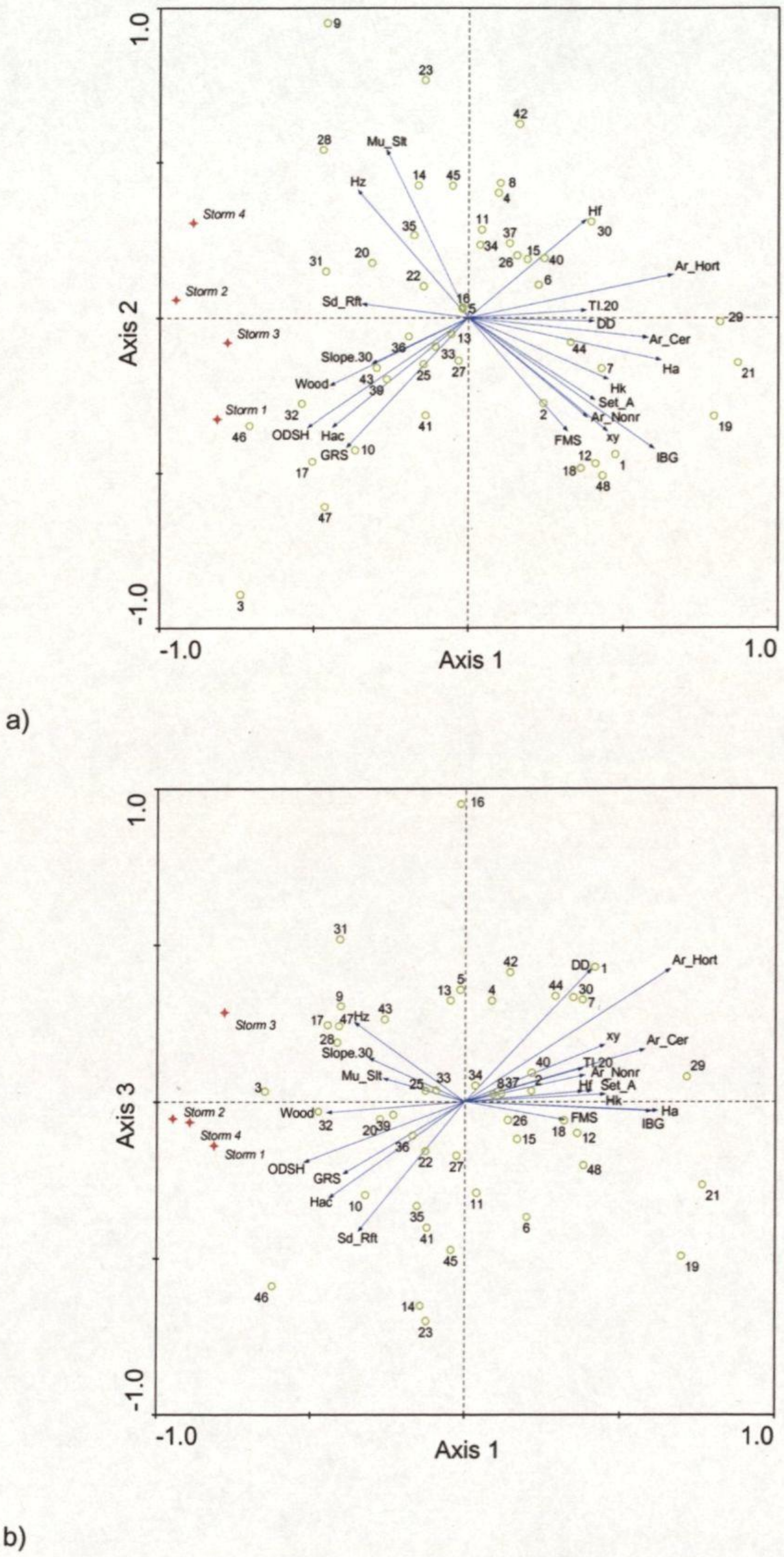


Figure 5.26 RDA ordination tri-plots performed on 46 catchments (less 24 and 38), four storms and the final 20 environmental variables a) axis 1 vs. 2 b) 1 vs. 3.

Results: Five bin class runoff dataset

Environmental variables	Variance inflation factors >20
X^2Y	6723
XY^2	2956
X^3	1500
SLOPE.6	495
XY	386
SLOPE	290
LST_O	258
SLOPE.12	144
BDP	143
ODSH	82
HF	53
HH	51
HA	36
IBG	36
AR_CER	26

Table 5.31 Variance inflation factors of environmental variables selected following analysis using the five bin class runoff dataset.

Table 5.31 presents all variables in the reduced set which exhibit VIF's greater than 20. Spatial variables demonstrated very high VIF's, ranging between 386 and 6723. The topographic parameters SLOPE<6, SLOPE and SLOPE<12 showed high VIF's at 495, 290 and 144 respectively. High VIF's were also apparent for several land use, soil and geology factors, which were in the range 26 to 258.

In order to establish the parameters for removal from the final set of environmental variables, a number of RDA analyses were run which successively excluded individual variables with observably high VIF's. With the exception of XY, all spatial parameters were omitted. RDA undertaken with XY as the only explanatory spatial variable showed a high overall percentage of variance in runoff explained. Moreover, XY demonstrated a high inter-set correlation with the key ordination axis, axis one and a low VIF.

RDA's were performed iteratively to investigate the effects of removing intercorrelated variables from the analysis, on the VIF's of other environmental variables and the total cumulative percentage variance in runoff data explained. Variables were removed in order of their VIF, starting with the highest first. The removal of highly intercorrelated variables lowers the overall percentage variance in runoff data accounted for by the remaining variables in the environmental set; the results are displayed in table 5.32.

Environmental variable	Cumulative % variance in runoff
SLOPE.6	0.825
LST_O	0.808
BDP	0.796
SLOPE	0.789
HH	0.785

Table 5.32 Total percentage variance in runoff data explained by selected environmental variables which exhibited high variance inflation factors.

Following the removal of SLOPE<6, LST_O, BDP, SLOPE and HH, all VIF's are reduced to below 13.5 (table 5.33). Intercorrelation between the remaining 25 environmental variables is reduced and the likelihood that individual parameters are providing an important individual contribution the variance in runoff is significantly increased. RDA analysis of the final environmental set revealed that the first four ordination axes explained 77.8% of the variability in the bin class runoff dataset. This represents a reduction of 10% from percentage explained by the RDA undertaken following forward selection. The percentage loss was distributed across all four axes, with 3.6% from axis one, 2.1% from axis two, 2.9% from axis three and 1.4% from axis four.

Environmental variable	Variance inflation factors
AR_CER	13.5
IBG	9.4
GRS	9
SET_A	8.3
HAC	8.2
FMS	7.9
DD	7.4
ODSH	7.2
XY	6.2
HK	5.2
AR_NONR	5
HA	4.9
HF	4.7
MU_SLT	4.7
AR_HORT	4.7
SLOPE.12	4
DEV	3.9
HQ	3.9
TI.20	2.9
HAE	2.9
WOOD	2.8
ROAD_D	2
BREC_C	1.8
HZ	1.6
CHER	1.6

Table 5.33 Variance inflation factors of the remaining 25 environmental variables, following the removal of highly intercorrelated variables.

The results of the RDA undertaken on the reduced set of environmental variables (table 5.33) and bin class runoff data are displayed in table 5.34 and in the ordination tri-plot in figure 5.27. Overall, the analysis was found to be significant at the 99% confidence interval following testing using 999 Monte Carlo permutations.

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.420	0.926	42.0	54.0		
2	0.158	0.871	57.8 (15.8)	74.3 (20.3)		
3	0.124	0.861	70.3 (12.4)	90.3 (16.0)		
4	0.076	0.751	77.8 (7.6)	100.0 (9.7)	1.000	0.778 (77.8%)
Test of significance of all canonical axes :				Trace = 0.778 P-value = 0.001		

Table 5.34 Results of RDA performed on 25 environmental variables, five runoff bin classes and 46 catchments.

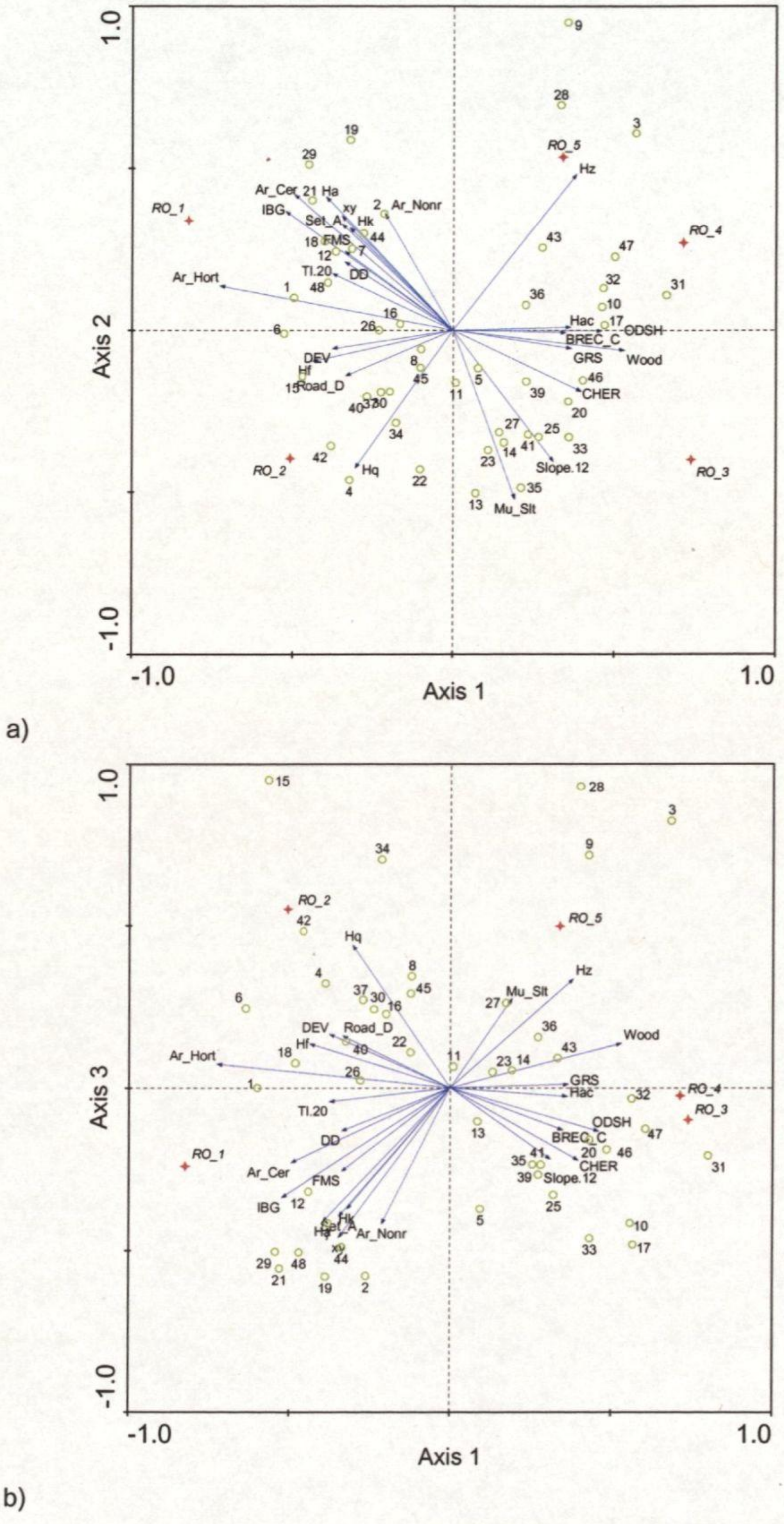


Figure 5.27 RDA ordination tri-plots performed on 46 catchments (less 24 and 38), five bin classes and final 25 environmental variables a) axis 1 vs. 2 b) 1 vs. 3.

Axis one is the principal environmental gradient, explaining 42.0% of the variance. Judging by the length and direction of arrows, AR_HORT, WOOD, ODSH, BREC_C and HAC are most strongly correlated to axis one. Axis two contributes 15.8% and axes three and four, 12.4% and 7.6% respectively. The environment-runoff correlations are all high, with 0.926 for axis one showing a strong relationship between the distribution of runoff and the environmental variables. MU_SLT and AR_NONR are most strongly correlated with axis two.

Removal of variables with high VIF's reduces the overall variance explained by the first four axes by 10% and increases the dispersion of catchments on the ordination plot. The difference in the compression of catchments on the ordination tri-plot can be seen by comparing figure 5.24 with figure 5.27. The direction and length of environmental vector arrows are unchanged.

5.7.3vi Variance partitioning

Inevitably, despite minimisation of intercorrelation through techniques such as examination of variance inflation factors, some of the remaining environmental variables will be related. Where two explanatory variables are correlated, they will share a fraction of their influence on the runoff data. The shared explanatory power of two variables is calculated as the difference between the marginal and conditional effects of the first variable, plus the effect of the second variable (Lepš and Šmilauer, 2003). The latter is true of subsets of environmental variables.

Through the calculation of a series of direct ordinations and partial ordinations, it is possible to isolate the portions of total variance in the runoff data matrix that are explainable by each of the sets of explanatory variables alone, and by interactions among the sets (Cushman and Wallin, 2002). In order to determine the relationships between

catchment environmental parameters and runoff, variance partitioning was performed using the final environmental variables, grouped into their original environmental subsets. A series of partial and conditional RDA's were employed to examine the percentage of the total variance in runoff data explained by a) individual environmental subsets, independent of other subsets and b) the shared effects of two or more subsets.

Variance partitioning on more than three variables becomes an incredibly complicated procedure, which is associated with a large amount of error (Økland, 2003). To reduce the number of computations and thus the inherent error in the analysis, three over-arching environmental groups were analysed. A land surface component represented the unique and shared contributions made by geology, soils and land use subsets. Where included, topographic and rainfall subsets were encompassed within a hydraulic component. The third and final component represented spatial parameters, calculated from the geographical coordinates of the centre of each catchment (centroid).

Results: Four storm runoff dataset

According to the results of RDA performed on the four storms runoff dataset, the final selection of environmental variables explained 83.7% of the variance in measured runoff (table 5.30). Figure 5.28 diagrammatically presents the results of variance partitioning.

Overall, land use factors explain the greatest amount of independent variation in the runoff data (18.4%). Secondary to the land use subset are the soils data, which provide a discrete contribution of 15.4%. Land use and soils show intercorrelation and together explain 14.9% of the variability in runoff. Contrastingly, geology variables only individually account for a small proportion of the variability (0.1%), but also make shared contributions with land use factors (0.7%) and soil parameters (0.1%).

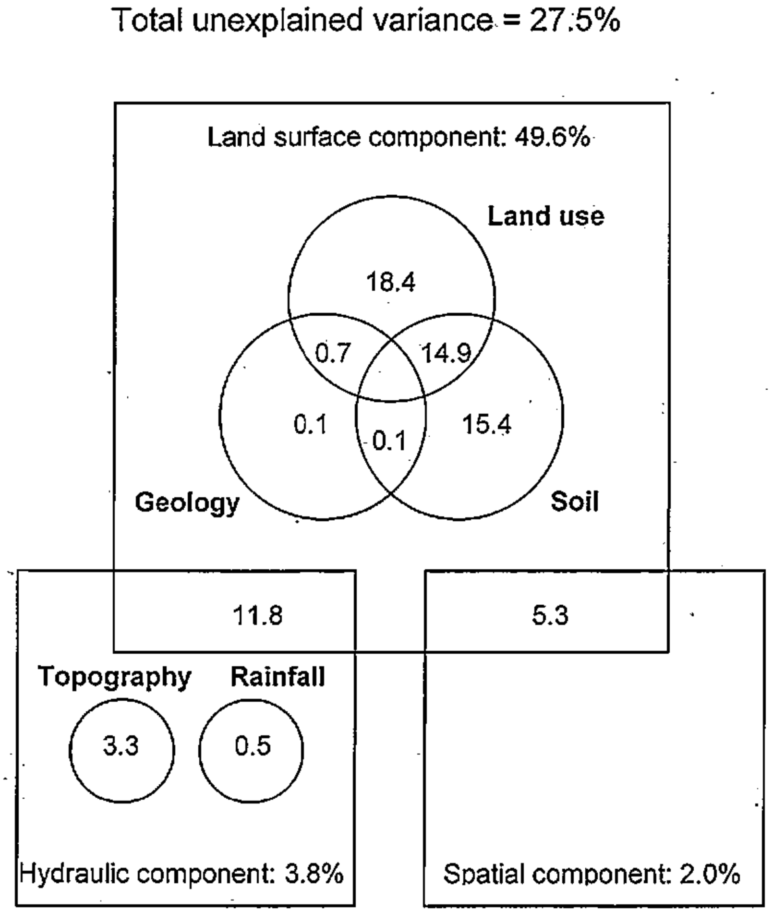


Figure 5.28 Results of variance partitioning performed on 46 catchments, four storms and the final 20 environmental variables, separated into subsets.

Collectively, the land surface component subsets explain the largest amount of variance in runoff at 49.6%. In comparison, variables incorporated within the hydraulic component independently accounted for 3.8%. Of this, 3.3% was attributable to topographic variables and 0.5% to rainfall factors. Spatial parameters explained 2.0%. Hydraulic and land surface components exhibited intercorrelation and a shared contribution of 11.8%. Furthermore, land surface components and spatial parameters together explained 5.3% of the variability in runoff. The total variability in runoff data explained by the partitioned environmental subsets was 72.5%. 11.2% of the variance was left unaccounted for following the analysis. As a result, the total unexplained variance is 27.5%.

Results: Five bin class runoff dataset

Redundancy analysis using the final environmental set and bin class runoff data, established that environmental variables explain 77.8% of the variance in measured runoff (table 5.34). Partitioning of the variance shows that variability in runoff is principally explained by land surface parameters (55.8%). The results of variance partitioning are illustrated in figure 5.29 and show that the largest individual proportion of variance in the runoff data is explained by the land use subset (17.7%). Of the land surface component, significant discrete contributions are also made by soil factors (15.4%) and by the geology subset (4.6%).

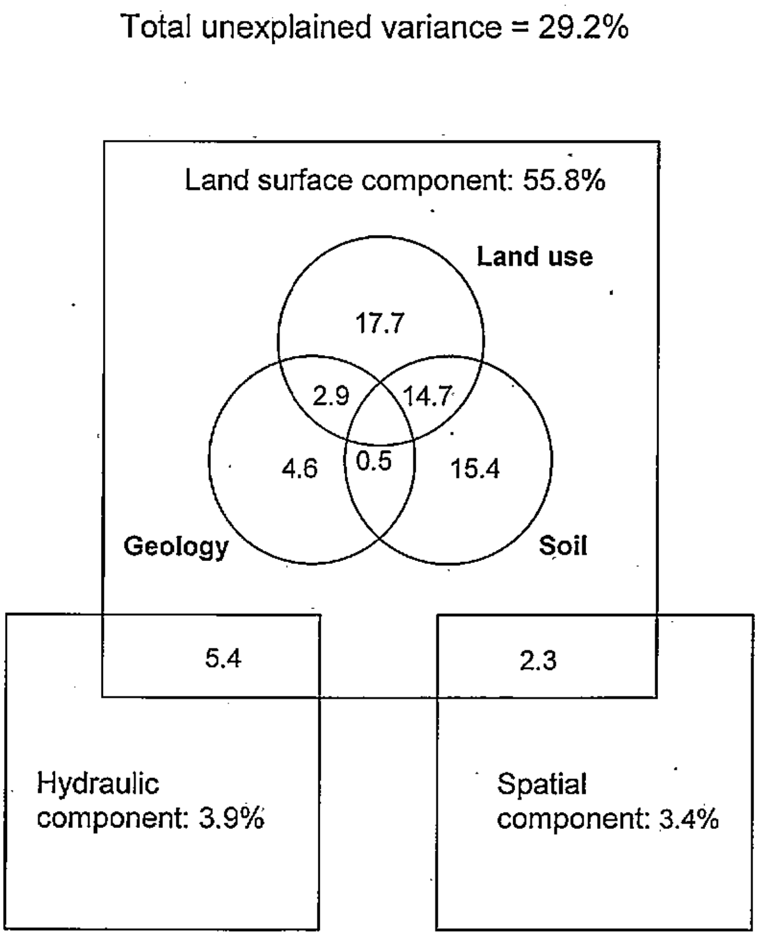


Figure 5.29 Results of variance partitioning performed on 46 catchments, five bin classes and the final 25 environmental variables, separated into subsets.

In addition to this, all land surface parameters showed a measured degree of overlap with one another. Soil and land use variables explained the greatest amount of shared variation in the runoff data, with an overlap of 14.7%. Relatively smaller overlaps were found between land use and geology (2.9%) and soil and geology (0.5%). Despite explaining significant independent variation in the runoff data, land use parameters displayed the strongest amount of intercorrelation.

The independent variation in the runoff data explained by the hydraulic component (TI<20, SLOPE<12) was calculated as 3.9%. The variability accounted for by both the land surface and hydraulic component was 5.4%. The spatial component made a discrete contribution of 3.4% and a shared contribution with land surface parameters of 2.3%. In total, the variance in runoff data explained by partitioned environmental subsets calculated as 70.8%, which indicates a 7% error in the analysis. Hence, the total unexplained variance is 29.2%.

Summary points

Four storm runoff dataset

- RDA performed using the final dataset, comprising 20 environmental variables, shows that the first four ordination axes explain 84% of the variance in measured storm runoff data.
- Land surface parameters are responsible for almost half of the total variability in runoff explained. 12% of this explanatory power is shared with the hydraulic component; whilst 5% is jointly attributed to the spatial component.
- Of the land surface environmental subsets, land use and soils, in addition to their overlap, account for 98% of the variance explained by this component.

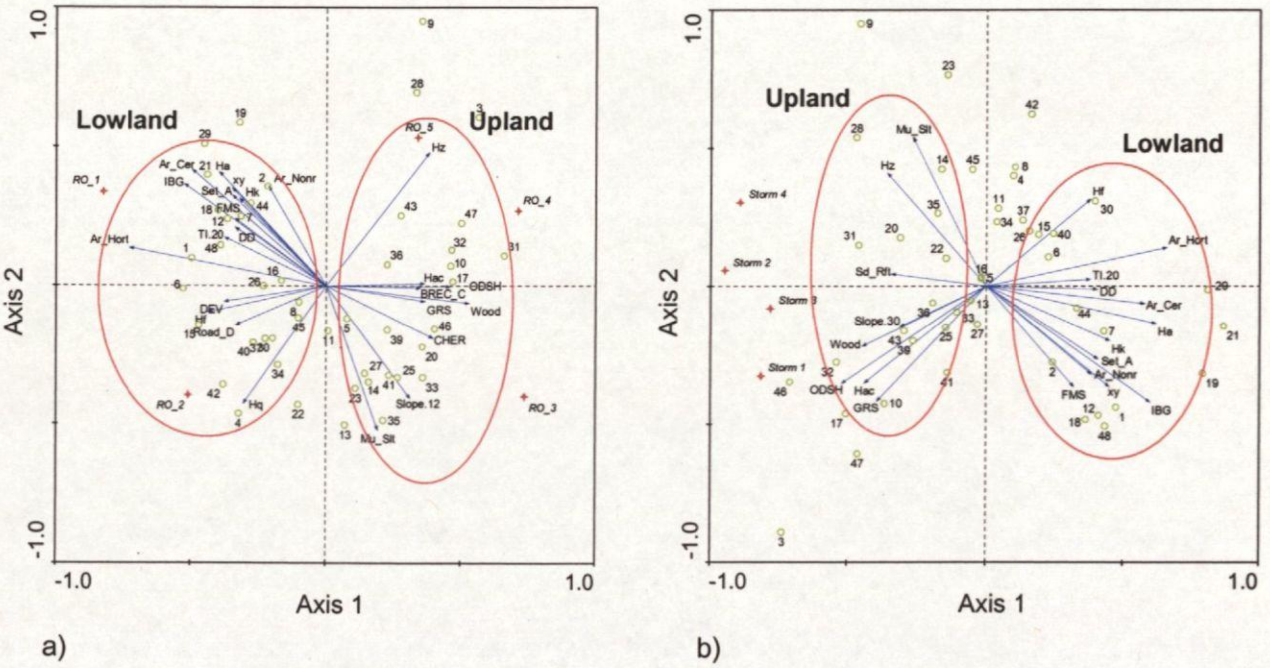
- The independent variability explained by the hydraulic component is 4% and the respective figure for the spatial component is 2%.
- 87% of the variance individually explained by the hydraulic component is attributed to topographic parameters; the remaining 13% is explained by rainfall variables.

Bin class runoff dataset

- RDA using the final set of 25 environmental variables reveals that the first four ordination axes explain 77.8% of the variance in measured bin class runoff data.
- Over half of the explained variance is attributable to environmental variables encompassed within the land surface component. This includes a shared contribution of 5% with the hydraulic component and 2% which is shared with the spatial component.
- The discrete contribution made by land use (18%) and soil (15%) environmental subsets, coupled with their joint explanatory power (15%) accounts for 86% of the explanatory power of the land surface component.
- The hydraulic component is responsible for explaining 5% of the total percentage variance in runoff explained by all components. 4% of the 77.8% is attributable to the independent contribution made by the spatial component.

5.7.3vii Variance partitioning of upland and lowland environmental parameters

The results of previous statistical analyses support earlier findings (section 5.7.3vi) that point towards an important control on high storm event runoff by land uses that are broadly characteristic of upland areas. This pattern is clearly discernible on the ordination tri-plots of RDA's performed using final environmental datasets for both sets of runoff data (figures 5.30a and b).



<u>Figure 5.30 Ordination tri-plots (axis 1 vs. axis 2) of RDA's performed using 46 catchments, final sets of environmental data and a) four storms b) five bin classes.</u>

It is impossible to clearly distinguish groups of upland or lowland catchments. However, analysing the distribution of catchments in relation to environmental and storm runoff variables may provide a better understanding of the parameters driving catchments generating higher volumes of runoff (per km^2). Hence, the refined sets of environmental variables were further explored by carrying out a series of separate RDA's coupled with

variance partitioning exercises on the distinct groups of environmental characteristics in figure 5.30, that are generally described as 'upland' and 'lowland' variables. The inter-set correlations were analysed to identify the environmental variables most strongly correlated with the key axis of variation in the data. Variance partitioning determined both the independent and shared variability in runoff explained by the environmental subsets.

Four storm runoff dataset: upland parameters

RDA undertaken using upland environmental data and the storm runoff dataset showed that the first four ordination axes explained 60.4% of the variability in runoff (table 5.35).

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.547	0.821	54.7	90.5		
2	0.036	0.713	58.3 (3.6)	96.4 (5.9)		
3	0.013	0.649	59.6 (1.3)	98.6 (2.2)		
4	0.008	0.31	60.4 (0.8)	100 (1.4)	1.000	0.604 (60.4%)
Test of significance of all canonical axes:				Trace = 0.604		
				P-value = 0.002		

Table 5.35 Results of RDA performed on upland environmental variables, four storms and 46 catchments.

The analysis was found to be significant ($p<0.01$) following testing using 999 Monte Carlo permutations. The principal gradient of variation is represented by axis one, which explains 54.7% of the variance in runoff. Axes two to four together explain just 5.7%. The high runoff-environment correlation (0.821) reveals that a strong relationship exists between environmental variables represented by axis one and the runoff data.

The ordination tri-plot of RDA undertaken on upland environmental variables and storm runoff data is displayed in figure 5.31. The strong positive relationship between storm runoff and axis one signifies that catchments distributed from the left to the right of the ordination plot will exhibit increasing runoff volumes. High runoff generating catchments are positioned towards the far right of the diagram and include Umberleigh (28), Upton (31), Pillaton Mill (17) and Laverstock (46).

Environmental Variable	Axis 1	Axis 2	Axis 3	Axis 4
ODSH	0.4837	0.3054	0.0138	-0.0507
WOOD	0.4221	0.2256	-0.1842	0.0847
HAC	0.4051	0.3166	0.0650	-0.1117
GRS	0.3578	0.3142	0.0188	-0.0632
HZ	0.3457	-0.3148	0.3981	0.1374
SD_RFT	0.3252	0.0389	-0.0204	-0.2183
SLOPE.30	0.3010	0.1086	-0.2742	0.1683
MU_SLT	0.2680	-0.4616	-0.3447	-0.0297

Table 5.36 Inter-set correlations between upland storm runoff environmental variables and the first four RDA ordination axes. Shaded cells represent the strongest relationships.

The inter-set correlations in table 5.36 and the direction of vectors in the ordination plot indicate that almost all factors are positively correlated with axis one. HZ is positively correlated with axis two and MU_SLT with axis three. Land uses, ODSH (heath) (r^2=0.5), WOOD (r^2=0.4) and GRS (r^2=0.4), and soil type HAC (r^2=0.4) are most strongly correlated with axis one. These results suggest that catchments with higher storm runoff volumes may tend to support greater proportions of 'upland' attributes.

The results of variance partitioning are illustrated in figure 5.32 and indicate that land surface parameters are largely responsible for governing variability in storm runoff data. The land surface component explains 44.2% of the variance, whereas topography independently contributes 1.0% and rainfall explains 0.7%. Of the land surface component, land use variables individually explain 15.6% and in addition, overlap with soil by 7.7% and geology by 2.9%. The soil subset comprises the second largest individual contribution (12.7%), whilst the geology subset independently explains 8.9%.

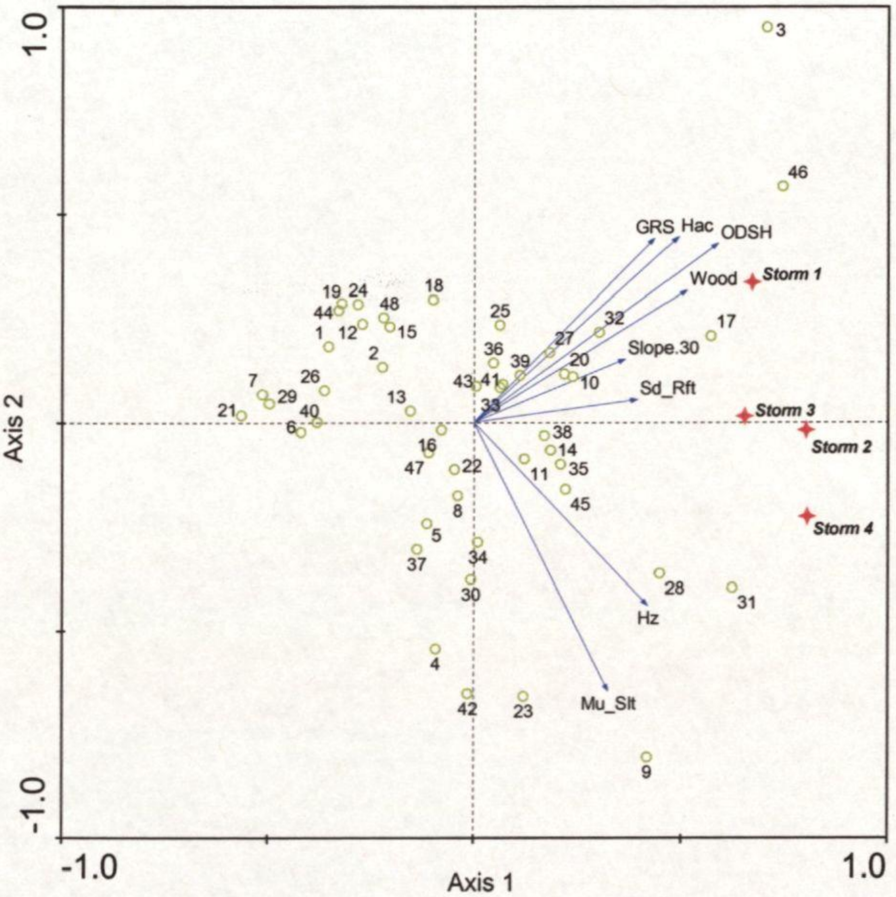


Figure 5.31 Ordination tri-plot (axis 1 vs. axis 2) of RDA undertaken on upland environmental variables, four storms and 46 catchments.

The variability accounted for by both the land surface and topography component is 6.3%. The shared contribution made by rainfall and land surface parameters is 7.7%. In total, the variance in runoff data explained by partitioned environmental subsets is 59.9%, leaving a 0.5% error. As a result, the total unexplained variance after variance partitioning is 40.1%.

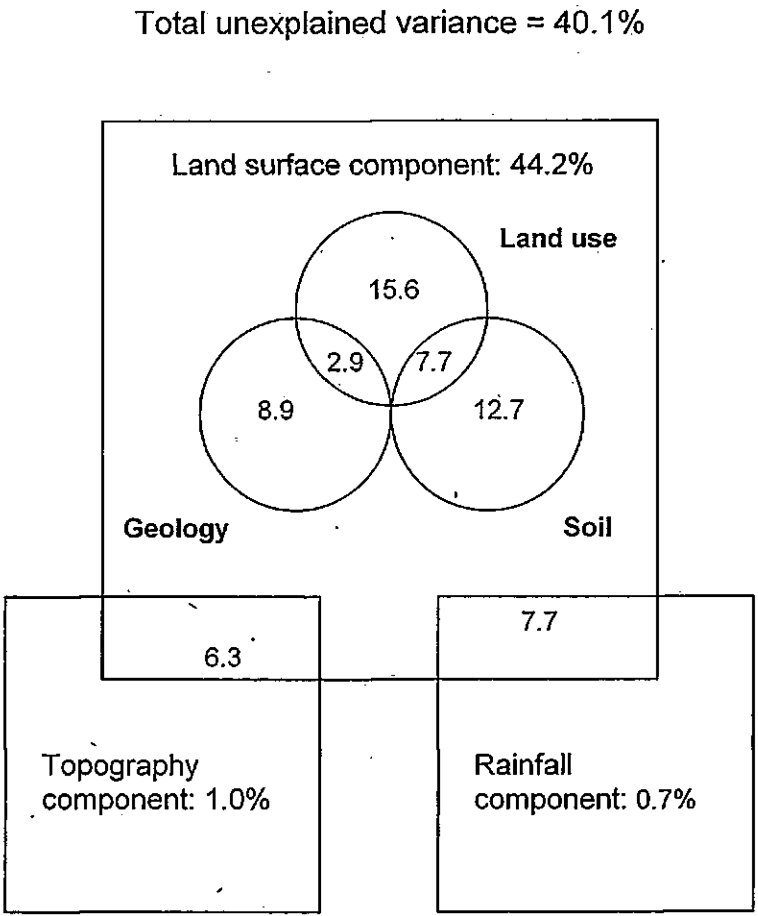


Figure 5.32 Results of variance partitioning performed on 46 catchments, four storms and upland environmental variables, separated into subsets.

Four storm runoff dataset: lowland parameters

The results of RDA employed using the lowland environmental data and storm runoff dataset are displayed in table 5.37. 54.5% of the variance is explained by the first four ordination axes with axis one responsible for explaining 49.3%, and axes two, three and four individually explaining 2.8%, 2.1% and 0.3%.

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.493	0.786	49.3	90.5		
2	0.028	0.633	52.1(2.8)	95.7 (5.2)		
3	0.021	0.473	54.2(2.1)	99.5 (3.8)		
4	0.003	0.263	54.5(0.3)	100 (0.5)	1.000	0.545 (54.5%)
Test of significance of all canonical axes:				Trace = 0.545		
				P-value = 0.002		

Table 5.37 Results of RDA performed on lowland environmental variables, four storms and 46 catchments.

The high runoff-environment correlation (0.786) indicates that environmental variables represented by axis one have a strong relationship with runoff data. The ordination tri-plot of RDA undertaken on lowland environmental variables and storm runoff data is displayed in figure 5.33. There is marked inverse relationship between high runoff and high lowland catchment characteristics. Hence, catchments with characteristics that are dominated by lowland parameters exhibit lower storm runoff volumes. The latter will be positioned towards the right-hand side of the ordination plot.

Environmental Variable	Axis 1	Axis 2	Axis 3	Axis 4
AR_HORT	0.6003	-0.1870	-0.0214	0.0015
AR_CER	0.5594	-0.0564	-0.0399	-0.0487
HA	0.5158	0.2340	-0.0530	-0.0096
HK	0.4458	0.0543	-0.0143	0.0565
XY	0.4285	0.2071	0.1215	-0.0847
SET_A	0.4082	0.0948	0.0293	0.0800
DD	0.3839	-0.2072	0.1242	-0.0098
AR_NONR	0.3814	0.0779	0.0856	-0.0518
TI.20	0.3585	0.0163	-0.0127	0.0869
IBG	0.3573	0.0410	0.2801	0.0725
HF	0.3486	-0.2642	-0.2333	-0.0439
FMS	0.3255	0.1840	0.0691	-0.0093

Table 5.38 Inter-set correlations between lowland storm runoff environmental variables and the first four RDA ordination axes. Shaded cells represent the strongest relationships.

The inter-set correlations show that all lowland environmental parameters are correlated with axis one (table 5.38). The strongest relationships are between the arable land uses AR_HORT, AR_CER and SET_ASIDE, the soil types HA and HK and the spatial parameter XY. This is also prevalent in the ordination plot through the long vector lengths of these factors. Catchments with lower runoff volumes will be characterised by arable land uses and naturally free draining soils, and will be located towards the north and east of the region.

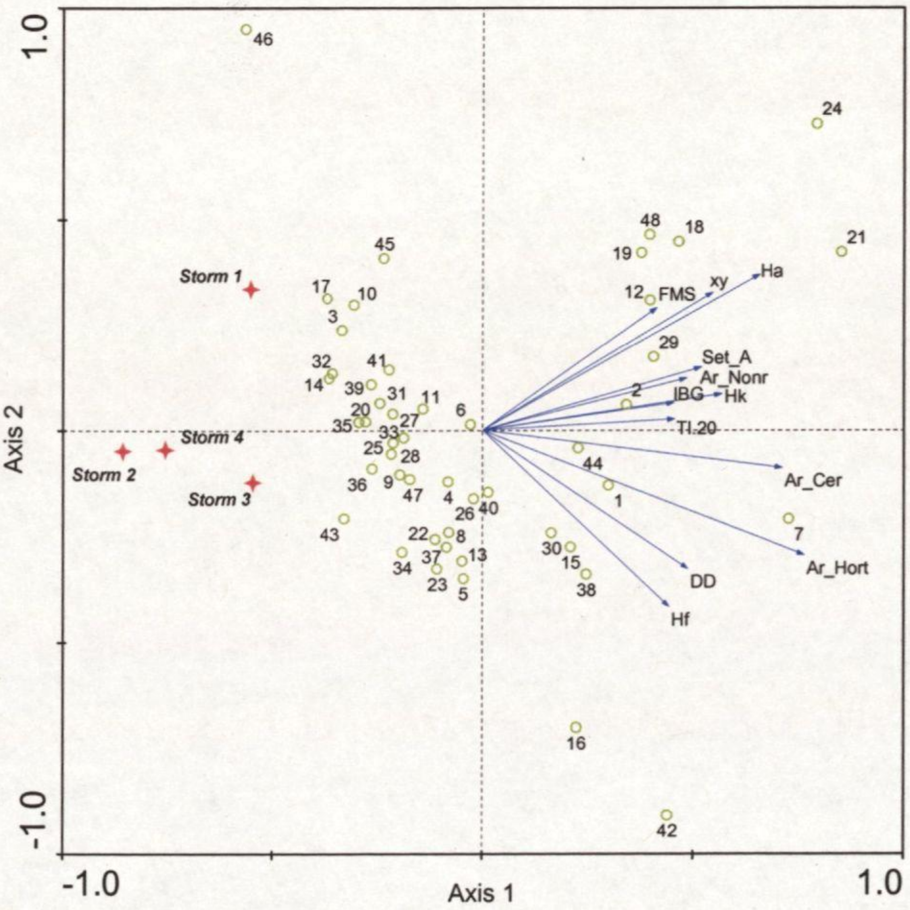


Figure 5.33 Ordination tri-plot (axis 1 vs. axis 2) of RDA undertaken on lowland environmental variables, four storms and 46 catchments.

The results of variance partitioning presented in figure 5.34 demonstrate that land surface parameters control the majority of the variability in storm runoff data (33%). The largest

proportion of this is collectively explained by the intercorrelation between land use and soil subsets (16.9%). Individually, land use parameters explain 9.8% and soil factors contribute 7.1%. The geology subset was not found to contribute a significant proportion of the variance in runoff.

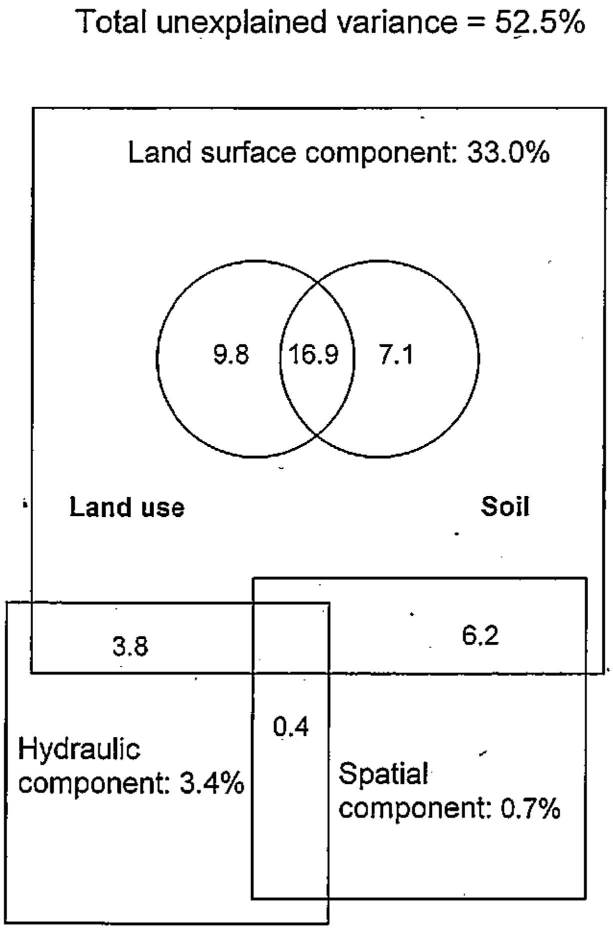


Figure 5.34 Results of variance partitioning performed on 46 catchments, four storms and lowland environmental variables, separated into subsets.

All environmental components share a proportion of their explanatory power with each of the other components. For example, land surface and spatial parameters jointly explain 6.2% of the variance. Land surface and hydraulic parameters together explain 3.8%, and 0.4% of the variance is explained by the overlap between hydraulic and spatial variables. The marginal percentage variability in runoff explained by the hydraulic component is

3.4%, whilst the equivalent figure for the spatial component is less at 0.7%. The total variance in runoff data explained by partitioned environmental data is 47.5%, leaving a 7% error. As a result, the total unexplained variance after variance partitioning is 52.5%.

Five bin class runoff dataset: upland parameters

RDA performed on upland environmental data using the bin class runoff dataset showed that the first four ordination axes explained 56.2% of the variability in runoff (table 5.39). The analysis was found to be significant at the 99% confidence interval following testing using 999 Monte Carlo permutations.

The percentage of runoff variance explained by axis one comprises approximately half of the total variance at 50.2%. This indicates the importance of the selected upland environmental variables in explaining the catchment runoff distributions across the dataset. Axis one forms the single most important gradient of variation and explains a significant percentage of the variation in the runoff-environment relationship (89.4%). Moreover, the runoff-environment relationship is highly correlated with axis one (0.807).

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.502	0.807	50.2	89.4		
2	0.033	0.643	53.5 (3.3)	95.2(5.8)		
3	0.018	0.383	55.3 (1.8)	98.4(3.2)		
4	0.009	0.555	56.2 (0.9)	100 (1.6)	1.000	0.562 (56.2%)
Test of significance of all canonical axes :				Trace P-value	= 0.562 = 0.001	

Table 5.39 Results of RDA performed on upland environmental variables, five runoff bin classes and 46 catchments.

The ordination tri-plot of RDA undertaken on upland environmental variables and bin class runoff data is displayed in figure 5.35. Runoff is positively correlated with axis one. Hence catchments distributed along axis one will generally have a gradient of increasing runoff from left to right of the ordination diagram. High runoff generating catchments are distributed in the top right quarter of the plot, including catchments Umberleigh (28), Bessom Bridge (32), Pillaton Mill (17) and Laverstock (46). Observations of the lengths of the environmental vectors and the inter-set correlations in table 5.40 shows that almost all factors are positively correlated with axis one. HZ is positively correlated with axis two (r^2=0.4).

Land uses, WOOD (r^2=0.5) and ODSH (r^2=0.4), and geology types CHER (r^2=0.4) and MU_SLT (r^2=0.4) are most strongly correlated with axis one. This reinforces the results of previous RDA's on the four storm runoff dataset, whereby catchments with higher storm runoff volumes (RO_ 3 to RO_5) will typically exhibit 'upland' geology and land use attributes.

Environmental Variable	Axis 1	Axis 2	Axis 3	Axis 4
WOOD	0.4980	-0.0337	0.0075	-0.2416
CHER	0.3735	-0.0001	0.1981	0.0726
MU_SLT	0.3570	-0.3107	-0.1961	0.1433
ODSH	0.3520	0.2525	0.1196	0.2145
SLOPE.12	0.3424	-0.1325	0.1495	0.1912
GRS	0.3202	0.0904	0.0656	0.0672
HAC	0.3002	0.1049	0.1024	-0.0125
BREC_C	0.2689	0.1825	0.1106	0.1538
HZ	0.1949	0.4017	-0.1585	-0.1787

Table 5.40 Inter-set correlations between upland bin class runoff environmental variables and the first four RDA ordination axes. Shaded cells represent the strongest relationships.

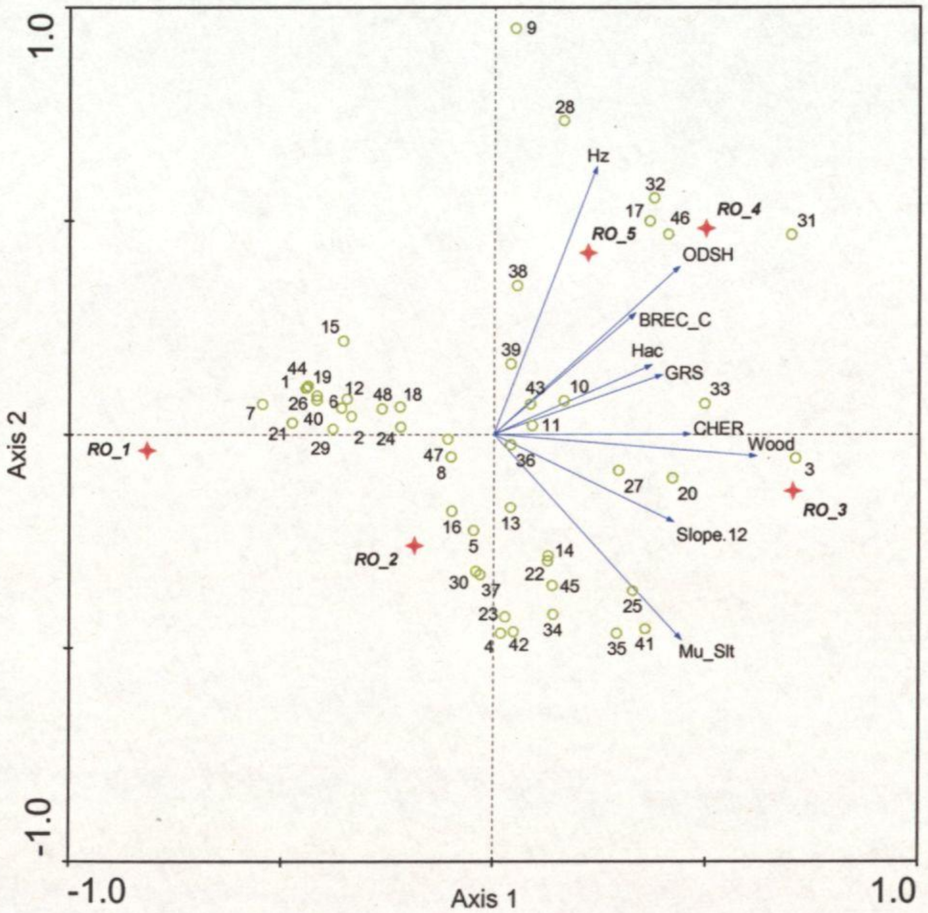


Figure 5.35 Ordination tri-plot (axis 1 vs. axis 2) of RDA undertaken on upland environmental variables, five bin classes and 46 catchments.

Variance partitioning supports the observation that variability in runoff is predominantly explained by land surface parameters (50.4%) (figure 5.36). The largest individual proportion of variance in the runoff data is explained by the geology subset (14.5%). Significant, discrete contributions are also made by land use factors (12.6%) and by the soil subset (7.8%). Land use parameters are intercorrelated. Land use and geology subsets jointly explain 7.1% variance, whilst 10.1% of the variability in runoff is shared by land use and soil subsets. Soil and geology subsets are not correlated.

Total unexplained variance = 43.8%

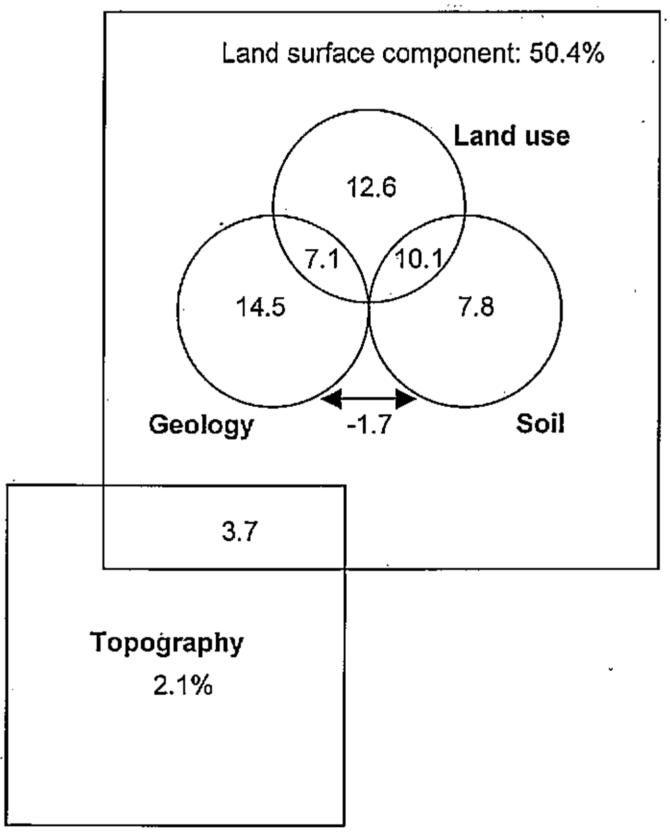


Figure 5.36 Results of variance partitioning performed on 46 catchments, five bin classes and upland environmental variables, separated into subsets.

The independent variation in the runoff data explained by the hydraulic component (SLOPE<12) was calculated as 3.7%. The variability collectively accounted for by both the land surface and hydraulic component is 3.7%. Spatial and rainfall parameters were not found to explain a statistically significant proportion of the variance in runoff. The overall variability in runoff data explained by partitioned environmental subsets totalled at 56.2%. Therefore, the total unexplained variance is 43.8%.

Five bin class runoff dataset: lowland parameters

Using the lowland environmental data, RDA on the bin class runoff dataset revealed that the first four ordination axes explained 60% of the variability in runoff (significant at the 99% confidence interval using 999 Monte Carlo permutations). The results are displayed in table 5.41. This is largely attributable to axis one, which explains 49.2%. Axis one is the key gradient of variation and explains a major percentage of the variation in the runoff-environment relationship (82.1%). In addition, the runoff-environment relationship is highly correlated with axis one (0.799).

Axis	Eigenvalue	Runoff-environment correlation	Cumulative % variance of runoff data	Cumulative % variance of runoff-environment relation	Sum of all eigenvalues	Sum of all canonical eigenvalues
1	0.492	0.799	49.2	82.1		
2	0.083	0.829	57.5 (8.3)	95.9(13.8)		
3	0.018	0.466	59.3 (1.8)	98.9 (3.0)		
4	0.006	0.521	60.0 (0.6)	100 (1.1)	1.000	0.600 (60.0%)
Test of significance of all canonical axes :				Trace = 0.600 P-value = 0.002		

Table 5.41 Results of RDA performed on lowland environmental variables, five runoff bin classes and 46 catchments.

Figure 5.37 illustrates the ordination tri-plot of RDA undertaken on 'lowland' environmental variables and the bin class runoff data. Lower runoff bin classes RO_1 and RO_2 are typical of catchments with greater lowland environmental characteristics. Catchments distributed along axis one will generally have a gradient of decreasing runoff from left to right of the ordination diagram. Catchments positioned in the left half of the plot will typically have higher runoff and fewer lowland attributes.

According to the inter-set correlations displayed in table 5.42, agricultural land uses AR_HORT, AR_CER and SET_ASIDE, and soil types HA and HK are among the factors most strongly correlated with axis one. This is also noticeable in their long vector lengths in the ordination plot. HQ and ROAD_D are more strongly related to axis two, which explains just 8.3% of the variance in runoff. The spatial variable XY is negatively correlated with axis two.

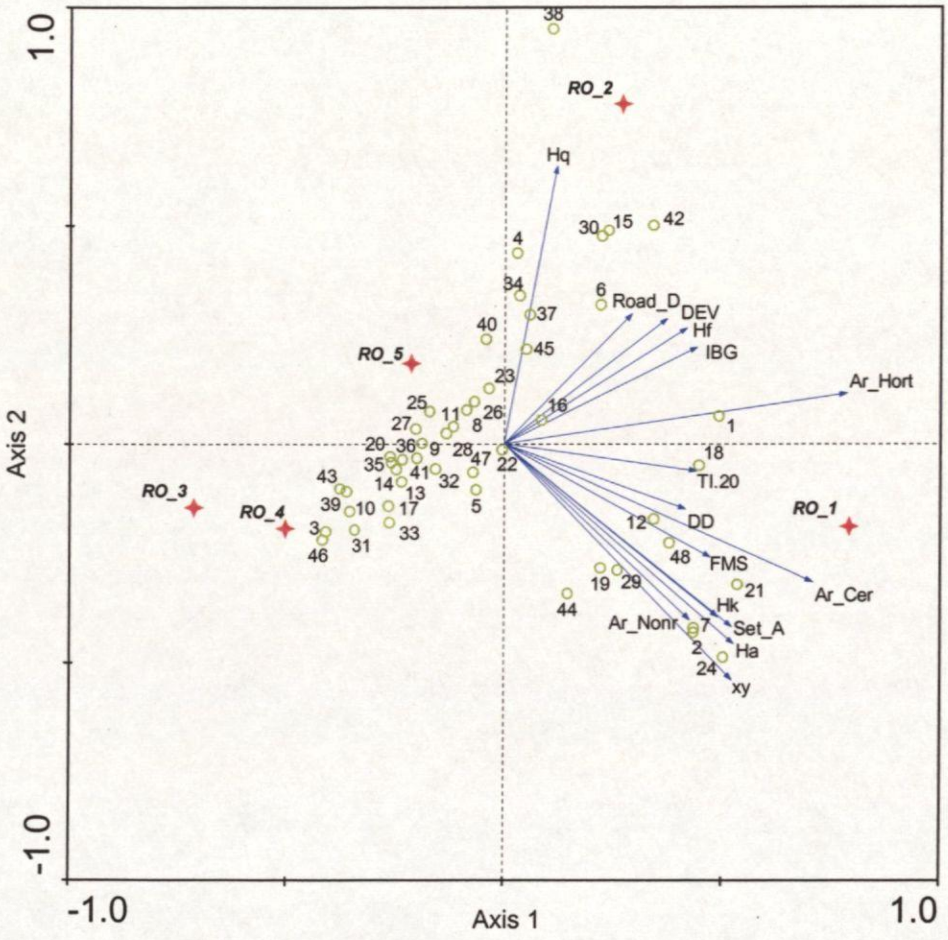


Figure 5.37 Ordination tri-plot (axis 1 vs. axis 2) of RDA undertaken on lowland environmental variables, five bin classes and 46 catchments.

Environmental Variable	Axis 1	Axis 2	Axis 3	Axis 4
AR_HORT	0.6270	0.0959	-0.0233	0.0067
AR_CER	0.5653	-0.2618	0.0401	0.1554
HA	0.4203	-0.3800	-0.0142	0.0785
SET_A	0.4170	-0.3471	-0.0052	0.0738
XY	0.4167	-0.4488	-0.0152	0.0158
HK	0.3916	-0.3285	0.0019	0.0749
FMS	0.3777	-0.2152	0.0122	0.0418
IBG	0.3529	0.1838	0.0799	0.3108
TI.20	0.3523	-0.0513	-0.1021	0.1369
AR_NONR	0.3406	-0.3340	0.2146	0.0073
HF	0.3341	0.2198	-0.0258	-0.1149
DD	0.3325	-0.1234	-0.1635	0.2005
DEV	0.2982	0.2372	0.0504	-0.0724
ROAD_D	0.2337	0.2463	-0.0115	-0.1289
HQ	0.0954	0.5265	-0.0947	-0.2398

Table 5.42 Inter-set correlations between lowland bin class runoff environmental variables and the first four RDA ordination axes. Shaded cells represent the strongest relationships.

Consistent with the previous analysis of 'lowland' parameters and four storm runoff data, catchments with a higher frequency of low runoff volumes, represented by low runoff bin classes RO_1 and RO_2, will support a greater proportion of arable land uses (AR_HORT, AR_CER and SET_ASIDE) and naturally good quality soils (HA and HK).

Partitioning of the variance reveals that the land surface component, comprising land use and soil factors, explains the largest proportion of variability in runoff (39.4%). The results of variance partitioning are illustrated in figure 5.38. The greatest individual percentage of variability in the runoff data is explained by the land use subset (15.8%). The soil subset individually explains 6.2% but shares a 17.4% overlap with land use parameters.

The hydraulic component independently accounts for 2.2% of the variance. Coupled with land surface subsets, it explains an additional 3.2%. The spatial component makes a discrete contribution of 1.8% and a shared contribution with land surface parameters of 6.6%. All together, the variability in runoff data explained by partitioned lowland environmental variables is 53.2%, which indicates a 6.8% error in the analysis. The total unexplained variance following variance partitioning is 46.8%.

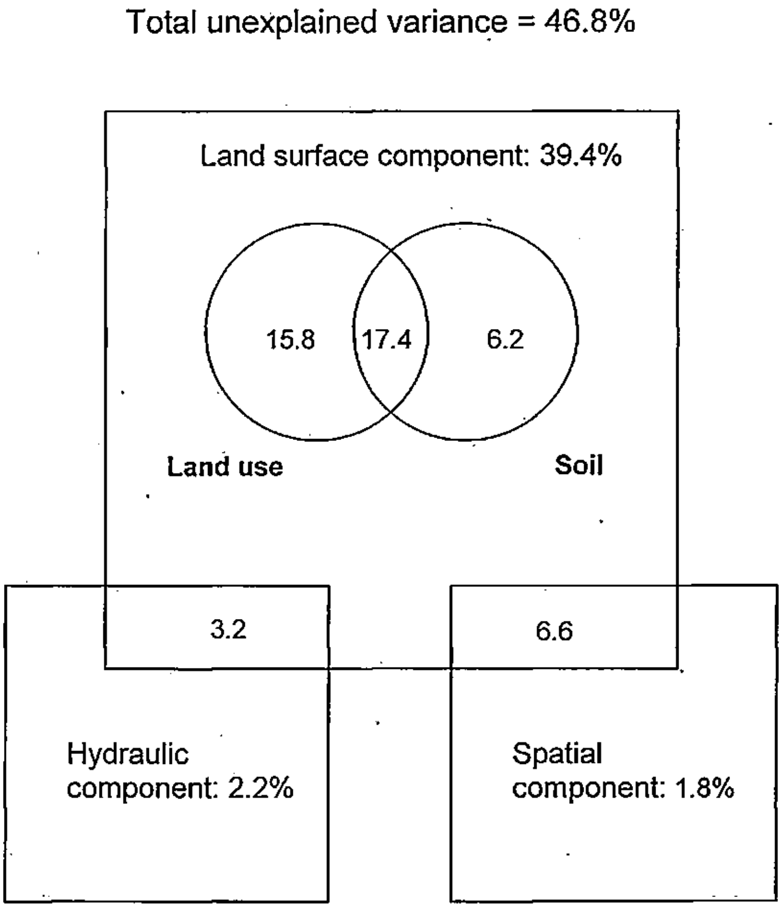


Figure 5.38 Results of variance partitioning performed on 46 catchments, five bin classes and lowland environmental variables, separated into subsets.

Summary points

Four storm runoff dataset: Upland parameters

- RDA performed using the upland environmental dataset shows that the first four ordination axes explain 60.4% of the variance in the measured storm runoff data.

- Axis one is the principal gradient of variation and explains 54.7% of the variance in runoff and 91% of the variability accounted for by the ordination.
- In order of the strength of the relationship, the environmental variables ODSH, WOOD, HAC, GRS, SD_RFT and SLOPE<30 are all correlated with axis one.
- The strong positive relationship between storm runoff and axis one signifies that catchments with higher storm runoff volumes will be more dominantly characterised by these broadly upland attributes.
- According to variance partitioning, the land surface component is largely responsible for governing variability in storm runoff data, explaining 44% of the variability in runoff and 73% of the variance explained by the ordination.
- The topographic component independently contributes 1.0% and jointly explains 6% with land surface parameters, whilst the discrete rainfall component is 1%. Rainfall shares 8% with the land surface component.
- Of the variance explained by land surface environmental subsets, land use individually explains 16%, soil independently accounts for 13% and the discrete contribution made by geology is 9%.
- The joint contribution made by the intercorrelated land surface subsets, land use and soils is 8% and land use and geology is 3%.

Four storm runoff dataset: Lowland parameters

- Results of RDA performed using the lowland environmental dataset demonstrate that the first four ordination axes explain 55% of the variance in the measured storm runoff.
- Axis one is responsible for explaining 49% the variability in runoff and 90% of the variance explained by the first four ordination axes.

- All environmental variables are most strongly correlated with axis one. The most significant relationships are observed between the arable land uses AR_HORT, AR_CER and SET_ASIDE, the soil types HA and HK and the spatial parameter XY.
- The extent of lowland parameters, notably arable land uses and naturally free draining soils, may be greater in catchments producing lower storm runoff volumes. Such catchments may be prevalent towards the northeast of the region.
- Variance partitioning demonstrates that approximately a third of the variance in runoff (33%) and just under two thirds (61%) of the variance explained by the ordination is attributable to the land surface component. This excludes the joint contributions with the hydraulic component (4%) and the spatial component (6%).
- The land use component consists of a 10% independent contribution from the land use subset, plus 7% discrete attributed to the soil subset, combined with the shared explanatory power (17%).
- The topographic component independently contributes 3%, whilst the discrete spatial component is 1%.

Bin class runoff dataset: Upland parameters

- RDA performed using the upland environmental dataset shows that the first four ordination axes explain 56% of the variance in the measured bin class runoff.
- The percentage of variability in runoff explained by axis one comprises approximately half of the total variance in runoff and 89% of the total variability explained by the ordination.
- Analysis of the inter-set correlations shows that land use factors, WOOD and ODSH, and geology types CHER and MU_SLT are most strongly correlated with axis one, followed by SLOPE<12, GRS, HAC and BREC_C.

- Runoff is highly positively correlated with axis one. Hence, catchments associated with medium to high runoff bin classes RO_3, RO_4 and RO_5, demonstrate greater proportions of attributes that are generally located in upland areas.
- Greater than half of the total variability in runoff and 90% of the total explained variance is attributable to environmental variables encompassed within the land surface component. This does not include the shared contribution of 4% with the hydraulic component.
- The percentage variance explained by the land surface component comprises discrete contributions made by geology (15%), land use (13%) and soil (8%) environmental subsets, together with the joint explanatory power of geology and land use (7%) and soil and land use (10%).
- The hydraulic component is responsible for 4% of the total percentage variance in runoff explained by the ordination.

Bin class runoff dataset: Lowland parameters

- RDA undertaken using the lowland environmental dataset demonstrates that the first four ordination axes explain 60% of the variance in the measured bin class runoff.
- Axis one is the key gradient of variation and explains 49% of the total variability in runoff and 82% of the variance explained by the first four ordination axes.
- Observation of the inter-set correlations shows that agricultural land uses AR_HORT, AR_CER and SET_ASIDE, and soil types HA and HK are among the factors most strongly correlated with axis one. Other factors correlated with this axis includes the land uses FMS, IBG, DEV and AR_NONR, topographic factors TI<20 and DD, and soils HK and HF.

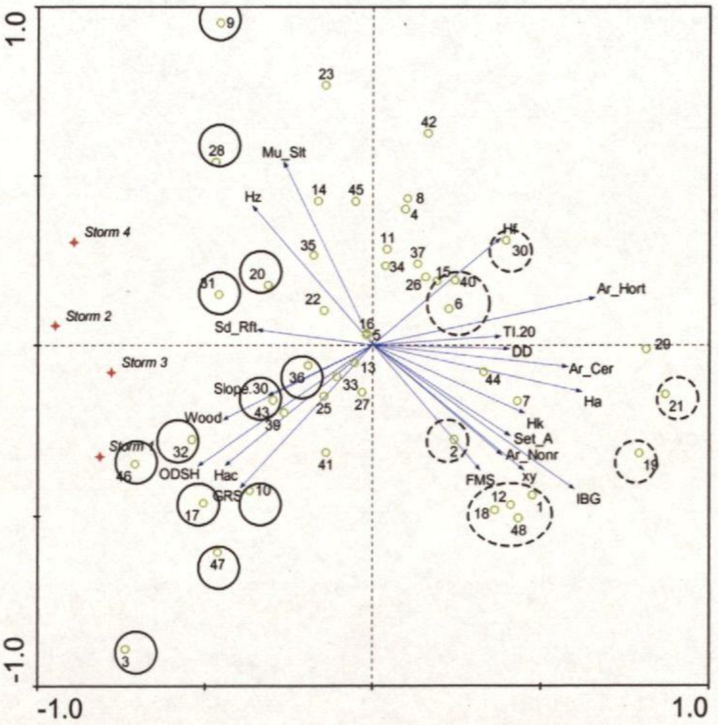
- Low runoff bin classes RO_1 and RO_2 are typical of catchments with a higher coverage of lowland characteristics.
- Partitioning of the variance reveals that over a third of the variance in runoff (39%) and two thirds (66%) of the variance explained by the ordination is attributable to the land surface component. This doesn't include the shared contributions with the hydraulic component (3%) and the spatial component (7%).
- The land use component comprises discrete contributions from land use (16%) and soil (6%) subsets, in addition to the explanatory power they share (17%).
- The independent variability explained by the both the hydraulic and spatial components is 2%.

5.7.3vii Higher (H_r) and Lower (L_r) runoff generating catchments

Results of variance partitioning confirmed the importance of land use, in addition to other factors, in controlling the volume of runoff produced during peak flow responses to four storm events. More importantly, it highlighted the intrinsic interrelationships between land use and environmental factors, through measured intercorrelation between parameter subsets. The nature and distribution of dominant land uses in study catchments across southwest England were fundamentally governed by the interactions between geology, relief and climatic factors and their influence on soil formation.

Subjective separation of catchments according to their position on ordination triplots enabled further investigation of factors controlling higher (H_r) and lower (L_r) runoff generating catchments. L_r and H_r catchments were those that plotted to the extreme right or left of the ordination triplots for both R1 and R2 RDA's (figures 5.39a and b). Analysis of the similarities in environmental characteristics within L_r and H_r catchments, in addition to the dissimilarities between them, provided a clearer indication of the patterns in land surface parameters that were driving variability in runoff across the region.

The land use characteristics of H_r and L_r catchments varied most widely in the proportion of improved grassland (I_GRS) they supported. Across the 48 study catchments, improved grassland was ubiquitous. For selected catchments (L_r and H_r), it comprised the most extensive land cover type in terms of the percentage cover per catchment (figure 5.40). The average percentage cover of I_GRS for H_r catchments was 3% higher than the average for L_r catchments, whilst the maximum percentage cover was 16% higher (figure 5.41).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-1.0
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Sd_Rft
Slope.30
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ODSH
Hac
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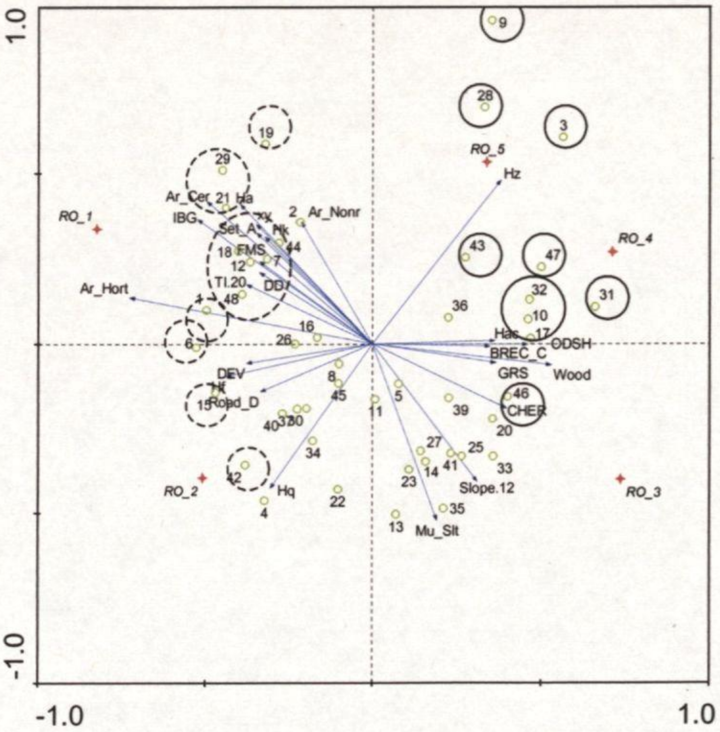
a)


1.0
-1.0
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RO_4
RO_5
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Ar_Cer
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IBG
xy
Set_A
Hk
FMS
TI.20
DD
Ar_Hort
DEV
Hf
Road_D
Hq
Hac
ODSH
BREC_C
GRS
Wood
CHER
Slope.12
Mu_Slt

b)

Figure 5.39 Ordination triplots of RDAs performed on reduced parameter subsets for a) R1 and b) R2 runoff datasets, with H_r (closed circle) and L_r (dashed circle) catchments highlighted.

Catchments which exhibited particularly high or extreme runoff volumes, including Bessom Bridge (32), Upton (31), Umberleigh (28), Pillaton Mill (17) and Stoodleigh (30), all supported above average I_GRS for all 48 catchments combined. Catchments containing greater than 50% of I_GRS were dominantly underlain by HQ, in addition to three other major soil HOST classes, including HX, HU, HR. HX, HU and also HR classes all demonstrated significant positive correlations with I_GRS (figure 5.42). These soils are described as slowly permeable or impermeable and are typically formed on clays and slate (figure 5.42 and table 3.5).

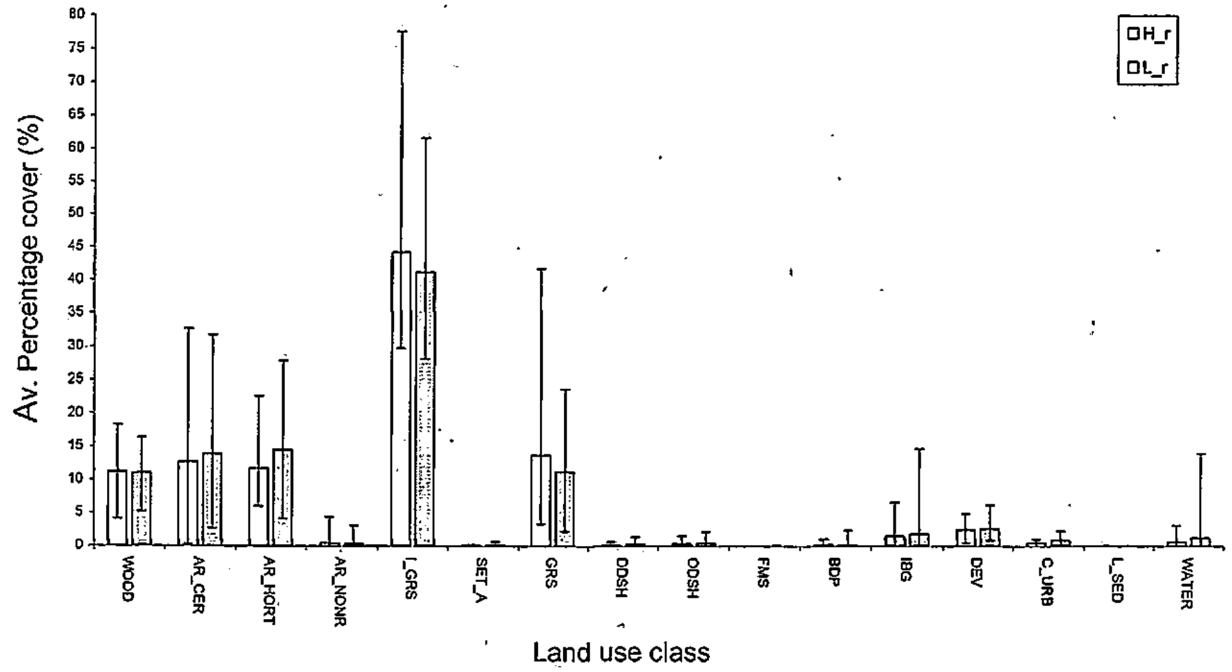

Figure 5.40 Average percentage cover of land use classes in H_r and L_r catchments.

Regionally, grassland was the second most important land use, encompassing an average of 15% of catchments. H_r catchments displayed a 2.5% greater grassland cover on average and an 18% increase in maximum values. Grassland (GRS), bog, deep peat (BDP) and open dwarf shrub heath (ODSH) each demonstrated significant positive correlations with HAC. HAC comprises peat soils that are generally underlain by granite bedrock. HAC was found to be strongly correlated with the geology class GRAN (figure 5.42). In addition to poor productive capacity, peat soils are typically limited in extent to exposed upland areas, where land cover is often restricted to rough grazing on open moorland and peat bog. The land use classes BDP and ODSH covered on average just 1.2% and 1.5% of catchments.

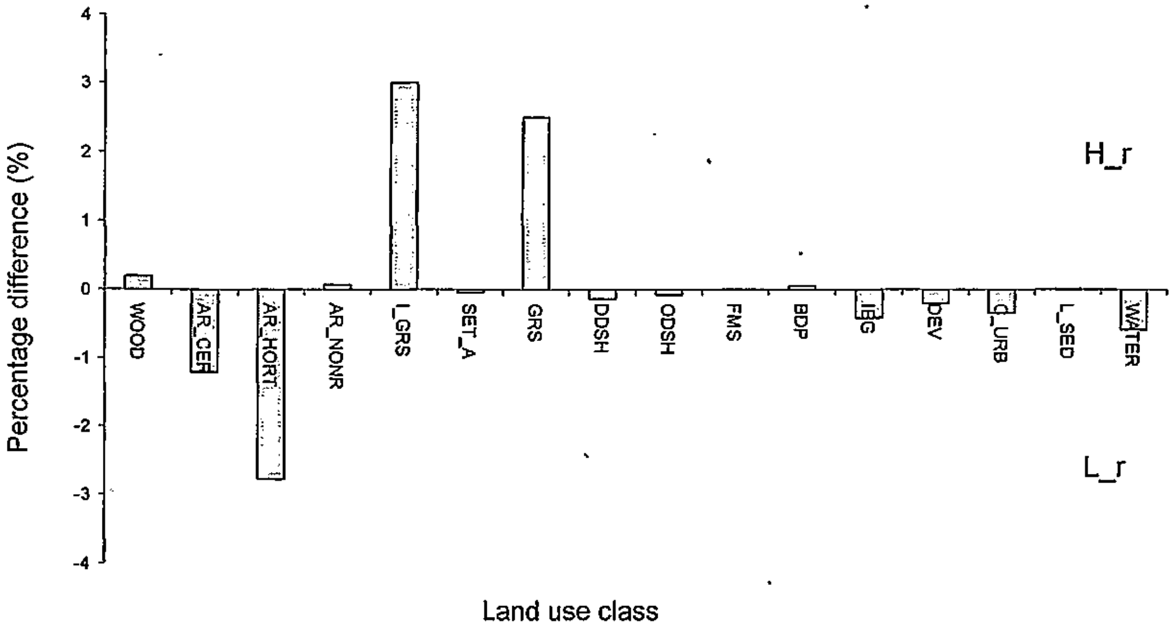

Figure 5.41 Difference in the percentage cover of land use classes between H_r and L_r catchments.

Cereal cultivation (AR_CER) and horticulture (AR_HORT) covered 13% and 12% of catchments on average (figure 5.40). For both H_r and L_r catchments, the minimum percentage cover of cereals was greater than the average of all 48 catchments. This represents a rise of 7% for H_r catchments and 8% for L_r catchments. L_r catchments supported 1.2% (AR_CER) and 2.8% (AR_HORT) more arable land uses than in H_r catchments (figure 5.41). Cereal production and horticulture were largely concentrated in areas where free draining brown earths have formed on drift deposits overlying slate, chalk and sandstone. Catchments with over 20% of land under cereals displayed predominantly HA soils, in addition to variable extents of HC, HE, HF, HJ and HK, which are all described as exhibiting good permeability (>10cm day-^{1}) (table 5.6). Positive correlations were observed between HA, HC, HE, HF and HK and AR_CER and AR_HORT (figure 5.42). The latter were also significantly correlated with geology class LST_O (limestone and chalk). Woodland covered 11% of catchments on average and showed little variability between H_r and L_r catchments. The average percentage cover of woodland in H_r catchments was just 0.2% greater than L_r catchments (figure 5.41). Woodland was positively correlated with slowly permeable clay soils, HX, HU and HAC (figure 5.42).

Slight differences in slope steepness between H_r and L_r catchments were characterised by a higher proportion of steeper slopes in H_r catchments and a higher proportion of shallower slopes in L_r catchments. The median percentage of SLOPE<6 was 9% less for H_r catchments, whilst the median percentage of SLOPE<12 was 10% higher for H_r catchments. H_r catchments exhibited 2.2% more steeper slopes (SLOPE<18) than L_r catchments.

The behaviour of extreme catchments, that were omitted at an early stage in the analysis, including Torrington (24) and South House (38), was thought to be primarily the result of steep topographic characteristics. Torrington displayed the greatest frequency of SLOPE<12. Moreover, South House (24) exhibited the second highest frequency of SLOPE<12 and the highest number of SLOPE<18. The average slope for South House was 7.2°, higher than the overall average of 4.8°. The nested catchments Little Puddle (39) and Briants Puddle (40) exhibited similar land use, soil and geology characteristics. Notwithstanding this, they were clearly distinct in terms of runoff and plotted apart on ordination triplots (figure 5.39). Little Puddle was found to be steeper on account of 19% fewer shallow slopes (SLOPE<6), 14% more SLOPE<12 and 5% greater SLOPE<18%.

Examples existed of H_r catchments which exhibited shallow reliefs. The average slopes of Laverstock and Upton, for instance, were 2.8° and 4.2°, which fell below the 4.8° average for all 48 study catchments. Average slopes for H_r catchments Amesbury (2.7°), East Mills Weir (3.5°) and Ponsanooth (3.4°) were also comparatively low. For H_r catchments, the minimum percentage of SLOPE<6 was 17% higher than equivalent Figures for L_r catchments. The range in average slope was 2.7°-6.4°. This is compared to L_r catchments, where the average slope steepness was in the range 2.4°-7.7°. Unusually, steep catchments including Stoodleigh (table 3.2), Thorverton and Craigshill Wood each exhibited low runoff volumes.

Summary points

- The land use characteristics of H_r and L_r catchments varied most widely in the proportion of improved grassland (I_GRS) and grassland (GRS) they supported.
- Catchments containing greater than 50% of I_GRS were predominantly underlain by slowly permeable or impermeable soils overlying clays and slate.
- Both H_r and L_r catchments exhibited minimum percentage cereal covers greater than the average of all 48 catchments.
- Cereal production and horticulture were located in areas where free draining brown earths have formed on drift deposits overlying slate, chalk and sandstone.
- H_r catchments exhibited a higher proportion of steeper slopes, whilst L_r catchments demonstrated a higher proportion of shallower slopes.
- Extreme catchments including Torrington (24) and South House (38), exhibited steep topographies.

	WOOD	AR_CER	AR_HORT	I_GRS	GRS	ODSH	BDP	GRAN	SST	MU_SLT	LST_O	HA	HC	HE	HF	HK	HO	HR	HU	HV	HX	HY	HAC	SLPE<6°	SLPE<12°
AR_CER	-0.29*	1.00																							
AR_HORT	-0.49**	0.68**	1.00																						
I_GRS	0.16	-0.23	-0.24	1.00																					
GRS	0.17	-0.6**	-0.42**	-0.33*	1.00																				
ODSH	0.26	-0.32*	-0.44**	-0.31*	0.55**	1.00																			
BDP	0.37**	-0.58**	-0.72**	-0.21	0.67**	0.77**	1.00																		
GRAN	0.05	-0.63**	-0.36*	-0.27	0.79**	0.48**	0.67**	1.00																	
SST	0.14	0.31*	0.16	0.30*	-0.48**	-0.28*	-0.28*	-0.61**	1.00																
MU_SLT	0.26	-0.10	-0.19	0.53**	-0.20	-0.11	-0.05	-0.21	0.07	1.00															
LST_O	0.00	0.58**	0.30*	-0.21	-0.40**	-0.01	-0.19	-0.45**	0.24	-0.31*	1.00														
HA	-0.33*	0.71**	0.50**	-0.38**	-0.43**	-0.21	-0.41**	-0.52**	0.17	-0.47**	0.82**	1.00													
HC	0.06	0.55**	0.32*	-0.22	-0.37**	0.06	-0.15	-0.51**	0.52**	-0.05	0.58**	0.51**	1.00												
HE	-0.10	0.39**	0.28*	-0.18	-0.26	0.14	-0.23	-0.39**	0.19	-0.01	0.39**	0.41**	0.58**	1.00											
HF	-0.31*	0.60**	0.60**	-0.16	-0.34*	-0.26	-0.49**	-0.34*	0.01	-0.09	0.51**	0.53**	0.28*	0.29*	1.00										
HK	-0.25	0.58**	0.34*	-0.38**	-0.18	-0.01	-0.31*	-0.39**	-0.05	-0.36*	0.66**	0.79**	0.33*	0.46**	0.47**	1.00									
HO	0.23	-0.73**	-0.45**	-0.16	0.76**	0.50**	0.67**	0.86**	-0.53**	-0.11	-0.46**	-0.59**	-0.47*	-0.39*	-0.36*	-0.44**	1.00								
HR	0.18	0.26	-0.03	0.47**	-0.46**	-0.03	-0.17	-0.52**	0.43**	0.52**	0.01	-0.03	0.21	0.27	-0.08	-0.12	-0.47**	1.00							
HU	0.34*	0.03	-0.19	0.46**	-0.19	-0.02	0.04	-0.28*	0.49**	0.54**	-0.13	-0.31*	0.25	0.09	-0.04	-0.33*	-0.25	-0.54**	1.00						
HV	0.25	-0.42**	-0.08	0.38**	0.19	0.08	0.14	0.19	-0.02	0.57**	-0.38**	-0.61**	-0.30	-0.30*	-0.21	-0.48**	0.32	0.23	0.19	1.00					
HX	0.34*	0.25	-0.09	0.32*	-0.36*	-0.04	-0.06	-0.39**	0.58**	0.40**	0.13	-0.08	0.40**	0.22	0.01	-0.15	-0.39**	0.45**	0.80**	-0.06	1.00				
HY	-0.09	0.42**	0.22	-0.21	-0.18	0.14	-0.20	-0.31*	0.09	-0.16	0.51**	0.57**	0.47**	0.57**	0.36*	0.68**	-0.44**	0.12	-0.09	-0.41**	0.11	1.00			
HAC	0.27	-0.54**	-0.54**	-0.25	0.65**	0.58**	0.73**	0.71**	-0.39**	-0.17	-0.14	-0.33*	-0.23	-0.15	-0.39**	-0.26	0.77**	-0.38**	-0.22	0.06	-0.18	-0.23	1.00		
SLPE<6°	-0.13	0.17	0.23	-0.13	0.05	-0.22	-0.32*	-0.01	-0.10	-0.15	-0.08	0.14	-0.13	0.08	0.16	0.31*	-0.18	-0.17	-0.11	-0.29*	0.05	0.30	-0.21	1.00	
SLPE<12°	0.11	-0.21	-0.27	0.14	-0.05	0.20	0.31*	0.04	0.05	0.15	0.01	-0.18	0.06	-0.14	-0.19	-0.34*	0.18	0.16	0.07	0.28*	-0.07	-0.31*	0.20	-0.98**	1.00
SPE<30°	0.36*	-0.03	-0.20	-0.04	0.13	0.36*	0.39**	0.04	0.18	0.06	0.36*	0.01	0.42**	0.11	0.03	0.00	0.15	0.01	0.20	0.12	0.23	0.04	0.27	-0.39**	0.29*

**Significant at $p<0.01$ *significant at $p<0.05$

Figure 5.42 Matrix of Spearman Rank correlation coefficients (r_s) between land, soil, slope and tchment parameters (n = 48)

Chapter 6:

Long-term investigation into agricultural land use change and hydrological response in the Camel Catchment, Cornwall (Part III).

6.1 Introduction

This thesis explores whether the influence of land use on peak flow responses can be identified at the catchment scale. In chapter 5, a statistical analysis of spatial patterns in the environmental characteristics and runoff responses of 48 heterogeneous catchments demonstrated a dominant land use control on variability in the volume of runoff produced during four high magnitude storm events.

Grassland and improved grassland, which are typical of upland areas, dominated catchments generating higher volumes of runoff (section 5.7.3vii). Notwithstanding this, these catchments also supported extensive cereal and horticultural production that is generally restricted to shallower slopes.

The following chapter further investigates the role of land use on peak flows and attempts to disentangle the specific influence of individual land uses on streamflow, through a longer-term investigation of the River Camel catchment and the De Lank sub-catchment. By separating the headwater subcatchment of the De Lank tributary (11) from the entire Camel catchment (8), this investigation adds an additional scale dimension to the thesis and facilitates examination of the effects of upland grazing and lowland cereal cultivation on peak river flows.

This temporal approach complements the spatial approaches adopted at regional (Part II) and field (Part IV) scales. The Camel and De Lank catchments comprise two of the 48 study catchments investigated in part II (chapters 3, 4 and 5), whilst the western Camel catchment forms the study site of the field survey undertaken in part IV. It is presented in the form of the paper by Sullivan *et al* (2004), which was published in the journal of Applied Geography, and is incorporated into the thesis in Appendix I.

The following sections provide a more comprehensive description of the Camel and De Lank catchments than is presented in the paper. Details of the aims and objectives, methodology and results of the River Camel investigation are discussed in the paper in Appendix I.

6.2 Site Description

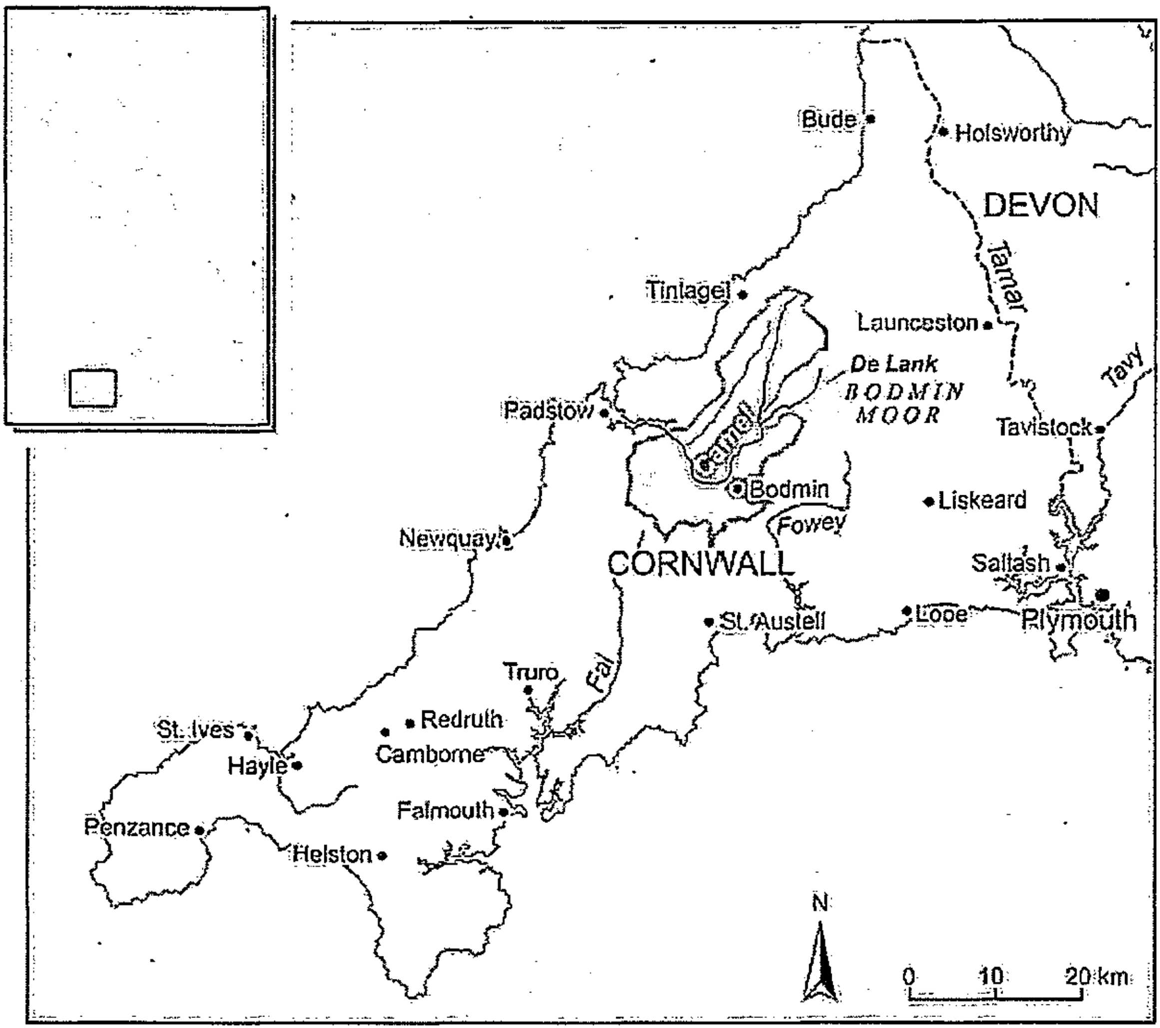

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Figure 6.1 Location of the Camel catchment and De Lank subcatchment in southwest England

6.2.1. Catchment selection criteria

The criteria for selecting the Camel catchment are summarised below.

1) Regular fluvial flooding has affected several local communities within the catchment, necessitating the construction of flood alleviation schemes at Camelford, Egloshayle, Wadebridge, Sladesbridge and Padstow (plate 6.1).

2) The Camel system has been awarded high conservation status at a national and European level due to a diversity of habitats which are of special interest for the wildlife they support, including populations of otters and bullhead fish. It represents one of the most important natural fisheries in the southwest for Atlantic salmon (*Salmo salar*) and Sea trout (*Cottus gobio*). One of the principal tributaries, the De Lank River, is also expected to be added to the Natura 2000 list.

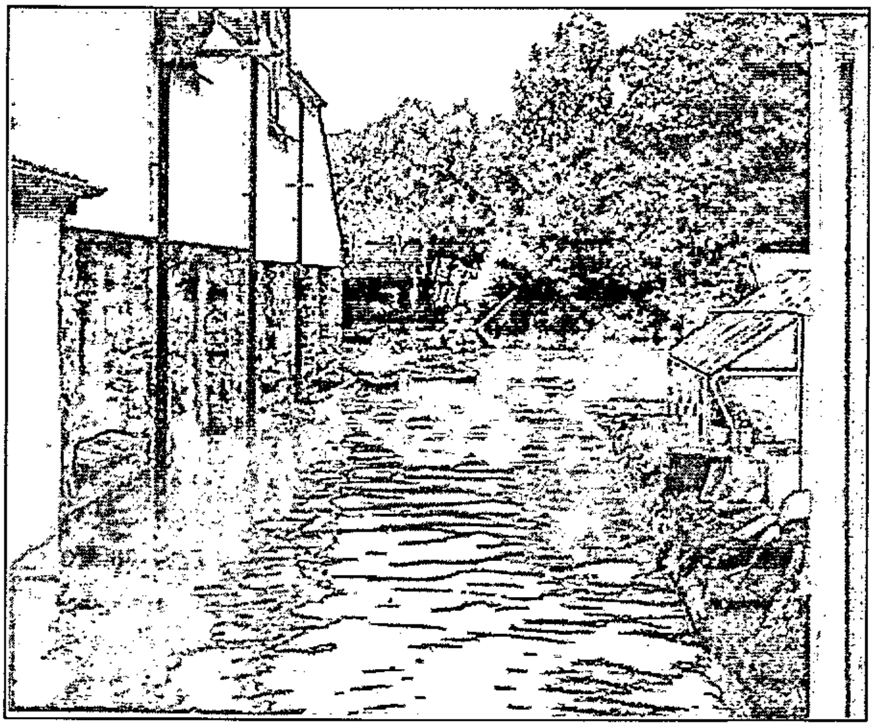


Plate 6.1. Flooding of the community at Sladesbridge in the Camel catchment in 1993.

3) Studies undertaken by the Environment Agency (1997) have revealed a reduction in the densities of juvenile salmon as a result of siltation and increased turbidity on the riverbed. Further increases in peak flows represent a serious threat to the conservation status of the catchment and the viability of local fisheries that play a fundamental role in the local economy.

4) The catchment has two river discharge gauges. This provides the opportunity to investigate the effect of land use on a pair of nested catchments, through a comparison of the Camel catchment with the De Lank subcatchment.

6.2.2. Catchment environmental and hydrometerological characteristics

i. Climate

The local climate of the Camel catchment is typical of southwest England. Less extreme conditions in the sheltered river valleys contrast the wet, warm and exposed conditions to the north. A wetter, cooler and more windswept climate is characteristic of the moorland in the east (Wheeler and Mayes, 1997). In the Camelford area, the average annual rainfall ranges from in excess of 1800mm on the most elevated areas of Bodmin Moor, to 1000mm near the coast.

At Lower Moor, Camelford, the average annual rainfall for the period 1965-2000 was 1600mm, with mean monthly values ranging from ca200mm in November to ca100mm in April, May and June (Staines, 1976).

ii. Geology and geomorphology

The catchment can be separated into two principal physiographic units, granite upland and the slate lowland. In the south and west, the area is underlain by a sequence of sandstones, siltstones and slates of the Upper Carboniferous and Lower to Middle Devonian, with basaltic lavas and volcaniclastics in younger successions (figure 6.2) (Selwood *et al*, 1998). The slate landscape typically comprises gently sloping interfluves between 245m and 305m O.D, alternating with V-shaped river valleys (Staines, 1976). The drainage pattern is dendritic and largely controlled by a series of north-south and

northeast-southwest trending faults, and the western margin of the granite moorland (Warr, 1994). Geologically limited to the east by the granite boss of Bodmin Moor, the River Camel drainage basin is long and narrow in shape and generally exhibits a flashy response (Sullivan *et al*, 2004).

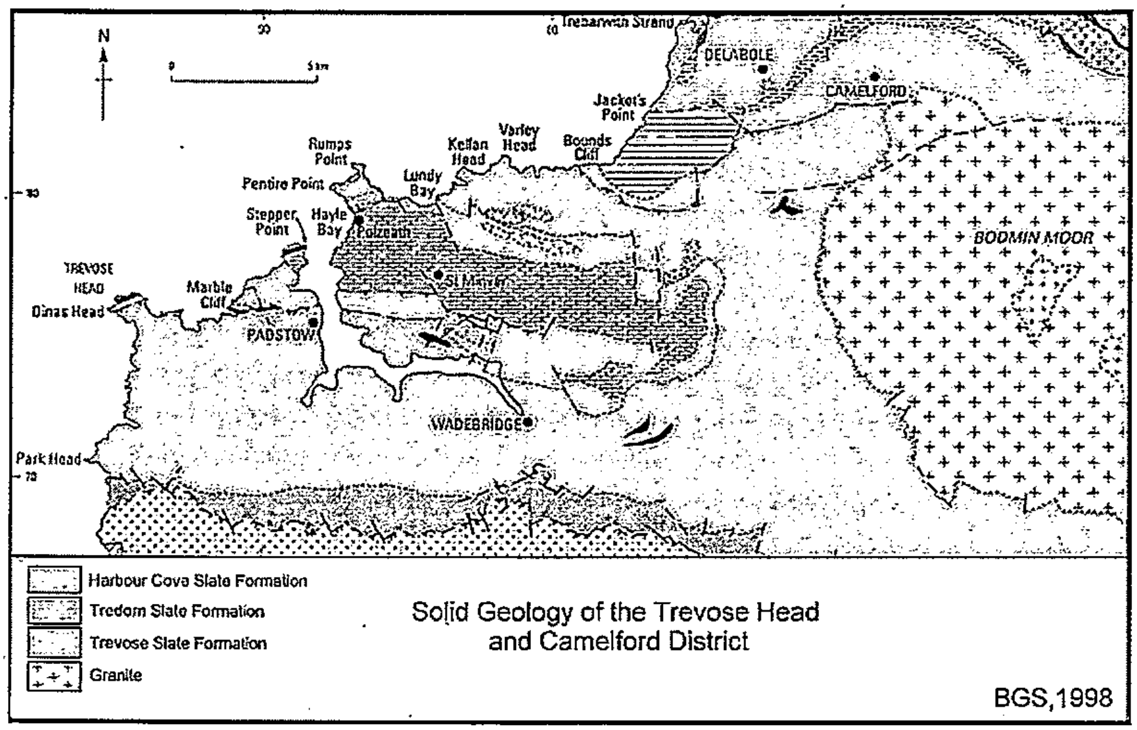


Figure 6.2 The solid geology of the north Cornwall district, including the Camel catchment (Selwood *et al*, 1998, p3)

The catchment is bounded in the east by the granite boss of Bodmin Moor. Flat-bottomed peaty valleys and rounded ridges characterise the undulating granite moorland, which is scattered with rocky tors and rises from 180m O.D to 420m O.D at Brown Willy (figure 6.2) (Selwood *et al*, 1998). The development of tors, or granite outcrops, has been ascribed to differential weathering processes (Brundsen, 1964) and periglacial processes during the Pleistocene (Waters, 1964), which stripped weathered granite (growan) from upper slopes and deposited them as roughly stratified head (Staines, 1976). Frost action and solifluction have generated a complex of gravely material overlain with boulders; head is deposited over much of the outcrop (Staines, 1976).

iii. Hydrology

The River Camel drains a 210km^2 area of north Cornwall, southwest England (figure 6.3). Rising at 280m O.D on Hendraburnick Down, northeast of Camelford (GR SX137, 876), it flows 40km to Wadebridge with an average gradient of 7mkm^{-1} before entering the Atlantic ocean at Padstow (Selwood *et al*, 1998). The underlying substrate of the river comprises boulder, cobbles, pebbles and gravel with some sandstone and slate bedrock (NCDC, 1998). The channel exhibits riffles, rapids, pools and slack, and is generally fast flowing (NCDC, 1998).

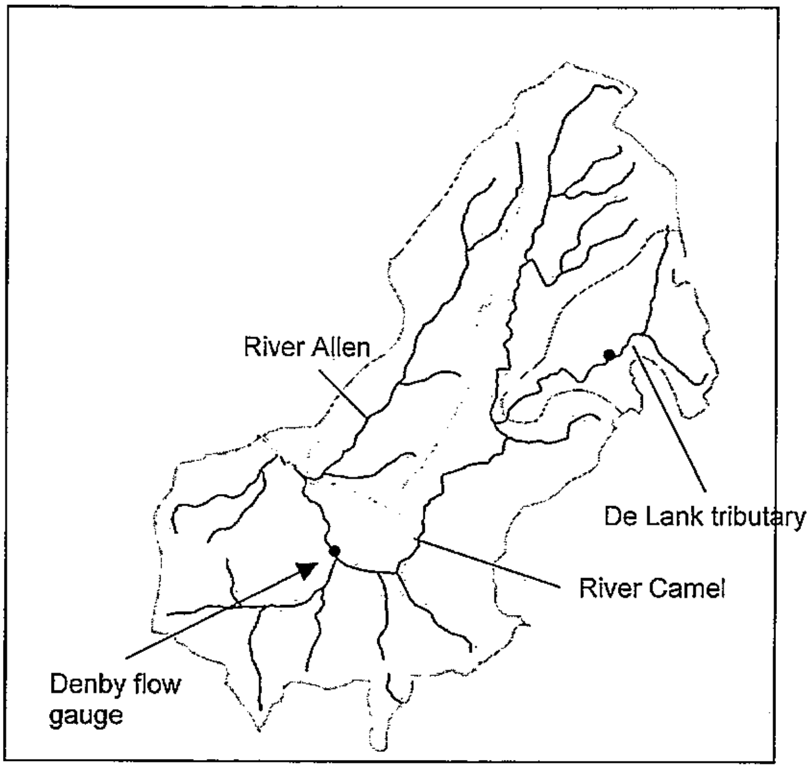


Figure 6.3 The Camel catchment system, including the De Lank subcatchment.

The River Allen runs parallel to the River Camel and is the main tributary (figure 6.3). Its catchment (60.7km^2) extends 18km from the source, northwest of Camelford, to its confluence with the River Camel, west of Sladesbridge (Halcrow, 2000b). Towards the confluence, the rivers become tidal. Other key tributaries, including the Davidstow, Stannon, De Lank and the Dunmere, flow down the eastern half of the catchment and drain the western slopes of Bodmin Moor.

On eastern slopes draining Bodmin Moor, the sands and gravels of the thick granite regolith promote surface drainage (Selwood and Thomas, 1994). Together with the large water-holding capacity of the peat, the regolith reduces direct runoff and allows a steady discharge of groundwater into moorland tributaries as baseflow (Selwood and Thomas, 1994; Findlay *et al*, 1984). During heavy winter rainfall the wet blanket peat readily becomes saturated. Hence overland flow is generated over various soil types, thereby enhancing the speed of streamflow responses to rainfall (Findlay *et al*, 1984). Williams *et al* (1983) have attributed the rapid response of granite upland catchments to the presence of an iron pan in the Stagnopodzols, which promotes saturation overland flow in winter due to rapid saturation above the hydrologically restrictive horizon. Moreover, baseflow is maintained for long periods in the deep regolith of weathered granite.

The drainage capability of the permeable brown soils overlying the lower slate rocks supply a continuous groundwater input into the channel (Findlay *et al*, 1984). According to the HOST (Hydrology of soil types) classification system, Denbigh soils are class 17 porous soils (Halcrow, 2000b). Soil hydrology is described as being controlled predominantly by vertical unsaturated flow processes, with bypass flow occurring over impermeable substrates and some risk of surface water runoff (section 4.3.2, tables 4.5 and 4.6).

Analysis of average daily discharge data taken from the Denby gauge, at grid reference (SX 017, 682), shows that the river has an average discharge of 5.993 m^3s^{-1} (Environment Agency, 1997). A discharge of 0.850m^3s^{-1} is exceeded 95% of the time and constitutes the Q95 value. The Q5 discharge value, the discharge that is exceeded 18 days per year on average, is 18.028 m^3s^{-1} (Environment Agency, 1997).

Crowdy reservoir was constructed in 1973 and is sited at grid reference (SX 145, 835). Small wetlands occur on the narrow floodplains (Environment Agency, 1997). Due to the low permeability of the bedrock there are no major aquifers in the catchment. Nonetheless, groundwater held in fractures and fissures provides enough water for small abstractions (Environment Agency, 1997). These are often unsustainable during the summer months when yields can be significantly reduced. Within the catchment there are approximately 12 licensed abstractions for public water supply and private use, 14 surface water and seven groundwater (Environment Agency, 1997). These abstractions represent 4% of the long-term annual average discharge and are not considered to exert a significant impact on the magnitude of daily flows.

iv. Soils

The interplay between past and present climate, relief and hydrology, bedrock composition, soil forming processes and land management is responsible for determining the distribution of soil types across the catchment (Findlay *et al*, 1984) (figure 6.4). The slates and sandstones have been subject to periglacial shattering. However, they are relatively resistant to weathering and generate loamy, stony permeable soils. Soil leaching is the major soil forming process, whilst some podzolisation is important on the higher land over the Lower Devonian sandstones (Selwood *et al*, 1998). In contrast, as a result of heavy rainfall and intense soil leaching, extensive areas of the higher land over Bodmin Moor, is covered with blanket peat and stagnohumic gley soils (Findlay *et al*, 1984).

Stagnopodzols with peaty topsoil are distributed over breaks of slope and marginal moorland areas. Moreover, on the lower granite moors and steep, wooded slopes brown podzolic soils are observed.

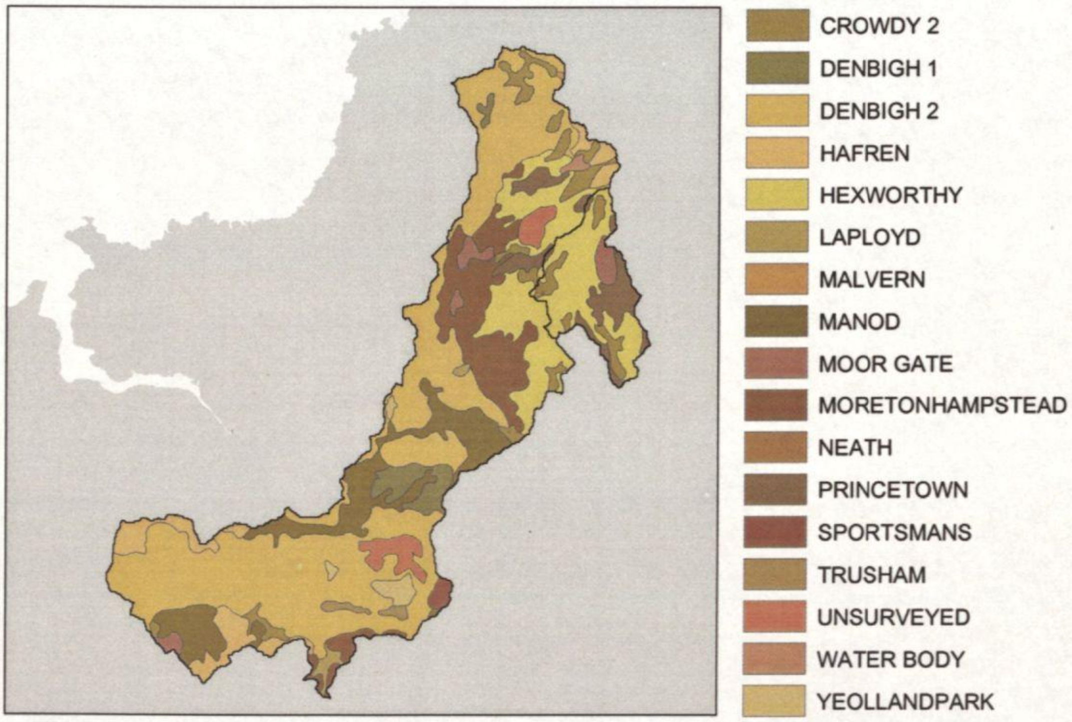


Figure 6.4 Soil map of the Camel catchment and the De Lank subcatchment, north Cornwall.

Denbigh Association: Soils overlying the topographically lower slate rocks are brown, permeable, fine clay loams of the Denbigh series and have a distinctive slate or stony layer at depth (Findlay *et al*, 1984) (figure 6.4). These soils are typical of the higher land which rises eastwards towards the moor and southwards to the Lower Devonian uplands of St.Breock Downs (Selwood *et al*, 1998).

Well drained coarse, loamy, brown podzolic soils can also be found along steep wooded river valleys and characterise the granitic head that has developed along the western fringes of Bodmin Moor (Selwood *et al*, 1998). Excess winter rain falling on Denbigh soils is easily absorbed due to good drainage. Hence, they are easily worked and support

arable cropping, particularly winter and spring barley production. The length of the growing season is limited only by extreme soil wetness and droughtiness in some seasons (Findlay *et al*, 1984).

Manod Association: The free draining, fine loamy soils of the Manod Association overlie Devonian and Carboniferous rocks on the steep valley sides of the Camel River corridor and on the metamorphic aureoles of Bodmin Moor, which fringe the moorland to the east of the catchment (figure 6.4).

The Manod Association comprises predominantly, brown podzolic soils of the Manod series and typical brown earths of the Denbigh series. The Manod series is a permeable clay loam with dark topsoil over ochreous subsoil and has a granular structure. This contrasts the brownish subsoil and blocky structure of the Denbigh series.

Manod soils are well drained but remain moist due to high rainfalls and typically support permanent grass leys or rough grazing. Aside from areas of steep land or where bedrock is shallow, Manod soils will readily absorb excess winter rainwater. Nonetheless, there is a risk of poaching in wetter seasons (Findlay *et al*, 1984).

Alluvium: Alluvial flats bordering the channel are characterised by coarse, loamy typical alluvial gley soils in alluvium derived from slates, volcanics and granite (Staines, 1976).

Crowdy 2 Association: Raw acid peat soils of the Crowdy 2 association are well developed in the valley bogs of Bodmin Moor. The basin peat is kept perennially wet by high groundwater and consequently, much of the winter rain runs rapidly to stream channels. As a result, the land is of little agricultural value and can only support moderate rough grazing in summer months.

Hexworthy Association: Extending over much of the granite outcrop and along a large section of the course of the River De Lank, the Hexworthy association consists of predominantly podzolic soils, including iron pan stagnopodzols which occupy most of the high ground (figure 6.4).

Due to the presence of an iron pan or slowly permeable upper horizon, Hexworthy soils are subject to regular water logging and have a low winter rainfall acceptance potential. However, where the soils have been extensively reclaimed through subsoiling, excess water is absorbed more readily. Consequently, reclaimed soils can be used to provide grassland for dairy and stock cattle. The high water holding capacity of the humus rich or peaty topsoil causes these soils to be susceptible to poaching in wet periods (Findlay *et al*, 1984).

Moretonhampstead Association: The lower reaches of the De Lank tributary pass through soils of the Moretonhampstead association (figure 6.4). These are dominated by the coarse, loamy typical brown podzolic soils of the Moretonhampstead series. Moretonhampstead soils are described as well drained podzolic soils over acid igneous rocks, granitic Head deposits passing into deeply weathered granite. Some surface runoff occurs over these soils on steep slopes, but in general they are well drained and can easily absorb winter rainfall. Moretonhampstead soils support grassland farming.

Princetown association: On Bodmin Moor, the Princetown association is confined to the higher, flatter ridges, where soils are principally coarse loamy cambic stagnohumic gley soils of the Princetown series. These soils generally support open moorland, wet grassland or heath, or rough grazing on enclosed land (Staines, 1976).

v. Vegetation and Land Use

Agricultural land use accounts for some 93% of the landscape of north Cornwall (Environment Agency, 1998). In the Camel catchment, the landscape is distinguished by gently undulating farmland, with a mixture of dairying and stock farming in conjunction to cereal and grass production (Warr, 1994). In the lower catchment to the south and west, good quality soils over slate lithologies support the widespread production of autumn-sown cereals and rape, potatoes, maize and fodder (Environment Agency, 1998), both maize and beet to supplement grass silage on dairy farms. To the east, thinner, impoverished soils that have developed above granite Head deposits adjacent to the moorland, limit farming practices to stock grazing and dairying (Selwood and Thomas, 1994).

On upland sites, for example around St. Breock Downs in the south, a peaty, gleyed soil profile supports semi-natural woodland (Selwood and Thomas, 1994). Limited woodland also covers much of the sheltered, steep sided valleys of the Allen and Camel river corridors. Open moorland, rocky tors and boulder fields typify the landscape along the eastern margin of the catchment. Here, high altitude and rainfall have fostered the development of broad areas of thick peat in valley floors, becoming thinner over the higher ridges (Selwood *et al*, 1998).

Hill farming is pronounced across Bodmin Moor and much of the moorland has been enclosed (Selwood and Thomas, 1994) (plate 6.2). This is especially true of marginal areas, where farming subsidies have facilitated the clearance of boulder fields, deep ploughing to disrupt the iron pan, fertilizer application and the reseeding of natural rough grazing plant species with better quality grasses.

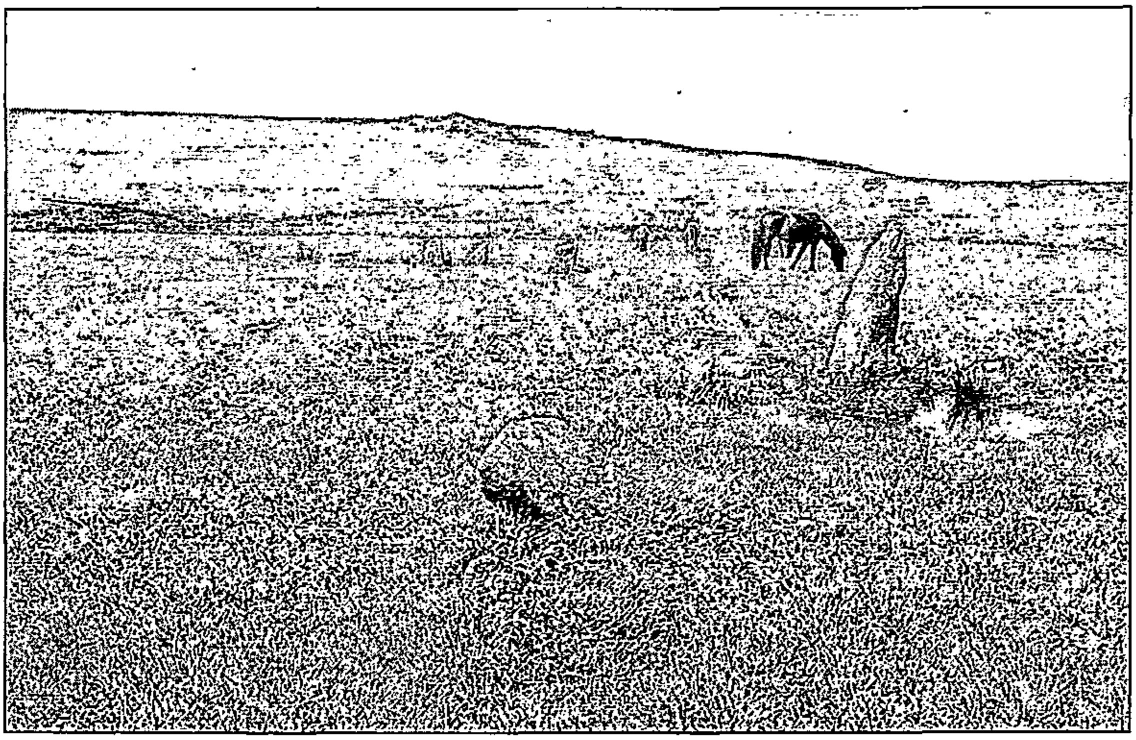


Plate 6.2. Typical landscape of Bodmin Moor, to the east of the Camel catchment

Such land management practices have raised the capacity of the moor to carry high stocking densities. Nonetheless, many parts of the open moor suffer from overgrazing, particularly during dry summer months (Selwood and Thomas, 1994). According to Findlay *et al* (1984), the heavier grazing pressure has also suppressed much of the natural heather and promoted the growth of Molinia or acid bent-fescue grassland. Camelford to the north and Bodmin to the south, form the major urban concentrations in the area. Together they account for 3.3% of the catchment (figure 6.5).

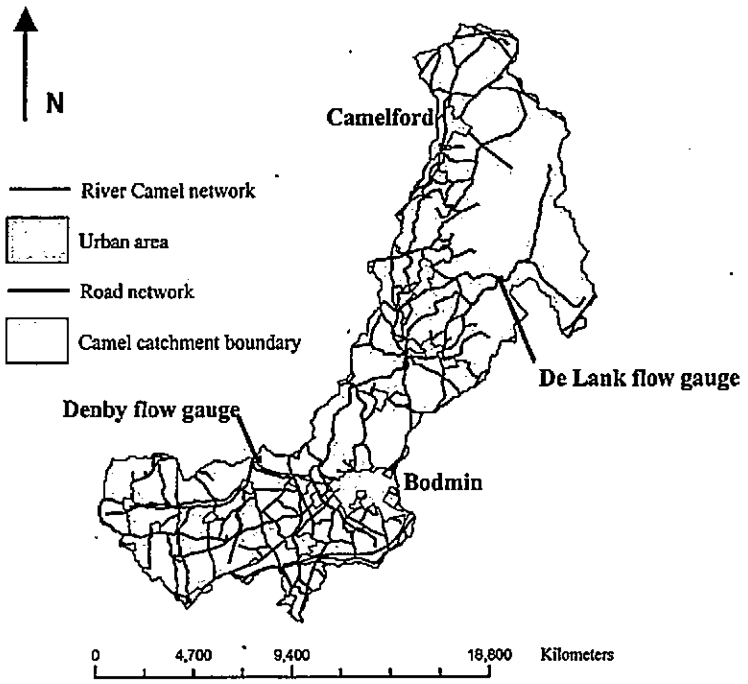


Figure 6.5 Location of urban areas, road network and river network in the Camel catchment.

vi. Conservation designations

In terms of conservation, the landscape and wildlife of the River Camel and its tributaries have been awarded both national and international recognition. The Rivers Camel, Ruthern, Allen and De Lank have all been notified as sites of special scientific interest (SSSI) under the Wildlife and Countryside Act 1981 (as amended). In addition, the Camel Valley has been attributed special area of conservation (SAC) status, under the EU Species and Habitats Directive due to the presence of otters and bullhead fish (NCDC, 1998). Further conservation designations include area of natural beauty (AONB) status for the Camel estuary and area of great landscape value (AGLV) status for the Camel and Allen valleys. The De Lank River is expected to receive further European recognition by being added to the Natura 2000 list (NCDC, 1998).

In addition to excellent water quality and good fish stocks, the conservation status of these rivers is a reflection of the importance of the habitat they support, including woodlands, carr, fen, heath and wet meadows, to a wide range of wildlife and in particular, many rare and internationally protected species (NCDC, 1998). Along much of the Camels' channel banks are some of the largest stands of ancient semi-natural woodland in Cornwall. Most commonly found are old sessile oak (*Quercus petraea*) woods (NCDC, 1998). However, the system also supports areas of wet grey willow (*Salix cinerea*) and alluvial forests, with alder (*Alnus glutinosa*) woodland on the floodplains (NCDC, 1998).

Significant areas of heath land and bog lie in the headwaters (Environment Agency, 1997). The ecological importance of the Camel River network represents the combination of high water quality, suitable habitats and sufficient water flows (Environment Agency, 1997), and is acknowledged principally due to the presence of the rare bullhead fish (*Cottus gobio*) and the Rivers' good populations of Atlantic salmon (*Salmo salar*) and sea lamprey (*Petromyyzon marinus*), which can all be found in Annex 2 of the EU Species and Habitats Directive. Additionally, the Camel is considered to be one of the best areas in the UK for populations of Otter (*Lutra lutra*) (Environment Agency, 1997).

6.2.3. The De Lank subcatchment

The presence of a flow gauge on the De Lank tributary adds another scale dimension to the project (figure 6.3). The De Lank subcatchment drains an area 37.4km^2.The river rises in acid peat on Bodmin Moor and flows 14km over granite and slate before joining the River Camel just below Poley's Bridge. The river has an average daily flow of 0.742 m^{3}s^{-1}, recorded at the De Lank gauge (GR SX 133, 766) (Environment Agency, 1997).

The tributaries of the De Lank River drain south along steep sided narrow gorges which occur near the aureole contact zone. Distinct changes in the fall of the moorland rivers occur where the shallow gradient on the flat valley heads of the granite increases quite sharply over the more steeply sloping lower reaches, as the granite gives away to Killas (Staines, 1976; NCDC, 1998). Southwest Water has a water intake from the De Lank River west of Carkeens Down (SX 1329, 7661), which supplies north Cornwall (Selwood and Thomas, 1994).

Summary

- This chapter focuses on two of the 48 study catchments. The role of agricultural land use changes on hydrological response is further explored through a long-term (30years) investigation of the Camel catchment and the De Lank sub-catchment.

- A more comprehensive description of the study catchments is provided, which sets the context for the methodology, results and discussion sections that are documented in the Applied Geography paper in Appendix I.

Results: Camel catchment

- No trends were observed in daily rainfall totals aggregated over seasonal or annual timescales. However, annual average October rainfalls exhibited a weak rising trend (r=0.3, p>0.05). The antecedent condition of the catchment was shown to exhibit a strong relationship with the volume of runoff.

- Between the time periods 1965-1982 and 1983-2000, the magnitude of a one in 25 year flow increased by 20%. Moreover, A 9.3% increase was detected in the median mean daily flow between the periods 1970-1975 and 1994-1999.

- Changes in catchment land use in the lower catchment were characterised by an increase in the area of Bodmin Town by 54% after 1965, and a 3% increase in cereal cultivation between 1965 and 1997. The latter was explained by the introduction of maize in 1969, coupled with an expansion of wheat and barley production.

- A decline in cereal production between 1997 and 2000 was attributed to a shift in policy emphasis towards the integration of environmental protection measures into agricultural practices.

Results: De Lank sub-catchment

- Notwithstanding an 8.7% increase in the median mean daily flow in the De Lank between the periods 1970-1975 and 1994-1999, no long-term trend was detected in the flow record (1965-2000).

- Land use in the De Lank catchment was dominated by upland grazing. Maximum grazing densities increased by 43% over the period 1969-2000.

- The problem is complex; no single factor was found to be responsible for increases in flood frequency and magnitude in the River Camel. Long-term changes in the response characteristics of the Camel system were thought to have resulted from the cumulative impact of subtle changes in climate, combined with increased agricultural activity and urban expansion.

The influence of land uses, such as lowland cereal cultivation or upland grazing on hydrological responses, will be largely dictated by the impacts of the agricultural management practices on the soil hydraulic properties that determine the dominant runoff generating mechanisms. The following chapter (7) examines the extent to which it is possible to identify an enhanced land management impact at the field scale, by characterising the textural, structural and hydraulic properties of soils subject to contrasting 30-year histories of management activity.

Chapter 7.

Field scale investigation into the effects of agricultural land management history on soil hydraulic properties (Part IV).

7.1 Introduction

Chapter 7 represents a study of field scale soil hydrological processes within the River Camel catchment (chapter 6, part III), one of 48 study catchments investigated in part II (chapters 3, 4 and 5), to satisfy objective three of the thesis (section 1.3);

'To explore whether the effects of land management on soil hydrology can be identified by characterising the textural, structural and hydraulic properties of soils subject to different land management activities.'

An inherent shortcoming of approaches targeted at large scales is their inability to explain the nature of hydrological processes operating at plot, field or hillslope scales. Understanding the hydrological impacts of land use at smaller scales is fundamental to underpin the establishment of practical land management changes designed to reduce runoff and enhance catchment storage.

Field and laboratory testing was undertaken on soils from the River Camel catchment in order to investigate whether the impacts of land management on hydraulic processes could be determined through characterisation of the texture, structure and hydraulic properties of soils under varying histories of land management. Primarily, this chapter explored the contribution that field approaches can make to improved understanding of the effects of land management changes on field scale hydrological processes of runoff generation.

To this end, the characteristics of soils sampled from fields under farm woodland (FW), permanent pasture (PP), semi permanent pasture (SPP) and continuous cereals (CC) were examined. These included soil texture, organic matter content and exchangeable cation concentration, soil structure, including bulk density, aggregate stability and pore size characteristics, and saturated hydraulic conductivity (Landon, 1984; Rowell 1994). The techniques adopted for soil sampling and analysis are presented and reviewed.

Principal components analysis (PCA) and clustering with factor analysis (ter Braak and Šmilauer, 2002) were undertaken on soil property data for a total of 36 samples in order to investigate variability in the parameters of soil samples from each field. The *t*-test was also used to statistically examine the difference between soil characteristics of sampled fields (Shaw and Wheeler, 1997). In addition, Pearson's correlation coefficients were used to explore deterministic relationships between key physical and hydrological soil properties that were found to be driving similarities or dissimilarities between samples.

7.2 Study area

A field study was undertaken in the catchment of the River Allen, on the lower lying slate area to the west of the River Camel system (figure 7.1).

7.2.1 Site selection criteria

Four field study sites were selected for soil sampling on the basis that they shared a number of physiographic characteristics, namely slope, geology and soil type; the key variable was land use.

1) Site land use history: Three fields with different long-term agricultural land use histories (30 years) were chosen (i-iii), in addition to an unmanaged control site of semi-natural vegetation (iv).

i) Intensive, continuous cereal cultivation (CC)
ii) Arable cultivation in rotation with pasture (SPP)
iii) Permanent pasture (PP)
iv) Farm woodland (FW)

2) Physical environmental characteristics: Each site had similar geology, soil type and relief characteristics in order to minimise heterogeneity.

3) Land owner cooperation: This was important to allow both access to the site and to obtain an accurate account of the 30-year management history of each field.

7.2.2. Field description

The field study site occupies the lowland slate area towards the west of the River Camel catchment, where the average relief is less than 122m O.D (Selwood *et al,* 1998) (figure 7.1). Fields selected for soil sampling drained the eastern slopes of the River Allen subcatchment and all exhibited gentle slopes, in the range 3 to 6° (figure 7.2). The average annual rainfall of this area is 1000mm (Wheeler and Mayes, 1997).

All sampled fields were underlain by fine loamy brown earths of the Denbigh series (section 4.3.2) that have developed on Devonian slate bedrock of the Tredorn formation. Denbigh soils (HQ) are permeable and well drained; leaching is the main soil forming process (table 4.5). Sampled soils fell into one of two textural classifications, silt loam or sandy silt loam, and were relatively shallow. The average depth to bedrock measurements were 39cm (FW), 43cm (SPP), 48cm (CC) and 49cm (PP), hence soils were stony at depth.

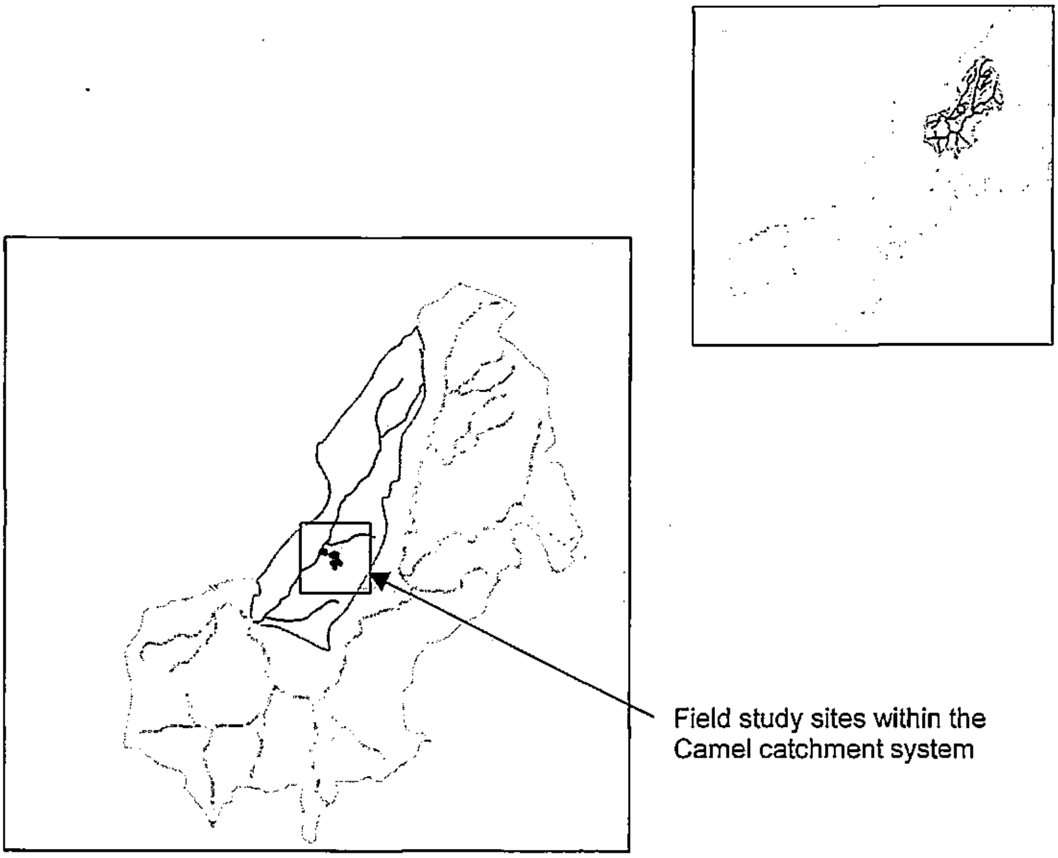

Field study sites within the Camel catchment system

Figure 7.1 Location of field study sites in the catchment of the River Allen, within the River Camel system, southwest England.

7.3 Soil sampling strategy

Soil sampling was undertaken in each field following a widely used, W-shaped sampling strategy, to obtain a representative survey of each field (Wilkinson *et al*, 1971; Rowell, 1994). Soils were sampled at five sites in each of the agricultural fields and at three sites in the smaller woodland area, where a V-shaped sampling strategy was followed. The location of soil sampling areas within each of the four field survey areas was recorded using a global positioning system and mapped using GIS (figure 7.2).

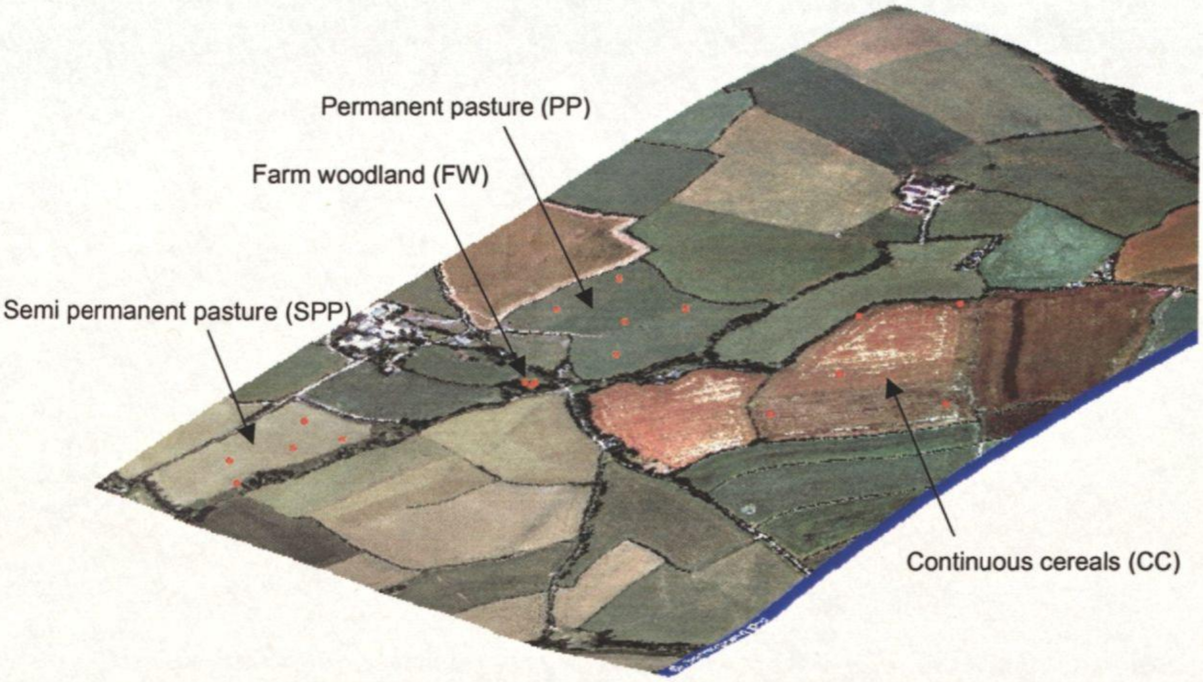


Figure 7.2 Location of sampling points in four soil survey sites (continuous cereals (CC), semi-permanent pasture (SPP), permanent pasture (PP) and farm woodland (FW)), western Camel catchment, north Cornwall.

7.3.1 Undisturbed core samples

In each field at all five sites, soil sampling was undertaken at two depths, 0-13cm and 13-26cm, in order to capture possible vertical stratification in the soil profile and changes in soil permeability due to the presence of a plough pan. All three sites were sampled at both depths in the smaller farm woodland, control site. Undisturbed soil core samples (1021.5cm^3) were extracted for laboratory measurement of saturated hydraulic conductivity (K_{sat}) and bulk density. A cylindrical steel core with a sharpened cutting edge, approximately 10cm in diameter was hammered into the soil until flush with the surrounding soil surface. A wooden batten was used to help prevent lateral displacement and damage to the core edge (lip). Smaller core samples (68.7cm^3) were also excavated

at each depth using an American Pitman Corer, for laboratory testing of the pore size distribution. Cores were removed, trimmed with a knife and double wrapped in cling film and plastic bags before being transported back to the laboratory and stored at 4°C, to minimise evaporation and biological activity prior to analysis.

7.3.2 *Bulk soil samples*

At each surface and subsurface site, a bagged bulk soil sample was also removed for particle size analysis, and determination of the organic matter content and the exchangeable cations in the soil. At each sample site, an average of three measurements of depth to bedrock was calculated and a description of the soil profile, including vertical stratification, horizon thickness and colour, and the presence of roots, stones and worms recorded.

7.3.3 Field soil moisture

Soil moisture can influence the rate of water movement into and through the soil, soil resistance to compaction, clay swelling and the potential for smearing during sampling. Hence, a theta probe was used to measure field soil moisture content at the time of sampling. At all surface and subsurface sample sites an average of three soil moisture readings was taken. The theta probe uses Frequency Domain Reflectometry (FDR), which is the reflection of a standing wave in four stainless steel rods when inserted into the soil (Meyles, 2002). A generalised calibration curve for mineral soils provided soil moisture content readings with typical errors of ± 0.05 m^3m^{-3}.

7.3.4 Soil compaction testing

A penetrometer is a device that can be forced into the soil to measure the resistance to penetration, or the shear strength of soils (Godwin, 1991). A penetrometer with a conical tip (cone penetrometer) is widely used to give an indication of soil strength from a static penetration test and therefore, the extent of soil compaction (Landon, 1984). The force per unit base area of the cone required to push the cone into the soil is considered to be an index of soil shear strength, which is related to density. The cone tip is forced vertically into the soil at a constant rate and the load required to penetrate the various horizons can be determined by comparing the dial gauge reading with the proving ring calibration. The shaft is graduated to show depth. The force (weight per unit area) required to push the cone intervals of 10cm into the soil was recorded. Consistent measurements are difficult on very dry soils, hard soils, or soils with a high stone content. Measurements were not recorded where roots or stones were encountered during compaction testing.

7.3.5 Limitations of soil sampling

Physical and hydraulic soil properties vary massively in space whilst soil moisture status, vegetation cover and water flows are dynamic in time (Fitzjohn *et al*, 2002). Field and laboratory testing may not be fully representative of the vast heterogeneity and uncertain boundary conditions of natural systems, which can exert a significant influence on the hydrological processes of runoff generation (Beven *et al*, 1988). Representing the extent of natural heterogeneity in soil characteristics during soil sampling and in-field tests is a fundamental problem. Interpretations of the results of field and laboratory testing must take into account the constraints imposed by the sampling and testing procedures adopted. Obtaining genuinely undisturbed cores for laboratory testing is very difficult. The use of coring is limited on very stony soils, heavy textured compact soils, on dry loose cultivated soils where the sample may shatter and under very wet conditions where compression can occur.

7.4. *Laboratory analysis*

A suite of laboratory analyses were performed on soil samples to determine the nature of soil textural, structural and hydraulic characteristics under each land management type; these are outlined in table 7.1

Soil characteristic		Sample method	Laboratory method	Units	References
Soil texture	Particle size distribution	Bulk sample removed from two depths (0-13cm and 13-26cm) in the soil profile and sealed in large plastic bag.	Sample dry-sieved to<2mm and laser diffraction applied using a Malvern Long Bed Mastersizer X.	(%)	Syvitski, 1991; Rawle, 2001
	Organic matter	Bulk sample removed from two depths (0-13cm and 13-26cm) in the soil profile and sealed in large plastic bag.	4g air-dried soil tested using loss on ignition technique. Experiment was repeated using an overnight burn and conventional 4h burn time.	(%)	Avery and Bascomb, 1982; Cuniff, 1994
Soil chemistry	pH	Bulk sample removed from two depths (0-13cm and 13-26cm) in the soil profile and sealed in large plastic bag.	Measurements of the pH of samples undertaken on a 1:2.5 soil: water suspension following equilibration for 1h, using a calibrated pH meter.		Peech, 1965; Landon, 1984
	Exchangeable cation percentage	Bulk sample removed from two depths (0-13cm and 13-26cm) in the soil profile and sealed in large plastic bag.	2mg of air-dried soil diluted with ammonium acetate and filtered. Soil extraction further diluted with 9 parts ammonium acetate and tested using flame photometer and atomic spectrophotometer. Percentage of exchangeable cations calculated. CEC calculated on summation.	(%)	Chapman, 1965; Hesse, 1972; Landon, 1984; Rowell, 1994
Soil structure	Dry bulk density	Undisturbed cores of 1021.5cm^3 taken at two depths (0-13cm and 13-26cm) through the soil profile, avoiding stones/roots and sealed in large plastic bags.	Cores oven dried for 48h. Dry bulk density calculated (soil weight/volume)	gcm^{-3}	Avery and Bascomb, 1982; Landon 1984
	Aggregate stability	Bulk sample removed from two depths (0-13cm and 13-26cm) in the soil profile and sealed in large plastic bag.	Rainfall simulation spray test: 20 air-dried aggregates were placed on 2mm, 4mm and 8mm plastic mesh trays and exposed to 30s runs of simulated rainfall at a constant intensity of 52mmhr^{-1}. The number of surviving aggregates was counted and a mean RSSI calculated for each sample.		Teman *et al*, 1996
			Wet sieving: 200g sample of air dried soil (2.8-16mm) was wet-sieved at a frequency of 60 cycles min^{-1} for three minutes. The weight of WSA>2.8mm (%) was expressed as a percentage of the original weight of soil (200g).	(%)	Teman *et al*, 1996; Barthes and Roose, 2002
	Runoff generation	Composite soil sample created, composed of 5 disturbed surface samples (0-15cm).	Soil micro-plots were set at 10° and exposed to simulated rainfall at 52mmhr^{-1}. Changes in upslope and down slope, surface and subsurface soil moisture was monitored using TDR. Runoff was captured and the volume of sediment determined using vacuum filtration.	(%)	
Soil hydrology	Pore size distribution	American Pitman cores (68.7 cm^3) extracted at two depths (0-13cm and 13-26cm) through the soil profile, avoiding stones/roots and sealed with cling film.	Cores were trimmed and saturated for 48h before being weighed. Cores were placed on a sand table at 50cm water tension and reweighed daily. Following equilibration, cores were exposed to 15bars using pressure plate apparatus and reweighed.	(%)	Hall *et al*, 1977
	Saturated hydraulic conductivity (K_{sat})	Undisturbed cores of 1021.5cm^3 taken at two depths (0-13cm and 13-26cm) through the soil profile, avoiding stones/roots and sealed in large plastic bags.	Cores were trimmed and saturated for 48h prior to testing using falling head permeameter technique. The rate of water movement through.the soil core was calculated from the average of five runs.	cm s^{-1}	Klute and Dirksen, 1986; Smith, 1990; Liu and Evett, 2003

Table 7.1 Summary of laboratory procedures used to characterise the textural, chemical, structural and hydraulic properties of sampled soils.

7.4.1 Soil texture

Particle Size

Particle size refers to the size distribution of mineral soil particles. The percentages of clay (<2µm), silt (2 µm- 50µm) and sand (50µm -2mm) determine the soil texture, which exerts a significant bearing upon soil hydrology through its control on soil porosity and water holding capacity, soil permeability (hydraulic conductivity) and drainage characteristics (Landon, 1984; Rowell, 1994). Soil texture strongly influences soil structure and the stability of soil aggregates, in addition to the cation exchange capacity. Characterising the texture of a soil is therefore essential to understanding the impacts of land use on the hydraulic properties governing soil susceptibility to runoff.

The sedimentation technique, based on Stokes' Law, has traditionally been used to measure soil particle size characteristics (Syvitski, 1991; Rowell, 1994). A fundamental limitation of this technique relates to the fact that Stokes' Law is only valid for spheres (Syvitski, 1991). More irregularly shaped 'normal' particles will possess greater surface area than a sphere and will therefore fall more slowly because of the increased drag, compared to equivalent spherical diameters (Rawle, 2001). This is distinctly problematic for disc-shaped kaolin particles. Moreover, due to the effects of Brownian movement displacement, large errors are associated with sedimentation when used to measure particles under 2µm in size (Rawle, 2001). As a result, sedimentation frequently gives an answer smaller than reality. Extensive calibration work carried out by Hartley (2005) has shown that laser diffraction consistently underestimates clay content (c10%) compared with sedimentation. The comparative advantages of using laser diffraction techniques for measurement of particle size are summarised by Rawle (2001). The laser diffraction technique was adopted in this thesis to characterise the particle size distribution of sampled soils.

Sub-samples of soil were extracted from disturbed bulk samples (surface and subsurface) and dry sieved to less than 1.7mm. Sieved sub-samples (>1.7mm) were treated with 6% hydrogen peroxide (H_2O_2) to remove binding organic material. Sub-samples were subsequently oven dried at 105°C for 24h. The particle size distribution of prepared sub-samples (>1.7mm) was determined using a Malvern Long Bed Mastersizer X (Rawle, 2001). This technique measures particle sizes in the range 0.1µm - 1700µm using low angle laser light scattering, or laser diffraction, based upon the inverse proportional relationship between the diffraction angle and particle size.

Further sub-samples were removed from prepared sub-samples and added to the Mastersizer's sampling bath, which contained 1l of water and 5ml of 8% Calgon to disperse the sample. The sample underwent ultrasonic dispersion for 30s before analysis.

Organic matter content

Soil organic matter is fundamental to the hydrological functioning of a soil on account of the binding influence on mineral particles, which improves and maintains soil aggregate stability and structure (Brady and Weil, 2004). The organic matter content of soils is dependent upon vegetation cover, biological activity, the prevailing climate and land use. Characterising the organic matter content of soils under different land management, may provide an indication of the influence of land use on soil structural parameters governing soil infiltration rate and water holding capacity. Soil organic matter content was measured using the loss-on-ignition technique (Cuniff, 1994). Four gram samples of air-dried mineral soil (<2mm) in tared porcelain crucibles, were placed in a muffle furnace at 550°C for four hours before being allowed to cool and re-weighed.

The percentage organic matter (%) was calculated as;

$$100 \times \frac{\text{Mass of oven dry sample} - \text{Mass of ignited soil}}{\text{Mass of oven dry sample}}$$

after Avery and Bascomb (1982).

Equation 7.1

7.4.2 Soil chemistry

It is essential to assess the proportions of exchangeable cations (Na^+, Ca^{2+}, Mg^{2+} and K^+) in the soil because of the significant influence that they exert on soil physical properties. The lower the valence of the exchangeable cation, the greater the effect it has on the deterioration of soil structure (Shainberg *et al*, 1981). It is widely acknowledged that a high exchangeable sodium percentage (ESP) can reduce the stability of aggregates and promote the development of surface seals and crusts, due to the enhancing effect on clay swelling and dispersion (Shainberg and Levy, 1994). Ca^{2+} can play an important role in neutralising soil acidity and in the remediation of soil structural deterioration by displacing Na+ on soil exchange surfaces (Rowell, 1994).

Measurement of soil cation exchange capacity (CEC) (cmolcKg-^{1}) can provide values that are related to the sum of cations held by the negative charge on the clay particles and the cations held by the organic matter (Landon, 1984). Soil CEC will increase with a rise in pH. Buffered ammonium acetate solution was used to maintain a neutral pH in the soil solution during laboratory measurement of the exchangeable cations. In addition, separate measurement of soil pH was undertaken.

Soil pH

Laboratory measurement of soil pH was carried out on 10g of soil diluted with 25ml of distilled water using a fully calibrated pH meter. Samples were allowed to equilibrate for 1h (Landon, 1984).

Cation exchange capacity (CEC)

Measurement of the major exchangeable cations (Na^+, Ca^{2+}, Mg^{2+} and K^+) was undertaken using an ion exchange process, whereby the exchangeable cations are displaced and measured in solution as $cmolcKg^{-1}$ (Rowell, 1994). Soil extractions for chemical analysis of the cation exchange capacity were created using 2.5g of air-dried soil, sieved to less than <2mm and diluted with 100ml of ammonium acetate (Chapman, 1965). Diluted samples were left to stand for 20 minutes before being thoroughly shaken in a rotary mixer for a further 20 minutes. The mixed samples were subsequently filtered to obtain the extractions required for laboratory analysis of exchangeable calcium (Ca^{+2}) and Magnesium (Mg^{+2}) using an atomic spectrophotometer. A flame photometer measured soil extractions for exchangeable sodium (Na^+) and potassium (K^+). The entire process was repeated to generate duplicate readings for calculation of an average figure for each sample. Results of testing for calcium (Ca^{+2}), magnesium (Mg^{+2}), potassium (K^+) and sodium (Na^+) were summed to facilitate calculation the percentage of each exchangeable cation in the soil (Hesse, 1972; Landon, 1984).

During measurement of soil CEC using a displacement technique, hydrogen (H^+) ions are neutralised and aluminium (Al^{3+}) is precipitated as $Al(OH)_3$. Calculations of CEC on summation will therefore underestimate the CEC as H^+ and (Al^{3+}) are excluded. This limitation will predominantly effect measurement of acidic soils with large concentrations of H^+ ions. This technique can also overestimate the exchangeable Ca^{2+} for calcareous soils and provide a very high value for Na^+, Ca^{2+} and Mg^{2+} for saline soils (Rowell, 1994). In addition, exchangeable K^+ levels can alter when soils are dried (Landon, 1984).

pH measurements are often undertaken using a $CaCl_2$ solution rather than distilled water because the concentrations of the test solutions are thought to be more representative of the salt solutions in natural soil solutions, and the values obtained are less dependent on the dilution ratio (Schofield and Taylor (1955) in Landon, 1984). In water, the pH value has been shown to increase with the dilution of the suspension (Peech, 1965). For example, Dewis and Freitas (1970) measured pH values for 1:5 suspensions that were 0.5-1.5 units higher than equivalent figures for saturated pastes (Landon, 1984). However, experimental work by Loveday *et al* (1972) has shown that the pH may not necessarily increase in water, nor is it dependent upon the dilution (Landon, 1984). Landon (1984) recommends pH determination in a soil/water suspension for routine soil survey work.

Errors can be introduced into laboratory testing of soil chemistry through operator faults, including the incorrect preparation of standard solutions, improper use of instruments and incorrect calculations. In order to detect potential errors, all analytical procedures were replicated.

7.4.3 Soil structure

Dry bulk density

Dry bulk density represents the mass of a unit volume of dry soil (Brady and Weil, 2004). Measurements of dry bulk density provide a guide to soil compaction and porosity, factors which strongly influence the movement of water into and through the soil profile (Landon, 1984; Rowell, 1994). Soils with a high proportion of pore space to solids have lower bulk densities than those that are compact and have less pore space (Brady and Weil, 2004).

Hence, parameters influencing soil pore space, including soil texture, structure and land use will strongly influence bulk density.

Soil core samples (1021.5cm^3) were oven dried at 105°C for 72h and weighed. Dry bulk density was calculated from the mass of oven dry soil (Md) and its field volume (V), using equation 7.2 (Avery and Bascomb, 1982). The soil sample and remaining debris were removed from each core. Empty core rings were weighed and the reading subtracted from the weight of the oven dry soil and core. In situations where the soil surface was not fully flush with the top of the core, the difference in soil sample volume was determined by pouring in sand from a beaker of a known volume. The volume of the void was subtracted from the total core volume.

Bulk density (Db) was calculated as,

$$Db = \frac{Md}{V} \ (gcm^3)$$

Equation 7.2

Due to the presence of stones in many of the soils sampled, the stone content of each core sample was screened after drying and the volume of stones incorporated into the bulk density calculations, using equation 7.3 (Avery and Bascomb, 1982).

$$\mathrm{Dbf} = \frac{\mathrm{Md} - \mathrm{Ms}}{\mathrm{V} - \mathrm{Vs}}$$

Where,

Md is total mass of oven dry soil

V is total field volume

Ms is mass of stones

Vs is volume of stones

Equation 7.3

Bulk density measurements vary considerably with moisture content, samples are susceptible to problems associated with coring in very wet or very dry conditions. The method cannot cope with gravelly or stony soils. Moreover, even in horizons of similar texture, dry bulk density values can be significantly variable depending on organic matter levels, root penetration and soil structure (Landon, 1984).

Aggregate stability

Aggregate stability refers to the ability of soil aggregates to resist disruption when outside forces, usually associated with water, are applied (Brady and Weil, 2004). The stability of aggregates is affected by soil texture, the predominant type of clay (Levy *et al*, 1994), extractable iron (Curtis *et al*, 1976) and extractable cations (Emerson, 1967; Shainberg, 1992), the amount and type of organic matter present (Tisdall and Oades, 1982), the type and size of the microbial population and land use (Grieve, 1980; Whitbread *et al*, 1998;

Shepherd *et al*, 2001; Dalal and Chan, 2001 and Francis *et al*, 2001). Soil infiltration rate and permeability are strongly dependent upon the soil aggregate stability through its influence on surface soil structure, bulk density and the proportion of large pores that are critical for soil drainage. (Brady and Weil, 2004). Aggregate stability, surface crust development and runoff generation are intimately linked (Tisdall and Oades, 1982; Fey, 2003).

Since the late 1930's various studies using a range of techniques with differing applications of energy, including rainfall simulation (Le Bissonnais and Singer, 1992; Barthès and Roose, 2002), rapid wetting (Bryan, 1976; Grieve, 1980) and mechanical or ultrasonic dispersion (Yoder, 1936; Hamblin and Davies (1977), in Grieve, 1980), have demonstrated the usefulness of measuring aggregate stability as an indicator of the resistance of a soil to breakdown under the impacts of raindrops or agricultural traffic, and crust development (Grieve, 1979).

The value of these techniques is governed by the accuracy with which field conditions are replicated (Grieve, 1979). The most frequently adopted method for testing aggregate stability is rapid wetting of air dried soil before mechanical dispersion by wet sieving. Wet sieving has been criticized for exaggerating breakdown by slaking as compared to rainfall forces, and failing to adequately simulate processes as they operate in the field (Bryan, 1976; Le Bissonnais, 1996). Arguably, the latter is true of any stability experiment (Blackman, 1992).

Much of the contention associated with wet sieving is directed towards the rate of wetting, which is thought to be unrealistic given the UK climate (Emerson, 1967). Following comparative tests using slow wetting by suction and rapid wetting methods, rate of wetting was shown to give results which discriminated differently between the aggregate stability of soils under contrasting land management types (Williams *et al* (1966), in Grieve, 1980).

In contrast, Grieve (1979) has demonstrated a significant correlation between the aggregate stability of soils measured using both the rapid and slow wetting tests. Rapid wetting was found to be a useful measure of the vulnerability of surface soils to crusting in conditions where sudden wetting of dry soil was likely to occur, as with bare arable soils under intense rainfall (Grieve, 1980). Soils under a vegetation cover were best tested using the slow wetting procedure (Grieve, 1980).

The application of different measurement techniques to soils with different vegetation covers is not practical given that the majority of aggregate stability investigations require a standard methodology to test soils under contrasting land uses. As a result of the wide variability in the behaviour of soils, ranging from weakly to strongly aggregated, not all soils can be tested accurately with the same amount of energy (Pierson and Mulla, 1989). For example, wet sieving has been shown to discriminate poorly between soils with weak aggregates (Le Bissonnais, 1996). Similarly, the findings of Bryan (1968) have illustrated that depending on initial soil moisture content, aggregates which are apparently stable in wet sieving tests may not be stable when exposed to rainfall. A uniform soil moisture status and structure must be maintained using a standard treatment applied to all soil samples. Air drying or controlled saturation, coupled with sieving have been used to standardise soil characteristics (Le Bissonnais, 1996).

In this investigation, assessment of aggregate stability and crust formation was undertaken using a three-stage approach, laboratory rainfall simulation on both individual soil aggregates and soil plots, in conjunction to a flood-wetting procedure.

i) Laboratory rainfall simulation

A major weakness of wet sieving techniques is their failure to simulate raindrop impact (Bryan, 1976). Rainfall simulation tests replicate aggregate breakdown under more natural

conditions than can be achieved with conventional wet sieving techniques. Stability data derived from laboratory rainfall simulation tests have shown close correlations with results gained from field investigations (Barthès and Roose, 2002). Ternan *et al* (1996) developed a procedure for testing aggregate stability in terms of their response to simulated rainfall using a laboratory rainfall simulator inside an environmental chamber. A similar technique was adopted here.

Soil samples were sieved in order to determine the dominant aggregate size classes. For three size ranges, >2.8mm, >5.6mm and >11mm, twenty air-dried aggregates were placed on 2mm, 4mm and 8mm plastic mesh trays. Aggregates were subjected to 30s runs of simulated rainfall at a constant intensity of 52mmhr^{-1}. After each run, the remaining aggregates were counted. After 40 runs, surviving aggregates were destroyed to check for stones. The mean Rainfall Simulation Survival Index (RSSI) was determined for each sample using equation 7.4 (Ternan *et al*, 1996).

$$\text{RSSI (\%)} = \frac{\text{Number of aggregates remaining} - \text{number of stones}}{\text{Total number of aggregates} - \text{number of stones}}$$

Equation 7.4

Sampled soils were very stable and failed to sufficiently breakdown after 40minutes exposure to simulated rainfall at an intensity of 52 mmhr^{-1}. Hence laboratory testing of soil aggregate stability was undertaken using the wet sieving procedure and characterised using the percentage of water stable aggregates (>2.8mm).

ii) *Wet sieving*

In a study by Imeson and Jungerius (1976), farmland aggregates exhibited a tendency to slake upon wetting and offered little resistance to falling rain drops. Slaking results from the compression of entrapped air inside wetted aggregates (Le Bissonnais, 1996), or from the forces associated with swelling (Imeson and Jungerius, 1976; Tisdall and Oades, 1982). It has been recognised as the principal mechanism controlling aggregate breakdown when a dry soil is immersed (Le Bissonnais, 1996). Hence, the use of wet-sieving may be a particularly appropriate technique for simulating conditions in exposed arable soils where wetting will be fairly rapid due the absence of a protective vegetation cover (Grieve, 1980). Wet-sieving maximises slaking breakdown but minimises stresses produced by either unidirectional wetting or by differential hydration (Bryan, 1976).

Dry sieving of bagged soil samples prior to testing revealed that soil aggregates were predominantly >2.8mm. A 200g sample of air dried soil, sieved to between 2.8-16mm was placed onto two 2.8mm mesh sieves. These were agitated in a sink of deionised water using apparatus described by Barthés and Roose (2002) at a frequency of 60 cycles min^{-1}, with a vertical stroke of *c.*1-1.5 inches for three minutes (Ternan *et al*, 1996). Soil retained on the sieves was washed into a beaker and dried at 105°C. Following deduction of the weight of stones in the sample, the weight of water-stable aggregates (WSA) >2.8mm was expressed as a percentage of the original weight of soil (*c.*200g).

iii) Laboratory rainfall simulation: variation in soil water content through time

Runoff is generated when the amount of rain falling exceeds that which can be absorbed by the soil (Barthés and Roose, 2002). It is widely acknowledged that reduced soil moisture storage is important in promoting runoff (Van Dijk *et al*, 1996; Martinez-mena *et al*, 1998; Barthés and Roose, 2002). British soils are particularly prone to surface runoff produced as a result of soil saturation, due to a high frequency of low intensity rainfall events that are typical of the winter climate, and the associated rise in water table levels (Bryan, 1976). However, in many soils runoff is largely controlled by the hydraulic properties of the soil surface and not the entire profile (Bryan, 1976). This condition is especially prevalent where the soil surface becomes sealed by aggregate disintegration and clogging of pores, or during high intensity, low frequency rainfall (Bryan, 1976).

Efforts to understand the processes controlling runoff and the effects of land management history on these processes are inherently difficult and cannot be examined sufficiently by conventional aggregate stability tests. An experiment was designed to investigate the potential for soils under different land management histories, to generate runoff by either saturation excess or infiltration excess mechanisms. Observation of runoff by these processes was assumed to be indicative of differences in soil moisture storage or susceptibility to crusting between the soils..

A composite soil sample for each land history type was created from the amalgamation of disturbed surface samples (0-15cm), taken from each sample site within each field. Large clods were manually broken down to simulate the mechanical action of ploughing. Remnant vegetation was removed and soils were air dried before spraying with deionised water to achieve 10% volumetric soil moisture content. This was undertaken to reduce structural breakdown during packing and to maintain a constant soil moisture status prior to testing.

Soils were carefully packed into 8400cm^{-3} (30cm by 40cm by 7cm), plastic trays with holes on the bottom that were covered by plastic mesh and voile to allow drainage and prevent soil loss (figure 7.3). Packing to average field bulk density (1.18-1.26gcm^{-3}) was achieved by placing each tray on a sieve shaker, allowing particles to settle, and by evenly distributed manual compaction. All soils were subjected to the same treatment.

The experimental design was developed from trial rainfall simulations and based upon the concept that runoff caused by a surface seal could be identified through high surface soil moisture and low subsurface soil moisture. Additionally, runoff produced following soil wetting from the bottom up, as indicated by higher subsurface soil moisture readings, would be symptomatic of a dominant saturation-excess runoff mechanism. Preliminary trial data provided the grounds for the selection of a standard rainfall intensity and drop size, in addition to the timing and duration of runoff and sediment sampling, and frequency of TDR readings. Testing was undertaken to ensure that the intensity of the rainfall was uniform across the plot surface. Soil trays were inclined to a 10% slope to facilitate runoff (Le Bissonnais and Singer, 1992; 1993) and subjected to two hours of simulated rainfall at a constant intensity of 52mmhr^{-1} (Ternan *et al*, 1996). This intensity was not intended to represent field conditions. Deionised water was used in all simulations.

During simulated rainfall, spatial and temporal variability in the volumetric soil content of soil in the trays was measured using Time Domain Reflectometry (TDR) (Meyles *et al*, 2003). It has been recognised that the dielectric constant of a soil is sensitive to volumetric soil water content, but is relatively uninfluenced by soil characteristics such as bulk density, temperature, salinity and mineral composition (Topp *et al*, 1980). TDR measures the dielectric constant of the soil through two steel rods, which are inserted into the soil and act as a wave-guide for an electromagnetic pulse from a cable tester (Meyles *et al*, 2003). The dielectric constant is determined from the time it takes for the pulse to reflect back and is subsequently used to calculate soil moisture (Meyles *et al*, 2003).
Four pairs of 2mm diameter steel TDR rods measuring 27cm in length were inserted horizontally into one side of each soil tray. At both upslope and down slope locations, two pairs of TDR rods were positioned above each other at 1.5cm and 4.5cm depths in order to measure changes in surface and subsurface soil moisture. These were connected to a Time Domain Reflectometer to enable accurate readings from each pair of rods to be taken in quick succession.

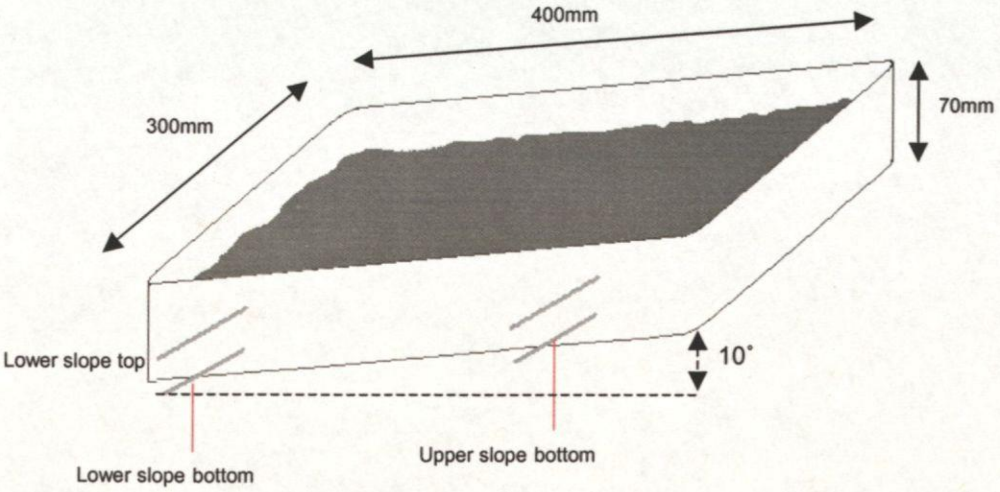


Figure 7.3 Positioning of TDR rods during rainfall simulation testing of soil plots

A receiving trough connected to a sample bottle was positioned at the bottom of the soil tray to collect surface runoff and transported sediment. The sample bottle was changed at two minute intervals for 0-0.5h, at 5 minutes intervals between 0.5-1h and at ten minute intervals during the period 1-2h. Sediment trapped on the tray lip or at the bottom of the trough was flushed out using a syringe containing 100ml of deionised water. TDR readings were taken at every bottle change. A vacuum filtration procedure was followed to obtain the amount of eroded sediment and volume of runoff collected in each sample bottle. After filtering, the residual sediment was oven dried to 105˚C and weighed, and the sediment loss rate plotted with losses in runoff volume.

Rainfall simulation testing of soil aggregates is limited on stable soils, which may be resistant to the impacts of simulated raindrops. In general, rainfall simulation techniques are also limited by the difficulty of maintaining a consistent rainfall intensity and drop size both across the soil plot and through time. Larger droplets can formulate when switching the simulator on and off between readings or bottle changes. According to the design of the simulation equipment and available spray nozzle sizes, a rainfall intensity of 52mmhr^{-1}

was selected because it was thought to most closely replicate general storm conditions, in terms of balancing spray pressure with drop size. Experiments on both soil aggregates and soil plots are comparative tests. It is acknowledged that simulated rainfall does not represent the intensity or variability in precipitation that can occur during a storm event. Moreover, soil plots comprise disturbed samples and are not intended to represent field conditions.

7.4.4 Soil hydrology

Water release characteristics

Soil-hydraulic interactions are moulded by the nature and size of pores through which water is channeled (Thomasson, 1978). This will be largely dependent upon soil texture and structure (Hillel, 1982; Rowell, 1994). Clay soils typically have a higher total porosity and thus greater water retention than a sandy soil, which usually comprises of mainly large pore sizes (Hillel, 1982). The pore size distribution can be determined by analysing the water release characteristics of pores when subject to different soil suctions (Hall *et al*, 1977). The quantity and size of pores in a soil provide an indication of the soils physical and hydrological condition. This is essential to understanding soil susceptibility to saturation and hence the generation of surface runoff.

Information on pore size and water release characteristics were derived in the laboratory through the application of advancing suctions on the smaller (68.7cm^3) undisturbed American Pitman cores, extracted at 0-13cm and 13-26cm depths. Samples were prepared by trimming each end and securing a piece of nylon voile to the bottom, to minimise soil loss, before leaving them to saturate. Saturated cores were transferred to sand tables, which enabled determination of the volumetric water content at 0, 50cm and 100cm of suction following a procedure outlined by Avery and Bascomb (1982).

Equilibrium was attained when daily weight loss was less than 0.05g (Avery and Bascomb, 1982).

Following equilibrium at 100cm suction, the volumetric water content at higher suctions was determined using pressure plate apparatus. Cores were subjected to a pressure of 1500cm until the outflow of water ceased. Finally, samples were oven dried at 105°C for 72h and reweighed. In order to estimate the pore size characteristics, the volumetric water content was calculated at saturation and at each suction using a procedure outlined by Hall *et al* (1977).

Several assumptions are made when using this method, including that the soil has uniformly circular pores and is devoid of rocks or planar voids. Hence it is not strictly accurate to describe the volume of water filled pores at 0.05 bars as pores <60μm and air filled pores as>60μm (Hall *et al*, 1977). Pore characteristics change between seasons as well as within a cropping season, this variability is not represented by the sampling strategy adopted.

Saturated hydraulic conductivity (K_{sat})

Infiltration is largely determined by the water physical properties of soil, in particular soil permeability. A soils ability to transmit water, or hydraulic conductivity, is critical for soil drainage and is largely determined by soil texture, structure and water content (Rowell, 1994). Hydraulic conductivity defines the volume of water which will pass through unit cross-sectional area of a soil in unit time, given a unit difference in water potential (Landon, 1984). At soil saturation, the conductivity of water through soil pores is at a maximum (Selby, 1982; Landon, 1984). Saturated hydraulic conductivity (K_{sat}) measurements can provide an indication of soil water movement and possible drainage problems within soil profiles.

A falling head permeameter method was applied to undisturbed core (1021.5cm^3) samples to measure saturated hydraulic conductivity (K_{sat}) in the laboratory (Klute and Dirksen, 1986). This method uses Darcy's law, given as;

$$\frac{Q}{A} \propto i$$

Where the flow rate of water Q through a soil of cross-sectional area A is directly proportional to the imposed gradient (Liu and Evett, 2003).

Equation 7.5

Cores were allowed to saturate in a water bath for 72h to remove air prior to testing. The rate of change in level of the head was observed as water percolated through the sample (Smith and Mullins, 1991). For each core, five consecutive runs were carried out and the average of the five runs used to determine the saturated hydraulic conductivity. Saturated hydraulic conductivity was calculated for each sample using equation 7.6.

$$K_{sat}\ (\text{cm s}^{-1}) = \frac{(2.302 \times a \times 12.7)}{A} \times \frac{(\log H_0 - \log H_1)}{t}$$

Where,

a = area of manometer tube (cm^2)

A = area of sample (cm^2)

H_0 = initial head

H_1 = final head (cm)

t = time of test (s)

Equation 7.6

Due to a number of problems associated with this technique, permeability measured in the laboratory may not be truly representative of in-situ permeability (Liu and Evett, 2003). Primarily, the natural flow of water in a soil may move both horizontally and vertically, not necessarily just in a downward direction as simulated. According to Smith (1990), the hydraulic head in the laboratory is typically 5-10 times greater than in the field, with the exception of lakes and reservoirs or in flooding events. This could potentially induce a washing out of fines, increasing K_{sat} when pores enlarge and interconnect (Smith, 1990). Conversely, where a 'filter skin' develops at the boundary, K_{sat} may be reduced as flow is inhibited (Smith, 1990). Marked increases or decreases in the speed of water movement through a sample in consecutive tests may provide an indication of this.

Cracks or voids may be generated during core excavation in the field, which is especially problematic in stony soils. Cracks and voids will greatly enhance soil water movement. Furthermore, the smooth walls of the core may act to channel and artificially enhance the flow. Grease placed around the soil edge at the top and bottom of the core was used to provide a seal, thereby preventing preferential flow along the core boundary.

7.5 Results: exploration of field soil characteristics

7.5.1 Ordination: Principal components analysis

In the first instance, ordination was performed on the soil data set, including 16 variables and 36 samples taken from land under farm woodland (FW), permanent pasture (PP) semi permanent pasture (SPP) and continuous cereals (CC) (figure 7.2). Using CANOCO for windows version 4 (ter Braak and Šmilauer, 1998), a standard PCA was performed on a correlation matrix with centring and standardisation of the soil data, to examine significant environmental gradients.

Axis	Eigenvalue	Cumulative % variance of soil data represented
1	0.527	52.7
2	0.384	91.1 (38.4)
3	0.056	96.6 (5.6)
4	0.018	98.5 (1.8)

Table 7.2 Results of PCA analysis on 16 soil variables and 36 samples (Numbers in parentheses indicate individual axes contributions).

Table 7.2 presents the eigenvalues and cumulative variance attributable to the first four ordination axes. The total percentage of variance in the data that was explained by the first four axes was high at 99%. A comparison of the proportion of variance explained by each of the axes individually, indicated that axes one (53%) and two (38%) represented the principal gradients of variation in the dataset. Figure 7.4 is the bi-plot of axis one against axis two. The length and direction of the arrows clearly illustrated that indicators of soil porosity, including the volume of storage pores (SP), transmission pores (TP) and total porosity (TPS) were most strongly negatively correlated with the primary axis, axis one. Aggregate stability, indicated by the percentage of WSA>2.8mm (WSA), and organic matter content (OM) appeared most strongly correlated with axis two (figure 7.4).

These observations were supported by an examination of the interset correlations of the soil variables versus the first four ordination axes (table 7.3), which showed that axis one was most strongly governed (in order of importance) by negative correlations with TPS, SP, TP and KSAT, and a positive correlation with ESP. Axis two was largely driven by WSA and OM (table 7.3).

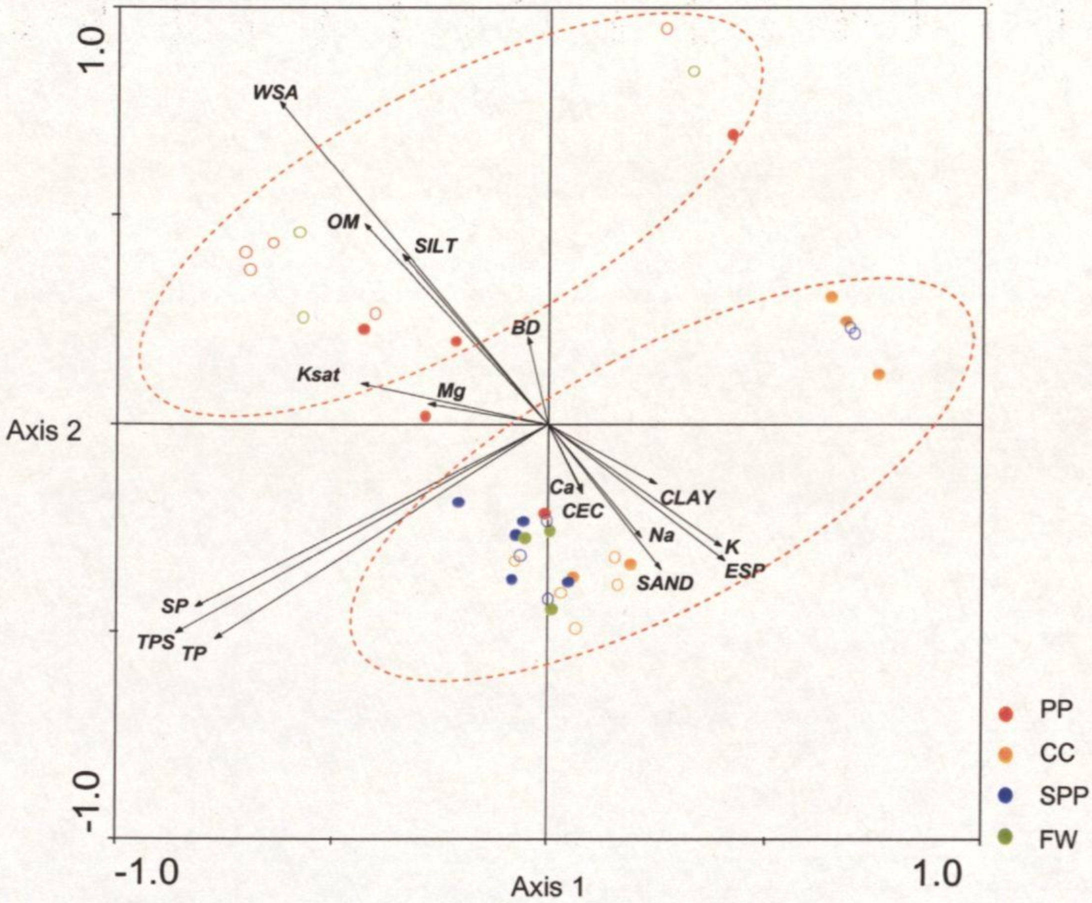


Figure 7.4 PCA bi-plot of axis one verses axis two, illustrating 16 soil variables and 36 samples from PP (red), CC (orange), SPP (blue) and FW (green) fields, where empty circles are surface samples and closed circles are subsurface samples.

Analysis of the distribution of samples on the ordination bi-plot revealed several distinct patterns relating to underlying soil parameter vectors, the sampled land management type

and depth of sample. Firstly, surface samples taken from FW soils showed very different characteristics compared to subsurface samples. Surface samples were distributed in the upper quadrants increasingly towards the left of the plot, whilst subsurface samples were located in the lower two quadrants (figure 7.4). On the basis of the distribution of the samples in relation to dominant soil parameter vectors, the apparent vertical stratification in the soil profile under FW was thought to be characterised by increased organic matter and enhanced aggregate stability at the soil surface with a marginally higher surface porosity and hydraulic conductivity.

Soil characteristic	Axis 1	Axis 2	Axis 3	Axis 4
TPS	**-0.86**	-0.50	-0.01	0.03
SP	**-0.82**	-0.44	-0.05	0.17
TP	**-0.77**	-0.52	0.07	-0.23
WSA	-0.63	**0.77**	0.07	0.01
KSAT	**-0.44**	0.10	-0.07	-0.16
OM	-0.43	**0.48**	-0.20	0.51
SILT	-0.34	0.41	**-0.83**	-0.14
MG	-0.28	0.05	-0.25	**0.63**
BD	-0.05	**0.21**	-0.12	-0.06
CEC	0.08	-0.17	-0.32	**0.86**
CA	0.08	-0.16	-0.30	**0.86**
NA	0.22	-0.27	**-0.42**	0.35
CLAY	0.25	-0.14	**-0.43**	0.23
SAND	0.26	-0.35	**0.89**	0.07
K	0.40	-0.29	-0.26	**0.40**
ESP	**0.41**	-0.33	-0.21	-0.02

Table 7.3 Interset correlations between 16 soil variables and the first four axes of ordination (for each variable, the axis it is most significantly correlated with is highlighted).

Although the variation between surface and subsurface samples was less distinct, PP samples also demonstrated a degree of vertical stratification. Surface samples were generally distributed above subsurface samples, towards the upper left corner of the plot. This spatial variability in the profile again appeared to be the result of a higher soil organic matter content and increased soil structural stability at the soil surface (figure 7.4). In

addition, surface soils under FW and PP exhibited very similar distributions; these are ringed by the upper red outline. This is likely to reflect comparable soil surface characteristics under FW and PP.

With the exception of subsurface soils under FW, the lower half of the ordination plot was dominated by surface and subsurface samples from SPP and CC land management types. The lower red outline highlights similarity in the positioning of SPP and CC soils on the ordination plot (figure 7.4) In contrast to surface FW soils and soils under PP, SPP and CC samples appeared to contain reduced soil organic matter and have lower aggregate stability, total porosity and hydraulic conductivity.

In general SPP samples were located further to the left of axis one and therefore were thought to have a higher porosity than soils under CC. This was particularly discernable in subsurface SPP samples, which were considered to have higher total porosity than surface soils under SPP and all CC samples. Compared to surface CC samples, subsurface samples demonstrated improved aggregate stability, with three of five subsurface samples positioned in the upper right quadrant. However, the positive correlation with axis one indicated reduced soil porosity. Surface CC soils were likely to have a higher ESP and clay content compared to all other sampled soils (figure 7.4).

7.5.2 Clustering

The apparent trends in soil property data were further examined through the classification of samples using hierarchical clustering. A similarity level was determined subjectively based on observation of distinct groups in the dendrogram. Clustering of catchments at the 80% similarity level identified two groups (figure 7.5). Group one consisted predominantly of both surface and subsurface samples from SPP and CC, in addition to subsurface samples from FW. Group two represented surface samples from FW and surface and subsurface samples from PP (figure 7.5). This distinction, based on the

similarities in soil properties of samples, was directly comparable to the differentiation (represented by dashed red ellipses) in the distribution of samples observed in the ordination plot in figure 7.4.

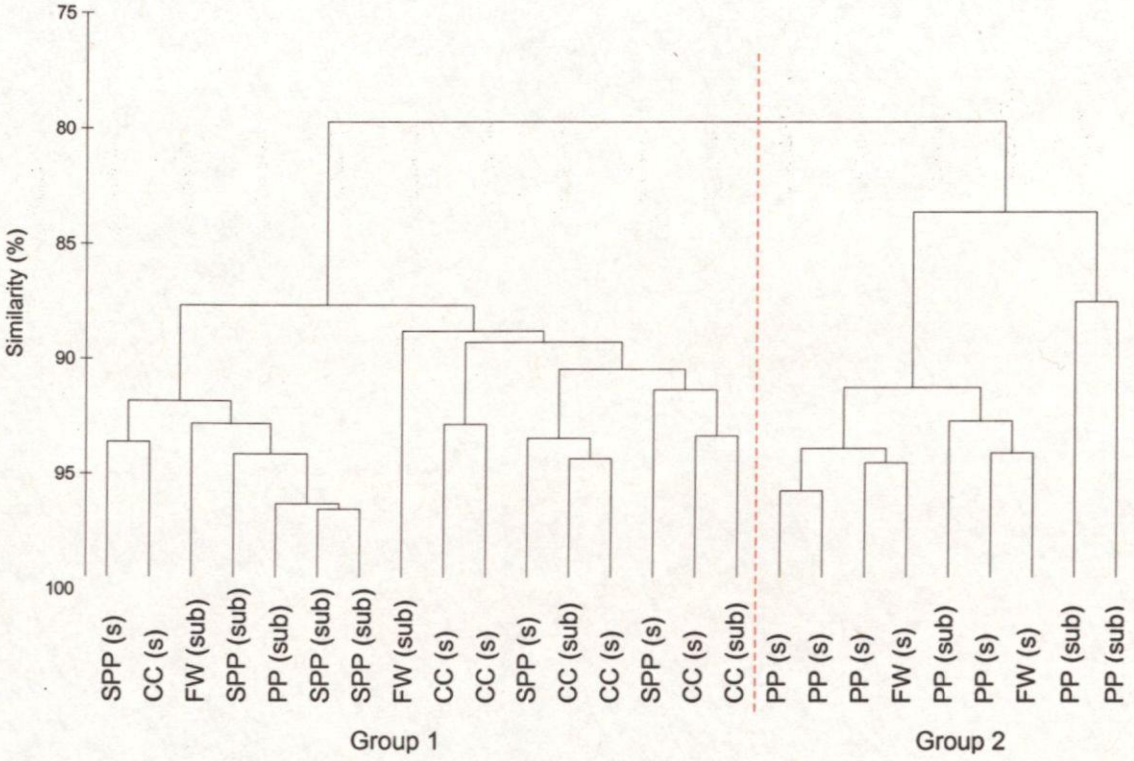


Figure 7.5 Dendrogram of cluster analysis performed on 16 soil variables and 36 surface (s) and subsurface (sub) samples.

The results of clustering were subsequently investigated using factor analysis to establish the soil parameters driving observed sample groups. According to the output table (table 7.4), samples in both groups one and two exhibited a relatively high percentage similarity, ranging between 85-87%. For group one, the percentage silt and total porosity (TPS) made the largest contribution, together explaining over half (58%) of the total explained variability in the data. Similarly in group two, these two variables accounted for 57% of the total variance explained (table 7.4).

a)

Soil parameter	Contribution to percentage variance explained (%)	Cumulative percentage variance explained (%)
SILT	28.2	28.2
TPS	26.0	54.2
TP	08.3	62.5
SAND	07.6	70.1
CLAY	05.4	75.5
WSA	05.1	80.6
CEC	05.0	85.6
CA	04.2	89.8
OM	03.7	93.5
Group 1 average similarity: 84.8%		

b)

Soil parameter	Contribution to percentage variance explained%	Cumulative percentage variance explained (%)
SILT	28.7	28.7
TPS	23.0	51.6
WSA	12.1	63.7
TP	09.4	73.2
CLAY	05.2	78.3
OM	04.4	82.7
SAND	04.2	86.9
CEC	03.8	90.7
Group 2 average similarity: 86.5%		

Table 7.4 Results of factor analysis of 16 soil variables and 36 catchments. Factors controlling the similarities in catchments are presented for a) group 1 and b) group 2.

7.5.3 Analysis of soil parameters

The results of PCA and clustering highlighted patterns in soil samples extracted from fields subject to varying histories of land management that were largely attributable to a number of key soil parameters. The following sections examine the nature of both the in-field and between-field variability in these parameters, which included soil texture (namely silt content), the percentage of exchangeable sodium (ESP), organic matter content, aggregate stability, soil porosity and hydraulic conductivity, and explore whether it is possible to identify a land management impact on soil parameters controlling hydrological process of runoff.

Soil moisture at the time of sampling showed marginal variability between fields. Figure 7.6 displays average in-field measurements of soil moisture content (%) in surface and subsurface soils under FW, PP, SPP and CC land uses. Across all soils, the average soil moisture content was highest in surface samples, where it ranged from 28% (FW) to 43% (PP). The higher vegetative cover and evapotranspiration rates of woodland areas were responsible for lower (<28%) average soil moisture readings in FW soils for both surface and subsurface samples. Variability in field soil moisture content was not thought to have exerted a significant effect on soil samples or through compression and smearing that can arise during coring in wetter conditions (section 7.3.3).

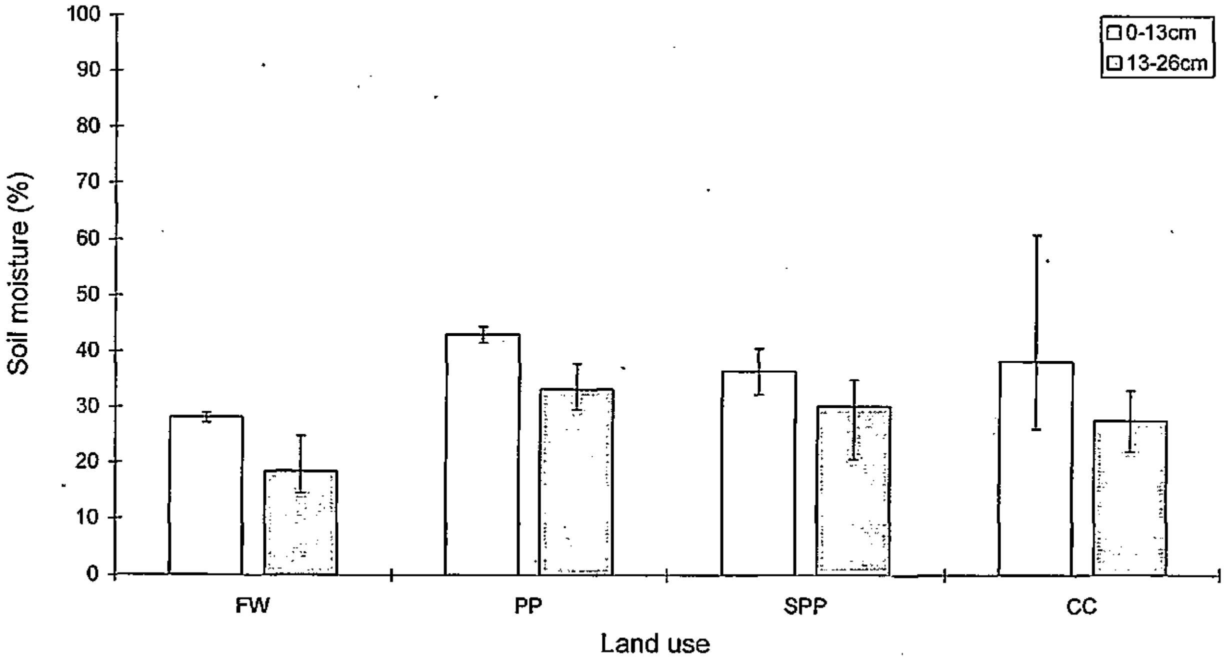


Figure 7.6 Average soil moisture content (%) of surface (0-13cm) and subsurface (13-26cm) soil samples for each land use type. Error bars indicate minima and maxima values

7.5.1 Soil texture

Soil textural properties, including the presence of bonding agents such as clay, organic and iron colloids are important for maintaining soil structure (Curtis *et al*, 1976). The results of PCA revealed that soil textural properties of sand, silt and clay were correlated with axis three, which accounted for a small proportion (5.6%) of the total variance in soil samples explained by the ordination (tables 7.2 and 7.3). However, factor analysis following clustering indicated that silt content was the principal soil property driving similarity between sample groups one and two (table 7.4).

Table 7.5 and figures 7.7 and 7.8, display the percentage sand, silt and clay within surface and subsurface soil samples extracted from FW, PP, SPP and CC land uses.

Parameter	Permanent pasture						Semi-permanent pasture					
	0-13cm			13-26cm			0-13cm			13-26cm		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Sand (%)	15.5	31.9	8.4	20.8	33.7	9.8	19.6	17.3	15.2	16.9	15.9	12.1
Silt (%)	72.0	80.1	56.3	67.7	78.2	56.2	65.8	69.9	59.4	68.7	72.4	57.8
Clay (%)	12.6	16.2	11.4	11.6	14.5	8.1	14.7	16.3	12.9	14.4	15.7	12.6

Parameter	Continuous cereals						Farm woodland					
	0-13cm			13-26cm			0-13cm			13-26cm		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Sand (%)	26.6	35.8	17.9	22.0	28.5	10.6	13.1	17.6	9.8	24.9	31.5	18.1
Silt (%)	59.4	67.3	51.6	64.5	75.3	59.6	73.8	76.6	69.3	64.3	70.8	58.4
Clay (%)	13.9	15.6	12.6	13.5	15.6	10.9	13.1	16.3	12.5	10.8	15.7	10.1

Table 7.5 Proportions of soil textural parameters (sand, silt and clay) in surface (0-13cm) and subsurface (13-26cm) soils sampled from fields under FW, PP, SPP and CC.

Slight variability in the average percentage silt was observed in surface soils between fields and ranged from 59% under CC to 74% under FW (figure 7.3). In subsurface horizons, the average percentage of silt varied by 3% about an overall mean of 67% table 7.5, figure 7.8).

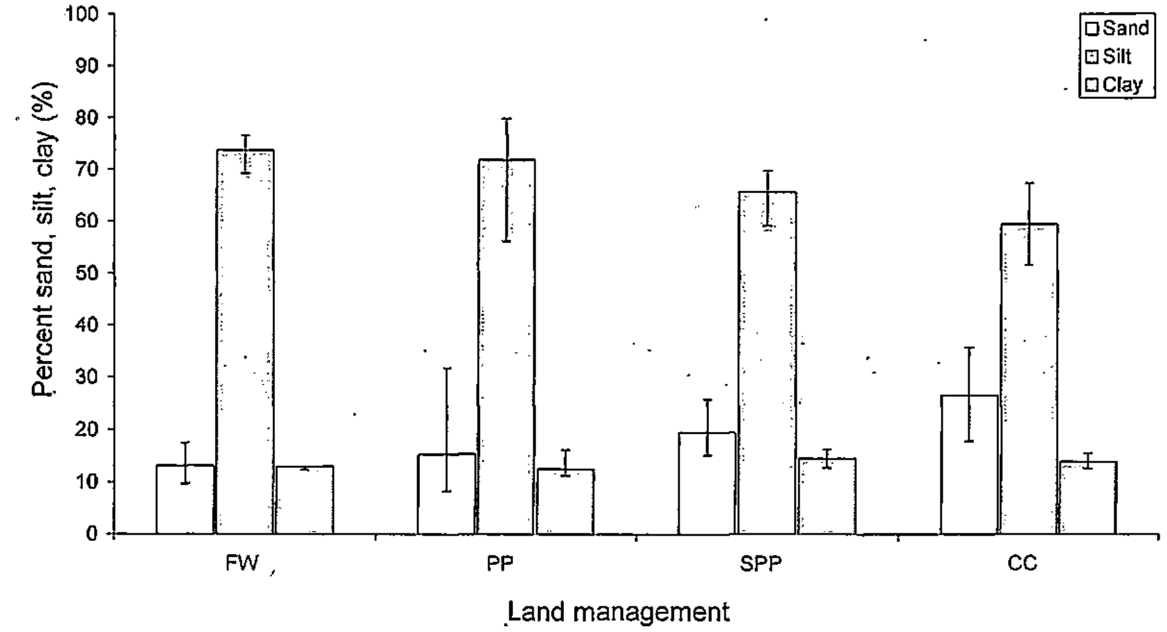


Figure 7.7 Average percentages of sand, silt and clay fractions in surface (0-13cm) soils sampled from FW, PP, SPP and CC land uses. Error bars represent the range of all five samples.

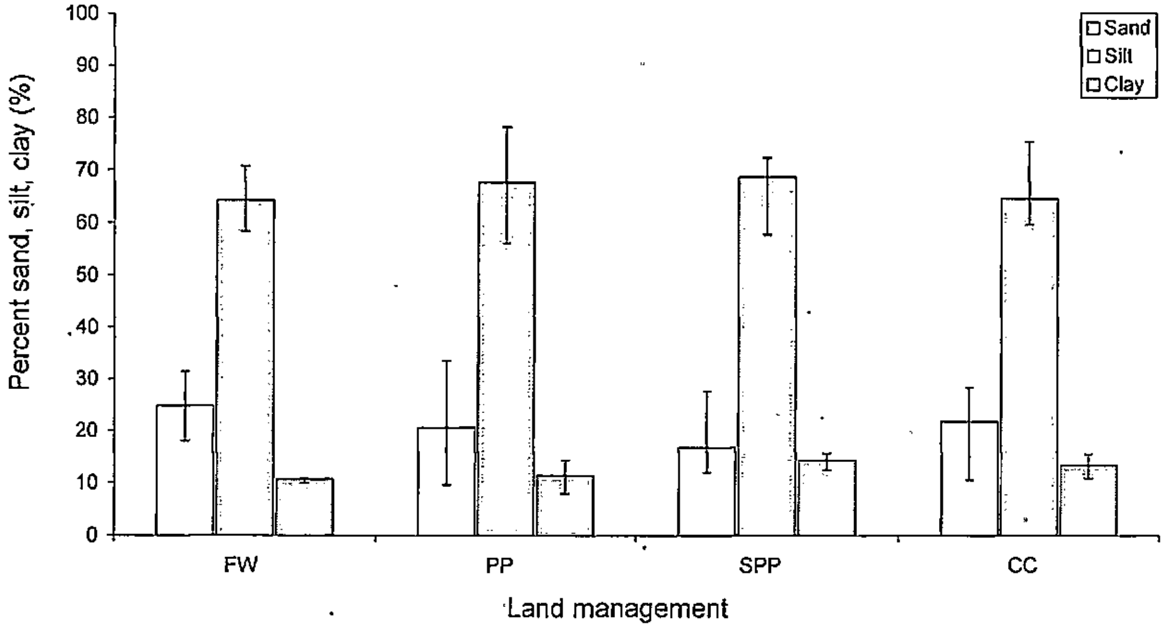


Figure 7.8 Average percentages of sand, silt and clay fractions in subsurface (13-26cm) soils sampled from FW, PP, SPP and CC land uses. Error bars represent the range of all five samples.

Following statistical testing using a *t*-test, the silt contents of samples from surveyed fields were not shown to be significantly different at the 95% confidence interval. The importance of silt in the grouping of samples may simply represent an artefact of strong intercorrelation between silt and WSA, indicated by the similar direction of WSA and SILT vectors in figure 7.4. The Pearson's correlation coefficient between the percentage silt content and the percentage WSA>2.8mm is high ($r^2 = 0.64$, $p<0.05$) (figure 7.24).

On average, the clay content of surface soils ranged by 2% between the four land uses. FW and PP displayed the lowest average clay content at 13%, whilst SPP contained the highest (15%) (figure 7.7). The proportion of clay in subsurface soils was lowest under FW (11%) and PP (12%) and highest under SPP (14%) and CC (14%), although the range was modest at 3% (figure 7.8). Clay content did not comprise a key gradient governing the distribution of samples following PCA and accounted for approximately 5% of the variance explained by sample groups (table 7.4). Pearson's correlation coefficients between clay content and WSA>2.8mm, total porosity and K_{sat} were not significant ($p<0.05$) (figure 7.24). However, the results of *t*-tests showed that the clay contents of samples from fields under FW, PP and SPP and CC were significantly different at the 95% confidence interval.

Percentage of exchangeable sodium (ESP)

Results of PCA showed that soil ESP was positively correlated with axis one (table 7.3) and exhibited a negative correlation with aggregate stability (WSA), represented by the opposite direction of vectors on the ordination plot (figure 7.4). The latter is supported by a negative correlation between ESP and WSA>2.8mm ($r = -0.49$) (figure 7.24). The average percentage of exchangeable sodium (ESP) for surface and subsurface soils across all sites is displayed in figure 7.9.

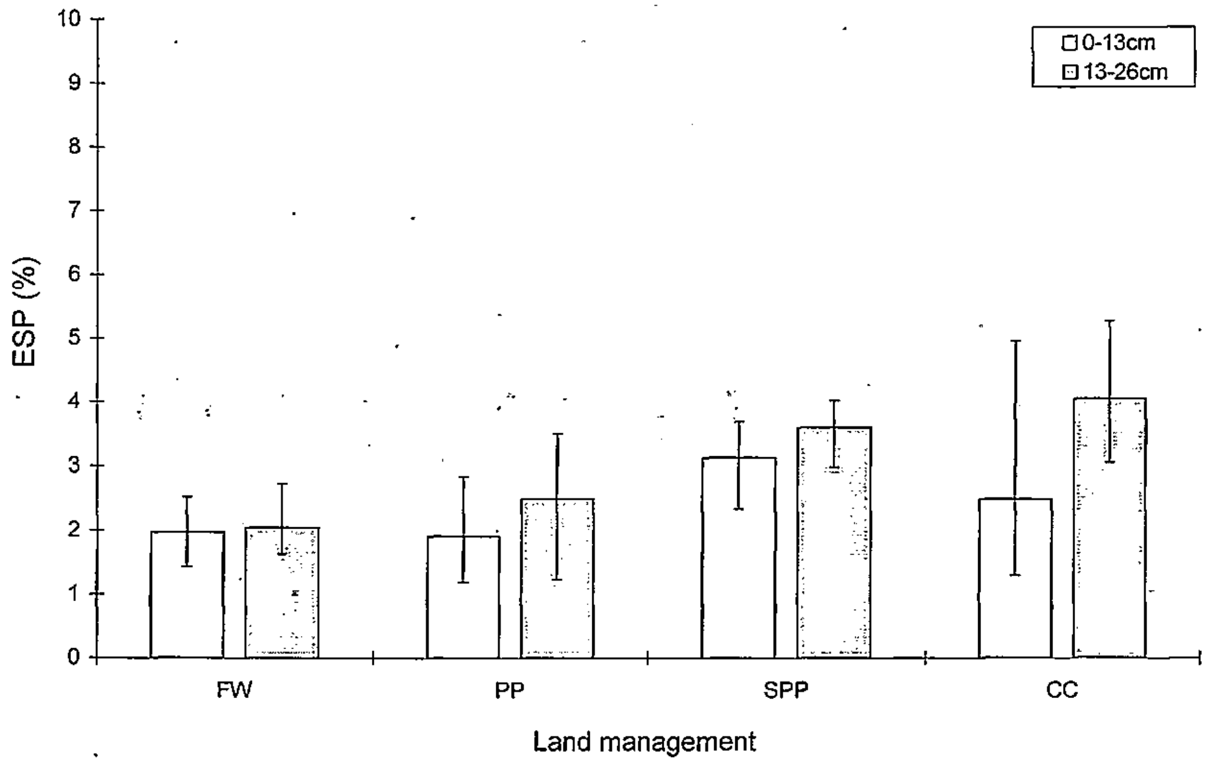


Figure 7.9 Average exchangeable sodium percentage (ESP) in surface (0-13cm) and subsurface (13-26cm) soils sampled from FW, PP, SPP and CC land uses. Error bars represent the range of all five samples.

ESP was higher in all subsurface soils. In soils under FW, there is marginal variability in ESP through the soil profile; ESP is approximately 2% for both surface and subsurface soils. However, in soils under agricultural land uses (PP, SPP and CC) there is greater vertical variability. In the lower horizon, ESP ranges from 2.1% under FW to 4.0% under CC. Overall the ESP of FW and PP soils tested significantly lower than soils under SPP (H_0 rejected at $p<0.05$).

In addition to organic matter content, the major ions of the cation exchange capacity (CEC) are associated with the surfaces of clay particles. The dispersive effects of ESP are particularly prevalent in fine textured soils containing high amounts of swelling clays. Clay content was found to be weakly positively correlated with ESP ($r=0.27$) (figure 7.24). The correlation was not significant ($p>0.05$).

Organic matter content

Soil organic matter content represented a key variable governing a major gradient (axis two) in the variation of soil samples on the ordination bi-plot (figure 7.4). Figure 7.10 displays the average organic matter content for surface and subsurface soils under FW, PP, SPP and CC land uses. The descriptive statistics for soil organic matter content are displayed in table 7.6.

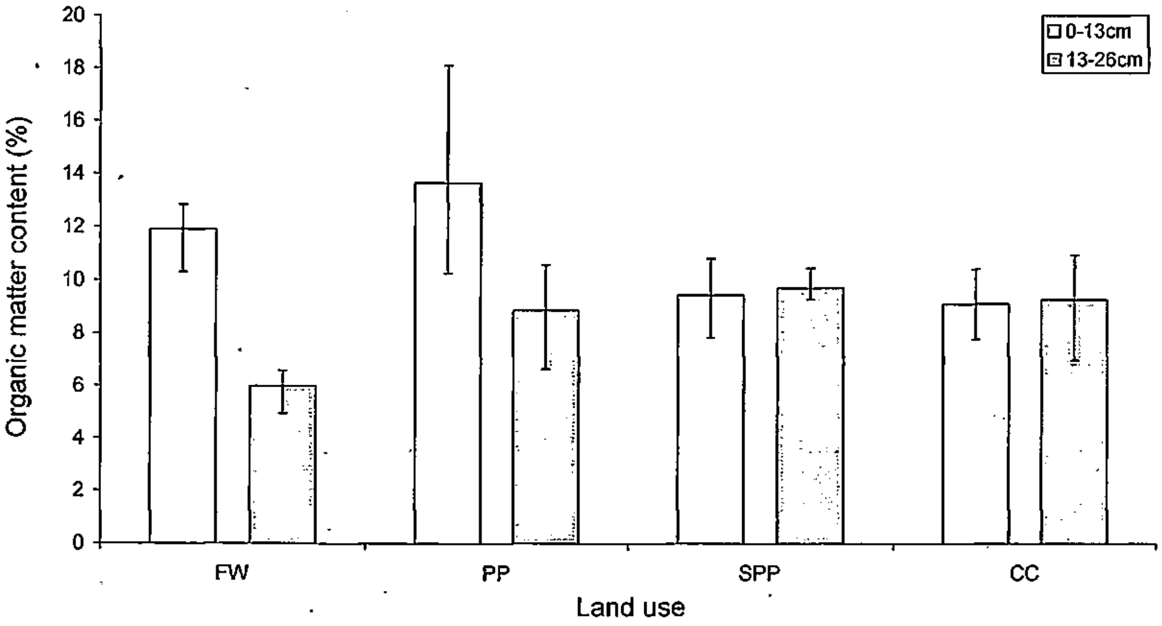


Figure 7.10 Average organic matter content (%) of surface (0-13cm) and subsurface (13-26cm) soil samples for each land use type. Error bars indicate minima and maxima values.

SPP and CC land uses contained the smallest quantity of organic matter at 9%. In comparison, PP soils retained 14% and FW soils 12% (figure 7.10). The extent of variation in organic matter content with depth was greatest under FW, where subsurface soils showed a 6% reduction in organic matter. Under PP and SPP soils the degree of vertical heterogeneity was reduced to 5% and 1%. The average organic matter content of CC soils appeared to be spatially uniform with 9% in both surface and subsurface samples. The range in spatial variability in the average organic matter contents of soils with depth mirrored the extent of vertical stratification observed in sample distributions in the ordination plot (figure 7.4).

Land cover type	0-13cm			13-26cm		
	Mean	Max	Min	Mean	Max	Min
FW	11.9	12.8	10.3	6.0	6.6	4.9
PP	13.7	18.1	10.3	8.9	10.6	6.6
SPP	9.4	10.8	7.8	9.7	10.5	9.3
CC	9.1	10.4	7.8	9.3	10.9	7.0

Table 7.6 Percentage of soil organic matter in surface (0-13cm) and subsurface (13-26cm) soils sampled from fields under FW, PP, SPP and CC.

The relative SOM contents of more actively managed sites under SPP and CC were lower, with a shared average of 9% and a maximum of 11%. The direction of OM and WSA vectors on the ordination plot suggested that soil organic matter content was positively correlated with aggregate stability. The Pearson's correlation coefficient between organic matter and WSA>2.8mm was significant at the 99% confidence interval (r=0.75, p<0.01) (figure 7.24).

7.5.2 Soil aggregate stability

Wet sieving (WSA >2.8mm)

Figure 7.11 displays the average percentage of water stable aggregates greater than 2.8mm (WSA>2.8mm) in surface and subsurface soils under FW, PP, SPP and CC land uses, determined using wet sieving (Bryan, 1976; Grieve, 1980). The distribution of samples in relation to axis two on the ordination plot was primarily driven by WSA (figure 7.4).

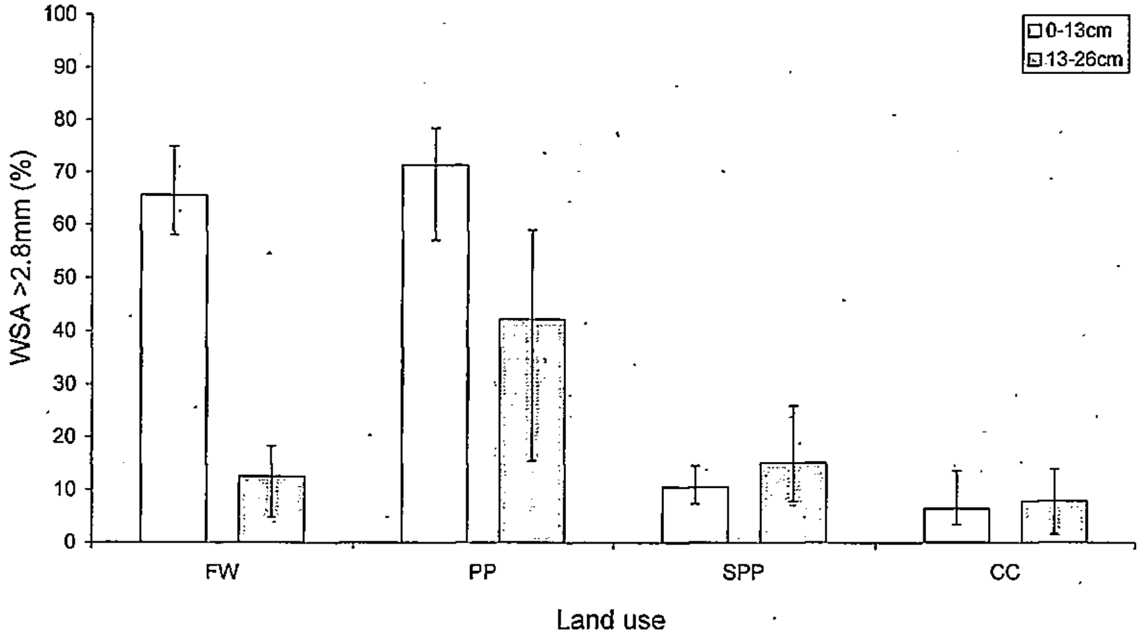


Figure 7.11 Average percentage of water stable aggregates (WSA>2.8mm) in surface (0-13cm) and subsurface (13-26cm) soil samples for each land use type. Error bars indicate minima and maxima values.

The aggregate stability of FW and PP soils tested significantly different from SPP and CC soils (H_0 was rejected at the 95% confidence interval). Surface soils under FW and PP contained the most stable aggregates, with average percentages of WSA at 66% and 71% (figure 7.11). This contrasted with surface soils under SPP and CC, where the average percentages of WSA were markedly lower at 11% and 6%. Under FW soils there was a 53% reduction in the average percentage of WSA>2.8mm at depth.

Considerable variability was also observed between surface and subsurface soils under PP, demonstrated by a 42% reduction in the average percentage of aggregates >2.8mm that were water-stable in subsurface samples. The extent of vertical discontinuity under FW and PP was not replicated in SPP or CC soils, where subsurface horizons showed only slight increases in average percentages of WSA>2.8mm of 4% and 2%.

Laboratory rainfall simulation: variation in soil water content through time

The average percentages of soil moisture measured during triplicate wetting of laboratory soil plots under simulated rainfall are displayed in figures 7.12 to 7.15. Comparison of figures 7.12 and 7.13 with figures 7.14 and 7.15 revealed two very distinct patterns in terms of the rate of wetting between soils from FW and PP land uses and those under SPP and CC. FW and PP soil plots wetted up slowly in comparison to the almost instant wetting that was apparent in SPP and CC soil plots. For example, surface soils in FW and PP plots showed a delay of 6mins (FW) and 3mins (PP) on average before significant wetting occurred. An evaluation of subsurface wetting between the soil plots showed a similar trend, with lag times of 6mins (CC) and 2mins (SPP) on average contrasting with 14mins (FW) and 10mins (PP).

Also of interest was the percentage soil moisture value at which the rate of wetting substantially decreased. This was subjectively determined from the point at which there was an obvious levelling in the soil moisture readings on the graph. It was possible to compare this point of 'near-saturation' for soils taken from each of the land uses, by calculating the average for the four TDR rods. The average near-saturation point appeared to be highest under FW at 46.3%, followed by PP at 44.9%. Corresponding values for SPP and CC were lower at 41.4% and 41.2%.

Figure 7.16 illustrates the change in the average soil moisture content of the four TDR rods through time, interpolated across the cross-section of each of the FW, PP, SPP and CC soil plots. This displayed more clearly the faster wetting rate of SPP and CC soils, compared to FW and PP soil plots; observe the relative colouring of soil plots after 8mins.

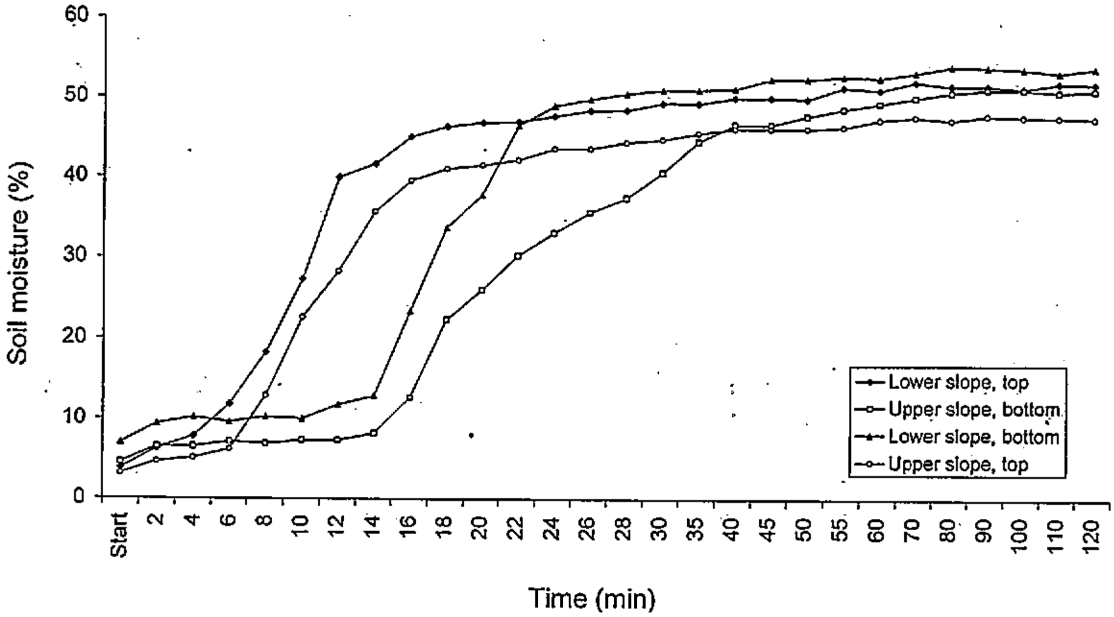


Figure 7.12 Average soil moisture of TDR rods in FW soil plots.

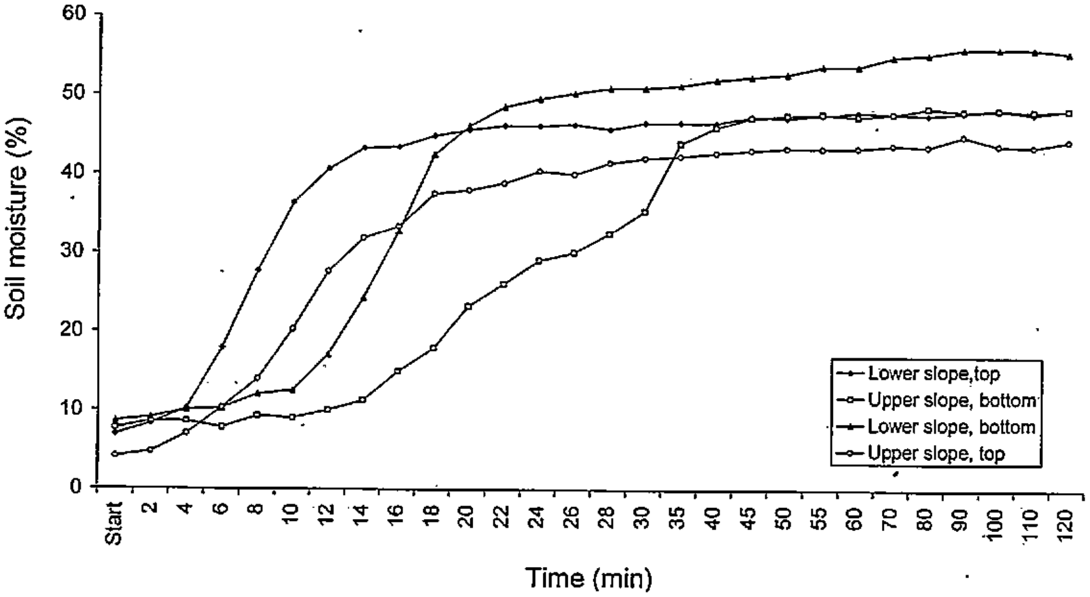


Figure 7.13 Average soil moisture of TDR rods in PP soil plots.

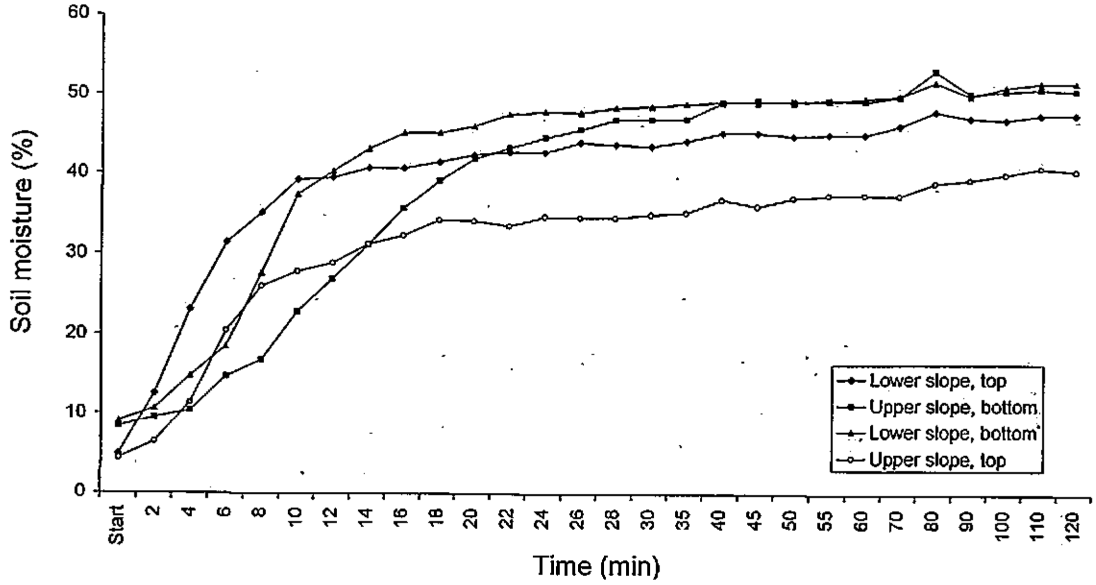


Figure 7.14 Average soil moisture of TDR rods in SPP soil plots.

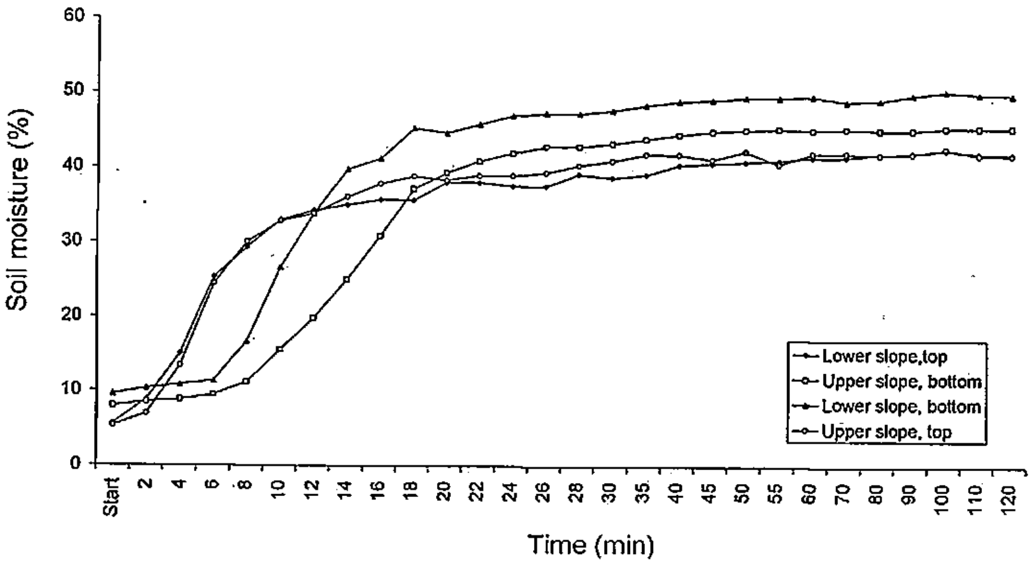


Figure 7.15 Average soil moisture of TDR rods in CC soil plots.

It is also apparent in figure 7.16 that FW soil plots appeared to show much less uniformity in soil moisture readings. Analysis of all four soil plots between 14 and 20 minutes showed greater vertical and lateral variability in the range of soil moisture in FW and PP plots compared to SPP and CC plots. Further analysis of the rate of wetting (increase in percentage soil moisture per minute) for each TDR after 10minutes and 20minutes revealed a pattern of decreasing variability and greater homogeneity in SPP and CC soils, where the soil management was most intense. After 10 minutes the range in wetting rate was 2% (FW) and 2.7% (PP) compared to 1.6% (SPP) and 1.8% (CC) (figure 7.17a). Following 20minutes of simulated rainfall, the variability in the rate of wetting was greatest in FW plots at 1.4% and lowest in CC plots at 0.33% (figure 7.17b) (cross-reference with figure 7.3).

Unsubstantial volumes of runoff and therefore sediment were produced from soil plots during laboratory rainfall simulations. This is presumed to be the result of limitations in the experimental design, namely the size and depth of soil blocks and the pre-treatment of soil prior to experimentation (section 7.4.3iii). Manual disturbance of the soil is thought to have significantly enhanced natural soil drainage through the creation of high numbers of large pores, or macropores. The testing and measurement of runoff from undisturbed soil blocks may yield results that are more consistent with in-field characteristics of soil water movement.

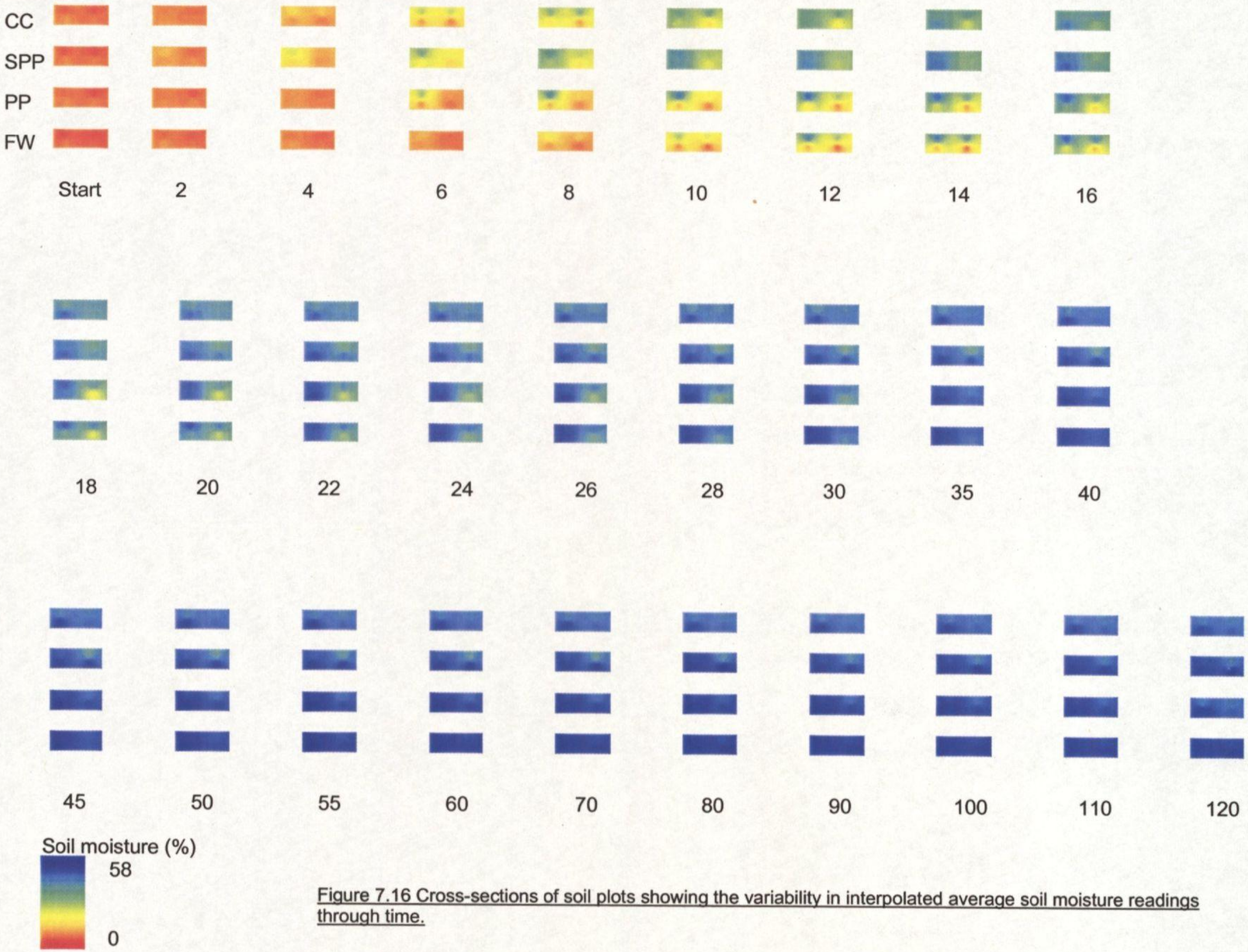


Figure 7.16 Cross-sections of soil plots showing the variability in interpolated average soil moisture readings through time.

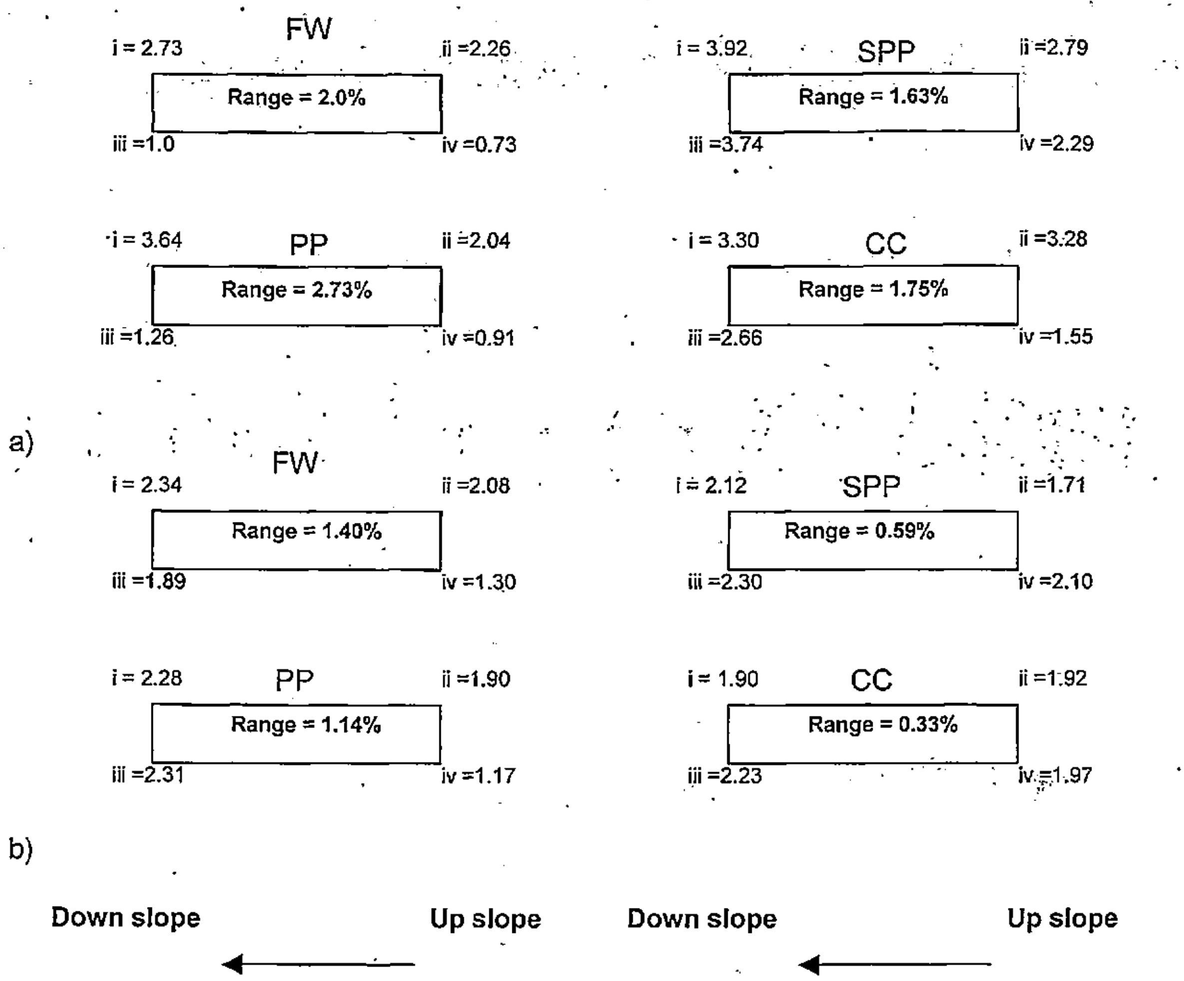


Figure 7.17 Variability in the average rate of wetting (average percentage increase in soil moisture per minute for triplicate simulations) across TDR measuring points i-iv for soil plot cross-sections after a) 10minutes and b) 20minutes of simulated rainfall. The ranges in rate of wetting for all TDR points (i to iv) are shown in bold.

7.5.3 Soil hydrology

Results of PCA revealed that the primary gradient of variation in soil data (axis one) was controlled by variability in soil pore size characteristics, namely total porosity (TPS), the percentage of storage pores (SP) and transmission pores (TP). K_{sat} also demonstrated a fairly strong negative inter-set correlation with this axis (table 7.2).

Water release characteristics

Table 7.7 presents the summary statistics of pore size characteristics and saturated hydraulic conductivity (K_{sat}) of surface and subsurface soils under FW, PP, SPP and CC.

Parameter	Permanent pasture						Semi-permanent pasture					
	0-13cm			13-26cm			0-13cm			13-26cm		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Ksat (mday-^{1})	1.6	2.6	0.3	3.9	6.3	0.9	2.8	6.7	0.04	4.0	6.7	1.8
Total Porosity	73.3	81.4	63.7	57.9	60.5	52.7	61.4	63.7	58.9	60.8	64.2	56.5
Transmission	22.6	28.3	16.1	24.6	31.1	20.8	16.3	25.4	11.0	25.0	29.1	20.4
Storage Pores	11.6	13.2	9.8	8.2	10.4	6.6	11.9	14.5	8.2	8.4	8.6	7.5
Residual Pores	39.2	42.6	37.2	25.2	31.3	21.9	33.2	35.5	25.7	27.3	30.0	23.6

Parameter	Continuous cereals						Farm woodland					
	0-13cm			13-26cm			0-13cm			13-26cm		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Ksat (mday-^{1})	1.2	1.6	0.6	2.3	4.3	0.6	4.6	6.9	1.8	4.4	5.3	3.5
Total Porosity	56.9	62.4	50.8	53.4	56.9	49.9	67.5	69.9	65.1	55.1	59.4	48.5
Transmission	20.3	25.4	14.4	16.2	20.4	12.0	27.2	30.7	23.7	25.6	30.0	21.4
Storage Pores	8.1	9.4	5.8	7.8	8.0	7.5	10.2	10.5	9.9	7.4	8.6	5.0
Residual Pores	28.6	31.9	25.7	29.4	29.9	29.0	30.1	30.9	29.2	22.2	29.5	18.7

Table 7.7 Soil hydraulic parameters for surface (0-13cm) and subsurface (13-26cm) soils sampled from fields under FW, PP, SPP and CC land uses (n= 5 at 2 depths for PP, SPP and CC, and n=3 at 2 depths for FW).

Total porosity

Total porosity exhibited the strongest negative inter-set correlation with axis one (table 7.3) and accounted for the second highest proportion of explained variance in sample groups at 26% and 23% (table 7.4). The total porosity of soils typically falls in the range 30-70% and like bulk density, can be used as a general indicator of the degree of compaction in a soil (Landon 1984). The total porosities of surface and subsurface soils ranged from 48.5% for a subsurface soil under FW to 81.0% for a surface soil under PP. Figure 7.18 displays the average total porosity of soils sampled under each land management type.

In surface soils the average total porosity was marginally higher under FW and PP at 68% and 71%, compared to SPP and CC land uses, where average soil porosity at the surface was 61% and 57%. In subsurface soils, average total porosity ranged by 8% between fields. SPP (61%), followed by PP (58%) had the highest average subsurface soil porosities. CC exhibited the lowest average total porosity in both surface and subsurface soils. Statistical testing using a t-test confirmed that there was a significant difference between the total porosities of both surface and subsurface soils under PP and CC (H_0 was rejected at the 95% confidence interval).

Under FW and PP, there was marked variability in the average total porosity between surface and subsurface horizons. Average total porosity decreased by 12.4% for FW and 15.4% for PP in subsurface horizons. This pattern was not reflected in soils under SPP or CC, where there was a marginal change in average total porosity with depth; a variability of 0.6% was observed in SPP soils and 2.5% for soils under CC.

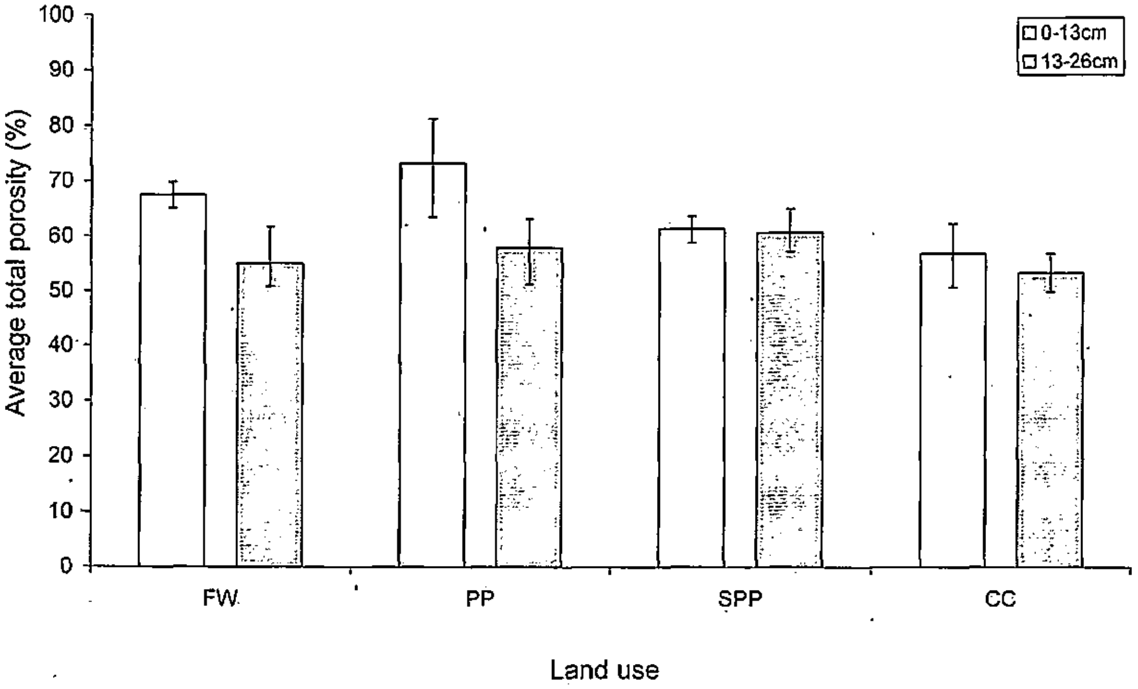


Figure 7.18 Average total porosity of surface (0-13cm) and subsurface (13-26cm) soils for each land use type. Error bars indicate minima and maxima values.

The total porosity can be divided into transmission pores, storage pores and residual pores according to the pore size classification system of Thomasson (1978). Water is conducted largely through bigger pores called transmission pores (Greenland, 1977; Ternan and Neller, 1999), or air capacity pores by definition (Thomasson, 1978), which drain freely under gravity and are >50µm. These enable the rapid movement of water through the soil.

Storage pores (Greenland, 1977; Ternan and Neller, 1999), or available water pores (Thomasson, 1978), range from 0.2µm to 50µm, and are important for retaining water against the pull of gravity and provide an essential supply of water to plants. Pores which are smaller than these parameters are termed residual pores (Landon, 1984).

Transmission pores

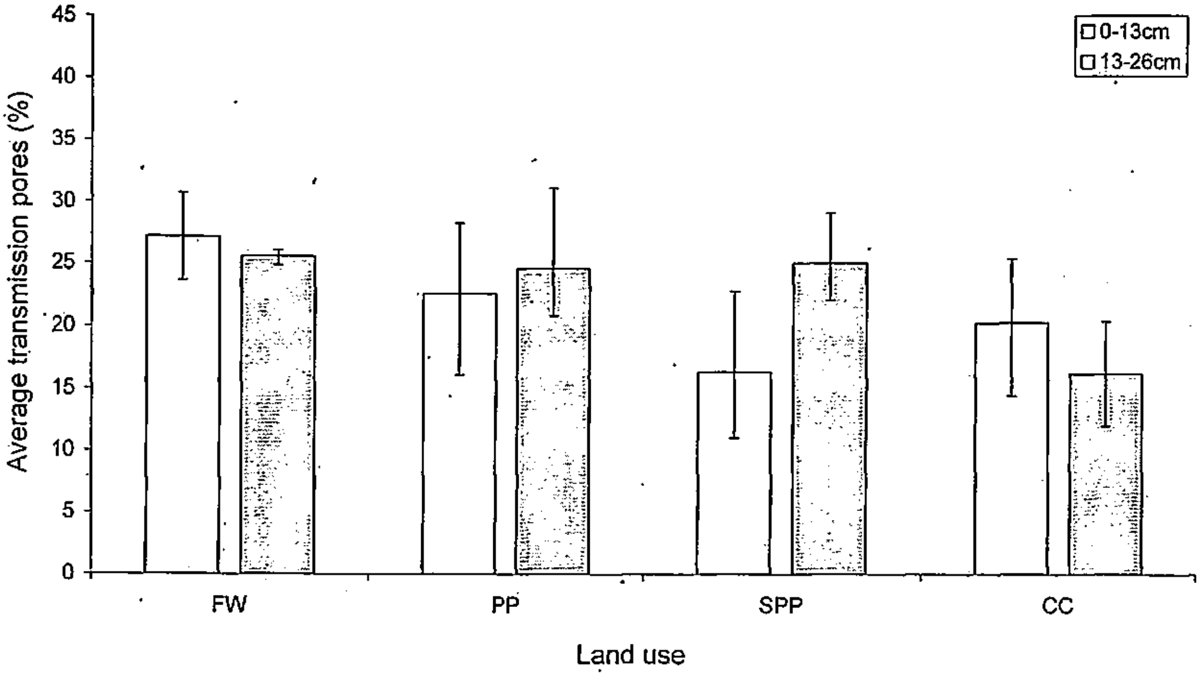


Figure 7.19 Average percentage volume of transmission pores in surface (0-13cm) and subsurface (13-26cm) soils of each land use. Error bars indicate minimum and maximum values.

Transmission porosity (TP) demonstrated a high inter-set correlation with axis one of 0.77 (table 7.3). The average percentage volume of transmission pores in surface and subsurface soils under FW, PP, SPP and FW are presented in figure 7.19. In surface soils the average percentage of transmission pores varied by 11% across the land management types, ranging from 16% under SPP to 27% under FW. At 26% FW soils also exhibited the highest proportion of transmission pores in subsurface horizons.

The average percentage volume of transmission pores in soils under PP and SPP increased in the deeper horizon to 25%. CC demonstrated the lowest percentage of transmission pores in subsurface soils, where they comprised on average 16% of total porosity. This represented a reduction of 4% from the percentage of transmission pores in samples taken from the soil surface.

Storage pores

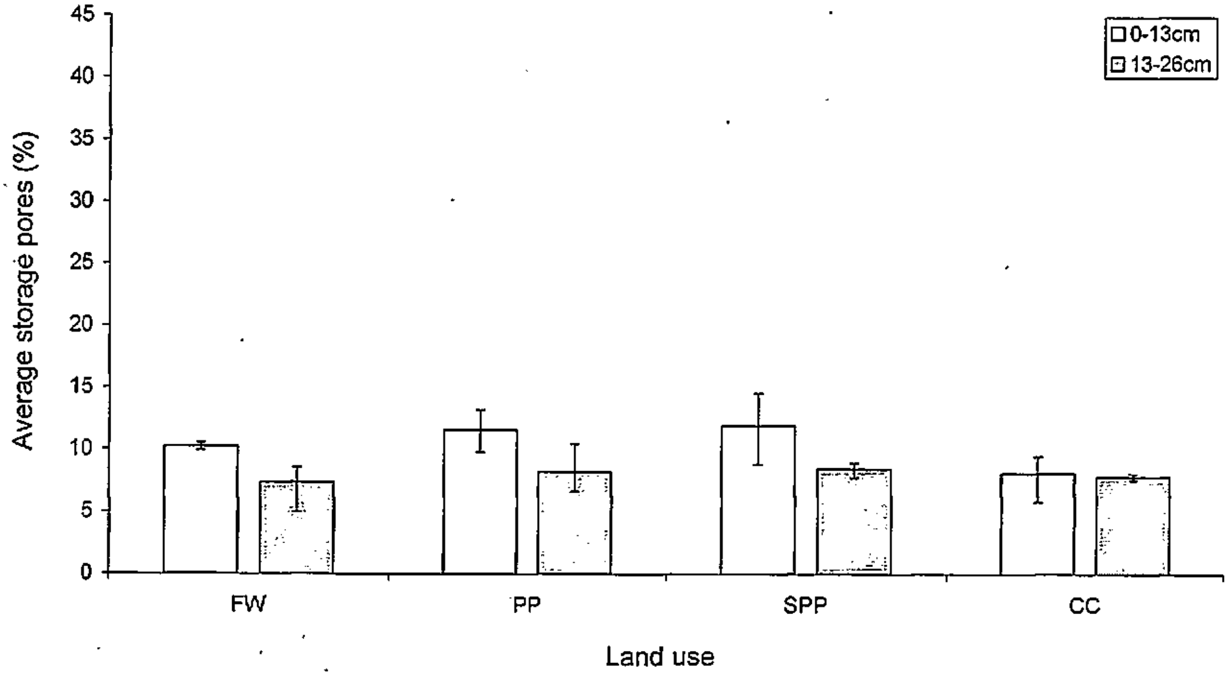


Figure 7.20 Average percentage volume of storage pores in surface (0-13cm) and subsurface (13-26cm) soils of each land use. Error bars indicate minimum and maximum values.

The percentage of storage pores exhibited the second strongest negative relationship with the main gradient of variation in the ordination (table 7.3 and figure 7.4). Figure 7.20 displays the average percentage volume of storage pores in surface and subsurface soils under each sampled land management type. In general, the average percentage of storage pores was consistently lower than the transmission porosity; the overall average was 9% compared to 23% for the average percentage of transmission pores.

For surface soils the average storage porosity showed a variability of 4% between land management types, with the percentage volume of storage pores falling in the range 8% (CC) to 12% (SPP). The percentage volume of storage pores in subsurface soils remained spatially consistent at 8% under PP, SPP and CC soils and 7% under FW. The variability in the storage porosity between FW and CC tested significantly different ($p<0.05$).

Residual pores

The average percentage volume of residual pores in surface and subsurface soils under each land management type are presented in figure 7.21. The total porosity of all sampled soils was predominantly composed of residual pores. The overall average of residual porosity was 30%.

Values across all land uses were in the range 29% to 39%, a variation of 10% was observed between soils under PP and CC. The average percentage volume of residual pores in subsurface horizons increased by 7%, from 22% under FW soils to 29% under CC. In subsurface soils under PP and SPP, 25% and 27% of total porosity consisted of residual pores.

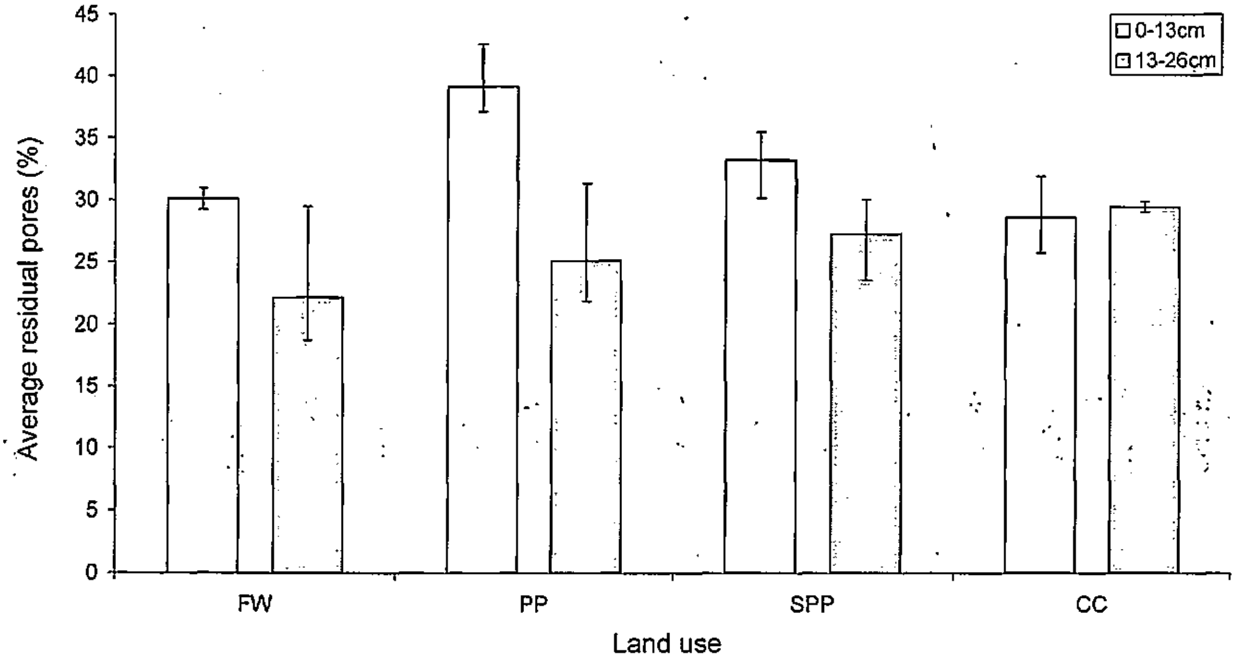
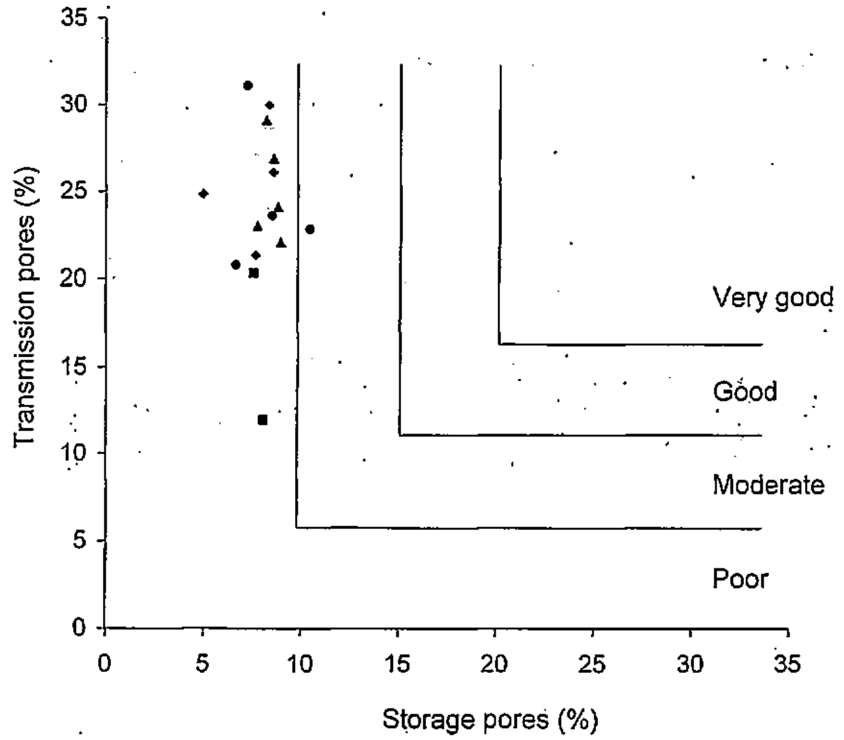
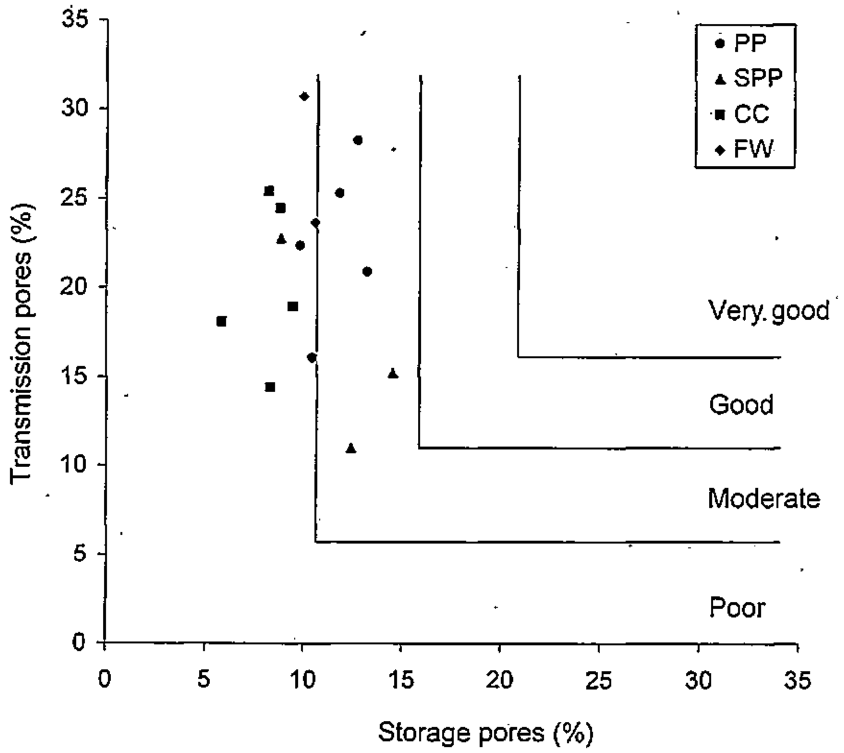


Figure 7.21 Average percentage volume of residual pores in surface (0-13cm) and subsurface (13-26cm) soils of each land use. Error bars indicate minimum and maximum values.

According to the soil structure classification of Thomasson (1978), which uses the relative proportions of transmission and storage pores, sampled soils demonstrated poor to moderate soil structure (figure 7.22). This was largely attributable to the low storage porosity of sampled soils, which were consistently less than 15%. In terms of the percentage of transmission pores, all soils exhibited greater than 10% transmission porosity, representing good to very good soil drainage.



a)



b)

Figure 7.22 Soil structure classifications for a) surface and b) subsurface soils for each land use (Thomasson, 1978).

On the basis of the percentage of storage pores, further distinctions were made between the characteristics of soils of different land uses. Compared to CC, surface soils under FW, PP and SPP land uses exhibited improved soil structures due to higher percentages of storage pores, which were generally classified as moderate (figure 7.22a). The percentage of storage pores in surface soils under CC were all less than 10%, at 8% on average, and thus were deemed structurally poor. With the exception of one PP sample, all subsurface soils were classified as having poor soil structure; storage porosity was consistently less than 10% (figure 7.22b).

Saturated hydraulic conductivity (K_{sat})

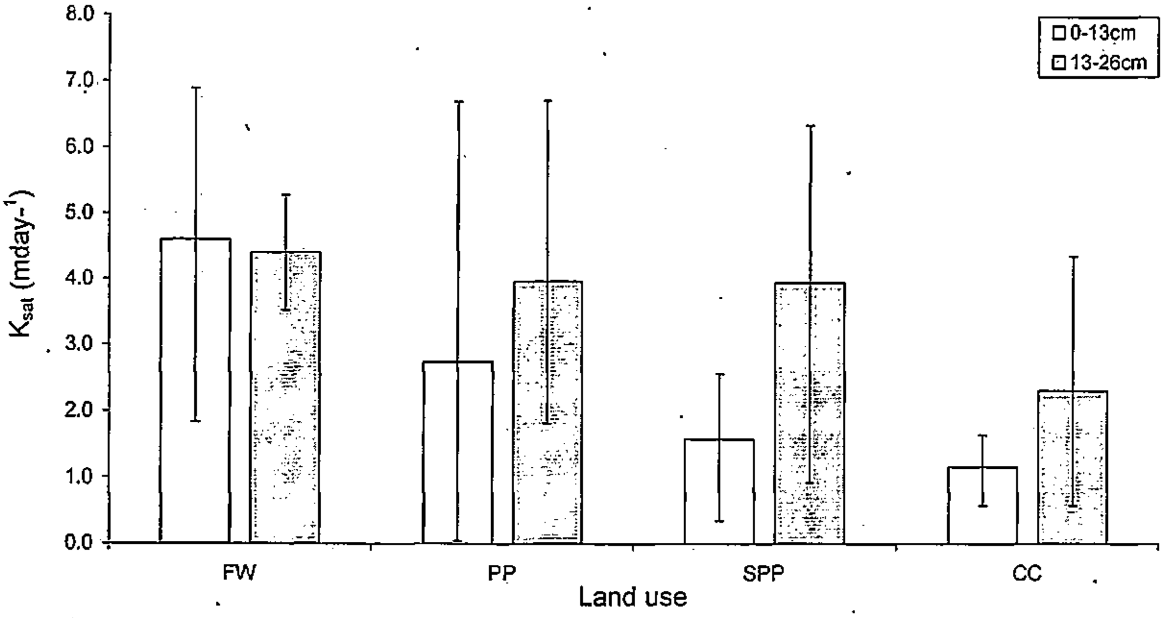


Figure 7.23 Average saturated hydraulic conductivity (K_{sat}) for surface (0-13cm) and subsurface (13-26cm) soils of each land use. Error bars represent minima and maxima figures.

The averaged K_{sat} figures (mday-^{1}) for five surface (0-13cm) and subsurface (13-16cm) soil cores taken from each land use are displayed in figure 7.23 and presented in table 7.7. The wide error bars in figure 7.23 indicate that the K_{sat} measurements of sampled soils demonstrate high in-field variability. This may be explained by spatial heterogeneity in soil characteristics, but it may equally represent an artefact of the limitations associated with the sampling technique adopted and/or errors introduced during laboratory analysis of soil permeability (section 7.4.4).

Farm woodland demonstrated the highest permeability, with average K_{sat} rates greater than 4m day-^{1} for both surface and subsurface soils. According to Landon (1984), such soils are described as having moderate to rapid drainage. These high conductivity rates were not considered to be an accurate representation of field permeability and were therefore interpreted here as relative values. Notwithstanding this, a significant positive correlation between K_{sat} and the percentage of transmission pores (r=0.56, p<0.05) indicates some degree of reliability in the measurements (figure 7.24).

Surface soil permeability was highest in FW soils with average K_{sat} at 4.6mday-^{1}, and appeared to be progressively lower under land uses involving more intensive working of the soil, such as SPP (1.6mday-^{1}) and CC (1.2mday-^{1}). Soils subject to greater agricultural management showed consistently lower K_{sat} at the soil surface. This increase was marked in soils under permanent pasture (PP), where average K_{sat} at the surface was 1.6mday-^{1}, compared to an average 3.9mday-^{1} for subsurface soils (table 7.7). Subsurface K_{sat} ranged from 4.0mday-^{1} under PP and SPP to 2.3mday-^{1} under CC. In FW soils, there was marginal change in permeability through the soil profile. In contrast, the average K_{sat} figures of subsurface soil samples taken from fields under PP, SPP and CC, exhibited an increase in permeability with depth. Results of statistical testing using a t-test showed that the K_{sat} of soils under CC was significantly different from both PP and FW soils at the 95% confidence interval.

	Sand	Silt	Clay	Bulk Density	Organic Matter	WSA	Transmission Pores	Storage Pores	Total Pore Space	Na+	K+	Ca^{2}+	Mg^{2}+	CEC	ESP	EMP	K$_{sat}$
Sand (%)	1																
Silt (%)	-0.97**	1															
Clay (%)	-0.29	0.04	1														
Bulk Density (gcm-^{3})	-0.18	0.10	0.36	1													
Organic Matter (%)	-0.65*	0.65*	0.10	0.13	1												
WSA (%)	-0.57*	0.64*	-0.20	0.17	0.75**	1											
Transmission Pores (%)	-0.15	0.20	-0.18	0.50	0.17	0.32	1										
Storage Pores (%)	-0.45	0.42	0.18	-0.10	0.55	0.41	-0.27	1									
Total Pore Space (%)	-0.66*	0.67*	0.09	0.28	0.81**	0.75**	0.36	0.62*	1								
Na+ (cmolcKg-^{1})	-0.05	-0.06	0.42	-0.12	-0.08	-0.32	-0.15	-0.04	-0.03	1							
K+(cmolcKg-^{1})	0.08	-0.18	0.36	-0.19	-0.22	-0.50	-0.43	0.01	-0.23	0.81**	1						
Ca^{2}+ (cmolcKg-^{1})	-0.12	0.05	0.28	-0.01	0.40	-0.07	-0.13	0.34	0.37	0.40	0.28	1					
Mg^{2}+ (cmolcKg-^{1})	-0.30	0.29	0.06	0.03	0.76**	0.35	0.08	0.43	0.57	0.11	-0.06	0.62	1				
CEC(cmolcKg-^{1})	-0.14	0.06	0.30	-0.02	0.43	-0.07	-0.13	0.35	0.38	0.45	0.33	1.00**	0.66*	1			
ESP (%)	0.13	-0.21	0.27	-0.12	-0.38	-0.49	-0.34	-0.24	-0.42	0.69*	0.80**	-0.24	-0.32	-0.18	1		
EMP (%)	-0.29	0.34	-0.14	0.06	0.65*	0.52	0.25	0.30	0.43	-0.18	-0.32	0.05	0.79**	0.11	-0.29	1	
K$_{sat}$ (mday-^{1})	-0.27	0.33	-0.17	0.28	0.12	0.41	0.56*	-0.07	0.28	-0.26	-0.36	-0.41	-0.06	-0.40	0.10	0.27	1

** Significant at $p<0.01$

* Significant at $p<0.05$

Table 7.24 Pearson's correlation matrix based on soil property data from all four land uses.

7.6 Discussion: The impacts of land use on soil hydrological processes

Principal components analysis employed on soil property data for 36 samples extracted from fields subject to ranging levels of management activity, pointed towards a distribution in the dataset that was fundamentally driven by the soil pore size characteristics, namely total porosity (figure 7.4). Clustering combined with factor analysis identified two distinct groups in the sample set which were largely distinguished on the basis of similarity in silt content and total porosity (TPS) (figure 7.5). The first group comprised surface soils from fields under FW and both surface and subsurface soils from PP. All soils from SPP and CC land uses, in addition to subsurface FW soils were encompassed in the second sample group.

The total porosities of soils from less intensively managed fields under permanent pasture were shown to be significantly higher compared to soils sampled from more intensively managed, cultivated fields under CC. Slower wetting rates and higher average soil moisture percentages at near-saturation in FW and PP soil plots compared to SPP and CC soil plots following rainfall simulation testing (figures 7.12 to 7.15), were related to increased total porosity under FW and PP. In particular, the percentage of storage pores in soils under CC tested significantly lower than FW soils ($p<0.05$). Variability in soil porosity between sampled land management types was most pronounced at the soil surface. Application of the soil structural classification of Thomasson (1978) illustrated a clear reduction in the surface soil structure of samples from CC, when compared to soils from SPP, PP and FW land uses (figure 7.22a).

In addition to soil pore size characteristics, saturated hydraulic conductivity (K_{sat}) was positively correlated with the first axis of variation in the ordination (table 7.3). Rates of surface and subsurface hydraulic conductivity were highest under FW and declined progressively as the intensity of the agricultural land management activity under PP, SPP

and CC increased (figure 7.23). Statistical testing determined that the hydraulic conductivities of FW and PP soils were significantly faster than those of soils taken from sites under CC.

Vertical and lateral soil water movement is contingent upon sufficient numbers of transmission pores which are essential for soil drainage and strongly dependent upon soil bulk density. Due to the inherent limitations of the sampling technique adopted, in conjunction with the high potential for errors to be introduced during coring and laboratory testing, measurements of saturated hydraulic conductivity were not deemed to be a reliable single indicator of the soil drainage characteristics of tested land uses. However, the matrix of Pearson's correlation coefficients in figure 7.24 showed positive correlations between the percentage of pores >50µm and both K_{sat} (r=0.56, p<0.05) and bulk density (r=0.50). Bulk density measurements were found to be insensitive to the modest changes in soil structure that were detectable in figure 7.22, using the soil structure classification system of Thomasson (1978).

Consistent with reduced surface total porosities, soils subject to agricultural land management (PP, SPP and CC) showed lower rates of hydraulic conductivity at the soil surface (figure 7.23). Classified in terms of the volume of transmission pores, all surface soils demonstrated good to very good soil drainage (figure 7.22a). In general, subsurface soils exhibited improved transmission porosity and were therefore classified as having very good drainage characteristics (Thomasson, 1978) (figure 7.22b). Differences in the relative transmission porosity between fields were characterised by higher numbers of transmission pores in FW soils, and lower numbers of transmission pores in surface soils under SPP and surface and subsurface soils under CC (figures 7.19 and 7.22a).

Variability in soil porosity and drainage that was discernible between surface samples from fields under FW and PP, and SPP and CC land management activities, was

predominantly the result of differences in the structural stability of topsoils. Soil structure represents the degree of stability of soil aggregates that form as a result of the rearrangement, flocculation and cementation of soil particles (Bronick and Lal, 2005). A good soil structure is governed by the presence of soil aggregates in the range 1-10mm that remain stable when wetted and contain pore sizes that facilitate rapid infiltration and drainage (Tisdall and Oades, 1982).

Aggregate stability (WSA>2.8mm) exhibited the strongest inter-set correlation with axis two, following ordination performed on the soil dataset which comprised 36 samples and 16 soil parameters (table 7.3). Moreover, the total porosity of soils was significantly correlated with aggregate stability at the 99% confidence interval (r=0.75, p<0.01). At the soil surface, aggregates under FW and PP were highly water-stable, with average percentages of WSA>2.8mm at 66% and 71% (figure 7.11). Contrastingly, the average percentages of water-stable aggregates of surface soils exposed to more intensive land uses were significantly reduced, with SPP soils having 11% and CC soils exhibiting just 6% (figure 7.11).

Surface soils with unstable aggregates are vulnerable to slaking when exposed to rapid wetting. Slaking involves the breakdown of aggregates into smaller aggregates or sub-units, and is prevalent where soil aggregates are not able to resist the pressure of entrapped air in capillaries or the pressures caused by swelling (Tisdall and Oades, 1982). Slaking can lead to the formation of an impermeable surface crust where it is accompanied by dispersion of resultant, smaller aggregates in the presence of swelling clays (Tisdall and Oades, 1982; Robinson and Phillips, 2001; Slattery and Bryan, 1994). The redistribution of dispersed clay particles can move into and block conducting pores that are responsible for storing and transmitting water (Tisdall and Oades, 1982; Slattery and Bryan, 1994).

Vegetation cover and management practice greatly influence the propensity for dispersive soils to crust when exposed to rainfall (Robinson and Phillips, 2001). Work undertaken by Robinson and Phillips (2001) recorded crust development on tilled land that was not detected on samples of aggregates obtained from beneath woodland and scrubland. Processes of surface crusting may be enhanced in cultivated soils, such as those under CC, which have little or no vegetative cover and are exposed to cycles of air-drying and rapid wetting, and the compactive forces of raindrops (Slattery and Bryan, 1994; Robinson and Philips, 2001; Hernández-Hernández and López-Hernández, 2002). Numerous workers have documented low aggregate stabilities in soils under arable land uses (Tisdall and Oades, 1982; Oades, 1984; Haynes *et al*, 1991; Hermawan and Bomke, 1997; Haynes and Beare, 1997; Haynes, 1999; Robinson and Philips, 2001). In the Robinson and Phillips (2001) study, crust development was inversely related to aggregate stability, which was most strongly determined by positive influence of organic matter and the negative effects of the percentage of exchangeable sodium (ESP).

According to Hernández-Hernández and López-Hernández (2002), the deleterious effects of cultivation on aggregate stability are dependent upon residue cover and the intensity of soil physical disturbance, in addition to the susceptibility of aggregates to disruption caused by wet and dry climate cycles. Hermawan and Bomke (1997) observed significant reductions in the structure of soils that were cultivated with winter cereals, due to prolonged wet conditions and a lack of surface cover over winter. In contrast to bare soil, the introduction of winter cover crops such as annual ryegrass, protected against aggregate breakdown during winter and improved soil structures after spring tillage operations (Hermawan and Bomke, 1997). In the context of the differential stability of aggregates, the surface soils of sites subject to more intensive land uses SPP and in particular CC, will be less resistant to structural deterioration and the development of surface crusts compared to FW and PP. Faster rates of wetting following simulated rainfall

in soil plots under SPP and CC compared to FW and PP, may serve to enhance processes of aggregate breakdown (figures 7.12 to 7.15).

Soil resistance to the development of surface crusts is largely a function of the rate and stability of soil aggregation. Mechanisms of aggregate formation are widely discussed in the literature (Tisdall and Oades, 1982; Oades, 1984; Oades and Waters, 1991; Jastrow, 1995; Bronick and Lal, 2005). The hierarchical model of aggregation, involving the bonding of primary particles into microaggregates (<250μm in diam.) that subsequently join together to form larger macroaggregates (>250μm in diam.), has been proposed by Tisdall and Oades (1982) and contradicts theories that advocate the development of microaggregates from macroaggregates that initially form around particulate organic matter (Jastrow, 1995; Bronick and Lal, 2005).

Any combination of processes may be operating at different scales to stabilize a single macroaggregate that will be governed by a range of factors. Fundamentally, soil aggregates are stabilised by organic carbon, in addition to soil biota, ionic bridging, clay and carbonates (Tisdall and Oades, 1982; Bronick and Lal, 2005; Jastrow, 1995). Tisdall and Oades (1982) present a range of studies that have observed correlations between the content of organic carbon in soils and water-stable aggregation. Haynes (1999) and Hernández-Hernández and López-Hernández (2002) have documented increases in the proportion of unstable aggregates under conventional tillage practices, compared to no tillage. Both studies observed subsequent reductions in the resistance of aggregates to seasonal climate changes that were attributable to reduced soil organic matter.

Soil microaggregates are resistant to rapid wetting and destruction by agricultural practices. This is primarily due to the presence of multivalent cations that act as strong bridges between organic colloids and clay particles, and to a lesser extent glues produced by bacteria, fungi and plant roots, such as polysaccharides (Tisdall and Oades, 1982;

Oades, 1984; Puget *et al*, 1998). Moreover, persistent organo-mineral complexes are a characteristic of the soil and hence are not influenced by changes in soil organic matter induced by agricultural management.

Alternatively, in the surface layers of many agricultural soils, organic matter plays a major role in forming and stabilising macroaggregates to withstand stresses caused by rapid wetting (Tisdall and Oades, 1982). The stability of macroaggregates in tested soils (>2.8mm) was shown to be fundamentally influenced by the presence of organic matter. The strong positive correlation between the percentage of organic matter and WSA>2.8mm for all four site data, was significant at the 99% confidence interval (r=0.75, p<0.01) (figure 7.24). Both soil organic matter (r=0.81) and aggregate stability (r=0.75) demonstrated strong positive relationships with total porosity (p<0.01).

More detailed analysis of the correlations between the content of soil organic matter (SOM) and aggregate stability for individual land uses, revealed strong positive correlations under FW (r=0.96, p<0.01) and PP (r=0.65, p<0.01), where maximum SOM contents were 13% and 18% (figures 7.25a and b). In contrast, SPP and CC soils exhibited no significant correlation between SOM content and aggregate stability (WSA>2.8mm) (figure 2.25c and d), where maximum SOM contents were 11% (table 7.6). This suggests that organic matter content was less important in stabilising aggregates in SPP and CC soils.

The average SOM content of all sampled soils was greater than 8%; sampled soils therefore exhibited high SOM levels for soils in the British Isles (Curtis *et al*, 1976). Furthermore, the lower SOM contents of SPP and CC were consistently higher than a range of agricultural soils, subject to very similar management practices that are presented in table 7.7 (Rowell, 1994).

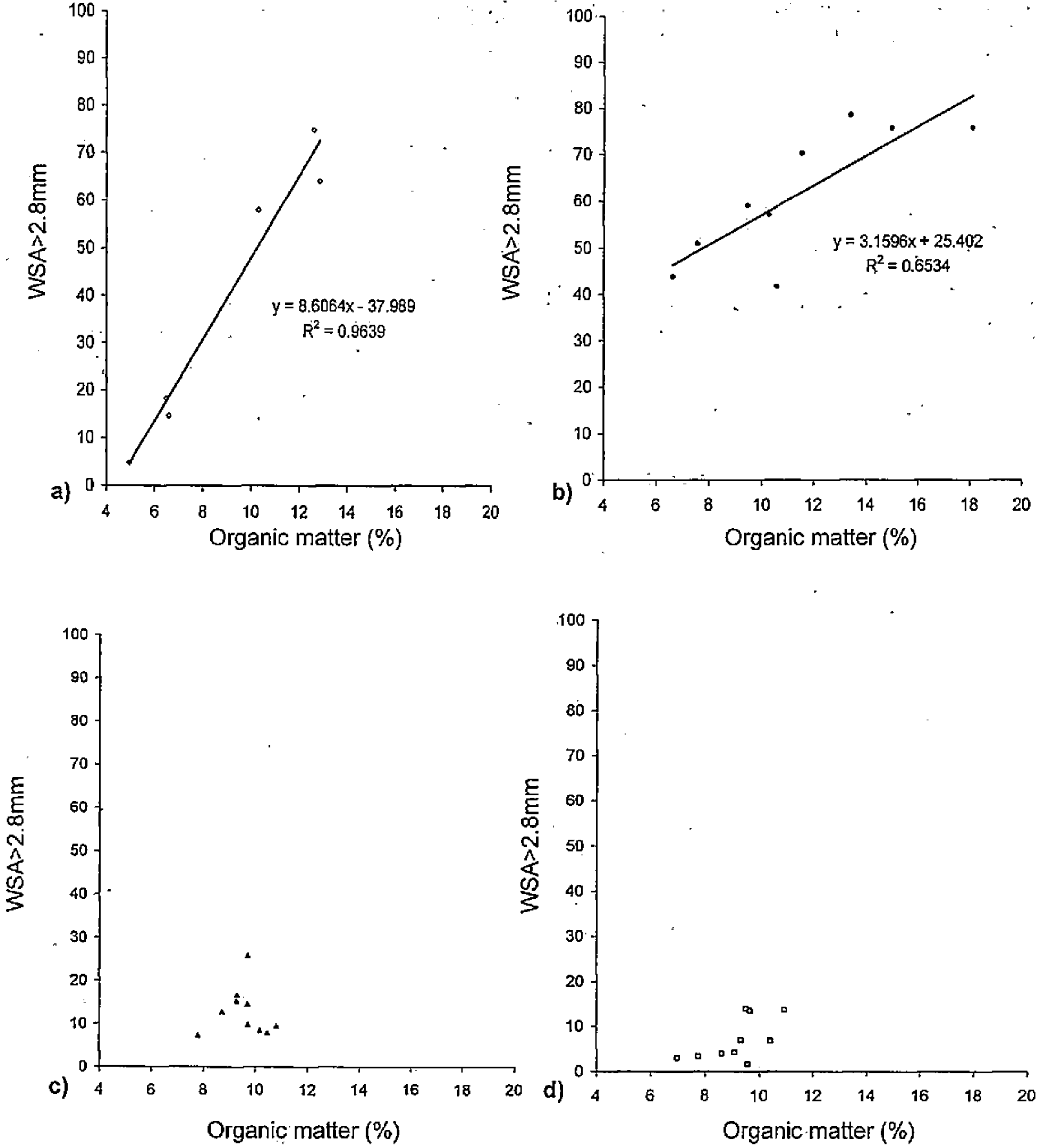


Figure 7.25 The relationship between soil organic matter content (%) and aggregate stability (WSA>2.8mm) under a) FW, b) PP, c) SPP and d) CC.

	Organic matter (%)		Mean annual rainfall (mm)	Clay contents (%)
	Continuous arable	Rotation*		
Boxworth, Cambridgeshire	3.31	3.70	550	45
Bridgets, Hampshire	3.38	4.26	780	25
Gleadthorpe, Nottinghamshire	1.54	1.81	600	5
Rosemaund, Herefordshire	2.63	2.93	650	6
Trawscoed, Dyfed	5.64	5.98	1180	27

*3 years grazed ley, 3 years arable

Table 7.8 The concentration of SOM in the topsoil (0-15cm) after 17 years' cropping under different rotations at six UK experimental husbandry farms (Rowell, 1994, pg 4).

Soils under FW and PP, which contained percentages of organic matter equal to or less than the SOM contents of SPP and CC, exhibited significantly higher aggregate stability (Figure 7.25). This is demonstrated in table 7.9 which displays the comparative percentages of WSA>2.8mm for FW, PP, SPP and CC soils that have approximately equal SOM contents.

Land use	SOM (%)	WSA>2.8mm (%)
FW	10.3	57.9
PP	10.6	41.7
SPP	10.8	9.4
CC	10.9	13.7

Table 7.9 The comparative aggregate stabilities (WSA>2.8mm) of soils with similar organic matter contents under FW, PP, SPP and CC.

Tisdall and Oades (1982) proposed that the stability of soil macroaggregates was better related to the amount of free organic materials, which represent temporary binding agents, such as roots and mycorrhizal hyphae, than the total organic matter content. Roots and hyphae enmesh fine particles into aggregates, produce decomposable organic residues or glues to stabilise them and support a large microbial population in the rhizosphere (Tisdall and Oades, 1982, Oades, 1984; Oades and Waters, 1991). In addition, intra-macroaggregate particulate organic matter helps to bind microaggregates to

macroaggregates by providing the nucleating sites for the growth of fungal hyphae, which are sticky and become encrusted with clay particles, and for additional microbial activities resulting in the deposition of polysaccharides (Tisdall and Oades, 1982; Jastrow, 1995). In this manner, the formation of macroaggregates promotes the formation and stabilisation of microaggregates because it protects soil organic matter and facilitates its accumulation (Oades, 1984; Emerson *et al*, 1986; Oades and Waters, 1991).

As a result of the dependency on growing root systems, the formation and stability of macroaggregates is extremely sensitive to changes in agricultural land management. Cultivated soils are inclined to have reduced amounts of organic matter compared with untilled sites, as a result of frequent exposure to physical disruption and rapid wetting, and the oxidation that occurs when cultivating tools shear soil aggregates and expose SOM to the action of microbial organisms (Tisdall and Oades, 1982). The rate of oxidation will depend upon a number of environmental parameters, including temperature and the availability of oxygen, water and nutrients (Bohn *et al*, 2001).

Arable practices that remove crop residues and cultivate soils to prevent plant growth, augment the decline of organic matter (Tisdall and Oades, 1982). Water-stable aggregation under soils that have been subject to arable land management, including SPP and CC, may have decreased considerably with decreasing organic matter given that cropping practices enhance the oxidation of organic carbon but more importantly, since roots and hyphae are decomposed and not replaced.

Laboratory examination of soil moisture, through the exposure of soil plots to simulated rainfall revealed greater spatial variability in the rate of wetting within FW and PP soil plots when compared with SPP and CC plots (figure 7.16). This variability was most pronounced under FW, whilst changes in soil moisture in CC soil plots were relatively spatially homogenous. Root networks in FW and PP soils were noticeably well developed

and served to tightly bind or aggregate soil particles, thereby forming larger soil clods with differential wetting rates that were more resistant to breakdown during laboratory handling. Under SPP, roots systems were poorly developed, whilst CC soils were devoid of roots and exhibited a loose and friable soil structure. SPP and CC soils showed faster rates of wetting as result of higher total porosity due to the creation of large numbers of macropores during the same degree of manual soil disturbance prior to experimentation.

Following a comparative study of the structural stability of 32 cropped soils, Benito and Diaz-Fierros (1992) concluded that soils from pasture and woodland were consistently more stable. This was primarily attributed to the effects of cropping on lowering of the soil organic matter content (Benito and Diaz-Fierros, 1992). The extensive root systems and fungal hyphae that are characteristic of growing trees and shrubs under FW and grasses under PP, serve to add organic residues to soils, retard the decomposition of organic matter and increase water-stable aggregation (Tisdall and Oades, 1982). Markedly higher aggregate stability in the surface horizons under FW and PP (figure 7.11) relates to the length of roots and hyphae and the fact that organic residues accumulate at the soil surface (Tisdall and Oades, 1982). Jastrow (1995) detected increased macroaggregation in tall grass prairie compared to arable systems, due to a combination of factors including the extent of root systems and hyphae, the presence of clays and polyvalent cations, the plant species, and the resistance of macroaggregates to cultivation and climate.

In addition to organic matter, the rate and stability of aggregation generally increases with clay surface area and CEC (Bronick and Lal, 2005). Clay swelling and dispersion are primarily controlled by clay mineralogy, the exchangeable ions (Ca^{2+} and Na^{+}) associated with the clay, electrolyte concentration and pH (Bronick and Lal, 2005). It is well documented that where present in sufficient concentrations, Na^{+} can accelerate soil structure deterioration and reduce soil permeability (Shainberg *et al*, 1991). The presence of exchangeable Na^{+} in the soil solution and at exchange sites can enhance particle

repulsion and break up aggregates by increasing the negative surfaces on clay particles (Bronick and Lal, 2005).

Cultivated soils tend to exhibit increased percentages of exchangeable sodium (ESP) (Cook and Dalal, 1992). The reasons for this are frequently not documented but may result from surface deposition of atmospherically derived Na^+ through precipitation, enhanced evaporation and concentration of Na^+ in cultivated soils, or through inputs of chemical or organic fertilizers (Haynes and Naidu, 1998; Bronick and Lal, 2005). For example, manure application can improve soil structures and increase the resistance of macroaggregates to slaking (Bronick and Lal, 2005). However, manures may also reduce the stability of soil aggregates to dispersion and affect soil pH by increasing the ionic concentration of Na^+, K^+ and Mg^{2+} (Haynes and Naidu, 1998; Hao and Chang, 2002).

ESP was positively correlated with the second ordination axis (table 7.3) and exhibited a negative correlation with aggregate stability ($r = -0.49$) (figure 7.24). ESP was significantly higher throughout the profiles of SPP and CC soils, compared to FW and PP soils (figure 7.9). Moreover, surface soils under CC were distributed alongside ESP and clay vectors on the ordination bi-plot. Under CC, the negative correlation between ESP and WSA>2.8mm was noticeably stronger ($r = -0.57$, $p<0.05$), and between ESP and total porosity there was a significant negative correlation ($r = -0.68$, $p<0.01$).

As a result of the dominance of Ca^{2+} in the exchange capacity, sampled soils maintained a near-neutral pH (figure 7.26). The ESP of all tested soils remained below accepted critical ESP levels (15%) for sodic soils (Rowell, 1994). However, Bohn *et al* (2001) have reported restricted water movement into and through soils as a consequence of the negative impacts of Na^+ on soil structure, where ESP was as low as 5%. According to Rowell (1994), low ESP Figures of 5% have been shown to reduce soil resistance to

rainfall and lead to retarded hydraulic conductivities as a result of aggregate breakdown and subsequent crust formation.

The effects of low ESP are associated with dilution of the soil solution concentration by winter rainwater and thus the reduced buffering capacity of lowered Ca^{2+} (Rowell, 1994). Irrespective of the mineralogy of the clay, but again depending upon the electrolyte concentration of the receiving water, the infiltration rate of soils with low ESP levels in the range 2-3% (Shainberg, 1981a) and 2-6% (Kazman *et al*, 1983) have been shown to exhibit extreme sensitivity to dispersion through both chemical and physical processes. According to work undertaken by Ternan et al (1998), in Central Spain, sediments with ESP values >1.5% were susceptible to the formation of pipes as a result of the effects on clay swelling.

In comparison to FW soils, the percentage of exchangeable calcium (ECP) was markedly lower in the subsurface horizon of CC, and negatively correlated with visibly higher ESP (r= -0.66, p<0.01). Under CC, ECP was positively correlated with SOM (r=0.79, p<0.01). On average all ESP values were >2% (figure 7.9). Maximum surface and subsurface ESP in soils under CC were equal to or greater than 5%, whilst the maximum ESP in SPP soils was 4%.

ESP exhibited a weak positive correlation with clay content (r=0.27) (figure 7.24). The clay content of SPP and CC soils were shown to be significantly higher than soils under FW and PP (H_0 rejected at the 95% confidence interval). There is limited evidence to suggest that CC soils may be more susceptible to structural deterioration resulting from clay swelling or dispersion. This is a result of higher clay content and the potentially enhancing effect of increased ESP levels, in conjunction with the indirect effects of reduced organic matter on lowering of the proportion of Ca^{2+} in the CEC. Higher ESP may increase the content of SOM required to maintain the stability and resistance of soil aggregates.

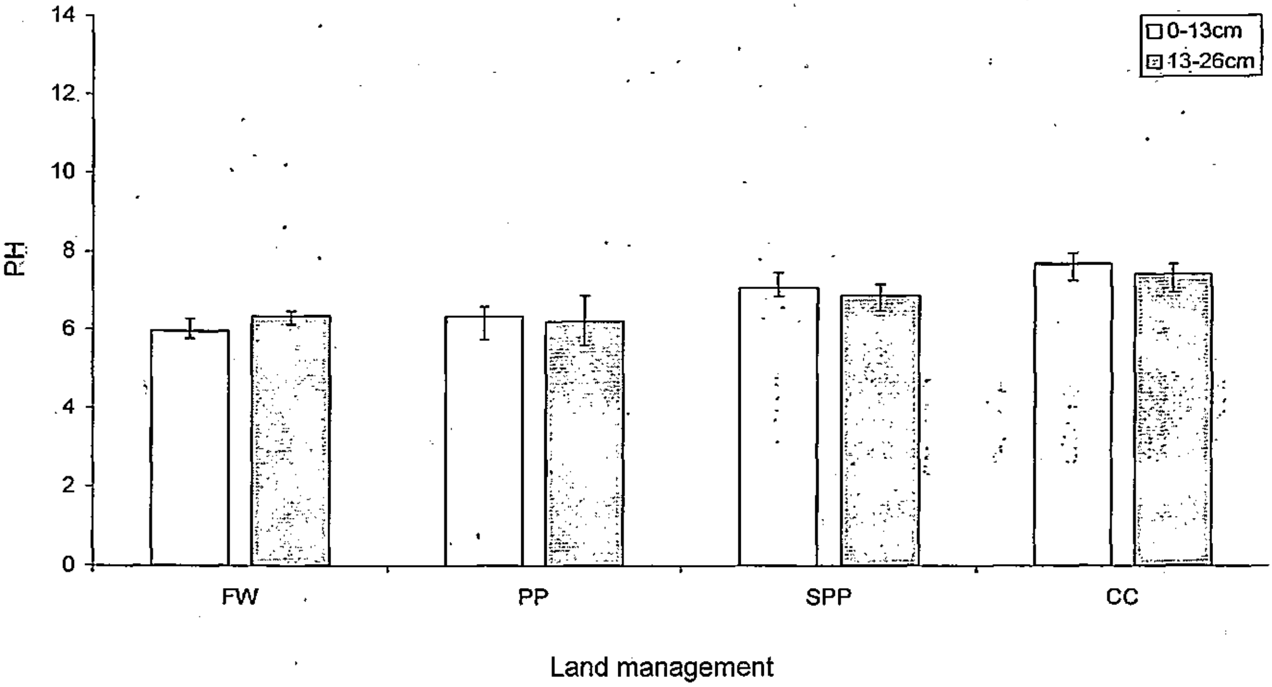


Figure 7.26 Average pH of surface (0-13cm) and subsurface (13-26cm) soils sampled from FW, PP, SPP and CC land uses. Error bars represent the range of all five samples.

Vegetation cover also imparts a significant bearing upon the hydrological properties of soils through the impacts of evapotranspiration on soil moisture content, the role of root systems in soil drainage and by protecting soil surfaces against rapid wetting and compaction from rain splash forces. Increased numbers of transmission pores and improved drainage in the topsoils of less actively managed sites under FW and PP, compared to SPP and CC may be explained in part by the capacity for preferential flow of water through macropores created by dense root systems that are a dominant characteristic of woodland and grassland land cover.

Differences in the intensity of management is believed to be controlling variability in the surface stabilities of soils underlying FW, PP, SPP and CC land cover types. In addition to trampling of the soil surface by grazing animals that can arise under pasture, arable practices can damage soil structures directly through compaction caused by farm machinery during cultivation, and by exposing the soil surface to rapid wetting and the

impacts of raindrops. The indirect effects of land management are related to changes to the organic matter content and dominant cations on the exchange complex, which influence soil sensitivity to compaction and processes of crust formation. The direct and indirect effects of cultivation on soil aggregate stability and hence, vulnerability to crusting, are summarised in figure 7.27.

Management of the vegetation cover through intensive grazing and cropping practices prevents the development of dense root systems that are essential for both soil structural stability and drainage. In particular, the resistance of surface soils to slaking and dispersion, and therefore crusting, is dependent upon extensive networks of roots and hyphae that play a key role in forming and stabilising macroaggregates. Stable macroaggregates provide the pore spaces required to store and transmit water. Furthermore, they protect soil organic matter and promote organic matter accumulation, thereby helping to stabilise potentially dispersive microaggregates (Tisdall and Oades, 1982).

Marked variability in the permeability of soils from FW, PP, SPP and CC, was characterised by rates of K_{sat} that decreased with increasing intensity of land management activity. Despite poor confidence in K_{sat} readings due to the limitations of the sampling and measurement technique adopted, the results were complemented by more subtle variations in the porosity of soils between the varying land uses. The latter was associated with lower surface porosity under SPP and CC, compared to PP and FW that was largely attributed to reduced structural stability.

Cultivated soils under SPP and CC may be more prone to the development of surface crusts following rapid wetting, as a result of reduced resistance to slaking and clay dispersion, and because these soils are exposed for prolonged periods over the wettest time of the year. Under pasture, SPP soils are less susceptible to crusting. However, in

relation to soils under PP, the reduced surface stability of SPP soils makes them more vulnerable to surface compaction.

Depending on the pattern of rainfall, the risk of infiltration-excess overland flow may be enhanced in cultivated soils, where structural deterioration at the soil surface and crust formation engender significantly reduced rates of soil infiltration. Sampled soils are shallow (45cm deep on average) and hence, in conjunction with slower conductivity rates, reduced numbers of transmission pores in subsurface soils under CC may enhance the relative risk of saturated-excess overland flow following prolonged wet conditions. On the basis of better structural stability and drainage, lower intensity management practices, including FW and PP, were thought to be less likely to generate surface runoff compared to soils under arable management.

Through field and laboratory testing of soil textural, structural and hydraulic properties, it is possible to distinguish a land management impact on the characteristics that control soil permeability and storage. By exploring the interrelationships between soil parameters, informed predictions can be made regarding the effects of different land management histories on the processes of runoff generation. Notwithstanding this, the limitations of the sampling techniques and laboratory procedures are such that, for many parameters such as K_{sat}, it is very difficult to replicate in-field conditions. Analysis of soil properties must therefore be comprehensive; this may facilitate cross-validation of soil property measurements. The inherent uncertainties in making assessments about runoff generation may be reduced through in-field observation and testing of dominant runoff processes, possibly using rainfall simulation or runoff plots that also incorporate seasonal variability in land cover and climate patterns. However, due to the large spatial and temporal variability of soil properties it is impossible to reliably upscale from soil property interactions determined at the field scale, to hydrological processes operating at the level of the hillslope.

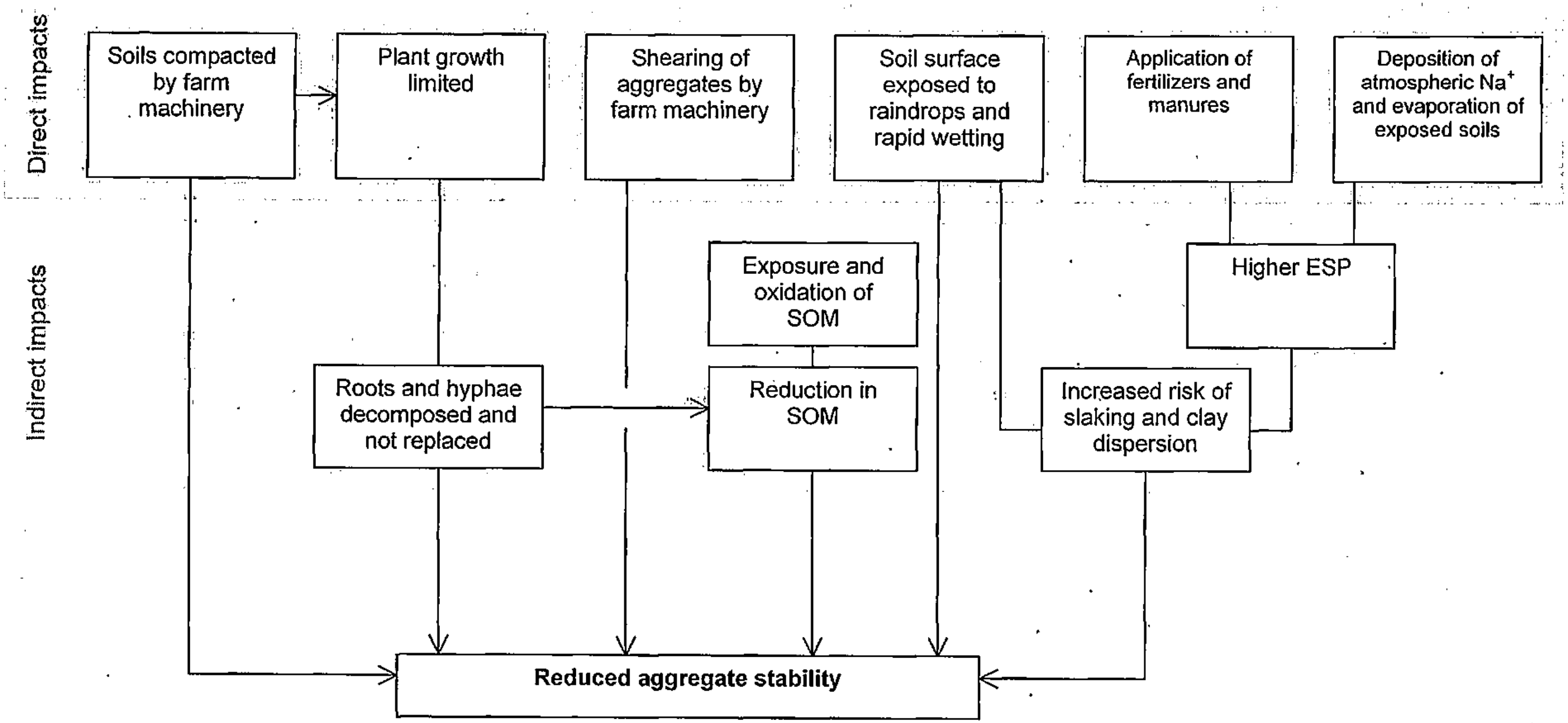


Figure 7.27 Interactions between arable land management practices and the soil properties governing soil aggregate stability

Summary

- The results from complementary spatial and temporal approaches in chapters 5 and 6 provided evidence of an enhanced land use effect on peak flows at the catchment scale.

- This chapter presents the methods of field testing (section 7.3) and laboratory analysis (section 7.4), and the results (section 7.5) of a field-scale analysis of the textural, structural and hydraulic properties of soils subject to varying intensities of land management.

- In section 7.6, the findings are discussed in relation to the impacts of land use on soil hydraulic properties. Less intensive land management practices including farm woodland (FW) and permanent pasture (PP) exhibited improved total porosities at the soil surface compared to more intensively managed land under semi-permanent pasture (SPP) and continuous cereal cultivation (CC).

- Subtle differences in the hydraulic properties of the soils under FW, PP and SPP and CC were related to the structural parameters of the topsoil, namely soil aggregate stability.

- Variability in soil structure and porosity was responsible for rates of surface and subsurface saturated hydraulic conductivity in the order FW>PP>SPP>CC.

- The stability of macroaggregates was related to the presence of organic matter, specifically the amount of free organic materials such as roots and mycorrhizal hyphae, which in cultivated soils, are decomposed and not replaced.

- CC soils were also thought to be more susceptible to structural deterioration resulting from clay swelling or dispersion as a result of higher clay content and increased ESP levels, in conjunction with the indirect effects of reduced organic matter on lowering of the proportion of Ca^2+ in the CEC.

- The limitations of techniques of field sampling and laboratory analysis are such that soil surveying is not accurate and cannot fully represent in-field variability. However, cross-comparison of a range of soil property data can help to validate results.

The following chapter (8) assimilates the results of both catchment scale (Chapters 5 and 6) and field scale (Chapter 7) approaches. It discusses the key findings in relation to contemporary research and understanding of the effects of land use changes on peak flow processes operating across multiple scales.

Chapter 8

Discussion and synthesis: The effects of land use change on hydrological response (Part V).

8.1 Introduction

Understanding the causes of extreme river flows has become the focus of growing research efforts (Bye and Horner, 1998; Mance *et al*, 2002; Marsh and Dale, 2002; Hall *et al*, 2005). This interest has arisen in response to perceived increases in high impact flood events over the last decade and broad scale recognition of the enhanced flood risks associated with future climate change predictions. In parallel, major concern about existing levels of flood prevention has moved to the forefront of the UK national environmental policy agenda. The need for effective and sustainable measures to prevent and mitigate flooding has become evermore acute. This is encapsulated in the governments new flood strategy document entitled 'Making Space for Water' (Defra, 2004), which emphasises the need for a new approach to flood management that combines conventional structural flood defences with non-structural measures, such as rural land management change.

Over the last 20 years, the use and management of rural landscapes has been characterised by a significant intensification of farming, coupled with urban expansion and the development of floodplains (Newson, 1997; O'Connell *et al*, 2004). This has compelled scientists and decision-makers to give greater consideration to the role of such land use changes in flood incidence.

Due to the inherent complexity of catchment systems in terms of the temporal and spatial variability of flow processes and pathways, a sufficient understanding of the importance of

land use in flood peak propagation has persistently evaded hydrologists. As a result, insufficient attention has been paid to the function of land management in moderating flood flows. Land use and its effects on soil condition are the only environmental components driving a catchment system that decision-makers are capable of exerting a significant control over. Considered modification of the interaction between these land surface parameters, represents a practical measure by which the short term impacts of climate change on flooding might be addressed.

In 1993, the Ministry of Agriculture, Fisheries and Food (now Defra) endorsed a strategic catchment-wide approach to flood defence (O'Connell *et al*, 2004). This has been recently manifested through the use of Catchment Flood Management Plans (CFMPs), which form an integral component of catchment planning and flood management aspects of the Water Framework Directive (WFD) (O'Connell *et al*, 2004). It is vital that decisions made in catchment flood management are underpinned by a comprehensive understanding of the impacts of current land management on runoff generation and river flows. The results presented in this thesis build upon existing knowledge of the hydrological impacts of land use and management, and contribute to fresh debate surrounding land use effects on peak flows. At multiple scales (plot, field and catchment) there is evidence to suggest a significant human impact on hydrological functioning and peak flow responses to storm events, as a consequence of discrete changes in land management practices.

8.2 Evidence of agricultural land use change

Since the Second World War, changes in planning and agricultural policy have played a principal role in initiating changes in land use in the countryside. Modern agriculture has been shaped by the Agriculture Act of 1947, which sought self-sufficiency in food production, and through the support available under the Common Agricultural Policy (CAP) following integration into the EC in 1973 (O'Connell *et al*, 2004) (figure 8.1).

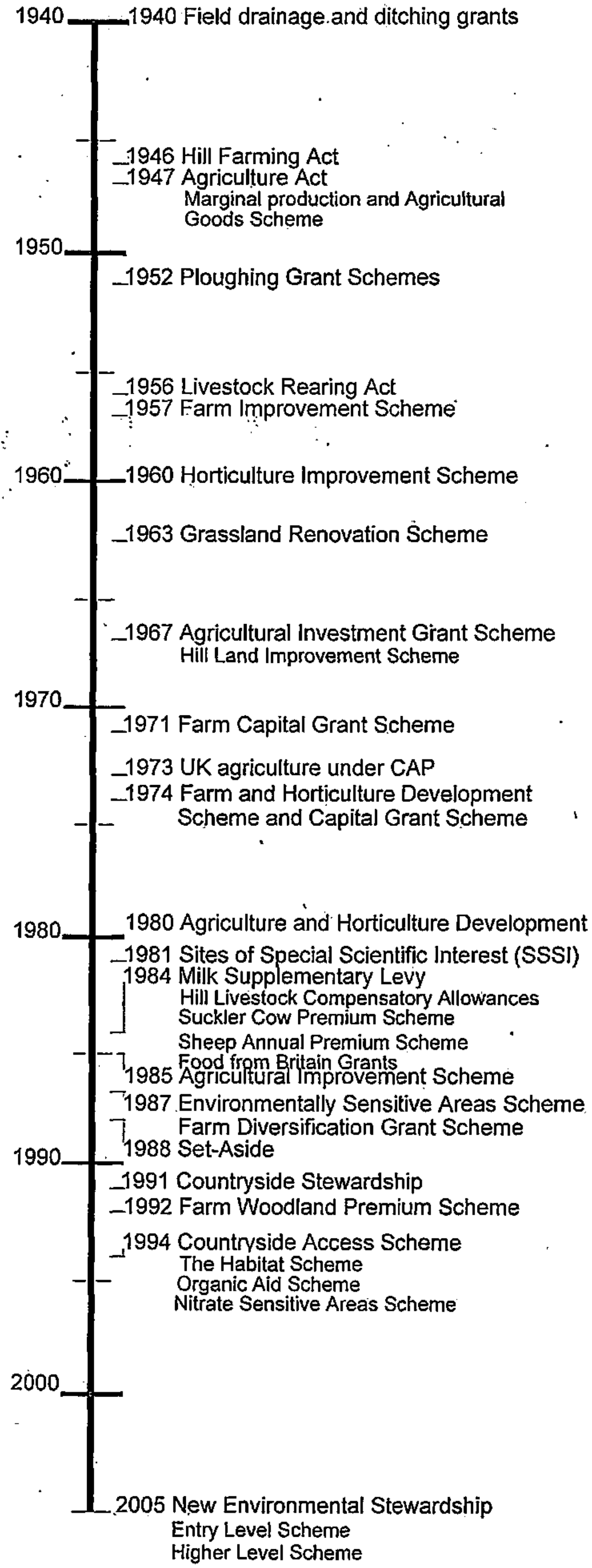


Figure 8.1 Timeline of key agricultural policy measures introduced.

Political devices including capital incentives and taxation reliefs, which were aimed at expanding output by reducing the private costs of adopting new technologies and maintaining farm incomes through price fixation and barriers to trade, facilitated the specialisation and regional concentration of farming (Lowe *et al*, 1994). A range of schemes were introduced which were developed to direct agriculture towards the intensification of production (figure 8.1). By diversifying the mechanisms for financial support, the government developed a political framework which compelled the adoption of exploitative and environmentally damaging land uses (Lowe *et al*, 1994).

In a recent review of changes in agricultural land management practices over the last 100 years, a number of prominent trends were observed (O'Connell *et al*, 2004). Grants made available after the 1940's facilitated an increase in the extent of field under drainage (chapter 2, figure 2.5). Changes in production agriculture were characterised by a rapid rise in the areas of specific cereal crops and the loss of permanent pasture. In particular, between 1950 and 2000, barley production increased from 719,000ha to 1,101,000ha, peaking at over 2,000,000ha in 1970 (O'Connell *et al*, 2004). Over that time, wheat cultivation also expanded, from 1,003,000ha to 1,996,000ha (O'Connell *et al*, 2004). These changes coincided with a progression away from planting in spring, towards autumn and winter sown cereals. During the period 1962 to 1998, for example, the percentage of winter sown wheat increased by 27% to 97%, whilst the percentage of winter sown barley rose by 55% to 65% (O'Connell *et al*, 2004).

Mechanisation led to the increased use of on-farm machinery and changes in farm trafficking. Moreover, the removal of hedgerows and infilling of ponds increased the area of land in production and caused an enlargement of fields (O'Connell *et al*, 2004). A 50% reduction in hedgerows has been recorded since 1945 (Robinson and Sutherland, 2002). The use of grassland also intensified, resulting in a 60% rise in the numbers of sheep between the 1960's and 1980's, and a threefold increase in cattle numbers over the

period 1866 to 1980. Subtler changes in grazing practices were associated with extended grazing seasons and a switch in feed crops from hay to maize silage (O'Connell *et al*, 2004).

Growing awareness of the environmental impacts emanating from agricultural change, namely reduced biodiversity and water quality brought about a shift in policy emphasis after the mid 1980's. Agri-environmental land use options gradually became integrated into agricultural policy, particularly after the MacSharry Reforms of 1992 (Moxey *et al*, 1998). Set aside was first introduced in the late eighties (figure 8.1) and has since risen from 110,000ha in 1990 to 567,000ha in 2000 (O'Connell *et.al*, 2004).

National trends in agricultural land management practices were locally evident in the catchment of the River Camel, north Cornwall. Sullivan *et al* (2004) undertook a long-term study (1969-2000) of land use changes in the catchment which revealed a gradual intensification of lowland cereal cultivation until 1997 (Chapter 6). The introduction of maize by 1979 and increases in the areas of wheat and barley cultivation, gave rise to a 70% expansion in the total area of land under production (figure 8.2). After 1997, a decline in the percentage cover of cereals by 1.8% was attributed to the introduction and take-up of set aside (figure 8.2).

Over the period 1969 to 2000, the maximum stocking density of grazing animals in exposed upland areas of the catchment progressively increased from 1.05 LUha-^{1} to 1.5 LUha-^{1} (Sullivan *et al*, 2004). Studies undertaken in nearby Dartmoor revealed an increase in the numbers of sheep on unenclosed hill areas from about 20,000 in 1952 to 142,000 in 2000 (Meyles *et al*, 2003). The rise in stocking rates was attributed to the availability of headage payments for ewes and cattle, referred to as the Hill Livestock Compensatory Allowance (figure 8.1) (Meyles *et al*, 2003).

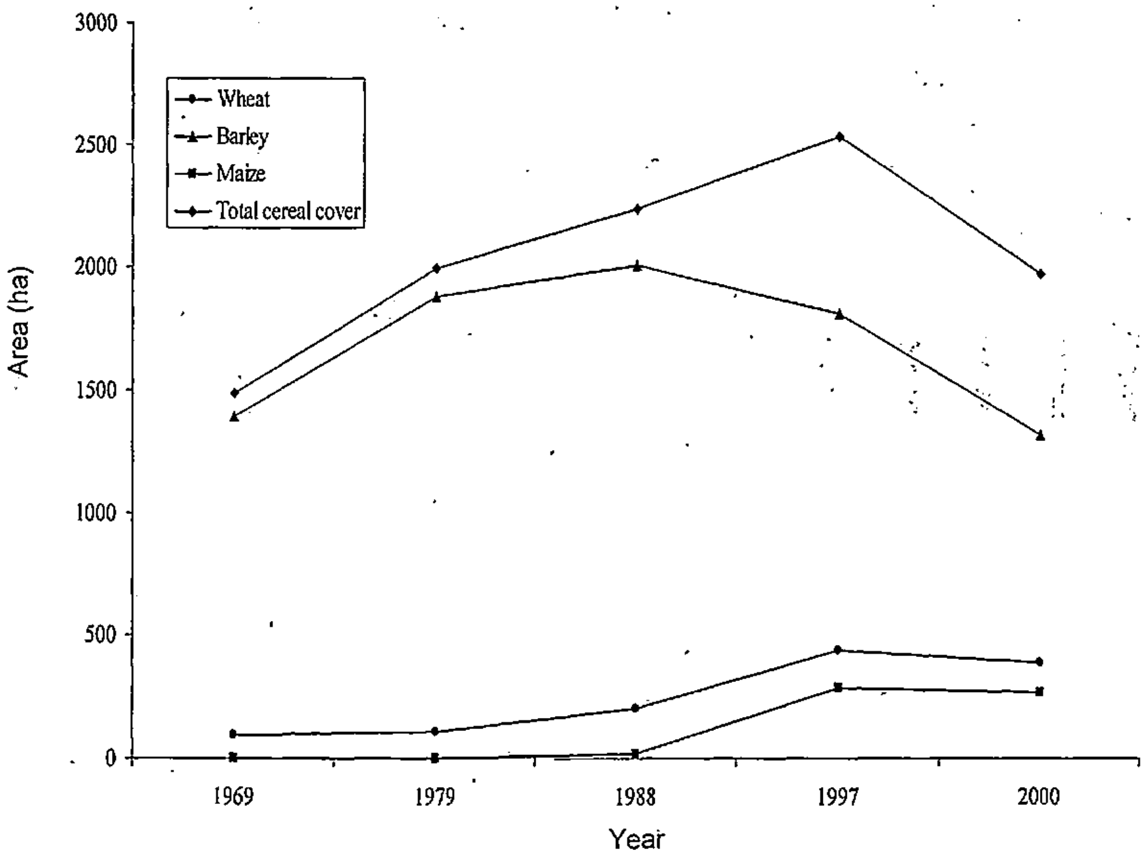


Figure 8.2 Changes in the area of land under cereal production in the Camel catchment, over the period 1969-2000 (Sullivan *et al.* 2004).

8.3 Evidence of land use impacts on soil hydraulic processes

The results of a field investigation presented in chapter 7 revealed subtle differences in the properties of soils subject to varying intensities of land management. Due to the limitations inherent in techniques of soil sampling and analysis, it is unwise to formulate predictions regarding the nature of runoff by extrapolating from these results alone. Notwithstanding this, these data contribute to a growing body of evidence of a link between changes in agricultural land management and increased runoff production. Largely in the context of observed differences in the structural parameters of the topsoil, soils subjected to contrasting 30-year histories of land management activity (CC = continuous cereal cultivation, SPP = semi permanent pasture, PP = permanent pasture

and FW = farm woodland) were thought to be associated with different levels of risk of runoff generation.

In general, more actively managed sites (SPP and CC) posed the greatest risk of generating runoff and contrasted with sites under low management activity (PP and FW), where the risk of runoff production was thought to be reduced (section 7.6). These findings were largely consistent with an assessment of the relative runoff risk associated with various land uses, proposed by Armstrong *et al* (1990) (figure 8.3).

Least risk	Forestry/woodland
↓	Permanent pasture
	Spring cereals
	Autumn cereals
	Short term grass ley
Greatest risk	Sugar beet/potatoes/horticultural crops

Figure 8.3 Relative erosion/runoff risks of various land uses (Armstrong *et al*, 1990).

Soil hydrology is governed by a range of parameters including texture, structure, hydraulic conductivity and pore size characteristics (chapter 7). Characterisation of these factors through field and laboratory testing provided evidence of variability in soil condition and drainage, as a result of differences in the level of impact associated with individual land management practices. In particular, variability in the structure and porosity of soils underlying tested land uses was responsible for rates of surface and subsurface saturated hydraulic conductivity that were in the order FW>PP>SPP>CC (figure 7.23).

8.3.1 Non-agricultural land (FW)

Non-agricultural vegetation, such as woodland, is much less susceptible to runoff than agricultural land cover types, on account of high infiltration rates and an effective soil

cover (Calder, 1992). Carroll *et al* (2004); measured infiltration rates in areas planted with young trees that were 60 times higher than adjacent grazed pastures. The average hydraulic conductivity of the surface horizon under FW was 40% higher than PP and 75% higher than CC (figure 7.23). The average subsurface conductivity of FW soils varied marginally from the surface horizon and was consistently higher than the other agricultural land uses (PP, SPP and CC).

The enhanced permeability of woodland soils is largely the consequence of increased numbers of transmission pores that are essential for soil drainage (Landon 1984), and the likely function of root systems as large pores or conduits for concentrated flow (Fitzpatrick, 1983; Rowell, 1994). The average transmission storage of surface and subsurface soils under FW was 27% and 26% respectively, exceeding equivalent transmission pore volumes in CC soils by 7% (surface) and 10% (subsurface) (figure 7.16).

The structured canopy of trees and shrubs not only protects the soil surface, but it also provides an important source of litter for the accumulation of soil organic matter (SOM). Improved water-stable aggregation in the topsoil under FW was thought to be the product of higher levels of organic matter in the surface horizon, particularly the binding and stabilising influence of complex root systems and fungal hyphae, which impacted positively on the stability of soil macroaggregates. Under FW, a near perfect correlation was observed between SOM content and aggregate stability (percentage of WSA>2.8mm) (r=0.96, p<0.01) (figure 7.25a). Greater spatial variability in the moisture readings and wetting rates of woodland soil plots, compared to SPP and CC plots during simulated rainfall, was attributed to the presence of roots and their role in maintaining soil aggregates during rapid wetting (figures 7.16 and 7.17).

8.3.2 Land managed for agriculture (PP, SPP and CC)

The risks of agricultural practices causing management problems such as ponding, water logging and high runoff and erosion, will vary according to the hydraulic properties of underlying soils and the soil moisture conditions under which such practices are carried out. The comparative surface conductivities of agricultural land management practices, PP, SPP and CC, directly corresponded with relative infiltration rates for old permanent pasture (60mmhr-^{1}), 3 or 4 year old pasture (30mmhr-^{1}) and cultivated bare soil (9mmhr-^{1}) that were documented by Holtan and Kirkpatrick (1950). Rates of soil infiltration and drainage are fundamentally dictated by the variable impacts of individual agricultural activities on the strength and stability of soil aggregates. This will ultimately determine the resistance of the soil to compaction and dispersion (Greenland, 1977; Barzegar *et al*, 1997).

a) Permanent Pasture (PP)

Under permanent pasture, land management may impact upon vegetation cover and soil condition through the effects of grazing animals. Sheep and cattle alter the composition of the vegetation, whilst animal hooves or other factors can lead to poaching of the soil surface (Greenland, 1977; Sansom, 1999). Notwithstanding this, managed grazing allows root and faunal activity to positively influence soil porosity. In comparison to recently worked soils under CC and SPP, soils under PP were undisturbed over a prolonged period (30 years).

Organic matter is able to accumulate under grass pastures as a result of reduced soil exposure and disturbance, and because the annual addition of phytomass is greater than for cultivated fields (Greenland, 1977; Shepherd *et al*, 2001). Organic matter improves the formation and stability of larger macroaggregates, thereby helping to increase soil

resistance to trampling and compaction and lower the risk of soil structural deterioration (section 7.6). Much of the aggregation will occur in the topsoil due to the length of roots and surface accumulation of organic residues (Tisdall and Oades, 1982).

In addition to surface soils under FW soils, PP soils exhibited good structural stability on wetting (figure 7.11). This was particularly discernable at the soil surface where 71% of aggregates were water-stable. At 14%, the average SOM content of surface soils under PP was 5% higher than SOM levels under SPP and CC. The surface soil structure under PP was relatively well developed; the average total porosity was found to be 12% higher than SPP soils and 16% higher than soils under CC. PP soils were thought to be at lower risk of runoff than more intensively managed sites under SPP and CC, as a consequence of enhanced infiltration and drainage associated with higher surface porosities, namely greater numbers of transmission pores (figures 7.19 and 7.22).

These findings are supported by Fullen (1991), who observed very little runoff from plots inserted into permanent grassland, even on steeper slopes. Moreover, in certain soil and landscape conditions, permanent grassland has been advocated as a runoff mitigation measure. In the South Downs, southern England, reversion of winter cereal fields to permanent grassland through set aside was effective in preventing further episodes of flooding, by reducing the contributing area and disconnecting runoff from valley floors (Evans and Boardman, 2003). In Belgium, Verstraeten *et al* (2001) predicted a 20-25% reduction in the risk of water erosion as a result of a 10% land use change to grassland.

b) Continuous cereal cultivation (CC) and semi-permanent pasture (SPP)

It is widely acknowledged that cultivated soils suffer lowered infiltration and hydraulic conductivity, in addition to poor soil storage (Cook and Dalal, 1992; O'Connell *et al*, 2004). Throughout the soil profile, CC soils exhibited the lowest average total porosity of all land

use practices (figure 7.18). The average soil moisture content of CC soil plots at 'near-saturation' was 5% lower than FW plots following applications of simulated rainfall (figures 7.12-7.15). Soil particles under CC were weakly aggregated. Aggregate stability tests using wet sieving showed averages of just 6% WSA>2.8mm at the soil surface and 8% WSA>2.8mm in subsurface horizons (figure 7.11).

Cultivation practices exert a direct impact upon soil structure and water movement through the physical effects of ploughing and compactive farm machinery on the breakdown of soil aggregates (Silgrim and Shepherd, 1999), and by disrupting the continuity of macropores (Harris and Catt, 1999). Indirectly, cultivation can have a profound effect on soil structural deterioration through the depletion of SOM to levels that prevent a stabilizing impact on soil aggregates (Grieve, 1980; Whitbread *et al*, 1998; Shepherd *et al*, 2001; Dalal and Chan, 2001 and Francis *et al*, 2001) (figure 7.27).

Cultivation is exploitative and causes a decline in SOM content through the removal of a vegetative cover, which reduces inputs of organic matter, increases the activity of soil micro-organisms, stimulating oxidation (Golchin *et al*, 1995). This decline is aggravated if crop residues are removed (Greenland, 1977; Tisdall and Oades, 1982). Dalal and Chan (2001) estimated that greater than 60% of SOM had been lost in the top 0-0.1m of the soil, following 50 years of cropping in the Australian cereal belt. Levels of SOM in all sampled soils were typically high for soils in the British Isles (Curtis *et al*, 1976). The SOM content of CC soils was 9% on average for both surface and subsurface samples, compared to 12% and 14% in the topsoil's of FW and PP (figure 7.10). The relationship between small percentage reductions in SOM and significantly lowered water-stable aggregation in CC topsoil was related to the lack of roots and hyphae, which through arable practices are decomposed and not replaced (section 7.6).

Small reductions in SOM content can exert a disproportionately large effect on infiltration rates by reducing soil resistance to sealing (Le Bissonnais and Singer, 1993). Frequent cultivation can lead to the formation of a thin crust or impermeable seal at the soil surface. This is often the result of the mechanical disintegration of soil aggregates by rapid wetting and prolonged exposure to the beating action of raindrops (Tisdall and Oades, 1982; Slattery and Bryan, 1992; Slattery and Bryan, 1994), and the chemical dispersion of clay particles (Levy *et al*, 1993). Both mechanisms can lead to the formation of a compacted layer of low permeability at the surface, through the suspension and rearrangement of fines that can move into and block conducting pores (Tisdall and Oades, 1982; Kazman *et al*, 1983; Levy *et al*, 1988; Lobe *et al*, 2001).

Of the range of soil properties governing the susceptibility of soils to crusting, including texture, clay content, the type and concentration of cations and $CaCO_3$, organic matter content (Tisdall and Oades, 1982) and the percentage of exchangeable sodium (ESP) (Emerson, 1967; Shainberg, 1992) are most frequently cited as playing a major role (Shainberg and Levy, 1994; Le Bissonnais, 1996; Phillips and Robinson, 1998). ESP has been repeatedly linked to reduced aggregate stability and the formation of surface seals through the enhancing effect on clay dispersion (Kazman *et al*, 1983; Shainberg and Levy, 1994). This process is particularly prevalent in fine textured soils containing high amounts of swelling clays. The dispersion and swelling of clays is less common in soils, such as those tested, where Ca^{2+} is the dominant exchangeable cation (Greenland, 1977; Tisdall and Oades, 1982). However, a number of studies have demonstrated that even in stable soils and at relatively low levels, ESP may exaggerate clay dispersion (Shainberg *et al*, 1981; Kazman *et al*, 1983; Rowell, 1994; Bohn *et al*, 2001).

There is limited evidence to suggest that slightly higher ESP levels throughout SPP and CC soils maybe cause them to respond more sensitively to land use effects (section 7.6). On average, all ESP values were higher than values quoted for sediments in Central

Spain that were susceptible to the formation of pipes (Ternan *et al*, 1998). In particular, CC soils may be more susceptible to structural deterioration through processes of slaking and dispersion, as a consequence of higher ESP levels, combined with the indirect effects of reduced organic matter on lowering of the proportion of Ca^{2+} in the CEC. Higher ESP may increase the threshold SOM content required to maintain the stability and resistance of soil aggregates.

Crust development is particularly associated with the production of autumn-sown cereals. This practice requires machinery on the land during poor conditions and offers less opportunity for the development of a vegetation cover to protect soils from rapid wetting and the impact energy of raindrops over the wettest part of the year (O'Connell *et al*, 2004). CC soils exhibited the greatest risk of runoff generation, on account of the reduced resistance to structural deterioration, coupled with the effects of enhanced exposure and disturbance. Runoff may be produced as a result of lowered soil infiltration and storage through either an infiltration-excess or saturation-excess process, depending upon antecedent conditions and the intensity, frequency and duration characteristics of the prevailing rainfall.

The percentage of WSA>2.8mm for all SPP soils fell in the range 8-11%, indicating poor aggregate stability. Lowered permeability in surface soils under SPP was chiefly attributed to numbers of transmission pores that were 7% lower than PP soils and 11% lower than surface soils under FW (figure 7.19). Soils subject to rotation pasture (SPP) were thought to be more susceptible to runoff than PP and FW soils, through a dominant infiltration–excess mechanism. It was anticipated that notable compaction of the soil surface under PP resulted from the reduced resistance of soil aggregates to trampling by grazing animals. The compactive effects of sheep and cattle on reduced infiltration and increased surface runoff have been documented by Heathwaite *et al* (1990) and (Sansom, 1999).

Davies *et al* (1973) have also reported significant reductions in infiltration from plots that were subject to trafficking animals.

Field sampling has provided some evidence to suggest an enhanced land management impact on the risk of runoff generation, through the influence of activity on soil structural stability and porosity. Soil sampling was undertaken in dry field conditions. The risk of runoff may be exacerbated under CC and SPP during winter months, as a result of heightened potential for soil compaction and the development of surface crusts in wet conditions.

8.4 Evidence of land use impacts on peak flows

A range of studies have reported runoff generation at plot and field scales in response to land use impacts on vegetation cover and soil properties. In particular, increased runoff has been associated with specific arable practices including among others, poor crop cover and soil exposure (Fullen and Reed, 1986; Chambers *et al*, 2000), compacted tramlines from tractor wheelings (Robinson and Naghizadeh, 1992) and up and down cultivation lines (Quinton and Catt, 2004).

Runoff from fields or plots under pasture has been observed where heavy trampling has resulted in soil compaction (Greenwood and McKenzie, 2001) and changes in species composition, vegetation cover and biomass, which have altered essential soil properties, namely nitrogen and soil organic matter contents (Allsopp, 1999) and patterns of soil moisture (Meyles *et al*, 2003). Intensively grazed sheep may contribute to high soil bulk densities, lowered soil porosity and changes in soil moisture characteristics by significantly reducing the throughput of organic matter (Meyles *et al*, 2003). The addition of organic matter will therefore decrease bulk density.

Proof of a link between small scale runoff processes and runoff generation, and flooding problems that are manifest at larger scales is much more limited. Sediment-laden runoff from arable fields has been associated with frequent episodes of so called 'muddy flooding' in southern England (Evans and Boardman, 2003) and Belgium (Bielders *et al*, 2003). In a review of similar events across north-western Europe, Boardman *et al* (2003) proposed two scenarios for agriculture-induced flooding that were governed by climate patterns, antecedent wetness and arable practices.

In the first scenario, winter flooding resulted from wet soils and the cultivation of winter cereals. The second scenario involved summer flooding following thunderstorm activity and runoff generated form row crops such as sugar beet, maize and potatoes (Boardman *et al*, 2003). In this case, flooding was largely related to localised runoff from high risk fields. More recently, Hall *et al* (2005) were able to conclude that modest changes in farming practices had significantly increased flood flows in the Red River catchment in west Cornwall. Repeated flooding of the nearby village of Crowlas was partly attributed to moderate levels of soil compaction and subsequent runoff from agricultural fields (Hall *et al*,.2005).

In the UK, very few studies are available which have attempted to identify and explain the effects of catchment scale land use change on over-bank flooding resulting from peak river flows. Plynlimon in Wales (Kirby *et al*, 1991), Balquidder in Scotland (Calder, 1993b) and Coalburn in England (Archer, 2003) are typical of existing catchment studies, which have tended to focus on the hydrological impacts of upland afforestation and drainage, and the differences in yields between predominantly grassland and forested watersheds. Similarly, the modelling work of Calder *et al* (2003) supports a reduction in the recharge characteristics of forest compared to grassland.

In the River Severn catchment, extensive land use changes on higher ground were shown to cause increases in flood peaks during modelling work by Gilman (2002). Investigations into the effects of field under drainage on river flows were undertaken by Robinson (1990), but proved to be largely inconclusive. Empirical studies carried out by Sansom (1996) have pointed towards an enhanced peak flow response as a result of increased stocking in the headwaters of the Swale and Ure catchments. However, no quantitative evidence was provided to substantiate these claims.

The complexity of hydrological, physical and biogeochemical interactions within a catchment system makes it very difficult to scale-up from smaller scale, process-based studies (Gove, 2001). Joel *et al* (2002) for example, calculated measured quantities of runoff from 50m plots that were just 40% of the volume of runoff produced from smaller soil plots (0.25m) during continuous runoff. At different scales, the generation of runoff will be variably dependent upon detailed feedback mechanisms between land use, soil hydraulic conductivity, microtopography and surface condition, which can change over time during the course of a rainfall event (Puigdefabres *et al*, 1999).

At larger scales, the details of catchment systems are attenuated. Catchment scale investigations, including the approach adopted in this thesis, often incorporate environmental data that has undergone considerable averaging out. Hence it is very difficult to disentangle the precise impacts of land use on the hydrological processes of catchments demonstrating extreme runoff responses.

More generally, using the statistical approach adopted in this thesis, it is possible to distinguish a dominant land use control on streamflow responses to large storm events. The results of statistical testing of regional trends in environment and runoff characteristics at the catchment and storm event scales indicate that the influence of hydraulic parameters, encompassing topographic and climatic drivers, is subordinate to

the effects of interactions between land surface characteristics, including land use, soil and geology.

These findings are consistent with the catchment-scale work undertaken by Fohrer *et al* (2001), which demonstrated the sensitivity of flood risk to changes in agricultural land uses, such as conversion to grassland from forestry. In a similar study, Bormann *et al* (1999) reported amplified peak flows as a result of a 180% increase in simulated runoff under a scenario of barley production that was attributed to soil exposure and compaction.

In chapter 5, variance partitioning (Borcard *et al*, 1992), employing direct ordination (i.e. RDA) was used to examine the correlations between two multivariate storm runoff datasets and the environmental characteristics of 48 catchments. Results presented in figure 5.28 indicated that measured land surface variables including land use, geology and soil HOST classes, explained approximately half (49.6%) of the variance in the runoff for the four storm events (runoff set one, R1). This finding was supported by partitioning of the variance in the five runoff bin class dataset (runoff set two, R2), where land surface parameters exhibited an explanatory power of 55.8% (figure 5.29). In both tests, the greatest proportion of the explained variance in runoff was attributed to land use parameter subsets, in conjunction to the combined explanatory power of land uses with soil HOST classes (figures 5.28 and 5.29) and geology (figure 5.29).

Prior to partitioning, the results of RDAs revealed that the first four ordination axes explained a significant proportion of the variance in R1 (84%, $p<0.002$) and R2 (78%, $p<0.001$). In each analysis, axes one represented the main axis of variation in the runoff data and accounted for 74% and 42% of the explained variance for R1 and R2 respectively (tables 5.30 and 5.34). Ordination triplots in figures 5.26 and 5.27 illustrate the distribution of catchments along axis one in relation to the key environmental drivers and runoff factors. Axis one in figure 5.27 appears to be positively correlated with

environmental parameters that are typical characteristics of upland areas, such as heathland (ODSH) and grassland (GRS). Environmental parameters that are commonly associated with lowland areas, including arable production (AR_CER and AR_HORT), exhibited a negative correlation with this axis.

Running separate analyses on 'upland' and 'lowland' parameters assisted identification of the environmental gradients most strongly correlated with axis one. The terms 'upland' and 'lowland' are not definitive but used here to arbitrarily categorise environmental parameters. Therefore, catchments located close to 'upland' or 'lowland' vectors on the ordination plot did not necessarily comprise upland or lowland catchments by nature or according to some established criteria. The length and direction of vectors on resultant triplots, in addition to inter-set correlations and subsequent variance partitioning, provided a range of evidence to suggest that key land surface parameters were significantly influencing patterns in peak flow runoff volumes. These were broadly similar for both R1 and R2 datasets.

Of the parameter subsets positively correlated with axis one (figure's 5.31 and 5.35), land use independently explained the greatest proportion of the variance in the runoff data. Specifically, open dwarf shrub heath (ODSH), woodland (WOOD) and grassland (GRS) were associated with higher storm runoff volumes and medium to high runoff bin classes three, four and five. The soil HOST class HAC was responsible for explaining 13% (R1) and 8% (R2), and combined with land use, explained a further 8% (R1) and 10% (R2). RDA performed on 'upland' environmental data and runoff data set R2, indicated the importance of geology classes, namely CHER, MU_SLT and BREC_C, which discretely explained 15% of the variance in runoff and jointly with land use, explained a further 7%. In comparison, topographic characteristics, including SLOPE<30 (R1) and SLOPE<12 (R2), explained just 1% (R1) and 4% (R2) of the variability. This is represented in figures

5.31 and 5.35 by relatively shorter vector arrows for slope parameters. Topographic characteristics demonstrated a 6% (R1) and 4% (R2) overlap with the land use subset.

Following RDA employed using runoff dataset R1, the rainfall variable SD_RFT was shown to be weakly positively correlated with axis one (*r*=0.33) (table 5.36). The standard deviation of total rainfall (SD_RFT) represented the only climate parameter significantly correlated with runoff. Independently, it explained 1% of the variance. There was no evidence of spatial structuring in the data.

The results of RDA undertaken using 'lowland' environmental data mirrored the findings of RDA employing upland environmental characteristics; the greatest explanatory power was awarded to land use parameters which accounted for 10% of R1 and 16% of R2 (figure's 5.33 and 5.37). Lower storm runoff volumes and low bin classes one and two, were predominantly explained by axis one, which in terms of land use, was mostly strongly governed by cereal production (AR_CER), horticulture (AR_HORT) and set aside (AR_SET). The inter-set correlations of these land uses with axis one were all stronger than 40% (*p*<0.01) (table 5.42).

Soil HOST classes HA and HK (R1) and HA, HK and HF (R2) explained 7% (R1) and 6% (R2) individually (refer to table 3.5). At 17%, the shared explanatory power of land uses and soil HOST classes was 9% greater on average than for the 'upland' RDA. Topographic variables, including topographic index less than 20 (TI<20) and drainage density (DD), were responsible for 3% (R1) and 2% (R2) of the explained variance in runoff. The statistical overlap between topographic and land use parameters was 4% (R1) (figure 5.34) and 3% (R2) (figure 5.38).

The length and direction of vector arrows for the spatial parameter XY (figure 5.37) and high inter-set correlations with axis one (*r*=0.42) (table 5.42), illustrated significant spatial

structuring in runoff data. The spatial parameter XY independently accounted for 1% (R1) and 2% (R2) of the variance. The overlap between XY and land surface variables accounted for an additional 6% (R1) and 7% (R2). Thus, catchments displaying land use patterns that are conducive to lower runoff volumes during storm events may be located further east, which is generally characterised by a drier climate and a more gentle relief.

Analysis of the factors controlling higher (H_r) and lower (L_r) runoff generating catchments in section 5.7.3vii, demonstrated that subtle alterations in the land use, soil and relief characteristics between H_r and L_r catchments may be responsible for enhanced volumes of runoff produced by H_r catchments during storm events. The only consistent feature of H_r catchments related to pasture land management. Improved grassland and grassland land uses were regionally dominant but proportionally, were more widespread in H_r catchments.

In general, these catchments exhibited a slightly steeper relief and were predominantly underlain by soils that are broadly categorised as reduced permeability soils. Catchments demonstrating this combination of factors will be increasingly responsive. In particular, steeper, higher energy environments under grassland, including uplands, will be especially prone to enhanced peak flows. Soil characterisation work undertaken in chapter 7, showed that the effects of such land uses will be largely dictated by soil management.

Using the statistical approach adopted, it is difficult to distinguish the relative roles of arable and pasture land uses on catchment scale runoff. Despite being marginally higher for L_r catchments, cereal cultivation and horticulture were observably higher than average for both sets of catchments. Variance partitioning revealed a stronger relationship between 'lowland' land use and soil parameters. Furthermore, decreases of 2.5% (R1) and 0.5% (R2) in the shared explanatory power of 'lowland' topographic and land use

parameters compared to 'upland' parameters may represent the reduced influence of relief in controlling runoff in arable areas.

According to a study of the River Camel catchment (chapter 6), the capacity for land management decisions undertaken at the field scale to impact significantly upon peak flow responses may be significantly governed by their spatial distribution in relation to proximity to the channel (Sullivan *et al*, 2004). Sullivan *et al* (2004) concluded that increases in annual maximum flows in the River Camel was the result of streamflow being progressively supplemented by sources of fast response runoff from arable areas in the lower catchment, in addition to local expansion of the urban area at Bodmin town.

Land uses in the Camel catchment were highly spatially organised. Much of the maize production was situated on low gradient slopes adjacent to the main channel. An increase in runoff from such intensively managed slopes was thought to have had a dramatic effect upon river discharges as a result of their high degree of connectivity to the river channel and because these areas are prone to saturation. The degree of connectivity or disposition of specific land uses are likely to be key factors controlling hydrological responses, but were not parameterised in the 48 catchment study on account of the major computational requirement this would entail. However, the findings from the River Camel study are consistent with the modelling work undertaken by Gilman (2002), which demonstrated that the magnitude of impacts on flows at the outlet of the River Severn largely depended on the location of the land use change within the catchment.

Grazing in the catchment was generally restricted to steeper slopes and granite upland areas, including the De Lank, which drained the eastern slopes of Bodmin Moor, north Cornwall (figures 6.3 and 6.6). Following RDA, the Camel (8) and the De Lank subcatchment (11) plotted close to one another on ordination triplots (figure 5.39). The environmental characteristics of the catchments are distinct. Hence the similarity of their

response characteristics to large storm events may be indicative of the sensitivity of the upland subcatchment and the major influence of inputs to streamflow in the River Camel, through the De Lank tributary.

Steeply sloping headwater catchments, such as the De lank, will be highly connected to first order streams. The principal land cover of the De Lank was grazing of grassland and open moorland by sheep, cattle and horses (79%), with 45% comprising improved grassland. The connectivity of these areas may be enhanced where high grazing pressures impact upon the hydrological properties of soils that determine their capacity to transmit and store water.

The situation should not be over simplified; examples exist of shallow H_r catchments and steep L_r catchments. Nonetheless, in low lying arable areas, where soils are able to drain naturally, there may be greater opportunity for water to move into and through the soil profile. Complex soil water storage and release mechanisms that are particularly prevalent on shallow gradient slopes may moderate the impacts of land use on stream flow responses, at the catchment scale.

Cerdan *et al* (2004) argue that as a result of the spatial variability in soil hydraulic properties, catchments cannot be considered as the sum of individual fields. They report a significant decrease in the runoff coefficient between the plot and catchment scales (Cerdan *et al,* 2004). The scaling transition between runoff at the plot, field, hillslope and catchment may be considered in terms of the connectivity between infiltrating and runoff producing areas. According to Cammeraat (2002), the connectivity of runoff generating (sources) and runoff absorbing (sinks) areas was found to be important at all scale levels, ranging from the micro-plot to the catchment. This reasoning is endorsed by Fitzjohn *et al* (2002), who describe the landscape as a mosaic of source or sink areas controlled by temporal variability in rainfall and spatial heterogeneity in land use and soil surface properties, namely soil moisture.

In dry weather conditions, runoff produced from source areas is spatially isolated and hydrological pathways are disconnected. Meyles *et al* (2003) demonstrated that in disconnected states, increasing soil wetness led to very slight increases in stream discharge. Drier areas on hillslopes functioned as storage areas for laterally moving water on slopes. In a semi-arid catchment, Bergkamp (1998) observed runoff at the level of a terracette or tussock that was not connected to slope and catchment runoff. This was found to be the result of increased variability at the rims of terracettes and rapid infiltration under oak shrubs and trees.

The connectivity of hydrological pathways and thus the conversion from a variable source dominated flow to a hillslope flow (Meyles *et al*, 2003) will be dependent upon rainfall characteristics and physically and biologically based thresholds. Catchment scale runoff generation will only be initiated once the thresholds of all smaller-scale hydrological response units have been exceeded (Fitzjohn *et al*, 2002). A pressure wave or water displacement mechanism has been put forward by Williams *et al* (2002) to explain the rapid movement of water from connected hillslopes to the channel.

Puigdefabregas *et al* (1999) noted that the connectivity of overland flow to first order streams was largely dependent upon the temporal distribution of rainfall, and soil properties controlling patterns of soil moisture. A soil moisture threshold of 0.60 cm-^{3} cm-^{3} was proposed by Meyles *et al* (2003) which once exceeded, would cause stream discharge to exponentially increase with increasing average soil water content (Meyles *et al*, 2003). According to Williams *et al* (2002), in wet or hydrologically connected states, stored rainwater can be rapidly expelled into flow networks and seepages, thereby

increasing the upslope contributing area and enabling significant areas of catchments to contribute to streamflow.

The impacts of land use may have significant repercussions on stream flow through the influence on thresholds that are essential for disconnecting hydrological pathways. Alterations to soil surface conditions, including the vegetation cover and topsoil, by surface sealing or compaction from intensive grazing, tractor wheelings and animal tracks, may affect the threshold soil moisture content between wet and dry states and thus the hydrological response, by lowering soil moisture characteristics at saturation or reducing the infiltration capacity of soil surfaces (Meyles *et al* 2003). Meyles *et al* (2003) concluded that although animal pressures may not be high enough to induce erosion, their influence on the soils and hydrology of a catchment may be linked to the processes responsible for the transition of 'small' to 'large' floods.

8.5 Future land use change

Over the last 50 years, incentives provided by agricultural policy engendered a significant intensification of farming (O'Connell *et al*, 2004). At the field scale, the impacts on the generation of runoff will be governed by the effects of land use history, the level of activity and the timeliness of specific agricultural operations on the vegetation cover and the properties of the underlying soils. Different practices are associated with relative levels of risk of runoff production (Armstrong *et al*, 1990). In chapter 7 improved soil quality and lowered runoff risk under permanent pasture was demonstrated at a site subject to a long history (30 years) of managed stocking density and no cultivation, following testing after a prolonged dry period.

At the field scale, continuous cereal cultivation was found to be a higher risk practice in terms of the generation of runoff. Similarly, at the catchment scale, Sullivan *et al* (2004)

concluded that runoff from arable cultivation on highly connected, floodplain areas contributed to a 20% increase in the 1:25 year flow over the period 1965-1982 and 1983-2000 (chapter 6). As a result of the relative risks associated with cultivation and permanent pasture, conversion to grassland has been repeatedly proposed as an effective runoff mitigation measure (Fullen, 1991; Evans and Boardman, 2003). Conversion of cropped land to perennial grasses has been associated with improvements in a number of soil quality attributes. For example, increases in soil carbon and nitrogen have been observed after 6 years under pasture, compared to soils cropped annually (Robles and Burke, 1998; Francis *et al*, 2001).

However, the results of spatial (part II and part III) and temporal (part III) studies into the effects of land use on hydrological response at the catchment scale, alternatively suggest that grassland land cover may be contributing to enhanced peak flows. The results of analysis of land use effects at the catchment scale (part II) suggest that across the southwest, grassland is a consistent characteristic of catchments generating higher runoff volumes in response to large storm events. The average percentage cover of arable land uses, identified as high risk practices in terms of runoff generation at the field scale (part IV), showed very little change between H_r and L_r catchments (section 5.7.3viii).

Moreover, similarities in the responses of the Camel catchment and the De Lank subcatchment support a dominant control on peak flow responses by runoff from grazed upland areas (Sullivan *et al*, 2004) (Chapter 6). It is widely acknowledged that all soils under pasture will be compacted to some extent (Greenwood and McKenzie, 2001). This impact is generally confined to the top 50-150mm of the soil, resulting in reduced rates of infiltration and increased risk of Hortonian overland flow (Trimble and Mendel, 1995). Indirectly, heavy grazing can also affect soil properties by altering the species composition of the vegetation. A decline in shrub density can result in the depletion of soil nutrients (Allsopp, 1999) and a lowering of the infiltribility of the soil by significantly reducing the

amount of biomass and vegetation cover. Previously ploughed soils and steeper slopes are most vulnerable to the effects of enhanced grazing pressures (Mwedera and Saleem, 1997). Francis *et al* (2001) detected improvements in soil macro-porosity, after ploughing relieved areas compacted by sheep during grazing. Under permanent pasture, the impacts on soil structural degradation are very difficult to ameliorate without the use of tillage (Greenwood and McKenzie, 2001).

The impacts of grassland will therefore be very much dependent upon specific soil and landscape conditions. These will govern the inherent risk of runoff, in terms of the effects of environmental characteristics, namely slope steepness, soil type and bedrock, in addition to the spatial organisation of land use, on the hydrological processes of runoff generation and dominant flow pathways. Variability in the land use characteristics of H_r and L_r catchments in chapter 5 and the properties of soils underlying varying intensities of land management in chapter 7, have highlighted the importance of prevailing hydrological processes in determining the nature of the hydrological impacts of land use. At the field scale, arable management practices, including the cultivation of cereals, were thought to exhibit higher risk of runoff generation compared to permanent pasture. This was primarily associated with a greater risk of infiltration-excess overland flow as a result of the reduced resistance of cultivated soils to surface crusting when exposed to rapid wetting (section 7.6).

At the catchment scale, catchments producing higher runoff volumes in response to extreme events were generally characterised by upland grassland land cover and underlain by low permeability substrate and bedrock (section 5.7.3viii). In these areas, the soils may be vulnerable to saturation and produce saturation-excess overland flow when exposed to prolonged wet conditions. The impact of land use on hydrological functioning is therefore fundamentally determined by the characteristics and management of the soils,

and will vary seasonally as different runoff mechanisms operate in response to changes in rainfall patterns.

8.5.1 Flood peak attenuation

Agricultural management systems are capable of playing an important role in attenuating peak flow responses to storm events by enhancing the availability of sink areas required to disconnect hydrological pathways, through restoration of the diversity of the landscape. Considered land management which ameliorates or prevents soil structural degradation will raise the hydrological thresholds governing the connectivity of source areas of runoff, by improving the availability of sink areas that encourage the movement of water into and through soil storages.

Increasing soil moisture thresholds

Techniques such as spiking or slot cutting have been employed to increase the infiltration rate of compacted soils under permanent pasture (O'Connell *et al*, 2004). Greenwood and McKenzie (2001) claim that improvements in the physical condition of grazed soils can be achieved simply by maintaining a vigorous pasture. In a study of three adjacent watersheds, runoff was found to be generated primarily as a result of winter feeding in pastures (Owens *et al*, 1997). Low volumes of runoff were produced with summer-only grazing patterns (Owens *et al*, 1997). On grassland, the restriction of the grazing season to avoid conditions where the soil is at or near field capacity and therefore has a low bearing strength, may help to reduce the risk of runoff (O'Connell *et al*, 2004).

In high risk fields under arable cultivation, cover crops such as grass and clover can serve to bind soil particles together, increase the surface roughness and reduce the compactive impact of raindrops (Morgan, 1992). Protection of the soil surface from the beating action

of rain will reduce the risk of surface sealing. This may also be afforded by the early drilling of winter cereals to encourage a protective crop cover during winter (Chambers *et al*, 2000). It is recommended that tramlines are set-up after the emergence of winter cereal crops and trafficking delayed or avoided in autumn (Chambers *et al*, 2000).

Reduced soil exposure can also be achieved through the adoption of minimum tillage, which involves leaving previous residues on the soil surface or only partially incorporating them (O'Connell *et al*, 2004). Across Europe, the use of minimum tillage has been progressively increasing (Holland, 2004) and has been advocated as an effective deterrent against surface seal development, especially on heavy clay soils (Rasmussen, 1999). Moreover, minimum tillage can increase SOM content, soil structure and stability and biological activity, thereby reducing the risk of water logging and runoff (Holland, 2004; O'Connell *et al*, 2004).

Across-slope cultivation is effective in mitigating runoff by increasing infiltration, particularly when applied in conjunction with minimum tillage practices (Basic *et al*, 2001; Quinton and Catt, 2004; O'Connell *et al*, 2004). According to Quinton and Catt (2004), the mean event runoff of 1.32mm from plots cultivated up and down slope was significantly greater ($p<0.05$) than that from plots cultivated across slope (0.82mm). Nonetheless on many farms in the UK, across-slope cultivation is not practical due to the irregular nature of field boundaries, and slope angles and directions (O'Connell *et al*, 2004).

Successful management will need to address both the direct and indirect impacts of intensive land use on soil hydrological properties, including the maintenance of levels of organic matter above a threshold content to improve soil structural stability and resistance to compaction. The critical organic matter level will be dependent upon individual site conditions, climate, soil type and land use, as will the rate of loss of important types of organic matter from the soil, namely roots and hyphae (Tisdall and Oades, 1982).

According to Rowell (1994), 50%-80% of newly added organic matter is removed from most temperate soils during the first year of application. Added organic residues therefore need to be regularly applied in order to maintain the favourable effects on soil properties.

Through cationic bridging, bivalent cations such as Ca^{2+} and Mg^{2+} can improve soil structures and the resistance of aggregates to slaking, through the formation of strong bonds between clay particles and soil organic matter (Tisdall and Oades, 1982; Bronick and Lal, 2005). Soils suffering structural deterioration as a result of an imbalance in the CEC, such as high ESP, may be reclaimed by ensuring that exchange surfaces are dominated by Ca^{2+} (Bohn *et al*, 2001). To this end applying soil amendments that contain Ca^{2+} and Mg^{2+}, such as lime ($CaCO_3$) or gypsum ($CaSO_4 \cdot 2H_2O$), can decrease clay dispersion and substantially improve soil organic matter and aggregation by increasing the concentration of calcium ions in the soil solution and raising the soil pH (Bohn *et al*, 2001; Bronick and Lal, 2005). At high pH, clay particles often flocculate and form large soil aggregates. This process may also be achieved through the application of certain fertilizers. For example, phosphoric fertilizers stabilise aggregates by increasing Al^{3+} and Ca^{2+} bonding (Bronick and Lal, 2005).

Disconnecting hydrological pathways

Local changes in runoff may be transferred to the stream network and propagate downstream. A range of management options are available that could serve to disconnect hydrological pathways from the main channel by providing a barrier to runoff, thereby reducing the upslope contributing area. In arable systems, grass leys, buffers or contour strips can act as 'soakaways', which brake, filter and infiltrate runoff (Fullen, 1998).

Fullen (1998, 1991) reported reduced erosion rates under mature strips of permanent grass ley in cultivated fields, that were highly effective even on steep slopes (>12°). The organic matter content of soils under the grassed strips had increased by 0.4% in the first 2 years and by 0.8% after 4 years (Fullen, 1998). Similarly, Le Bissonnais *et al* (2004) detected increases in the infiltration rates of 3m and 6m wide buffer strips that were positioned at the down slope end of a winter wheat field. On average, the infiltration rates increased by 80% under the 3m buffer strip (coefficient of variation 19%) and by 87% (coefficient of variation 16%) under the 6m strip (Le Bissonnais *et al,* 2004).

Reinstating hedgerows and relocating farm gates can provide effective barriers to runoff. Investigations into the importance of the bocage hedge networks in Brittany, France have highlighted their multifunctionality in providing a protective windbreak, a barrier to surface runoff and erosion, a sink zone to promote infiltration and an ecological corridor (Merot, 1999). The bocage is able to buffer quickflow during storm runoff, by modifying Hortonian overland flow and the contributing flow on saturated areas (Merot, 1999).

Numerous workers have reported the ameliorative effects of in-field grass hedge systems on infiltration. For example, in Machakos, Kenya, hedgerows planted 4m apart in a maize and cowpea rotation on a 14% slope were shown to be a valuable runoff control measure (Kiepe, 1995). Largely as a result of increased macropores in the topsoil, the hedges exhibited 30% higher infiltration rates in the dry season and 94% higher infiltration rates in the wet season, compared to adjacent alleys (Kiepe, 1995). Chandler and Walter (1998) have also observed greater infiltration under a pasture containing contour hedgerows.

Rachman *et al* (2004) reported improved soil water transport after 10 years under a switch grass (*Panicum virgatum*) hedge management system. In accordance with Kiepe (1995), switch grass hedges displayed greater macroporosity than the adjacent row crop and a six-fold increase in hydraulic conductivity (Rachman *et al*, 2004). Following testing of a

range of in-field runoff barriers, the addition of switch grass to fescue filter strips (0.7m) was found to be most effective, compared with continuous fallow (Blanco-Canqui *et al*, 2004). This combined management practice was found to reduce runoff by 18%, trapping 92% of sediment and 74% of nutrients in the first 4m of the strip (Blanco-Canqui *et.al*, 2004).

The effectiveness of land management practices that are designed to reduce the risk of runoff generation, such as the conversion of arable areas to grassland, or options to infiltrate runoff, including buffer strips, will be contingent upon the quality of the underlying soils. After 3 years in rotation pasture, tested soils (SPP) showed no improvement in the SOM content compared to cultivated soils (CC) (figure 7.10). SPP soils were susceptible to infiltration-excess runoff as a consequence of structural deterioration at the surface.

Robles and Burke (1998) and Francis *et al* (2001) detected slight increases in soil carbon and nitrogen after 6 years under pasture compared to soils cropped annually. However, reductions in SOM content and nitrogen following cultivation were still detectable after 20 years of fallow in a study by Allsopp (1999). Evidently, without accompanying measures to regain damaged soil structures, land management practices aimed at attenuating runoff will be largely ineffective. More work is required to assess the timescales associated with soil structural recovery.

Due to higher rates of evapotranspiration, a protective canopy cover, dense root systems and litter for the accumulation of SOM, farm woodland offers the potential to provide a long term runoff control measure. Soil testing under farm woodland showed average surface horizon hydraulic conductivity under farm woodland to be 75% higher than under continuous cereal cultivation (figure 7.23). In the Nant Pontbren catchment, mid-Wales, a study by Carroll *et al* (2004) determined that tree shelterbelts in fields grazed by sheep were effective in reducing runoff and creating a more diverse landscape, whilst comprising

a small proportion of the land cover. Farm woodland may help to attenuate flood peaks where it is not accompanied by intensive drainage systems (O'Connell *et al*, 2004).

In Belgium, retention ponds have been widely used to prevent episodes of muddy flooding and are effective in retaining sediment and improving catchment water storage (Verstraeten and Poesen, 1999). Verstraeten *et al* (2001) measured reductions in the delivery of sediment to surface waters of 50% following the installation of filter ponds. The effectiveness of retention wetlands, ditches or ponds, will be crucially dependent upon their location within a catchment. Ponds may attenuate runoff if they successfully increase the storage and buffering capacity of upland headwater subcatchments (O'Connell *et al*, 2004).

Within a catchment, the disposition of individual land management activities is thought to be a major factor in determining the delivery of runoff to the channel. The long-term study of the catchment of the River Camel (chapter 6), pointed towards the significance of cereal production on highly connected slopes in the lower catchment, to increases in annual maximum flows over the period 1965-2000 (Sullivan *et al*, 2004). A given slope will demonstrate an inherent level of risk on the basis of this degree of connectivity, in addition to the prevailing soil type and climate conditions. Land managers must give greater consideration to areas within catchments that are, by their nature, high risk slopes. In these areas whole land use change may be required to lessen the potential for significant runoff generation to contribute to streamflow. For example, floodplain areas that are prone to saturation or row crops grown on steep slopes may need to be taken out of production. Surrendering low productivity areas to copses and non-grazed areas may provide the opportunity for upslope runoff to be re-incorporated into soil storage (O'Connell *et al*, 2004).

Measures to mitigate runoff through changes in land use must be undertaken in the context of the catchment system. For example, non-headwater retention ponds may bring runoff delivery from lower catchment in line with the flood hydrograph of the upper catchment (O'Connell *et al*, 2004). The presence of field drains may expedite the movement of water from the land and into ditches, thereby by-passing buffer strips and rendering them ineffective. Furthermore, the planting of woodland may have significant implications on water resources (O'Connell *et al*, 2004).

In addition, considerable synergies exist between measures to control the movement and storage of water for flooding alleviation and management of the transportation of pollutants. For example, disconnecting catchments through good soil husbandry and conservation tillage, and the use of buffer strips or hedgerows as runoff barriers, also reduces the pollution of surface waters with sediment, pesticides and nutrients and creates important wildlife habitats (Morgan, 1992; Holland, 2004).

Crop residues available through the practice of conservation tillage may offer additional food for insects, birds and small mammals (Holland, 2004). A richer soil biota will enhance nutrient recycling and help to combat pests and diseases (Holland, 2004). In addition, restoring SOM contents raises carbon sequestration, increasing the long-term greenhouse carbon sink (Dalal and Chan, 2001). Whilst energy crops, such as *Miscanthus*, may provide a dual function by providing an effective soil surface cover (O'Connell *et al*, 2004).

Recently, farmers in the UK have been urged to consider strategies to manage the water resource implications of climate change. In particular, the government has publicly advocated the establishment of on-farm reservoirs to combat potential water deficits in summer months (Andersen, 2005). On-farm ponds may be adapted to perform a range of functions, including water storage, flood retention, habitat creation and a filter for diffuse pollutants.

A holistic catchment management approach is required that has a strong scientific foundation, in order that mitigation measures applied at the farm scale are targeted, effective and do not impose adverse repercussions on wider catchment functions. Management must be fully integrated to ensure that land management practices afford the maximum environmental benefit. To this end, joined-up decision-making is fundamental.

Through the reform of CAP and a decoupling of support payments from production, current agricultural policy is progressing towards reconnecting agriculture with the environment. In March 2005, Defra launched the Entry Level (ELS) and Higher Level (HLS) Schemes, which comprise a new Environmental Stewardship (ES). ELS and HLS go beyond the Good Agricultural and Environmental Condition (GAEC) requirements of cross compliance for the Single Farm Payment Scheme, by providing a financial reward to farmers who take up a range of conservation management options.

Options are available to all farmers under ELS that will help them to reduce the risk of runoff generation, for example, through considered management of high risk cultivated land and good soil husbandry, or by encouraging the movement of surface water into soil storages by means of the installation of buffer strips and management of ditches. Under HLS, a limited number of farmers may receive financial assistance where more involved management is required to mitigate specific problems in locally targeted areas. This may incorporate the creation of wetlands or ponds and hedgerows, or the reversion of arable land to grassland.

The primary high level objectives of the new ES include natural resource protection, wildlife conservation and maintenance of landscape quality; flood management is a secondary objective. Very little progress has been made in terms of identifying and strengthening the link between flood risk management and agricultural land management practices in a policy context. Undoubtedly, a significant proportion of the options available under the resource protection and wildlife conservation strands of ES will fulfil multiple functions, including options that reduce and mitigate runoff.

Decision-makers have yet to realise the full environmental benefits of existing schemes. Moreover, a much clearer distinction still needs to be made of the considerable overlap between agricultural management practices promoted in agri-environmental schemes, and multiple environmental policy objectives. For example, the Woodland Grant Scheme (WGS) offers grants towards the costs to farmers and land managers of establishing and maintaining woodland areas, whilst the Farm Woodland Premium Scheme (FWPS) provides annual payments for income forgone by installing wooded areas on farms. The underlying objectives of these schemes are improvement in landscape quality and biodiversity. The significance of establishing woodland for peak flow attenuation remains poorly recognised or endorsed. Modification of farm woodland schemes could provide additional subsidy where there will be a perceived hydrological benefit.

Historically, set aside has often been located along river corridors. However, for the most part, land set aside has been used to produce oilseed rape and not designed for the purpose of reducing runoff (O'Connell *et al*, 2004). Little incentive is provided for farmers to utilize land set aside for flood retention purposes, which may be achieved through the planting of woodland in these areas. At present, the inclusion of woodland in set aside area calculations may result in woodland scheme payments being reduced or stopped in order that set aside payment obligations are met.

The successes of ELS and HLS both in terms of the take up by farmers and the nature of the options selected are uncertain and will need to be carefully monitored. Hall *et al* (2005) have highlighted both the lack of specific aims to reduce flood risk within ELS and the reduced profit margins that are associated with the creation of buffer strips under this scheme. Ultimately, improved management of water in the profile and landscape, will be

contingent upon a parallel education of farmers about the off-farm impacts of specific practices and the wider environmental and financial advantages of reducing farm emissions, including water, topsoil (sediment) and agro-chemical inputs (nutrients and pesticides). Policy-makers need to convey clearer messages to farmers and land managers about the practical land management changes required to satisfy the range of regulatory burdens placed upon them, whilst ensuring such schemes help to promote the economic viability of farm businesses.

Whole farm planning encouraged in recent agri-environmental schemes must be undertaken in a catchment context. Under ELS, farmers may opt to develop a risk-based soil management plan. Emphasis must be placed on using such plans to identify the inherent risk of fields of generating off-farm impacts such as increased flows, in relation to soil type, climate and relief factors, and the effect of the disposition of slopes on catchment connectivity. In some areas, reducing the potential for catchment management problems, such as flooding and diffuse water pollution, may require considerable changes in land management practices, particularly in response to the impending impacts of climate change. Improved management of rural catchments will require an assessment of the capacity of the catchment to support particular land uses through a continual evaluation of inherent risks, against the relative risks associated with specific land management practices.

Farming and land management underpins the sustainability of rural environments. However, in an era of growing environmental awareness and concern, farmers are being challenged with an evolving responsibility towards providers of services such as water storage, waste disposal, fuel production, flood protection and maintainers of biodiversity and landscape quality. A long-term balance between the sustainability of farm livelihoods and the environment will ultimately depend upon farmers taking ownership of the causes and solutions of these problems. This may be achieved through collaborative planning by

farmers within catchments or subcatchments, supported by a partnership approach between local and regional stakeholders. Agricultural policy must provide the framework through which this is possible, by reducing or streamlining the regulatory burdens placed upon farmers, making optimum use of agri-environmental schemes offering financial incentives, and by empowering farmers in the decision-making process.

Chapter 9

Summary of key conclusions (Part V)

9.1 Introduction

This thesis set out to explore the role of land use on hydrological functioning using a multi-scale approach to fulfil three key aims that are presented below. This chapter summarises the major findings from each of the investigations, targeted at different spatial and temporal scales, which were encompassed within the study.

- To investigate the influence of catchment scale patterns of land use on peak flow responses.
- To explore the nature and significance of land management impacts on field-scale hydrological processes in relation to local environmental conditions.
- To better understand the effectiveness of adopting specific land use practices and measures, to reduce flood incidence.

9.2 Evidence of land use change (Part V, chapter 8, section 8.2)

Since the Second World War, national and European agricultural policies have played a principle role in instigating key land use changes in the UK countryside. Through the introduction of financial incentives under CAP, agricultural change has been directed towards an intensification of production. These impacts are manifest locally in the catchment of the River Camel, north Cornwall, where successive policy measures have

served as a vehicle for patterns of advancing intensification in cereal cultivation and grazing pressure that are particularly apparent after 1979. The height of intensive agriculture has been reached. More recently, with the integration of agri-environmental measures into CAP, agricultural policy is shifting towards the promotion of more environmentally friendly land management practices.

9.3 Evidence of land use change impacts on hydrological processes: field scale (Part IV, chapter 7)

Results of a soil survey in chapter 7 were unable to provide definitive answers regarding the likelihood and processes of runoff generation, associated with different levels of land management activity. However, the results indicated a potential link between land practice change and enhanced risk of field-scale runoff, in the context of land management effects on soil structural degradation.

The potential for specific agricultural management practices to generate runoff will largely be dictated by the complex interactions between the intensity and history of the activity, the prevailing climate and factors influencing soil structural stability. Fields subject to 30-year histories of continuous cereal cultivation and rotation pasture were thought to be less resistant to aggregate breakdown as a result of surface compaction and processes leading to the formation of surface crusts, in comparison to sites under permanent pasture and farm woodland. The limited management intervention associated with permanent pasture and farm woodland fostered improved aggregate stability and soil drainage in the surface horizon.

Reducing the risk of runoff requires soil management that is targeted at improving and preserving the structure of the soil. Successful management will need to address the

direct impacts of agriculture, such as the compactive effects of farm machinery and grazing animals, in addition to the indirect impacts, including maintaining levels of organic matter above a threshold content required to improve structural stability and increase soil resistance to compaction.

9.3 Evidence of land use change impacts on peak flows: catchment scale

There is limited understanding of the way in which the local effects of land management practices on runoff may propagate downstream and contribute to flooding problems that are manifest at much larger scales. At the catchment scale, averaging reduces the complexity of hydrological systems. Consequentially, it is very difficult to disentangle the impacts of land use practices on the hydrological processes of catchments demonstrating extreme runoff responses. Notwithstanding this, separate spatial and temporal investigations into the effects of land use change on peak flows presented in this thesis, point towards a significant land use control on catchment responses to extreme storm events.

9.3.1 Regional trends (Part II, chapter 5)

Statistical testing of regional trends in environment and storm event runoff characteristics at the catchment scale, established a dominant control on runoff by interactions between land surface characteristics, including land use, soil and geology factors. In separate analyses of two storm runoff datasets, approximately half of the explained variance in runoff was attributed to land use parameter subsets, in conjunction to the combined explanatory power of land uses with soil HOST classes.

Improved grassland is a consistent feature of catchments generating higher runoff volumes in response to large storm events. Moreover, similarities in the hydrological

behaviour of the Camel catchment and the De Lank subcatchment support a dominant control on peak flow responses by runoff from grazed upland areas. The connectivity of these areas may be enhanced where high grazing pressures impact upon the hydrological properties of soils that determine their capacity to transmit and store water.

At the catchment scale, soil water storage and release mechanisms that are particularly complex on shallow gradient slopes may moderate the impacts of land use on stream flow responses. However, where the impacts of intensive arable production have discouraged spatial heterogeneity in soil properties, the continuity of sources of runoff in these areas may be enhanced. Runoff produced as a result of high risk arable practices will have less opportunity to be reabsorbed into the soil profile before reaching the river channel. The impact of increased connectivity will be particularly prevalent where intensive production practices are undertaken on low gradient slopes adjacent to the main channel, such as maize cultivation in the Camel catchment. An increase in runoff from such intensively managed slopes may significantly contribute to river discharges as a result of their high degree of connectivity to the river channel and because these areas are prone to saturation.

9.3.2 Long term trends (Part III, chapter 6)

The long term study of the Camel catchment, north Cornwall undertaken by Sullivan *et al* (2004), revealed an increase in the annual maximum daily flow over the period 1965-2000. This was characterised by a 20% increase in the magnitude of the one in 25 year flow, together with a 3% rise in the median daily flow between the periods 1965-1982 and 1983-2000. Exploration of hydrometric and land use data using spatial and temporal approaches indicated a number of potential causes that were associated with both climate and the disposition of a complex picture of land use changes. The cumulative impacts of a subtle, long-term rise in October rainfall totals, coupled with urban development and the

expansion of arable cultivation in the lower catchment, and a rise in the intensity of grazing in the upper catchment, altered the discharge regime by influencing the potential for and rate of water transfer to the channel.

9.4 Future agricultural change and the role in flood peak attenuation

By altering the hydrological thresholds controlling the variability of soil moisture in the landscape, contemporary agricultural land uses have connected previously discrete components of the hillslope. This has increased the capacity for runoff to activate intermittent systems and 'tap into' storages that are distributed across the catchment. Variability in the land use characteristics of H_r and L_r catchments in chapter 5 and the properties of soils underlying varying intensities of land management in chapter 7 has revealed that the precise nature of the hydrological impacts of land use will strongly depend upon the prevailing hydrological processes.

Future changes in agricultural management systems are therefore capable of playing an important role in attenuating peak flow responses to storm events. Considered land management which ameliorates or prevents soil structural deterioration, such as the provision of a protective vegetation cover over winter, reduced grazing densities and the increased timeliness of arable operations, represent relatively subtle changes in land use that may enhance the availability of sink areas required to reduce catchment wetness and encourage the movement of water into storages within the hillslope. A range of management options are also available that could serve to disconnect hydrological pathways from the main channel by providing a barrier to runoff, thereby reducing the upslope contributing area. The restoration and widening of hedgerows or the introduction of forested areas to act as sinks, could facilitate a reduction in food risk by localising upslope runoff and dampening catchment responses.

Recently, agricultural policy has provided the platform for such changes, through the provision of financial incentives linked to more environmentally targeted land management options under agri-environmental schemes. Supported by raised awareness of the on and off-site environmental impacts of farm activities, agri-environmental schemes may be used to promote less intensive practices or whole land use change in target areas that are high risk in terms of the production of runoff. A proliferation of measures is being imposed upon farmers that require the production of farm plans. Farm planning must include an assessment of the inherent risk of slopes in terms of the prevailing soil, geology and climate conditions, and the disposition in relation to major hydrological pathways.

By promoting a collaborative decision-making process, involving local stakeholders and farmers, greater consideration may be awarded to the importance of farm management planning to the wider functioning of the catchment system. This framework will enable a better assessment and broader understanding of the land use changes required to meet the carrying capacities of catchments, particularly in relation to changes in inherent risk that may occur with higher rainfall amounts and intensities that are predicted under future climate change scenarios.

9.5 Recommendations for catchment management

Long-term catchment management requires a holistic approach that recognises the natural connectivity and heterogeneity of catchment systems. This requires a comprehensive knowledge of the complexity and spatial and temporal variability of functional catchment processes and the nature of the impacts that land use change exerts on these processes over different scales.

There is a pressing need to reconcile the socio-economic and political factors that persistently undermine conservation management and promote exploitative resource use.

Balancing the multiple functions of catchments will involve greater education, communication and co-operation between the government, conservation bodies, the general public and those farmers and landowners that directly manage the land.

In rural areas, reducing the potential for catchment problems such as flooding and diffuse water pollution will be contingent upon a narrowing of the gap between policy makers and action on the ground. Achieving the significant changes in land use and management practices that are required to alleviate these problems, demands a political and management framework that supports a bottom-up approach, encouraging land managers to identify with and take responsibility for the impacts of their activities on the functioning of local environments.

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Appendix I

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Land use change and hydrological response in the Camel catchment, Cornwall

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Abstract

The paper attempts to determine the extent to which rainfall trends and land use changes influence the river flow regime and flood response of a predominantly agricultural catchment (210 km^2) in southwest England. Temporal changes in daily rainfall totals were analysed over annual, seasonal and monthly timescales but although annual average October rainfalls exhibited a weak rising trend ($r = 0.3$, $p > 0.05$), no long-term patterns were observed. Analysis of daily mean discharge data for the River Camel over the period 1965–2000, using the Gumbel distribution, revealed an increase in the magnitude and frequency of peak flows. Land use changes were examined using Agricultural Census Data for 1969, 1979, 1988, 1997 and 2000. Both the number of stock and the area under cereals increased from 1969 to 1997, but cereal production declined substantially between 1997 and 2000. Spatial response patterns were also examined through a comparison of the flow response of the entire Camel catchment with its more complex land use, with the predominantly pastoral De Lank headwater sub-catchment (22 km^2), to ascertain the amount of change due to increased livestock numbers alone. No single factor was found to be responsible for the increases in flood frequency and magnitude in the River Camel. Rather, long-term changes in the response of the Camel system appear to emanate from the cumulative impact of subtle changes in climate, combined with increased farming activity plus urban expansion. The paper highlights the inherent difficulties of attempting to disentangle the precise effects of individual land uses on flood responses at the catchment scale and underlines the need for a holistic approach to the management of floods. By the same token, sustainable catchment management can only be achieved through greater awareness of the potential for complex, small-scale land use decisions to result in large-scale hydrological changes.

Keywords: Landuse; Runoff; Catchment; Flooding; Agriculture

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Introduction

During autumn 2000, extensive flooding across areas of southern England raised public, political and scientific awareness of the large-scale consequences of increases in the frequency and magnitude of peak flows and highlighted the urgency of improving knowledge of the significant system changes that drive these events. The need for a sustainable solution to flooding has been publicly highlighted by the recent production, by the Institute of Civil Engineers, of a report entitled 'Learning to live with rivers,' which joins together technical aspects of flood risk management with long-term solutions (ICE, 2001).

Agricultural developments have led to a widespread deterioration in soil structures, a process which favours soil sealing and crusting, and reduced rates of infiltration and soil storage (Reed, 1979; Robinson, 1990; Boardman and Favis-Mortlock, 1993; De Roo, 1993). A comprehensive body of evidence exists to support the supposition that in predominantly rural regions, agricultural land use changes, specifically enhanced grazing pressure and intensive cultivation practices, have repeatedly led to soil compaction, reduced infiltration and groundwater recharge, and rapid and excessive runoff (Evans, 1990b; Boardman, 1995; Holman, Hollis and Thompson, 2000; Fohrer, Eckhardt and Frede, 2001; JNCC, 2002; Manse, Raven and Bramley, 2002; Moussa, Voltz & Andrieux, 2002; Tollan, 2002). The effect of land drainage on river discharge has also been widely debated and the issue is comprehensively reviewed by Robinson (1990). Field drainage can substantially enhance peak flows by increasing the density of ephemeral streams and inhibiting water flow and storage within the soil matrix (Howe, Slaymaker & Harding, 1967).

Land use impacts on peak flows are generally most pronounced at the small scale, such as the patch, field or hillslope (Tollan, 2002). At small catchment scales, field studies can identify the relative hydrological impacts of specific land uses on increased runoff production, for example, impervious surfaces associated with urbanisation (Hollis, 1974), poaching and compaction of the soil surface from overgrazing (Sansom, 1996; Evans, 1998; Meyles et al., 2002) and lowered soil aggregate stability under intensive arable cultivation (De Roo, 1993; Holman, Hollis & Thompson, 2000). At large catchment scales however, the impact of land use changes has routinely been considered to exert a comparatively minor influence on flood responses as a result of the compensating effects of complex water storage and release mechanisms (Fohrer, Haverkamp, Eckhardt & Frede, 2001).

In addition to the natural heterogeneity in the physical characteristics of the catchment, the distribution and disposition of different land uses may hugely influence catchment response by modifying the connectivity and continuity of drainage lines (Schulze, 2000). Field-scale changes in land use have the potential to alter the hydrological attributes of the land surface considerably by changing the hydraulic properties of the soil, causing a lowering of the catchment wetness threshold (Fitzjohn, Ternan, Williams, Perez-Gonzalez & De Alba, 2002; Meyles et al., 2002). As a result, intensive land uses may increase channel flow by enhancing the degree to which source areas in the catchment become connected (Grayson, Western, Chiew

& Blöschl, 1997; Western, Blöschl & Grayson, 2001). Individual management decisions are ultimately responsible for driving changes in the response of catchment systems.

Given that the magnitude of land use effects will be dictated by the nature and scale of the land use change and is intimately linked to the physical characteristics of the catchment and climate (Dunn & Mackay, 1995), establishing clear linkages between specific land use changes and changes to hydrological responses at the catchment scale poses a formidable problem in hydrological studies. This paper investigates the relationship between changes in agricultural land use and the hydrological response of the Camel River, north Cornwall. Its principal aim is to explore the significance of land management changes on hydrological processes and contribute to discussion regarding the precise nature of these impacts, particularly in relation to floods.

The study is especially timely because of increasing concern in the area about the increased risk of floods and the related impact on fish stocks. As well as existing flood alleviation schemes, increased flood magnitudes have necessitated the construction of further works at Bodmin and Sladesbridge, at an estimated cost of over £3m in 1998 (Environment Agency, 1997). Furthermore, studies undertaken by the Environment Agency (1997) have revealed a reduction in the densities of juvenile salmon locally, as a result of siltation and increased turbidity on the riverbed. Notwithstanding the economic impact on local fisheries, the River Camel and its tributaries have been awarded Special Area of Conservation (SAC) status under the EC Species and Habitats Directive, on account of the presence of Atlantic salmon, Sea trout, Bullhead fish and Otter populations.

Catchment description

The research presented uses a temporal approach to investigate the extent to which climate and land use change has affected the flood response of the Camel catchment system. A spatial approach is also adopted. This separates the headwater subcatchment of the De Lank tributary which drains Bodmin Moor to the east of the catchment, from the Camel catchment, in an attempt to isolate the potential impacts of distributed land uses on river flow. The De Lank subcatchment supports predominantly upland grazing, which contrasts cereal cultivation to the west.

The River Camel drains a 210 km^2 area located in north Cornwall, southwest England. From its source on Bodmin Moor, at approximately 280 m O.D, the river flows 40 km to Wadebridge, before entering the Atlantic Ocean through the estuary at Padstow (Selwood et al., 1998) (Fig. 1).

In the east, the catchment is underlain by granite and predominantly consists of brown podzolic soils of the Moretonhampstead Series, with a humic topsoil. In the south and west, there are Upper Carboniferous and Lower Devonian slates. Soils overlying the slates are loamy, stony, permeable soils of the Denbigh Series (Findlay et al., 1984). Fine, loamy, brown, well-drained soils are typical of the

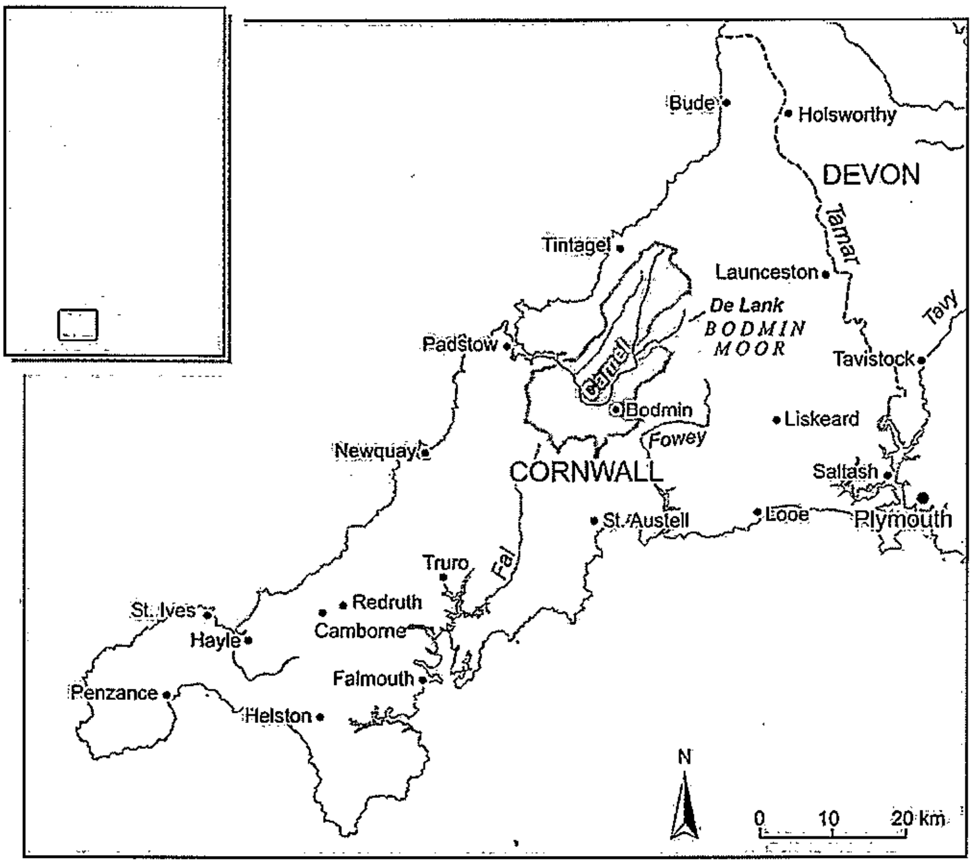

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Fig. 1. Location of the Camel catchment, north Cornwall.

higher land, which rises eastwards towards Bodmin Moor and southwards to the Lower Devonian uplands of St. Breock Downs.

Land use in the catchment is predominantly agricultural. Arable farming is important at lower altitudes in the west, where autumn-sown cereals and rape, potatoes, maize and fodder beet are the most commonly sown crops (Environment Agency, 1997). Camelford and Bodmin form the major urban concentrations in the area and together they account for 3.3% of the catchment (Fig. 2).

The De Lank head-water subcatchment drains a 22 km^2 area to the east (Fig. 1). It rises on acid peats on Bodmin Moor and flows over granite and slate bedrock for 14 km before joining the Camel. The interaction of increasing altitude and rainfall in this area has resulted in a predominance of grassland with sheep and cattle grazing.

Average annual rainfall at Lower Moor, Camelford over the period 1965–2000 was 1600 mmy^{-1}, with the wettest period of the year being over the winter months

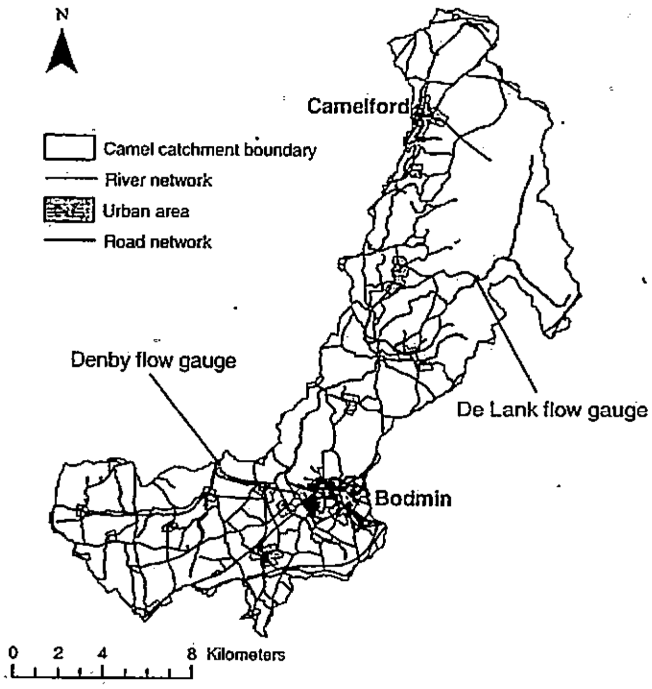


Fig. 2. Location of the Denby and De Lank flow gauges, and the urban extents of Camelford and Bodmin in the Camel catchment.

of October to January. Due to the low permeability of the bedrock, there are no major aquifers in the catchment. Nonetheless, groundwater held in fractures and fissures provides sufficient water for small abstractions (Environment Agency, 1997). These represent approximately 4% of the long-term annual average discharge and are not considered to exert a significant impact on the magnitude of daily flows.

Methodology

Hydrometeorological analysis

A detailed description of the rainfall-runoff characteristics of the Camel catchment was developed from rainfall and river discharge data available on a daily time step only. Patterns in daily rainfall totals for the period 1965 to 2000 were analysed from records measured at Lower Moor, near Camelford, which provide the most complete and reliable data set of three rainfall stations, and standard hydrological techniques were applied to daily mean river discharges at Bodmin (Denby flow gauge) (1965–2000) and De Lank (1970–2000). The three-stage analysis comprised:

1. Daily rainfall totals aggregated on an annual, seasonal and monthly basis and annual maximum daily flows were plotted to reveal any long-term trends.
2. In order to examine the importance of high magnitude rainstorms on peak flows in the River Camel the Gumbel distributions of the annual maximum series of both mean daily flows and daily rainfall totals were produced (Loaiciga & Leipnik, 1999), to represent the probability distribution of flood peaks and high magnitude storm events over the 36-year time frame. The long term flow record was arbitrarily divided into two equal time periods in order to provide 18 data points in each data set. This is consistent with Dunne and Leopold (1978), who have shown that 18 data points are more than satisfactory for flood analyses using the Gumbel distribution. The study did not presuppose trends in flow. Data for the time periods 1965–1982 and 1983–2000 were fitted to the Type III Gumbel (Gumbel, 1958) extreme value distribution and differences in flood frequency and magnitude determined (Yue, Ouarda, Bobee, Legendre & Bruneau, 1999).
3. A seven-day antecedent precipitation index (API^7) was calculated from daily rainfall totals using eq. (1) to characterize antecedent wetness (Weyman, 1975; Houghton-Carr, 1998).

$$API^7 = \sum\left(\frac{P_t}{t} + \frac{P_{t+n}}{t+n} + \frac{P_{t+2n}}{t+2n} \cdots \frac{P_{t+7n}}{t+7n}\right) \tag{1}$$

where API^7 is antecedent precipitation index over seven days; P_t, precipitation on day t, n, number of days prior to the event.

Land use

Long-term changes in the distribution of land use within the catchment are difficult to determine at a low spatial resolution. Due to restrictions relating to farmer confidentiality, the study used Agricultural Census Data (DEFRA, held at Edinburgh University Data Library), aggregated using a 4 km^2 grid, for the years 1969, 1979, 1988, 1997 and 2000, to represent the spatial distribution and the intensity of specific agricultural practices within the area of the catchment draining into the Denby flow gauge.

From these data, the total area of cereal cultivation was extracted and expressed as a percentage cover for each grid square, thereby providing a grid-based characterisation of land use change over the study period. Similarly, the number of livestock units (LU) per hectare was calculated for each grid square to provide a grid-based Pasture Index (PI) to illustrate changes in patterns of grazing. According to DEFRA guidelines (2001), cattle between 6 months and 2 years equal 0.6 LUs, older cattle equal 1 LU and one sheep is 0.15 LUs (DEFRA, 2001). Inconsistencies in the collation of the census data sets means the precise ages of the cattle cannot be accurately determined for each year. Therefore, an average figure of 0.8 was assigned to all cattle, including dairy, that were older than 6 months to represent the range of ages of cattle included in the study (Meyles, 2002).

It is acknowledged that different crop types and additional grazing animals are associated with distinct management practices, growth rates and soil-hydrological impacts but it is beyond the scope of the study to investigate these issues here. The methods were designed to provide a general indication of the extent of agricultural land use across the catchment.

Results

Hydrology

No long term trends were observed in the 36-year record of annual and winter (October to January) precipitation totals recorded at Lower Moor (Fig. 3). In total October daily rainfalls, there is a weak upward trend ($r = 0.3$, $p > 0.05$) (Fig. 4).

The annual maximum daily discharge on the Camel (Denby gauge) shows a rising trend through time (from 1965 to 2000) (Fig. 5) and five of the six highest river flows, ranging from 64 to 150 cumecs occurred within the last decade. Runs tests confirm the trends are not due to randomness. No trend was observed in the annual maximum daily flows from the De Lank headwater tributary over the period 1970–2000 (Fig. 9). However, a differential increase of 9.3% for the River Camel and 8.7% for the De Lank was detected in the median mean daily flow of each river for the periods 1970–1975 and 1994–1999 ($n = 2200$), which represent the temporal extremes.

A comparative study of the Gumbel distributions of daily rainfall totals and mean daily flows on the Camel for the period 1965 to 2000 provided no indication of a relationship between high magnitude rainstorm events and peak flows (Fig. 6).

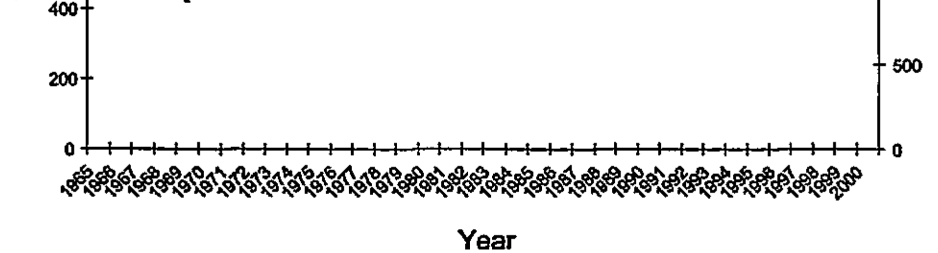


Fig. 3. Total annual and winter (October to January) precipitation for the Camel catchment over the period 1965–2000.

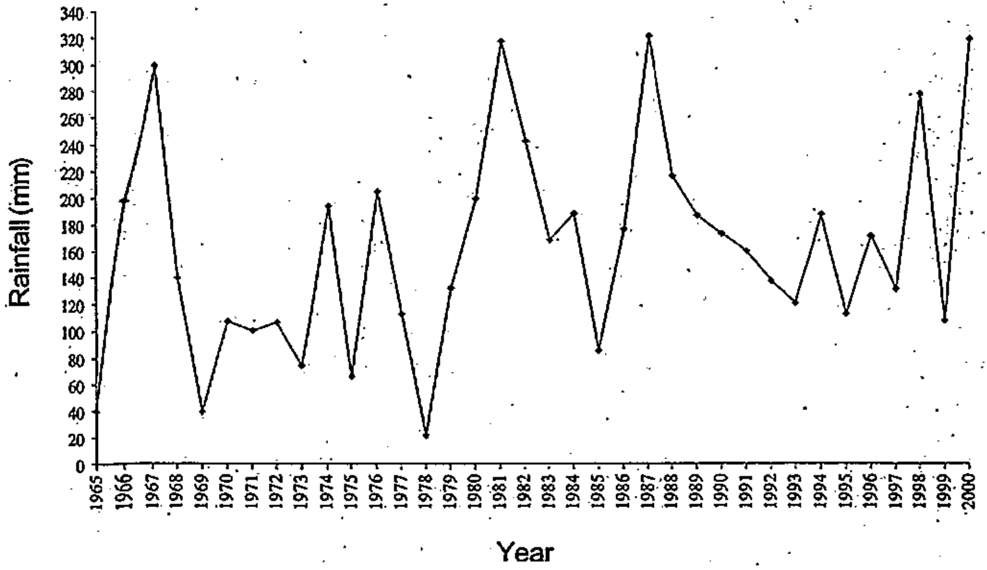


Fig. 4. Total October precipitation for the Camel catchment over the period 1965–2000.

Allowing for storm lag times, the dates of flows with a return period of greater than five years did not coincide with the timing of high magnitude rainstorms, which have less than a two percent chance of occurrence.

The Gumbel Type III distribution of peak flows for the period 1965 to 1982 shows the 1 in 25 years recurrence interval to have a discharge of 96 cumecs

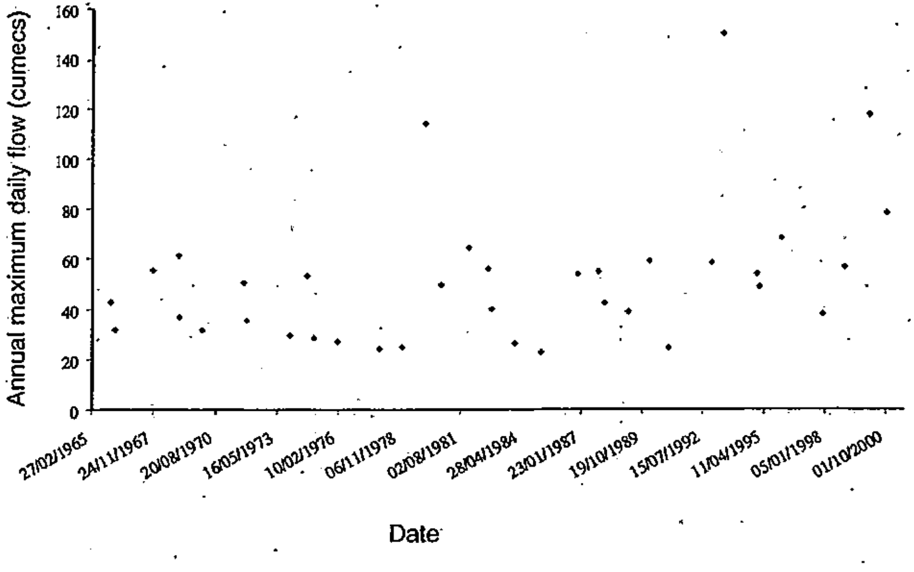


Fig. 5. The annual maximum daily flow in the River Camel over the period 1965–2000.

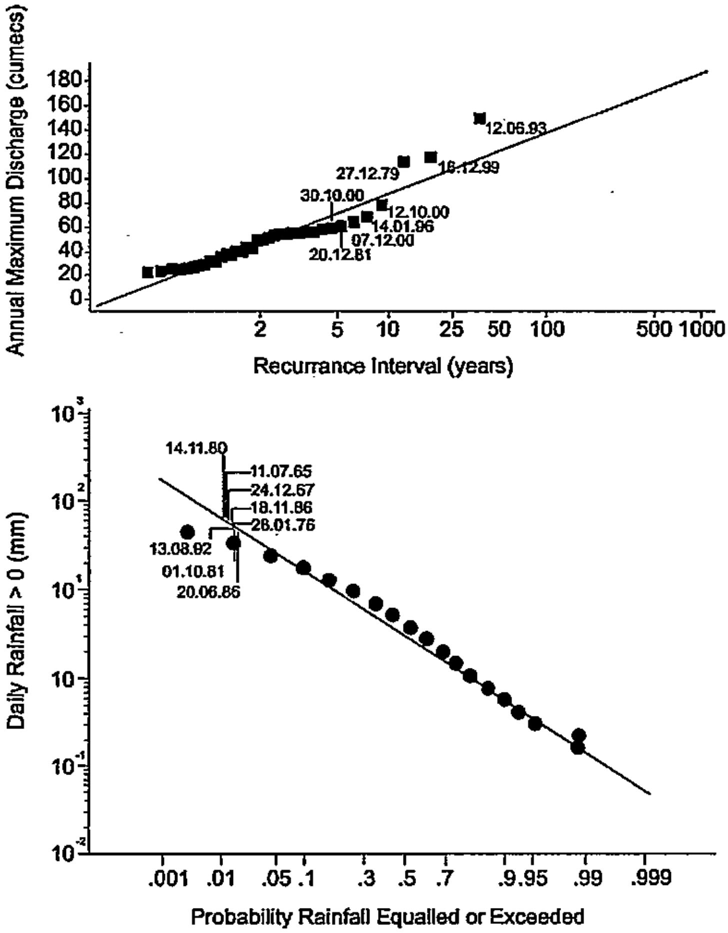


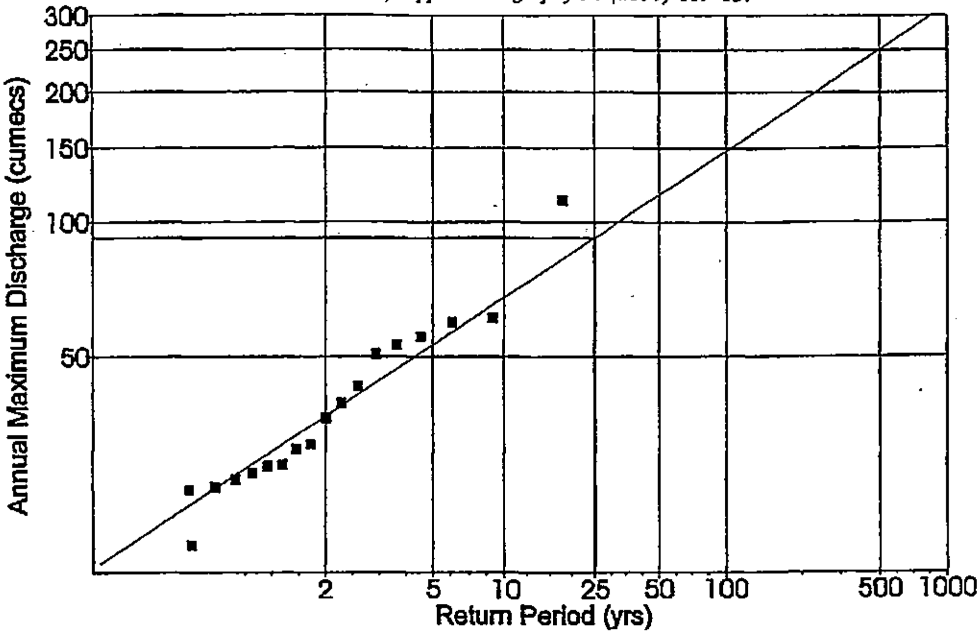
Fig. 6. Gumbel Type III distribution of annual maximum discharge and rainfall for the period 1965–2000. Dates are presented for extreme events.

(Fig. 7a). When mean daily flow records from 1983 to 2000 are fitted to the same distribution, the discharge of a one in 25-year flood has increased by 20% to 115 cumecs over the 36 years (Fig. 7b).

Peak flows in the River Camel are strongly controlled by antecedent wetness (Fig. 8), with a significant positive relationship between API[7] and the annual maximum daily flow ($r = 0.7$, $p > 0.01$).

Land use

Between 1969 and 2000, grazing and cultivation practices in the Camel catchment exhibited progressive changes (Figs. 10a–e and 11a–e). In 1969, 14.9 km^2



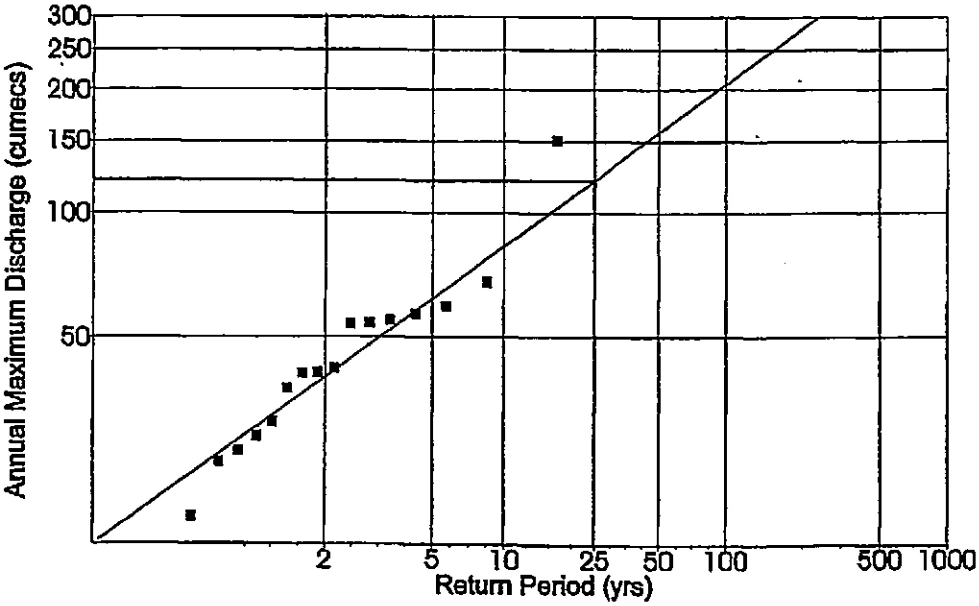


Fig. 7. Gumbel Type III distribution of annual maximum discharge for the periods (a) 1965–1982 and (b) 1983–2000.

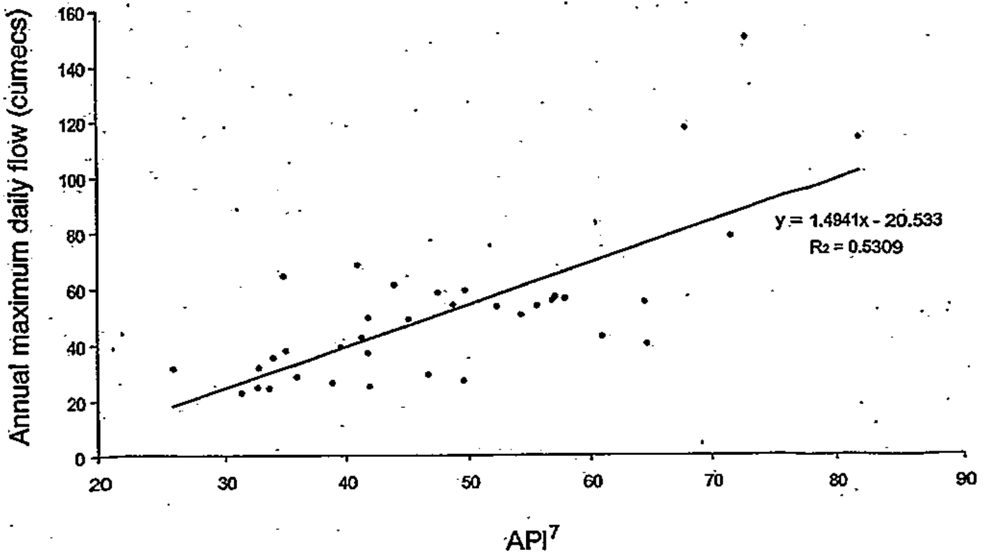


Fig. 8. The relationship between the seven-day Antecedent Precipitation Index (API^7) and the annual maximum daily discharge in the River Camel, over the period 1965–2000.

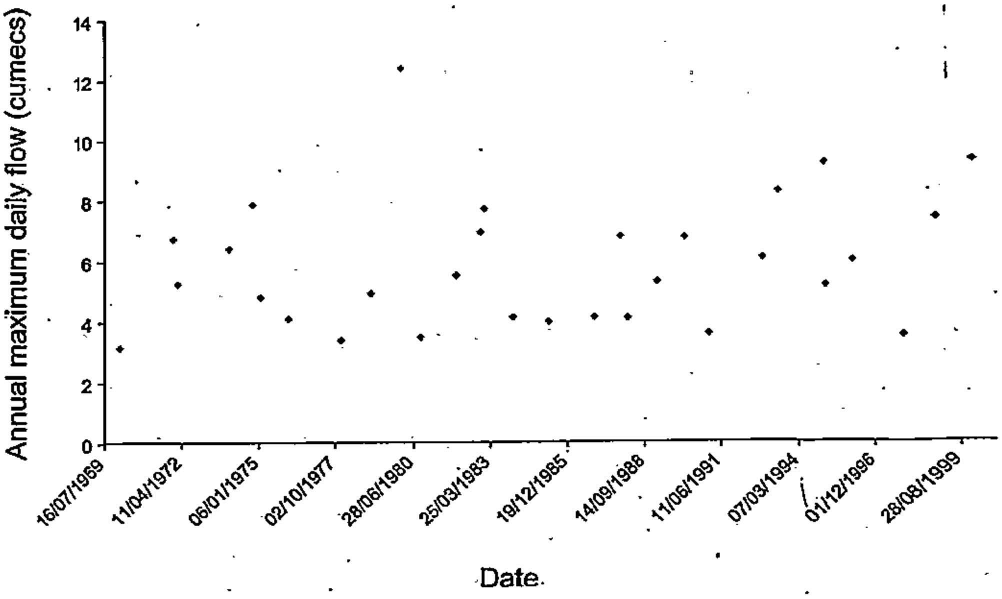


Fig. 9. The annual maximum daily flow in the De Lank River, over the period 1970–1999.

Table 1
Major changes in land use within the Camel catchment, over the period 1969–2000

Year	Range of livestock units (LU) per ha	Total % cover of cereals	Total % cover of wheat	Total % cover of barley	Total % cover of maize	Total % cover of oats
1969	0.15–1.05	5.34	0.29	4.2	0	0.86
1979	0.2–1.27	6.27	0.33	5.7	0.0003	0.26
1988	0.19–1.27	6.96	0.62	6.1	0.06	0.23
1997	0.15–1.3	8.02	1.32	5.5	0.86	0.39
2000	0.06–1.5	6.17	1.17	3.96	0.81	0.24

of the catchment was under cereal production. By 1997, this figure has risen to 25.3 km^2 representing 8% of the total catchment area (Table 1). This increase followed the introduction of maize by 1979 and an expansion of the areas of wheat and barley by 3.4 km^2 and 4.1 km^2, respectively. During the period 1997–2000 there was a notable decline in arable activity, with a reduction in the percentage of the catchment sown to cereals of 1.8% (Table 1). Maximum stocking densities increased over the period 1969–2000 (Fig. 11a–e). In 1969 the maximum grazing pressure equalled 1.05 LU ha^{-1} but by 2000 areas on eastern slopes experienced maximum grazing densities of 1.50 LU ha^{-1} (Fig. 11e). These grazing densities greatly exceed those which are considered satisfactory for open moorland areas under the Environmentally Sensitive Area (ESA) management plan for nearby Dartmoor. The Dartmoor ESA agreement stipulates a stocking level of 0.36 LU ha^{-1} (16 April and 31 October) and 0.17 LU ha^{-1} (1 November to 15 April) (DEFRA, 2001).

Agricultural activity within the catchment is strongly related to the catchment physiography. Cereal cultivation is generally concentrated along lower reaches, close to the main channel (Fig. 10d). Lower grazing pressures in the middle of the catchment, contrast with the higher densities of grazing animals in headwater and higher relief areas along the northern and southern boundaries (Fig. 11d).

Statistics provided by North Cornwall District Council (NCDC) show an increase in the urban area of Bodmin town, located upstream of the Denby flow gauge by 54% since 1965. Today, Bodmin accounts for 2.3% of the catchment area (Fig. 2).

Discussion

A 20% increase in the magnitude of the one in 25 year flow, together with a 3% rise in the median daily flow between the periods 1965–1982 and 1983–2000, support the thesis of an overall increase in the annual maximum daily flow in the River Camel, which is apparent from the 36-year flow record ($r = 0.4$, $p > 0.05$).

In 28 of the 36 years under investigation, the annual maximum daily flow occurred during the wetter winter months of October to January. A temporal study

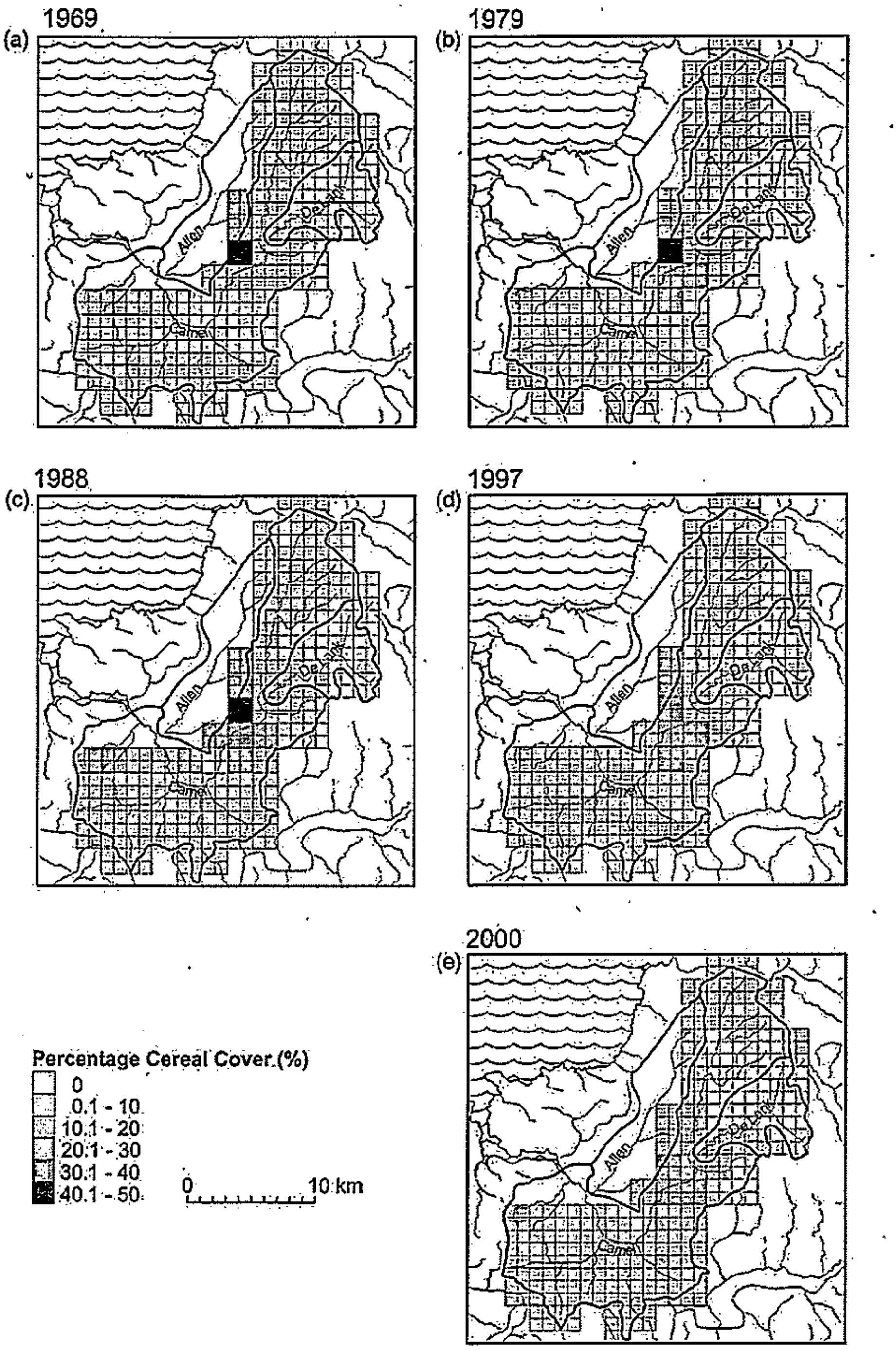


Fig. 10. Percentage cover of cereals in the Camel catchment for the years (a) 1969; (b) 1979; (c) 1988; (d) 1997; and (e) 2000.

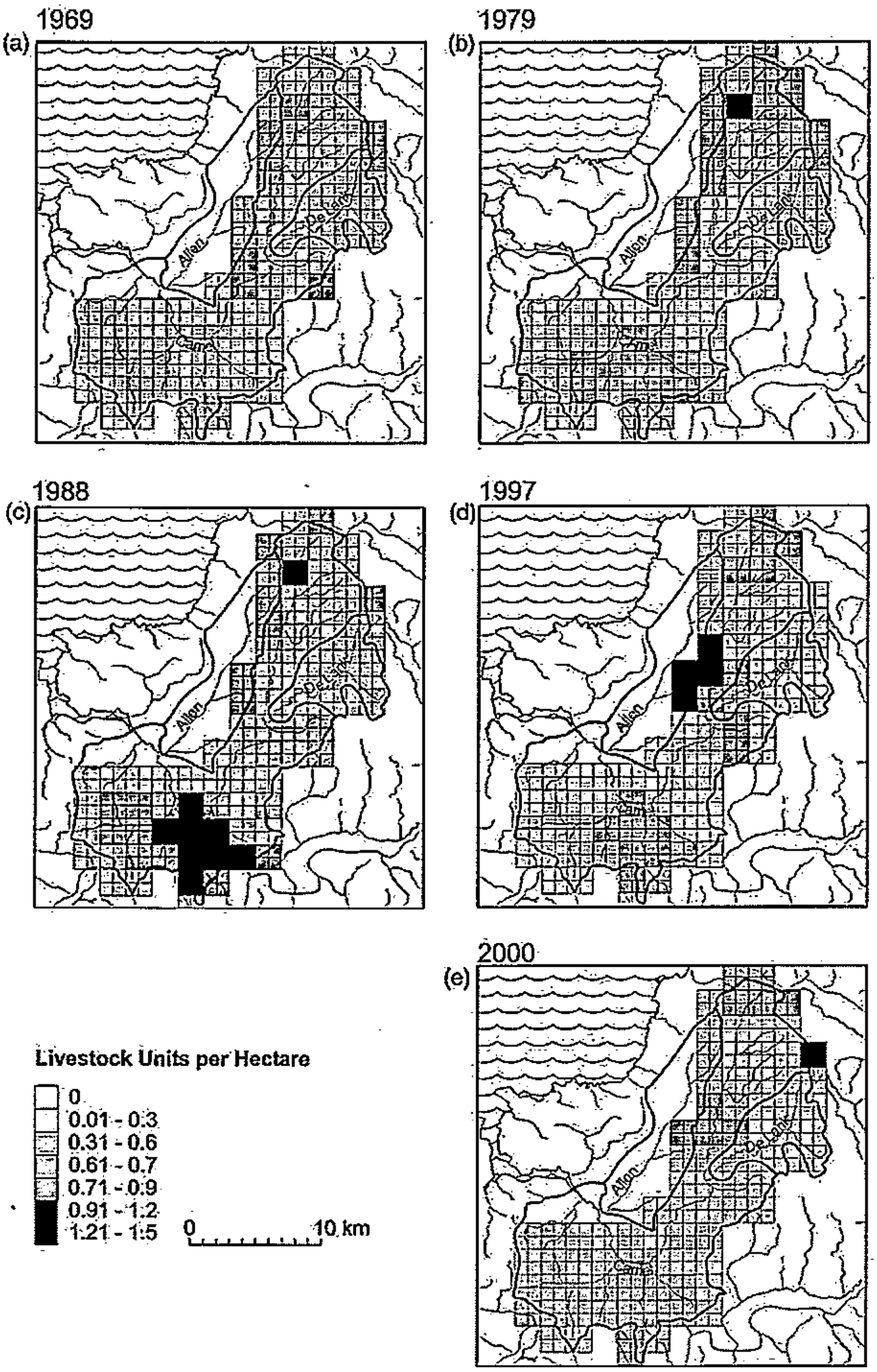


Fig. 11. Distribution of livestock units across the Camel catchment for the years (a) 1969; (b) 1979; (c) 1988; (d) 1997; and (e) 2000.

into the impacts of rainfall on enhanced peak flows has found no evidence of a significant corresponding change in annual and seasonal rainfall patterns that explains the variability in river discharge over the 36 years; no trend was detected in rainfall totals aggregated on an annual ($r = 0.005$, $p > 0.05$) and winter basis ($r = 0.05$, $p > 0.05$) (Fig. 3). It is possible that heightened river discharges in October could be accounted for by a slight upward trend in October daily rainfall totals ($r = 0.3$, $p > 0.05$) (Fig. 4).

During flood events in the River Camel, the volume of runoff is largely controlled by the initial condition of the catchment. The wetter the antecedent state of the catchment, the greater the proportion of incident rainfall that contributes to the flood peak, since the amount of rainfall that is retained as catchment storage diminishes with increasing storm volume (Beven, 1993).

Exploration of the land use data has uncovered a complex picture of land use changes that may well have exerted a fundamental impact on peak flows, by influencing the potential for and rate of water transfer to the channel. In the lower catchment, there is anecdotal evidence to suggest that the cumulative impacts of a 54% expansion of Bodmin town since 1965 and a 3% increase in cereal production between 1965 and 1997 altered the nature of water movement through the system. At Bodmin town, sited approximately 3.5 kilometres upstream of the Denby flow gauge, highly connected surface water is transported rapidly from impervious surfaces to the channel via ephemeral streams, which avoid natural obstacles and inhibit water flow and storage within the soil matrix (Howe, Slaymaker & Harding, 1967; Robinson, 1990; Moussa, Voltz & Andrieux, 2002).

The effect of this urban expansion on the flood response of the River Camel is difficult to isolate from the hydrological impact of arable land uses also focused in the lower catchment. Cereals including wheat and barley and row crops such as maize, take time to provide adequate crop cover, and expose the soil to raindrop forces (De Roo, 1993; Boardman, 1995; Kwaad, van der Zijp & van Dijk, 1998). Cereal cultivation amplifies the risk of capping of the soil surface and consequently, the production of infiltration excess overland flow. Land under wheat and barley, which is left bare or sparsely vegetated for long periods prior to and after sowing, as well as over the wettest months of the year, expanded by 7.5 km^2 between 1969 and 1997. Due partly to the proximity of the cereal cultivation to the channel, this may have increased the likelihood of surface runoff production that is able to contribute to channel flow (Hewlett & Hibbert, 1967; Beven & Wood, 1983; Boardman & Favis-Mortlock, 1993; Blöschl & Sivapalan, 1997; Western, Blöschl & Grayson, 2001).

The capacity for individual land management decisions, undertaken at the field scale, to impact significantly upon catchment response is largely governed by their spatial distribution. For example, much of the maize production is situated in areas adjacent to the main channel. Patterns of rising discharges in the River Camel that are markedly discernible following the early 1980s correspond to changes in maize production, which were introduced between 1969 and 1979 and subsequently increased from 0.2 km^2 in 1988 to 2.7 km^2 in 2000. An increase in runoff from such intensively managed slopes may have a dramatic effect upon river discharge as a result of their high degree of connectivity to the river channel and because these lower lying areas are prone to saturation.

A decline occurred in the area under cereal production between 1997 and 2000, perhaps as a result of a recent shift in agricultural policy towards the integration of environmental protection measures into agricultural practices. A corresponding reduction in the volume of peak runoff is not however apparent at present. This may be due to field drains continuing to act as ephemeral channels or to longer term damage to the soil structure.

An 8.7% increase in the median mean daily flow in the De Lank River was detected between the periods 1970–1975 and 1994–1999. Over a similar timescale, there was a 43% rise in the intensity of maximum upland grazing levels (1969–2000) (Table 1). High soil bulk densities resulting from animal-induced compaction may have increased total runoff amounts and the number of runoff events, as a result of lowered soil porosity, limited soil water storage and saturation (Owens, Edwards & Van Keuren, 1997; Meyles et al., 2002).

Although there was a comparable rise (9.3%) in the median mean daily flow on the River Camel, in contrast to the Camel a long term trend in the annual maximum daily flow was not apparent in this headwater catchment. This would seem to distinguish land uses in the lower catchment as important controls on enhanced peak flows.

The 1993 and 1999, flood peaks in the River Camel which measured 150 and 117 cumecs were traced in the De Lank flow record, where the relative magnitudes of the responses are distinctly lower. Flows in the De Lank reached levels 10.8 and 12.2 times the average flow of 0.76 cumecs as compared to the River Camel, where flood flows were 24.4 and 19.1 greater than the average flow of 6.14 cumecs.

The growing magnitude of the response of the River Camel in comparison to the De Lank sub-catchment combined with its general flashiness during flood conditions, adds weight to the supposition that flow in the River Camel is being progressively supplemented by sources of fast response runoff from highly connected areas in the lower catchment, especially Bodmin town and arable areas adjacent to the main channel.

Conclusion

Over the period 1965–2000, the magnitude of high flows in the River Camel increased. Spatial and temporal approaches point towards a number of potential causes that are associated with both climate and land use changes. Flooding in the River Camel is not the consequence of a discrete problem. The cumulative impacts of a subtle, long-term rise in October rainfall totals, coupled with urban development and the expansion of arable cultivation in the lower catchment, and a rise in the intensity of grazing in the upper catchment, have altered the discharge regime.

The problem is complex, and data limitations as well as the simple methodology adopted, are such that the study is unable to fully characterise the routing of rainfall through the catchment or explain the specific nature of the impacts of changes

to individual land uses on peak flows. Sophisticated techniques, including modelling, may present a clearer picture.

This paper has highlighted the need for a holistic approach to the management of floods, involving a greater understanding of spatially and temporally variable hydrological processes operating across a range of scales. Given the potential future increases in flood risk that are associated with climate change, it is imperative that the impacts of field-scale land use changes on peak flows at the catchment-scale are fully recognised. A failure to understand the implications of diverse land use change impacts on flooding may also serve to direct attention away from the reality that decision-makers already possess the means to address the problem sustainably (Pielke, 1999).

Acknowledgements

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APPENDIX II

List of acronyms

API	Antecedent Precipitation Index
AR_CER	Arable cereals
AR_HORT	Arable horticulture
AR_NONR	Arable non-rotational
AREA	Area of catchment
BAS	Basalts
BAS_IG	Basic igneous
BD	Dry bulk density
BDP	Bog deep peat
BFI	Base flow index
BREC_C	Breccias and conglomerate
C_URB	Continuous urban
CAP	Common agricultural policy
CC	Continuous cereals
CCA	Canonical correspondence analysis
CEC	Cation exchange capacity
CHER	Chert
CL_S_S	Clay, sand and silt
DCA	Detrended correspondence analysis
DD	Drainage density
DDSH	Dense dwarf shrub heath and bracken
DEM	Digital elevation model
DEV	Suburban/rural development
ECP	Exchangeable calcium percentage
ELS	Entry Level Scheme
ES	Environmental stewardship
ESP	Exchangeable sodium percentage
FDR	Frequency domain reflectometry
FEH	Flood estimation handbook
FGAIG	Fine grained acidic igneous
FMS	Fen marsh swamp
FSR	Flood studies report
FW	Farm woodland
FWPS	Farm woodland premium scheme
GAEC	Good agricultural and environmental condition
GIS	Geographic information system
GRAN	Granites
GRS	Grassland (acid/calcareous/neutral)
H_r	Higher runoff generating catchments
HA	Host class 1
HAC	Host class 27
HAD	Water
HAE	Unknown soil type
HB	Host class 2

HC	Host class 3
HD	Host class 4
HE	Host class 5
HF	Host class 6
HG	Host class 7
HH	Host class 8
HI	Host class 9
HJ	Host class 10
HK	Host class 11
HL	Host class 12
HLS	Higher Level Scheme
HM	Host class 13
HO	Host class 15
HOST	Hydrology of soil types
HP	Host class 16
HQ	Host class 17
HR	Host class 18
HS	Host class 19
HT	Host class 20
HU	Host class 21
HV	Host class 22
HW	Host class 23
HX	Host class 24
HY	Host class 25
HZ	Host class 26
I_GRS	Improved grassland
IBG	Inland bare ground
ICM	Integrated catchment management
KSAT	Saturated hydraulic conductivity
L_r	Lower runoff generating catchments
L_SED	Littoral sediment
LCM2000	Land cover map 2000
LST_O	Limestone and Oolite
MAXQ	Peak Discharge
MAXQT	Time to peak
MU_LST	Mudstone and limestone
MU_SLT	Mudstones and silts
MU_SST	Mudstones and sandstones
nMDS	Multiple dimensional scaling (non-metric)
ODSH	Open dwarf shrub heath
OM	Organic matter
OS	Ordnance survey
PCA	Principal components analysis
PP	Permanent pasture
R1	Runoff set one
R2	Runoff set two
RBD	River basin districts
RDA	Redundancy Analysis

RF_AV	Average rainfall intensity
RF_MAX	Maximum rainfall intensity
RF_T	Total rainfall per event
RO	Total volume of runoff per event
RO_1	Runoff bin class 1 (< or = 0.26)
RO_2	Runoff bin class 2 (< or = 0.44)
RO_3	Runoff bin class 3 (< or = 3.5)
RO_4	Runoff bin class 4 (< or = 6.3)
RO_5	Runoff bin class 5 (< or = 14)
ROAD_D	Road network density
RSSI	Rainfall simulation survival index
SD_RFT	Standard deviation of rainfall totals
SET_A	Set Aside
SLOPE	Average slope steepness
SLOPE<12	No. of grid squares 7-12° steep
SLOPE<18	No. of grid squares 13-18° steep
SLOPE<24	No. of grid squares 19-24° steep
SLOPE<30	No. of grid squares 25-30° steep
SLOPE<35	No. of grid squares 31-35° steep
SLOPE<40	No. of grid squares 36-40° steep
SLOPE<45	No. of grid squares 41-45° steep
SLOPE<6	No. of grid squares 0-6° steep
SOM	Soil organic matter
SP	Storage pores
SPP	Semi permanent pasture
SPR	Standard Percentage Runoff
SPR	Standard percentage runoff
SST	Sandstones
STRM_L	Total stream length
TBR	Tipping bucket rainfall
TDR	Time domain reflectometry
TI_10	No. of grid squares with a Topographic Index 0-10
TI_15	No. of grid squares with a Topographic Index 11-15
TI20	No. of grid squares with a Topographic Index 16-20
TI25	No. of grid squares with a Topographic Index 21-25
TI30	No. of grid squares with a Topographic Index 26-30
TP	Transmission pores
TPS	Total porosity
U	Unknown geology type
UNCON	Unconsolidated <64mm in diameter
UP_L	Upper lias
VIF	Variance Inflation Factors
WATER	Water body
WGS	Woodland grant scheme
WOOD	Woodland (coniferous/broad-leaved/mixed)
WSA	Water-stable aggregates
X	Catchment centroid easting
Y	Catchment centroid northing