STUDIES OF SOURCE AREA HYDROLOGY UNDER INDIGENOUS FOREST AND PASTORAL AGRICULTURE IN THE HAPUAKOHE RANGE, NORTH ISLAND, NEW ZEALAND

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CHAPTER 1 - 6

ABSTRACT

This thesis describes a systematic study of hillslope runoff processes and stream flow processes from two forms of land use characteristic of the New Zealand steep land environment: indigenous forest (podocarp-hardwood association) and pastoral agriculture.

In humid temperate environments, hillslope runoff is now recognised to result from a variety of mechanisms, that are dynamic and spatially variable. In these environments, surface and subsurface hillslope runoff processes are dependent on the soil, topographic and vegetation characteristics of individual catchments. The terms 'partial and variable source area models' have been used to describe these concepts and flow processes.

The new concepts of hillslope runoff generation have important implications for the way in which land is managed to maintain desirable stream flow characteristics and stream water quality. However, this information has not been used widely as a basis for land management procedures in areas where conflicts of land and water use occur. This situation has occurred because most of the studies of source area hydrology have been qualitative and have not provided information suitable for use in applied management problems. Also, few comparative land use studies have been established since the new concepts of source area hydrology have been developed.

The main aim of this study was to clarify the processes of hillslope runoff under indigenous forest and pastoral agriculture, and to interpret the hydrologic implications of these two forms of land use on the basis of the new concepts of hillslope runoff.

A comprehensive, integrated study of source area hydrology was established in a steepland catchment supporting the two vegetation types. Although the areas of forest and pasture vegetation were contiguous areas within a single catchment, each vegetation type was treated as a separate hydrologic entity and referred to as an individual catchment. Both 'process' scale experiments and some 'catchment' scale

experiments were established to understand fully the processes of hillslope runoff and the relationships between hillslope flow processes and stream flow processes in the two land use catchments.

An experimental design was developed for this study based on the partial and variable concepts of source area hydrology. The experimental catchments were subdivided into three geomorphically distinct sub-catchment units (riparian, midslope and spur regions) on the basis of a preliminary survey of the spatial distribution of soil moisture.

Data were collected on rainfall, stream flow, surface and subsurface runoff components and soil moisture, during weekly visits to the catchments over a two year period, July 1979 - July 1981. Quantitative estimates of the spatial variability of surface and subsurface hillslope runoff components were made in the sub-catchment units of each land use catchment. The processes of hillslope runoff were also examined within each sub-catchment unit. Additional studies of forest interception processes, soil permeability and other soil, topographic and vegetation characteristics were completed during this period.

The results of this study show that the hillslope runoff regimes are complex in both land use catchments. In each land use, hillslope runoff processes vary spatially and seasonally. The results also show that the differences in hillslope runoff processes are not consistent, either between the sub-catchment units of each land use catchment, or between similar sub-catchment units of both land use catchments. Despite the complexity of the hillslope runoff processes, the integrated stream flow responses from each land use catchment are less variable, and show the differences expected for the two vegetation types.

For most storm events, the spatial distribution of hillslope runoff conforms with the patterns described by the variable source area model of hillslope runoff. However, the mechanisms of hillslope runoff and the causes of the spatial distribution of these processes are not described well by this model.

Infiltration-excess overland flow is generated above the mineral soil in each land use catchment, despite the intermittent, low intensity, rainfall. Infiltration-excess overland flow occurs because the catchment soils are considerably less permeable than in other catchments in similar environments. The spatial distribution of surface runoff is dependent on the spatial variability of soil permeability in each land use that is, in turn, determined by variations of soil moisture in space and time.

Subsurface discharges are also less important in determining the stream hydrograph from the two land use catchments studied, than reported in other studies of similar forms of land use. The catchment soils are so slowly permeable that large volumes of subsurface runoff do not reach the stream channel in time to contribute to storm runoff.

An examination of stream flow processes and water balance data was completed to provide an analysis of the integrated runoff response from the two land use catchments. Compared with the forest, greater stream discharges occur from the pasture land use for all flow regimes. However, the time distribution of the storm runoff response is independent of vegetation type or antecedent catchment conditions. The principal differences in the water balance components from each land use catchment are caused by differences in interception losses: similar transpiration rates were observed for the two vegetation types.

Selective catchment management, of riparian areas in pasture catchments in the Hapuakohe Range, is suggested as a method of improving general stream flow characteristics from these areas, while the multiple use of the land and water resources is maintained. Estimates of the effectiveness of this management strategy are presented. However, the degree to which riparian re-afforestation causes a satisfactory change in stream flow characteristics, depends entirely on the objective of the land management practices proposed for a given catchment.

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TABLE OF CONTENTS

VOLUME ONE

VOLUME TWO

LIST OF FIGURES, TABLES, PLATES AND APPENDICES

LIST OF FIGURES

VOLUME ONE

FIGURE

VOLUME TWO

Page

Page

LIST OF TABLES

VOLUME ONE

TABLE

Page

VOLUME TWO

LIST OF PLATES

VOLUME ONE

PLATE

LIST OF APPENDICES

VOLUME TWO

APPENDIX

CHAPTER ONE

INTRODUCTION

CONTENTS

1.1 INTRODUCTION

This thesis describes a study of the physical processes of runoff production from two characteristic vegetation types - pastoral agriculture and indigenous forest - within a small steepland basin in the Hapuakohe Range, North Island, New Zealand.

Since the advent of predictive hydrology in the 1930s, the development of surface water hydrology has been dictated by the needs of engineering hydrology, principally the data requirements for flood prediction, reservoir design and other downstream channel works (Kirkby, 1978). These demands were satisfied by two simple, yet effective, concepts:

i) Horton's (1933) infiltration-excess theory of surface runoff for estimating the volumes of water appearing in the stream channels after rain;

and ii) Sherman's (1932) unit hydrograph theory for determining the time distribution of runoff following precipitation inputs.

This focus on down stream problems delayed considerably the understanding of source area hydrology (Hewlett and Hibbert, 1967). During the period from 1933 to the 1960s, continued research revealed that the early concepts of source area hydrology described inadequately the processes of runoff generation in upstream areas of many environments. This realisation led to the establishment of several comprehensive field experiments in upstream source areas (e.g. Dunne, 1969), where rainfall-runoff processes can be most easily determined (Freeze, 1972b).

As a result of two decades of intensive research, the mechanisms of runoff generation and their interaction with a wide range of environmental controls are now well understood (Freeze, 1980). However, recent research has not established a simple, universal, concept of runoff production to replace the early rainfall-runoff models. Instead, a great variety of rainfall-runoff mechanisms have been demonstrated in the many environments examined.

The Horton model of infiltration-excess overland flow is based solely on interactions between the net rainfall input and the soil infiltration capacity. These interactions result in storm runoff being generated uniformly over large areas within a catchment. The Horton model of infiltration-excess overland flow has been shown to be most applicable to semi-arid areas with little vegetation cover, or to catchments that have been modified by human activity (Emmett, 1970; Dunne, 1978).

In contrast, the new rainfall-runoff models place a greater emphasis on the spatial variability of the mechanisms governing storm runoff production in catchments. The rainfall-runoff response described by these models has been shown to be highly variable within and between catchments, and is dependent primarily on features of topography, the water storage and transmission characteristics of the soil, and characteristics of land use. The new models have been shown to be most applicable in vegetated catchments in humid temperate environments.

The new models of source area hydrology have been categorised into two major groups (Freeze, 1972b; Dunne, 1978): subsurface flow models; and the partial or variable source area models. In the subsurface flow models, rainfall is transferred to the stream channel via a variety of subsurface routes. The partial area models are characterised by infiltration-excess overland flow, that is generated from restricted, but relatively fixed areas within catchments (Betson, 1964). Runoff responses, originating from restricted, but dynamically variable areas within catchments, are described by the variable source area models (Tennessee Valley Authority, 1965; Hewlett and Hibbert, 1967). In the variable source area models, a combination of surface and subsurface storm flow is generated, usually from near channel areas within catchments. The areas that contribute runoff expand and contract both within and between storm events, and seasonally.

The partial and variable source area models of runoff generation are applicable to many areas in New Zealand (Pearce and McKerchar, 1979). These models have fundamental implications for the way in which land is managed to maintain the quantity and quality of water resources. The great diversity of rainfall-runoff responses described by these new concepts of source area hydrology, has meant that it has become necessary to define carefully the environments in which the different flow mechanisms dominate (Mosley, 1979).

Land use change has been a common feature of the New Zealand environment, the present regimes having evolved comparatively rapidly since European settlement. Exploitative land use, combined with little perception of the environmental consequences of land development in marginal areas, led quickly to conflicts in land use (McCaskill, 1973). The deterioration of plant cover was associated with soil erosion and flooding in many sensitive areas throughout the country.

As the environmental problems developed rapidly, hydrological data were not available from local studies. Thus, early attempts to ameliorate the problems were based on information derived from overseas. These studies emphasised the soil-plant-erosion-runoff continuum and the importance of the protective role of vegetation. Early New Zealand studies supported the overseas findings (e.g. Taylor et al., 1939). The retirement of sensitive hill country, the establishment of protection and production forestry and the improvement of pasture management regimes, have all alleviated the land use problems in areas where such techniques have been applied.

The continuing demands of agriculture, and the expansion of production forestry on unimproved steepland, have led again to a widespread conflict between these two forms of land use (Molloy, 1980). Coupled with this problem has been the question of multiple use of steepland areas, while adequate protection of land and water resources is maintained.

Despite the significant advances in the understanding of source area hydrology, the new concepts have not been applied widely to practical land management problems. Several reasons for this are apparent. In the past, studies of process hydrology and land use change have been conducted on two distinct scales, being either 'catchment' scale experiments (eg. replicated catchment studies) or 'process' scale experiments (eg. interception or infiltration studies) (Courtney, 1980). More recent studies in New Zealand and overseas have tended to combine both approaches (e.g. Clarke and Newson, 1978; Mosley, 1979).

Most 'catchment' scale experiments have been undertaken to quantify the influences of different vegetation covers on water yield, although considerable emphasis has been placed on determining hydrological processes from these data. 'Process' studies, however, have sought to determine the soil-plant-runoff continuum and the hydrological effects of land use change. Even so, most 'process' studies of source area hydrology has been qualitative: there have been few systematic studies of the spatial variability of hillslope runoff processes within catchments (e.g. Yair _et al_., 1978). As these two research methodologies have been conducted in relative isolation, the research completed has not provided the information necessary to apply the present knowledge of source area hydrology to field management problems.

Additional information is required on several critical aspects of source area and land use hydrology to enable the development of rational land management practices. Considerably more research is required to evaluate the role of soil and water interactions as first order modifiers of rainfall-runoff relationships (Watt, 1979). The hydrologically active areas within catchments must be identified, along with criteria that can be used to distinguish easily these areas (Dunne _et al_., 1975). Information on the degree to which these areas differ from the remainder of the catchment is also required, as is an assessment on the degree to which these subareas can be treated or managed as homogeneous units.

Research on the interactions and behaviour of runoff processes following the conversion of forest to pasture, or other forms of land use, is also required to understand the hydrologic implications of the developing land use conflicts in this country and to establish rational land management programmes.

As water resource management decisions are based increasingly on the new concepts of runoff generation, it is necessary to define precisely the environments in which they are dominant. In this way the developing land use conflicts between pastoral farming and forestry production in the marginal and idle steepland areas can be ameliorated. As in the 1930s - 1940s, little local information exists from which land management decisions can be made on the developing land use conflicts. In the absence of such data, watershed managers have again had to rely on overseas research and on predictions based on model studies. To avoid the mis-application of hydrologic principles, detailed information is required on the mechanisms of hillslope runoff processes for sensitive environments where land use conflict occurs.

It is clear that a contribution to the understanding of process hydrology of different forms of land use can be made by developing a comprehensive, systematic study of the rainfall-runoff processes of two land use regimes characteristic of the New Zealand rural environment. To date few studies of this type have been completed.

1.2 THE RESEARCH PROGRAMME

1.2.1 STUDY OBJECTIVES

The principal aim of this research investigation is to clarify the processes of runoff generation from two characteristic land use regimes - pastoral agriculture and indigenous forest - in the Hapuakohe Range, North Island, New Zealand. The Hapuakohe Range is a sensitive steepland area where land use conflict occurs. Two specific areas of research must be considered to achieve this goal.

Few quantitative, systematic studies on the variability of hillslope runoff and the relations between hillslope runoff and stream flow processes have been completed since the advent of partial and variable source area models. The new concepts of hillslope runoff can be extended and quantified, by using the available knowledge on source area hydrology to develop an experimental design that can be used to examine rigorously the components of hillslope runoff within catchments. Process studies within the framework of this type of experimental design are also necessary to quantify the hillslope runoff response from hydrologic response units within catchments.

The complex interactions between hydrologically important soil physical properties, hillslope runoff and land use are not well understood. This deficiency has arisen because few recent comprehensive studies of the processes of hillslope runoff have been completed for contrasting land use regimes. Information of this type is necessary to understand the processes governing the observed runoff response between different forms of land use.

The general aim of this study is thus divided into four major objectives:

i) to identify the mechanisms of runoff production in each land use for selected sub-catchment units considered likely to have homogeneous runoff responses;

ii) to determine the factors (characteristics of soil, topography and vegetation) governing the processes and contributions of the components of the hillslope runoff regime;

iii) to relate the hillslope flow processes to the stream flow characteristics and water balance of each form of land use;

and iv) to use the results to comment on land management practices in the region studied.

An improved understanding of the hydrologic regimes of the two land uses will permit the development of appropriate land management regimes and enable a greater utilisation of the land and water resources of the Hapuakohe Range.

1.2.2 SCOPE OF THE PROPOSED STUDY

The aim and objectives outlined above constrained the study methods and the scale on which they could be achieved most effectively. This study required information on both integrated catchment responses and on detailed processes operating within the catchment boundary for two land use regimes. Thus, the research had to be carried out on a catchment scale, yet include process scale studies within this experimental unit.

The paired catchment technique (Hewlett, et al., 1969) is the most suitable method for comparative land use studies. However, physical constraints precluded the development and calibration of this type of experimental unit. Instead, an observational study of two contiguous land uses was established within a small catchment. Both forms of land use within the catchment were considered as separate hydrological entities. In this way it was still possible to link the individual process studies to an integrated response observed in a stream channel.

CHAPTER TWO

LITERATURE REVIEW

CONTENTS

A review of pertinent aspects of source area hydrology and land use hydrology is presented in this chapter.

2.1 SOURCE AREA HYDROLOGY

The response of a watershed to precipitation has been described as one of the most important, yet least understood, relationships in the science of hydrology (Corbett *et al.*, 1975). The mechanisms by which rainfall makes its way from hillslopes to the stream channel have been the subject of intensive study, since the early 1930s. Yet, only during the last decade has a clear understanding of these processes and their environmental controls been achieved (Freeze, 1980). Reviews of the literature on this subject are available from many sources, but the most comprehensive to date is a collection of monographs edited by Kirkby (1978).

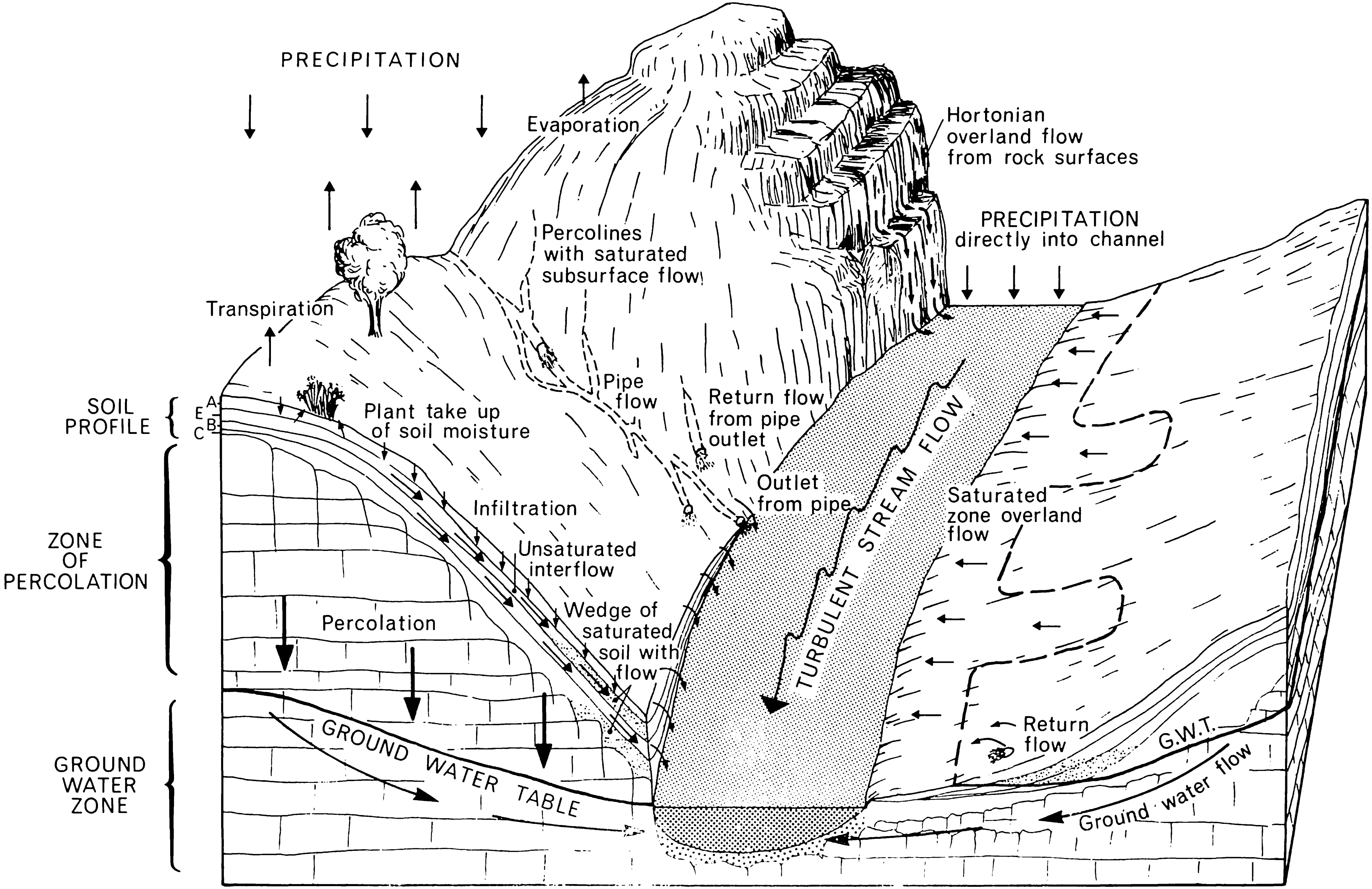
2.1.1 PROCESSES OF HILLSLOPE RUNOFF

Streamflow is an integrated response to interactions between surface runoff, saturated and unsaturated subsurface flow, direct channel precipitation and ground water inputs. The pathways by which precipitation may reach the stream channel are outlined by Dunne (1978). Figure 2.1 shows the different types of runoff from hillslopes and the sources and paths of the runoff water.

2.1.1.1 *Ground water flow*

Channel inflow may arise from ground water flow, derived from deep percolation of infiltrated water that enters the permanent ground water system. Ground water flow provides the low flow component of streams and sustains flow between storm periods. As flow paths tend to be long,

Figure 2.1 : A schematic landscape illustrating the different types of runoff and the sources and paths of the runoff water (after Selby, 1982)


PRECIPITATION
Evaporation
Hortonian overland flow from rock surfaces
Transpiration
Percolines with saturated subsurface flow
PRECIPITATION directly into channel
SOIL PROFILE
A
E
B
C
Plant take up of soil moisture
Pipe flow
Return flow from pipe outlet
Outlet from pipe
Infiltration
Unsaturated interflow
TURBULENT STREAM FLOW
Saturated zone overland flow
ZONE OF PERCOLATION
Percolation
Wedge of saturated soil with flow
GROUND WATER ZONE
GROUND WATER TABLE
Return flow
G.W.T.
Ground water flow

rates of ground water movement are slow and vary usually on a seasonal basis. Most short term variations of stream flow, in response to rainfall, are derived from overland flow or rapid subsurface flow. However, Sklash and Farvolden (1979) describe the occurrence of rapid ground water movement that can provide most of the storm runoff response observed in the stream channel.

2.1.1.2 Subsurface flow

Subsurface flow may occur if infiltrated water encounters an impeding layer within the soil profile, or the underlying parent material. If this occurs the infiltrated water may be diverted laterally through the more permeable upper soil horizons, or in percolines and soil pipes. Greater hydraulic gradients and shorter flow paths mean that subsurface flow may reach the stream channel more rapidly than ground water flow, and in time to contribute to the storm hydrograph. In environments where subsurface flow regimes dominate, rapid rises in ground water levels may also cause significant contributions to storm flow. Where this occurs, it is difficult to distinguish between the two flow regimes.

Conditions for rapid subsurface flow are restrictive (Freeze, 1980). Highly permeable soil horizons and a rapid development of the subsurface flow regime are necessary to deliver enough water in time to contribute to the stream rise. These criteria are satisfied most commonly in forest soils in humid, temperate climates.

2.1.1.3 Surface flow

Saturation of surface layers of the soil and surface ponding are prerequisites for overland flow to develop at any point within a catchment. Surface saturation and surface ponding are now recognised to occur by two distinct mechanisms (Freeze, 1980).

In the first, the soil profile is completely saturated from below. Lateral inflows from upslope may cause the local water table to rise above the soil surface causing an up-welling of previously infiltrated precipitation. By this mechanism, 'return flow', originating as slower subsurface flow, is able to contribute rapidly to the storm hydrograph. Further rain falling on the saturated soil will fail to infiltrate and may move rapidly down slope to the stream channel. This mechanism is referred to as 'direct precipitation on saturated areas' (Dunne, 1969) and occurs often in association with return flow (Musgrave and Holtan, 1964). Contributions from these two mechanisms are difficult to separate and are together called saturation overland flow (Dunne, 1978). Saturation overland flow may occur when rainfall intensities are lower than the infiltration capacity of the surface soil horizons.

In the second case, surface saturation and surface ponding occur when rainfall intensities exceed the infiltration capacity of the soil surface. Ponding occurs on the soil surface by saturation from above, thus initiating 'Hortonian' overland flow. This mechanism forms the basis of the classical model of runoff generation outlined by Horton (1933). Rubin (1966) has shown that two conditions are necessary for the development of ponding by saturation from above. These are:

i) a rainfall rate greater than the infiltration capacity of the surface soil;

and ii) a rainfall duration greater than the time required for the soil to become saturated at the surface.

Freeze (1972b) has suggested that Rubin's first criterion is satisfied only rarely, because rainfall intensities seldom exceed the soil infiltration capacities of vegetated slopes. More recently, Freeze (1980) suggested that Hortonian overland flow is more common in upslope positions within catchments, and is generated from areas where soil infiltration capacities are lowest. In contrast, saturation overland flow is generated where the water table is closest to the soil surface. This occurs more commonly in lower slope positions near the stream channel. Both mechanisms lead to the generation of overland flow from variable source areas that expand and contract through wet and dry periods, albeit for different reasons.

2.1.1.4 Models of hillslope runoff

Dunne (1978) has outlined the occurrence of hillslope runoff processes and their environmental controls. The timing and contribution of runoff vary in response to many characteristics, particularly topography, soil properties, and rainfall characteristics, and less directly with climate, vegetation and land use.

Hillslope runoff processes are described by models, whose structures reflect, not only the influence of the environment and runoff mechanisms, but also the historical development of the science of process hydrology. These models are outlined by Freeze (1972b) and Chorley (1978), who discuss the mechanisms of runoff generation in terms of Hortonian overland flow mechanisms, subsurface flow mechanisms, and partial and variable source area contributions of surface and subsurface flow.

In its simplest form, the Hortonian overland flow model is most applicable in regions of arid to sub-humid climates with soils that support sparse vegetation. Hortonian overland flow also occurs in other environments where the soils have been modified by the activities of man. In regions of humid climates with dense vegetation, partial and variable source area models are more appropriate. These models best describe hillslope runoff processes on gentle, concave slopes with wide valley bottoms, where soils are thin and have a moderate permeability. Subsurface flow mechanisms predominate in similar environments, but particularly where slopes are steep and convex with incised channels and very permeable soils.

It is well established that Hortonian overland flow and subsurface flow models represent end members of a wide spectrum of rainfall-runoff regimes (Dunne, 1978). Partial or variable source area models form the basis of a range of models, that have become recognised as being intermediate between the two extremes (Hewlett and Nutter, 1970). Recent theoretical and field studies have demonstrated the great diversity of response mechanisms that can operate within catchments from similar environments (Walling, 1977). These studies show that hydrographs result from a varying mix of Hortonian overland flow, saturation overland flow and unsaturated/saturated subsurface flow (Dunne and Black, 1970a).

As a result of the continued research, the traditional boundaries between the models of hillslope runoff have become eroded and more diffuse with time. For example, Yair et al. (1980) discuss the expansion and contraction of areas of Hortonian overland flow generated in steep talus slopes in the Negev desert. The apparent diversity and observed complexity of rainfall-runoff processes have meant that catchment behaviour is explained more accurately by the fundamental concepts of runoff generation, instead of by the application of simplified model structures.

The fundamental concepts associated with each of the main models of process hydrology have been identified from the literature surveyed. Table 2.1 shows the historical development of these concepts. In table 2.1, the concepts have been grouped to enhance the distinction of the model structures. However, there is considerable overlap between concepts that are accepted as 'diagnostic' criteria for the three models of hillslope runoff. For example, the importance of seasonal moisture variations on the runoff regime is recognised as a principal concept in the variable source area model. However, Horton (1933) also identified the importance of seasonal moisture variation in the infiltration-excess model of hillslope runoff.

Concepts embodied in: i) Horton's rainfall excess model

ii) Partial and variable source area models

iii) Subsurface flow models

Author	Year	Stream flow	Deep seepage - ground water	Depression storage	'Hortonian' overland flow	Rainfall duration	Rainfall intensity	Infiltration capacity	Soil moisture	Soil physical properties	Basin morpho-metry/geology	Other	Land use - vegetation	Seasonal variation	Spatial variation	Topography - slope form	Dynamic source area	Saturation overland flow	Translatory overland flow	Flow divergence - convergence	Subsurface flow: diffuse	Subsurface flow: concentrated	Channel precipitation	Deep seepage - ground water	Stream flow	Year	Author
Horton	1931	*	*	*	*	*	*	*	*																	1931	
Sherman	1932											*														1932	
Horton	1933	*	*	*	*	*	*	*	*				*	*												1933	
Horton et al.	1934		o	o	o						o															1934	
	1934									*							*				*				*	1934	Lowdermilk
Horton	1935			*	*								*													1935	
Musgrave	1935	*		*	*			*																		1935	
	1936																				*				*	1936	Hursh
Baver	1937							o	o	o																1937	
Horton	1937	*	*	*	*	*	*	*	*	*			*	*												1937	
	1938																									1938	
	1939	*	*		*																*				*	1939	Barnes
Ree	1939			o	o																					1939	
		1940 - 1950 Numerous Infiltration Soil Erosion Studies by the U.S.D.A.																									

U.S.D.A. - United States Department of Agriculture

Table 2.1: The historical development of the fundamental concepts of hillslope hydrology

Fundamental Concepts Author	Year	Stream flow	Deep seepage - ground water	Depression storage	'Hortonian' overland flow	Rainfall duration	Rainfall intensity	Infiltration capacity	Soil moisture	Soil physical properties	Basin morphometry/geology	Other	Land use - vegetation	Seasonal variation	Spatial variation	Topography - slope form	Dynamic source area	Saturation overland flow	Translatory overland flow	Flow divergence - convergence	Subsurface flow: diffuse	Subsurface flow: concentrated	Channel precipitation	Deep seepage - ground water	Stream flow	Year	Fundamental Concepts Author
	1941									*			*		*						*		*	*	*	1941	Hursh & Brater
	1941								*	*			*								*	*	*	*	*	1941	Hursh & Hoover
	1942								*	*											*			*		1942	Hursh & Fletcher
Bodman & Coleman	1943							o	o	o																1943	
	1943						*	*		*		*	*			*	*				*	*			*	1943	Hoover & Hursh
	1943						*														*				*	1943	Horner
Schiff	1943	*			*	*	*						*	*												1943	
	1944																					*		*	*	1944	Barnes
	1944								*	*				*	*		*				*	*		*	*	1944	Hursh
Sherman	1944							*	*	*																1944	
Horton	1945	*	*	*	*	*	*	*	*		*			*												1945	
Cook	1946	*	*	*	*	*	*	*	*				*	*Era of Infiltration Studies*												1946	
	1947				*										*			*			*					1947	Kirkham
	1948																									1948	
	1949																									1949	
	1950					*															*	*		*	*	1950	Roessel

Table 2.1 cont../

Fundamental Concepts		Stream flow	Deep seepage - ground water	Depression storage	'Hortonian' overland flow	Rainfall duration	Rainfall intensity	Infiltration capacity	Soil moisture	Soil physical properties	Basin morpho- metry/geology	Other	Land use - vegetation	Seasonal variation	Spatial variation	Topography - slope form	Dynamic source area	Saturation overland flow	Translatory overland flow	Flow divergence - convergence	Subsurface flow: diffuse	Subsurface flow: concentrated	Channel precipitation	Deep seepage - ground water	Stream flow		Fundamental Concepts
Author	Year																									Year	Author
	1951									*											*					1951	Reeve & Kirkham
	1952																									1952	
	1953																									1953	
	1954							*		*												*				1954	Fletcher et al.
	1954								*						*	*					*					1954	van't Woudt
Hansen	1955							o																		1955	
	1955								*						*	*					*	*				1955	van't Woudt
Schumm §	1956				*		*	*			*															1956	
Phillip	1957						o	o	o	o																1957	
Phillip	1958						o	o	o	o																1958	
	1959																									1959	
	1960								*					*		*										1960	Stoeckeler & Curtis
	1961								*	*					*	*	*				*	*			*	1961	Hewlett
	1961								*	*					*	*	*				*	*			*	1961	U.S.F.S.
	1962								*	*			*	*	*											1962	Helvey & Hewlett
	1963															o	o				o			o	o	1963	Hewlett & Hibbert

§ 1956a, 1956b

U.S.F.S. - United States Forest Service

Table 2.1 cont../

Fundamental Concepts Author	Year	Stream flow	Deep seepage - ground water	Depression storage	'Hortonian' overland flow	Rainfall duration	Rainfall intensity	Infiltration capacity	Soil moisture	Soil physical properties	Basin morpho- metry/geology	Other	Land use - vegetation	Seasonal variation	Spatial variation	Topography - slope form	Dynamic source area	Saturation overland flow	Translatory overland flow	Flow divergence - convergence	Subsurface flow: diffuse	Subsurface flow: concentrated	Channel precipitation	Deep seepage - ground water	Stream flow	Year	Fundamental Concepts Author
	1963							*											*							1963	Rubin & Steinhart
Schumm & Lusby	1963	*		*	*	*	*	*						*												1963	
Betson	1964	*			*	Partial Area Concept									*											1964	
	1964								*	*			*	Dynamic source area							*	*			*	1964	T.V.A.
	1965								*	*									*							1965	Horton & Hawkins
	1965								*	*						*					*	*			*	1965	Whipkey
Rubin	1966							o	o	o																1966	
	1966									*									*			*				1966	Zimmerman _et_ _al_.
	1967								*					*	*		*	*					*		*	1967	Hewlett & Hibbert
	1967				*	*	*	*	*	*	*		*	*	*	*	*	*		*	*				*	1967	Kirkby & Chorley
	1968					*	*	*									*	*			*	*			*	1968	Patric & Swanston
	1968					*	*	*	*	*			*	*	*		*				*		*		*	1968	Ragan
	1969								*	*								*							*	1969	Betson & Marius
	1969					*	*	*	*	*				*	*	*	*	*		*	*		*	*	*	1969	Dunne
Freeze	1969					o	o	o																		1969	
	1969													*	*	*	*				*	*			*	1969	Tischendorf

T.V.A. - Tennessee Valley Authority

Table 2.1 cont../

Fundamental Concepts		Stream flow	Deep seepage - ground water	Depression storage	'Hortonian' overland flow	Rainfall duration	Rainfall intensity	Infiltration capacity	Soil moisture	Soil physical properties	Basin morpho- metry/geology	Other	Land use - vegetation	Seasonal variation	Spatial variation	Topography - slope form	Dynamic source area	Saturation overland flow	Translatory overland flow	Flow divergence - convergence	Subsurface flow: diffuse	Subsurface flow: concentrated	Channel precipitation	Deep seepage - ground water	Stream flow		Fundamental Concepts
Author	Year																									Year	Author
	1969								*	*												*			*	1969	Whipkey
	1970					*	*	*	*	*				*	*	*	*	*		*	*		*	*	*	1970	Dunne & Black §
Emmett	1970	*		*	*	*	*	*	*				*													1970	
	1970					*	*		*	*			*	*	*		*	*	*		*	*	*		*	1970	Hewlett & Nutter
	1970								*	*					*	*	*				*	*			*	1970	Weyman
	1971								*	*			*								*	*				1971	Aubertin
	1971									*							*					*			*	1971	Jones
	1972					o	o	o	o	o					o	o	o	o		o	o		o	o	o	1972	Freeze†
	1972								*				*	*	*											1972	Helvey et al.
	1973								*	*						*					*	*			*	1973	Weyman
Bauer	1974					o	o	o	o	o																1974	
	1975								*				*		*	*	*	*			*		*		*	1975	Corbett & Sopper
	1975					*	*	*	*	*				*	*	*	*	*		*	*		*	*	*	1975	Dunne et al.
	1975								*			*		*	*	*										1975	Murray et al.
	1976						+	+	*	+	+			+	+	+	+	*	o	+	+				+	1976	Kirkby et al.

§ 1970a,1970b
† 1972a,1972b

Table 2.1 cont../

Fundamental Concepts		Stream flow	Deep seepage - ground water	Depression storage	'Hortonian' overland flow	Rainfall duration	Rainfall intensity	Infiltration capacity	Soil moisture	Soil physical properties	Basin morpho-metry/geology	Other	Land use - vegetation	Seasonal variation	Spatial variation	Topography - slope form	Dynamic source area	Saturation overland flow	Translatory overland flow	Flow divergence - convergence	Subsurface flow: diffuse	Subsurface flow: concentrated	Channel precipitation	Deep seepage - ground water	Stream flow		Fundamental Concepts
Author	Year																									Year	Author
	1977								*					*	*	*	*			*	*			*	*	1977	Anderson & Burt[§]
	1977					*	*	*	*	*											*	*				1977	Bouma et al.
	1977								*	*			*		*	*	*				*	*	*		*	1977	Harr
	1978								*						*	*	*	*		*					*	1978	Beven
	1978					*	*	*	*	*			*	*	*	*		*			*	*			*	1978	Bonell & Gilmour
Yair et al.	1978	*			*	*	*	*							*	*	*									1978	
Bren & Turner	1979	*			*	*	*						*													1979	
	1980					o	o	o	o	o					o	o	o	o		o	o			o	o	1980	Freeze
	1980								*	*	*	*			*	*				*	*	*			*	1980	Gilman & Newson
Yair et al.	1980	*			*	*	*	*	*	*			*	*	*	*	*	*								1980	
	1981								*			*		*	*	*				*						1981	Dunin & Aston
	1981							o	o	o											o	o				1981	Germann & Beven[†]
	1980					o	o	o	o	o					o	o	o	o		o	o			o	o	1981	Murray
	1981								o	o					o	o	o			o				o	o	1981	O'Loughlin
Tricker	1981							*					*	*	*											1981	
	1982								*	*			*		*	*	*			*	*	*			*	1982	Mosley

[§] 1977a, 1977b, 1978a, 1978b

[†] 1981a, 1981b

Included in the table are a list of papers dealing with aspects of hillslope hydrology. Adjacent to the authors names are a series of columns identifying the 'diagnostic' concepts used to describe the hillslope processes observed. Topics covered in the papers are noted in the appropriate column by an '*' for field studies and an 'o' for model or experimental studies. Topics examined by a combination of research methodologies (e.g. field and model studies) are denoted by a '+'. The list is not comprehensive, but includes those papers that describe a significant contribution to the development of hillslope hydrology.

Table 2.1 shows that the development of process hydrology has been through the improved understanding of the mechanisms of hillslope runoff and the interactions between surface and subsurface flow regimes. The following discussion considers the development of hillslope hydrology outlined in table 2.1.

2.1.2 HISTORICAL DEVELOPMENT OF HILLSLOPE HYDROLOGY - an outline

2.1.2.1 The infiltration approach to hillslope hydrology

In 1931 Horton introduced his concepts on the relationships between storm runoff, infiltration and rainfall. Two years later, he outlined in full, a model of hillslope hydrology based on infiltration theory and surface runoff. Horton (1933) implied that infiltration-excess overland flow is common and widespread.

Central to Horton's model is an analysis of infiltration based on the simple division of rainfall into two components.

> 'Infiltration divides [rainfall] into two parts .... One goes via overland flow and stream channels ... , the other goes initially into the soil and thence through the ground water flow to the stream.'
>
> (Horton, 1933, p. 446)

Two further assumptions were postulated.

i) In a prolonged storm of constant intensity, the infiltration capacity decreases continuously until a constant low value is reached. The decrease in infiltration was attributed to an increase in surface moisture, rain drop packing of the surface particles, air entrappment, the closing of drying cracks, the swelling and break down of soil structure and the clogging of pores by the in-washing of fine particles (Horton, 1933, 1937).

ii) For prolonged rainfall, overland flow is produced uniformly over the slope at any time the infiltration capacity falls below the rainfall intensity, but only provided the surface detention storage capacity is full.

Steady-state conditions occur if these processes continue for a sufficient duration. If the rain intensity falls below the infiltration rate, the infiltration-excess diminishes progressively from the head of the slope (Horton, 1937). Recovery of the infiltration capacity begins following slope drainage. Depending on soil characteristics and soil drying, this takes between a few hours and several days, but the infiltration capacity is usually at a maximum before the next rain (Horton, 1933).

Horton extended his theories to encompass many aspects of fluvial geomorphology and finally to the development of drainage basins (Horton, 1933, 1935, 1937, 1945). During the development of this model, Horton identified several of the factors now recognised to be important in controlling infiltration. He suggested that infiltration capacities were influenced by variations in soil physical properties, soil moisture and land use or vegetation. In turn, variations in infiltration capacities determined differences in runoff behaviour within and between catchments, but did not cause changes in the mechanisms of runoff generation.

Horton (1933) identified the importance of seasonal variations of infiltration on hillslope runoff regimes, but he failed to recognise the importance of spatial variations of infiltration within catchments. This factor was not appreciated widely until the early sixties, when its recognition had major implications for hydrologists' interpretations of process hydrology.

The experimental studies of infiltration by Baver (1937) verified the decline of infiltration rates with time. He also noted the importance of soil horizons of differing permeability in governing final, steady-state infiltration rates. Bodman and Coleman (1943) concluded that the decrease of infiltration rates is a result of physical laws controlling the rate of water entry into soils. These theories were examined further by Rubin (1966), who used simplified assumptions of infiltration to remove the confusing effects of hysteresis, soil structural changes and field heterogeneity from his analyses. The hydraulics of the wetting front were examined by Hansen (1955) who showed the rate of water entry is greater for prewetted soils than for dry soils. Phillip (1957, 1958) examined the development of the wetting front and the processes of water transmission behind the wetting front.

Early field verification of infiltration-excess overland flow was provided by Musgrave (1935), who studied the relationships between infiltration, rainfall and runoff on small plots. Numerous infiltration-runoff-soil erosion studies were initiated during the 1940s by the United States Department of Agriculture (U.S.D.A.). These studies further strengthened Horton's suppositions on rainfall-runoff relationships.

However, several deficiencies in the infiltration approach were outlined in a review by Cook (1946). The separation of surface runoff from base flow had been difficult in catchments where infiltration capacities were high, and where large volumes of the storm runoff response were derived from ground water flow. In catchments with delayed storm flow responses, overland flow travel times could not be reconciled with observed stream responses without the use of correction factors. A shortage of information on the fluctuations of infiltration during intermittent rainfall was reported. The difficulties in reconciling surface runoff volumes observed in the stream channel with measured infiltration rates were also described. Schiff (1943) also discussed the variations of infiltration-excess overland flow with respect to rainfall patterns and rainfall distribution. He observed that calculated infiltration curves varied markedly in response to rainfall parameters, even when catchments were in similar antecedent conditions.

2.1.2.2 The development of subsurface flow models

Most research on process hydrology during the 1930s - 1940s was concentrated on the development and applications of the Horton model of runoff generation. However, some studies had provided evidence to show that Horton's model was not universally applicable.

Observations made in small forested catchments during this period had shown that overland flow is rare. Instead, subsurface storm flow along soil layers, and ground water movement near channels were proposed to account for a major portion of the hydrograph peak. Lowdermilk (1934) suggested that 'a dynamic form of subsurface storm flow, shallow seepage or discharge from wet weather springs', was associated with certain soil profiles. This process could not be considered true overland flow nor true ground water discharge. Hursh (1936) proposed the term 'subsurface storm flow' to describe 'storm water' that had infiltrated, but moved down slope through upper soil horizons much faster than normal ground water seepage.

The importance of strongly differentiated soil horizons in initiating lateral subsurface flow was discussed by Hursh and Brater (1941). Hoover and Hursh (1943) concluded that, under certain conditions, soil characteristics control basin runoff more than slope form and basin morphometry. Hursh (1944) discussed the importance of concentrated lateral flow through biological channels in upper soil horizons. Significantly, he suggested that traditional flow theory might not apply in these channels. Reeve and Kirkham (1951) discussed the relationships between soil anisotropy and lateral subsurface flow.

Many of the concepts recognised now as being important determinants of subsurface flow were discussed by the authors cited above. However, the relationships between rapid stream rises and subsurface flow regimes remained uncertain. Hursh (1944) proposed several hypotheses to account for stream rises in the absence of overland flow. These included ground water rise that discharged laterally through the permeable surface soil horizons, and lateral flow initiated from the formation of a perched water table that was independent of the position of the true water table.

Barnes (1939, 1944) presented one of the first practical applications of the concept of stream runoff derived from subsurface sources. He developed a graphical method for separating components of storm flow into subsurface flow, storm seepage and ground water.

During the next decade, research on overland flow and subsurface flow mechanisms continued in parallel, although the Hortonian model was still accepted and bolstered by the findings of geomorphological research in semi-arid areas (Schumm, 1956a, 1956b) and the requirements of engineering hydrology (Freeze, 1972b).

2.1.2.3 The development of partial and variable source area models

The two individual lines of research described above coalesced in the early 1960s. This occurred for two main reasons. Firstly, further measurements and inferences became available regarding the occurrence of subsurface flow (Chorley, 1978). Unsaturated subsurface flow had been shown experimentally to maintain base flow for up to 145 days without rainfall (Hewlett and Hibbert, 1963). Whipkey (1965, 1967) simulated high intensity rainfall on experimental plots and found that individual soil layers produced hydrographs similar in shape to those observed in stream channels. Impeding layers, close to the soil surface, were shown to cause extensive saturation in the near surface horizons. Subsurface flow could thus be expected to contribute significantly to storm runoff, particularly in forested catchments.

However, Weyman (1970) demonstrated that the subsurface flow response is delayed considerably when vertical percolation is unobstructed. As overland flow was not observed in his study catchments, he suggested that flow through structural fissures and biogenic channels must provide the bulk of the storm runoff observed in the stream channels.

Although the occurrence of subsurface flow had been established, Freeze (1972b) doubted that this process could deliver sufficient volumes of water in time to cause the hydrograph peak. Published examples of subsurface flow hydrographs have been mostly for artificial storms, with intensities that seldom occur in natural rainfall (Dunne, 1978). In all, but the most permeable soils, Freeze (1972b) considered the main role of subsurface flow should be restricted to generating areas of surface saturation from which saturation overland flow could develop.

Secondly, it became recognised that the entire catchment may not contribute to storm runoff. The acceptance that soil properties are more spatially variable than Horton had assumed was coincident with this concept. Studies by van't Woudt (1955), Stoeckeler and Curtis (1960) and Hewlett (1961), showed that upslope soils tend to be drier than those nearer the stream channel. Results from studies by Helvey and Hewlett (1962) supported these findings. They found that spatial and seasonal soil moisture variations are correlated positively with increasing distance from the stream channel.

The importance of spatially variable runoff processes was recognised more or less simultaneously by several researchers. Almost identical models of storm runoff were developed by the United States Forest Service (U.S.F.S.) (1961) and the Tennessee Valley Authority (T.V.A.) (1964). Both models incorporated a 'dynamic' concept of catchment runoff behaviour.

Variations of streamflow in small upland watersheds were explained by the formation of saturated areas marginal to streams and in concave hollows. These saturated areas develop when subsurface flow from upslope exhausts the moisture storage capacity of near channel soils. By these mechanisms, the saturated areas expand and contract depending on rainfall, soil and topographic characteristics (Hewlett and Hibbert, 1967). In prolonged rain storms, previously infiltrated water may come to the soil surface and travel rapidly to the stream channel, and so contribute to the observed storm runoff response. Hewlett and Nutter (1970) considered the development of saturation overland flow by this mechanism as an effective increase in channel length.

Earlier, the concept of spatial variability of infiltration capacities was used to improve predictions of the volumes of storm runoff from small drainage basins (Betson, 1964). A scaling factor was incorporated in his catchment model to reconcile predicted and observed runoff volumes. The scaling factor was interpreted as the proportion of the catchment area producing overland flow during a storm. Betson (1964) introduced the term 'partial area concept' to describe this mechanism of runoff generation.

The distinction between infiltration-excess overland flow and saturation overland flow was coincident with the recognition of the spatial variability of surface and subsurface flow regimes. Kirkby and Chorley (1967) identified areas within catchments that might be expected to produce overland flow at rainfall intensities much lower than required to produce infiltration-excess overland flow. Included were zones marginal to stream channels, topographic hollows, and areas of thin soils. These areas produce overland flow preferentially, for reasons of higher antecedent moisture, convergence of subsurface flow lines, and lower initial available soil moisture storage.

The development of the models of hillslope runoff suggested a need for field investigation of the mechanisms by which water reaches the stream channel (Dunne, 1978). It has been toward these goals that the more recent research on source area hydrology has been directed.

2.1.2.4 Recent developments in source area hydrology

2.1.2.4.1 Continued field experimentation

Numerous recent field studies have highlighted the wide diversity of runoff responses from a range of environments (Dunne, 1978). Dunne (1969) describes a 'benchmark' field study of hillslope runoff processes following the acceptance of the partial and variable source area models. He investigated the hydrologic response of three adjacent grassed slope units, with contours that were respectively convex, concave and straight (Dunne, 1978). The straight and divergent plots rarely contributed hillslope runoff in any form. Instead, the storm runoff response was derived from direct precipitation into stream channels, and from saturation overland flow. Saturation overland flow was generated from areas adjacent to the stream channel and from the convergent slope units

(Dunne, 1969). Subsurface contributions to storm flow were small for all three plots, although they increased significantly in the autumn and winter months.

The contributing areas were mapped and observed to vary with season and during storms (Dunne, 1969). The differences in contributing areas observed between the three slope units emphasised the importance of topography in determining the areas of runoff generation. However, the simple effects of this variable were complicated by variations in soil physical properties (Dunne *et al.*, 1975).

The role of topography in controlling the spatial pattern of subsurface saturation has been examined further by Anderson and Burt (1977a, 1977b, 1978a, 1978b). Variations of the soil moisture regime were monitored in single hillslope hollows and adjacent spurs. The maximum extension of subsurface saturation was shown to coincide with the stream 'throughflow' discharge peak. The areas of soil saturation were observed to expand and contract in response to precipitation inputs, but subsurface flow convergence was evident at all times. Anderson and Burt (1978a) introduced a 'sub-catchment' model to characterise the spatial variation of soil moisture and hillslope runoff in catchments. They defined 'sub-catchment units' as those areas of contour convergence bordered by regions of contour divergence.

Anderson and Kneale (1980, 1982) applied the sub-catchment model to an area of more subdued relief. Compared with steeper environments, they found that the saturated zone at the hillslope base persisted for much longer periods after rainfall ceased. The focus of flow convergence migrated significantly in response to precipitation inputs. However, the focus tended toward the hillslope spur on the downstream side of the sub-catchment unit, because of streamline moisture gradients.

Weyman (1973) also discussed the role of topography in determining the spatial variation of subsurface flow, as have Kirkby et al. (1976) and Beven (1978), who considered the importance of contour convergence-divergence with respect to the stream hydrograph.

The most prominent result of recent field experiments is the large variations in hillslope runoff processes that have been observed within and between catchments. These results suggest that extremely delicate relationships occur between rainfall characteristics, features of topography, soil physical properties and the hillslope runoff regime. Similar results have been demonstrated in theoretical model studies by Freeze (1972b, 1975, 1978, 1980) and Murray (1981). The delicate relationships, between soil physical properties and the integrated catchment runoff response, have stimulated research on the spatial variability of hydrologically important soil physical properties (Sharma and Luxmoore, 1979).

2.1.2.4.2 Spatial variability of soil physical properties

Several recent field studies of soil heterogeneity show that the range of variability is far greater than has been generally acknowledged (e.g. Nielsen et al., 1973; Sharma and Luxmoore, 1979; Sharma et al., 1980). However, most field descriptions of the variability of hydrologically important soil physical properties have been qualitative. The relationships between the spatial variability of soil hydraulic properties and subsurface flow are discussed by Whipkey and Kirkby (1978). In fine textured soils, structural fissures, the presence of biogenic channels and shrinkage cracks are cited often as important in determining soil permeability and its variation (Weyman, 1970; Knapp, 1974; Arnett, 1976). Bouma et al. (1977), Bouma and Dekker (1978), Bouma and de Laat (1981) describe the geometry and spatial distribution of large structural fissures in the soil and have estimated the hydraulic conductivity from this information.

The need for more information on the importance of macro-pores in hydrology is reviewed by Beven and Germann (1982). They conducted experiments to show the importance of the macro-pore system on water flow through field soils. When micro-pores approach saturation, or when vertical flow exceeds the infiltration capacity of the micro-pores, there may be an immediate and dramatic increase in soil permeability. This increase is caused by the initiation of rapid flow in the soil macro-pores. In these situations the assumptions of Darcy's law may not be applicable, and alternative models may be required (Germann and Beven, 1981a, 1981b). Mosley (1982) suggests that rapid flow through macro-pores can contribute large volumes of subsurface flow to stream flow. However, the flow rates observed in his study were highly variable.

Pipe flow may also be initiated in lower permeability soils if large structural voids connect. The formation, extent, and hydrological significance of soil pipes and pipe flow are reviewed by Gilman and Newson (1980).

Investigations of the spatial and seasonal variability of infiltration rates within a small catchment have been reported by Tricker (1981). His analyses show that soil horizon dimensions exert the greatest control on the spatial variability of infiltration. In contrast, changes in soil moisture regimes account for most of the seasonal variation of infiltration.

Murray *et al*. (1975) investigated the spatial variability of soil moisture contents on a hillslope. Soil moisture gradients were observed on the hillslope, but the results were inadequate to support or refute the partial or variable source area hypotheses of hillslope runoff. More recently, Dunin and Aston (1981) reported statistically significant differences in the water balance for three distinct slope units within a small catchment. They concluded that it is possible to delineate hydrologic zones, within which soil moisture behaviour can be regarded as uniform.

The spatially variability of hydrologically important soil physical properties has implications for land management in areas where the partial and variable source area mechanisms of hillslope runoff are known to operate. Model studies have also revealed the complexities of evaluating the influence of soil variability on the processes of runoff generation. However, the consequences of this variability are not well understood at present (Sharma and Luxmoore, 1979).

The field studies mentioned above suggest that the processes of hillslope runoff may be unique in each drainage basin. Nevertheless, these studies also show that the various models of storm runoff are complementary, rather than contradictory (Dunne, 1978). The different emphasis shown in individual studies often reflects the dominant environmental characteristics of the region in which the experiments were completed.

Further research on source area hydrology must determine which hillslope parameters control the observed mechanisms of downslope water movement, and what ranges of these values will generate the various runoff mechanisms (Freeze, 1974). The implications of the spatial variability of these parameters must also be considered, but to date this aspect has not been studied extensively in the field. Tricker (1981) suggests there is a need for studies of spatial interrelationships on a 'plot' scale to be combined with 'catchment' scale experiments. In this way, the processes of hillslope runoff can be understood and linked to an integrated catchment response.

2.2 HILLSLOPE HYDROLOGY AND LAND USE

2.2.1 THE LAND USE PROBLEM

New Zealand is a developing country in the sense that land use changes have been in the past, and still are, a common feature of the environment. In overseas countries, land use regimes have evolved over many thousands of years, but in New Zealand this evolution has been compressed into about 100 years. Substantial land use changes, involving large areas, have occurred since the beginning of European settlement. These have included swamp drainage and the conversion of indigenous covers, native forest, scrub and tussock, to pasture, cultivated land and exotic forest. Calamitous impacts on the quality and yield of water resources are associated with the history of land development in New Zealand. These have been recorded by many authors (e.g. McCaskill, 1973; Molloy, 1980).

Hayward (1978) provides a succinct review of the early conflicts between water resources and different forms of land use in this country. Although public concern over the land use problems had been increasing for nearly 10 years, the Soil Conservation and Rivers Control Act was not passed until 1941. The main aims of the Act were to promote soil conservation, to prevent and mitigate soil erosion, to prevent damage from flooding and to utilise land in a way that would promote these aims.

At that time, there was little information from New Zealand studies on the plant-soil-sediment continuum and its relationship to hydrological processes. Consequently, early attempts at ameliorating land use conflicts relied heavily on overseas research, particularly from the United States of America. Remedial measures used in New Zealand were based, therefore, on the premise that 'erosion control and stream stabilisation could be controlled by improved infiltration, through the establishment of an improved vegetation cover' (Horton, 1937, p. 1026). Also, the urgency of the situation dictated a need for remedial measures, rather than research into the land use problems peculiar to the New Zealand environment (Hayward, 1978).

As part of the International Hydrological Decade (I.H.D.), a network of experimental basins was established in New Zealand to examine the hydrological effects of land use change. The specific objectives of this research programme are outlined by Toebes (1970). The requirement for practically orientated research is apparent: the general objectives emphasise research to ameliorate the conflicts of land use and water resources. A lower priority was given to research to determine changes in the hydrologic regime that had occurred as a result of land development.

Unfortunately, in setting up the most comprehensive research programme ever undertaken in this country, the 'fundamental truth' of the hypothesis derived from overseas was not questioned. The Hortonian concepts of runoff generation and the importance of vegetative cover thus pervaded practical land management decisions in this country for the next two decades.

The theoretical and empirical advances in understanding hillslope runoff production described in section 2.1, have been made since the I.H.D. experimental network was established in New Zealand. Partial and variable source runoff concepts have fundamental implications for management of land and water resources. The new concepts of runoff generation have been used overseas in catchment modelling and land management studies for sometime (e.g. Engman and Rogowski, 1974; Dunne et al., 1975; Dunin and Aston, 1981), but they have not been recognised fully in New Zealand (Pearce and McKerchar, 1979). Consequently, many land management procedures in this country are still based on the assumption of spatially uniform runoff production generated by Hortonian overland flow.

However, catchment rainfall-runoff processes have been interpreted based on the new concepts of source area hydrology, in several recent studies of single forms of land use (e.g. Hayward, 1976, 1978; Pearce and McKerchar, 1979; Cooke and Dons, 1982; Dell, 1982). Many of these studies have used the proportion of net rainfall appearing as quick flow as an indication of catchment contributing area. Some studies have extended this relationship, to show the relative importance of different runoff producing mechanisms operating in each catchment.

However, the notion, that the proportion of rainfall yielded as quick flow is an indicator of catchment contributing area, has been substantiated only rarely. Mosley (1979) has shown this technique to be a poor indicator of contributing area in a steepland forested environment in New Zealand. Cooke and Dons (1982) found reasonable agreement for small storms, but an increasing under-prediction for progressively larger storms. Thus, there is a need for comprehensive studies of source area hydrology for many areas of New Zealand, to avoid the mis-application of hypotheses derived from inadequate data.

Considerable data on water yield changes have become available in many areas of New Zealand, for various forest management practices and for the re-afforestation of pasture with exotic forest species (Rowe, 1979; Dons, 1980; Duncan, 1980; Pearce, 1980; Waugh, 1980). However, little research has been directed toward describing the source area hydrology of indigenous forest types in New Zealand, or to determining the hydrologic consequences following conversion of indigenous forests to pasture. Consequently, the changes in hillslope runoff mechanisms following this type of land use change are poorly understood.

In the absence of these data, estimates of the hydrological consequence of various forms of land use have, again, had to be based on overseas data or on predictions from theoretical models.

2.2.2 WATER RESOURCE BEHAVIOUR AND LAND USE CHANGE

The relationships between water resources and land use change are reviewed by Watt (1969). They fall into two distinct categories: those associated with changes in vegetation characteristics; and those associated with changes in soil characteristics. Research into land use change has tended to be directed to one or other of these groups, although they cannot be considered in isolation.

2.2.2.1 Vegetation characteristics and land use change

Most catchment studies, established to determine the influence of land use change, have used treatment-control comparisons as a basis of study. However, Ward (1971) has reported some studies that have examined two different forms of land use within a single catchment, as a means of evaluating land use change.

Most of the early research on land management and the hydrologic implications of land use was directed towards determining the influence of forests and agricultural land use on floods and sediment yield. Leopold (1972) has reviewed the results of this early work and presented the following general conclusions.

i) Forests reduce the size of all, but the largest floods, through interception losses and through higher infiltration rates in forest soils. In the largest floods, it was observed that forests did not prevent floods, but reduced erosion and channel bank collapse.

ii) Forests tend to reduce (not increase as was a popular misconception at that time) stream flow during dry weather.

iii) Forests prevent erosion because the presence of litter reduces raindrop impact, reduces overland flow, and reduces the surface sealing of pores.

It was recognised that the differences in runoff and erosion regimes between forested and non-forested lands were numerous and complicated (Leopold, 1972). Many basin studies were initiated during the following years. Continued experimentation was justified because it was necessary to extend the results from earlier studies, and to describe the hydrologic effects of a variety of forms of land use for a wide range of environments (Rodda, 1976).

The results of 39 catchment experiments completed by 1967 are reviewed by Hibbert (1967). The following generalisations were made.

i) A reduction of forest cover increases water yield.

ii) The establishment of forest cover on sparsely vegetated land decreases water yield.

iii) The response of catchments is highly variable and, for the most part, unpredictable.

These results have been largely unchanged by the addition of results from a further 55 studies (Bosch ánd Hewlett, 1982). Results from New Zealand basin studies (e.g. Luckman and Duncan, 1978; Herald, 1979; Pearce and Rowe, 1979; Dons, 1980; Duncan, 1980; McKerchar, 1980b; Waugh, 1980) support the general observations made by Hibbert (1967).

Nevertheless, these results are considered useful for general predictions of water yield changes following land use change (Bosch and Hewlett, 1982). The predicted changes in water yield vary considerably with land use and the prevailing climatic regime. They range from, a 40 mm change in annual yield per 10 % change in forest cover for coniferous and eucalyptus types, to a 10 mm change in annual yield per 10 % change in scrub or grassland. No inferences were made about the causes of these changes, although yield increases are related positively to the mean annual precipitation (Bosch and Hewlett, 1982).

Only a few land use studies have involved forest-grass comparisons. Most results show that the conversion of forest vegetation to grassland is followed by an increase in streamflow (Rich et al., 1961; Hill and Rice, 1963; Lewis, 1968; Gupta, 1980). However, in one study, water yields from grassland were about the same or lower than those predicted for the original forest vegetation (Hibbert, 1969). The implications of these results were not appreciated at the time.

Recent theoretical and experimental studies have clarified many of the factors that determine water use by forest and pasture vegetation, particularly the relative importance of interception and transpiration losses for each vegetation type (McMillan and Burgy, 1960; Rutter, 1963; McIlroy and Angus, 1964; Calder, 1978; Stewart, 1977; Singh and Szeicz, 1979; Pearce et al., 1980b, 1980c). The detailed interactions between transpiration, evaporation and interception from forest and pasture vegetation are discussed by Pearce and Rowe (1979).

Differences in water yield behaviour, between forest and pasture under similar meteorological conditions, are ascribed to differences in evaporative loss from the two vegetation covers (Pearce and Rowe, 1979). In this context, evaporative losses comprise three major components; interception, transpiration and evaporation from the ground surface. On vegetated slopes, evaporation from the ground surface is generally small compared with the other two components. The differences in evaporation (interception and transpiration) between vegetation types can be explained by interactions between two micro-meteorological characteristics of the vegetative covers; the bulk surface resistance (Montieth, 1965), and the aerodynamic resistance.

A detailed theoretical evaluation of these characteristics is presented by Pearce and Rowe (1979). Briefly; when the plant canopy is dry, evaporation losses (transpiration) are determined by the bulk surface resistance of the vegetation surfaces. The surface resistance is generally lower (by a factor of 1.5 - 3.0) for pasture than for forest vegetation. Evaporation rates from a dry forest can therefore be lower than for pasture, provided soil moisture is not limiting. However, when the canopy surfaces are wet, the evaporation rates for the two vegetation types are determined by the aerodynamic resistance, that is a function of the roughness of the vegetation surface. The aerodynamic resistance of forest vegetation is about 10 times less than that for pasture.

Consequently, interception losses are considerably greater for wet forests, compared with wet pasture. Thus, the frequency and duration of canopy wetness are major determinants of the relative importance of interception and transpiration losses between contrasting vegetation types, and between similar forest covers in different climatic regimes. Interception losses from different vegetation types can also be expected to vary greatly, in response to local rainfall regimes.

Water balance data from overseas and local basin studies have verified the findings from the theoretical studies cited above, subject to variations in annual rainfall totals, frequency of rain periods, mean annual temperatures and the degree of seasonal soil moisture deficit (Swank and Miner, 1968; Hibbert, 1969; Jackson, 1972, 1973; Swank and Douglass, 1974; Rowe, 1979; Pearce, 1980; Waugh, 1980).

2.2.2.2 Soil properties and land use change

Except for infiltration studies, little research has been reported on the relationships between soil physical properties, soil moisture regimes and land use change. This has arisen because few 'comprehensive' land use studies have been established since the acceptance of the partial and variable source area models of runoff generation (Ward, 1971).

In the Hortonian concept of runoff generation, changes in soil properties following land use change are important only in the way they influence surface detention, moisture holding capacities and infiltration rates (Horton, 1937; Kitteridge, 1948; Watt, 1969). Differences in the yield and time distribution of storm runoff production following land use change can be explained simply by the magnitude and frequency of overland flow (see Kitteridge, 1948, p. 254), instead of by changes in the processes of runoff generation.

However, other factors are important in determining the differences in hillslope runoff from different forms of land use, in areas where the partial and variable source area concepts are applicable. For example; differences in the water storage and transmission characteristics of a catchment's soil and differences in the distribution and degree of saturation within a catchment may have a profound influence on the processes of hillslope runoff under forest and pasture vegetation.

This aspect of land use hydrology has been not been studied in detail, although Birrell (1962), Campbell (1962) and Gradwell and Jackson (1970) discuss briefly specific relationships between soil properties and hydrology. Selby (1967a), Gray (1970) and Pain (1971) have summarised the hypotheses regarding changes in the hydrologic properties of soils following the conversion of forest to pasture, but only as they determine the occurrence of mass movement features under the two different forms of land use.

Infiltration has been the soil property studied most commonly in land use-hydrology studies. The overseas literature on infiltration and land use is reviewed by Dunne (1978), who presents data from many studies for a variety of land use environments. Infiltration data are published for only a few New Zealand soils and the data relate to specific areas (Watt, 1979). Usually infiltration rates under forest soils are greater than under grassed agricultural soils (e.g. Selby, 1971; Lynch, 1975; Parker, 1978).

Many factors influence the infiltration process: they include rainfall and soil characteristics, and vegetation and land use. However, the exact relationships are complex and often difficult to determine. The importance of these factors in determining infiltration have been discussed in several New Zealand studies (Campbell, 1956; Gillingham, 1964; Selby, 1971; Lynch, 1975). All agree that the differences attributable to soil and vegetation characteristics (forest-pasture) are effectively masked by pasture management regimes.

A series of papers by Gradwell (1960, 1965, 1968) show that stock trampling and compaction by machinery are important factors that reduce infiltration capacities within pasture environments. Jackson (1973) suggests similar factors cause large differences in infiltration capacities between forest and pasture sites in yellow-brown pumice soils. However, the complex inter-relationships between soil, vegetation and land use characteristics make it virtually impossible to predict infiltration rates (Lynch, 1975). Consequently, it is unwise to compare directly infiltration data derived from different soil-vegetation-land use regimes.

The only major study of the forest floor in New Zealand has been reported by Webster (1977). Estimates of the saturated hydraulic conductivity of the organic litter horizon in a beech-podocarp-hardwood forest are about 6100 mm h^{-1}, while estimates of the saturated hydraulic conductivity for the surface mineral soil horizon are about 250 mm h^{-1}. Both the presence of the forest litter layer and the incorporation of organic material into the surface mineral horizons of forest soils have been cited as factors responsible for different infiltration rates between forest and agricultural soils (Storey et al., 1964). Rapid infiltration, at the base of tree stems and along roots, and the concentration of flow through biological voids and root channels also cause high infiltration capacities in forest soils (Hursh and Hoover, 1941; Holtan, 1961; Reynolds, 1966; Aubertin, 1971; Aldridge and

Jackson, 1973; Arnett, 1976; Bonell _et al_., 1981).

McDonald (1961) describes a comparison of soil properties from native and pasture sites for eleven steepland soils derived from greywacke parent material. No important differences in soil texture, bulk density, aggregation, available moisture, total porosity and macro-porosity were observed between the forest and pasture sites. However, Parker (1978) found large differences in percolation rates between forested and pasture sites in a similar type of soil. Mean percolation rates (n = 30) for the surface mineral horizons were 494 mm h^{-1} for forest soils and 351 mm h^{-1} for pasture soils. These differences were attributed to a greater macro-porosity and more abundant biogenic channels in the forest sites. Significant differences between macro-porosities (p = 0.01) were also found for the 0 - 50 mm depth, but not for the 100 - 150 mm depth. This result confirms Jackson's (1973) finding that soil structural changes, following land use change, tend to be restricted to the surface horizons. These observations are supported by the findings of overseas studies, but the degree of structural change is variable and dependent on the intensity of land use change (Wood, 1977).

In some soils, dessication cracks tend to form more readily in pasture soils, than in forest soils. Their presence causes important differences in the hydrologic properties of soils in these two forms of land use (Selby, 1967a; Parker, 1978). The degree to which these structural features persist, or develop, following conversion of forest to grassland, may have important influences on the mechanisms of runoff generation.

The role of soil moisture in controlling the processes, frequency and yields of hillslope runoff have been well documented for single forms of land use (Dunne, 1969, 1978). However, in most comparative land use studies, interest in soil moisture is restricted to its role as a residual in the annual water balance (e.g. Jackson, 1973; Stewart, 1977; Calder, 1978; Pearce, 1980).

The direct measurement of soil moisture profiles have been reported for a variety of single vegetation types (Rowe and Reinman, 1961; Rutter and Fourt, 1965; Shachori et al., 1967; Holmes and Colville, 1968; McColl, 1977). These studies show that seasonal moisture regimes vary considerably for different forms of land use. These differences are governed by complex interactions between soil characteristics, plant rooting habit, rainfall regimes and the local water and energy balances. Consequently, only a few generalisations can be made from the data available. However, the processes and seasonal distribution of runoff depends on the degree to which soil characteristics and the underlying material interact with the water balance, by determining the rate of storage and release of soil moisture (Jackson, 1973).

The relationships between catchment water yields from exotic forest and pasture vegetation are generally well defined for many areas in New Zealand. However, the preceding review shows that little detailed information is available on the processes of hillslope runoff under forest and pasture vegetation. This type of information is required so that more sophisticated land management strategies can be developed. These strategies must provide adequate protection of land and water resources in sensitive steepland environments, while allowing these resources to be used efficiently.

CHAPTER THREE

THE PHYSICAL ENVIRONMENT OF THE STUDY AREA

CONTENTS

3.1 CHOICE OF THE STUDY AREA

An experimental catchment was established in the headwaters of the Mangawhara River in the Hapuakohe Range, some 60 km north east of the University of Waikato, Hamilton. The Mangawhara Valley was chosen for several reasons:

i) a conflict of land use between indigenous forestry and pastoral agriculture was evident;

ii) the conversion of forest to pasture was associated with problems of excess runoff and widespread erosion;

iii) the Mangawhara Valley represents a large area of steepland where land use conflicts have occurred and are likely to intensify;

and iv) several geomorphic and hydrologic studies allied to the proposed research have been completed in the area. The results of this study will add to the information already derived from the area.

3.2 LOCATION

The experimental catchments are contiguous areas in a 32 ha elongated basin, situated in the headwaters of the Paiaka Stream (37° 28' 30" S, 175° 25' 30" E) (plate 3.1). The basin has a north easterly aspect and drains from a high point of 310 metres to 140 metres at its outfall (plate 3.2).

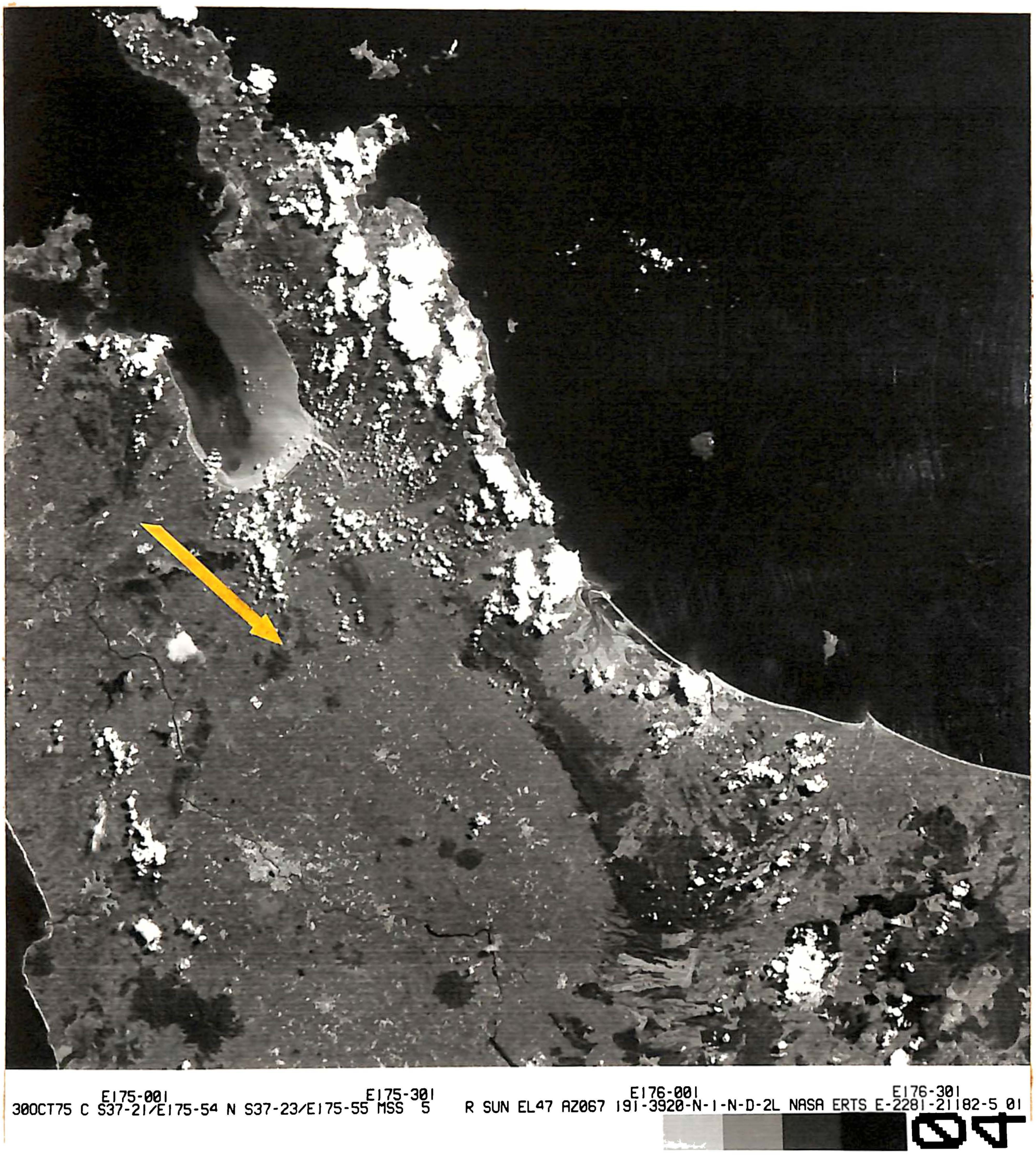


Plate 3.1 : A Landsat image of the Waikato district showing the location of the Upper Mangawhara Valley and the experimental catchments (photo credit N.A.S.A.)

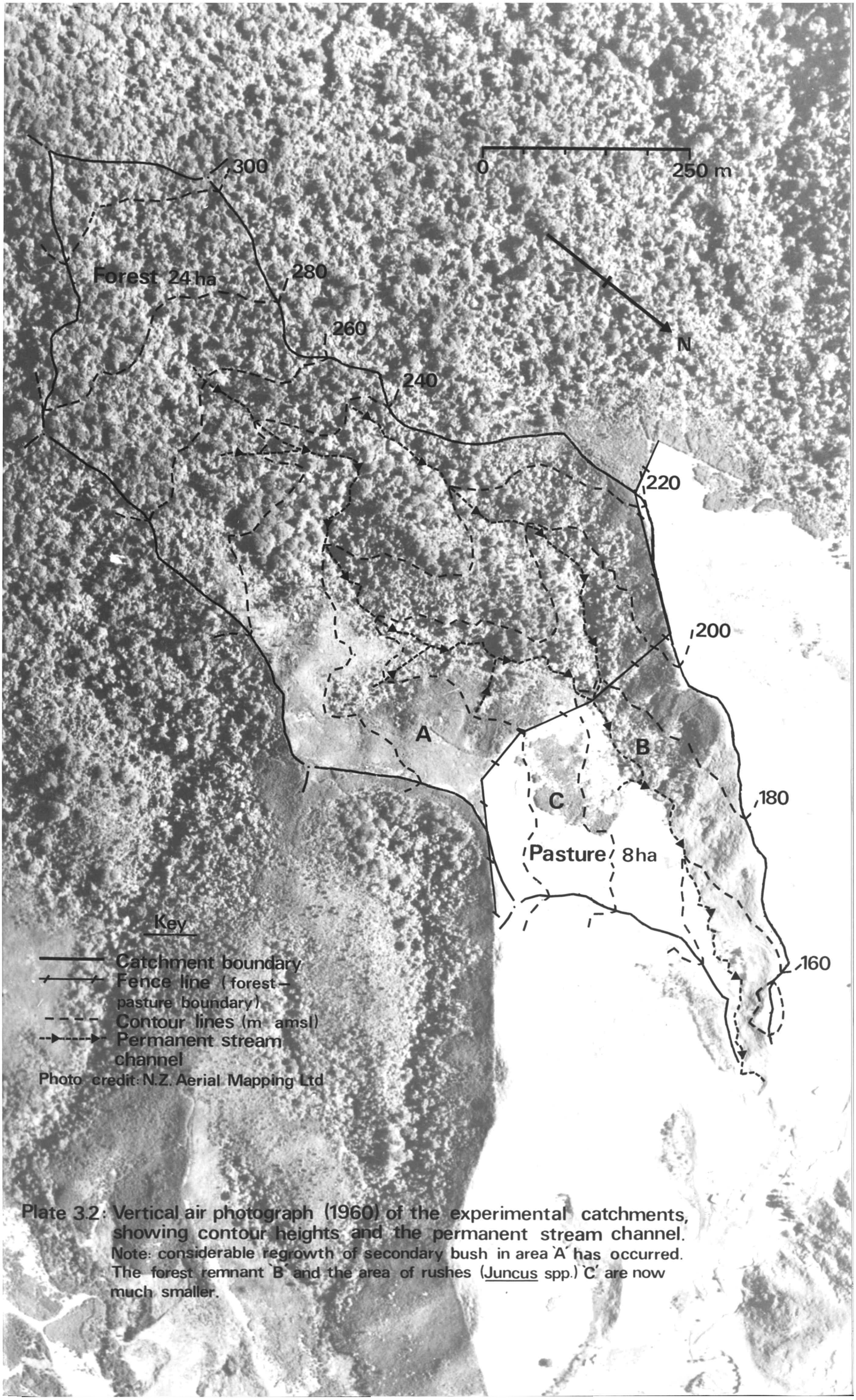


Photo credit: N.Z. Aerial Mapping Ltd

Plate 3.2: Vertical air photograph (1960) of the experimental catchments, showing contour heights and the permanent stream channel. Note: considerable regrowth of secondary bush in area 'A' has occurred. The forest remnant 'B' and the area of rushes (<u>Juncus</u> spp.) 'C' are now much smaller.

The upper 24 ha are in the Hapuakohe State Forest, the remaining 8 ha support pastoral agriculture. The two vegetation types are in the same drainage basin, but in this study they are considered as two distinct hydrologic units and are referred to as distinct catchments. Research described in this thesis was completed entirely within the experimental catchments, but the following description characterizes the general physiographic condition of the catchments and the Hapuakohe Range.

The Paiaka Stream is a tributary of the Mangawhara River that drains the Upper Mangawhara Catchment, an area of about 3050 ha of steep hill country in the Southern Hapuakohe Range (figure 3.1 and plate 3.3). Discharging from the upper catchment at Hoe-o-Tainui the river flows westward, initially between the southern margin of the Hapuakohe Range and the Hoe-o-Tainui peat bog. Then, constrained by extensive flood protection works the river flows across the late Pleistocene alluvial, lacustrine and peat deposits of the North Waikato Basin to join the Waikato River at Taupiri (plate 3.4).

3.3 GEOLOGY

The geology and associated structural features of the Hapuakohe Range have been well documented: detailed descriptions are presented by Kear (1967), Schofield (1967) and Kear and Schofield (1978). The Hapuakohe Range is part of an uplifted greywacke horst block (Schofield, 1967) that comprises indurated Mesozoic sediments of the Manaia Hill Group mantled with a thin layer of volcanic ash. The most common lithologies of the Manaia Hill Group are massive, medium greywacke sandstones, 'chipwackes' (greywacke with dark siltstone chips), and dark or black argillites. Bedding is difficult to determine as the greywacke is finely shattered, folded and faulted.

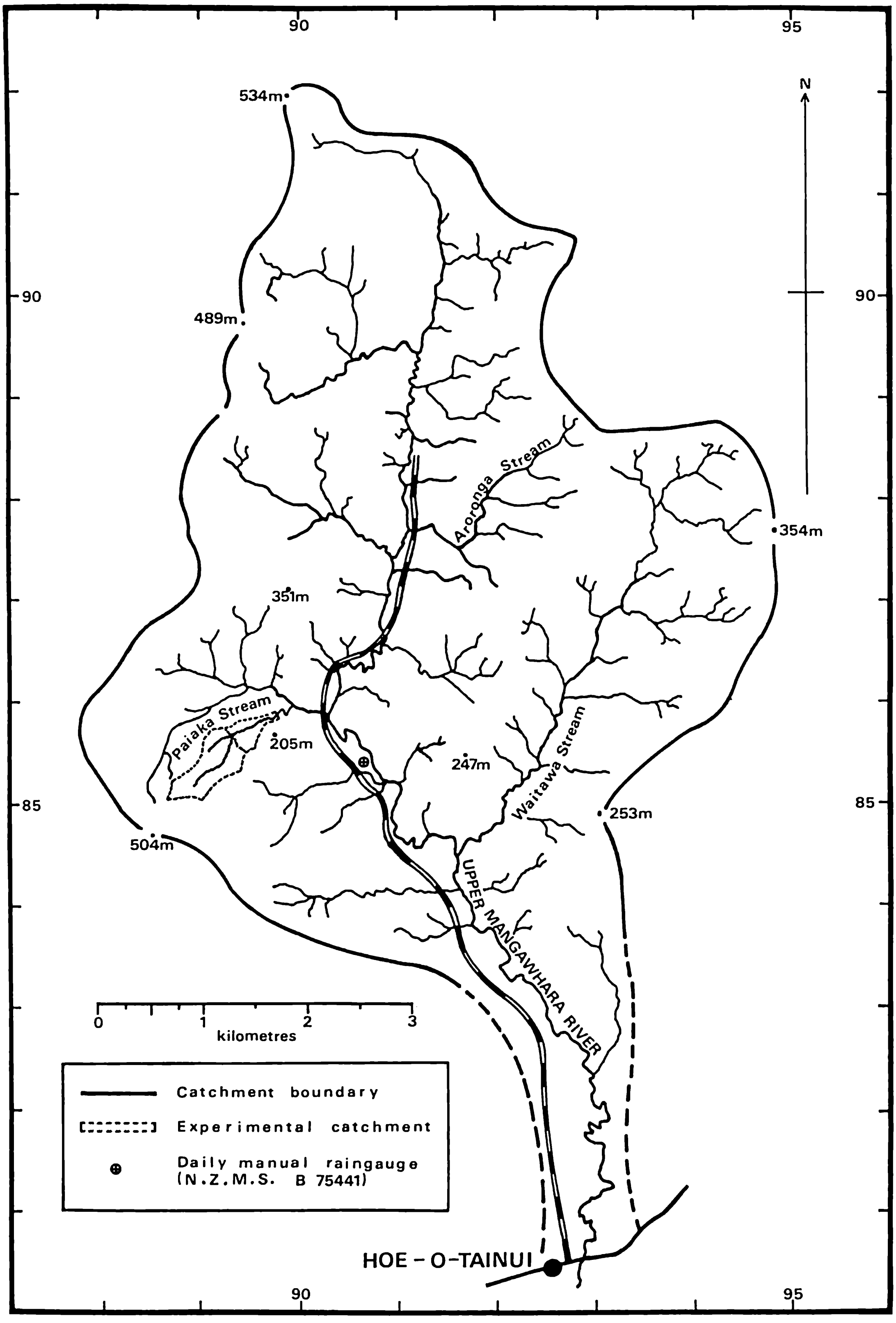


Figure 3.1 : The Upper Mangawhara Catchment and experimental catchment

Plate 3.3 : An oblique view of the Upper Mangawhara Catchment from above Hoe-o-Tainui

Plate 3.4 : Flood protection works on the Lower Mangawhara River

However, Blong (1971) has interpreted the shorter, steeper slopes on the western and southern valley sides as indicating tilting toward the south west. Unweathered bed rock is exposed rarely in the upper catchment, except occasionally in third and forth order channels.

Throughout the ranges the depth of weathered regolith is variable, but sections to depths of twenty-five metres have been reported (Selby, 1967a; Blong, 1971). Weathering extends along numerous joints and structural discontinuities to form a yellowish-brown clay-rich (halloysite) material. Dark brown deposits of manganese dioxide are also found in these weathering sites. On stable upper slopes the greywacke has been red weathered to a depth of up to twenty metres. Remnants of late Pleistocene and Holocene tephras persist still on the broad interfluves and gentle slopes.

Structural control of the drainage network is considered unlikely because of the deeply weathered regolith and shattered nature of the greywacke. Usually, channels are infilled by colluvium and alluvium derived from episodic mass-wasting (Selby, 1967b). However, where this is eroded away, the shattered in situ yellow-brown greywacke regolith is exposed.

Little information on the hydraulic properties of the greywacke basement has been reported. Schofield (1956) and Kear (1967) suggest the underlying greywacke has a low porosity and is only slowly permeable, but the degree of shattering, the processes of weathering, and the presence of deep weathering profiles, are all evidence that the experimental catchments are not impervious. Estimates of the annual losses to ground water are about 3 - 30 mm, assuming a permeability of between 1×10^{-9} to 1×10^{-10} m s^{-1} for the 'C' horizon of the catchment soils (Pender, 1971; Rogers, 1978). The hydraulic properties of the basement are considered spatially uniform within the experimental catchments.

3.4 PHYSIOGRAPHY

Detailed surveys by Selby (1966, 1967a, 1976), Pain (1969), Blong (1971), Parker (1978) and Rogers (1978) have determined the general slope morphology and the active geomorphic processes operating within the Hapuakohe Ranges and South Auckland region.

The land surface of the Hapuakohe Range is finely dissected with drainage densities ranging from 3.6 - 15.4 (Pain, 1969) to 15.78 (Selby, 1967a) km of channel per square km (plate 3.5). In the Hapuakohe Range, the fine textured relief and the drainage basin initiation and extension are dependent on the dominant land forming processes of mass wasting and not surface water flow (Selby, 1967b).

Hillslopes in both forested and pasture areas are generally steep, ranging from 18 - 34 degrees. South facing slopes in the catchments are noticeably steeper and shorter than north facing slopes (plate 3.6). Slope forms of incised first, second and third order channels are generally rectilinear, with narrow or broad upper convexities and almost no basal concavity. Concave foot slopes are rare, being mainly restricted to fourth and fifth order channels where they have developed from the deposition of colluvium and alluvium derived from mass wasting.

The incised perennial channel of the study catchments has a mean width of about 1.5 metres. The average channel gradient is 0.19 % in the forest and 0.08 % in the pasture. The longitudinal channel profile is characterised by a series of irregularly spaced, boulder or cobble, riffle and pool systems (plate 3.7). In the forest, occasional debris dams also occur. Following widespread mass wasting, large quantities of colluvial and alluvial material may be stored behind the debris dams and in individual pools (Bridson, 1981). This material is released periodically as the debris dams collapse and the channel returns to state of equilibrium. Similar channel morphologies occur elsewhere within the South Auckland region (Pain, 1969).

Plate 3.5 : Fine textured relief of the Hapuakohe Range. The experimental catchments are in the lower right of the view

Plate 3.6 : View of the experimental catchments from the north-east

Plate 3.7 : Riffle and pool systems in the forest catchment

3.5 ACTIVE GEOMORPHIC PROCESSES

The dominant geomorphic processes operating within the Hapuakohe Range are episodic (Selby, 1976). The rainfall of the Hapuakohe Range is characterised by periodic, large, high intensity, rainfall events. Most recently these have occurred in 1966, 1967, 1973, 1979. These storm events have caused widespread denudation by mass wasting and have been associated with the initiation of general geomorphic instability in the Upper Mangawhara Valley. A new period of long term channel instability has been initiated by the increased stream discharges and sediment supplied to stream channels following these storms (Bennett, 1975).

Between the large storm events, 'restorative' (Wolman and Gerson, 1978) processes return the land form to a quasi-equilibrium. Restorative processes appear to operate within the catchments on two distinct time scales (Bridson, 1981). In the short term, elements of the landscape left in an artificially unstable condition are removed, eg. channel bank collapse. In the long term, hillslope and channel form are restored to a condition largely determined by the period between large storm events.

Increased susceptibility to shallow translational landsliding has been associated with the conversion of indigenous forest to grass pasture in the Hapuakohe Ranges. The density of mass movement forms is far less beneath forest than beneath adjacent pasture, in spite of the steeper slopes in the forested areas (Selby, 1967a, 1967b; Pain, 1969). In Varnes' (1958) classification the landslides fall into the general category of debris avalanches (Selby, 1976). Under forest vegetation, landslides show less evidence of sliding and more flow features than those in the pasture areas.

Parker (1978) and Bridson (1981) have estimated that tree roots increase soil shear strength by 3.9 - 5.1 kPa to 6.0 - 11.0 kPa. However, Bridson (1981) stresses that this increase in strength operates only at the periphery of the landslide and the real contribution of roots to soil strength is considerably less (0.4 - 0.7 kPa). He concludes that the soil hydraulic regime or some other factors may be responsible for increased mass wasting in non-forested areas.

Bennett and Selby (1977) describe details of the channel changes in the Mangawhara River that have been caused by land use change. An increase in bedload has been associated with the storms known to have produced widespread landsliding within the Upper Mangawhara Valley. Combined with an increase in storm runoff, this factor has caused significant changes in the channel geometry. Channel width, width-depth ratios and channel gradient have increased since 1942, while sinuosity has decreased during the same period.

The principal effects of these changes have been an increase in the frequency and magnitude of flooding and aggradation in the Lower Mangawhara Catchment. These problems are now serious and have prompted the Waikato Valley Authority to propose retirement and afforestation of 1722 ha of farm land in the Upper Mangawhara Catchment (Waikato Valley Authority, 1977).

3.6 SOILS

The complex pattern of soils in the Upper Mangawhara Valley and experimental catchments is dominated by the influence of parent material. Continuing mass movement, a discontinuous mantle of ash, and the changing intensity of soil forming factors during the Pleistocene have caused a mosaic of soil types. The soils of the Upper Mangawhara Valley include the following major soil groups; yellow brown loams (alvic soils), brown granular loams (prospadic soils), yellow brown earth (fulvic and surfulvic soils) and gleyed recent soils (mandenti-luvic) (Wilson, 1980).

Yellow-brown earth, (gleyed yellow-brown earth), pre-weathered yellow-brown earth, gleyed recent and brown granular loam soil groups occur in the experimental catchments. Brown granular loams tend to occur only in hydrologically passive areas (upper slope convexities) in the two catchments and are not present at any of the sites chosen for detailed hydrological monitoring. Soils on the steep rectilinear slope units and on the concave footslopes show a great range of profile morphologies and horizon development, in a pattern that can be explained by Campbell's (1974) model of steepland soil variants. Yellow-brown earths form in pre-weathered greywacke in the more stable sites, but where erosion has removed most of the regolith, young, shallow yellow-brown earths are found. In lower slope positions, poorly drained yellow-brown soils form in colluvium, but where mass wasting is common, recent soils with shallow 'A' horizons and undeveloped 'B' horizons predominate.

The soil profiles that represent the dominant soil groups in the catchments are described in detail below (figure 3.2 - 3.5).

Analysis of clay mineralogy was not completed for this study, although the amount and type of clay may influence hydrologically important soil physical properties of the catchment soils. However, mineralogies for the catchment soils have been described by Parker (1978) and Wilson (1980). Generally, the yellow-brown earth subsoils consist of a weak to moderately swelling vermiculite-halloysite-illite mineral assemblage. Yellow-brown earths on pre-weathered greywacke have high clay contents, with halloysite-vermiculite assemblages that give a sticky plastic consistency and a moderate tendency for expansion and contraction. Gleyed recent soils have variable mineralogies, depending on the soil parent material composition.

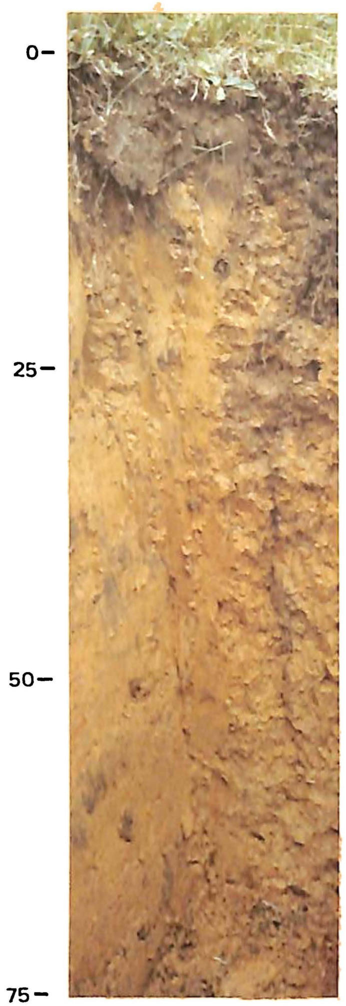
Location: Site M4P - Paiaka Stream Headwaters N.Z.M.S. 1 N 52 898.860

Topography: Rectilinear 30 degree slope unit, aspect north-west
Vegetation: Pasture grasses; ryegrass, browntop, clover Weeds; plantain, cats ear
Land use: Pastoral agriculture
Drainage: Imperfectly drained

Parent material: Weathered greywacke
Soil type: Tauhei hill soil
Classification: Central yellow-brown earth

A_1	0- 5	cm	Brownish black (10YR 3/2) silt loam; moderately developed fine and medium nut structure; friable; many fine roots:
AB	5- 12	cm	brownish black (10YR 3/2) and greyish yellow brown (10YR 4/2) heavy silt loam; friable; weak to moderately developed fine and medium blocky structure; many fine roots; abundant earth worm casts; wavy distinct boundary:
B_2	12- 45	cm	bright yellowish brown (10YR 6/6) clay loam; firm in place and in hand; a moderately developed coarse and very coarse blocky structure breaking to a more strongly developed fine and medium blocky structure; very weakly developed coarse prismatic structure; many fine roots with 50 percent in fissures; slight dull yellowish brown (10YR 5/4) organic staining on ped faces:
B_3	45- 65	cm	bright yellowish brown (10YR 6/8) clay loam with many large, bright reddish brown (5YR 5/8) mottles; friable; weakly developed medium blocky structure; few fissures with some dull yellow orange (10YR 7/2) stains on ped surfaces; very few roots; smooth distinct boundary:
C_1	65 +	cm	orange (7.5YR 6/8) and dull yellow orange (10YR 7/2) fine sandy loam; non-sticky and non-plastic; light grey (5Y 7/2) mottles in a matrix of strongly weathered greywacke.

Figure 3.2 : Soil profile; Central yellow-brown earth



Location: Site R4P - Paiaka Stream Headwaters N.Z.M.S. 1 N 52 898.860

Topography: Concave 25 degree colluvial slope unit, aspect north-west
Vegetation: Pasture grasses; ryegrass, clover Weeds; plantain, rushes
Land use: Pastoral agriculture
Drainage: Imperfectly drained

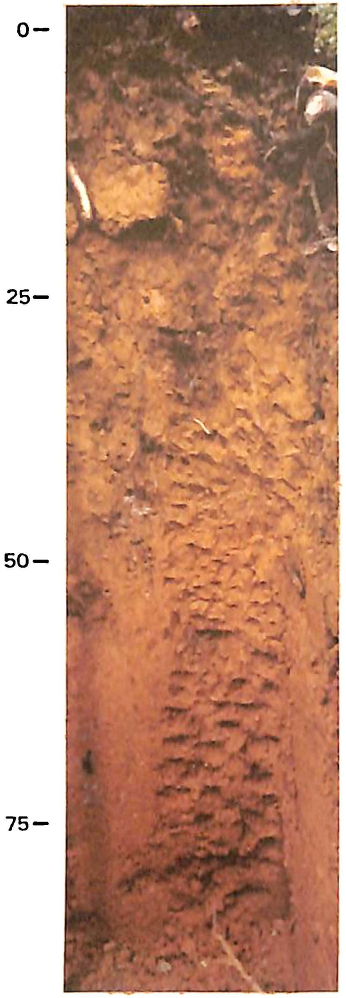
Parent material: Weathered greywacke
Soil type: Tahuna hill soil
Classification: Gleyed central yellow-brown earth

A_1	0- 15 cm	Dull yellowish brown (10YR 4/3) silt loam; slightly hard; weak to moderately developed medium nut structure; many fine roots, but few extending below 5 cm; few small subangular stones and a few fine charcoal fragments; many fine reddish brown (5YR 4/8) and yellowish brown (10YR 5/8) concretions; distinct wavy boundary:
B_2	15- 60 cm	bright yellowish brown (10YR 6/8) clay loam with dull yellowish brown (10YR 5/3) ped surfaces; friable to firm; strongly developed coarse blocky structure breaking to a medium and coarse blocky structure; a few large continuous vertical fisures in the profile; some fine roots and large stones; many fine, distinct, dark reddish brown (2.5YR 3/4) mottles; indistinct smooth boundary:
B_3	60- 77 cm	light yellow (2.5Y 7/4) clay loam; friable to firm; massive, breaking to a weakly developed medium blocky structure; few fine roots; few large stones; many distinct, medium, bright yellowish brown (10YR 6/8) mottles; indistinct smooth boundary:
C_1	77-100+ cm	light yellow (2.5Y 7/3) stony silt loam; friable to firm; massive; many prominent medium to coarse bright brown (7.5YR 5/8) and yellowish brown (10YR 5/8) mottles.

Figure 3.3 : Soil profile; Gleyed central yellow-brown earth

Location: Site M2F - Paiaka Stream Headwaters N.Z.M.S. 1 N 52 898.860

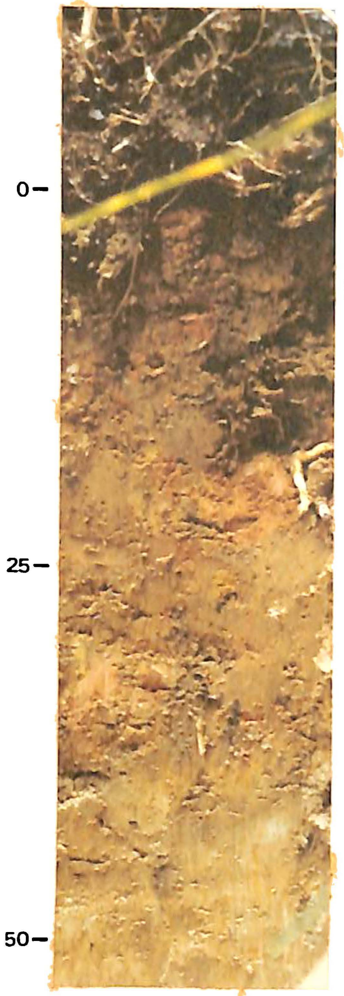
Topography: Rectilinear 32 degree midslope unit, aspect south-west
Vegetation: Indigenous forest, Podocarp-hardwood association
Land use: State Forest
Drainage: Well drained



Parent material: Red weathered greywacke
Soil type: Kaawa hill soil
Classification: Yellow-brown earth from pre-weathered greywacke

O_2F	9- 0 cm	Brownish black (7.5YR 2/2) matrix of partly decomposed organic material; friable; weakly developed granular structure; many recognisable plant fragments and fibrous roots; sharp wavy boundary:
A_3	0- 10 cm	bright yellowish brown (10YR 6/8) clay loam; firm in place and in hand; weak to moderately developed medium and very coarse nutty structure breaking to very fine and very blocky structure; abundant dull yellow orange (10YR 7/3) fine granular material in fissures and root channels; many fine, medium and coarse roots; indistinct wavy boundary:
B_1	10- 46 cm	bright brown (7.5YR 5/8) clay loam; friable in place, but peds firm in hand; weakly developed medium and coarse nutty structure, breaking to very fine and fine blocks and many fine and very fine granules; abundant fine granules in fissures and root channels; many fine and medium roots; indistinct wavy boundary:
B_2	46- 66 cm	bright brown (2.5YR 5/6) clay loam; friable in place, but firm in hand; moderately developed medium and coarse prismatic structure, breaking to moderately developed fine and medium blocks; abundant very fine and fine granules in fissures and root channels; some organic staining on ped faces; indistinct smooth boundary:
B_3	66-150 cm	bright brown (2.5YR 5/8) clay loam; massive, breaking to a weakly developed fine and very fine nutty structure; no roots and no large fissures; few small strongly weathered gravels increasing to many at the horizon base; colour becomes paler towards the horizon base:
C_1	150 +	yellowish brown (10YR 5/8) gravelly loam.

Figure 3.4 : Soil profile; Yellow-brown earth from pre-weathered greywacke



Location: Site R3F - Paiaka Stream Headwaters N.Z.M.S. 1 N 52 898.860

Topography: Concave 25 degree colluvial slope unit, aspect north-west
Vegetation: Indigenous forest, Podocarp-hardwood association
Land use: State Forest
Drainage: Poorly drained

Parent material: Colluvium and alluvium from weathered greywacke
Soil type: Unnamed soil
Classification: Gleyed recent soil

O_2F	5- 0 cm	Dark brown (10YR 3/4) matrix of partly decomposed organic material; friable; weakly developed granular structure; many fibrous roots; sharp wavy boundary:
AC	0- 25 cm	reddish brown (2.5YR 4/8) and brown (7.5YR 4/4) gravelly sandy clay; non-sticky, non-plastic; weakly developed coarse prismatic structure, breaking to weakly developed fine and medium blocks; many fine and medium weakly weathered greywacke gravels; many fine and medium roots; few fine and indistinct light yellow (5Y 7/3) mottles; some small manganese nodules; indistinct wavy boundary:
IIBg	25- 60 cm	dull yellowish brown (10YR 5/3) and greyish olive (5Y 6/2) clay loam; slightly sticky, slightly plastic; moderately developed coarse blocky structure grading to massive at the horizon base; some organic staining on ped faces; many fine and medium roots in the upper part, grading to few towards the horizon base; many indistinct, medium, pale yellow (5Y 8/3) mottles; some fine manganese nodules; indistinct wavy boundary:
Cg	60+ cm	Gravelly sandy silt; water saturated.

Figure 3.5 : Soil Profile; Gleyed recent soil

3.7 VEGETATION

Bennett and Selby (1977) have outlined the vegetation and land use change in the Upper Mangawhara Valley during this century. Before 1925, the slopes at the head of the valley were covered with vegetation similar to that still remaining in the Hapuakohe State Forest Park. In contrast, the flats had been planted to pasture before the 1920s. During the period 1925 - 1930 a soldier settlement was established in the upper reaches of the valley. Since that time, land has been progressively developed and development continues to the present day.

3.7.1 PASTURE VEGETATION

The pasture vegetation found within the experimental catchment is typified by low and medium fertility grasses, legumes and weeds. In areas of poorly drained soils the pasture swath includes many species adapted to damp conditions. Table 3.1 lists the pasture species present within the areas delineated for detailed hydrological monitoring. Isolated remnants of native vegetation occur on some lower slopes, but these are considered unlikely to alter the general runoff regime from the pasture catchment.

3.7.2 FOREST VEGETATION

An ecological survey of the Hapuakohe State Forest, including the area within the experimental catchment, was completed in 1968 by staff of the Forest Research Institute. A brief summary by tiers follows (table 3.2).

Most of the species listed are present in the forest catchment. The general condition of the forest is healthy, there being extensive regrowth of hardwood and sub-canopy species. However, minor damage to under-storey vegetation, caused by stock grazing, is evident near the forest-pasture boundary. Also, a small (15 %) area of mature secondary regrowth is present in the north eastern sector of the forest catchment.

Grasses	cocksfoot	(*Dactylis glomerata*)
	perennial ryegrass	(*Lolium perenne*)
	browntop	(*Agrostis tenuis*)
	danthonia	(*Danthonia spp.*)
	ratstail	(*Sporobolus capensis*)
	sweet vernal	(*Anthoxanthum odoratum*)
	Yorkshire fog	(*Holcus lanatus*)
	timothy	(*Phleum pratense*)
Legumes	white clover	(*Trifolium repens*)
	suckling clover	(*T. dubium*)
	strawberry clover	(*T. fragiferum*)
	lotus major	(*Lotus pedunculatus*)
Weeds	plantains	(*Plantago spp.*)
	hawkweed	(*Crepis capillaris*)
	cats ear	(*Hypochaeris radicata*)
	pennyroyal	(*Mentha puleguium*)
	rushes	(*Juncus spp.*)
	California thistle	(*Cirsium arvense*)
	blackberry	(*Rubus fruticosus*)

Table 3.1 : Pasture species list for the pasture experimental catchment

Aerial photographs taken in 1960 show a similar area in juvenile regrowth and scrub. Uncontrolled fires used for land clearing during the early part of the century may have destroyed the original vegetation. This region was excluded from the area chosen for intensive hydrological study, although is is assumed that the different species composition does not influence the integrated hydrologic response from the catchment.

Tier	Height (m)	Dominant species	
Emergents	20 - 30	matai	(Podocarpus spicatus)
		miro	(Podocarpus ferrugineus)
		Northern rata	(Metrosideros robusta)
		rimu	(Dacrydium cupressinum)
tier 1	15 - 20	hard beech	(Nothofagus truncata)
		hinau	(Elaedocarpus dentatus)
		kohekohe	(Dysoxylum spectabile)
		rewarewa	(Knightia excelsa)
		pukatea	(Laurelia novae-zelandiae)
		tawa	(Beilschmiedia tawa)
tier 2	8 - 15	hinau	
		kohekohe	
		mahoe	(Melicytus ramiflorus)
		mangeao	(Litsea calicaris)
		miro	
		rewarewa	
		tawa	
tier 3	1 - 8	kanono	(Coprosma australis)
		manuka	(Leptospermum scoparium)
		mapou	(Myrsine australis)
		nikau palm	(Rhopalostylis sapida)
		ponga	(Alsophila tricolor)
		pukatea	
		various Olearia spp.	
tier 4	0.1 - 1	hardwood seedlings	
		kiekie	(Freycinetia bankskii)
		Lycopodium spp.	
		manuka	
		parataniwha	(Elatostema rugosum)
		ponga	
		supplejack	(Ripogonum scandens)
		ground and filmy ferns	

Small areas of tanekaha (Phyllocladus trichomanoides) and kauri (Agathis australis) exist in all tiers.

Table 3.2 : Indigenous forest types in the Hapuakohe State Forest Park

3.8 CLIMATE

Only general features of the climate of the Hapuakohe Range are described in this section. More detailed analyses of rainfall and water balance components are presented in chapter 5 (rainfall) and chapter 8 (water balance data).

The weather of the Hapuakohe Range is determined by a succession of anticyclones, fronts and by cyclonic developments in low pressure troughs. Rainfall is associated usually with the passage of fronts, but the heaviest rainfalls are produced by depressions originating in the South west Pacific, which reach New Zealand during the summer and autumn months (de Lisle, 1967). Although rainfall is spread evenly throughout the year, the greatest variability of monthly rainfall is associated with the passage of the autumnal equinox.

Statistics for annual rainfall in the experimental catchments are estimated from a 26 year record, collected from a N.Z.M.S. site (B 75441) (see figure 3.1). The mean annual rainfall is 1575 mm with a standard deviation of 177 mm. The mean number of rain days per year is 189 with a standard deviation of 17 days. Annual rainfall totals for the study period were 1725 mm (1979), 1405 mm (1980) and 1604 (1981).

The most intense rainfalls in the Hapuakohe Range are associated with convective thunderstorms, or with the passage of vigorous frontal systems during late summer or autumn. Intense rainfall from these sources occurred during 1966, 1967, 1973, and 1979. The storm of March 22, 1979 was centered near the experimental catchments. It caused considerable devastation, triggering numerous landslides and destroying many instrument sites in the experimental catchments. However, the rainfall record was undamaged, and for the first time a continuous recording of such an event was obtained (see chapter 5). Table 3.3 shows brief details of the rain that fell from 0900 March 22, 1979 to 0900 March 23, 1979.

Total rainfall	151.2 mm
Maximum 1 hour intensity	63.0 mm h^{-1}
Maximum 30 minute intensity	75.4 mm h^{-1}
Maximum 5 minute intensity	>120.0 mm h^{-1}

Table 3.3 : Details of the extreme rainfall event, March 22, 1979

The mean annual temperature of the Hapuakohe Range is about 14 degrees C. (reduced to sea level), and the average duration of bright sunshine hours is about 1800 per year. The frost season (the number of days between the first and last screen frost each year) is on average 100 days.

Water balance data (Cox, 1968) show that annual precipitation exceeds annual evapo-transpiration. However, during the summer months evapo-transpiration exceeds rainfall.

3.9 REPRESENTATIVENESS OF THE EXPERIMENTAL CATCHMENTS

The physical environment of the Hapuakohe Range has been considered representative of the South Auckland greywacke ranges (Selby, 1967a; Blong, 1971). The experimental catchments are representative of the general physiographic condition of the Hapuakohe Range, based on the criteria mentioned in preceding sections of this chapter. It is thus realistic to interpret observations made in this thesis on a wider regional basis.

CHAPTER FOUR

EXPERIMENTAL DESIGN AND CATCHMENT INSTRUMENTATION

CONTENTS

4.1 INTRODUCTION

A process oriented field measurement programme, within a catchment framework, was considered essential to achieve the study objectives presented in section 1.2.1. The principles, objectives, and problems encountered with data collection network design, have been discussed for a variety of hydro-meteorological objectives (e.g. W.M.O. 1965, 1972; Boughton, 1967; Hayward, 1967; Rodriguez-Iturbe and Mejier, 1974; Moss _et al_., 1978).

However, little attention has been given to the development of experimental designs for research on hydrologic processes in small catchments (Hayward, 1967). In a critical review of 50 runoff and soil loss experiments, Hayward (1967) cited 46 studies that did not have an adequate experimental design. He suggested that the results from these studies were of little value.

The need for further research on the design of hydrologic data collection programmes is discussed in detail by Moss _et al_. (1978). They imply, that it may never be possible to determine a set of explicit rules with which to design a data collection network[1], as the most appropriate design will always depend on the particular objective being pursued.

Guide lines for data collection network design are described in detail by the authors cited above. Two important factors must be considered to specify the data collection network accurately.

i) A clear definition of the data requirements must be presented. The several specific factors necessary to define the data requirements are presented by Moss _et al_. (1978).

ii) An objective assessment, of the data requirements necessary to

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[1] Network is used to mean synonymously; a group of instruments used to measure a single variable in space or time, or a group of instruments measuring different components of a process in space or time.

achieve the study objectives, must be made from existing data sources using standard statistical procedures. Preliminary field surveys may be necessary where such data are unavailable.

The likelihood of designing an appropriate data collection network is enhanced by evaluating these factors carefully.

Data collection methods and techniques must be determined once the type and quantity of data to be collected are established. Usually the appropriate measurement technique is apparent immediately from the network design criteria. However, physical constraints often preclude the development of an ideal network design.

The following discussion describes the data requirements, the development of the experimental design, and the data collection network and instrumentation necessary to provide a data base suitable to achieve the aims and objectives of this research programme. The data collection scheme was, of necessity, a compromise between research goals, and restrictions imposed by material constraints. However, an attempt was made to design a collection network that would provide an optimal data base for analysis.

4.2 DATA REQUIREMENTS TO ACHIEVE THE STUDY OBJECTIVES

Figure 4.1 shows the major components of hillslope runoff and their interactions, that are of importance in this research programme. An evaluation of the information presented in figure 4.1, shows that data are required on hydrologic processes on a 'catchment' scale and on a 'plot' scale.

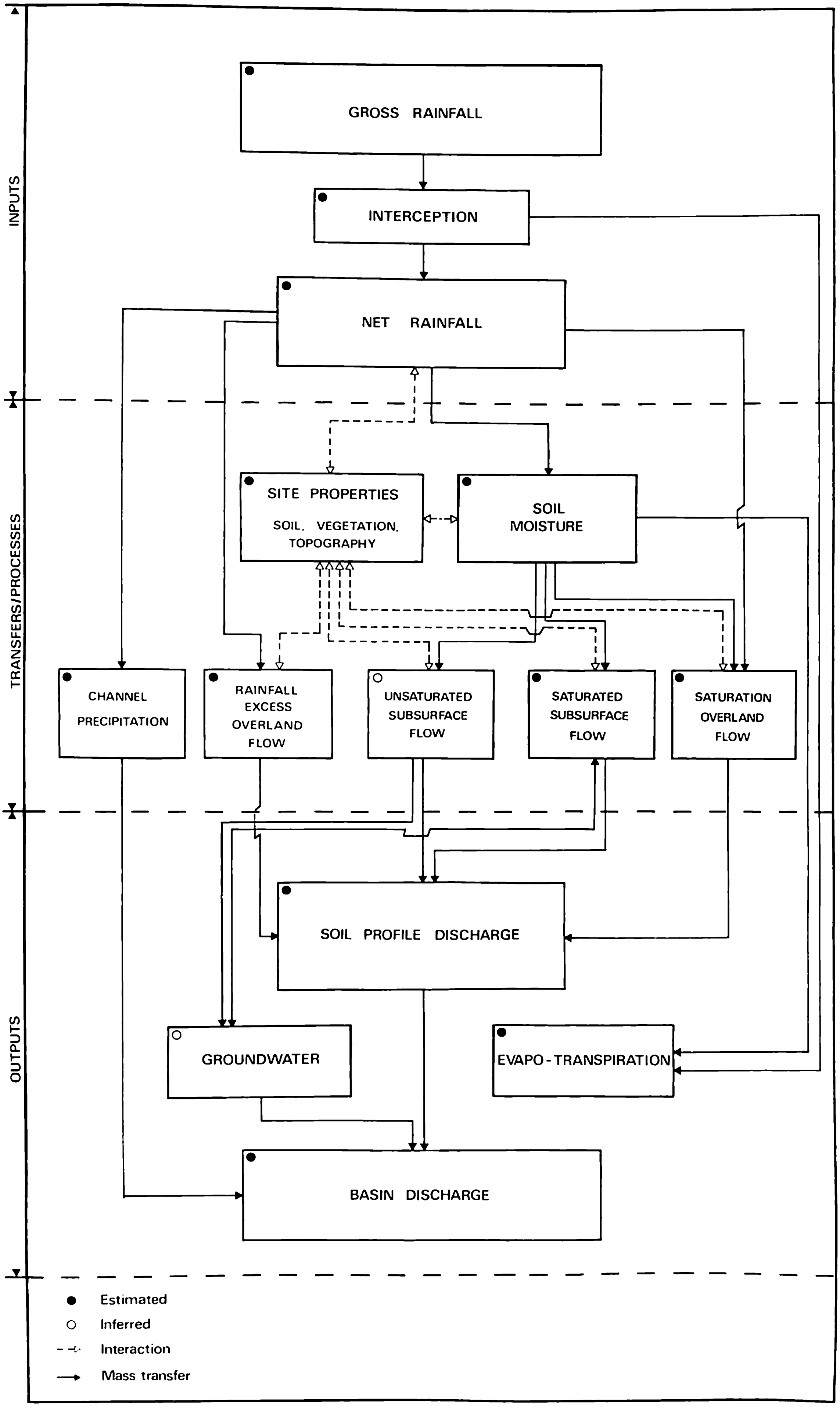

Figure 4.1: Components and interactions of the hillslope runoff regime of importance in this reseach programme

Each of these requirements place different demands on the data collection network. Consequently, a comprehensive, integrated instrumentation network was necessary to monitor these variables in the experimental catchments, and provide data suitable for the 'catchment' scale and 'process' scale experiments.

4.2.1 DATA REQUIREMENTS FOR THE CATCHMENT SCALE STUDIES

Hydrologic data, estimated on a 'catchment' scale, were required for two main purposes. These were:

i) to provide data on water balance components for general comparisons of the hydrologic behaviour of the two land use catchments;

and ii) to provide a hydrologic framework within which to conduct the process studies of hillslope runoff.

The principal hydrologic input, rainfall, and output, stream flow, were measured to provide this information. Estimates of evapo-transpiration losses were made for each land use catchment from an analysis of the water balance. The errors in the estimate of evapo-transpiration using this technique are probably small, because losses to ground water are small. However, estimates of potential evaporation losses were also made. In addition, an estimate of interception processes was made in the forest catchment to confirm the role of vegetation type on the general hydrologic regime of the two land use catchments, and to provide information on the anticipated differences in hillslope runoff processes.

Rainfall and stream flow were recorded continuously, to provide detailed data to integrate with the process studies.

4.2.2 DATA REQUIREMENTS FOR THE PROCESS STUDIES OF HILLSLOPE RUNOFF

Several specific types of data were required to achieve the objectives of the hillslope runoff studies. These are described below.

4.2.2.1 Rainfall

Estimates, of the spatial variability of rainfall, were necessary to provide data suitable for a systematic study of the spatial variability of hillslope runoff processes. Recent studies have provided evidence to show that rainfall patterns may vary in a systematic way over small areas, in response to interactions between the local topography and the wind regime (Sharon, 1970, 1980; Yair et al., 1978, 1980). Sharon (1970) suggests that areal patterns of rainfall should be accredited a greater importance in analyses of rainfall-runoff regimes, particularly since the recent advances in the understanding of runoff production in small catchments.

4.2.2.2 Hillslope flow processes

Detailed estimates of hillslope runoff processes were necessary to quantify the surface and subsurface flow regimes within the experimental catchments, and to provide an estimate of the systematic variability of these flow processes.

Techniques for measuring surface and subsurface hillslope runoff components are well established and are described by many authors (e.g. Hayward, 1967; Anderson and Burt, 1978b; Atkinson, 1978). However, the literature outlined in chapter 2 suggests that a variety of surface and subsurface flow mechanisms may occur within the experimental catchments. The experimental design and data collection network must therefore be capable of distinguishing these processes. These aspects are considered in section 4.3.

4.2.2.3 Environmental variables

Detailed measurements of rainfall, soil, topographic and vegetation properties, are necessary to determine hydrologically important environmental controls of hillslope runoff processes within catchments. Care must be taken when choosing an appropriate suite of site variables with which to explain the contributions of surface and subsurface runoff.

Difficulties arise because many of the process-response mechanisms that determine hillslope runoff can occur within single catchments (Whipkey and Kirkby, 1978). Also, difficulties are often encountered in determining precise relationships between non-linear rainfall-runoff processes, and the many inter-dependent and auto-correlated variables known to control hillslope runoff processes (Burton, 1966).

Thus in this study, it was felt better to concentrate on a few major variables known to be important in determining hillslope runoff in similar land use environments, instead of attempting a wide ranging assessment of many variables. It was appreciated that this strategy increased the risk of excluding other important variables.

After a critical evaluation of the literature outlined in section 2.1, ten variables were selected to describe the soil, topographic and vegetation characteristics of each land use catchment and to explain the runoff regime measured at individual sites. The variables chosen were considered to be the most likely factors influencing the runoff regime in the experimental catchments. However, the correct selection of the environmental variables presuppose a considerable knowledge of the processes of runoff likely to occur within the experimental catchments, and the likely relationships between the environmental variables and hillslope runoff processes. The rationale for selecting these variables is presented below.

4.2.2.3.1 Soil physical properties

Estimates of the variability of soil moisture and water transmission characteristics of the catchment soils were necessary to explain the mechanisms of the hillslope runoff regime. In the past, interactions, between rainfall characteristics and the soil infiltration capacity, have been considered the major controls of hillslope runoff. The recent research described in chapter 2 has shown that these interactions are seldom applicable in vegetated slopes in humid temperate environments. However, these processes may still be important in these environments, during infrequent, large, rain events.

In smaller, less intense rainfall events, the recent field studies of source area hydrology show that the hillslope runoff regime is highly variable and depends mainly on the spatial distribution of soil moisture. The spatial distribution of soil moisture is, in turn, governed by the water storage and transmission characteristics of the surface and subsurface soil (e.g. Hewlett and Hibbert, 1967; Dunne and Black, 1970a, 1970b; Harr, 1977), and by topographic controls (Dunne, 1969; Anderson and Burt, 1977a, 1977b, 1978a, 1978b).

A measure of soil particle sizes was also included as a variable important in determining hillslope runoff processes in the experimental catchments. This variable was chosen because interactions, between the seasonal moisture regime and the amount of clay present in the catchment soils, are important in determining seasonal variations of soil hydrologic properties (Parker, 1978; Rogers, 1978).

4.2.2.3.2 Topographic variables

The main influence of topography was incorporated in this study as a grouping variable, that describes the degree of contour convergence-divergence at sites within the two catchments. This variable also forms the basis of the spatial sampling programme and the experimental design, that are described in greater detail in section 4.3. A measure of contour convergence-divergence was chosen because several recent field studies have shown the importance of contour convergence-divergence and elevation potential in determining the processes and spatial variability of hillslope runoff (e.g. Dunne, 1969; Anderson and Burt, 1977a, 1977b, 1978a, 1978b; Anderson and Kneale, 1980, 1982).

Unfortunately, many of these field experiments have been complicated by interactions between topographic factors and other factors that determine hillslope runoff. Consequently, it has been difficult to define and separate the influence of soil properties, hillslope shape and form, and antecedent conditions on the hillslope runoff response (Beven et al., 1977). In this study, it was hoped that some of these problems would be reduced, by incorporating contour convergence-divergence as the major grouping variable and by examining the effects of other important variables within the catchment sub-areas identified.

Several other variables, that describe the topographic characteristics at sites within the catchments, were incorporated in this study. Aspect was included, because hydrologically important relationships have been shown between aspect and soil moisture variation in other steepland environments (Gillingham and Bell, 1977; Crozier et al., 1980). Slope angle was included for its obvious importance in determining both surface and subsurface hillslope runoff processes. The effect of different surface detention characteristics on hillslope runoff processes have been reported for contrasting vegetation types in several areas in New Zealand (Selby, 1971; Yates, 1973). Thus, a measure of surface detention was considered important in the two land use catchments used in this study. Surface roughness was used as a measure of surface detention characteristics at individual sites in the two land use catchments.

4.2.2.3.3 Vegetation characteristics

Several variables that describe characteristics of the vegetation in the two catchments were included to explain the anticipated spatial variability of hillslope runoff processes. In forest environments, canopy density has been cited as an important factor in determining the spatial variability of interception processes (Jackson (I.J.), 1970, 1975). The presence or absence of an organic litter horizon has also been cited as being important in determining the runoff response in forest environments (Webster, 1977; Bonell et al., 1981).

The importance of pasture dry matter production on hillslope runoff processes has also been suggested by Selby (1971) and Yates (1973). For this reason, pasture dry matter vegetation was considered likely to be an important determinant of surface runoff within the pasture land use catchment.

4.2.2.3.4 Summary of the environmental variables

Table 4.1 shows the complete suite of site variables measured during this study.

Soil characteristics	soil moisture, surface and subsurface soil permeability, and particle sizes
Topographic characteristics	the degree of contour convergence-divergence (sub-catchment unit), slope angle, the aspect of the site with respect to geographic north, and the surface roughness of the observation site
Vegetation parameters	dry matter production (pasture only), canopy cover (forest only), and litter layer depth (forest only)

Table 4.1 : Variables measured to explain the processes of hillslope runoff at individual observation sites in the experimental catchments

It was thought likely that a detailed description of the source area hydrology in the two land use catchments would be achieved, by measuring the various components of the hillslope runoff regime and the site variables presented above, and by relating these process studies to observations made of the general hydrologic characteristics of the experimental catchments. However, the complete research programme had to be completed within a pretested experimental design, so that the applicability of the current models of source area hydrology could be tested rigorously in the two catchments studied.

4.3 EXPERIMENTAL DESIGN

Several factors must be considered when developing an experimental design as a basis of a systematic study of hillslope runoff production. Not only must the hydrologically active areas be recognised and delineated within catchments, but an indication of the degree to which these areas differ from other contiguous sub-catchment units must be achieved (Moore et al., 1976).

The recent field studies have emphasised the importance of topographic characteristics in determining the hydrologically active areas within catchments. However, the hydrologic response of a catchment is also determined by the spatial variability of soil physical properties (Sharma and Luxmoore, 1979; Luxmoore and Sharma, 1980; Russo and Bresler, 1981). Thus, the experimental design developed for this study had to include an assessment of:

i) the spatial variability of surface and subsurface hillslope runoff processes;

ii) the spatial variability of hydrologically important soil physical properties;

and iii) the changes in hydrologically important soil physical properties with soil depth.

The development of a systematic study of the spatial variability of hillslope runoff processes therefore creates important problems of methodology, as an investigation of this type is fundamentally a sampling project (Boughton, 1967). Such studies require careful experimental design, with due regard to adequate replication, in order to assess the variance within the experimental units and to improve the precision of the experiment; and adequate randomisation to assure an unbiased estimate of the treatment means, and variances, within and between experimental units (Steele and Torrie, 1960).

4.3.1 IDENTIFICATION OF HYDROLOGIC RESPONSE UNITS IN THE TWO LAND USE CATCHMENTS

The process of identifying hydrologically active areas within catchments is not simple. In some environments, the source areas of hillslope runoff are defined clearly and vary in a predictable way. Usually this occurs in catchments with steep slopes and well drained soils (Dunne, 1969). However, in other areas of more subdued relief or less permeable soils, the distribution of hillslope runoff may be highly variable, with source areas developing in a less predictable way (Beven, 1978; Anderson and Kneale, 1982).

Evidence, from the studies cited above, suggested that the development of the experimental design for this study could not be based directly on information presented in the literature. Instead, a careful examination of the soil, topographic and vegetation characteristics was required to identify the hydrologically important response units within the two land use catchments. Moore et al. (1976) have identified a number of simple observations that may show hydrologically active areas within catchments. They suggest that repeated field mapping, features of topography, soil gley morphology, and plant species distribution, are all viable indicators of runoff producing areas.

A combination of these methods were used to delineate hydrologically active areas in the experimental catchments. Field observations, of soil gley morphology and the distribution of vegetation species (principally Juncus spp.), provided evidence that suggested the hydrologically active areas in the two experimental catchments were related closely to the degree of topographic convergence and divergence.

However, observations of soil profile morphology also showed that the catchment soils were only moderately permeable. Thus, the simple relationships between topography and hillslope runoff processes were likely to be modified considerably (Murray, 1981). The possibility that they might be sufficiently impermeable to cause widespread infiltration-excess overland flow could not be discounted. Therefore, the possibility of both partial and variable source area contributions of saturation overland flow and infiltration-excess overland flow had to be considered in the development of the experimental design.

4.3.2 DEVELOPMENT OF THE EXPERIMENTAL DESIGN

Sub-catchment units, considered to have similar mechanisms of runoff production, were identified within the experimental catchments. Areas of concavity were distinguished from rectilinear and convex slope units. The convergence and divergence of slope form and plan, implied subsurface flow lines, and inferred soil moisture distribution, were the principal criteria used to distinguish these areas. Figure 4.2 shows a schematic representation of the sub-catchment units. The individual subdivisions are referred to, respectively, as riparian and re-entrant, midslope, and spur sub-catchment units.

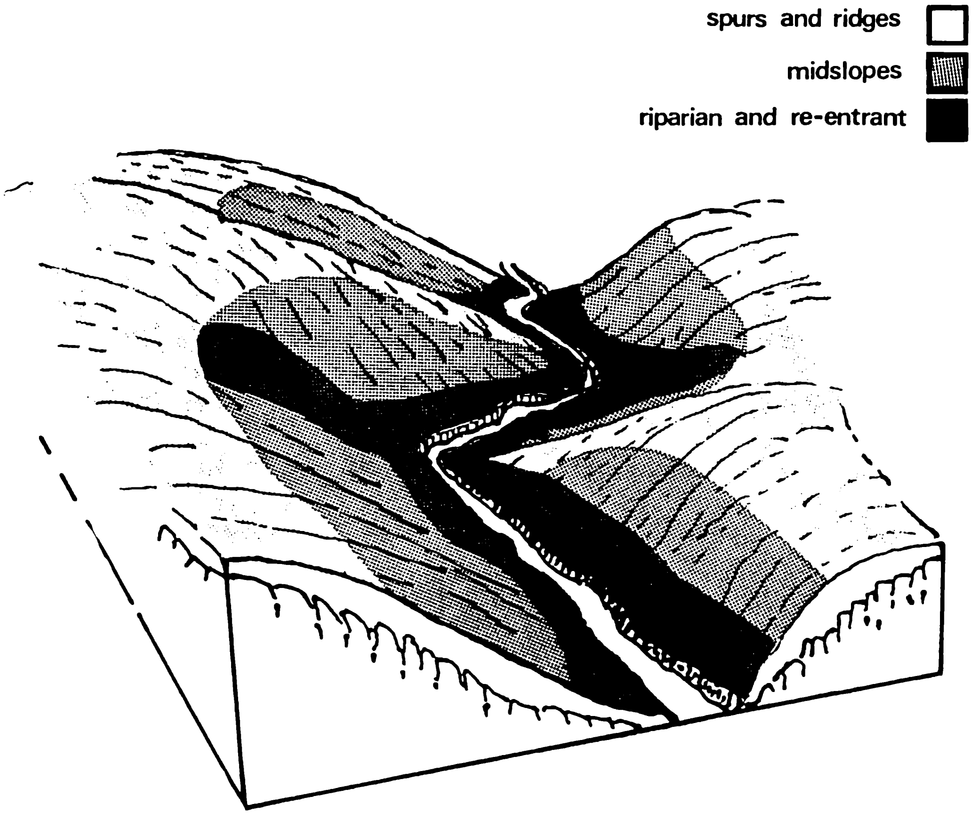

Figure 4.2 : A schematic representation of the relationships between the sub-catchment units

Although the sub-catchment units were distinguished primarily on topographic features, they are not necessarily continuous regions parallel to the stream channel (see figure 4.2). Areas of convex and rectilinear slope units near to the stream channel, were instead included in the riparian and re-entrant areas, on the basis of soil moisture status.

The extension of the experimental design to include an assessment of soil physical properties is also not simple. Criteria, on which to distinguish hydrologically important, yet homogeneous soil horizons, are defined poorly in the literature surveyed. Diagnostic criteria used in pedological classifications do not necessarily coincide with those that determine the hydrologic behaviour of the soil profile. This was particularly apparent in the highly variable soils of the experimental catchments. Ultimately, soil horizons of hydrological importance were distinguished by a visual assessment of the profile macro-structure, following the method used by Bouma and Dekker (1978).

Three hydrologically important horizons were distinguished in the catchment soils and incorporated in the experimental design. The upper hydrologically important soil horizon corresponds to the 'A' and 'AB' pedological soil horizons in the pasture catchment, and to the 'O' horizon in the forest catchment. The second hydrologically important soil horizon corresponds to the 'B_1' and 'B_2' soil horizons in both catchments, while the third hydrologically important soil horizon corresponds to the 'B_3' pedological horizon in both land use catchments.

Figure 4.3 shows the full experimental design. The major components of the experimental design, groupings by vegetation, topography and soil horizon, are shown clearly. This design, enables an assessment of the variability of hillslope runoff for the two land use regimes. It also enables an understanding of the changes in the hillslope runoff regime and hydrologically important soil physical properties, following land use conversion.

4.3.3 PRELIMINARY FIELD SURVEY

A preliminary soil moisture survey was completed in the pasture experimental catchment during a 126 mm storm in September 1978, to test the viability of the experimental design presented in figure 4.3. If hydrologically important differences in soil moisture could be shown between some, or all the sub-catchment units, then the experimental design would be validated. The initial survey was completed in the pasture catchment; soil moisture was assumed to be similarly distributed in the forest catchment.

Table 4.2a shows the descriptive statistics of the soil moisture survey. Results from a one way analysis of variance test (table 4.2b), show that the subdivision of the catchments into sub-catchment units results in a reduction ($p = 0.05$) in the standard errors of the estimated catchment mean soil moisture content.

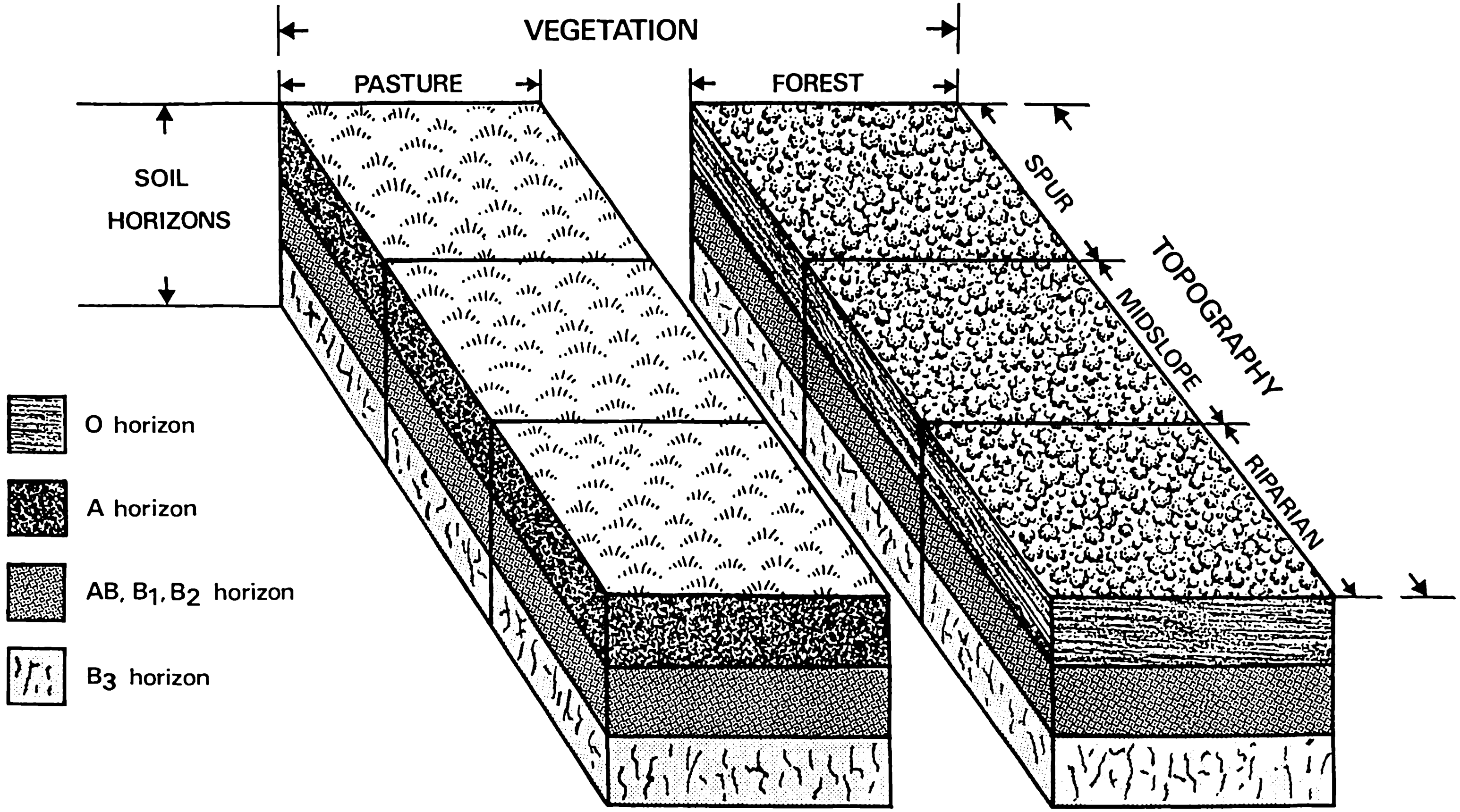

Figure 4.3 : The major components of the experimental design

sub-catchment unit	n	mean	s.d.	c.v.
riparian	33	9.8	8.8	89.8%
midslope	33	21.5	12.7	59.1%
spur	33	24.5	12.2	49.8%

n - number of samples
s.d. - standard deviation
c.v. - coefficient of variation

Individual 95 % confidence intervals for the sub-catchment unit means (based on the pooled standard deviation)

```
-----------|----+-----|-----+-----|-----+-----|-----+-----|-----+-----|-
 riparian  |  ********M*******
 midslope  |                           ********M*********
 spur      |                                  ********M*********
-----------|----+-----|-----+-----|-----+-----|-----+-----|-----+-----|-
          5.0        10.0        15.0        20.0        25.0        30.0
m - mean
```

a) Descriptive statistics

	degrees of freedom	sum of squares	mean square	F
sub-catchment unit	2	3974	1987	15.42 *
error	96	12370	129	
total	98	16344		

* - significant at p = 0.05

b) Analysis of variance

sub-catchment unit	riparian	midslope	spur
	9.8	21.5	24.5

c) Duncan's multiple range test

Table 4.2 : Descriptive statistics and results of an analysis of variance and Duncan's multiple range test of the initial soil moisture survey (units 0.01 bars moisture tension)

Similarly, a Duncan's multiple range test (table 4.2c) shows the riparian and re-entrant areas are more moist ($p = 0.05$) than either the midslope, or spur sub-catchment units. The mean moisture content in the spur areas is less than in midslope regions, but the difference is not statistically significant ($p = 0.05$).

The preliminary survey illustrates some of the difficulties of applying the partial and variable source area models to practical land management decisions. There are obvious difficulties in identifying the hydrologically sensitive areas, and in assessing the degree to which these areas may be considered homogeneous. The riparian and re-entrant areas were considered likely to be the most hydrologically active regions in the experimental catchments as they are more moist than either of the other two sub-catchment units. However, the role of the other sub-catchment units was unclear. Thus, it was necessary to treat the remaining upslope sub-catchments units as separate entities, instead of combining them and treating the experimental catchments as having only two, hydrologically distinct, sub-areas.

4.4 NETWORK DENSITIES AND SAMPLING ERROR

Data sampling errors and network densities must be determined once the types of data, and the experimental design have been established. In the past, many catchment experiments have suffered from inadequate data, to an extent that their results are of little value (Ward, 1971).

In this study, it was necessary to consider carefully the sampling error associated with estimating hydrological variables at individual sites within the catchments, and to estimate the sampling density required for variables where spatial variability was of hydrologic importance. A priori estimates were made of the precision with which the sample means of these variables could be determined with the resources available. The procedure and notation used in these estimates follow that described by Steele and Torrie (1960, p. 86).

Precision is defined as half the width of the confidence interval described by Steele and Torrie (1960). The sample variances necessary to make these estimates were obtained from studies already completed in the Hapuakohe Range, or where this information was not available locally, from reports of similar field studies. However, in this study, material constraints usually determined the sampling density of the variables to be estimated. Thus, the available resources were allocated so that hydrologically important[2] differences could be detected between the different sub-catchment units for as many variables as possible.

4.4.1 DATA ACCURACY AND ESTIMATION OF NETWORK AND SAMPLING DENSITIES

4.4.1.1 Precipitation

Precipitation data were required to serve two main purposes (see section 4.2). Estimates of weekly mean catchment rainfall were required for the catchment scale experiments. Estimates of the spatial variability of rainfall were also required to explain the spatial variability of hillslope runoff (Sharon, 1970, 1980). In addition to these requirements, it was anticipated that some analyses would require rainfall data on time intervals as short as 15 minutes. However, there were insufficient resources available to establish a raingauge network capable of estimating mean catchment rainfall within an acceptable precision, for time intervals shorter than one week.

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[2] A hydrologically important difference is equivalent to the minimum acceptable precision for an estimate of the mean of a variable. This value depends on the objectives of a particular study and may be different for each variable considered.

Data from Taita experimental basin were used to estimate an appropriate network density for the Mangawhara experimental catchments (Jackson and Aldridge, 1972). The physiography and aspect of the Taita and Mangawhara catchments are similar: the network density data from Taita are thus considered applicable to the Mangawhara.

Table 4.3 shows the network density required to estimate the mean weekly catchment rainfall, with a precision of +/- 10 % at the 95 % significance level, for several storm size classes. Also shown in table 4.3 are the percentage errors for estimating the mean catchment rainfall for each storm size class with only 2 raingauges.

The percentage of rain falling in the experimental catchments for each storm size class is also presented, to show the relationship between network errors and the typical rainfall input. These rainfall data were estimated from the daily manual gauge, N.Z.M.S. B 75441, located 2 km east of the experimental catchments. The data relate to the 1977 year. On the basis of this information, two raingauges were adequate to provide an estimate of mean basin rainfall to within +/- 10 % precision at the 95 % significance level, for all but a few of the smallest storms. A realistic assessment could not be made for rainfall estimation errors for shorter sampling intervals.

Rainfall depth class (mm)	Network density (precision = +/- 10% @ p = 0.05)	Estimated error of the mean with 2 gauges	Percentage weekly rainfall in each depth class (1977)
0.0 - 7.5	5.98 (6)	+/- 17.30 %	1.96
7.6 - 15.1	2.72 (3)	+/- 11.68 %	6.22
15.2 - 22.8	1.70 (2)	+/- 9.22 %	4.97
22.9 - 43.2	1.49 (2)	+/- 8.63 %	26.79
> 43.2	0.70 (1)	+/- 5.94 %	59.86

Table 4.3 : Estimated raingauge network densities for selected weekly rainfall depths.

Four additional gauge sites, including one in the forest catchment, were established to determine the spatial pattern of rainfall in the catchments. Individual gauge errors at the Mangawhara were considered to be similar to those observed at Taita. These were typically less than 5 %, for about 90 % of rainfall depths greater than 25 mm. Slightly larger errors were associated with smaller storm events (Jackson and Aldridge, 1972). In this study, systematic rainfall variations smaller than these errors were considered to be hydrologically unimportant.

4.4.1.2 Throughfall

Throughfall could be estimated at only one site in the forest catchment with the equipment available. Hogg et al. (1975) have estimated the sampling errors for a measurement system similar to the one used in this study. Their estimates are considered applicable to this study. They suggest that the sampling errors of the throughfall measurement system should be less than 10 % for storms greater than about 20 mm. More precise estimates are suggested for smaller storms. It was not possible to confirm these estimates during this study, because the throughfall collected from individual troughs was bulked into a single recording device.

4.4.2 HILLSLOPE RUNOFF REGIME

4.4.2.1 General

In this study, a sampling procedure was necessary at individual sites within the sub-catchment units to determine hillslope runoff processes and to estimate the variability of these processes within the two land use catchments. This restricted the observation techniques that could be used, to an evaluation of individual sites or plots within each experimental cell (figure 4.3).

Two aspects of the data collection were considered.

i) For each variable, the appropriate area or volume that had to be sampled was identified. The appropriate sample volume or area had to take account of variability on a scale appropriate to the objectives being pursued.

ii) The number of samples required to estimate the experimental cell means, with an appropriate precision and at the required significance level ($p = 0.05$), was determined for each variable.

These two problems are related, because the observed variation within an area increases usually with the size of area sampled (Beckett and Webster, 1971).

In this study a compromise was made, between sample areas that were so small as to introduce unwanted variation, and those so large, that systematic variability was masked by averaging in time and space.

4.4.2.2 Surface runoff

Estimates of surface runoff[3] were required to provide information on the relationships between runoff, and rainfall, soil, vegetation and topographic characteristics. Estimates of surface runoff were also required for quantitative estimates of the size of the runoff response from the sub-catchment units. Plots were used for the study of surface runoff, as they are an effective method of sampling the surface runoff phenomenon, provided the data are carefully interpreted (Hayward, 1968). The plots were installed and maintained carefully: the sampling errors are considered to be negligible. Many of the sampling errors discussed by Hayward (1968) are not applicable in the more moderate climatic

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[3] Surface runoff is defined in this thesis as being any flow over the mineral soil. It thus includes rapid flow over and through the discontinuous organic layer in the forest land use catchment.

conditions of the Hapuakohe Range.

The major defects of runoff plots relate to their use for sediment and runoff collection, and the extrapolation of these data to whole catchments (Hayward, 1967, 1968). Plots tend to under-estimate runoff, as they isolate only part of the surface runoff continuum. However, in this study, the main use of the information derived from the runoff plots was to distinguish the chief factors influencing surface runoff. The problems of under-estimation were not important, as no attempt was made to extend quantitatively the plot information to a larger areas.

Plots of 5 m^2 were considered suitable to encompass a sampling area that represented the surface runoff processes operating in the land use catchments. The plots are larger than those used commonly in other studies (e.g. Hayward, 1968; Soons and Rainer, 1968; Selby, 1971). However, this size was chosen because unwanted variation was spatially averaged.

Few data were available from which to make a valid, a priori estimate of the sampling densities required to estimate surface runoff in this study. Data from the few replicated plot studies reported in the literature were rejected because they related to specific soil types and land use environments (e.g. Hayward, 1968; Selby, 1971). Consequently, the network density was determined by the availability of equipment and labour.

Both Hayward and Selby consider 20 plots is the maximum number that can be tended by an operator in one day; this number was accepted and plots were distributed among the sub-catchment units (figure 4.4).

The distribution of the plots among the sub-catchment units was considered carefully on the basis of several criteria. At least two sites were required to estimate the variation within individual cells. The preliminary study of soil moisture had suggested the riparian cells as being hydrologically active regions and, as hydrologic responses are commonly heteroscedastic, a minimum of four sites was considered

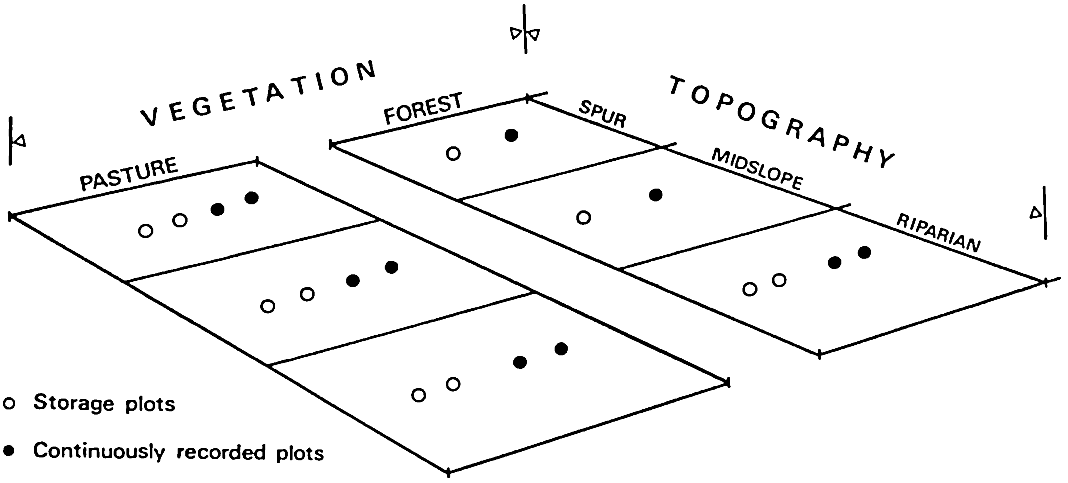

Figure 4.4 : The distribution of surface runoff plots among the sub-catchment units

necessary in these areas. For similar reasons, the remaining four sites were distributed among the midslope and spur units in the pasture catchment, instead of in the forest. The proposed distribution of experimental sites was considered the best possible with the number of plots available.

4.4.2.3 Subsurface flow

The problem of determining subsurface flow was approached in two ways.

i) Measurements of permeability and soil moisture were used as surrogates for determining qualitatively, the likelihood for subsurface runoff within each sub-catchment unit. Measurements of soil permeability were made during both the winter and summer months, to ascertain any changes in permeability resulting from seasonal moisture variation.

ii) The magnitude and spatial variability of the subsurface flow response was measured by instrumenting a first order basin in each experimental catchment with transects of piezometers. Piezometers were used because more sophisticated recording equipment was unavailable.

The use of piezometers was considered a satisfactory alternative, in view of the continuity and time scale of response implied from the research of Anderson and Burt (1977a, 1977b, 1978a, 1978b). Discharge from the first order basins was also measured to determine any relationships between saturated soil conditions and base flow. The subsurface flow regime was not measured directly in the experimental catchments because of the deficiencies associated with this type of measurement system (Atkinson, 1978).

4.4.2.3.1 Permeability and soil moisture

Data gathered on soil moisture and hydraulic conductivity were needed for several purposes. These were:

i) to provide quantitative information for the analysis of the surface and subsurface flow regimes;

ii) to characterize the water storage and transmission characteristics of the sub-catchment units;

and iii) as surrogate variables for an examination of the spatial variability of the subsurface flow regime.

Each of these data uses required different sampling densities. However, sites for soil moisture and permeability measurements were established immediately adjacent to the surface runoff sites, to maintain continuity between the surface and subsurface sampling programmes. Thus, the location and number of observation sites for permeability and soil moisture were fixed.

Permeability

Estimates of sampling densities were required for observations of permeability made at individual sites in each land use catchment and for permeability observations averaged over sub-catchment units. However these estimates are complicated by two factors.

Soil properties that are highly variable (e.g. soil permeability) are often described better by a log normal distribution (or other skewed distributions) (Nielsen *et al.*, 1973; Sharma and Luxmoore, 1979; Luxmoore and Sharma, 1980; Russo and Bresler, 1980). It is important to identify the correct probability density function, to avoid incorrect estimates of the required sampling density for soil properties that are not described well by the normal distribution (Sharma and Luxmoore, 1979). These problems are compounded by spatial correlation: observations of soil physical properties made close together are seldom independent (Sharma and Luxmoore, 1979; Luxmoore and Sharma, 1980; Russo and Bresler, 1981). Furthermore, soil properties that are better described by skewed distributions are often heteroscedastic (Warrick and Nielsen, 1980).

For these reasons, a logarithmic transformation of permeability was considered more suitable as the *primary permeability variable*. In this thesis, estimates of the sampling density and most other analyses of soil permeability are based on the transformed permeability variable.

No data were available from which to make estimates of the sampling density necessary to estimate soil permeability at *individual* sites. It was assumed that by measuring large sample volumes, an adequate representation of soil permeability would be made. This assumption appears justified, in view of the recent developments on the spatial variability of soil properties, and the high degree of correlation found commonly between adjacent sample sites. Three observations of soil permeability at each observation site were the maximum number that could be incorporated into the sampling programme.

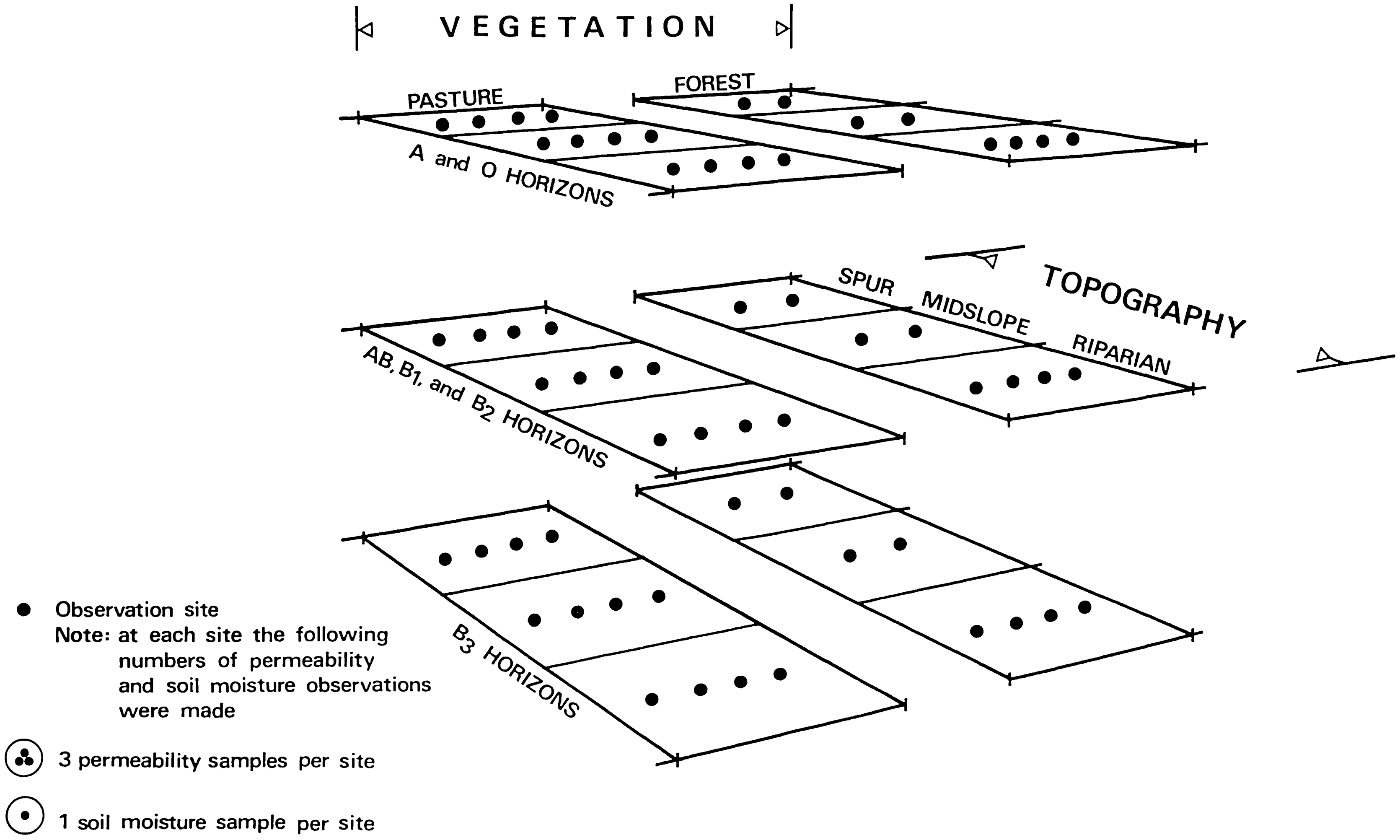

Figure 4.5 : The distribution of permeability and soil moisture observation sites within the experimental catchments

The spatial sampling programme of soil permeability was thus fixed.

Figure 4.5 shows the number of samples and the distribution of the permeability measurements completed in the experimental catchments. Permeability measurements were made in each of the three hydrologic soil horizons identified at the twenty surface runoff sites. A field method developed by Talsma and Hallam (1980) was used to estimate soil permeability. This method is based on final, steady-state, infiltration rates into cylindrical holes and is particularly suited for rapid field tests.

The precision of the proposed sampling network for estimating the mean sub-catchment unit soil permeability was estimated from permeability data presented by Parker (1978). These data were observed in an adjacent valley in the Hapuakohe Range, but were restricted to the surface soil horizons. Table 4.4a shows the descriptive statistics of the untransformed data and transformed data obtained by Parker (1978). The coefficient of variation, for the untransformed data obtained by Parker, is generally less than the range of 100 - 200 % given by Warrick and Nielsen (1980) for soil permeability. This may reflect the large soil samples (0.038 m^3) used by Parker.

Table 4.4b shows the the number of samples required to estimate the transformed mean sub-catchment unit soil permeability for selected levels of sampling precision, at the 95 % significance level. Using the network proposed, the estimate of the sub-catchment mean surface permeability was likely to be made with a precision of 15 - 25 % (see figure 4.5 and table 4.4). This estimate is based on only 4 independent observations of permeability in each sub-catchment unit. The three observations made immediately adjacent to each other at each site were likely to be correlated significantly, and therefore could not be considered as independent observations of permeability for the sub-catchment units (see figure 4.5).

	Pasture		Forest	
	saturated	dry	saturated	dry
Untransformed				
mean	292.15	307.32	392.58	411.30
s.d.	167.29	271.77	392.70	559.08
c.v.	57.26	88.43	100.03	135.93
Transformed				
mean	5.517	5.392	5.512	5.662
s.d.	0.631	0.891	0.984	0.774

units untransformed data - mm h^{-1}
transformed data - $\log_{(e)}$ mm h^{-1}
s.d. standard deviation

a) Descriptive statistics

	Pasture		Forest	
Precision	saturated	dry	saturated	dry
+/- 5 %	27 (26.78)	56 (55.84)	66 (65.26)	39 (38.22)
+/- 10 %	7 (6.49)	14 (13.96)	17 (16.31)	10 (9.88)
+/- 20 %	2 (1.67)	4 (3.49)	5 (4.07)	3 (2.38)
+/- 25 %	1 (1.07)	3 (2.23)	3 (2.60)	2 (1.52)

b) Sample numbers required to estimate the sub-catchment unit mean soil permeability within the stated precision at the 95 % significance level

Table 4.4 : Descriptive statistics of the permeability data obtained by Parker (1978) and estimates of sampling densities for selected levels of precision (p = 0.05)

No data were available that could be used to estimate the precision of the proposed network for estimating soil permeability in the lower soil horizons. Rogers (1978) estimated the mean permeability of the B_2 horizon to be 5 orders of magnitude less, than those observed by Parker (1978) for the surface horizons. Given the heteroscedastic nature of soil permeability, it is probable that the lower soil horizons will be estimated to a greater degree of precision than shown in table 4.4. It must be appreciated that the precision of the estimate of the mean will vary if seasonal changes of permeability occur.

No estimate of the size of a hydrologically important difference of soil permeability was found in the literature surveyed. In this study, the size of a hydrologically important difference of soil permeability must be considered in terms of a hydrologic response from the individual sub-catchment units, and from the individual observation sites. An estimate of the mean transformed permeability data, within +/- 15 - 20%, is equivalent to approximately +/- half an order of magnitude of the median of the untransformed permeability data (Aitchison and Brown, 1957).

Studies by Harr (1977) and Murray (1981) show that an abrupt change of permeability of one order of magnitude, is enough to cause the development of saturated conditions and lateral subsurface flow. For soils with permeabilities similar to those observed by Parker (1978), Freeze (1972b) suggests that a change of an order of magnitude in soil permeability causes minor changes in the total storm hydrograph, but considerable changes in the proportion of surface and subsurface flow (Freeze, 1972b, p. 1281, figure 11). These observations suggested that errors of about +/- 20 % were acceptable for estimating the transformed <u>mean sub-catchment unit</u> soil permeability.

An investigation of soil permeabilities with the proposed experimental network (figure 4.5) was considered warranted, given the general lack of information on the spatial relationships between soil physical properties and hillslope runoff processes reported in the literature. The errors estimated for the planned sampling programme of soil permeability were considered conservative because the soil permeability estimates made in this study were based on larger soil volumes than those used by Parker (1978).

Soil moisture

A non-destructive soil moisture sampling technique was necessary, to measure repeatedly soil moisture at depths within the soil profile, at the twenty sites in the experimental catchments. Moisture determinations by neutron moderation was considered the most appropriate method because of this sampling requirement. Figure 4.5 shows the distribution of soil moisture sampling sites.

As with all indirect methods of determining soil moisture, a calibration of the neutron probe was required. The sampling errors associated with neutron moderation methods of soil moisture determination are dominated usually by the adequacy of the calibration (Toebes and Ouryvaev, 1970). The calibration procedure used in this study followed that outlined by Eeles (1969). The calibration curves are presented in appendix A. Standard errors of the estimate for the mean volumetric moisture content for individual sites vary from 1 - 7 % of the mean, but are generally greatest for the surface horizons. Insufficient resources precluded the installation of more than one access tube per site, thus individual measurements had to be considered to represent the site.

The precision with which the network was capable of estimating the sub-catchment unit mean moisture content varied continually, because soil moisture varied through time. Thus, realistic estimates of the precision of the soil moisture sampling network were not possible because the data required for these estimates were not available for the soil types in the Mangawhara Valley.

The data obtained from the initial soil moisture survey were not used as a reliable estimate of the variance of the sub-catchment unit soil moisture likely to be encountered when determining soil moisture by neutron moderation. The reasons for this decision are presented below.

i) The soil moisture tension data were determined from a very small sample; the surface of the ceramic tip of the tensiometer is 7.85×10^{-4} m^2 in area, whereas the neutron probe could be expected to determine the moisture content of a volume between 4.2×10^{-3} and 1.4×10^{-2} m^3, depending on the moisture content at the time of measurement.

ii) The initial moisture survey was conducted during a rain event. Thus, the apparent spatial variation in soil moisture was likely to be exaggerated, because of moisture gradients between the surface and the interior of soil peds.

The importance of the inter-relationships between the spatial variability of soil moisture and soil hydraulic properties, meant that some estimate of soil moisture was necessary within the experimental catchments. The proposed data collection network was used, despite being uncertain of the precision with which soil moisture content could be determined.

4.4.3 EVAPO-TRANSPIRATION

Estimates of potential evapo-transpiration were made from weekly observations of open water evaporation, reduced by a correction factor of 0.69 (Finkelstein, 1961). The sampling errors of a U.S. class 'A' evaporation pan have been estimated to be +/- 1.0 mm, for weekly estimates of evapo-transpiration (Pelton and Korven, 1969). Few similar estimates, or comparisons between other methods and pan evaporation measurements, have been made in New Zealand (Heine, 1976). Estimates of potential evapo-transpiration were used only for comparative purposes in the analysis of the water balance components of the two land use catchments (see chapter 8): further discussions of instrument and sampling errors are therefore not warranted.

4.5 INSTRUMENTATION

Plate 4.1 shows the location of the instrumentation within the experimental catchments. Plates 4.2 to 4.7 show various components of the network.

All instruments and equipment used in this research programme were of standard hydrological design and were installed to meet or exceed the standard design criteria. They were all operated in accordance to standard hydrological procedures (Toebes and Ouryvaev, 1970), except for open water evaporation measurements. Open water evaporation was measured on a weekly, instead of a daily interval: thus the measurement errors are likely to be greater than normally expected.

A description of the catchment instrumentation and operating procedures is presented in tabular form in table 4.5, to avoid a repetition of information that is available in many hydrological texts. Included in the table are a list of the variables measured, the measurement techniques, the estimated sampling and instrument errors, and a list of references that describe the equipment, and pertinent operating procedures. Additional comments follow the table to clarify various aspects of the information presented. A summary of the remaining site variables (see table 4.1) and the techniques used in determining them are presented in appendix B.

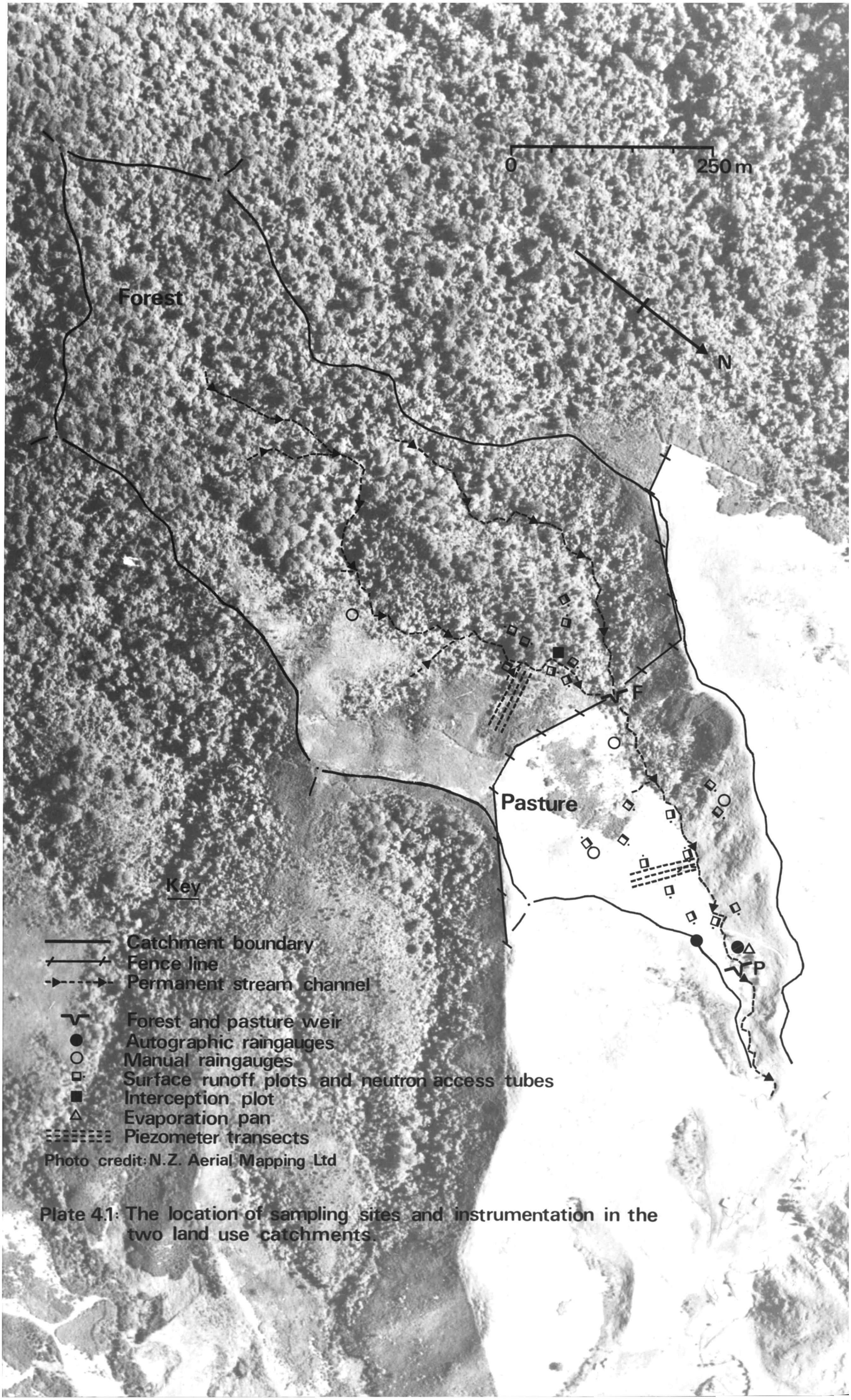

Photo credit: N.Z. Aerial Mapping Ltd

Plate 4.1: The location of sampling sites and instrumentation in the two land use catchments.

Plate 4.2 : The weir site at the outfall of the forest catchment showing the 'V' notch and rectangular addition

Plate 4.3 : The forest interception plot showing the arrangement of the collecting troughs. Throughfall from these troughs was bulked into a single recording device

Plate 4.4 : The arrangement of a surface runoff plot and soil moisture sampling site. Note the tipping bucket for recording surface runoff continuously

Plate 4.5 : Raingauge site 2, the evaporation pan and the pasture flow site in the distance (see plate 4.1)

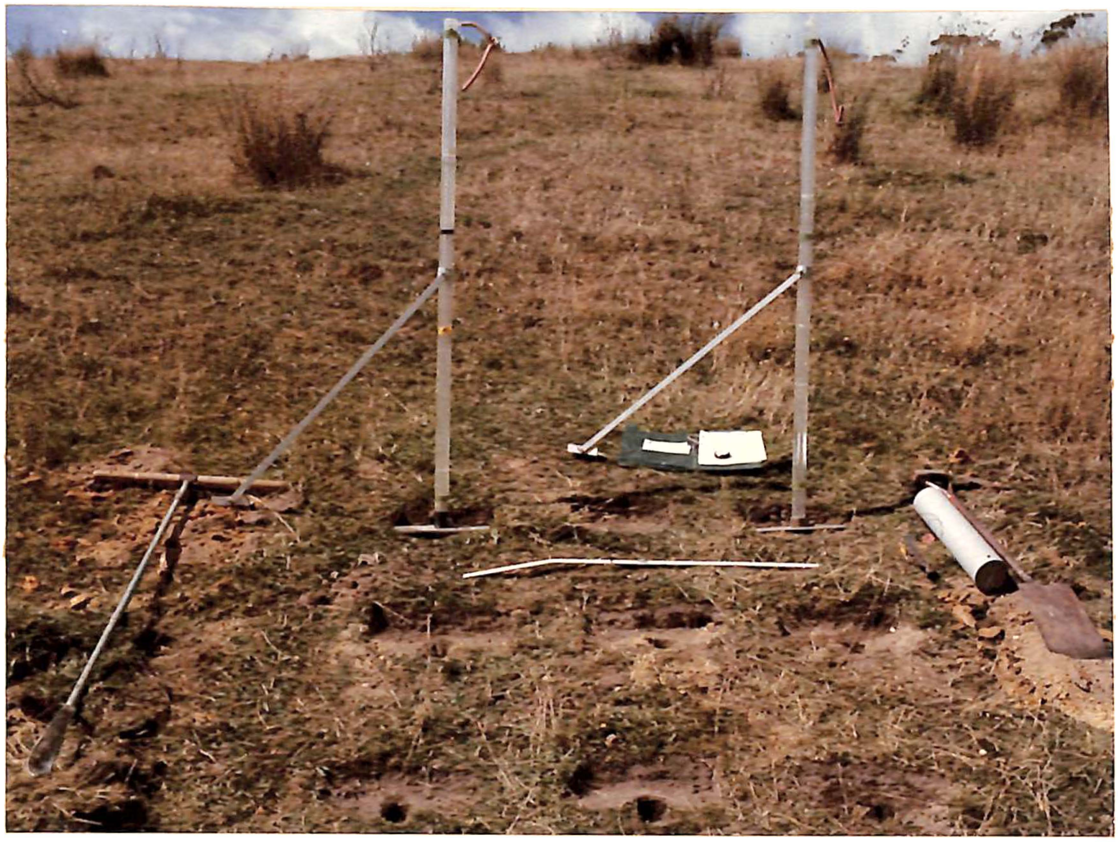

Plate 4.6 : The constant head permeameters used for estimating soil permeability and the arrangement of the sampling sites at each runoff plot site. Three estimates of soil permeability were made in each soil horizon at each site

Plate 4.7 : Saturated soil moisture conditions were measured with narrow bore piezometers (orange). Observations were made of the weekly peak water table elevations and the water table elevations at the time of observation. The P.V.C. tubes are vacuum lysimeters used by Phipps (1982)

Major hydrologic and soil variables	Measurement technique	Errors (see below)	Record type (see below)	Data resolution	Sampling interval	Period of observation	References
Rainfall	2 Lambrecht autographic raingauges (gauge 1)	* 5 - 20 %	C	5 min	4 weekly	780818 - 810801	Hutchinson (1969); Toebes and Ouryvaev (1970); Rodda (1969); W.M.O. (1965, 1972).
	(gauge 2)	5 - 20 %	C	0.1 mm	4 weekly	790212 - 810801	
	4 storage raingauges	5 - 20 %	I	0.1 mm	weekly	790707 - 791009	
Throughfall	10 0.3 m^2 collecting troughs with a modified Kent recorder	* 10 - 20 %	C	15 min 0.1 mm	weekly	790707 - 801014	Aldridge and Jackson (1973); Hogg *et al*. (1975); Rowe (1979).
Evaporation	U.S. class 'A' evaporation pan	* 10 - 15 %	I	0.01 mm	weekly	790707 - 810714	Finkelstein (1961, 1973); Pelton and Korven (1965); Heine (1976).
Stream flow (see note 1 in the text below)	Forest: 1/2 90 deg. 'V' notch weir with rectangular addition; capacity 0.63 m^3 s^{-1} ; direct drive Lea recorder	+ 2.5 % @ 2.2 l s^{-1} ; 0.5 % @ 119.0 l s^{-1} ; 5.0 % @ >130.0 l s^{-1}.	C	15 min 1.0 mm stage	weekly	790212 - 810801	Toebes and Ouryvaev (1970); Bos (1978); Waugh and Fenwick (1979).
	Pasture: as above	as above x 2	C	as above	weekly	790212 - 810801	
Surface runoff	Pasture:						
	6 5.0 m^2 plots (24 mm storage capacity)	*	I	0.02 mm	weekly	790707 - 810714	Hayward (1967, 1968); Boughton (1967); Selby (1971).
	6 5.0 m^2 plots (recorded with data logger and 0.5 l tipping buckets)	low	C	15 min 0.1 mm	weekly	800722 - 810714	
	Forest:						
	4 5.0 m^2 plots (24 mm storage capacity)		I		weekly	790707 - 810714	
	4 5.0 m^2 plots (recorded, as above)		C		weekly	800729 - 810714	Jordan (1979).
Subsurface runoff	Forest and Pasture: Indirect estimates from piezometer and permeability measurements	* unknown	I	n/a	weekly	790707 - 810714	Swanston (1967); Anderson and Burt (1977a,b, 1978a,b); Atkinson (1978).
Soil moisture	Neutron moderation Pasture: 12 sites Forest: 8 sites	* 1 - 7 %	I	n/a	2 weekly	790707 - 810714	Eeles (1969); Watt and Jackson (1981).
Piezometry (see note 2)	Pasture: 17 1.5 m piezometers Forest: 14 1.5 m piezometers	* unknown low	I	2.0 mm depth	weekly	790707 - 810714	Gibson (1963); Swanston (1967); Premchitt and Brand (1981).
Permeability	Inverse auger hole method: 3 measurements per horizon per site per season; 360 measurements in total	* unknown low	I	1.0 sec 0.1 ml	seasonally	winter 1980 summer 1981 winter 1981	Talsma and Hallam (1980).

errors: * = sampling + = instrument record type: C = continuous I = interval

Table 4.5: Summary of the data collection network for the main hydrologic and soil variables measured in this study

Note 1). The use of calibrated structures is considered mandatory for all experimental basin research, as they are the most accurate of all discharge measurement techniques commonly used (Toebes and Ouryvaev, 1970). Many discussions of the errors associated with the use of pre-calibrated flow measurement structures have been reported in the literature (e.g. Bos, 1978). The errors associated with the weirs installed in the two experimental catchments, were estimated from a simplified method presented by Toebes and Ouryvaev (1970). The errors for estimating discharge from the pasture catchment are twice those for the forest catchment because discharge from the pasture catchment is obtained from the difference between the observed discharge from the two weirs.

The weirs were field calibrated, using the dam draw-down method outlined by de Laine (1964). Field calibrations were completed to check the accuracy of the theoretical rating of the 'V'-notches, and to establish a rating for the rectangular additions. The stage discharge curves for each weir are presented in appendix C.

Note 2). Subsurface soil saturation in the two first order basins was monitored using grids of piezometers based on a design reported by Swanston (1967). Piezometers were placed in the ground to measure the piezometric surface above the soil-saprolite boundary. Field observations show a sharp reduction in permeability and porosity with depth at this boundary. Thus, the observed hydrostatic surface was assumed to be a measure of the saturated conditions throughout the profile; i.e. the piezometers were acting as shallow, narrow bore wells recording the transient water table.

Piezometers of similar design have been used in several recent geomorphological and hydrological studies (e.g. Parker, 1978; Pierson, 1980). However, the accuracy with which these instruments follow the changes of the piezometric surface has not been discussed, as only recently has a full understanding of the equalisation process of cylindrical piezometers in compressible soils been achieved.

The methods of analysis of piezometer equalisation are outlined in Brand and Premchitt (1980) and Premchitt and Brand (1981). However, methods have not yet been developed fully for piezometers with large length to diameter ratios (similar to those used in this study) for operation at, or near, the water table. Nevertheless, for increasing length/diameter ratios, the response time decreases considerably, particularly when the ground surface is within only a few piezometer lengths of the water table surface. Thus, it is probable that the piezometers used in this study follow closely changes in subsurface saturation, as the observed level of soil saturation was always close (less than one piezometer length) to the base of the stand pipe.

4.6 DATA COLLECTION AND ANALYSIS

Data were collected on the variables listed in table 4.1 and 4.5 during weekly visits to the experimental catchments, between July 1979 and July 1981; 104 observation periods in total. Data on all variables were reduced to computer compatible format, for analysis on the University of Waikato computer system.

All missing or censored data were identified. Data analyses were completed on the University computer system, using existing package programs or user written programs. Computer programs used for data analysis are not included in this thesis, but copies are available on request, from the Department of Earth Sciences. A list of the main programs developed for this thesis is presented in appendix D.

Standard parametric, non-parametric, and other descriptive and analytical statistical techniques, in association with simple physical models were used in the data analysis. Statistical techniques must be applied carefully for the analysis of hydrologic data if the assumptions underlying their use are not to be violated. This is of particular importance in this study, where spatial and serial correlation are a feature of the data sets. Further details of the data analyses are presented in individual chapters describing the various components of hillslope runoff.

4.7 LIMITATIONS OF THE DATA COLLECTION NETWORK

The availability of resources imposed limitations on the data collection network: this also had implications for the experimental design. Several of these factors are discussed below.

The restriction of the experimental programme to a nested catchment arrangement, instead of the more common paired catchment arrangement means that the study is observational rather than experimental (i.e. where a treatment is applied as part of an experimental programme and the treatment effects monitored). Thus, some of the hydrological consequences of the two different forms of land use cannot be shown conclusively because of possible complicating effects of differences in catchment size and physiography, and channel routing.

However, the many recent studies of source area hydrology have shown the important role of the sub-catchment unit in determining hillslope runoff processes in catchments. The presence of many first order basins and re-entrants in the two catchments studied will reduce the effects of differences in physiography and size on the hydrological response from each catchment. This assertion is supported by field observations of the storm runoff response times from the two forest tributaries, that are of different size and different physiography (see plate 4.1). The storm runoff response times showed only small (less than two minutes) differences in the time from the onset of rain to the initiation of observable stream rises.

The limited resources available to this study imposed constraints on some of the components of the data collection network. The rapid response of stream flow to rainfall, including peak flow up to 500 times larger than typical base flows, posed several problems for weir design. The design of the weirs reflects a compromise between sensitivity at low stages and capacity to accommodate the largest flows. Sensitivity was of paramount importance in this study, but, although a rectangular addition was added to the 'V' notch weirs, they were both over-topped briefly on occasions during the two year observation period.

The continuous recording of soil moisture and piezometric responses at some sites within the catchments would have added value to the data sets. However, some inferences, about the more detailed aspects of the response of these two variables, can be made from data collected on a weekly basis; for example, the characteristics of soil drying and piezometric recession, over periods of no rain.

Additional resources to establish four measurement sites in all the sub-catchment units would have permitted a more confident assessment of the variability of the runoff regime in the two upslope forest sub-catchment units.

4.8 CONCLUSIONS

The research programme outlined in this chapter is considered to be the best that could be achieved with the resources available. An attempt was made to develop a preplanned, integrated series of process studies, based on a rigorous experimental design developed from pretested hypotheses. The process studies were completed within the framework of an experimental catchment, to provide continuity between the observed hillslope runoff regime, and the integrated response observed in the stream channel. The experimental design was applied to two characteristic land use regimes, to determine in detail, the differences in the hillslope runoff regime between the two forms of land use.

Although some compromises were inevitable, the proposed experimental design and data collection network were considered adequate to provide a data base, from which valid, reasoned, scientific conclusions could be made about the stated research objectives. If some aspect of the experimental design of data collection network were proved subsequently to be inadequate, the data would at least provide information on which future studies of this type could be based.

CHAPTER FIVE

PRECIPITATION AND INTERCEPTION ANALYSIS

CONTENTS

5.1 INTRODUCTION

Recent studies of source area hydrology have established the rainfall-runoff processes for a wide range of land use environments. Almost all studies of source area hydrology completed in humid temperate environments cite the importance of interactions between characteristics of the incident rainfall and the processes of hillslope runoff. However, only a few studies have included analysis of either the intensity-duration characteristics of the rainfall input (e.g. Freeze, 1972b; Pearce and McKerchar, 1979), or the serial pattern of the rainfall input.

In most studies of rainfall-runoff processes in humid temperate climates, it has been assumed that rainfall intensities exceed infiltration capacities of soils only occasionally. However, results from more recent studies of hillslope runoff suggest that this assumption may not be as widely applicable within humid temperate environments as previously thought (e.g. Bonell and Gilmour, 1978; Pilgrim, et al., 1982).

The role of interception processes in determining the net rainfall under forest and pasture vegetation has been established in several recent micro-meteorological studies of interception processes (Stewart, 1977; Thom and Oliver, 1977) and by continued basin studies in different climatic regimes (Swank and Miner, 1968; Pearce and Rowe, 1979; Pearce, 1980). These studies have established the interactions between transpiration and evaporation and the importance of the frequency and duration of canopy wetness in determining water losses as a result of interception. Differences in water yields from contrasting vegetation types are now ascribed to different rates of evaporation of intercepted water, instead of to differences in transpiration rates between forest and pasture crops.

The important interactions between hillslope runoff processes and the gross and net rainfall regimes of the two land use catchments require a detailed analysis of rainfall characteristics as part of this study. In this chapter, the data analyses of gross and net rainfall are considered in two sections. In the first, the analyses of the gross rainfall input are presented (section 5.2); in the second, the analyses of net precipitation are presented (section 5.3).

5.2 GROSS RAINFALL

Data collection, analysis and interpretation of gross rainfall were completed to achieve the following sub-objectives:

i) to provide a general description of the rainfall in the Upper Mangawhara Valley;

ii) to establish systematic variations of catchment rainfall that may be important in determining the spatial distribution of hillslope runoff processes;

and iii) to provide information on the intensity-duration characteristics and the serial pattern of the gross rainfall input, so that inferences about the processes of hillslope runoff could be made for each land use catchment.

These sub-objective were chosen after a careful evaluation of the literature on interactions between the rainfall regime and source area hydrology.

A general description of the long term precipitation record was made to enable a comparison between the long term precipitation record for the area and the precipitation that fell during the 2 year period of intensive observations. In this way, the applicability of the observations of rainfall-runoff processes made during the study could be assessed.

Estimates of the systematic variation of the catchment rainfall were made because of the importance of these variations in determining the spatial variability of hillslope runoff (Yair et al., 1978). Few studies of source area hydrology have included this type of analysis.

Information on the intensity-duration characteristics and the serial pattern of the catchment rainfall were required for several reasons. Interactions between characteristics of the rainfall regime and the soil infiltration capacity form the basis for differentiating between the Horton overland flow model, and both the partial and variable source area models and subsurface flow models. In catchments where the soils are of low permeability, infiltration-excess overland flow will occur when rainfall intensities exceed the soil infiltration capacities for long enough to cause surface saturation from above, and surface ponding (Rubin, 1966).

In environments where catchment soils are more permeable, interactions between rainfall characteristics and soil physical properties also determine characteristics of the surface and subsurface flow response. For example, the generation of return flow (Dunne, 1969), the generation of saturated subsurface flow above permeability breaks in the soil profile (Whipkey, 1965; Weyman, 1970, 1973) and the initiation of rapid subsurface flow in the soil macro-pore system (Bouma and Dekker, 1978; Germann and Beven, 1981a, 1981b), are all determined by interactions between rainfall characteristics and soil physical properties.

Two aspects of the gross rainfall input were examined to provide this information. Intensity-duration analyses were completed to provide information on the distribution of rain intensities for various integration times. This type of analysis has been used successfully to establish rainfall-runoff relationships in several New Zealand experimental catchments (Pearce and McKerchar, 1979). However, these data provide no information on the serial pattern of the rainfall input or on the hydrologically important rainfall events.

The distribution of rain and rainless events, their durations and their serial pattern, are also likely to have an influence the hillslope runoff regime. Different hillslope runoff responses are likely from storms with different serial patterns, but with similar average intensity and duration.

These characteristics were determined by analysing the micro-periodicity and serial structure of gross rainfall observed in the experimental catchments. This type of analysis has not been applied widely as an aid to understanding the processes of source area hydrology, although micro-scale rainfall patterns have been recognised as an important variable in the interception process (e.g. Rutter, 1963; Pearce and Rowe, 1979), and in model studies of infiltration (e.g. Bauer, 1974; Chu, 1978).

Together, analyses of these characteristics were considered capable of providing an adequate description of the catchment gross rainfall input and a data base that could be incorporated into the analyses of hillslope runoff and the catchment water balance.

5.2.1 MODIFICATION OF THE DATA COLLECTION NETWORK, NETWORK PRECISION, AND THE SPATIAL VARIABILITY OF CATCHMENT RAINFALL

The development of the data collection network and the instrumentation are described in chapter 4. The raingauge network installed initially, comprised 2 autographic gauges and 4 storage gauges (see plate 4.1). During the period of data collection, the network was reduced on two occasions when enough data had been collected to show that some elements of the network were unnecessary.

The four storage gauges, installed to detect spatial variations of catchment rainfall, were removed after a period of observation from July 1979 to October 1979, because no consistent, systematic, spatial variations of rainfall were observed during this period. The rainfall depths estimated by these raingauges varied between, less than 5 %, to about 10 %. Variations of this size were considered too small to be hydrologically important in this study. It was thus assumed that the systematic and random rainfall variations that occur in the catchments do not influence the spatial variability of runoff generation.

At the end of 1980, a further attempt was made to reduce the raingauge network to simplify the analyses of gross rainfall. The errors for estimating catchment mean rainfall with only one raingauge were examined by comparing the weekly totals observed at each of the two remaining gauge sites. The two sites represent extremes of exposure and are therefore likely to encompass a wide range rainfall variation. Site two was located in the valley floor adjacent to the outfall of the pasture catchment (plate 4.1): site one was located on an exposed ridge about 100 m upstream from site two.

Data for the comparison were obtained from the two gauge sites for the period February 1979 to December 1980. The data from the two sites show a strong linear relationship, but estimates of weekly rain totals recorded at site 2 are about 4 % larger than those recorded at site 1 (table 5.1). These differences are attributed to the degree of exposure at each site and agree with other results reported in the literature (Aldridge, 1975; Sharon, 1980).

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rainfall at site one (mm) = 0.96 x rainfall at site two (mm) - 0.74

$n = 62$ $r^2 = 0.99$ $s_{y.x} = 2.62$ (mm)

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n - number of samples r^2 - coefficient of determination

$s_{y.x}$ - standard error of the estimate

Table 5.1 : Regression equation describing the relationship between the weekly rainfall totals estimated from site one and site two

A deviation of less than 4 % between two contrasting sites was considered not sufficiently different to warrant further investigation. A sufficiently accurate estimate of catchment mean rainfall could be made from only one raingauge.

Site two was chosen as the master raingauge site, but both raingauges were operated for the remainder of the research programme to minimise record loss. If this occurred, data from site one were used to fill the gaps in the record from site two. The final data set for gross rainfall was obtained from site two, supplemented where necessary from site one, for the period 18 February 1978 to 1 August 1981.

5.2.2 GENERAL CHARACTERISTICS OF THE LONG TERM PRECIPITATION RECORD IN THE UPPER MANGAWHARA VALLEY

Data, from the New Zealand Meteorological Service (N.Z.M.S.) site B 75441 Hoe-o-Tainui, were used for a comparison between the long term rainfall characteristics and the rainfall that was observed in the experimental catchments. The N.Z.M.S. site B 75441 is located 2 km east of the experimental catchments and has been operated since mid 1956.

Regression analysis was used to compare monthly rainfall totals for N.Z.M.S. site B 75441 and those observed in the experimental catchments, for the period September 1978 to July 1981. Figure 5.1 shows the results of this analysis; tests of parallelism and concurrence (Seber, 1977) show the two sites receive the same amount of rainfall on a monthly basis ($p = 0.01$). These results suggest that the following description of the long term rainfall record from N.Z.M.S. B 75541 (1957 to 1981) is applicable to the experimental catchments. Table 5.2 shows the monthly mean rainfalls, the monthly mean rain days, and the mean consecutive days without rain per month, estimated from the record from the N.Z.M.S. site. A slight seasonal trend is apparent in all these variables. However, the coefficients of variation (c.v.) of monthly rainfall show considerable seasonal variation. These are largest during

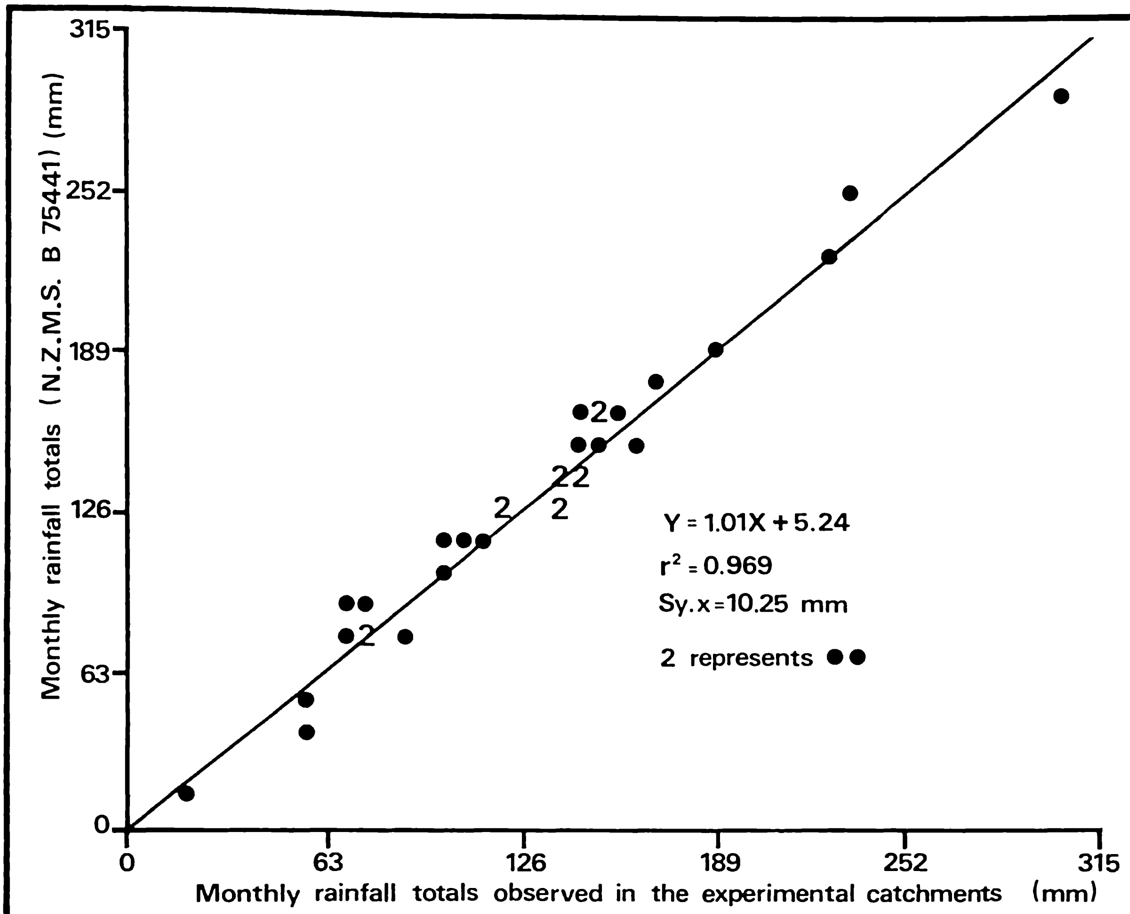


Figure 5.1 : A comparison between monthly rainfall observed at N.Z.M.S. B 75441 and in the experimental catchments

the late summer and early autumn months (January - April) and reflect the occurrence of high intensity convective rain storms common in the Hapuakohe Range during this period.

Figure 5.2 shows the annual rainfall totals from the N.Z.M.S. site B 75441, for the period 1957 to 1981. Annual rainfall totals are evenly distributed about the mean. Rainfall for 1979 was the second largest on record. Rainfall for 1980 was considerably lower than the long term average, while in 1981 rainfall was about average.

In figure 5.3, the monthly mean rainfall totals observed in the experimental catchments are compared with monthly means estimated from the long term record. A wide range of rainfall inputs occurred during the period of intensive study (July, 1979 to July, 1981), including some unusually large rainfall events, and some unusually long periods with no rain.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
mean rainfall (mm)	86.1	111.8	128.4	122.6	139.1	154.3	170.3	147.5	149.1	117.6	111.5	129.7	1586.2
standard deviation (mm)	46.8	85.1	80.9	69.1	52.6	61.9	56.9	32.3	56.6	53.2	52.9	45.1	173.6
c.v.	0.54	0.76	0.63	0.56	0.42	0.40	0.33	0.22	0.37	0.45	0.47	0.34	0.11
mean number of raindays	11.0	9.0	11.8	13.4	15.1	17.1	17.1	17.9	17.7	16.0	14.3	12.8	-
standard deviation	4.2	3.6	4.2	4.2	4.7	4.7	4.8	4.1	3.9	5.4	4.3	3.7	-
mean number of consecutive rainless days	3.8	4.3	3.8	3.2	3.0	2.7	3.0	2.5	2.3	2.5	2.9	3.3	-
standard deviation	3.2	3.4	3.0	2.8	2.4	2.1	2.7	1.8	1.8	2.0	2.3	3.0	-

c.v. - coefficient of variation

Table 5.2 : Descriptive statistics of monthly rainfall in the Upper Mangawhara Valley: estimated from the N.Z.M.S. site B 75441 Hoe-o-Tainui, for the period 1957 - 1981

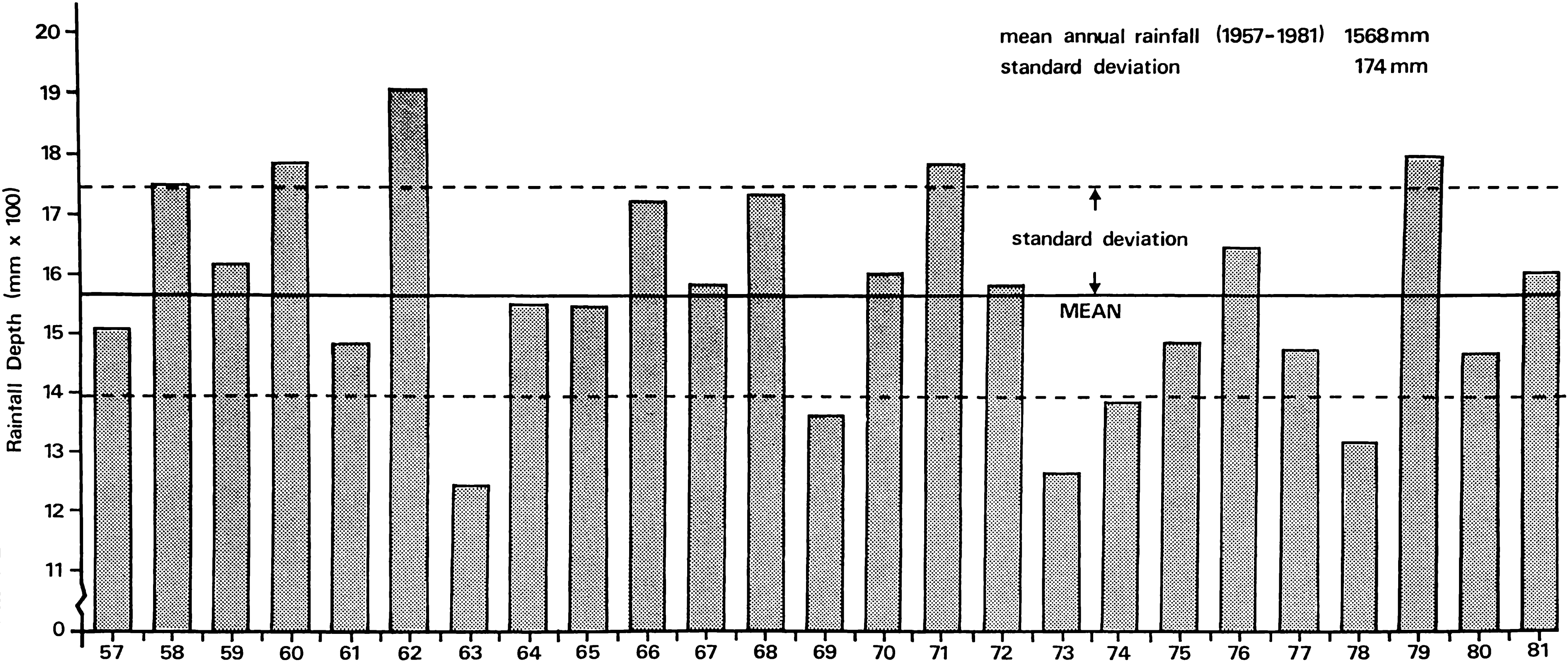


Figure 5.2 : Mean annual rainfalls for the Upper Mangawhara Valley, Hapuakohe Range: 1957–1981 (Data source N.Z.M.S. B 75441)

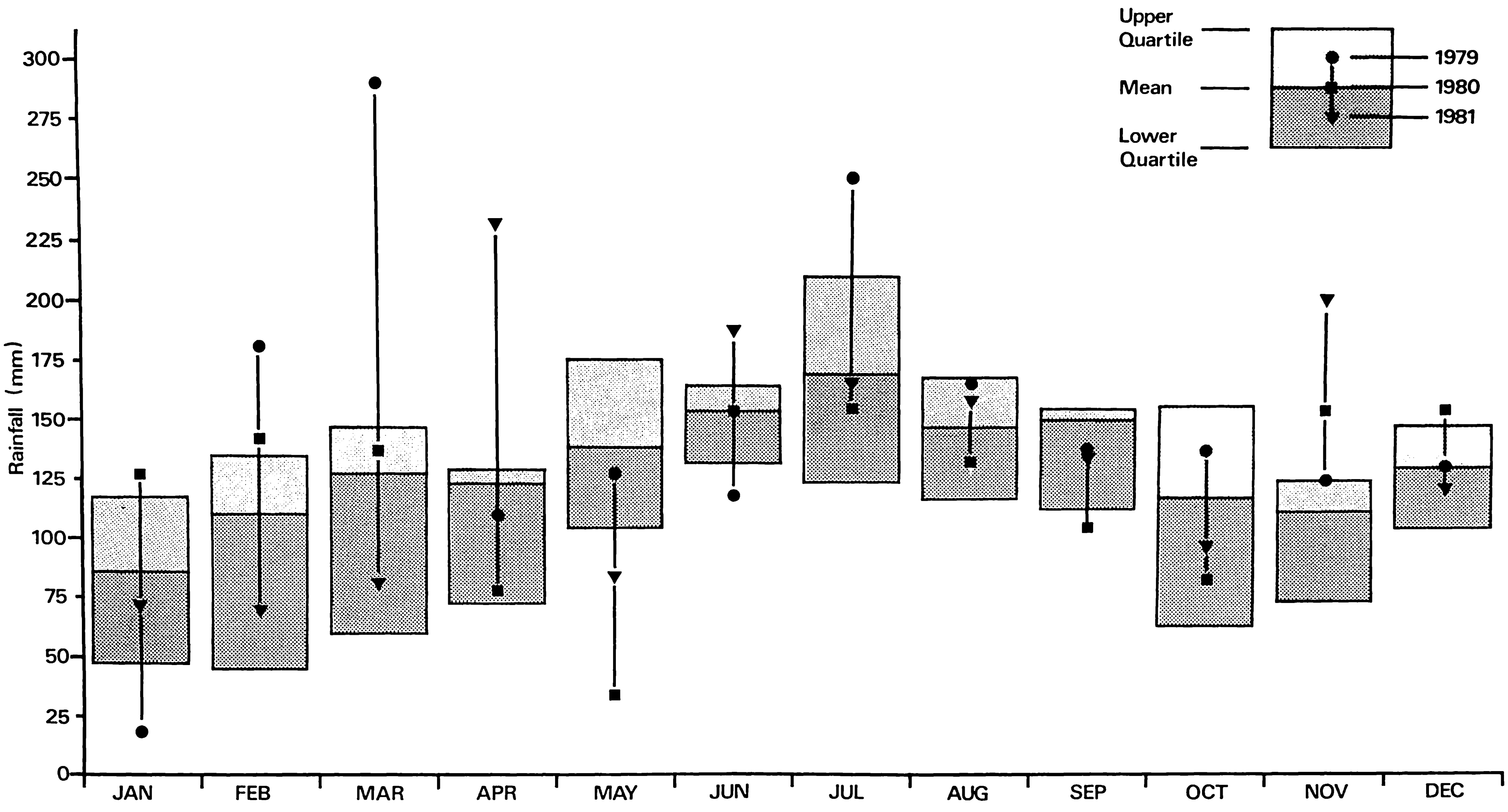


Figure 5.3 : Mean monthly rainfalls for the Upper Mangawhara Valley with individual monthly totals for 1979, 1980 and 1981
(Data source N.Z.M.S. B 75441: 1957 - 1981)

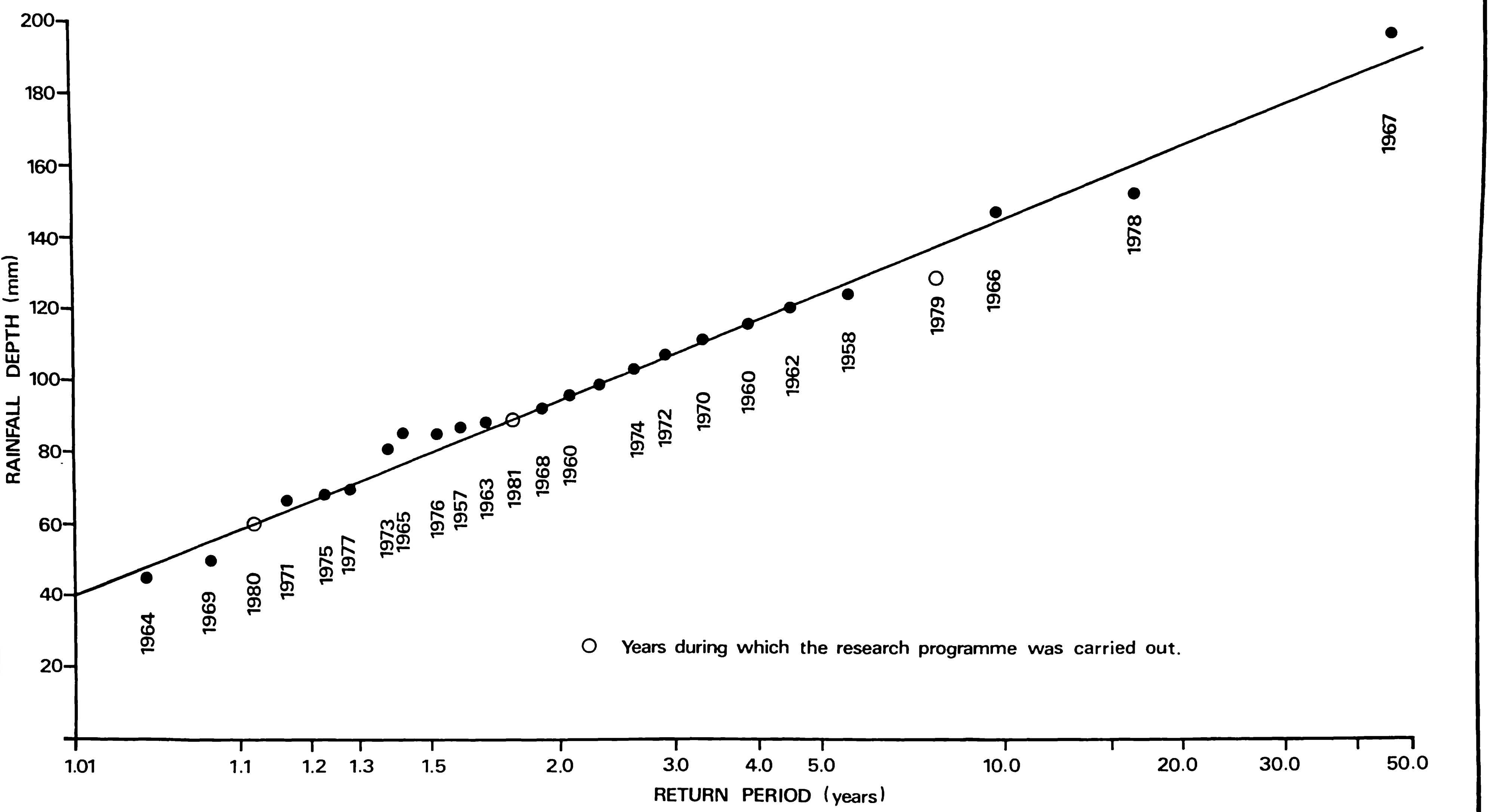


Figure 5.4 : Return periods of annual maximum daily rainfall for the Upper Mangawhara Valley, Hapuakohe Range (Data source N.Z.M.S. B 75541)

Figure 5.4 shows the recurrence intervals for annual maximum daily rainfall totals observed at N.Z.M.S. site B 75441. Of note is the high intensity convective storm of 22 March, 1979. This storm contributed about half of the rainfall total for March 1979 (see figure 5.3) and caused the initiation of numerous landslides in both experimental catchments, and in other areas of the Upper Mangawhara Valley. Figure 5.5 shows the storm trace recorded at the master raingauge site in the experimental catchments. Total rainfall recorded in the study catchment, from 0900 hours March 22 to 0900 hours March 23, was 151 mm. This total is about 17.5 % greater than observed at the N.Z.M.S. site. The estimated return period of this storm is 7.5 years (see figure 5.4).

The storm severely damaged the instrumentation network in the catchment and the precipitation record was the only useful data set obtained. However, there was ample evidence that widespread overland flow was the principal mechanism of runoff generation in both experimental catchments.

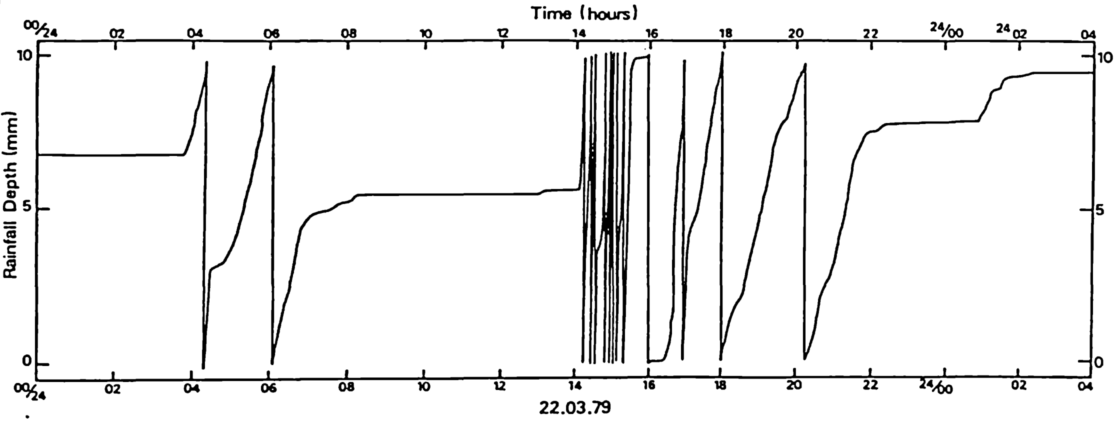


Figure 5.5: The Lambrecht trace of the March 22, 1979 extreme event

The storm was large enough to cause similar damage to both the catchments. However, even in their depleted condition, the catchments represent the general physiographic condition of the Upper Mangawhara Valley and Hapuakohe Range. Thus, comparisons between the runoff response from the catchments are still valid.

5.2.2.1 Summary

A comparison, between the 26 year rainfall record from an adjacent N.Z.M.S. site and the rainfall record from the experimental catchments, shows that the rainfall observed during the study period was typical for the area. Hence inferences about rainfall-runoff processes observed in the experimental catchments may be considered typical of those likely to occur in the long term. The opportunity to observe the catchments' hillslope runoff response to several unusually large precipitation inputs, and periods of low rainfall enables more confident predictions for conditions that might not otherwise have been observed.

5.2.3 INTENSITY DURATION CHARACTERISTICS AND THE SERIAL PATTERN OF THE CATCHMENT RAINFALL

An examination of the intensity-duration characteristics and the serial pattern of the rainfall observed in the experimental catchments is presented in the following sections. The rationale for these analyses is presented in section 5.2.

5.2.3.1 Results

5.2.3.1.1 Intensity-duration characteristics of the catchment rainfall

Rainfall intensity-duration curves were estimated from the rainfall record for the two year period of intensive observations (July 1979 to July 1981). Figure 5.6 shows the results for the 5, 15, 30, and 60 minute observations and figure 5.7 shows those for 1, 2, 6, 12, and 24 hour durations. Standard return periods were not estimated for each duration, as the rainfall record was too short. However, the maximum intensities observed in the experimental catchments for each duration are similar to the two year return period intensities for the adjacent N.Z.M.S. stations, Ruakura and Paeroa (Robertson, 1963); (see table 5.3).

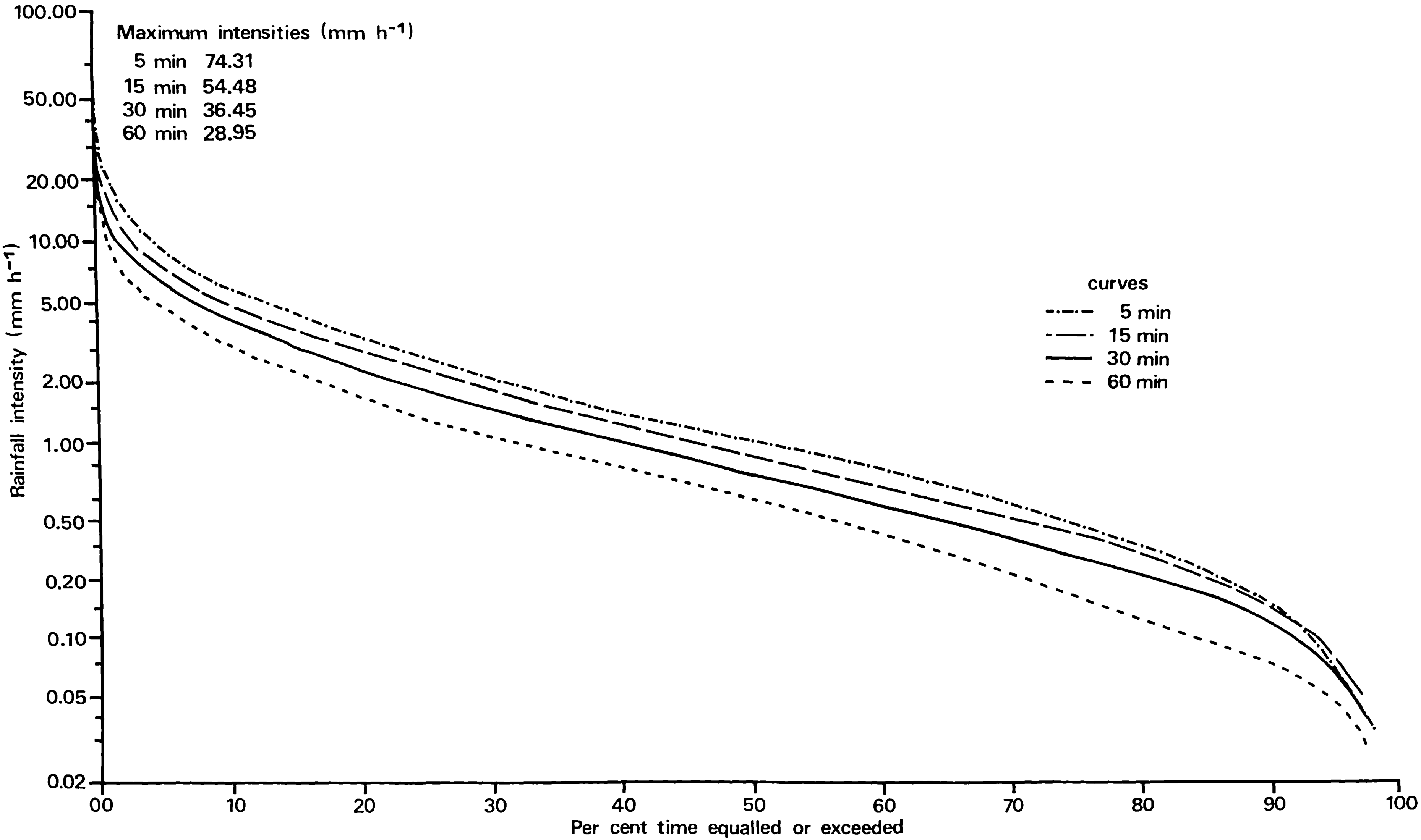


Figure 5.6 : Intensity-duration curves (5, 15, 30, 60 min) for rainfall in the experimental catchments

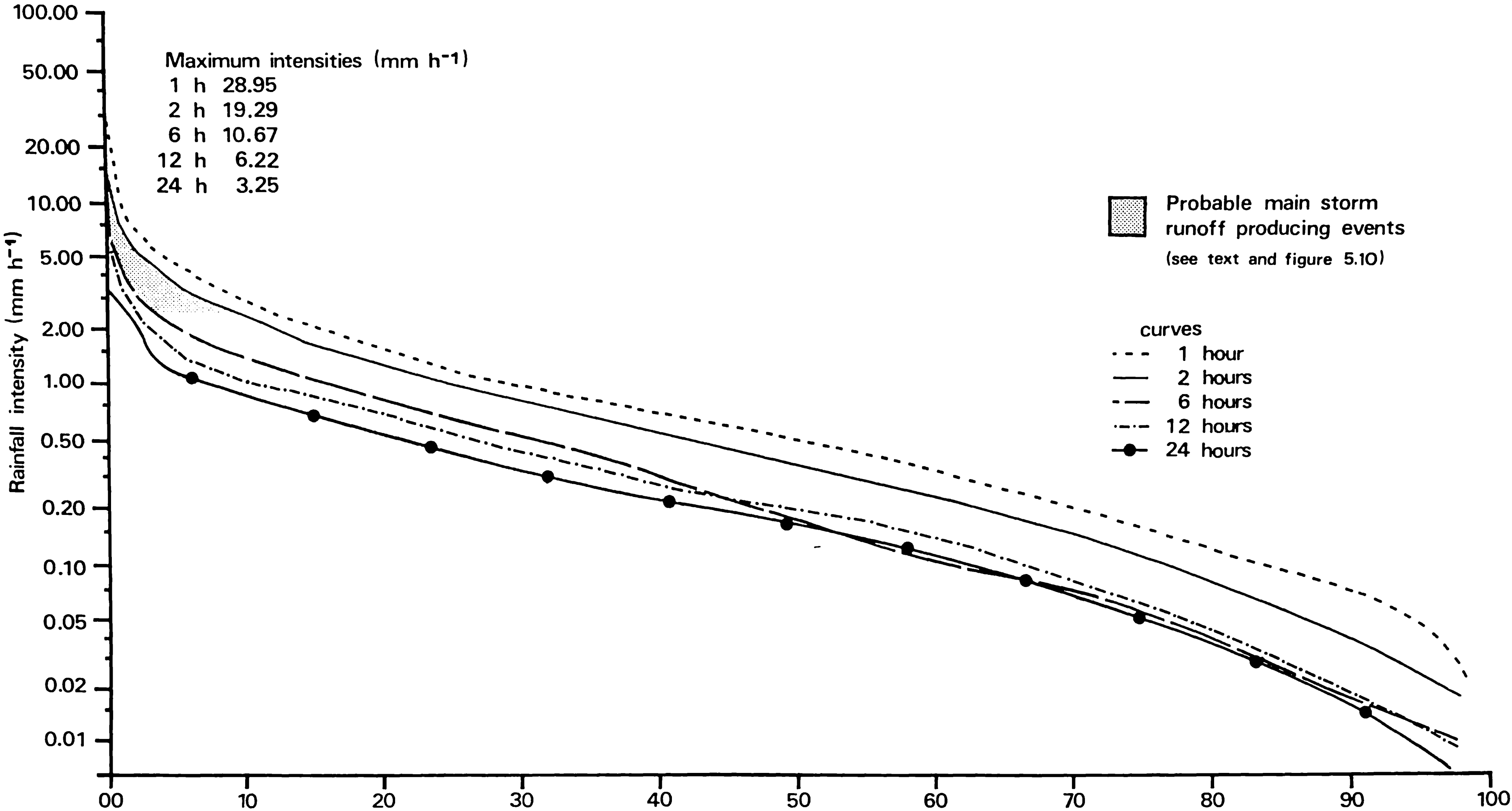


Figure 5.7: Intensity-duration curves (1, 2, 6, 12, 24 h) for rainfall in the experimental catchments

Event duration		5 min	10 min	15 min	20 min	30 min
Experimental catchment		74.31	57.60	54.48	43.83	36.45
Ruakura	C 75731		56.39	-	40.39	33.52
Paeroa	B 75361	-	-	-	-	32.02

Event duration		1 h	2 h	6 h	12 h	24 h
Experimental catchment		29.95	19.29	10.67	6.21	3.25
Ruakura	C 75731	23.62	15.11	7.62	4.72	2.86
Paeroa	B 75361	20.57	13.72	9.27	6.60	4.54

units - mm h^{-1}

Table 5.3 : A comparison between the maximum rainfall intensities observed from the two year record from the experimental catchments and the estimated two year return period intensities for N.Z.M.S. sites, Paeroa and Ruakura

Rainfall in the experimental catchments appears to be characterized by low intensity rainfalls with only infrequent high intensity falls, even for the shortest durations: for example, intensities exceed 10.0 mm h^{-1} for only 5 % of the rain time for durations five minutes long. These results suggest that infiltration-excess overland flow is not likely to occur in either experimental catchment. Instead, saturation overland flow processes and subsurface flow processes are more likely. These flow processes will be generated mainly in the long duration, low intensity storms, following complete saturation of the soil profile.

5.2.3.1.2 Micro-periodicity of the catchment rainfall

The micro-periodicity of the catchment rainfall was described by the analysis of three data series:

i) the duration of rainless events;

ii) the duration of rain events;

and iii) the rainfall depths for each rainfall event duration.

These data series were estimated from the rainfall record for the period July 1979 to July 1981. Relative frequencies for each data series were calculated for increasing event durations, from 5 minutes to 6 hours, in five minute increments (the shortest time resolution of the rainfall record). Figure 5.8 a,b,c show the relative frequency distributions for the three data series. For convenience of data presentation, the relative frequency of events greater than six hours duration were summed to the relative frequencies of six hour events.

The distribution of rain event durations is characterised by many short duration (5 - 30 minutes) rain events, but fewer long duration events (figure 5.8b). By comparison, the rainless event durations are more evenly distributed (figure 5.8a). Twenty-two per cent of the rainless event durations are greater than 6 hours duration and include the numerous inter-storm periods. The median durations for each distribution (see figure 5.9) are 15 minutes for rain events and one hour 25 minutes (85 minutes) for rainless periods.

Despite the many short duration rain events, proportionally less rainfall occurs for these durations (figure 5.8c). This shows that long duration rainfall events are important in providing the bulk of the rainfall input. The events of 6 hours and longer comprise 2 % of the total rain events, yet yield nearly 19 % of the annual rainfall input. These storms are likely to be responsible for generating saturation overland flow or subsurface flow (figure 5.8c and figure 5.9).

Figure 5.10 shows the average rainfall intensities for each event duration from 5 minutes to 6 hours. No statistically significant relationship was found between average intensity and event duration ($p = 0.05$). However, the highest average intensities tend to be associated with events of durations greater than 2.5 hours. These high average intensities may be related to intense 'bursts' of rainfall that are common in most major storm types (Huff, 1967; Farmer and Fletcher, 1972).

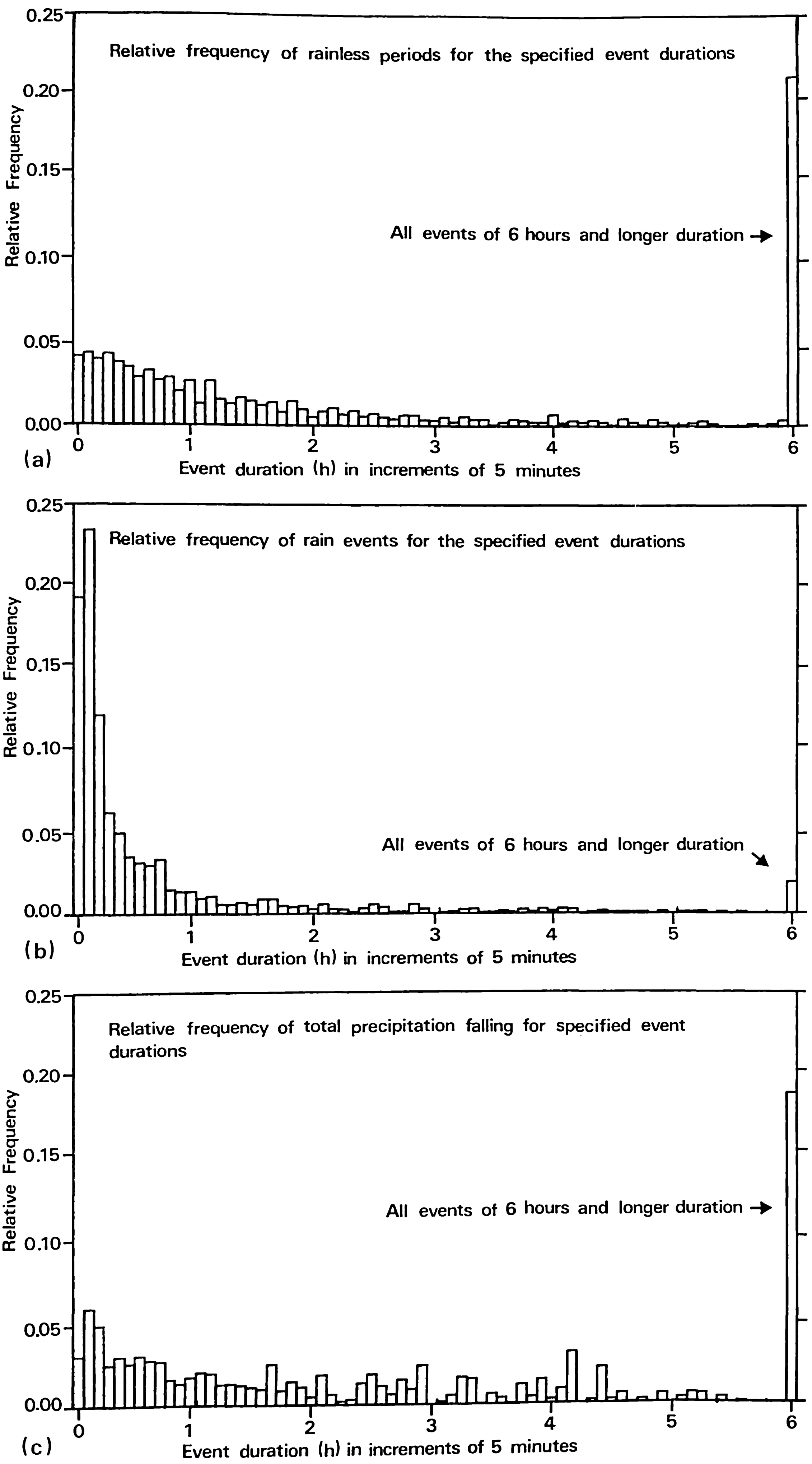


Figure 5.8. a,b,c. Relative frequency distributions for rainless periods, rain events and total precipitation

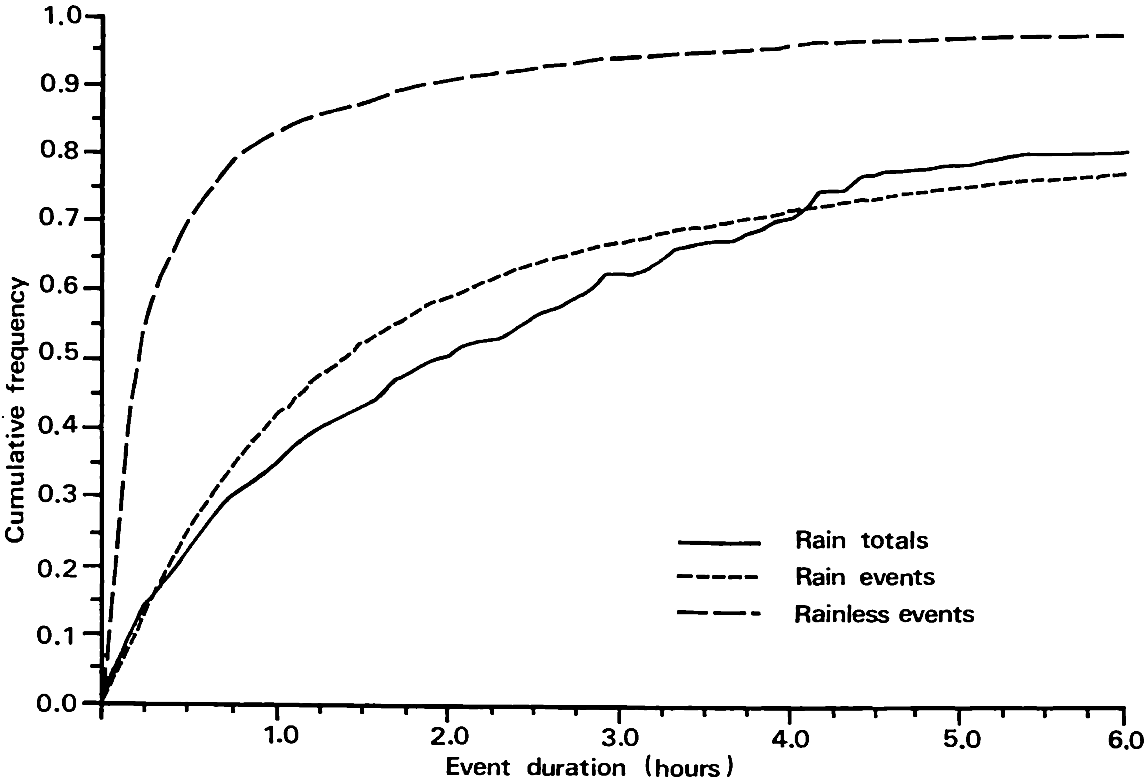


Figure 5.9 Cumulative frequency distributions for rainless periods, rain events and total rainfall for durations up to six hours

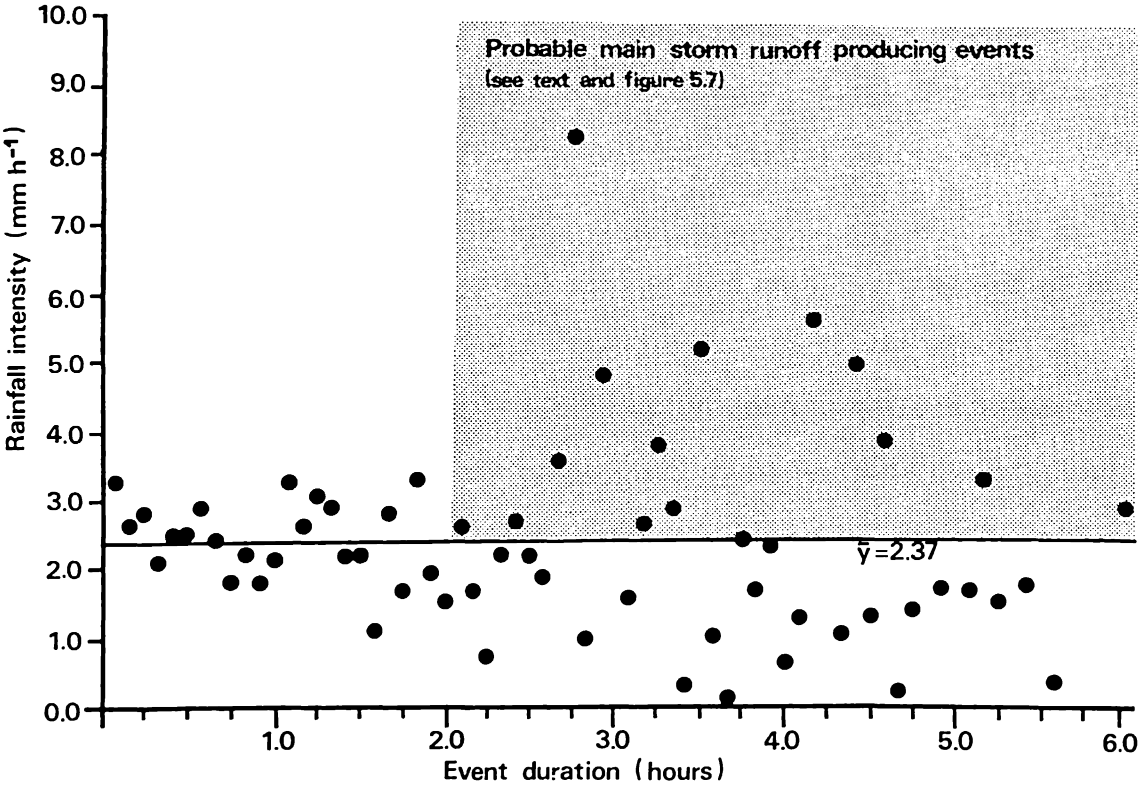


Figure 5.10 Mean rainfall intensities for specified event durations

The results of the analysis of rainfall micro-periodicity suggest that inferences about the mechanisms of rainfall-runoff processes from the rainfall intensity-duration curves may be misleading, because they do not identify correctly the major storm runoff producing events. This is illustrated by considering those storms with intensities greater than the mean average intensity for events of all durations.

These storms are all longer than about 2 hours (see figure 5.9) and relate to those encompassed by the shaded portion of figure 5.10. These same storms are represented by the shaded portion of figure 5.7, neglecting the few rainless periods that may be incorporated in events in the region identified. It is apparent that the rainfall intensity-duration analyses alone, are inadequate to identify the hydrologically important storm patterns and for making inferences regarding rainfall-runoff processes.

5.2.3.1.3 Serial structure of the catchment rainfall

The serial structure of the rainfall input was analysed by reducing the rainfall record to a series of elements, comprising a rainless period and the rain period immediately following. Also, the durations of the rainless and rain periods in the individual elements were estimated.

Figure 5.11 shows a bivariate plot of the relative frequencies of rain event durations, conditional on the durations of the preceding rainless periods. The relative frequency of event durations longer than six hours are included with the conditional distributions for six hour events (see also figure 5.8 a,b,c).

Most short duration (< 1 hour) rain events (see figures 5.8b and 5.9) follow variable length, but generally longer, rainless periods (figure 5.11). A negative relationship is apparent between rain event duration and the preceding rainless duration. About 50 % of the rain periods greater than 2 hours follow rainless periods of less than

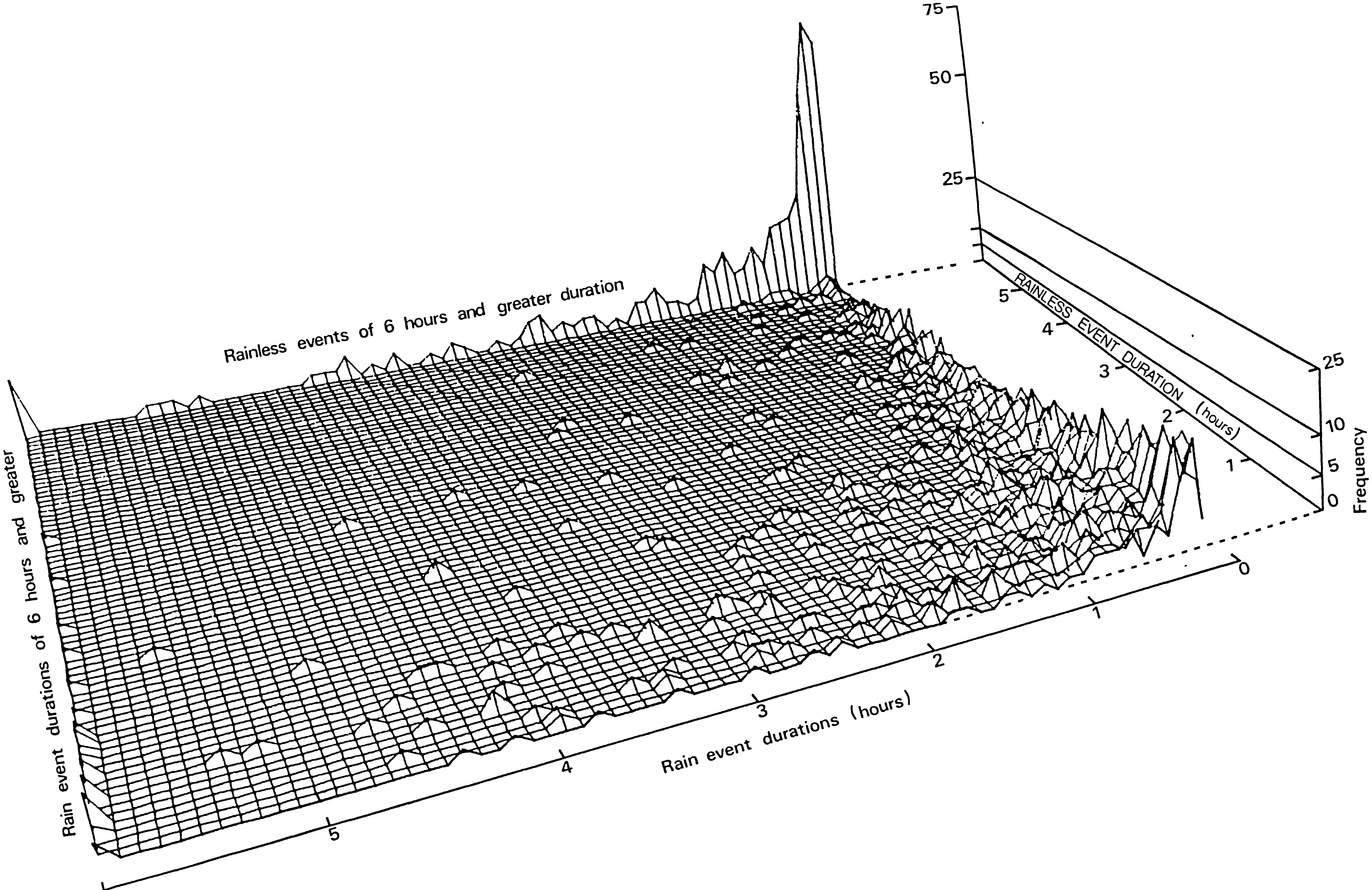


Figure 5.11: Bivariate distribution of rain event durations conditional on rainless event duration

one hour duration. These events are likely to be the main body of major storm events that are often preceded by intermittent rainfall.

Also of note is that 50 % of the total rain falls in event durations shorter than two hours and in a highly intermittent form (figure 5.9 and figure 5.11). Little runoff is likely to occur from these individual events because the hillslope runoff system is likely to have time to recover between each event.

5.2.3.2 Discussion

The results of the preceding sections have significant implications for the magnitude and mechanisms of the hillslope runoff regime in the experimental catchments.

Analysis of the rainfall intensity-duration characteristics show that widespread infiltration-excess overland flow is unlikely to occur in either land use catchment, assuming soil permeabilities estimated in an adjacent catchment (Parker, 1978: Forest soils; mean 537.52 mm h^{-1}, standard deviation 548.20 mm h^{-1}: Pasture soils; mean 347.73 mm h^{-1}, standard deviation 237.51 mm h^{-1}). However, permeabilities of an order of magnitude lower are thought more probable for the surface soils of each catchment, particularly for those in the pasture catchment.

Even if the surface soils in the pasture catchment have permeabilities similar to other grazed pasture soils (e.g. 11.7 mm h^{-1} (Duncan, 1972) to 20 mm h^{-1} (Musgrave and Holtan, 1964)), infiltration-excess overland flow will still be generated only occasionally. Instead, these results suggest a combination of saturation overland flow and subsurface flow is most likely in the two catchments.

However, the analyses of the interactions between rainfall intensities and surface soil permeabilities show that small changes in the permeability of the surface soils in each land use catchment may cause large changes in the processes of hillslope runoff.

Infiltration-excess overland flow may predominate in either catchment if soil permeabilities are lower than the values suggested.

In both land use catchments, analysis of the micro-periodicity and serial pattern of the rainnfall input provides further evidence to suggest the predominance of saturation overland flow and subsurface flow mechanisms. Rainfall input to the experimental catchments is characteristically intermittent: there are many short duration rain events following rainless periods of variable length. Subsurface flow is likely in response to this type of rainfall input because the catchments' hillslopes are able to drain to a quasi-equilibrium before the next rainfall input and so restrict the development of saturation overland flow.

More than 50 % of the rainfall input falls as long duration (> 2 hour) events. These storms are suggested as the major runoff producing events, although they account for only 10 % of the total number of rain events. Short duration rainfall bursts are associated with these events (see 5 and 10 minute intensity-duration curves; figure 5.6), but saturation overland flow or subsurface flow are likely to be produced from these storms because they are generally of low average intensity.

The intensity-duration characteristics, the micro-periodicity and the serial structure of the net rainfall input to the forest catchment will not be the same as observed for the gross rainfall input: the net rainfall input will be modified by interactions with interception processes. Short duration, small storms are likely to be affected considerably. In large storms, the time distribution of net rainfall is likely to remain relatively unaffected once the canopy is saturated, although the total depth of net rainfall will be reduced. The resolution of the net rainfall data precluded a detailed analysis of the intensity-duration characteristics of the net rainfall regime.

Interactions between the precipitation input and interception processes are discussed in section 5.3 of this chapter.

5.2.4 SUMMARY AND CONCLUSIONS OF THE STUDY OF GROSS RAINFALL

The rainfall observed in the experimental catchments during the 2 year period of intensive observations can be considered typical of the long term rainfall regime of the Upper Mangawhara Valley. Consequently, the hillslope runoff processes described in this thesis are considered representative of those that occur over a longer period.

The rainfall input to both the land use catchments is spatially variable, but no hydrologically important systematic patterns of rainfall could be detected with the raingauge network installed. Thus, it was assumed that spatial variations of the rainfall input do not influence the spatial distribution of hillslope runoff processes in the two catchments studied. Further analyses of the spatial variability of catchment rainfall showed that one raingauge was capable of providing an estimate of weekly mean catchment rainfall to within the precision required for this study (see chapter 4).

Several inferences regarding the rainfall-runoff processes in the experimental catchments can be derived from the intensity-duration characteristics, the micro-periodicity and the serial structure of the two year rainfall record.

Rainfall in the experimental catchments is characterized by low intensity rainfalls with only infrequent high intensity falls, even for the shortest event durations. The gross rainfall input is also intermittent, as there are many short duration rain events following rainless periods of variable length. About half the total annual rainfall input falls in this form. However, the dominant runoff producing storms are generally longer than two hours and are often associated with short duration, high intensity rainfall bursts.

In each land use catchment, saturation overland flow and subsurface flow appear to be the only plausible mechanisms of hillslope runoff processes, assuming soil permeabilities inferred commonly for each form of land use. However, the hillslope runoff regime appears extremely sensitive to interactions between the rainfall input and the surface soil permeabilities. Thus, it is not possible to make definitive statements about hillslope runoff mechanisms without detailed measurements of soil physical properties. Estimates of hydrologically important soil physical properties are presented in chapter 6, along with an analysis of the interactions between the catchment rainfall and these soil properties.

5.3 NET RAINFALL AND INTERCEPTION PROCESSES

5.3.1 INTRODUCTION

The role of interception in determining water yields from different land use regimes has been subject to considerable research since the early part of this century: there is now extensive literature on the subject. The process of interception is recognised generally as comprising two major components:

i) the canopy storage component, being the depth of rainfall stored on canopy surfaces until drainage begins;

and ii) evaporation, now recognised to occur in all phases of the interception process.

In the past, differences in water yield behaviour between forest and pasture vegetation have been ascribed to differences in transpiration rates between the two vegetation types (Baumgartner, 1967). However, micro-meteorological studies of interception processes

(Stewart, 1977; Thom and Oliver, 1977) and continued basin studies in different climatic regimes (Swank and Miner, 1968; Pearce and Rowe, 1979; Pearce, 1980) have established the interactions between water losses by transpiration and by evaporation, for a variety of forest vegetation types.

This research has shown that the frequency and duration of canopy wetness determine water losses by interception: transpiration losses are generally independent of climatic regime and forest species type (Roberts, J.M. cited in Pearce and Rowe, 1979). Similarly, differences in water yields from contrasting vegetation types are now ascribed to different rates of evaporation of intercepted water, instead of differences in transpiration rates between the vegetation types.

The mechanisms that determine comparative interception losses of intercepted water for forest and pasture vegetation have been described by the authors cited above. Evaporation rates from wet forests have been shown to be 2.5 - 20 times greater than when the forest canopy is dry (Singh and Szeicz, 1979). In contrast, evaporation rates from short grasses are similar, irrespective of whether the leaves are wet or dry (Stewart, 1979). These anomalous observations may be explained by differences between the aerodynamic roughness and the surface resistance of each vegetation type.

Evaporation from wet vegetation surfaces is controlled mainly by the aerodynamic roughness of the vegetation surface. The aerodynamic roughness is typically 10 times greater for forests than for pasture, and therefore enables greater evaporation rates from wet forest canopies compared with wet pasture (Pearce and Rowe, 1979). However, only small differences are found commonly in the evaporation rates (transpiration) between the two vegetation types, when they are dry. This occurs because transpiration losses are controlled by the surface resistance of the leaves, that is similar for the two vegetation types. Thus, differences in catchment water yield behaviour can be explained by differences in the evaporation rates from the two vegetation types when they are wet. Hence, the frequency and duration of canopy wetness becomes the controlling agent of comparative water yield behaviour between forest and pasture vegetation.

In this study, an estimate of interception losses from the forest experimental catchment was made to confirm the differences in water yield behaviour and the differences in the water balance observed for the two experimental catchments. The estimate was also made to assist in the explanation of anticipated differences in components of the hillslope runoff regime.

5.3.2 EXPERIMENTAL AND DATA ANALYSIS

5.3.2.1 Experimental

Throughfall was estimated in the forest catchment for the period June 1979 to May 1980, using the equipment described in chapter 4. Only the throughfall component of the net rainfall was estimated because stem flow is small (1.5 % of net rainfall) in similar beech-podocarp-hardwood forest types (Rowe, 1976). It was thought better to obtain a reliable estimate of throughfall and to accept the limitations of such a measurement. An systematic under-estimate of net rainfall of 1.5 % was considered unimportant, given the data requirements of this study, and the sampling errors associated with measuring throughfall (see chapter 4).

The throughfall plot was situated in an area of forest considered representative in terms of the following principal selection criteria: canopy structure; canopy density; and species composition (see plate 4.1). The vegetation species composition in the throughfall plot is similar to that described in chapter 3 (section 3.72). Gross rainfall was estimated from raingauge site two in the pasture catchment.

5.3.2.2 Data analysis

The analysis of interception processes in the forest experimental catchment was restricted to the use of empirical rainfall-throughfall regression models. However, the concepts embodied in the analytical model of interception (Gash, 1979) were used to establish more clearly the interactions between evaporation, canopy storage and the rainfall regime.

Throughfall and gross rainfall depths for 63 summer storms (November 1 to April 31) and 76 winter storms (May 1 to October 31) were analysed. A storm was defined as a rain event separated by more than one hour of rainless time. A one hour separation period is long enough to allow time for canopy drainage between successive storms, yet is not so long that the processes of interception are masked by the integration of many events through time.

Linear regression analysis was used to determine any relationships between throughfall and gross rainfall, for both winter and summer storms separately. Tests for parallelism and concurrence (Seber, 1977) showed that no differences could be detected between the two regression models ($p = 0.05$). Thus, a simple linear regression model was established between throughfall and gross rainfall for all storms considered as a single group.

The regression equation for all storms is:

$$\text{throughfall depth (mm)} = 0.64 \times \text{gross rainfall (mm)} - 0.90$$

$n = 139$ $r^2 = 0.98$ $s_{y.x} = 0.79$ mm

---

n - number of samples r^2 - coefficient of determination

$s_{y.x}$ - standard error of the estimate

Figure 5.12a shows the results of this analysis. The 95 % confidence belts are constrained tightly around the regression line, and thus not shown on figure 5.12a.

The interception loss is about 36 % for those storms large in comparison with the canopy storage component, neglecting the proportion of net rainfall occurring as stem flow. However, interception losses determined on an annual basis will depend on the distribution of individual storm rainfall depths. These estimates are made in section 5.3.4.

The importance of evaporation rates in determining water loss by interception has been described by several authors (see section 5.3.3). Estimates of the mean evaporation rate during rainfall were made in this study, to compare the relative importance of evaporation and canopy storage components in the forest experimental catchment, and to enable an estimate of net interception losses from the forest land use catchment (see section 5.3.4.3). The concepts embodied in the analytical model (Gash, 1979) and a method outlined by Pearce et al. (1980c) were used in this analysis. Seventy-two day time storms (0700 to 1900 hours) and 71 storms that occurred during night time (1900 to 0700 hours) were used in the analysis. Storms that fell across the day-night boundary were included in the period in which most of the storm occurred.

The estimated mean evaporation rate is 0.93 mm h^{-1} for storms occurring during the day and 0.72 mm h^{-1} for those occurring at night. These results are different (Wilcoxon signed rank test; $p = 0.05$) and occur because the average rainfall intensity during day time is greater (2.58 mm h^{-1}) than for rain occurring during night time (2.00 mm h^{-1}). These results also suggest that considerable energy for evaporation of intercepted water is available from advective sources, when energy from radiant sources is not available.

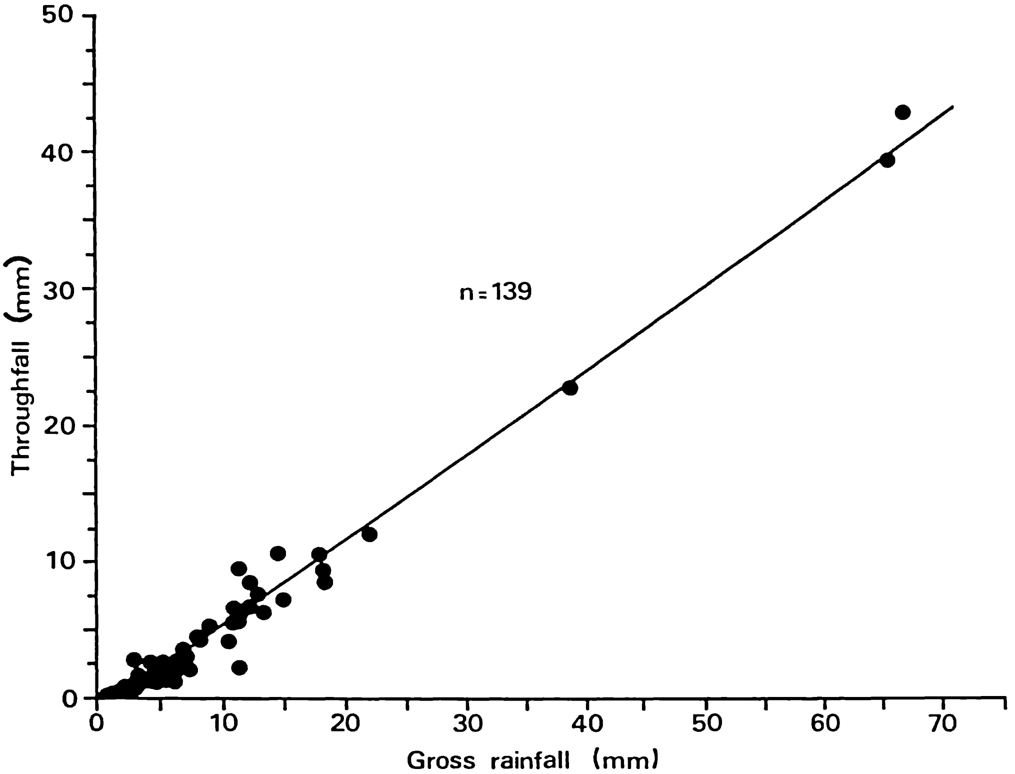


Figure 5.12a : The relationship between gross rainfall and throughfall in the forest land use catchment

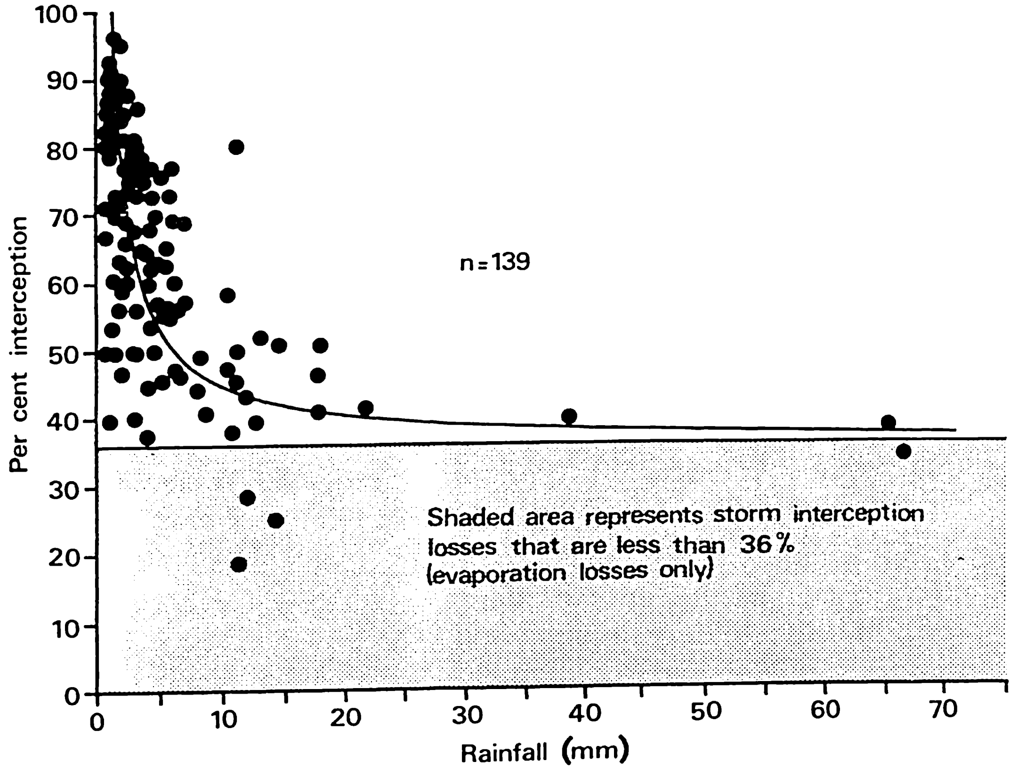


Figure 5.12b : Per cent interception vs storm rainfall depth in the forest land use catchment

The canopy storage value estimated from the regression analysis of gross rainfall and throughfall is 1.4 mm +/- 0.2 mm (estimated from the 95 % confidence belts).

In some environments, the canopy storage component varies considerably in response to wind induced canopy movement and to variations in the evaporative potential of the atmosphere (Gash and Morton, 1978). An estimate of the range of effective canopy storage was made from the data available in this study (i.e. the canopy storage minus reductions because of wind induced canopy movement, plus additions attributable to evaporation before complete saturation).

An estimate of the maximum value of canopy storage was made by an analysis of order statistics of the population of small storms that just failed to produce throughfall, using a technique outlined by Robson and Whitlock (1964). An estimate of the minimum size of the canopy storage component was made, in a similar way, from the population of small storms that just produced throughfall. These estimates were made for summer and winter storms. Table 5.4 shows the results of this analysis.

	Summer	Winter
Estimated maximum value of the canopy storage component	2.1	1.4
Estimated variance	0.01	0.01
Estimated minimum value of the canopy storage component	0.4	0.2
Estimated variance	0.01	0.01

units - mm

Table 5.4 : Estimates of the largest and smallest values of the canopy storage component for summer and winter storm events

The effective physical volume of canopy storage varies by a factor of five within each season, but considerably less between seasons. The differences between seasons most probably reflect the influence of slight changes in seasonal evaporation rates, not identified in the rainfall-throughfall regression model. Canopy characteristics tend to remain constant throughout the year and are less likely to cause the differences observed (table 5.4). The importance of canopy storage in determining total interception losses in the forest experimental catchment are discussed below (section 5.3.3.2).

5.3.3 DISCUSSION

5.3.3.1 Evaporation and interception

A strong linear relationship was found between throughfall and gross rainfall, despite a wide range of storm depths, antecedent canopy conditions and intra-storm rainfall patterns. This result suggests that the energy source required to evaporate intercepted water is largely independent of these factors.

Advective energy derived from upwind sources, in addition to radiant energy inputs, determine evaporation from wet forest canopies (Thom and Oliver, 1977; Singh and Szeicz, 1979; Stewart, 1979). Energy from the sensible heat content of the air (Stewart, 1979), or from sensible heat contained within the forest (Moore, 1976) can maintain latent heat fluxes in excess of the available incoming energy and so cause the strong linear relationships observed between gross rainfall and throughfall. The evidence is supported further by Pearce *et al.* (1980c) who observed night time evaporation rates from wet canopy surfaces similar to those occurring during daylight hours.

Estimates of the day and night evaporation rates made in this study are larger than similar estimates reported in the literature (e.g. 0.19 mm h^{-1}, Stewart, 1979; 0.37 mm h^{-1}, Pearce et al., 1980c). Several factors may account for the larger evaporation rates observed in the forest catchment compared with the other studies.

i) The low latitude of the experimental catchments, compared with other study areas, means that more energy is likely to be available from both advective and radiation sources in the Mangawhara Valley.

ii) The steep, rough terrain of the Hapuakohe Range means that the aerodynamic resistance may be smaller than for the other areas cited (e.g. Stewart, 1977).

iii) The relative isolation of the Hapuakohe State Forest Park means that advective enhancement is likely in the forest experimental catchment and can contribute to the high evaporation rates observed in this study.

Figure 5.12b suggests that about 36 % of the interception loss from all storms is attributable to evaporation from canopy surfaces during the storm event. Some evaporation can occur during intra-storm rainless periods, but the data collected in this study show that there is a potential for large evaporation rates during rain storms, even at low vapour pressure deficits. In several storms, including the two largest (65.9 and 64.6 mm; figure 5.12a), only short periods of no rain occurred.

The demonstrated potential for high evaporation rates has implications, for estimating the net interception component of the water balance of the forest catchment and for comparing water yields and hillslope flow processes between both catchments, especially if considerable rainfall occurs at night.

Estimates of the total interception losses from the water balance are made in section 5.3.4 following.

5.3.3.2 Canopy storage and interception

The importance of canopy storage as a component of interception has been highlighted since the frequency and duration of canopy wetness have become recognised as important determinants of water loss from vegetated surfaces. Water losses attributable to the canopy storage component are magnified in the intermittent rainfall of the Mangawhara Valley, compared with other areas where climates are dominated by different storm structures (e.g. Singh and Szeicz, 1979).

Interactions between the canopy storage component and small, short duration storms are not apparent in figure 5.12a. However, these interactions are shown clearly when percentage interception is plotted against storm rainfall depth (figure 5.12b). The interception losses attributable to evaporation are shown by the shaded area (figure 5.12b). Large variations in percentage interception are apparent for the smaller storms. This variation can be explained by the observed variation of the canopy storage value and by variations in the gross rainfall pattern. Large variations in percentage interception are therefore expected for the intermittent rainfall input of the Upper Mangawhara Valley because, for most storm events, the influence of the canopy storage component is large compared with evaporative processes operative during the remainder of the storm.

5.3.4 OVERALL INTERCEPTION LOSSES

5.3.4.1 General

Estimates of both gross and net interception losses are required to understand the comparative water yield behaviour between the two land use catchments. Gross interception losses can be estimated simply (see below). However, it is more difficult to estimate net interception on an annual basis (Singh and Szeicz, 1979; Pearce *et al*., 1980c).

Results from the recent micro-meteorological studies cited earlier in this chapter show a reduction in transpiration rates during evaporation from wet canopy surfaces. Thus, if net interception losses are to be estimated accurately, interception losses occurring during night time (where no compensatory transpiration occurs) must be considered separately from those that occur during daylight hours (Pearce *et al*., 1980c). This problem is particularly important in regions where a larger proportion of annual rainfall occurs at night.

5.3.4.2 Gross interception losses

Gross interception losses for the two year research period (July 1979 to July 1981) were obtained by estimating the proportion of precipitation events that fell into storm size classes, ranging from 1.0 mm to 72 mm (in increments of 1.0 mm) and by calculating a weighted mean throughfall loss from the data presented in figure 5.12b.

The mean annual throughfall loss, estimated by this method was about 49 % for the study period. This estimate is considerably more than the 36 % estimated in the previous section. The difference between these two estimates is attributable to the large portion of rainfall that falls in small, intermittent storms and interacts directly with the canopy storage component.

5.3.4.3 Net interception losses

During the study period, about 49 % of the total annual rain fell during the day time (0700 to 1900 hours). The net loss of intercepted water from the water balance is the sum of the losses that occur during the night time and a proportion of the evaporation that occurs during daylight hours.

Latent heat fluxes from wet canopies have been shown to exceed those from dry forest canopies by a factor of 2.5 - 20 (Singh and Szeicz, 1979). Thus, about 5 - 40 % of the interception loss by evaporation during daylight hours is compensated for by suppressed transpiration rates. Therefore, the net interception loss to the catchment water balance is likely to be between 80 - 97 % of the estimated gross interception loss. A value of 85 % is thought to be appropriate for the conditions in the Mangawhara Valley. This is similar to the net interception losses observed by Pearce and Rowe (1979) for a similar forest type (i.e. 80 - 85 %).

The net annual interception loss in the forest land use catchment is thus estimated to be about 42 %, but may lie between about 39 and 48 %. A more accurate estimate of this loss is not possible without further information on other components of the water balance.

5.3.5 SUMMARY AND CONCLUSIONS OF THE STUDY OF NET RAINFALL

The relationships established between rainfall and throughfall show clearly the importance of evaporation that occurs during and after a rain event, and the interactions between the canopy storage component and total storm depth.

A strong linear relationship was found between throughfall and gross rainfall, despite a wide range of storm depths, antecedent canopy conditions and storm rainfall patterns. Also, no significant differences were observed between the rainfall-throughfall relationships between storms from different seasons.

Both these findings suggest that the energy required to maintain evaporation before, during and following a rain event, is derived from advective sources, in addition to the incoming radiant energy. Evidence from large storms, when the effects of canopy storage are at a minimum, suggests that high evaporation rates can occur even at low vapour deficits during rain. This result implies that there is always sufficient advective energy to maintain high evaporation rates from the forest canopy.

Results from this study show the physical volume of canopy storage varies by about half an order of magnitude within seasons, but by a much smaller amount between seasons. The variability of the effective canopy storage component may explain the variation in interception losses that occur during small storms. As a considerable proportion of the total catchment rainfall input falls in small, intermittent rain events, much of this rain is lost in the continual re-wetting and drying of canopy surfaces. Failure to consider the distribution of rainfall depths, and the contribution to total precipitation by small rainfall events, may result in a significant under-estimate of the gross interception losses from the water balance of forested catchments.

Neglecting the contributions of stem flow to net precipitation, the estimate of the annual gross interception loss in the forest experimental catchment is about 49 %. Net interception losses are estimated to be about 42 %, but may be between 39 and 48 %.

These results are of considerable value for explaining differences between the water balance of the two land use catchments, and in addition, the different mechanisms and relative magnitudes of the surface and subsurface flow regimes observed in the experimental catchments. These aspects are considered in chapter 7.

Differences in annual water yield from the two land use catchments will depend on total evaporative losses from each vegetation type and any differences in soil moisture loss to ground water. Detailed assessments of water balance components are made for the two land use catchments in chapter 8.

CHAPTER SIX

CATCHMENT SOIL MOISTURE AND PERMEABILITY

CONTENTS

6.1 INTRODUCTION

Since the mid - 1960s, the traditional concepts of runoff generation, for vegetated catchments in humid temperate environments, have been challenged by the results of many studies of source area hydrology. The development and evidence for the various models of storm runoff production have been discussed in chapter 2.

The expansion and contraction of runoff contributing areas is central to both the variable source area and subsurface flow models of hillslope runoff production (Hewlett and Hibbert, 1963, 1967; T.V.A., 1965; Whipkey, 1965; Dunne, 1969). Within catchments, runoff contributing areas expand and contract during and between storms and seasonally, depending on antecedent soil moisture conditions. Between catchments, differences in the size and behaviour of runoff source areas have been attributed to differences in topographic, pedologic and other physical characteristics, and to vegetation type.

The studies reviewed in chapter 2 have also shown the factors that determine the distribution of soil moisture within catchments and the importance of soil permeability in determining the processes of runoff generation in humid temperate climates. A great diversity of rainfall-runoff processes have been described in these studies, for the many different environments studied. Nevertheless, in all the environments considered in the studies cited above, rainfall-runoff processes are sensitive to variations in soil moisture distribution and soil permeability.

Dunne (1978) has suggested that quantitative analyses of the components of hillslope runoff are necessary, to apply the accumulated knowledge on rainfall-runoff processes for the development of effective land management programmes. To date, few quantitative assessments of the spatial variability of soil moisture and soil permeability have been reported. In this chapter, a quantitative analysis is presented of the spatial variability of soil moisture and soil permeability in the two land use catchments.

The data collection and analyses of catchment soil moisture and soil permeability were completed to achieve the following sub-objectives:

i) to determine the variation of unsaturated and saturated soil moisture conditions in space and time, within the individual sub-catchment units in both experimental catchments;

ii) to determine the spatial variation of soil permeability that occurs between the sub-catchment units of each land use catchment, for summer and winter antecedent conditions;

iii) to determine the factors that determine soil permeability in the two land use catchments;

and iv) to make inferences about the rainfall-runoff regime of the experimental catchments.

In this chapter, the soil moisture characteristics of the sub-catchment units are examined first, as a precursor to the soil permeability characteristics described in the second section of this chapter. An initial examination of soil moisture characteristics in each land use catchment is necessary because hydrologically important changes in soil permeability occur in the clay-rich soils of the experimental catchments. Seasonal changes in soil structure have been suggested as the cause of the variation of soil permeability throughout the year (Selby, 1967a; Parker, 1978; Rogers, 1978).

6.2 SOIL MOISTURE REGIMES OF THE EXPERIMENTAL CATCHMENTS

Numerous field, experimental and some model studies have confirmed the importance of the topographic control of soil moisture variation in space and time, and the relationships between soil moisture and hillslope runoff processes (Hewlett and Hibbert, 1963; Ragan, 1968; Dunne, 1969; Weyman, 1970, 1973; Freeze, 1972b, 1980; Corbett et al., 1975; Kirkby et al., 1976; Anderson and Burt, 1977a, 1977b, 1978a, 1978b; Anderson and Kneale, 1980, 1982; Dunin and Aston, 1981; Murray, 1981). The results and implications of these studies are reviewed in chapter 2.

The general patterns of soil moisture distribution, found in catchments by the studies cited above, verify the spatial pattern of soil moisture suggested earlier by Kirkby and Chorley (1967). These authors suggested, that in humid temperate regions with vegetated slopes, the highest soil moisture is likely to be restricted to limited areas within catchments. These areas are:

i) zones marginal to the stream channel, where lateral drainage from upslope produces high antecedent soil moisture conditions;

ii) convexities and topographic hollows where surface and subsurface flow lines converge;

and iii) in areas of thin soil cover.

Runoff is generated first on these areas. In larger storm events, runoff occurs from larger areas within catchments.

Quantitative estimates of the spatial variability of hillslope runoff components have been suggested as necessary, to apply the accumulated knowledge of source area hydrology to practical management problems (Dunne, 1983). Few of the studies cited above have attempted to establish quantitatively whether the spatial distribution of soil moisture conditions within catchments is large enough to cause hydrologically important differences in the hillslope runoff regime.

In some catchments, hillslope runoff processes are generated from areas that can be identified clearly. However, in other environments, the processes and contributing areas of hillslope runoff are less obvious, particularly in catchments where surface and subsurface soil permeabilities are close to the critical values that determine whether surface or subsurface flow mechanisms will predominate (e.g. Beven and Kirkby, 1976). Also, it is often difficult to recognise the processes and source areas of hillslope runoff in catchments of low relief.

In this study, quantitative estimates were made of the unsaturated soil moisture regimes in the two land use catchments, despite the difficulties described above. In addition, the saturated soil moisture regimes were examined in each catchment. The soil moisture data are used to make inferences about the processes and distribution of runoff in the two experimental catchments (see section 6.4).

6.2.1 SPATIAL AND SEASONAL VARIATION OF UNSATURATED SOIL MOISTURE CONDITIONS IN THE TWO LAND USE CATCHMENTS

6.2.1.1 The data set, network precision and data analysis

6.2.1.1.1 The data set

In both experimental catchments during the period of intensive observation, unsaturated soil moisture estimates were made by neutron moderation. Soil moisture was determined at the following depths, 0.1, 0.2, 0.3, 0.5, 0.7, 1.0, 1.2, 1.5 m. At some sites, the soil profile was less than 1.5 m deep. At these sites, soil moisture was determined at the maximum depth, if it did not coincide with the depths listed above. Soil moisture observations were made, usually at fortnightly intervals, at 12 observation sites in the pasture catchment and at 8 sites in the forest catchment (see figure 4.5).

The soil depths listed above were chosen after examining the soil profiles at the individual sites. Observations of soil moisture were planned to coincide with the principal hydrologic soil horizons identified in chapter 4 (see figure 4.3), but with a greater sampling density near the soil surface where it was anticipated the greatest soil moisture variation would occur. Depths below 0.5 m were sampled less intensively because these depths coincided with the B_3 horizon, where soil moisture variation was likely to be small. The 'sphere of influence' (Olgaard, 1965) varied between 0.2 and 0.3 m, depending on soil moisture content. Thus, almost the whole soil profile was sampled by measurements at the preselected depths. To reduce bias, data for unrecorded depths were determined by linear interpolation between the recorded depths.

Only 37 complete samplings of soil moisture were made during the two year period of intensive observation (July 1979 - July 1981) because of failures in the neutron probe. Fortunately, periods of uninterrupted sampling spanned the winter season of 1979 and the summer season of 1981, so useful results were still obtained.

6.2.1.1.2 Estimation of the network sampling precision for soil moisture

The precision of the soil moisture sampling network is discussed in chapter 4. No general model for estimating the variance of soil moisture for the sub-catchment units of either land use catchment was found in the literature. Consequently, an _a priori_ estimate could not be made of an appropriate sampling density.

An _a posteriori_ estimate of the precision of the sampling network was made from the data collected during this study, to determine if hydrologically important differences in soil moisture could be detected between the sub-catchment units of the two land use catchments. The precision of the soil moisture sampling network was determined for soil moisture observed at individual soil depths, at a given time, but averaged over the sub-catchment units:

i.e. $$\bar{x}_{DT} = 1/L \sum_{I=1}^{L} (x_{IDT}) \qquad (1)$$

where x_{IDT} is the soil moisture at site (I) at depth (D), at time (T), with L the number of observation sites in each sub-catchment unit.

In addition, the precision of the soil sampling network was determined for <u>profile</u> soil moisture contents averaged over each sub-catchment unit, for single observations in time:

i.e. $$\bar{x}_{T} = (LM_I)^{-1} \sum_{I=1}^{L} \sum_{D=1}^{M_I} (x_{IDT}) \qquad (2)$$

where x_{IDT}, I, D, T and L are defined in (1), and M_I is the number of observations made at each site.

In each case, the standard errors of $\bar{x}_{DT}$ and $\bar{x}_{T}$ are $s\bar{x}_{DT}$ and $s\bar{x}_{T}$ respectively. For the case of $s\bar{x}_{DT}$, the maximum and minimum standard errors are defined:

$$s\bar{x}_{DT\ max} = \max (s\bar{x}_{DT_1}, s\bar{x}_{DT_2}, \ldots . s\bar{x}_{DT_{37}}),$$

and $$s\bar{x}_{DT\ min} = \min (s\bar{x}_{DT_1}, s\bar{x}_{DT_2}, \ldots . s\bar{x}_{DT_{37}}).$$

Table 6.1a and table 6.1b show the minimum and maximum standard errors observed during the two year observation period, for estimating the mean sub-catchment unit soil moisture at individual soil depths, at a given time ($s\bar{x}_{DT\ min}$ and $s\bar{x}_{DT\ max}$), for the forest and pasture catchments respectively. The mean soil moisture content ($\bar{x}_{DT}$) associated with these standard errors, and the 95 % confidence interval (95 % C.I.) are also presented in table 6.1a and 6.1b. The 95 %

confidence intervals were estimated following the procedure outlined in Steele and Torrie (1960; p. 23) and expressed as a percentage of the mean soil moisture content ($\bar{x}_{DT}$). For example; the 95 % confidence intervals for $\bar{x}_{DT}$ were estimated as follows:

$$95\ \%\ \text{C.I.}_{\bar{x}_{DT}} = 2(t_{0.05}\ s\bar{x}_{DT})\ /\ \bar{x}_{DT}\ /\ 0.01 \qquad (3)$$

where $t_{0.05}$ is the tabulated 't' value for n-1 degrees of freedom.

These estimates were not made for depths below 1.0 m because of the small number of observations made below this depth in most sub-catchment units.

In all sub-catchment units of both land use catchments, few extreme standard errors ($s\bar{x}_{DT}$) of the mean soil moisture contents were observed for the individual soil depths. Most of the standard errors ($s\bar{x}_{DT}$) were near the minimum value shown in table 6.1a and b. The minimum standard errors shown in table 6.1 are generally small. Thus, most of the 95 % confidence intervals for estimating sub-catchment unit mean soil moisture contents at individual soil depths ($\bar{x}_{DT}$) are generally less than +/- 10 % of the mean ($\bar{x}_{DT}$), in all the pasture sub-catchment units and in the forest riparian sub-catchment unit. However, these estimation errors are much larger in the two upslope sub-catchment units in the forest catchment because fewer samples were taken. Consequently, hydrologically important differences in soil moisture may not be identifiable between these areas.

Table 6.2 shows the minimum and maximum standard errors for estimating mean profile soil moisture contents averaged over the sub-catchment units, at a given time ($s\bar{x}_{T\ min}$ and $s\bar{x}_{T\ max}$). These estimation errors are much smaller than those shown in table 6.1. The sampling density is clearly adequate for making inferences from the estimates of sub-catchment unit mean profile soil moisture ($\bar{x}_{T}$).

Pasture riparian sub-catchment unit

soil depth (m)	$\overline{sx}_{DT\ min}$			$\overline{sx}_{DT\ max}$		
	$\overline{sx}_{DT}$	$\overline{x}_{DT}$	95 % C.I.	$\overline{sx}_{DT}$	$\overline{x}_{DT}$	95 % C.I.
0.10	0.70	41.88	5.29	5.36	52.94	32.26
0.20	0.25	43.36	1.82	1.50	42.57	11.21
0.30	0.06	50.77	0.35	1.07	47.63	7.13
0.40	0.002	50.04	0.03	1.20	50.32	7.59
0.50	0.04	50.26	0.38	1.00	50.38	6.33
0.60	0.14	51.01	0.85	1.02	50.88	8.65
0.70	0.10	51.27	0.60	0.99	50.87	24.61
0.80	0.01	51.41	0.21	0.76	51.40	6.39
0.90	0.01	51.87	0.37	0.75	51.76	6.24
1.00	0.06	50.38	0.52	0.89	50.31	7.62

Pasture midslope sub-catchment unit

soil depth (m)	$\overline{sx}_{DT\ min}$			$\overline{sx}_{DT\ max}$		
	$\overline{sx}_{DT}$	$\overline{x}_{DT}$	95 % C.I.	$\overline{sx}_{DT}$	$\overline{x}_{DT}$	95 % C.I.
0.10	0.73	40.09	5.79	3.88	55.64	22.16
0.20	0.36	36.02	4.33	1.67	38.84	13.66
0.30	0.22	36.40	2.51	3.58	30.17	22.16
0.40	0.34	37.19	2.91	2.47	36.96	21.22
0.50	0.71	42.77	5.30	2.88	46.44	19.74
0.60	0.55	46.40	3.78	2.98	49.61	25.84
0.70	0.90	54.96	5.19	2.89	51.41	24.22
0.80	1.15	45.58	8.02	2.84	41.35	23.76
0.90	1.36	46.32	9.34	3.00	51.30	25.14
1.00	1.41	47.09	12.85	5.39	51.11	134.12

Pasture spur sub-catchment unit

soil depth (m)	$\overline{sx}_{DT\ min}$			$\overline{sx}_{DT\ max}$		
	$\overline{sx}_{DT}$	$\overline{x}_{DT}$	95 % C.I.	$\overline{sx}_{DT}$	$\overline{x}_{DT}$	95 % C.I.
0.10	1.04	26.84	12.35	7.52	55.54	78.28
0.20	0.27	23.22	3.71	4.61	23.15	63.35
0.30	0.17	41.85	1.33	1.74	31.84	17.38
0.40	0.24	40.76	1.86	3.13	37.49	26.56
0.50	0.70	43.56	5.14	3.29	38.01	27.54
0.60	0.25	45.36	1.72	2.26	47.18	20.59
0.70	0.07	44.70	0.49	2.20	43.69	16.00
0.80	0.14	44.57	1.38	1.88	43.99	18.39
0.90	0.07	48.67	1.91	1.27	45.56	11.99
1.00	0.06	48.60	1.65	1.39	49.15	12.21

$\overline{sx}_{DT\ min}$, $\overline{sx}_{DT\ max}$, $\overline{x}_{DT}$, 95 % C.I. as defined in the text

Table 6.1a : $\overline{sx}_{DT\ min}$'s and $\overline{sx}_{DT\ max}$'s, $\overline{x}_{DT}$'s and the 95 % C.I. (expressed as a percentage of $\overline{x}_{DT}$) for soil moisture observations in the pasture catchment

Forest riparian sub-catchment unit

soil depth (m)	$s\bar{x}_{DT\ min}$			$s\bar{x}_{DT\ max}$		
	$s\bar{x}_{DT}$	$\bar{x}_{DT}$	95 % C.I.	$s\bar{x}_{DT}$	$\bar{x}_{DT}$	95 % C.I.
0.10	0.46	45.76	4.32	7.31	48.99	47.47
0.20	0.67	46.77	6.21	5.79	48.82	37.77
0.30	0.95	45.45	6.62	2.71	46.38	18.62
0.40	0.97	46.75	6.61	2.19	48.65	14.32
0.50	0.09	49.25	2.23	2.69	50.58	22.90
0.60	0.02	47.39	0.47	1.86	51.66	15.48
0.70	0.93	48.64	3.36	1.00	53.24	5.99
0.80	0.19	52.57	4.69	2.44	51.09	60.65
0.90	0.56	48.49	4.98	3.77	51.22	93.45
1.00	0.96	53.24	5.74	3.41	49.99	86.58

Forest midslope sub-catchment unit

soil depth (m)	$s\bar{x}_{DT\ min}$			$s\bar{x}_{DT\ max}$		
	$s\bar{x}_{DT}$	$\bar{x}_{DT}$	95 % C.I.	$s\bar{x}_{DT}$	$\bar{x}_{DT}$	95 % C.I.
0.10	2.84	30.71	117.34	7.66	32.55	299.05
0.20	3.19	31.37	129.25	6.93	31.57	298.88
0.30	3.09	38.63	101.47	9.02	36.44	314.61
0.40	1.61	39.56	51.55	6.98	36.44	243.35
0.50	0.52	42.67	15.38	5.54	37.87	185.78
0.60	0.75	42.65	22.39	4.67	39.11	151.87
0.70	0.10	41.67	3.16	3.81	40.34	120.03
0.80	0.20	43.47	6.45	2.95	41.58	90.08
0.90	0.18	43.97	5.29	2.08	42.81	61.85
1.00	0.01	43.93	0.36	1.37	45.44	38.41

Forest spur sub-catchment unit

soil depth (m)	$s\bar{x}_{DT\ min}$			$s\bar{x}_{DT\ max}$		
	$s\bar{x}_{DT}$	$\bar{x}_{DT}$	95 % C.I.	$s\bar{x}_{DT}$	$\bar{x}_{DT}$	95 % C.I.
0.10	1.07	35.55	39.53	5.19	29.86	220.80
0.20	1.91	29.25	82.79	4.31	32.31	169.54
0.30	2.06	38.62	67.84	5.01	38.54	165.31
0.40	1.56	40.42	49.11	3.40	46.16	105.44
0.50	0.87	42.58	25.96	2.19	44.10	63.15
0.60	0.34	42.95	10.19	1.53	42.63	45.50
0.70	0.03	42.41	0.83	1.05	42.87	31.14
0.80	0.01	46.36	0.35	0.89	43.04	26.31
0.90	0.21	46.21	5.88	1.54	43.32	45.25
1.00	0.04	46.16	1.17	2.19	43.59	63.95

$s\bar{x}_{DT\ min}$, $s\bar{x}_{DT\ max}$, $\bar{x}_{DT}$, 95 % C.I. as defined in the text

Table 6.1b : $S\bar{x}_{DT\ min}$'s and $s\bar{x}_{DT\ max}$'s, $\bar{x}_{DT}$'s and the 95 % C.I. (expressed as a percentage of $\bar{x}_{DT}$) for soil moisture observations in the forest catchment

PASTURE

sub-catchment unit	$s\bar{x}_{T\ min}$			$s\bar{x}_{T\ max}$		
	$s\bar{x}_{T\ min}$	$\bar{x}_T$	95 % C.I.	$s\bar{x}_{T\ max}$	$\bar{x}_T$	95 % C.I.
Riparian	0.32	47.49	1.34	0.82	46.56	3.58
Midslope	0.61	46.67	2.63	1.41	44.58	6.37
Spur	0.65	43.59	2.99	1.56	39.24	8.04

FOREST

sub-catchment unit	$s\bar{x}_{T\ min}$			$s\bar{x}_{T\ max}$		
	$s\bar{x}_{T\ min}$	$\bar{x}_T$	95 % C.I.	$s\bar{x}_{T\ max}$	$\bar{x}_T$	95 % C.I.
Riparian	1.25	51.74	4.95	0.53	46.64	2.32
Midslope	1.01	39.80	5.21	2.14	38.22	12.34
Spur	0.78	41.05	3.92	1.58	41.94	8.32

$s\bar{x}_{T\ min}$, $s\bar{x}_{T\ max}$, $\bar{x}_T$, 95 % C.I. as defined in the text

Table 6.2 : $S\bar{x}_{T\ min}$'s and $s\bar{x}_{T\ max}$'s, $\bar{x}_T$'s and the 95 % C.I. (expressed as a percentage of $\bar{x}_T$) for the two land use catchments

6.2.1.1.3 Data analysis

Parametric statistical techniques cannot be applied directly for the analysis of the unsaturated soil moisture data because of several characteristics of the data set. These are serial correlation, non-normality, and inequality of variances for data from individual sub-catchment units. Consequently, non-parametric statistical techniques were used because they are less sensitive to these characteristics (Siegel, 1956). Problems of serial correlation were avoided by analysing the data from individual samplings separately.

6.2.1.2 Spatial variation of unsaturated soil moisture conditions

6.2.1.2.1 Results

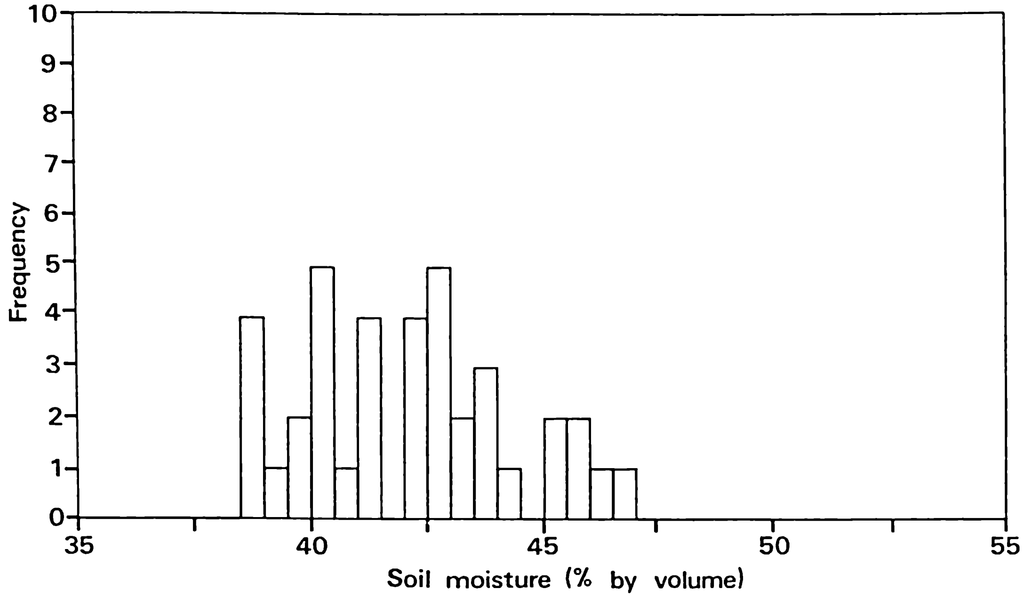
A non-parametric one way analysis of variance (Kruskal-Wallis) was completed to determine whether there were any differences between the mean profile soil moisture observations from individual sub-catchment units in each land use catchment (Ho: $\mu_{rip} = \mu_{mid} = \mu_{spur}$). Serial correlation is present in the data and violates a requirement of this analysis. However, the test results will be conservative because of the correlated observations.

	Pasture				Forest			
sub-catchment unit	n	$\bar{x}_T$	std dev	rank sum	n	$\bar{x}_T$	std dev	rank sum
riparian	37	49.17	1.43	2911.0	37	48.84	2.05	3441.0
midslope	37	48.34	2.89	2560.0	37	39.76	1.08	929.5
spur	37	41.84	2.24	745.0	37	41.11	0.93	1845.0
Kruskal-Wallis test statistic		70.52 **				84.29 **		

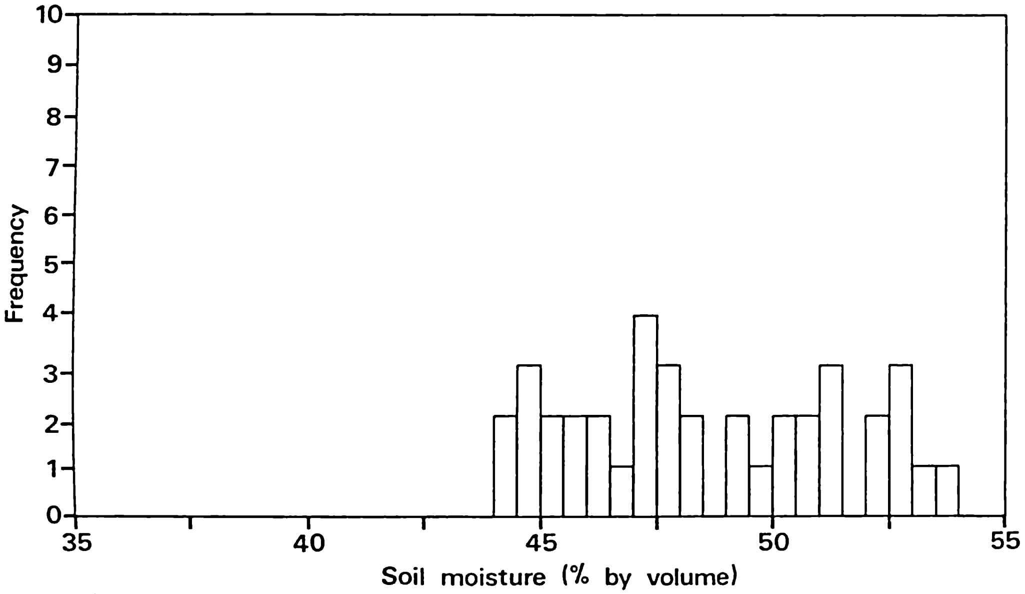
n - number of samples std dev - standard deviation
** - significant at p = 0.01
mean - mean profile soil moisture contents for the sub-catchment units ($\bar{x}_T$) (% by volume)

Table 6.3 : Kruskal-Wallis test results for mean profile moisture contents ($\bar{x}_T$) for the sub-catchment units in the land use catchments

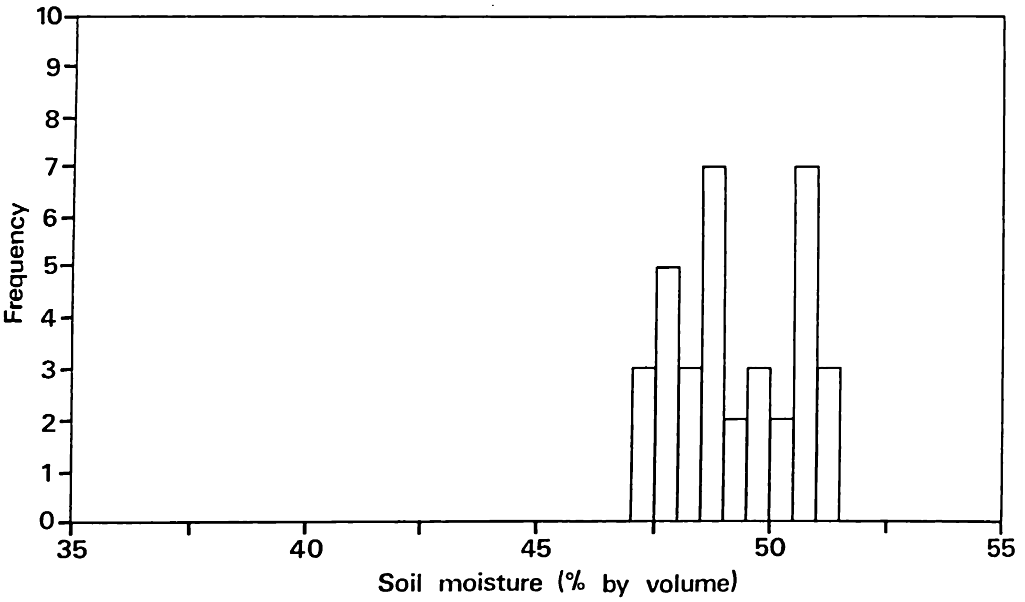
Table 6.3 shows the results of this analysis. A highly significant test statistic was obtained for both land use catchments. This implies that the three sub-catchment units in each vegetation type have different mean profile soil moisture contents ($\bar{x}_T$). Figure 6.1 (pasture) and figure 6.2 (forest) show clearly the differences in the profile soil moisture data observed in each sub-catchment unit. The size of the differences in mean profile soil moisture contents



c) Spur sub-catchment.

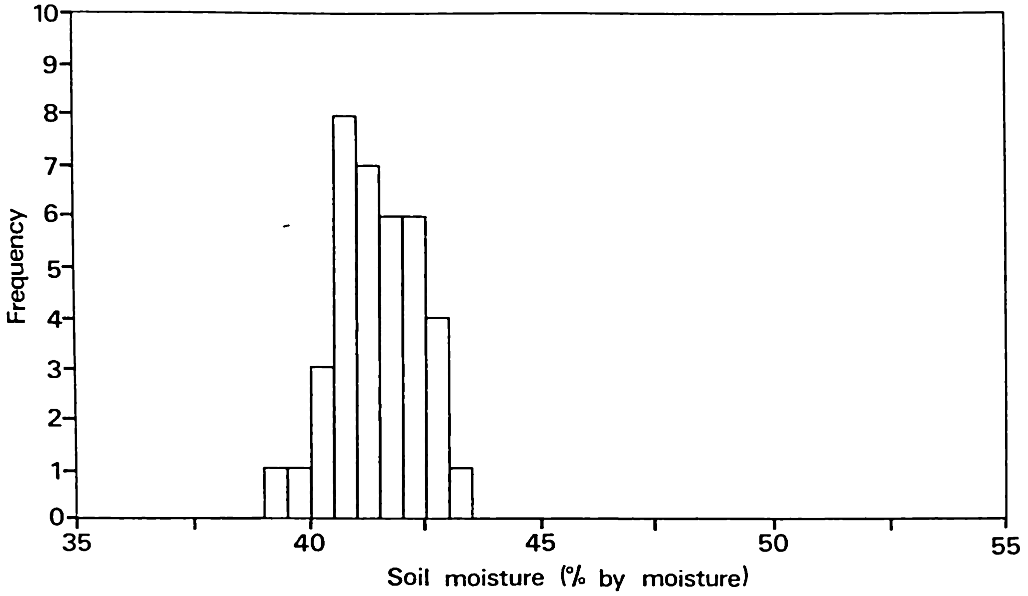


b) Midslope sub-catchment unit.

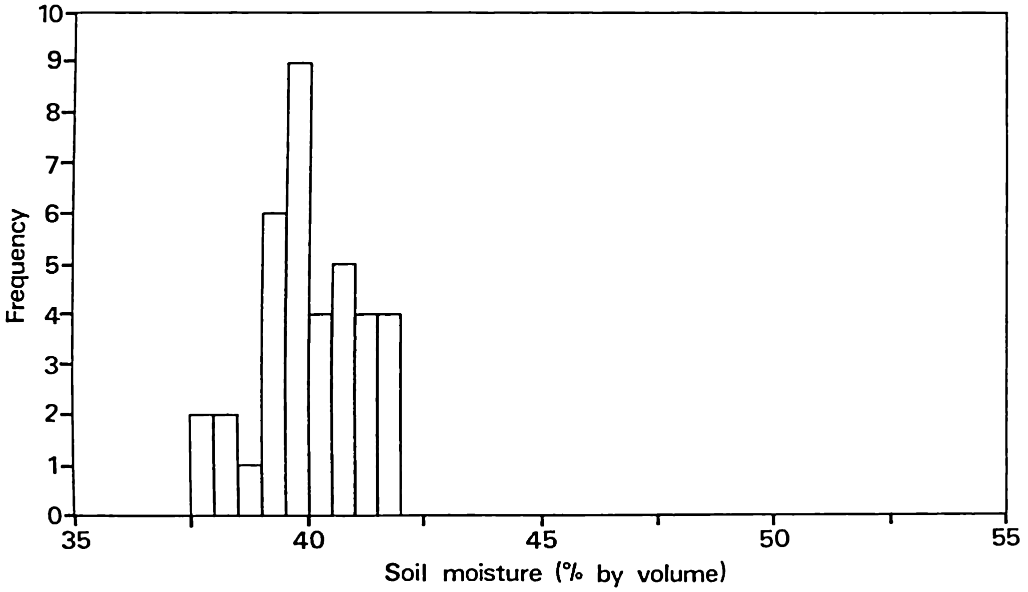


a) Riparian sub-catchment unit.

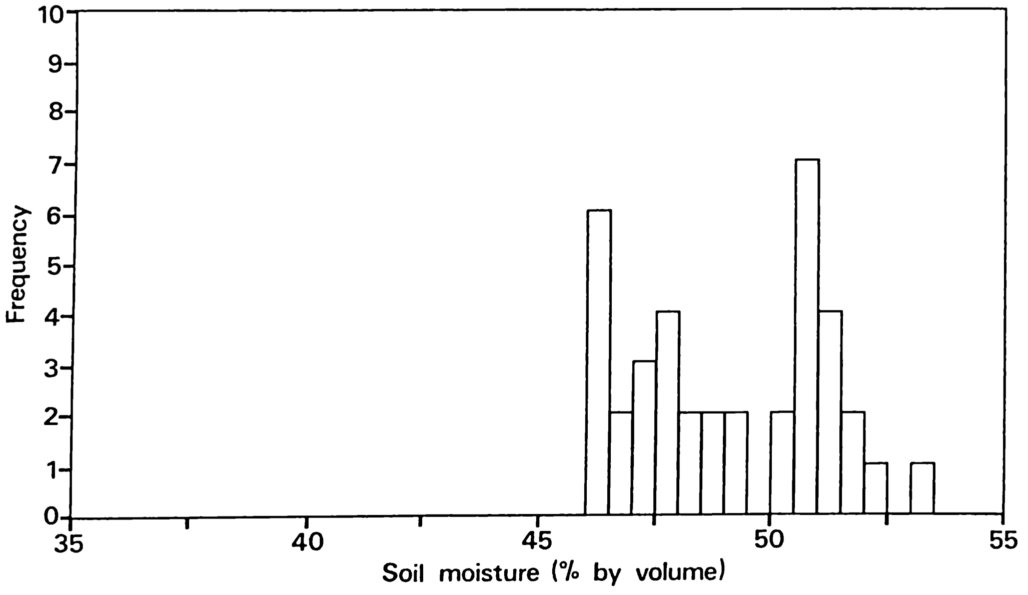
Figure 6.1: Distribution of sub-catchment unit mean profile soil moisture contents in the pasture experimental catchment



c) Spur sub-catchment unit.



b) Midslope sub-catchment unit.



a) Riparian sub-catchment unit.

Figure 6.2 : Distribution of sub-catchment unit mean profile soil moisture contents in the forest experimental catchment

suggest that hydrologically important differences in available soil moisture storage occur between the sub-catchment units of each land use catchment. These differences are likely to result in different runoff responses in each sub-catchment unit.

Figure 6.3a (pasture) and figure 6.3b (forest) show the mean sub-catchment unit moisture contents observed at individual soil depths, averaged over the duration of the study period:

$$\text{i.e.}\quad \overline{x}_D = (37L)^{-1} \sum_{I=1}^{L} \sum_{T=1}^{37} (x_{IDT}) \qquad (4)$$

where x_{IDT}, I, D, T and L are defined in (1).

The standard error of $\overline{x}_D$ is $s\overline{x}_D$.

The hydrologically important soil horizons identified in chapter 4 (figure 4.3) are also shown in figure 6.3a and b.

As expected, the riparian sub-catchment unit in both catchments has the highest soil moisture content at most depths in the soil profile (figure 6.3a,b). The mean moisture contents ($\overline{x}_D$) vary only slightly with depth and vegetation type in the riparian catchment areas apart from small differences between the surface soil horizons in each land use catchment.

The mean soil moisture contents ($\overline{x}_D$) in the midslope sub-catchment units contrast with those observed in the riparian areas. In the pasture midslope areas, soil moisture differs considerably from the riparian areas only in the upper soil horizons and in the saprolite (figure 6.3a). However, larger differences occur at all depths between the corresponding sub-catchment units of the forest catchment (figure 6.3b). For most soil depths, the forest midslope sub-catchment unit is the driest region in both land use catchments.

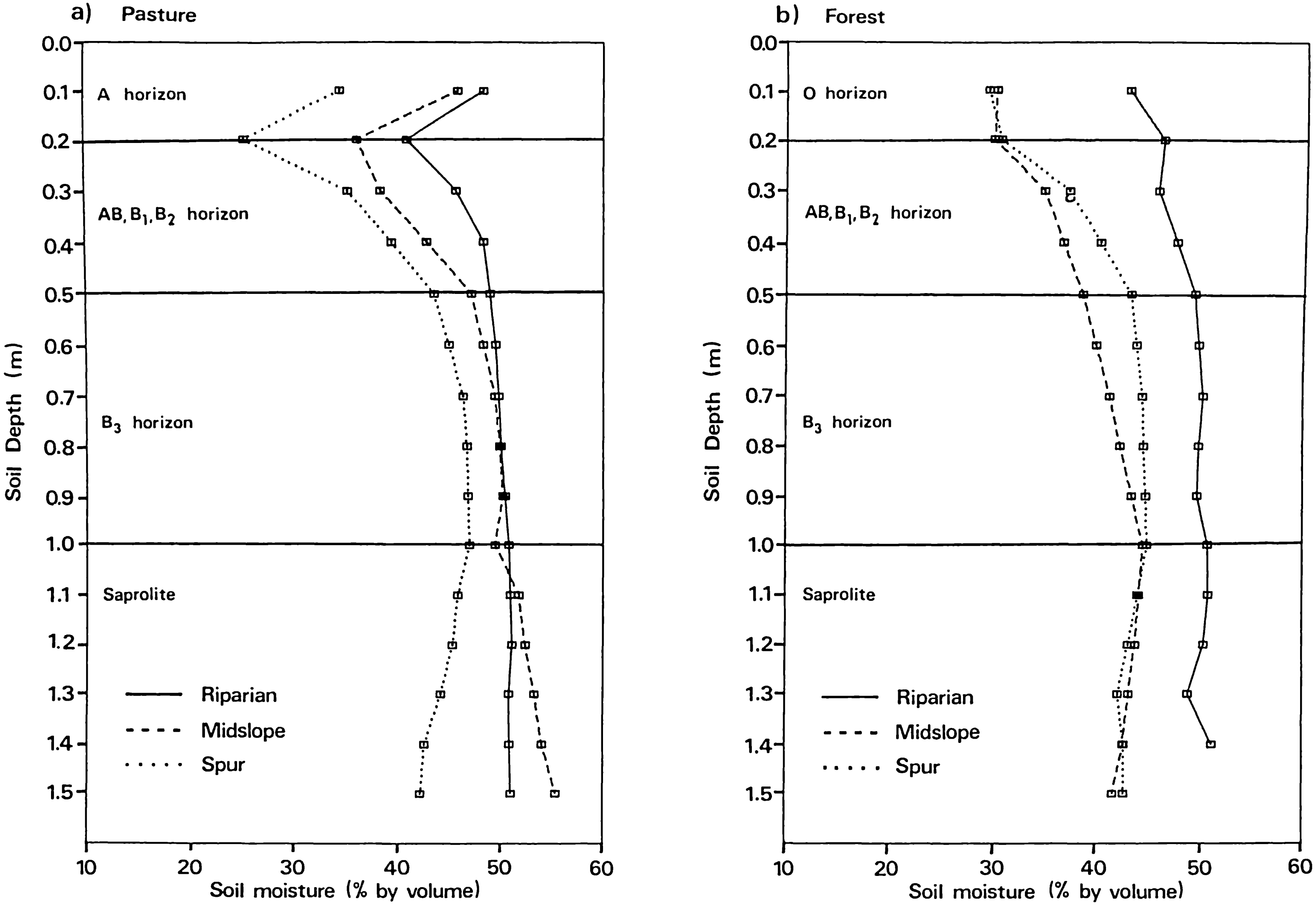


Figure 6.3 : Sub-catchment unit soil moisture contents for each land use catchment meaned over the observation period

The average soil moisture profile ($\bar{x}_D$) for the pasture spur sub-catchment unit is drier than that observed for the riparian and midslope sub-catchment units. In contrast, the forest spur regions are wetter than those in midslope positions. However, the differences in soil moisture observed between the forest midslope and spur sub-catchment units may not be hydrologically important. Nevertheless, both the midslope and spur sub-catchment units are consistently drier than the riparian sub-catchment unit in the forest catchment.

6.2.1.2.2 Discussion

The results presented in this study show important differences in the spatial distribution of soil moisture in both land use catchments, although these are defined more clearly in the pasture. The spatial distribution of soil moisture observed in the sub-catchment units provides direct evidence to suggest that contributions of hillslope runoff are likely to occur from restricted but variable source areas in the experimental catchments.

The small differences between the soil moisture content of the two forest upslope sub-catchment units does not imply that the variable source area hypotheses are not applicable in the forest land use catchment. Compared with the pasture catchment, the small difference in soil moisture between the forest upslope sub-catchment units can be explained most simply by the differences in the net rainfall. The reduced net rainfall under the forest vegetation (see chapter 5) restricts subsurface saturation from extending upslope and causing detectable soil moisture differences between the midslope and spur sub-catchment units (see section 6.2.2.2).

The same factors explain the small soil moisture differences observed between the lower soil horizons in the pasture riparian and midslope sub-catchment units. Greater net rainfall in the pasture cause areas of subsurface saturation to extend further upslope than in the forest. This reduces soil moisture differences between the lower soil horizons of the midslope and riparian sub-catchment units (figure 6.3a). Differences between the pasture spur areas and lower slope units are still evident because subsurface saturation does not extend that far upslope.

The interactions between the spatial variability of soil moisture and storm runoff mechanisms are discussed in section 6.4.

6.2.1.3 Seasonal variation of unsaturated soil moisture conditions

6.2.1.3.1 Results

The unweighted catchment mean profile soil moisture contents ($\bar{y}_T$) were estimated for both land use catchments for each soil moisture sampling, where ($\bar{y}_T$) is defined:

$$\bar{y}_T = (M_I U)^{-1} \sum_{D=1}^{M_I} \sum_{S=1}^{U} (y_{SDT}) \qquad (5)$$

where y_{SDT} is the soil moisture at site (S) at depth (D) at time (T), M_I is the number of observations at each site and U is the number of sampling sites in each land use catchment (12 in the pasture; 8 in the forest).

The standard error of $\bar{y}_T$ is symbolised as $s\bar{y}_T$.

Figure 6.4 shows the seasonal variation of the unweighted catchment mean profile moisture contents ($\bar{y}_T$) for both land use catchments. A seasonal pattern is apparent in both catchments. A summer minimum and winter maximum of these soil moisture contents occur in both land use catchments, although seasonal moisture variation is attenuated in the forest catchment. Except during the summer months (January to March), soil moisture is considerably greater in the pasture than in the forest.

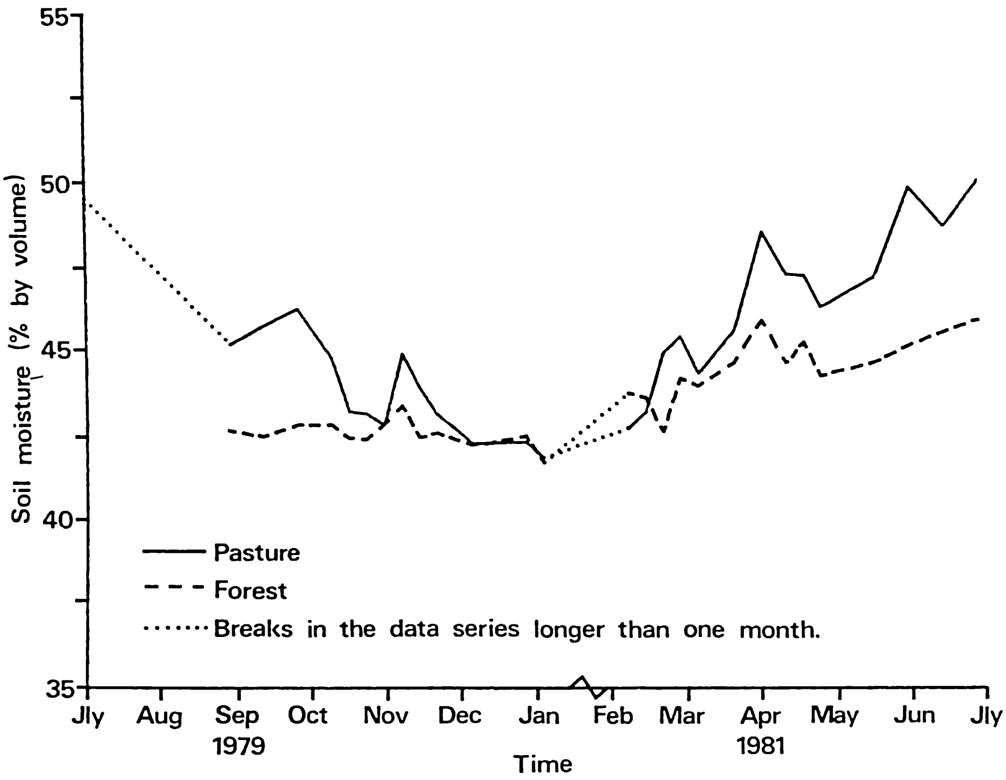


Figure 6.4: Seasonal variations of unweighted mean profile catchment soil moisture for the two land use catchments

Different hydrologic responses are suggested for the forest and pasture catchments by the different seasonal variations of mean soil moisture. However, the differences of the integrated runoff response from each vegetation type depends on where, in the land use catchments, most of the soil moisture variation occurs.

Figure 6.5 a,b,c shows the seasonal variation of the mean profile soil moisture content ($\bar{x}_T$) observed in the sub-catchments units of each land use catchment. The mean profile moisture contents observed in the riparian sub-catchment unit of each land use catchment are similar throughout the year (figure 6.5a). The seasonal soil moisture variation in both riparian sub-catchment units is small, and responses to individual rain events are similar.

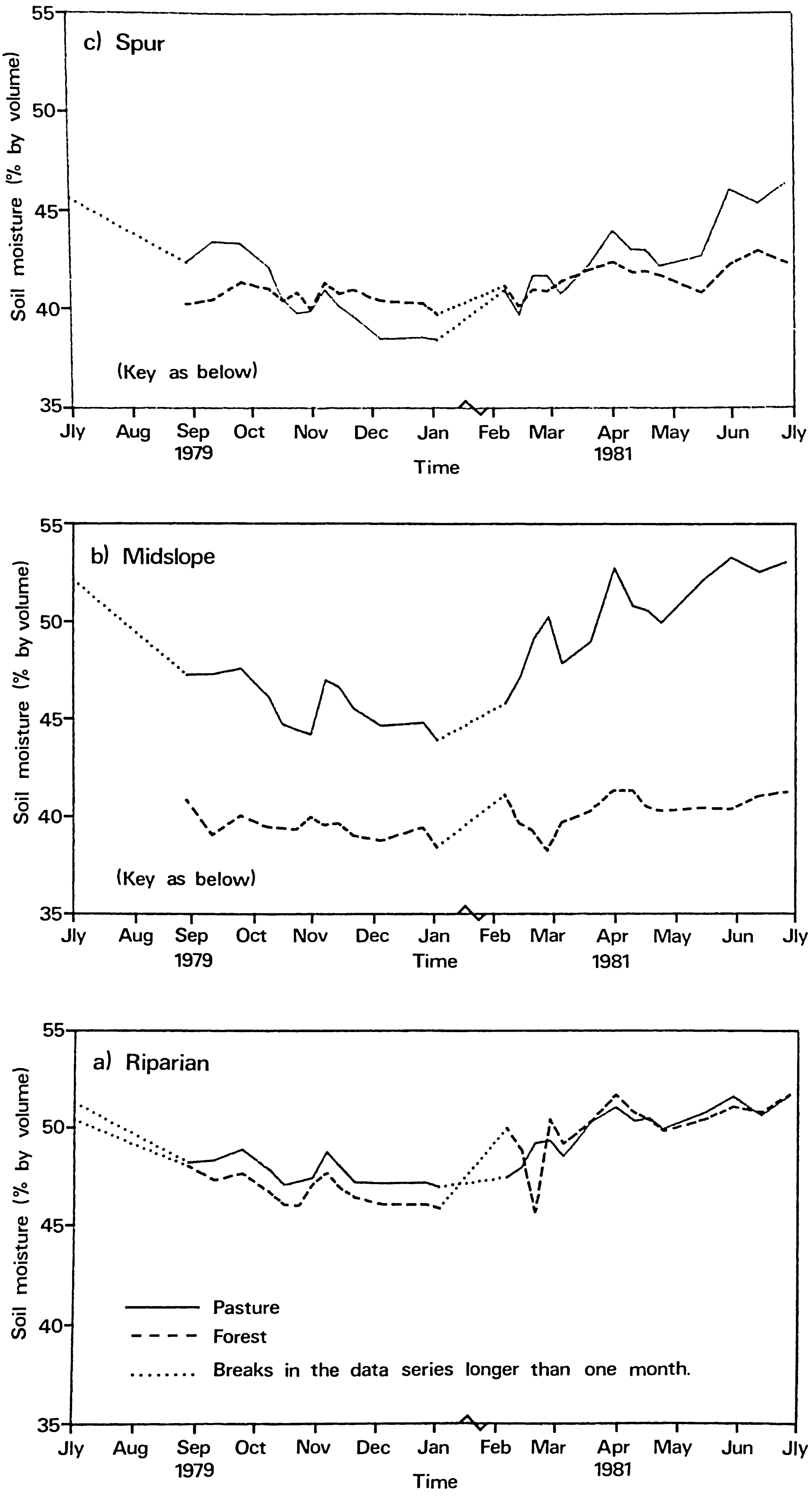


Figure 6.5 a,b,c: Seasonal variations of mean soil moisture for sub-catchment units in the forest and pasture land use catchments

In the midslope sub-catchment units, very different seasonal variations of mean profile moisture content occur in each land use catchment. The seasonal soil moisture variation is larger in the pasture catchment than in the forest.

Differences in the seasonal variation of mean profile moisture content ($\bar{x}_T$) in the spur sub-catchment unit of both land use catchments are intermediate compared with the riparian and midslope areas. The forest spur areas are wetter than similar areas in the pasture for about 6 months of the year (November to April).

The general observations presented above can be interpreted by considering the interactions between the processes controlling the magnitude and distribution of soil moisture in the sub-catchment units of each land use catchment. This discussion is presented in section 6.2.1.3.2.

Figure 6.6 a,b,c (pasture) and figure 6.7 a,b,c (forest) show the seasonal variation of mean sub-catchment unit soil moisture, for individual soil depths ($\bar{x}_{DT}$) in each land use catchment. Various statistics, for the mean sub-catchment unit soil moisture observed at each depth, are presented in these two figures. From these results, it is possible to identify the sub-catchment units and soil horizons in which soil moisture change occurs. These results can also be used to make inferences about the processes and source areas of hillslope runoff in the two land use catchments. However, few generalised soil moisture patterns are obvious within and between the two land use catchments.

Most of the seasonal variation of soil moisture in the pasture riparian sub-catchment unit is restricted to the upper 0.3 m of the soil profile (figure 6.6a). Soil moisture remains comparatively uniform through time below this depth. In contrast, the forest riparian sub-catchment unit exhibits greater seasonal soil moisture variation at all depths. For all depths below 0.5 m, almost all the moisture

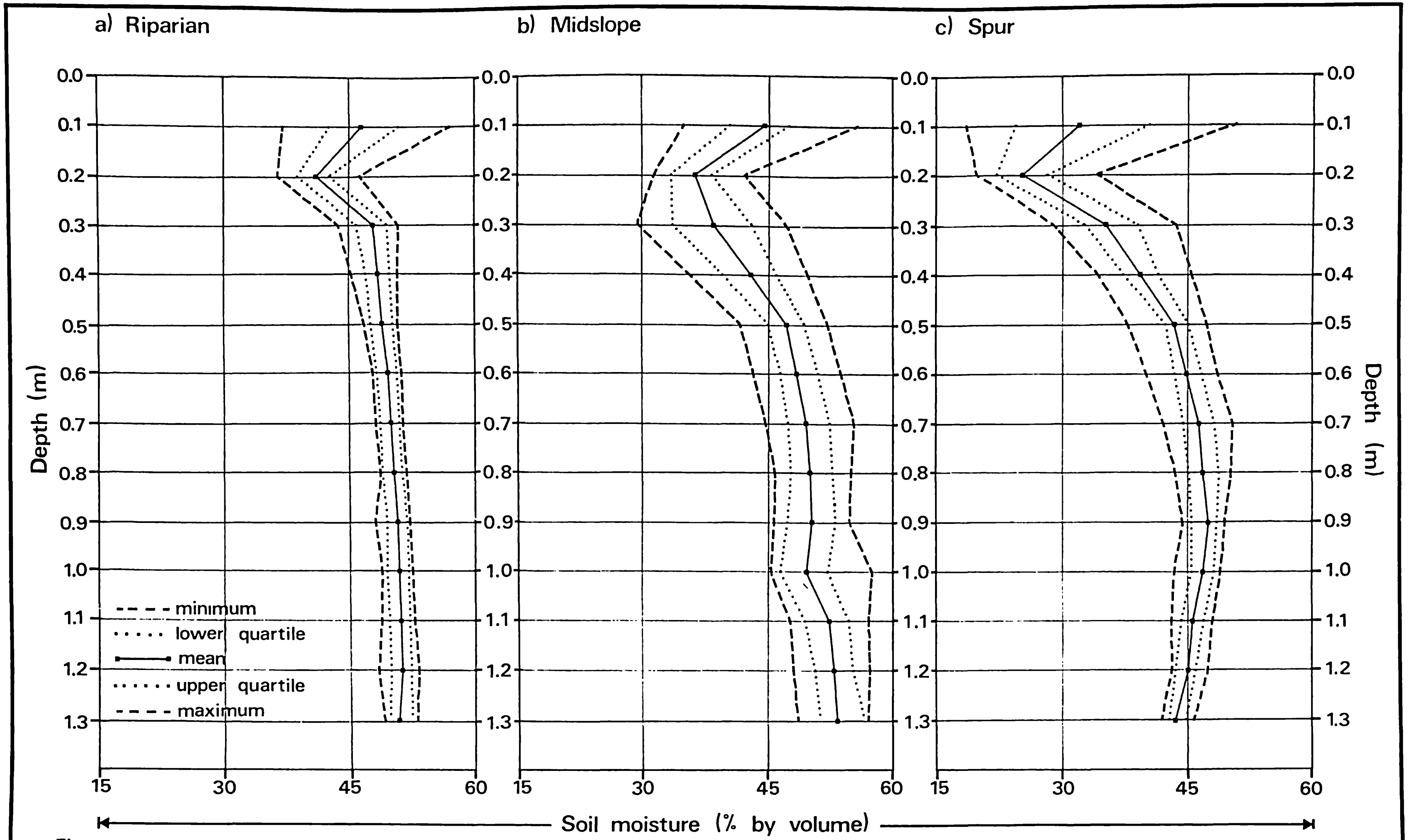


Figure 6.6a,b,c: Soil moisture profile envelopes (quartiles) for sub-catchment units in the pasture land use catchment

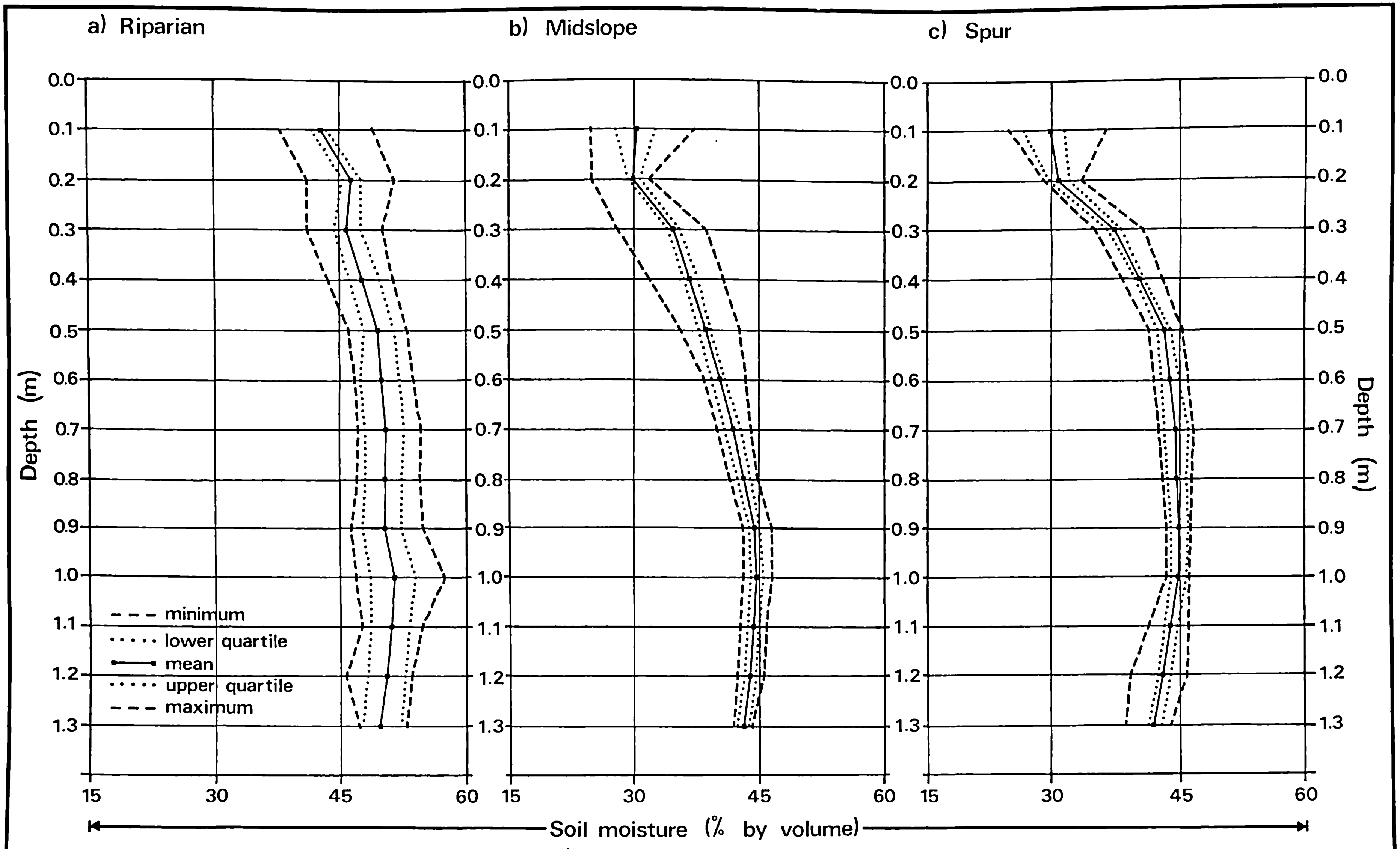


Figure 6.7a,b,c : Soil moisture profile envelopes (quartiles) for sub-catchment units in the forest land use catchment

observations in the pasture sub-catchment unit fall within the upper and lower quartiles for the forest riparian areas (c.f. figure 6.6a and 6.7a).

Wilcoxon signed rank tests were completed to determine if there were any differences in the mean profile soil moisture contents ($\bar{x}_T$) of the riparian sub-catchment unit in each land use catchment (Ho: $\bar{x}_{T_{for}} = \bar{x}_{T_{past}}$). The results are presented in appendix E (see 'whole profile') and show that the soil moisture regimes are similar for each vegetation type ($p = 0.01$). Similar tests were completed for the seasonal soil moisture contents observed at individual soil depths in the riparian sub-catchment units ($\bar{x}_{DT}$). These tests show that the seasonal soil moisture regimes are different at some individual soil depths at these sites ($p = 0.05$; see appendix E).

In the midslope sub-catchment units of each land use catchment, the relationships between soil depth and soil moisture variation are the reverse of those observed in the riparian areas. The largest seasonal moisture variations ($\bar{x}_{DT}$) in the forest midslope areas are restricted to the upper 0.5 m of the soil profile, except in very wet or very dry conditions. In contrast, large seasonal moisture variations occur at all soil depths in the pasture midslope regions. Thus, the large differences in the mean profile soil moisture contents ($\bar{x}_T$) observed between the midslope sub-catchment unit of both land use catchments (see figure 6.5b) appear to result from uniform soil moisture differences throughout the soil profile (c.f. figure 6.6b and 6.7b).

The seasonal moisture variation of ($\bar{x}_{DT}$) observed in the pasture spur sub-catchment units are much larger than those observed in similar areas in the forest, although the annual mean moisture contents are similar in both vegetation types (c.f. figure 6.3a and 6.3b).

Note: figure 6.6 and 6.7 are descriptive only; serial correlation between successive $\bar{x}_{DT}$'s prevents their use as estimated probability density functions for soil moisture observed at each depth.

The seasonal variation of soil moisture in the forest spur regions is similar to that observed in the forest midslope positions, although the range of soil moisture contents of the B_1 horizon is not as large. The largest seasonal soil moisture variation occurs in the surface soils of the pasture spur sub-catchment unit (figure 6.6c). This variation decreases with depth and becomes uniform below about 0.9 m.

6.2.1.3.2 Discussion

The data presented above show that complex seasonal and spatial soil moisture variations occur within the sub-catchment units of each land use catchment. These results also suggest that several different processes control soil moisture loss and redistribution in each catchment. Clearly, the relative importance of these processes is variable in space, time, and between vegetation types.

Variation of unsaturated soil moisture conditions in the pasture land use catchment

The riparian sub-catchment unit shows the least seasonal soil moisture variation of all areas in the pasture land use catchment. This result suggests that the net effect of rainfall addition and soil moisture loss is small in the riparian areas, compared with other catchment areas. The smaller seasonal soil moisture variation in the pasture riparian area can be explained partially by the proximity of these sites to the stream channel and thus to the seasonal water table. For at least 25 % of the time, soil moisture in the B_3 horizon is close to saturation (i.e. see the similarity between the upper quartile and the maximum soil moisture contents observed in the pasture riparian catchment areas; figure 6.6a). Downslope drainage, from upslope areas, is likely to maintain near saturated soil moisture conditions after rainfall (c.f. Dunin and Aston, 1981). Capillary rise, from the water table or stream channel, may also prevent extreme drying of the soil profile and so reduce moisture variability in the A and B_1 soil horizons of the riparian areas in the pasture catchment.

In contrast to the riparian areas described above, the midslope sub-catchment unit shows similar seasonal soil moisture variations throughout the soil profile. This result suggests that the midslope area is a zone of transient hydrologic activity (c.f. Dunin and Aston, 1981). Similar soil moisture additions and removals in the B_2 and B_3 soil horizons are shown by the large, sub-parallel, shifts in the soil moisture profiles. This soil moisture variation is likely to be caused by temporary extensions of saturated conditions into midslope areas (see section 6.2.2.2), and rapid drainage from these areas following storm rainfall.

The pasture spur sub-catchment unit is characterised by decreasing soil moisture variability with depth. McGowan (1974) has suggested that similar patterns of profile soil moisture variation are attributable to additions and withdrawals of soil moisture at the soil surface. This sub-catchment unit is likely to produce only small yields of subsurface runoff and saturation overland flow because the available soil moisture storage is always large. In addition, the long distances between these areas and the stream channel will act to buffer the hydrologic responses from the spur sub-catchment unit.

Several factors, other than those described above, are suggested as causing the observed seasonal moisture variations in the sub-catchment units of the pasture land use catchment.

When the soils are dry, dessication cracks may extent to about 0.7 m in the soils of the pasture midslope and spur sub-catchment units. Dessication cracks and other large structural fissures are preferred pathways for water and vapour movement and can cause pronounced changes in the seasonal variation of soil moisture in soils (Lawrence, 1976; Bouma and Dekker, 1978; Bouma et al., 1979; Omoti and Wild, 1979). Much of the rain entering the soil can by-pass the soil structural peds by moving preferentially in dessication cracks and so be lost to ground water flow or lateral drainage (Quisenbury and Phillips, 1976; Bouma and de Laat, 1981). Consequently, the recovery from seasonal soil moisture deficits is delayed often in soils with large structural fissures. In addition, enhanced evaporation rates may also occur from dessication cracks (Ritchie and Adams, 1974).

Both enhanced evaporation and preferential water movement between soil peds may occur in the spur regions of the pasture land use catchment. These processes may cause the catchment soils to dry more rapidly and to lower soil moisture contents, in comparison with riparian catchment areas, where fewer large structural fissures occur.

Rapid drainage, through large structural fissures, may also result in a rapid redistribution of soil moisture to the downslope sub-catchment units. This process could cause the large soil moisture variation observed in the B_3 soil horizon in the pasture midslope sub-catchment unit (figure 6.6b).

Field observations, made in the experimental catchments during winter, showed that shading causes the riparian sub-catchment units to receive up to 4 hours per day less direct radiation than the spur regions. This effect is less pronounced in summer, but may still contribute to the spatial variation of soil moisture observed in both the catchments. Greater evaporation rates may also occur from the upslope catchment areas because of increased turbulence above the exposed spur sites.

Together, the processes described above are suggested as the main factors causing the observed spatial and seasonal soil moisture variations observed in the pasture land use catchment.

Variation of unsaturated soil moisture conditions in the forest land use catchment

The seasonal and spatial moisture variations in the forest soils can be explained partially by the interactions described above. For example, the high average soil moisture content in the forest riparian areas can be explained by the proximity of these sites to the stream channel and the seasonal water table (figure 6.7a). However, net rainfall in the forest catchment is about 42 % less (i.e. 590 mm less) than in the pasture catchment (see chapter 5). Bosch and Hewlett (1982) suggest that a reduction in annual net rainfall of this amount should cause drier soils, reduced base flow conditions, and smaller storm runoff yields compared with areas of greater net rainfall. In addition, it has been assumed that smaller net rainfall inputs tend to cause reduced seasonal soil moisture variations compared with pasture covered catchments (e.g. Selby, 1967a; Holmes and Colville, 1968; Gray, 1970; Pain, 1971).

The results from this study show that differences in net rainfall input do not cause simple and consistent differences between the seasonal soil moisture variation observed in the forest and pasture land use catchments. The soil moisture data suggest, that the lower net rainfall input causes an increase in the seasonal variations of soil moisture in the forest riparian areas, compared with similar areas under pasture. The lower net rainfall input in the forest causes a lowering of the seasonal water table (see section 6.2.2.4). This, in turn, may reduce the water supplied to the surface soil horizons by capillarity. These mechanisms can explain why the soils in forest riparian areas tend to dry more rapidly during periods of no rain compared with soils in similar areas under pasture.

The seasonal variations of profile soil moisture ($\bar{x}_T$) observed in the forest midslope and spur sub-catchment units show the characteristics suggested by the authors cited above (c.f. figure 6.6 b,c and 6.7 b,c). Compared with the riparian areas, the soil moisture contents are low in the forest midslope and spur catchment areas and vary little throughout the year. During storm rainfall, saturated soil moisture conditions do not extend from the forest riparian catchment areas into the midslope and spur areas. This factor may explain the small seasonal moisture variations found in the lower soil horizons in the forest midslope and spur sub-catchment units (see the discussion of saturated soil moisture conditions in section 6.2.2.4). The reduced net rainfall in the forest catchment may also be partially responsible for the small seasonal moisture variation observed in the upper soil horizons of the midslope and spur areas.

Several factors, other than those described above, may also cause the small seasonal soil moisture variations observed in the upslope areas of the forest catchment. The seasonal soil moisture variation observed in the forest midslope and spur sub-catchment units is also determined by the net effect of transpiration losses, evaporative losses from the soil surface and slope drainage.

Slope drainage and evaporation from the soil surface are probably small in the upslope areas of the forest land use catchment. Snelgar and Green (1981) have estimated that the mean evaporation rate from the litter layer is about 0.12 mm day $^{-1}$, in a forest type similar to that in the forest land use catchment. This evaporation rate is considerably smaller than the mean evaporation rate (transpiration) estimated from a dry canopy surface of a similar forest type (Pearce, 1980) (e.g. 1 - 1.3 mm day $^{-1}$). Soil drainage is likely to be slow in the midslope and spur areas of the forest land use catchment because the soil moisture content is usually low in these areas. Consequently, the soil matrix diffusivities should be low. In addition, the net rainfall inputs are seldom adequate to generate non-Darcian flow mechanisms (see section 6.3.4.2.3).

Together, the seasonal variation of slope drainage and soil evaporation is unlikely to determine the seasonal soil moisture variations in the forest midslope and spur catchment areas. Instead, the soil moisture variation observed in the upslope regions of the forest catchment must result mainly from interactions between the seasonal variations of net rainfall and transpiration losses. The soil moisture profiles shown in figure 6.7b and 6.7c provide evidence to support this assertion. Large soil moisture variations seldom occur in the forest midslope and spur areas, and possibly only in response to drought and to large storm events. Thus, for most of the year, additions to soil moisture from net rainfall appear to be balanced by losses to transpiration.

Soil moisture variations and vegetation type

Pearce (1980) has summarised the forest management effects on interception, evaporation and water yield, for several New Zealand experimental catchments based on:

i) the interpretation of water balance data from the catchments;

ii) overseas evidence of the characteristic processes of evaporation for pasture and forest vegetation;

and iii) the Penman-Monteith evaporation equation.

Pearce and Rowe (1979) have summarised the factors that determine the soil moisture regimes (inferred from comparative water yields) characteristic of forest and pasture vegetation. These include:

i) the total rainfall and its seasonal distribution

ii) the smaller net rainfall under forest compared with pasture vegetation;

and iii) the greater rooting depth of forest vegetation compared with pasture vegetation, enabling comparatively larger transpiration rates from forest vegetation when soil moisture is limiting.

The annual rainfall is generally evenly distributed in the Mangawhara Valley and should not affect the seasonal soil moisture regimes in the two vegetation types. Thus, the principles described above suggest that soil moisture should be consistently lower in the forest than in the pasture because of the differences in net rainfall. If a seasonal soil moisture deficit occurs in the two catchments, the forest soils should continue to dry more rapidly and to lower moisture contents than in the pasture.

The soil moisture regimes observed in each land use catchment show that effect of vegetation type is more complex than suggested by Pearce and Rowe (1979) and depends also on geomorphic position within the catchments (see figure 6.5 a,b,c). The simple effects of vegetation type are shown most clearly in the midslope catchment areas, where soil moisture in the forest is consistently lower and less seasonally variable than in the pasture (figure 6.5b). The seasonal soil moisture regimes are similar in the riparian areas of both land use catchments (see section 6.2.1.3.1), while in the spur sub-catchments units, the forest soils are wetter than those in the pasture for about 6 months of the year.

The causes of the anomalously high soil moisture conditions in riparian areas of the forest land use catchment have been discussed in the previous section.

Two unusual features are apparent in the soil moisture regimes observed in the upslope areas of both land use catchments. Firstly, after the maximum soil moisture contents have been reached in winter, soil moisture in the midslope and spur catchment areas is depleted more rapidly in the pasture than in the forest. In the midslope areas, this can be explained simply by more rapid lateral and vertical slope drainage in the pasture, compared with the forest. However in the spur areas, the rapid depletion of soil moisture occurs in the pasture even during periods of low soil moisture and possible moisture stress (figure 6.5b and 6.5c). Secondly, the lack of seasonal moisture variation in the forest midslope and spur sub-catchment units appears unusual, particularly during summer periods when evaporative demands are high. Soil moisture should vary in the forest midslope and spur areas in response to seasonal evaporative demands, even though the rainfall in the Mangawhara is distributed evenly throughout the year. Some hypotheses have been suggested in the previous section to account for the small seasonal soil moisture variation observed in these areas.

Apart from differences in soil drainage rates, several other factors may account for these apparently anomalous soil moisture observations. For the forest species common in the Hapuakohe Range, most of the root mass is restricted to the upper 0.3 m of soil; tap roots seldom extend to a depth of 0.7 m (Parker, 1978; Bridson, 1981). Table 6.4 shows the distribution with depth, of several sizes of roots in the forest soils of the adjacent Aroronga Valley.

	Root size class (mm)					
Depth (m)	(<2)	(2-5)	(5-10)	(10-20)	(>20)	Total
0.00 - 0.25	2.53	2.89	2.38	4.91	13.47	26.18
0.25 - 0.50	0.67	1.53	1.49	0.59	0.36	4.64
0.50 - 0.75	0.67	1.38	1.16	0.28	0.00	3.49
0.75 - 1.00	0.26	0.43	0.19	0.18	0.00	1.04

Units - kg m^{-3}

Table 6.4 : The distribution with depth of the dry root mass in forest soils of the Aroronga Valley (after Parker (1978))

Field observations made in the pasture land use catchment show that pasture roots often extend to depths of 0.7 m in dessication cracks and other large structural fissures (see plate 6.2; section 6.3.4.2.2). A comparison of the the rooting habit of both vegetation types suggests that similar volumes of soil are explored by the two vegetation types. Thus, the soil moisture available for plant growth and transpiration may be considerably greater for the pasture than for the forest vegetation. Consequently, the pasture vegetation may not enter water stress much earlier than forest vegetation.

Jackson (1972) has observed greater transpiration rates from pasture crops than for forest vegetation, in an area where soil moisture is not a limiting factor. Greater transpiration rates for pasture vegetation have also been implied in several micro-meteorological studies (e.g. Stewart and Thom, 1973; Gash and Stewart, 1975, 1977). However, the lower albedos of forest canopies tend to reduce the differences in the transpiration rates between forest and pasture vegetation. Nevertheless, the potential for greater transpiration rates from pasture, compared with forest vegetation, has been demonstrated in areas where soil moisture is not limiting (Pearce and Rowe, 1979).

Differences in transpiration losses are unlikely to explain the continued, rapid depletion of soil moisture in the upslope pasture areas when the soil moisture is low. The soil moisture data provide evidence, that suggests pasture vegetation in the spur sites suffers considerable water stress during summer (figure 6.5b and c).

During summer, greater evaporation from the soil surface and from dessication cracks may occur in the pasture, than in the forest. Ritchie and Adams (1974) have observed daily average evaporation rates from dessication cracks as high as 0.6 mm day $^{-1}$. In comparison, evaporation rates from the forest litter are generally much lower, in forest types similar to those in the forest land use catchment (e.g. 0.12 mm day $^{-1}$; Snelgar and Green, 1981).

The preceding discussion suggests that the seasonal moisture variations in the upslope sub-catchment units of the two land use catchments are dominated by several factors: different net rainfall inputs; different rates of soil drainage; different transpiration losses; and different evaporation rates from the soil surface. Compared with the forest, the greater seasonal soil moisture variation in the upslope areas of the pasture catchment can be explained by the greater additions to soil moisture by the higher net rainfall, greater slope drainage, and by greater transpiration losses when soil moisture is not limiting. During summer, when the pasture vegetation may by subjected to water stress, slower soil drainage and the lower transpiration losses may be compensated by high evaporation rates from soil surface, including evaporation from structural fissures.

In the riparian areas of the two land use catchments, the seasonal soil moisture regimes are similar because of the proximity of these sites to the stream channel. Compared with the pasture, the slightly greater seasonal variation of soil moisture observed in the riparian areas of forest catchment can be explained by a lower water table in these areas.

6.2.1.4 Summary of the analyses of unsaturated soil moisture conditions in the two experimental catchments

A sampling network was established to examine the spatial and seasonal variation of unsaturated soil moisture conditions within the two land use catchments. Hydrologically important differences in the spatial distribution of mean profile soil moisture content ($\overline{x}_T$) were observed between most of the sub-catchment units of each land use catchment. In both land use catchments, the riparian areas have the highest soil moisture contents compared with the upslope catchment areas. In the pasture, the spur catchment areas are drier than the midslope areas. No statistically significant differences were found between the midslope and spur areas of the forest. Nevertheless, the midslope and spur regions of the forest catchment are both considerably drier than the riparian catchment areas. Thus, in both land use catchments, the spatial distribution of unsaturated soil moisture conditions is similar to the pattern of soil moisture suggested by the variable source area hypothesis.

A comparison was made between the mean profile soil moisture contents ($\bar{x}_T$) of each sub-catchment unit in the two land use catchments. No differences could be detected between the mean profile soil moisture regimes observed in the riparian catchment areas of each vegetation type. This result suggests that the relationships between hillslope runoff and the net rainfall regime may be similar in these catchment areas.

The seasonal and spatial variations of mean sub-catchment unit soil moisture observed at individual depths ($\bar{x}_{DT}$'s) show few consistent patterns in each land use catchment. However, within each land use catchment, the spatial variation of soil moisture can be explained by:

i) the interactions between the net rainfall regime and the soil moisture regimes observed in each sub-catchment unit;

ii) the spatial variability of evaporation rates within each vegetation type;

iii) the proximity of a site to the stream channel and hence to the water table;

and iv) lateral and vertical drainage.

In addition to the factors mentioned above, the differences in seasonal moisture regimes observed between the two land use catchments can be explained by:

i) the different interception losses of the two vegetation types;

ii) the seasonal differences in transpiration rates between the two vegetation types;

and iii) the differences between the evaporation rates from the soil surface (including losses of soil moisture via dessication cracks) of the two vegetation types.

The spatial and seasonal variations of soil moisture observed in this study show that vegetation type does not cause simple or consistent changes in the soil moisture regimes of the sub-catchment units in each land use catchment. Consequently, inferences made in comparative land use studies, about changes in the mechanisms and spatial distribution of runoff, may be inaccurate if they are made from water yield data alone.

The hydrologic implications of the spatial variability of unsaturated soil moisture conditions are considered in section 6.4.

6.2.2 SPATIAL AND SEASONAL VARIATION OF SATURATED SOIL MOISTURE CONDITIONS IN THE LAND USE CATCHMENTS

Saturated moisture conditions were monitored to determine the variation of surface and subsurface saturation within and between the two land use catchments. The development of saturated soil conditions within small basins depends on several pedologic and topographic characteristics: the water storage and transmission characteristics of the soil horizons; slope angle and curvature; and soil depth (Kirkby and Chorley, 1967; Anderson and Burt, 1978a; Anderson and Kneale, 1982).

6.2.2.1 The data set and data analysis

6.2.2.1.1 The data set

Saturated moisture conditions were monitored by piezometry in two small first order basins, one from each experimental catchment. As nearly as possible, similar convergent hollows and adjacent spurs were chosen for study, to minimise the effects of other soil and topographic variables that influence soil saturation within catchments. The forest basin was slightly larger than the pasture basin, but both contained ephemeral streams. Figure 6.8a and 6.8b show the topographic features and piezometer grids in the two first order basins (sub-catchments).

Piezometers were placed in the ground to a depth of about 1.0 m to measure water table elevations above the soil-weathered bedrock boundary. The observed water table elevation was a measure of saturated conditions throughout the soil profile. Saturated conditions were considered unlikely to form above soil horizon boundaries because:

i) large, structurally isolated prisms and structural fissures extend deep into B_3 horizon (plate 6.1; section 6.3.4.2.2);

and ii) the observed permeability differences between the soil horizons are too small to initiate saturation above the horizon boundaries (e.g. Harr, 1977; Murray, 1981).

The piezometer grids each comprised 3 transects, one passing up the basin thalweg, another up an adjacent spur and the third in a midslope position. Two additional transects per grid were considered unnecessary because other field studies have shown that saturated soil moisture conditions tend to occur symmetrically across small basins (e.g. Anderson and Burt, 1978a; Pierson, 1980).

Recordings were made for all piezometers (22 in the pasture and 14 in the forest) at weekly intervals for 2 years. The maximum water level for the preceding week, and the water table elevation at the time of observation, were recorded as a positive or negative distance from the surface of the mineral soil (below the soil surface as negative). Saturated soil moisture conditions were indicated in 17 of the pasture piezometers and in all the forest piezometers at some time during the 2

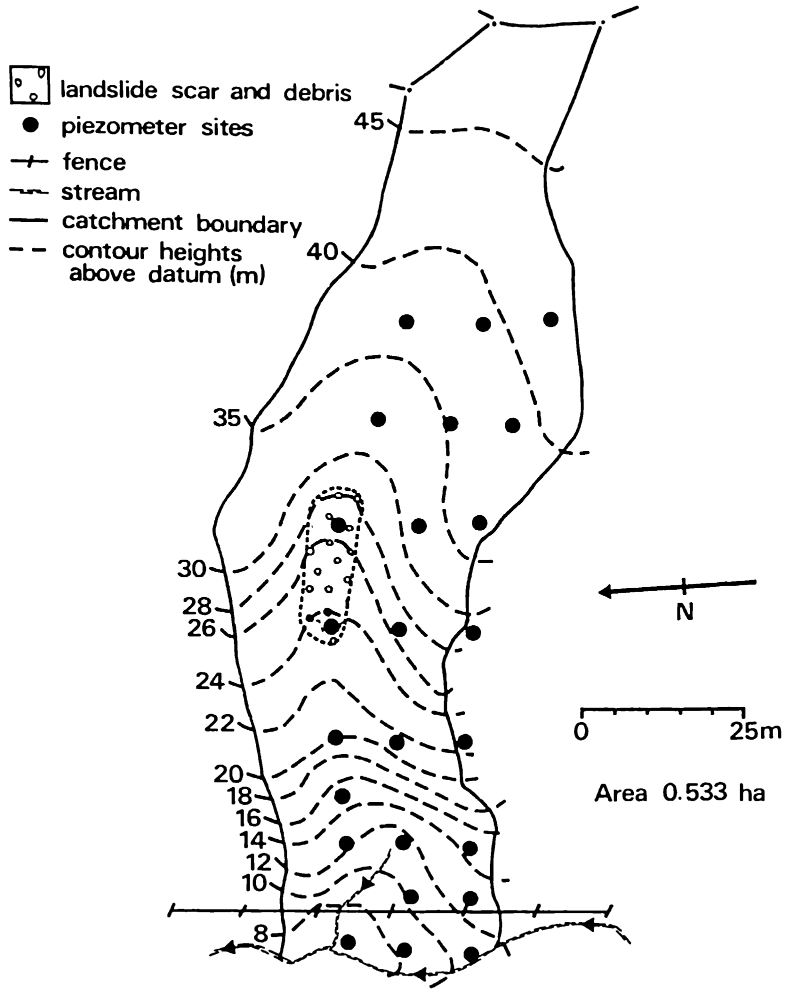


Figure 6.8a : Pasture sub-catchment: Topographic features and piezometer grid

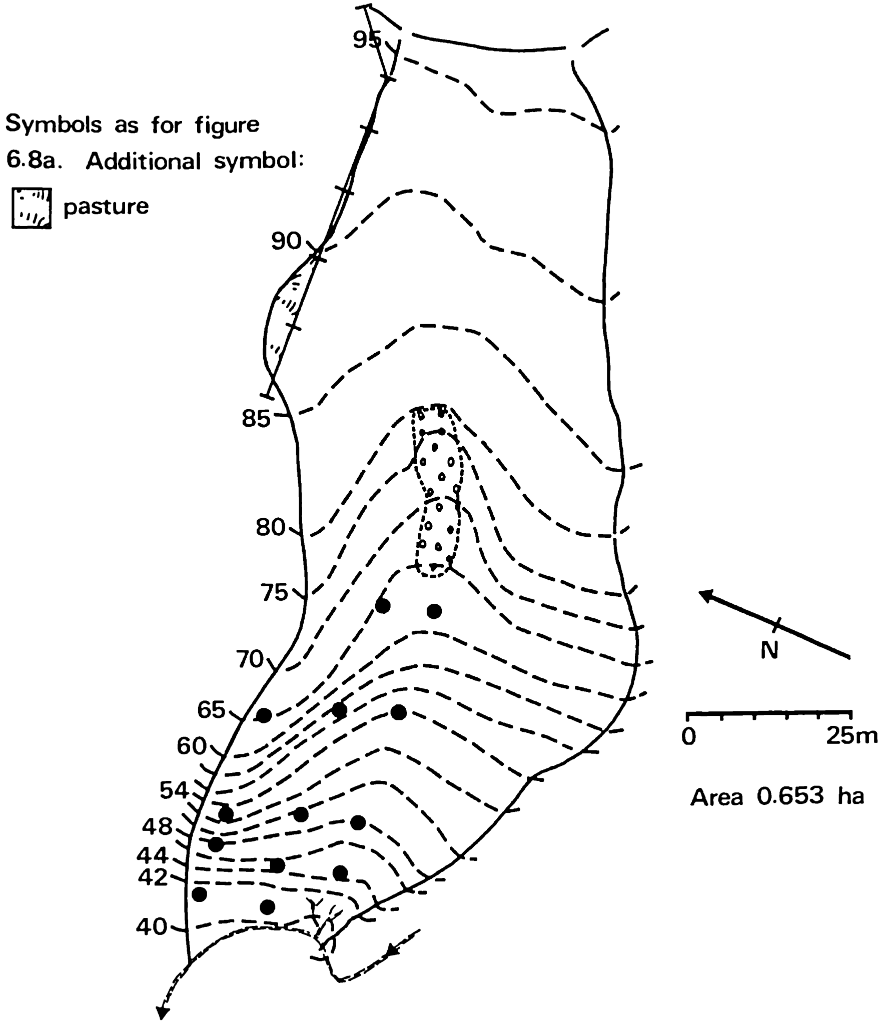


Figure 6.8b : Forest sub-catchment: Topographic features and piezometer grid

year observation period. Water table elevations were observed above the soil surface on occasion at several sites within the pasture basin, but at no times in the forest basin. Except for one pasture piezometer (no. 7) and one forest piezometer (no. 1), the data series recorded at the remaining sites were censored at some time (i.e. the water table was below the bottom of the piezometer and could not be recorded).

Data censoring increased in frequency with increasing distance from the stream channel. Apart from the weekly peak water table elevations, saturated soil moisture conditions were seldom recorded, except at the piezometers immediately adjacent to the main stream channel. This suggests that saturated soil moisture conditions do not persist after the end of rainfall.

6.2.2.1.2 Data analysis

An analysis of the timing and spatial distribution of saturated soil conditions was restricted to an examination of the weekly peak water table elevations observed at each site. A simple probability analysis of the weekly peak piezometric surfaces observed at each site was considered the most appropriate analysis technique to achieve the objectives of this section (see section 6.1). This type of analysis enables the data recorded at each piezometer site to be summarised by a few parameters. In addition, the degree of subsurface saturation in each catchment and the probability of saturation of the surface soil can be estimated simply.

The extreme value distributions (EV I, EV II, EV III) were considered an appropriate distribution for use in this case because the data satisfied most of the requirements of the extreme value model (see Johnson and Kotz, 1970). However, weak serial correlation was a feature of the data from some of the sites.

The genesis and characteristics of the three extreme value distributions have been described by Johnson and Kotz (1970). The EV I (Gumbel) distribution is a two parameter, unimodal, shape invariant distribution with positive skew. Compared with the EV I distribution, the EV II distribution has a third (shape) parameter, a lower bound, and is strongly positively skewed. The EV III is also a three parameter distribution, but has an upper bound and a strong negative skew. The correct choice between the three extreme value distributions (EV I, EV II, EV III) is important, as there are considerable differences between their tail probabilities (Van Montfort, 1970).

The test described by Otten and Van Montfort (1978) was used to find which of the three distributions best described the data recorded at each piezometer site. In this test, the null hypothesis is that the EV I distribution describes the data better than either, the EV II, or EV III distributions. (Note: this test assumes that one of the three distributions holds exactly for each data set). The test as given, was not applicable for use with heavily censored data. However, the test was applied to sites with less than 10 % censoring and showed that the EV III distribution described the data most accurately.

The EV III distribution has physical justification for use at all sites. As the water table rises upward through the soil profile it encounters increasing porosity and permeability. A constant rainfall input leads, therefore, to non-linear increases in water table rise. Thus, the frequency distribution of peak water table elevations will tend to be truncated toward the soil surface. As the EV III distribution has both an upper bound and a left tail, it describes the distribution of weekly peak water table elevations observed at each site more accurately than the other extreme value distributions.

Using the notation of Johnson and Kotz (1970), the EV III distribution function is defined:

$$P_{(x \le x)} = \exp - \left(\frac{\xi - x}{\theta}\right)^{c} \qquad (x \le \xi) \qquad (6)$$

where ξ is the location parameter (upper bound),

θ is the scale parameter,

and c is the shape parameter.

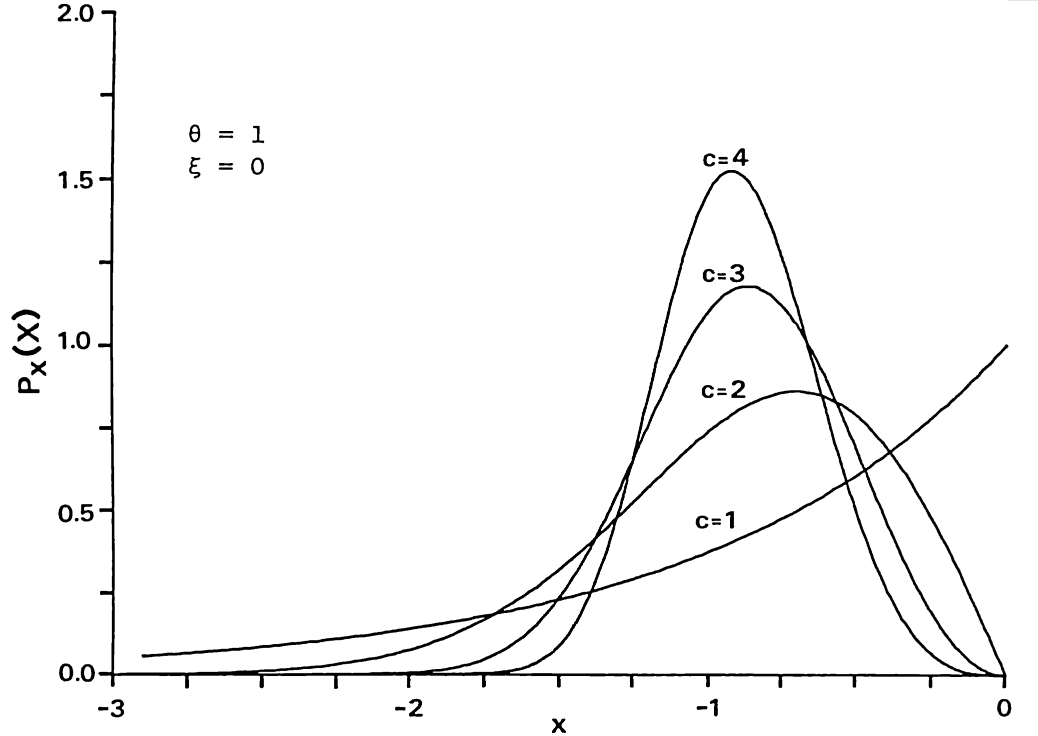


Figure 6.9: EV III density functions for selected values of the shape parameter (c)

Figure 6.9 shows standard EV III density functions for selected shape parameters (c) ($\theta = 1$, $\xi = 0$). The parameters of the fitted EV III distributions were estimated graphically from optimised linear plots of the observed data, using the Gringorton (1963) plotting position formula.

				EV III distribution parameters		
	Site	n	r	Scale (θ)	Shape (c)	Location (ξ)
Pasture	1	94	0.99	0.375	1.754	0.08
	2	94	0.99	0.329	1.842	-0.01
	3	76	0.94	0.816	2.268	-0.18
	4	94	0.97	0.460	2.101	0.08
	5	95	0.94	0.660	4.167	-0.47
	6	42	0.98	0.287	3.597	-0.25
	7	98	0.96	0.309	4.329	0.25
	8	44	0.92	0.979	2.653	-0.14
	9	23	0.99	1.487	1.466	-0.32
	10	27	0.98	2.094	3.690	-0.23
	11	12	0.98	4.573	1.045	-0.66
	12	7	0.97	10.579	1.016	-0.74
	13	2	*	2.474	2.538	-0.31
	14	5	0.98	3.490	1.327	-0.62
	15	4	0.95	0.799	4.274	-0.66
	16	4	0.86	2.435	1.220	-0.80
	17	5	0.99	1.052	3.857	-0.12
Forest	1	91	0.95	0.278	5.747	-0.05
	2	24	0.98	0.406	3.082	0.14
	3	65	0.99	1.092	2.070	-0.16
	4	31	0.98	3.062	1.198	-0.29
	5	19	0.94	1.766	1.802	-0.50
	6	7	0.95	5.018	1.398	-0.52
	7	83	0.94	0.658	1.466	-0.38
	8	9	0.95	4.894	1.054	-0.98
	9	3	0.96	2.248	2.320	-0.70
	10	58	0.90	1.640	1.409	-0.22
	11	24	0.99	1.289	2.020	-0.64
	12	2	*	3.232	2.538	-1.19
	13	2	*	4.963	2.538	-0.78
	14	9	0.97	5.930	1.041	-0.76

n - number of samples   r - correlation coefficient

Table 6.5 : Extreme value (EV III) distribution parameters for piezometer sites in the two experimental catchments

Table 6.5 shows the estimated parameters of the distributions for each piezometer site, the number of observations of peak water table elevations made at each site, and the correlation coefficients (used as a measure of goodness of fit) of the optimised linear plots of the observed data. The shortage of data from the censored sites is apparent immediately, particularly at sites upslope and distant from the stream channel. The use of the fitted distributions for piezometer sites with few samples seems justified since:

i) the correlation coefficients show the distributions can describe the observed data accurately;

and ii) the EV III distribution parameters estimated for the censored sites are similar to those estimated for sites with few censored data (table 6.5).

6.2.2.2 Variations of subsurface and surface soil saturation

The probability of a weekly peak water table elevation (piezometric surface) exceeding selected soil depths was estimated from the fitted EV III cumulative distribution functions for each piezometer site. These estimates were plotted and contoured for 4 soil depths (the soil surface, 0.5 m, 1.0 m, 1.5 m), to estimate the areas of soil saturation in each land use catchment (figure 6.10; pasture: figure 6.11; forest). The soil depths shown in figure 6.10 and 6.11 were chosen instead of horizon depths for two reasons. Firstly, soil profile development varies considerably within the first order basins; and secondly, by using standard depths, comparisons could be made directly between the two vegetation types.

Figure 6.10 a,b,c,d and 6.11 a,b,c,d show the progressive development of soil saturation in the two first order basins. Figure 6.10a and 6.11a show the probabilities of a weekly peak water table elevation exceeding the soil surface. Thus, these two figures show the probability of saturation overland flow occurring in a given week and the areas from which this flow mechanism can occur.

The threshold of subsurface saturation is represented by the areas encompassed by the 0.0 - 0.09 probability contour (figure 6.10 b,c,d and 6.11 b,c,d). Subsurface saturation develops initially in areas of low elevation in both land uses, and progresses upslope to areas of contour convergence. The widespread development of subsurface saturation in the upper soil horizons is inhibited, in both land uses, by increased soil permeability toward the soil surface and a concomittant increase in slope drainage. Much larger areas of subsurface saturation occur deeper in the soil profile, where the soil is less permeable. At all soil depths, the areas of saturation for selected probabilities are larger in the pasture than in the forest. The relationships between subsurface saturation and vegetation type are discussed in section 6.2.2.4.

Both contour convergence-divergence and elevation potential (induced by slope angle) influence the shape and extent of subsurface soil saturation (Anderson and Burt, 1978b). The influence of elevation potential appears to be more important than contour convergence-divergence in the two land use catchments. The influence of contour convergence-divergence is shown in figure 6.10 and 6.11 by differences in the direction between the topographic and piezometric contours. 'Islands' of greater probability (figure 6.10 and 6.11) indicate regions where contour convergence-divergence is more important than elevation potential for controlling the distribution of saturated soil conditions. This occurs most often in areas of low elevation, or in regions of steeper slopes where contour convergence is pronounced. It is in these areas that subsurface saturation develops most rapidly (figure 6.10c and 6.10d; and 6.11c and 6.11d).

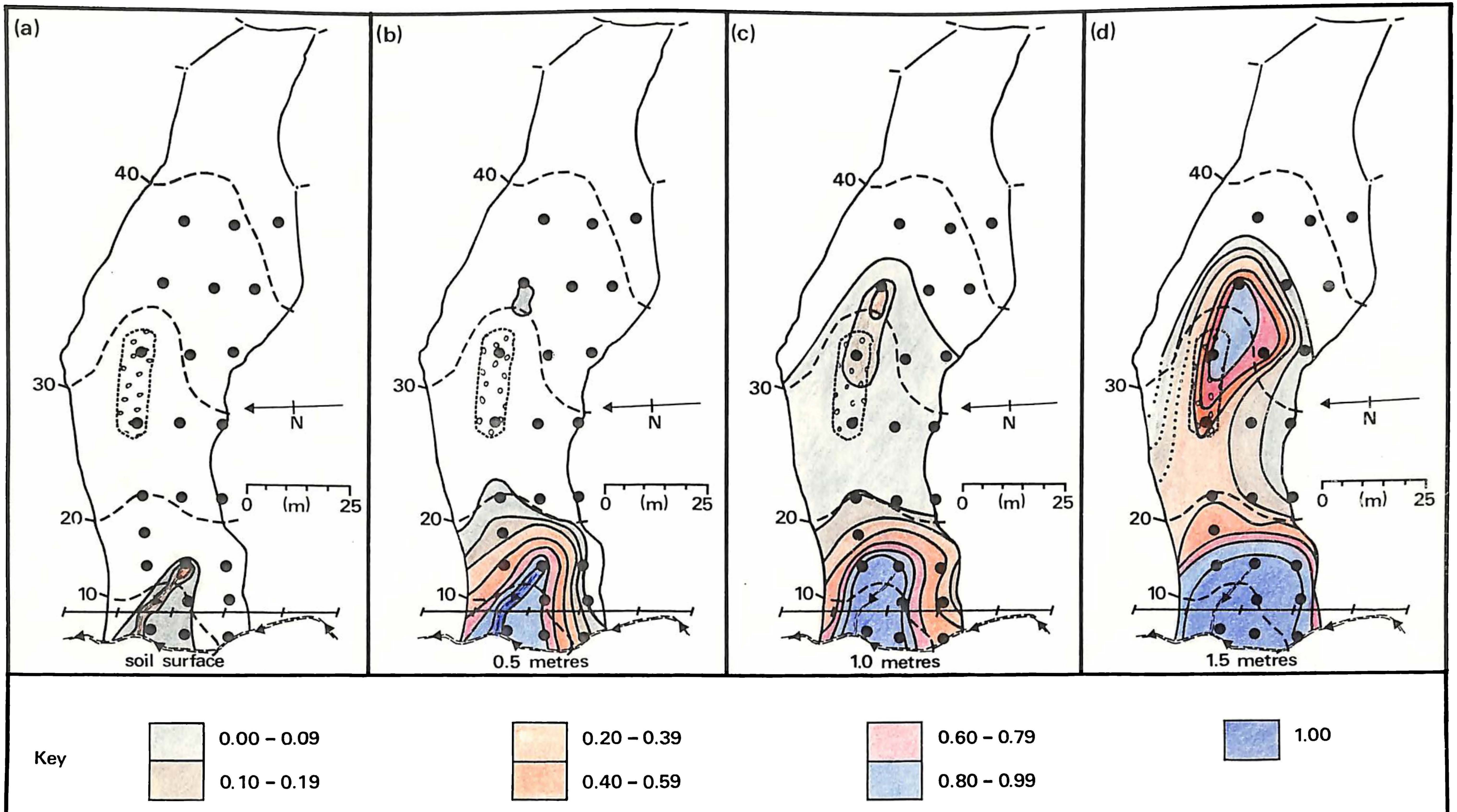


Figure 6.10 : Pasture sub – catchment : The probability of weekly peak water table elevations exceeding selected soil depths

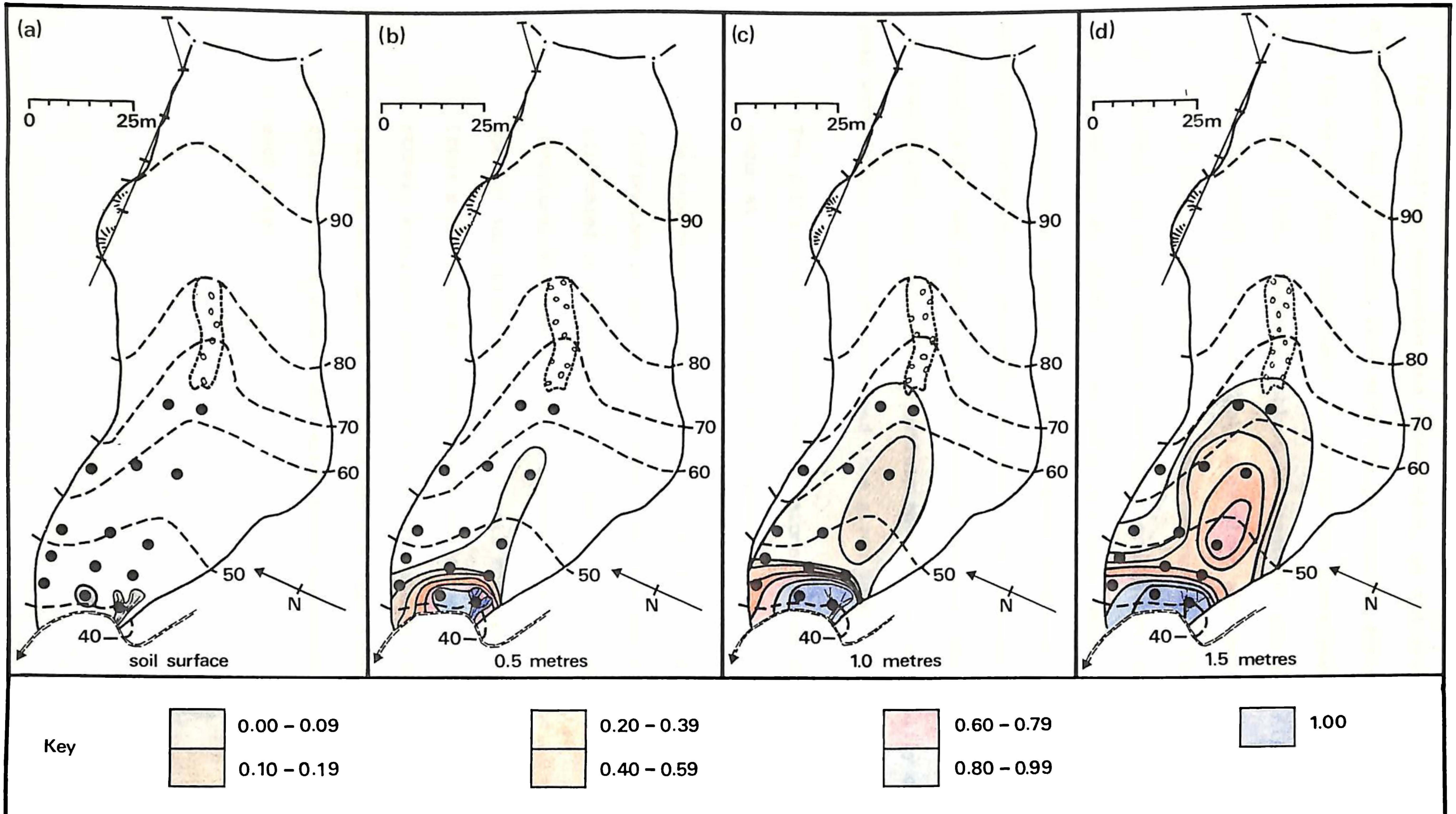


Figure 6.11 : Forest sub–catchment : The probability of weekly peak water table elevations exceeding selected soil depths

The consistent expansion and contraction, of the areas of surface and subsurface saturation implied by the probability contours, suggests that the weekly peak water table elevations are correlated significantly at individual sites. However, table 6.6a (pasture) and 6.6b (forest) show that the weekly peak water table elevations are correlated spatially at only a few sites in both sub-catchments. This implies that, although the water table is spatially continuous, the peak water table elevations are spatially variable in a given week. Thus, factors other than rainfall, slope position, elevation potential, contour convergence-divergence, antecedent moisture, and vegetation type, are responsible for the short term fluctuations in water table elevations.

Two factors are suggested to explain the spatial variability of the peak water table elevations observed in a given week.

i) The differences in antecedent moisture conditions that occur at individual piezometer sites.

ii) The occurrence of small, but hydrologically important differences in soil structure at each piezometer site (discussed in section 6.3.1.2.2 and 6.3.3.2). Such small structural differences can be induced by seasonal and spatial variations of antecedent soil moisture conditions. These soil structural differences can alter the soil moisture storage available during rain and the rate of water entry into the soil matrix. In this way they can cause considerable changes in the weekly peak water table elevations observed at each site.

PASTURE

Site	1	2	3	4	5	6	7	8	9
1	1.00								
2	0.59**	1.00							
3	0.52**	0.54**	1.00						
4	0.72**	0.58**	0.61**	1.00					
5	-0.05	-0.05	0.09	-0.03	1.00				
6	0.06	0.28	0.22	0.06	-0.18	1.00			
7	0.44**	0.23*	0.25*	0.32**	-0.10	-0.14	1.00		
8	-0.28	-0.09	-0.07	-0.16	0.06	-0.13	-0.03	1.00	
9	-0.15	-0.19	-0.10	-0.13	0.23	-0.41	0.01	0.25	1.00
10	0.20	0.38*	0.31	0.16	-0.19	0.74**	-0.14	-0.14	-0.34
11	-0.20	-0.22	-0.45	-0.30	-0.02	-0.11	0.06	0.07	0.01
12	-0.15	-0.13	-0.11	-0.16	0.01	-0.22	0.07	0.19	0.22
13	0.03	0.03	-0.05	-0.07	-0.00	-0.13	0.16	0.10	0.21
14	-0.17	-0.01	-0.13	-0.18	0.06	-0.06	0.08	0.24	0.10
15	-0.15	-0.13	-0.24	-0.28	-0.06	-0.11	0.10	0.13	0.04
16	-0.12	-0.07	-0.16	-0.23	0.01	-0.16	-0.01	0.13	0.06
17	-0.27	-0.23	-0.12	-0.18	0.03	-0.18	-0.05	0.18	0.14

Site	10	11	12	13	14	15	16	17
10	1.00							
11	-0.17	1.00						
12	-0.20	0.35	1.00					
13	-0.12	0.05	0.68	1.00				
14	-0.17	0.19	0.56	0.37	1.00			
15	-0.17	0.53	0.64	0.38	0.56	1.00		
16	-0.15	0.42	0.70	0.40	0.59	0.91*	1.00	
17	-0.17	0.46	0.76*	0.09	0.48	0.53	0.60	1.00

* - significant at p = 0.05   ** - significant at p = 0.01

Table 6.6a : Correlation matrix for weekly peak water table elevations in the pasture catchment

Over longer time periods (i.e. the study period), these processes are averaged considerably in time and space and so cause the consistent and systematic variations of saturated soil moisture conditions shown by the probabilistic descriptions given earlier. The significant correlations between the piezometers marginal to the pasture stream channel can be explained by the higher average antecedent moisture conditions in these areas and hence the less frequent occurrence of soil structural fissures. In drier catchment areas, soil moisture is more variable and structural fissures are more common (see section 6.2.1.3.1 and 6.3.4.2). In addition to the factors described for the pasture, root channels and other structural features can explain the highly variable water table elevations observed in the forest catchment.

FOREST

Site	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00													
2	0.04	1.00												
3	0.20	0.24	1.00											
4	-0.03	0.23	0.35*	1.00										
5	0.01	0.42	0.24	0.29	1.00									
6	-0.11	0.27	0.15	0.30	0.36	1.00								
7	0.18	0.12	0.43**	0.22	0.16	0.01	1.00							
8	-0.26	0.23	-0.01	0.13	0.16	0.16	0.01	1.00						
9	-0.18	0.21	-0.07	0.11	0.05	0.17	-0.05	0.40	1.00					
10	0.02	0.23	0.49**	0.25	0.36	0.07	0.40	0.10	0.01	1.00				
11	-0.08	0.19	0.10	0.36	0.31	0.15	-0.01	0.04	0.04	0.26	1.00			
12	-0.04	0.20	0.03	0.23	0.19	0.52	-0.01	-0.04	-0.03	-0.15	0.05	1.00		
13	-0.00	0.08	-0.04	0.04	0.08	-0.04	0.08	-0.04	-0.03	0.01	0.12	-0.02	1.00	
14	-0.23	0.27	0.06	0.31	0.21	0.50	-0.03	0.47	0.55	0.04	0.18	0.24	-0.04	1.00

* - significant at p = 0.05 ** - significant at p = 0.01

Table 6.6b : Correlation matrix for weekly peak water table elevations in the forest catchment

6.2.2.3 Estimation of the largest possible saturated area in the land use catchments

The largest possible areas of surface and subsurface saturation are estimated from the data presented in table 6.5. The location parameter of the fitted EV III distributions is an estimate of the largest weekly peak water table elevation at each piezometer site. The largest possible areas of surface and subsurface saturation were estimated from the contoured site location parameters for both the first order basins (sub-catchments) (figure 6.12; pasture: figure 6.13; forest).

An additional source of information was used in compiling these contour diagrams. In the pasture, landsliding destroyed two piezometers at important recording sites (see figure 6.8a). A water table elevation of 1 - 1.2 times the soil depth has been suggested as a necessary precursor for landslide initiation in similar sites in the Hapuakohe Range (Rogers and Selby, 1980). This fact was incorporated in the construction of the contours around these sites.

The shape of the largest possible areas of saturation is similar to the shape of the areas of subsurface saturation, observed in both sub-catchments, for smaller rainfall events (see section 6.2.2.2).

Water table elevations can be expected above the ground surface in both land use catchments for the largest possible event (figure 6.12 and figure 6.13). However, the saturated areas will be restricted to swampy areas marginal to the main and ephemeral stream channels (figure 6.12 and 6.13). Saturation overland flow can develop on the saturated areas. Greater velocities of overland flow (e.g. 2.78×10^{-3} to 2.78×10^{-2} m s^{-1}; Dunne, 1978) enable rain falling on saturated areas to reach the stream channel more quickly as saturation overland flow, than as subsurface flow from the same areas. However, the hydrologic implications of the small differences in the saturated area implied for the two land use catchments, will depend on the relative importance of saturation overland flow and subsurface flow mechanisms in determining the total storm runoff response observed in the stream channel. These factors are considered in chapter 7.

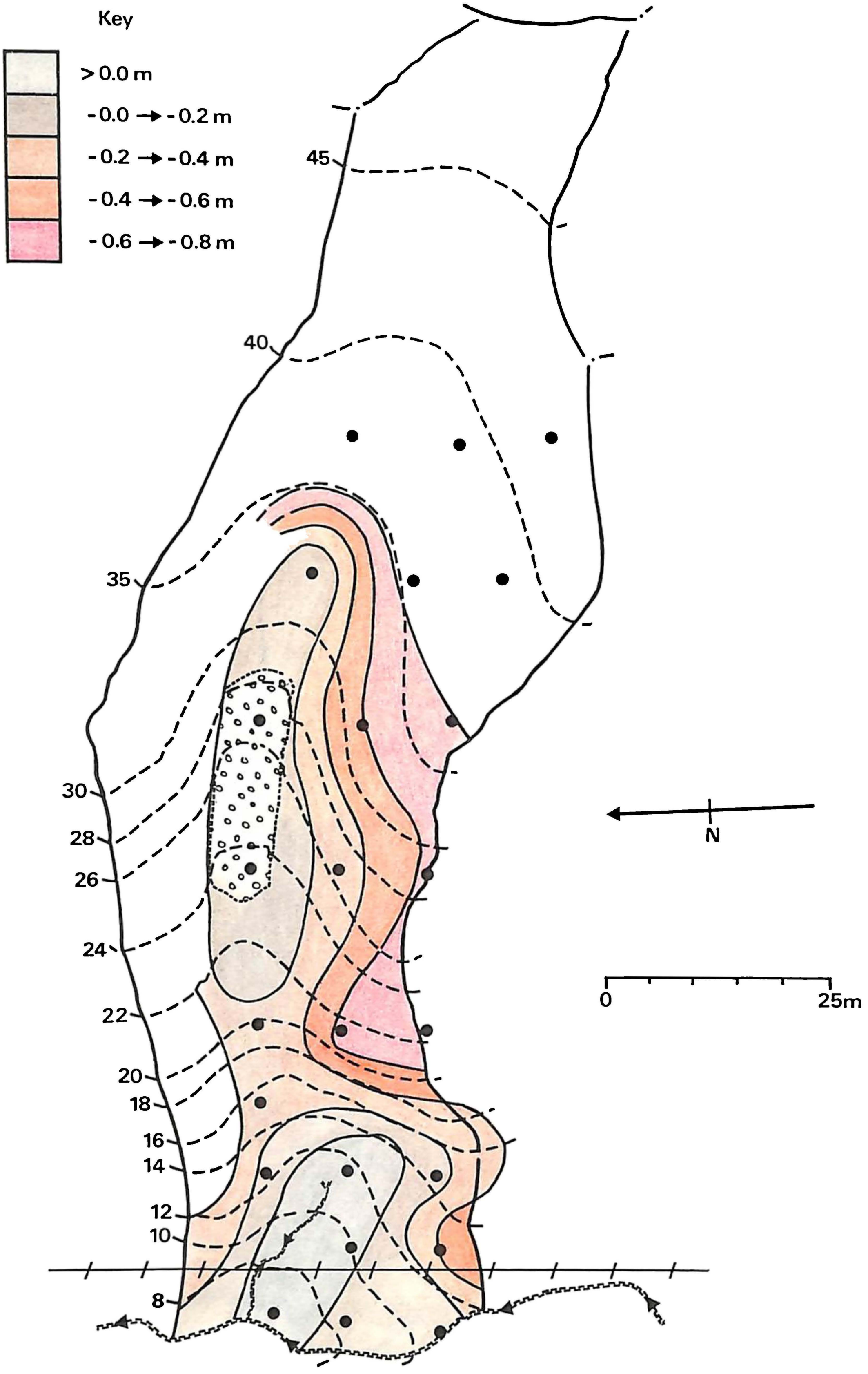


Figure 6.12 : Pasture sub-catchment : Depth contours for the largest expected saturated area

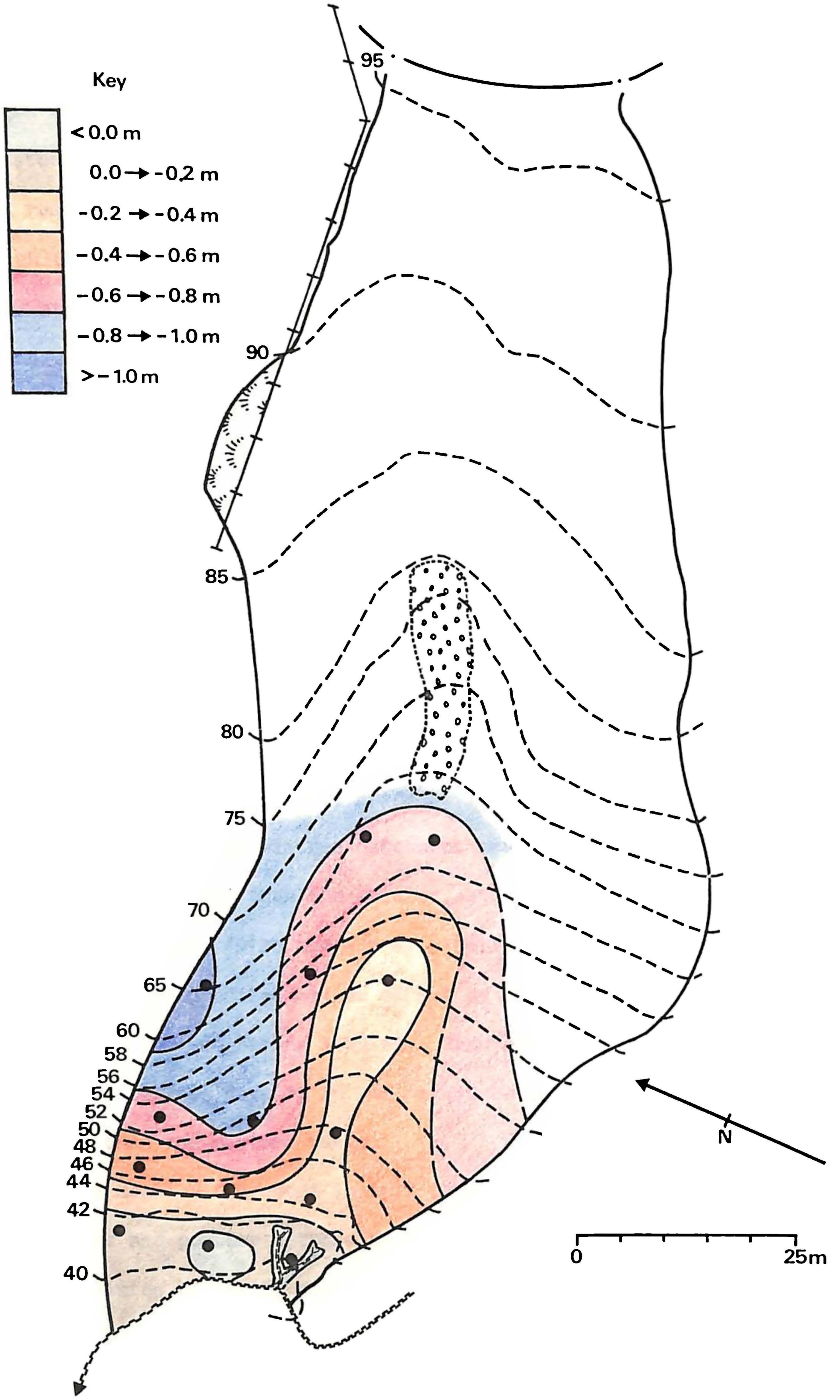


Figure 6.13 : Forest sub-catchment : Depth contours for the largest expected saturated area

6.2.2.4 Saturated soil conditions and vegetation type

The data presented in the preceding sections show that the weekly peak water table elevations are usually lower in the forest, than in the pasture. The results also show that surface and subsurface saturation is restricted to riparian areas in both land use catchments. Compared with the pasture catchment, the reduction in weekly peak water table elevations in the forest land use catchment can be explained by the smaller net rainfall inputs characteristic of this vegetation type. The slightly greater soil moisture holding capacity of the forest riparian soils also acts to reduce the areas of subsurface saturation in the forest catchment (appendix F).

Other factors may also cause the differences in saturated soil moisture conditions observed between the two first order basins examined. The pasture land use catchment has been deforested for about 60 years and a general lowering of slope angles and infilling of valley floors has occurred during this period (Selby, 1967b, 1976; Parker, 1978; Rogers and Selby, 1980; Bridson, 1981). As a consequence, the slope profiles of the pasture catchment are more likely to produce saturated conditions than the steeper, straighter slopes in the forest catchment (Freeze, 1972b and Murray, 1981). However, the effect of the different slope profiles may be offset by the differences in the shape and size of the two basins studied. Saturated soil moisture conditions are more likely to develop in the forest basin, as it is larger but less elongate than the pasture basin.

Only small differences in soil permeability were observed between the forest and pasture catchments (section 6.3.3). However, the soil permeabilities of the B_3 soil horizon in the forest riparian areas are slightly lower, than those in similar areas in the pasture. These small differences in soil permeability will favour the formation of saturated conditions in the forest land use catchment.

The net effect of the different soil and topographic characteristics observed in each land use catchment is unknown. Nevertheless, the differences in saturated conditions observed between the two first order basins are assumed to result from a difference in vegetation type. Such vegetation changes alter immediately the net precipitation. In a longer time interval, they also alter soil profile morphology, the water storage and transmission properties of the soil, and slope morphology. Nevertheless, changes in these variables all result from alterations of the soil-slope-vegetation continuum, that have been caused ultimately by vegetation change.

6.2.2.5 Summary

A simple probability analysis of the weekly peak water table elevations was carried out in a small first order basin in the two land use catchments.

The probability of weekly peak water table elevations exceeding selected soil depths (the soil surface; 0.5 m; 1.0 m; 1.5 m) show that the areas of saturation are controlled by soil moisture potentials generated by contour-convergence and elevation. Elevation potential is generally more important than contour convergence-divergence in determining the spatial distribution of saturated soil moisture conditions in each land use catchment. However, contour convergence-divergence is important in areas of shallow slope angles and in steeper areas where the hillslopes are incised.

Weekly peak water table elevations at most individual sites appear spatially uncorrelated, except at sites marginal to the main stream channel in the pasture catchment. This implies that, although the water table is spatially continuous, the peak water table are spatially variable at a given time. Two factors are suggested as the cause of the short term fluctuations of the water table elevations observed in the two catchments. These are:

i) differences in antecedent soil moisture at the individual piezometer sites;

and ii) seasonal variations in the soil structure in response to seasonal soil moisture variations at the individual piezometer sites;

However, over a longer time period, the probability of high water table elevations appears to be related, in a systematic way, to the topographic characteristics of each catchment. Considerable averaging, of the distribution of saturated conditions in time and space, must occur to account for this anomaly.

At all soil depths, the areas of subsurface saturation are larger in the pasture, than in the forest catchment. In both catchments, surface and subsurface saturation are restricted to the riparian sub-catchment units. The differences in areas of soil saturation between the two vegetation types are attributed to differences in the net rainfall regimes and to small differences in available soil moisture storage in the riparian areas of the two land use catchments. Additional effects of other soil and topographic variables may occur, but these are probably small.

An estimate of the largest possible areas of subsurface saturation shows that positive water table elevations can occur under both vegetation types. However, even in response to the largest possible event, saturated conditions at the soil surface are likely to be restricted to swampy areas adjacent to the stream channel in each land use catchment.

The hydrologic implications of the formation and distribution of saturated conditions within the land use catchments are discussed in section 6.4, following the presentation of the catchment soil permeability data.

6.3 SOIL PERMEABILITY IN THE EXPERIMENTAL CATCHMENTS

6.3.1 INTRODUCTION

The importance of soil permeability, in enabling contributions of subsurface storm flow to the stream hydrograph, has been recognised almost as long as Hortonian overland flow (see Hursh and Brater, 1941; Hursh and Hoover, 1941; Hursh, 1944). Not only does soil permeability control the rate of water entry into soils and thus apportion rainfall into surface and subsurface runoff components (Horton, 1933, 1945), it also determines directly the magnitude of subsurface and surface flow responses through the mechanisms implicit in the partial and variable source area models.

Many recent field studies in humid temperate climates have shown qualitatively the relationships between soil permeability, its variation with soil depth and hillslope runoff processes (e.g. Whipkey, 1965; Ragan, 1968; Dunne and Black, 1970b; Weyman, 1970, 1973; Arnett, 1974; Mosley, 1979, 1982). In several of these studies, subsurface flow responses have been interpreted based on traditional concepts of flow theory and the application of Darcy's (1856) law and Richards' (1931) equation. In other studies, these concepts have been rejected in favour of non-Darcian flow through macro-pores, including soil structural fissures and biogenic channels.

6.3.1.1 Macro-pores and soil permeability

The role of macro-pores in determining soil permeability have been studied previously in considerable detail. However, several problems have prevented a rigorous analysis of the interactions between macro-pore flow, soil permeability and source area hydrology (Beven and Germann, 1982). These problems include:

i) problems in defining macro-pores (Luxmoore, 1981);

ii) difficulties in determining the size and continuity of macro-pores that are hydrologically effective (e.g. Bouma *et al*., 1977, 1979);

iii) uncertainties about the flow regimes within macro-pores (e.g. Beven and Germann, 1981);

and iv) the uncertainty of the applicability of traditional concepts of flow in porous media to flow processes in heterogeneous field soils (e.g. Beven and Germann, 1982).

Rapid soil water movement in macro-pores has been observed in both saturated and unsaturated soil matrix conditions (e.g. Reynolds, 1966; Ligon *et al*., 1977; Mosley, 1982). Water entry into macro-pores during saturated soil conditions can be explained simply. However, the processes of macro-pore flow in an unsaturated soil matrix are more complex (Beven and Germann, 1982).

Most reported cases of macro-pore flow in unsaturated soils have been generated by long return period storms or from irrigation inputs (e.g. Ragan, 1968; Omoti and Wild, 1979; Topp and Davis, 1981). Dunne (1978) suggests that results of this type are of little value, in determining the processes of source area hydrology in response to most natural storm events. Nevertheless, macro-pore flow has been observed in dry clay soils, for a range of rainfall characteristics, antecedent moisture conditions, and soil structures (Bouma and Dekker, 1978).

The rationale for examining the soil permeability characteristics in the two experimental catchments has been outlined in section 6.1.

6.3.2 THE DATA SET AND DATA ANALYSIS

6.3.2.1 The data set

Estimates of soil permeability were made using a field method outlined by Talsma and Hallam (1980), based on the traditional concepts of flow through porous media. There are now recognised limitations to these concepts when applied to flow in structured field soils, but at present there are no alternative models that can be used (Beven and Germann, 1981).

Estimates of permeability were made in all the experimental cells identified in the experimental design (figure 4.3), for both summer and winter soil conditions. Three observations of soil permeability were made in each of the three soil horizons at the 12 runoff plot sites in the pasture catchment, and at the 8 runoff plot sites in the forest catchment (see figure 4.3 and 4.5). Several other co-variates were measured in the mineral soil horizons for use as explanatory variables of soil permeability (see table 6.10 and appendix B).

6.3.2.2 Data analysis

Two types of statistical data analysis were used to achieve the sub-objectives of the analyses of catchment soil permeability (see section 6.1). An analysis of variance was used to identify the possible differences in permeability between the horizon-sub-catchment unit-vegetation cells, for summer and winter conditions (see figure 4.3). In each case, the null hypothesis was that soil permeability was independent of the soil horizon, the geomorphic position within the catchment, vegetation type and season.

Strictly, analysis of variance techniques should be used only on designed experiments, to ensure adequate randomisation of the applied 'treatments'. However, this was not possible in this study, as the major 'treatments' were fixed. Regression analysis was used to identify the more important factors determining catchment soil permeability. The co-variates measured as explanatory variables of soil permeability are presented in table 6.10.

Inferences about seasonal variations of soil permeability are based on only two observation periods, one in summer and one in winter. Consequently, details of seasonal permeability variations may have been missed, but it was not practicable for measurements to be made at shorter intervals. The permeability data recorded during the summer and winter are considered to represent the range of typical soil permeabilities. Linear responses are not likely to occur between the two data sets (summer and winter observations), but have been assumed to show the direction of seasonal permeability change.

Non-normality is a feature of the raw data set. This problem was removed, by using a logarithmic transformation of observed soil permeability, as the primary permeability variable. The three permeability observations made in each soil horizon at each observation site were dependent because of spatial correlation. Thus, the mean of these three samples was used as an independent observation of the soil permeability in each soil horizon, at each site (see chapter 4).

6.3.3 PERMEABILITY VARIATION IN TIME AND SPACE

6.3.3.1 Results

Table 6.7a (pasture) and 6.7b (forest) show the seasonal and spatial variation of soil permeability for each land use catchment. The tables show the statistics of the experimental cell permeability means and the 95 % confidence (95 % C.I.) intervals of the cell mean permeability[1], expressed as a percentage of the cell mean. The descriptive statistics for the major co-variate, soil moisture, are also presented in table 6.7a and 6.7b.

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[1] The method for estimating the 95 % confidence intervals follows the procedure described by Steele and Torrie (1960). This procedure is outlined in section 6.2.1.1.2.

Note: Additional copies of the experimental design (figure 4.3) can be found in the pocket at the rear of this thesis, for use while reading these sections.

P A S T U R E

Geomorphic unit	Soil horizon	SUMMER						WINTER					
		Permeability				Soil moisture		Permeability				Soil moisture	
		n	mean	sx	% err	mean	sx	n	mean	sx	% err	mean	sx
Riparian	1	4	-5.215	0.233	14.23	21.83	3.11	4	-5.841	0.063	3.39	44.34	0.94
	2	4	-5.791	0.222	12.19	27.19	3.78	4	-6.258	0.309	15.71	34.87	3.49
	3	4	-6.130	0.263	13.64	29.78	2.90	4	-7.010	0.443	20.08	33.06	1.94
Midslope	1	4	-5.084	0.231	14.44	21.23	2.76	4	-5.419	0.160	9.39	42.40	2.61
	2	4	-5.455	0.261	15.22	28.31	3.35	4	-6.503	0.307	15.01	38.94	2.84
	3	4	-6.136	0.432	22.37	33.84	0.92	4	-7.425	0.245	10.49	40.07	1.10
Spur	1	4	-5.308	0.105	6.28	17.73	1.21	4	-5.208	0.057	3.44	40.58	3.02
	2	4	-5.243	0.170	10.28	23.78	1.78	4	-5.988	0.178	9.44	31.45	1.00
	3	4	-5.826	0.143	7.79	29.67	1.90	4	-7.005	0.105	4.77	37.37	0.96

n - number of samples
sx - standard error of the cell mean permeability
mean permeability - cell mean soil permeability ($\log_{10}$ m s^{-1})
mean soil moisture - cell mean soil moisture (% by weight)
% err - 95 % confidence interval expressed as a percentage of the cell mean permeability

Table 6.7a : Descriptive statistics for permeability and the principal co-variate soil moisture for the experimental cells in the pasture catchment

FOREST

Geomorphic unit	Soil horizon	SUMMER						WINTER					
		Permeability				Soil moisture		Permeability				Soil moisture	
Riparian		n	mean	sx	% err	mean	sx	n	mean	sx	% err	mean	sx
	1	2	-3.099	0.115	4.80	*	*	2	-3.243	0.327	128.11	*	*
	2	4	-5.837	0.195	10.60	30.00	1.88	4	-6.079	0.166	8.69	38.09	1.19
	3	4	-6.788	0.239	11.19	33.63	1.64	4	-7.341	0.251	10.86	36.87	1.45

Geomorphic unit	Soil horizon	Permeability				Soil moisture		Permeability				Soil moisture	
Midslope		n	mean	sx	% err	mean	sx	n	mean	sx	% err	mean	sx
	1	2	-2.912	0.261	113.74	*	*	2	-3.236	0.193	75.92	*	*
	2	2	-4.880	0.257	66.82	28.70	0.70	2	-5.771	0.093	20.56	35.32	0.66
	3	2	-5.572	0.107	24.26	31.04	0.28	2	-7.350	0.049	8.38	34.01	0.74

Geomorphic unit	Soil horizon	Permeability				Soil moisture		Permeability				Soil moisture	
Spur		n	mean	sx	% err	mean	sx	n	mean	sx	% err	mean	sx
	1	2	-2.880	0.206	90.75	*	*	2	-3.254	0.091	35.47	*	*
	2	2	-5.254	0.174	10.28	23.78	2.52	2	-5.697	0.016	9.44	31.45	1.41
	3	2	-6.601	0.250	48.04	33.59	1.34	2	-7.696	0.349	57.70	36.63	1.07

n - number of samples
sx - standard error of the cell mean permeability
mean permeability - cell mean soil permeability ($\log_{10}$ m s^{-1})
mean soil moisture - cell mean soil moisture (% by weight)
% err - 95 % confidence interval expressed as a percentage of the cell mean permeability

Table 6.7b : Descriptive statistics for permeability and the principal co-variate soil moisture for the experimental cells in the forest catchment

Soil permeability was estimated to within the required precision in all, but two, experimental cells in the pasture catchment (i.e. +/- 20 % of the transformed cell mean permeability; see chapter 4). In the forest, it was not possible to estimate mean permeability to within the required precision for several experimental cells, because of the smaller number of observation sites in these catchment areas. Hydrologically important differences in soil permeability may not be detectable between these experimental cells.

Figure 6.14 shows the data presented in table 6.7a and 6.7b in graphical form. Soil permeability varies seasonally in all experimental cells. Compared with observations made during summer, soil permeabilities are typically 3 - 5 times lower in winter (increased moisture content). However, in the pasture-spur-A horizon cell, the seasonal trend is reversed (figure 6.14). This apparent anomaly may be caused by the surface soils becoming water repellent, by mechanisms similar to those described by McGhie and Posner (1981). Permeability variations with season and soil horizon are likely to have an important influence on the rainfall-runoff regime in each land use catchment.

Large differences in soil permeability also occur between soil horizons. Soil permeability is related inversely to horizon depth and decreases by about one half an order of magnitude in each horizon in the mineral soil. However, a larger permeability difference is apparent between the organic litter horizon and the upper mineral soil horizon in the forest catchment.

Soil permeability differences between the two vegetation types appear to be restricted to the surface soil horizons in each land use catchment. Only small, inconsistent, differences in soil permeability occur between the respective sub-catchment unit pairs in the two land use catchments (c.f. table 6.7a and 6.7b and see figure 6.14).

A parametric analysis of variance was completed for the four main grouping variables; vegetation, sub-catchment unit (stratum), soil

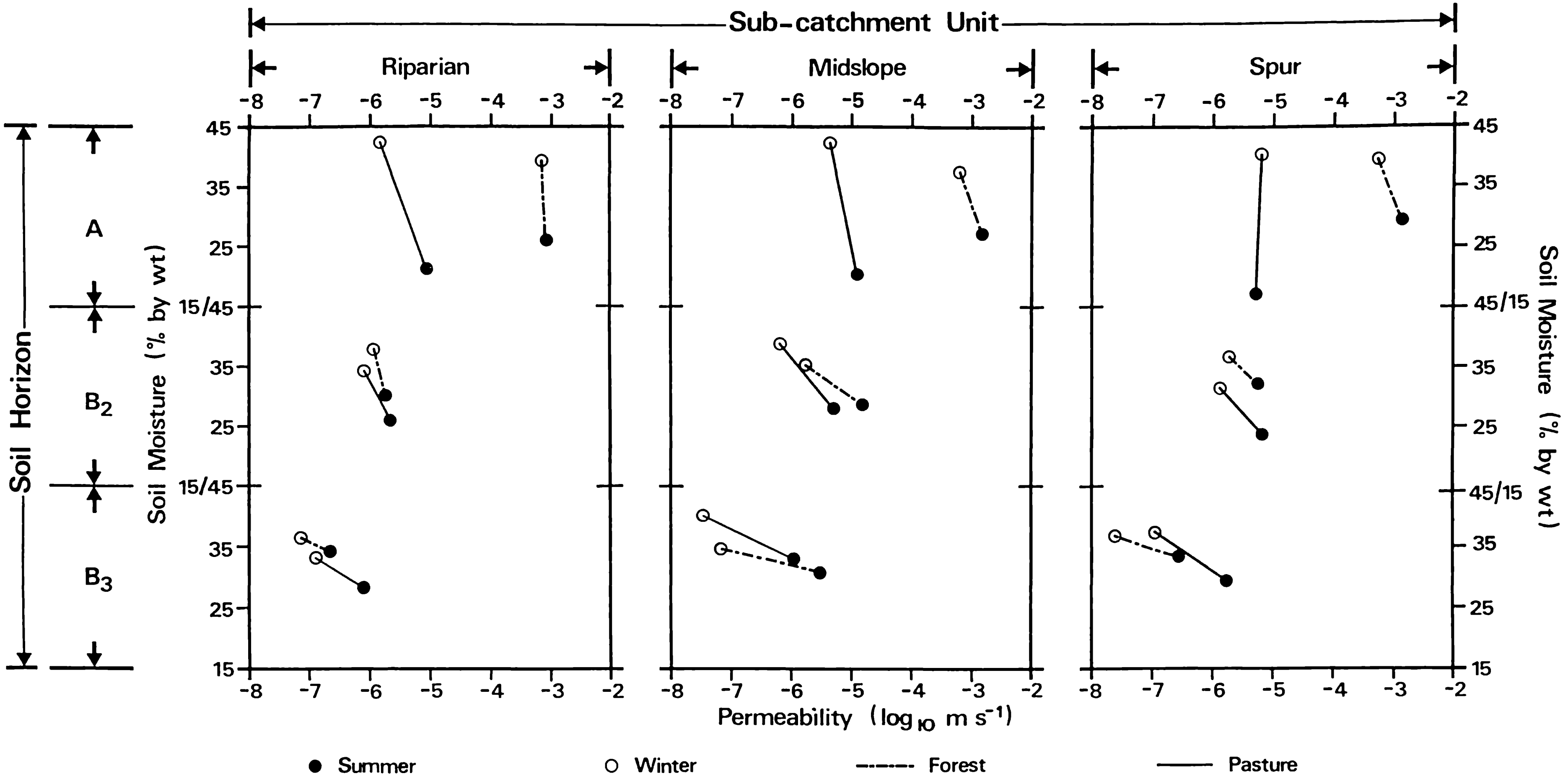

Figure 6.14 : Permeability vs soil moisture : Experimental cell means, sub-catchment unit by soil horizon by vegetation by season

horizon and season. Table 6.8 shows that significant test statistics were obtained for all the four grouping variables. This implies that soil permeability differs beyond chance in response to each of the grouping variables. The hydrologic implications of these results are considered in section 6.4.

The relationships between the grouping variables and soil permeability are not simple and linear. Instead, they are complicated by first order interactions between vegetation and soil horizon, and between season and soil horizon (p = 0.01; table 6.8).

source	sum of squares	degrees of freedom	mean square	f	tail probability
mean	17022.29	1	17022.29	15950.49	0.00 **
vege	75.65	1	75.65	70.88	0.00 **
stratum	7.15	2	3.58	3.35	0.04 *
horizon	571.93	2	285.97	267.96	0.00 **
season	64.31	1	64.31	60.26	0.00 **
v.st	6.41	2	3.21	3.01	0.06
v.h	156.92	2	78.46	73.52	0.00 **
v.se	0.17	1	0.17	0.16	0.69
st.h	3.01	4	0.75	0.71	0.59
st.se	5.14	2	2.57	2.41	0.10
h.se	16.30	2	8.15	7.64	0.00 **
v.st.h	5.61	4	1.40	1.31	0.27
v.st.se	1.44	2	0.72	0.68	0.51
v.h.se	0.45	2	0.22	0.21	0.81
st.h.se	3.49	4	0.87	0.82	0.52
v.st.h.se	1.78	4	0.44	0.42	0.80
error	85.37	80	1.07		

* - significant at p = 0.05   ** - significant at p = 0.01
v - vegetation   st - stratum (sub-catchment unit)
h - horizon   se - season

Table 6.8 : Analysis of variance of the catchment permeability data for all grouping variables

Separate analyses of variance were completed for the individual soil horizons, to examine further the effects of the main grouping variables; vegetation, sub-catchment unit and season (table 6.9 a,b,c,). The causes of the first order interactions can be identified from these analyses.

source	sum of squares	degrees of freedom	mean square	f	tail probability
mean	3028.25	1	3028.25	5793.30	0.00 **
vege	213.16	1	213.16	407.80	0.00 **
stratum	1.31	2	0.66	1.26	0.30
season	3.42	1	3.42	6.54	0.02 *
v.st	0.28	2	0.14	0.27	0.77
v.se	0.01	1	0.01	0.00	0.98
st.se	0.48	2	0.24	0.46	0.64
v.st.se	1.61	2	0.81	1.54	0.23
error	12.55	24	0.52		

* - significant at p = 0.05   ** - significant at p = 0.01
v - vegetation   st - stratum (sub-catchment unit)
se - season

Table 6.9a : Analysis of variance of horizon 1 soil permeability for the vegetation, stratum and season variables

source	sum of squares	degrees of freedom	mean square	f	tail probability
mean	6265.80	1	6265.80	6128.98	0.00 **
vege	3.92	1	3.92	3.84	0.06
stratum	7.80	2	3.90	3.81	0.03 *
season	19.50	1	19.50	19.08	0.00 **
v.st	3.18	2	1.59	1.56	0.23
v.se	0.62	1	0.62	0.61	0.44
st.se	3.21	2	1.61	1.57	0.23
v.st.se	0.04	2	0.02	0.02	0.98
error	28.63	28	1.02		

abbreviations as table 6.9a

Table 6.9b : Analysis of variance of horizon 2 permeability for the vegetation, stratum and season variables

source	sum of squares	degrees of freedom	mean square	f	tail probability
mean	8670.46	1	8670.46	5491.92	0.00 **
vege	4.37	1	4.37	2.77	0.11
stratum	1.38	2	0.69	0.44	0.65
season	60.82	1	60.82	38.52	0.00 **
v.st	8.85	2	4.43	2.80	0.10
v.se	0.01	1	0.01	0.00	0.94
st.se	5.74	2	2.87	1.82	0.18
v.st.se	1.43	2	0.71	0.45	0.64
error	44.21	28	1.58		

abbreviations as table 6.9a

Table 6.9c : Analysis of variance of horizon 3 permeability for the vegetation, stratum and season variables

6.3.3.2 Discussion

The analyses of variance for the individual soil horizons show that statistically significant differences in soil permeability were detected between the two vegetation types only in the surface soil horizon ($p = 0.01$). In this soil horizon, the forest organic litter horizon is 100 to 1000 times more permeable than the 'A' horizon in the pasture catchment. With the data collected, no differences in soil permeability could be detected between the B_2 and B_3 horizons of the two land use catchments ($p = 0.05$).

Forest soils have been considered traditionally to be more permeable than pasture soils, principally because of an increased organic content and a greater number of root channels, compared with similar soils under pasture vegetation. These factors are summarised in greater detail by Selby (1967a). The large differences between the permeability of the forest litter horizon and the pasture 'A' horizon verify the traditionally held concepts about the differences in soil physical properties of these two vegetation types (e.g. Kitteridge, 1948; Storey et al., 1964). However, in this study, the results observed for the B_2 and B_3 soil horizons do not support the traditionally held concepts for these two forms of land use. Instead, the results support the studies by Gradwell (1960) and McDonald (1961). These researchers showed that most of the differences in soil physical properties found between forest and pasture vegetation are restricted to the surface soil horizons.

The first order interactions, between the seasonal variations of soil permeability and the individual soil horizons, are less obvious than the interactions between soil horizon and vegetation type. In all soil horizons, different soil permeabilities were observed for summer and winter soil conditions (see table 6.9 a,b,c). Instead, the interactions appear to be caused by the different relationship between soil permeability and season moisture change found in each horizon (see figure 6.14).

The only differences in soil permeability that are attributable to geomorphic position (sub-catchment unit (stratum)) occur in the B_2 soil horizon ($p = 0.05$) (table 6.9b). In each catchment, soil permeabilities of the B_2 horizon tend to increase in upslope positions. Exceptionally large soil permeabilities were observed in the forest midslope cell during summer: these estimates appear anomalously large.

All the results discussed above have important implications for the interpretation of the hillslope runoff regimes in each land use catchment. These implications are considered in detail in section 6.4.

6.3.4 DETERMINANTS OF SOIL PERMEABILITY IN THE LAND USE CATCHMENTS

6.3.4.1 Forest organic litter horizon

Seasonal variations of soil permeability were observed in the forest organic litter horizon in all sub-catchment units (see figure 6.14). However, statistically significant differences could be detected only in the midslope and spur sub-catchment units because of the small number of permeability observations made in these experimental calls (($p = 0.05$); 2 tailed 't' test). In all the sub-catchment units, the seasonal permeability variations of the forest litter layer are hydrologically important, in terms of the untransformed permeability data.

The causes of the seasonal permeability variations observed in this horizon could not be established because no independent variables were determined with the permeability measurements made at these sites. No reports of seasonal permeability variations in forest organic litter horizons were found in the literature surveyed. However, considerable spatial variability of soil hydraulic properties have been observed in other recent studies of forest floor hydrology (e.g. Webster, 1977; Bonell and Gilmour, 1978; Talsma and Hallam, 1980; Mosley, 1982).

Seasonal variations in the morphology of the forest litter horizon were observed during the 2 year period of data collection. Changes in horizon morphology may cause the observed seasonal variation of permeability in this soil horizon.

An increase in apparent bulk density and aggregation of the litter horizon was observed during wet, winter conditions. This change can be explained by an increase in soil moisture incorporated in the decaying organic detritus and in the organic matrix. An increase in soil moisture should cause the following changes in the morphology of the forest litter layer:

i) an increase in capillary tension forces;

ii) an increase in bulk density;

and iii) a decrease in porosity and permeability.

During summer, a decrease in soil moisture appears to cause these trends to reverse. In addition, differential drying of decaying leaf surfaces appears to cause the leaves to curl and so cause an increase in horizon macro-porosity and permeability.

The smallest seasonal differences in the permeability of the forest litter horizon were observed in the riparian sub-catchment unit, while the largest differences were observed in the upslope catchment areas. These observations can be explained by the mechanisms described above and by the seasonal soil moisture regimes observed in each sub-catchment unit. The higher average soil moisture contents of the riparian sub-catchment unit prevent the forest litter horizon from drying to the same extent as in the upslope catchment areas. Thus, the changes in soil profile morphology tend to be smaller in the riparian areas than in the upslope catchment areas.

6.3.4.2 Mineral soil horizons

The controls of permeability within the mineral soil of the experimental catchments were examined by a correlation analysis, using soil permeability and several independent variables estimated at each observation site. Linear regression analysis was also used to establish relationships between soil permeability and the independent variables. A list of the independent variables determined at each observation site is presented in table 6.10. Several of the variables listed in table 6.10 are discrete (e.g. the main grouping variables used in the analyses of variance), while others are continuous variables that were determined with the permeability observations.

6.3.4.2.1 Results

Table 6.10 shows the results of the correlation analysis. Significant correlations were found between soil permeability and all the major grouping variables, except sub-catchment unit (stratum). The size and direction (positive or negative) of the correlations are consistent with the results of the analyses of variance presented in table 6.8 and 6.9. Of the remaining co-variates, only the 'soil moisture' variables are correlated significantly (negatively) with permeability (table 6.10). The transformed 'soil moisture' variable describes the relationships between soil moisture and permeability better than the untransformed soil moisture variable.

Some of the poor correlations between permeability and the other independent variables can be explained simply. The particle size variables are more likely to explain permeability variations in response to soil structural changes in the catchment soils, instead of the absolute permeability of a site. However, neither aspect, nor slope angle are correlated significantly with soil permeability. This result is unexpected, because several studies have shown that both these variables influence the seasonal soil moisture regime and other

Variable	log k	log mst	moist	slope	aspect	clay	silt	sand	vege	stratum	horizon	season
log k	1.00											
log mst	-0.29**	1.00										
moist	-0.27**	0.99**	1.00									
slope	-0.10	-0.17	-0.17	1.00								
aspect	0.10	0.11	0.11	0.25*	1.00							
clay	0.11	-0.10	-0.07	-0.65**	-0.35**	1.00						
silt	-0.00	-0.18	-0.16	0.42**	0.12	-0.31**	1.00					
sand	-0.12	0.21*	0.16	0.46**	0.31**	-0.90**	-0.09	1.00				
vege	-0.21*	0.18	0.13	0.07	-	0.02	0.20*	-0.06	1.00			
stratum	0.17	-0.09	-0.09	0.59**	-	-0.56**	0.37**	0.43**	-	1.00		
horizon	-0.66**	0.24*	0.15	-	-	-0.35**	-0.13	0.43**	-	-	1.00	
season	-0.43**	0.63**	0.66**	-	-	-	-	-	-	-	-	1.00

* - significant (p = 0.05)

** - significant (p = 0.01)

Variable names:

log k - logarithm (base 10) of soil permeability
moist - sample soil moisture (% by weight)
aspect - sample site slope direction (deg. M)
silt - % silt size particles at the sample site
vege - site vegetation
horizon - soil horizon

log mst - logarithm (base 10) of sample soil moisture
slope - sample site slope angle (degrees)
clay - % clay size particles at the sample site
sand - % sand size particles at the sample site
stratum - sub-catchment experimental unit
season - summer or winter

Table 6.10 : Correlation matrix for the catchment soil permeability data and co-variates

Regression equation	r^2	Sy.x	F
Step 1 Permeability = -4.513 + -0.715 x horizon	0.43	0.636	77.82 **
Step 2 Permeability = -3.430 + -0.715 x horizon + -0.721 x season	0.61	0.524	81.93 **
Step 3 Permeability = -5.722 + -0.781 x horizon + -0.991 x season + 1.893 x log mst	0.64	0.501	63.07 **
Step 4 Permeability = -6.253 + -0.780 x horizon + -1.015 x season + 2.062 x log mst + 0.162 x stratum	0.67	0.485	53.49 **
Step 5 Permeability = -5.368 + -0.788 x horizon + -0.985 x season + 1.853 x log mst + 0.205 x stratum + -0.025 silt	0.68	0.478	44.09 **

** - significant (p = 0.01)

r^2 - coefficient of determination

Sy.x - standard error of the estimate

All variables included in the regression are significant (p = 0.01) except silt (p = 0.05)

Variable names are the same as in table 6.10

Units as in table 6.7 and 6.10

Table 6.11 : Stepwise linear regression equations for the catchment soil permeability data

soil forming processes, that influence the spatial variability of soil permeability within catchments (e.g. Gillingham, 1974; Gillingham and Bell, 1977; Dunin and Aston, 1981).

The correlation matrix aids the selection of variables suitable for use in the regression analysis. Co-variates with highly significant correlations should be avoided to prevent the development of an unstable model structure (Chatterjee and Price, 1977). The untransformed variable 'soil moisture', and the variable 'sand' were removed immediately from the variables available for selection in the regression model. Stepwise linear regression analysis was used to establish relationships between soil permeability and the remaining independent variables. The development of a stable model structure followed the 'robust' procedures described by Hocking (1976).

Table 6.11 shows the results of the stepwise linear regression analyses. Figure 6.15 shows a comparison of the observed permeability data with values predicted from the regression model. With the exclusion of vegetation type, the major grouping variables are shown to be important in explaining soil permeability within each catchment (table 6.11). Two additional variables are also included in the regression model: logarithmically transformed 'soil moisture' and 'silt' content. 'Soil horizon', 'season' and 'silt content' are related negatively with permeability in the regression model, while 'soil moisture' and 'sub-catchment unit (stratum)' are related positively.

6.3.4.2.2 Discussion

Both the correlation analysis (table 6.10) and the regression analysis (table 6.11) show that complex relationships exist, between soil permeability and the soil, topographic and vegetation characteristics of the two land use catchments. The interpretation of these relationships is difficult because many of the variables entered in the regression model have similar relationships with soil

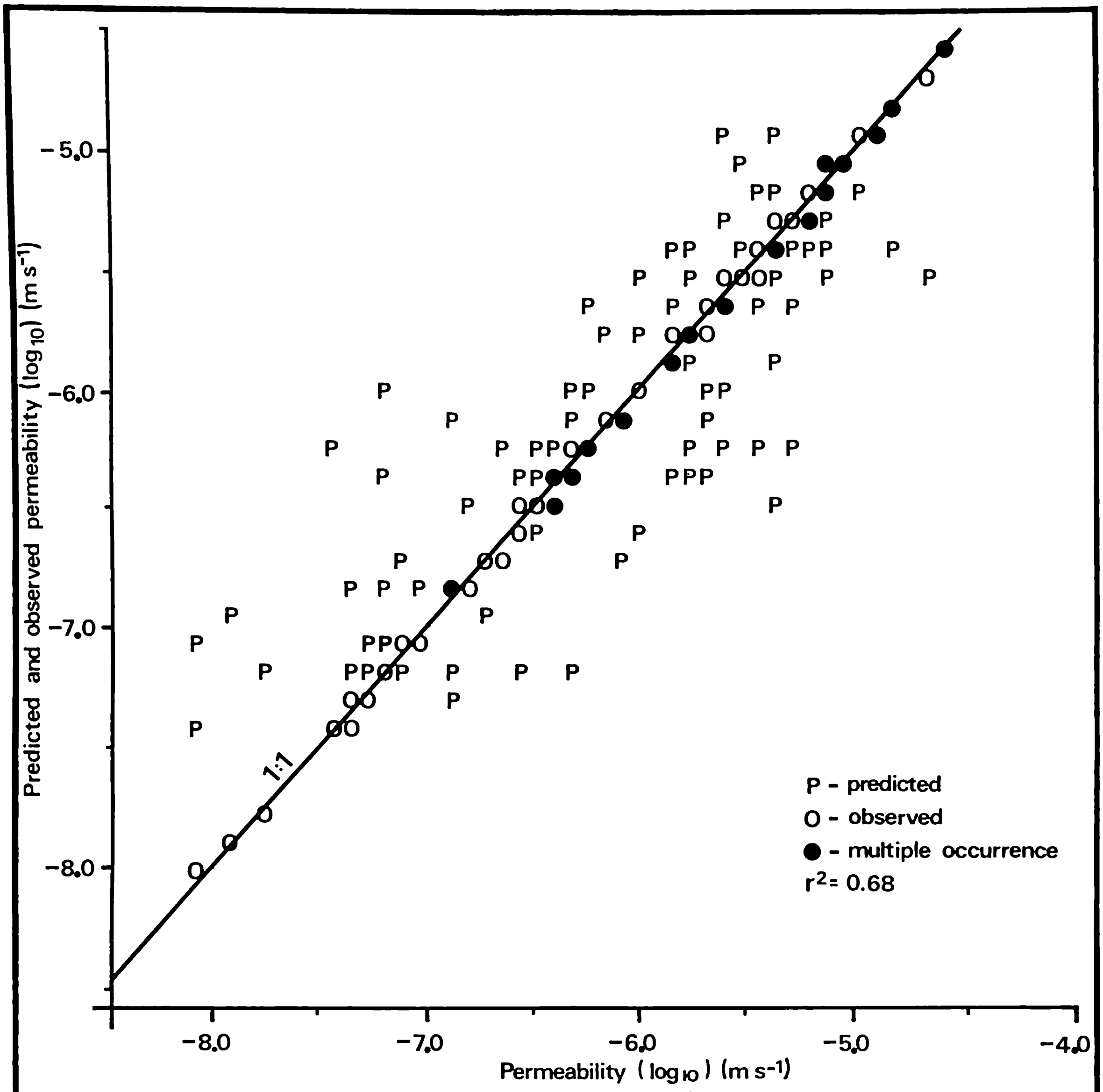

Figure 6.15 Predicted and observed values of permeability ($\log_{10}$) derived from the stepwise regression model presented in table 6.11

permeability.

Table 6.10 shows that all variables entered in the regression equation (table 6.11) are correlated, either directly or indirectly, with soil moisture and a measure of particle size. The importance of these two variables suggests that soil permeability variations in the two land use catchments may be related to variations in soil structure, that are in turn related to spatial and seasonal variations of soil moisture.

The importance of relationships between soil structure and soil permeability have been suggested in earlier land use studies in the

Upper Mangawhara Valley (Parker, 1978; Rogers, 1978) and in other catchments with clay-rich soils (e.g. Blake et al., 1973; Ritchie and Adams, 1974; Arnett, 1976; Bouma and Dekker, 1978; Bouma, 1980). Variations in the soil structure are caused by the contraction and expansion of the soil matrix in response to soil moisture changes (Blake et al, 1973). Soil structural changes of this type result usually in small, but hydrologically important changes in the soil macro-porosity (Beven and Germann, 1982). The formation, and expansion and contraction of shrinkage cracks are also important in determining variations of soil permeability. Soil structural changes of this type can cause large changes in soil permeability (Beven and Germann, 1982), although accounting only for a small proportion of total porosity (Bouma et al., 1977, 1979). The relationships between soil permeability, soil moisture and soil particle size are considered in the following discussion.

By itself, soil moisture is correlated negatively with soil permeability (see the correlation matrix, table 6.10). Indirectly, soil moisture is correlated negatively with soil permeability in the first two variables entered in the regression equation (soil horizon and season) (table 6.11). The negative relationships, between soil permeability and soil moisture, suggest that changes in soil structure are important in determining the seasonal and spatial variations of soil permeability within the land use catchments. Figure 6.14 shows different relationships between soil moisture and soil permeability in each soil horizon. The relationships between soil moisture, soil structure and soil permeability are dependent on the general morphology of each soil horizon. The relationships between these three soil properties have been discussed in detail by Whipkey and Krikby (1978) and are not repeated here.

The positive relationship between soil moisture and permeability shown in the regression model (table 6.11) appears to conflict with the negative relationship between these two variables shown in the correlation analysis (table 6.10). These two contrasting observations suggest that, the usual positive relationship between soil permeability and soil moisture occurs in the catchment soils at a given time (season), but over a year, these positive relationships are dominated by the large seasonal permeability changes associated with soil structural changes.

The relationships between soil particle size and the hydrologically important aspects of soil structure are well established (e.g. Arnett, 1974, 1976; Bouma, 1980). These studies suggest that hydrologically important changes in soil structure depend on seasonal and spatial soil moisture variations and the type and amount of clay. Consequently, it is unclear why the variable 'silt' is included in the regression equation, instead of the variable 'clay'. Despite this uncertainty, the clay content of the catchment soils is large enough to influence the processes of soil water movement at all sites in the land use catchments (see Arnett, 1974, 1976).

The catchment soils have considerable potential for volume change in response to soil moisture variation. Kaolinite and weakly swelling assemblages of vermiculite-halloysite-illite have been identified in the yellow-brown earth that predominates in the pasture land use catchment (Parker, 1978; Rogers, 1978; Wilson, 1980). Assemblages of halloysite and vermiculite clays have been identified for the yellow-brown earth formed on pre-weathered greywacke, that occurs at most sites in the forest catchment (Wilson, 1980). These soils have a tendency for moderate expansion and contraction, with measured volume changes up to 20 % being recorded for soils equivalent to B_3 horizons in the pasture catchment (Rogers, 1978).

Figure 6.14 shows that, in the B_2 and B_3 mineral soil horizons, the relationships between soil permeability and soil moisture appear independent of both geomorphic position and vegetation type. This occurs despite the large variations in soil particle size distribution between the experimental cells and the seasonal moisture regimes in the two land use catchments (see appendix G and figure 6.5 a,b,c). This observation suggests that interactions occur, in both land use catchments, between:

i) the seasonal moisture variations in each land use catchment;

ii) the proportion of clay sized particles in the catchment soils;

and iii) the predominant clay mineralogies of the soils in each land use catchment.

For example; compared with the pasture midslope and spur mineral soil horizons, soil permeability variations in the forest appear to be determined by smaller soil moisture variations, and larger contents of a clay type with a greater likelihood for volume change. The net effect of these interactions can explain partially the similar seasonal permeability variations observed in the mineral soils of the two land use catchments (figure 6.14).

The correlation and regression analyses provide only indirect evidence to suggest the importance of soil structure in determining soil permeability variations within the two catchments. Field observations in the two catchments provided direct evidence of the relationships between soil structure, soil moisture and soil permeability. These relationships are discussed below.

Seasonal and spatial variations of soil structure were observed in the two experimental catchments, in a pattern that can be explained by the observed seasonal and spatial variations of soil moisture. Seasonal variation in the size and spatial distribution of dessication cracks was the most obvious indication of variations in soil structure.

Dessication cracks were observed to extend commonly to depths of 0.7 m; extending continuously from the soil surface to within the B3 horizon. Dessication cracks were observed most frequently in the midslope and spur sub-catchment units in the pasture land use catchment. Fewer dessication cracks were found in riparian areas of the pasture catchment or in the forest soils.

Plate 6.1 shows an example of a dessication crack. Plate 6.1 was taken at a freshly exposed soil pit in a riparian slope unit, when the soil was near field capacity. Accumulations of organic material and stainings and coatings on the ped surfaces are visible to depths of 0.5 m. The presence of these features shows that water flows preferentially through dessication cracks and other large structural features of the soil matrix.

More detailed inferences about the seasonal variations of flow processes can be made from evidence presented in plate 6.2 and plate 6.3. Plate 6.2 shows the arrangement of large, structurally isolated prisms in the B_2 horizon of a dry, but freshly exposed soil pit, at a midslope position in the pasture catchment. Plate 6.3 shows a soil prism that was removed to show the structural features in plate 6.2. The reddish-brown ferro-organic cutans (arrowed (A) plate 6.2) and coatings on the prism (plate 6.3) are evidence that intermittent soil water flow occurs down in these fissures and that oxidising conditions persist for much of the year. Accumulations of roots on the faces of soil prisms and in large fissures are additional evidence that these discontinuities persist throughout the year (plate 6.2 and 6.3).

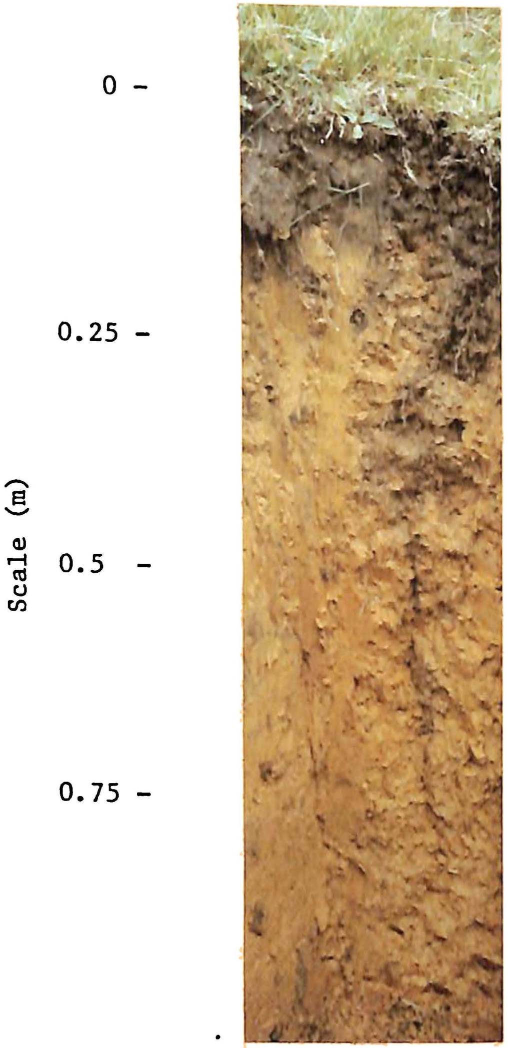

Plate 6.1 : A dessication crack in a freshly exposed soil pit showing accumulations of organic material and staining on the ped surfaces

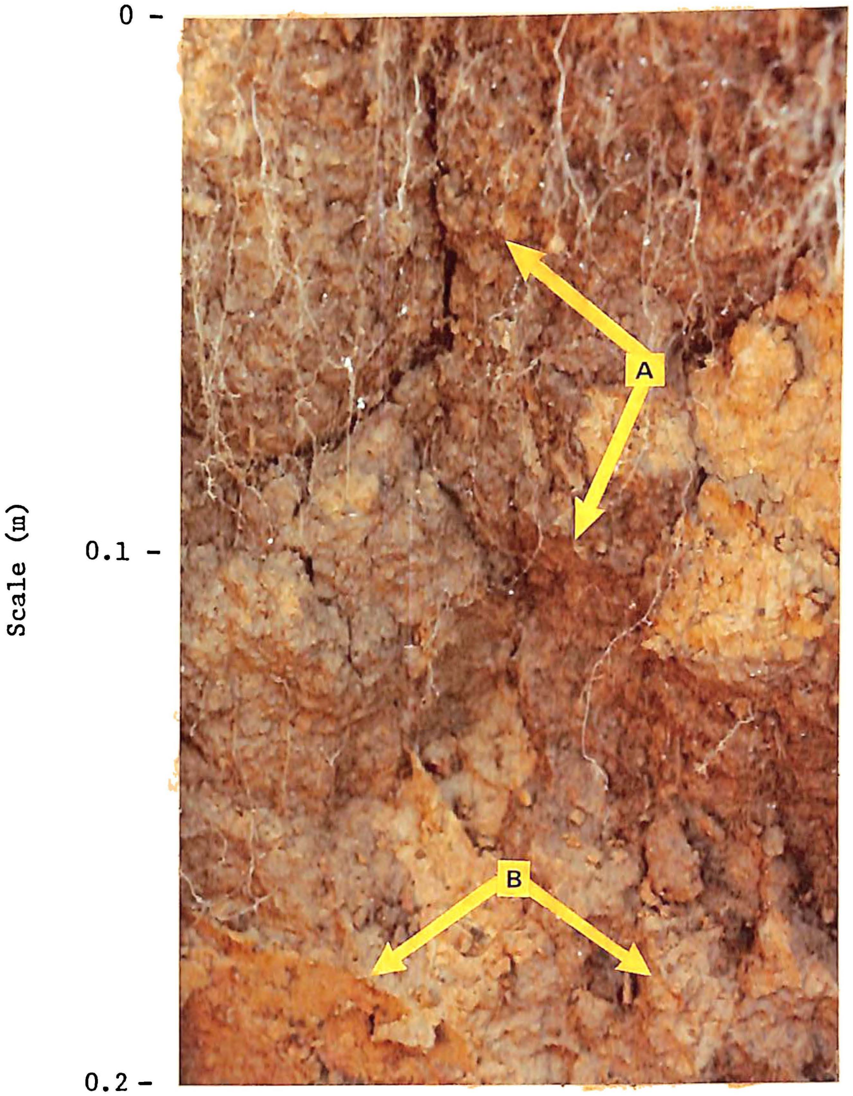

Plate 6.2 : The arrangement of large structurally isolated prisms in the B_2 soil horizon (c.f. plate 6.3). Ferro-organic cutans and evidence of gley conditions are arrowed

Plate 6.3 : The soil prism that was removed to show the features in plate 6.2. Note the roots and organic coatings on the prism surface

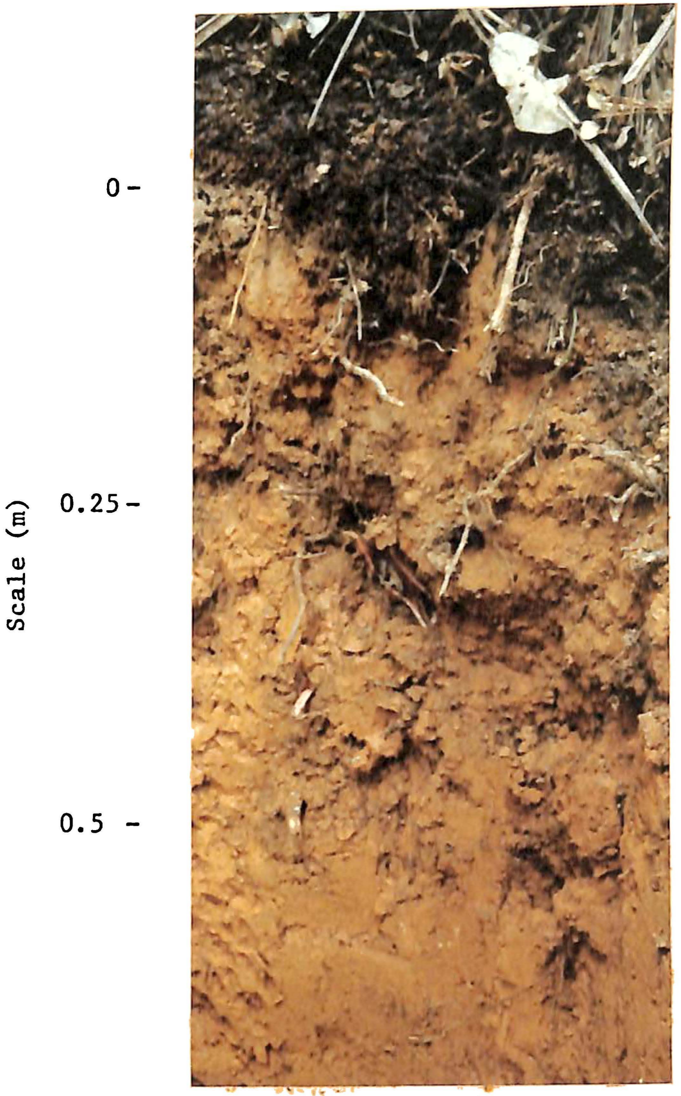

Plate 6.4 : Numerous root channels occur in the upper 0.5 m in the forest soils, although they are less structured than the soil in the pasture

The presence of grey staining is evidence of gley conditions in the soil profile, particularly where it occurs adjacent to reddish-brown ferric deposits (arrowed (B) plate 6.2). The presence of gley soil conditions suggests that the soil matrix expands at times during the year and causes the structural discontinuities to diminish. When this occurs, macro-pore flow is reduced and anaerobic soil conditions are enhanced in the remaining narrow fissures. The absence of gley morphology within the prism matrix shows that the diminished structural fissures are still preferred flow pathways, in an otherwise unsaturated soil. Several dye tests were completed with the permeability observations made during winter. These tests showed qualitatively that structural fissures are preferred flow pathways, even when they are appear fully closed.

The importance of preferential flow paths, through decayed tree roots and other biogenic channels, have been reported in many studies of source area hydrology completed in forest environments (e.g. Aubertin, 1971; Ehlers, 1975; Webster, 1977; Mosley, 1982). Flow velocities of 3 to 4.2×10^{-3} m s^{-1} have been observed through this type of macro-pore (Mosley, 1982).

Plate 6.4 shows the concentration of roots in the upper 0.5 m soil, (in a midslope position in the forest catchment) and the presence of numerous partially decayed root channels. Few roots occur below 0.5 m, but the high flow velocities that can occur in decayed root channels, are likely to be important in determining the processes of water movement in the upper mineral soil horizons in the forest catchment.

The presence of roots in the upper mineral soil horizons in the forest land use catchment should mean that these soil horizons are more permeable than those in similar positions in the pasture catchment. However, no hydrologically important differences in the soil permeabilities of these soil horizons were detected between the two land use catchments (see table 6.9b and 6.9c). Field observations show that the pasture soils tend to be more structured than those in the forest (see soil profile descriptions in chapter 3 and compare plate 6.4 and 6.2). Thus, the soil permeability data suggest that the high flow velocities that can occur in biogenic fissures in the forest soils are similar to the flow rates that occur in the more fissured soils of the pasture land use catchment.

No data were obtained during the study, to show whether the increased structural development in the pasture soils has occurred as a consequence of de-afforestation, or whether this feature has been caused by differences in other properties of the soil types in the two land use catchments. However, Selby (1967a) has suggested the greater degree of soil structural development under pasture may be enhanced by the greater seasonal soil moisture variation characteristic of this form of land use, compared with similar sites under forest vegetation.

The preceding discussion shows the importance of soil structure in determining soil permeability in the two land use catchments. The importance of water flow in macro-pores is also suggested. These factors are considered in the next section.

6.3.4.2.3 Occurrence of macro-pore flow

Considerable uncertainity exists about the conditions required to generate apedal flow in unsaturated soils (Bouma and Dekker, 1978; Beven and Germann, 1982). A review of the quantitative studies of macro-pore flow suggests that the initiation of macro-pore flow in unsaturated soils can occur during rainfall intensities as low as 0.7 to 1.5 mm h^{-1}. More often, however, macro-pore flow is induced by rainfall intensities of 10 mm h^{-1}, for periods of greater than one hour (Bouma and Dekker, 1978; Topp and Davis, 1981). Intensities up to 50 mm h^{-1} are required to generate macro-pore flow to depths of 0.8 - 1.0 m (Bouma and Dekker, 1978).

Macro-pore flow was observed occasionally in the experimental catchments during large storms. However, it was not possible to collect data on the soil and rainfall conditions required to generate macro-pore flow in unsaturated soil matrix conditions. Nevertheless, inferences, about the likelihood of macro-pore flow in the experimental catchments, can be made from data presented in the studies of macro-pore flow cited above.

The intensity-duration characteristics of the catchment rainfall show that macro-pore flow is probably rare in both catchments, assuming the permeabilities of the surface mineral soils in each land use catchment and a rainfall input similar to that suggested by Topp and Davis (1981) (figure 5.6 and table 6.12).

When the soil is dry, the rainfall intensities (figure 5.6 and 5.7) seldom exceed the soil infiltration capacities in either catchment, for durations long enough to provide a storm depth capable of inducing extensive macro-pore flow (i.e. for 1 % of the time in the pasture and for 3 % of the time in the forest (assuming interception losses)). During wet soil conditions, the soil structure is less conducive for macro-pore flow (i.e. fewer apedal fissures and larger matrix diffusivities), but the antecedent soil moisture conditions are more suitable for macro-pore flow (i.e. less available soil moisture storage in the macro-pore and micro-pore domains). Even so, storm characteristics suitable to generate macro-pore flow occur still infrequently (i.e. for 3 % of the time in the pasture and for 10 % of the time in the forest).

This evidence suggests that the rainfall pattern of the Hapuakohe Range is seldom adequate to produce extensive macro-pore flow in unsaturated soil conditions.

Note: in the preceding analyses it is assumed that permeabilities of the litter horizon do not restrict the development of saturated conditions above the forest mineral soils.

This evidence thus supports Dunne's (1978) assertion, that non-Darcian flow mechanisms are uncommon in catchments in humid temperate climates. Macro-pore flow in the experimental catchments is more likely to be restricted to discontinuous areas of completely saturated soil. Discontinuous subsurface saturation may form above the comparatively impermeable saprolite, by mechanisms similar to those observed by Mosley (1982). However, large structural fissures tend not to occur in the wetter riparian areas. Thus, the preceding analysis suggests that the likelihood of macro-pore flow in the land use catchments is probably small.

The results of this section conflict with the field evidence of macro-pore flow presented in section 6.3.4.2. Field observations suggest macro-pore flow may occur under less restrictive conditions, particularly in the pasture land use catchment during the summer months. It is possible that the permeability measurements do not describe adequately the permeability conditions of the soil surface. Macro-pore flow may develop more regularly than suggested, if the permeability of the surface soil is lower than estimated in this study. Alternatively, the field evidence presented in section 6.3.4.2 may develop in response to only infrequent occurrences of macro-pore flow. The additional evidence required to investigate these two hypotheses was not obtained as part of the overall study.

6.3.5 SUMMARY

Results of the permeability analyses have important implications for the processes of hillslope runoff in the two land use catchments.

The following conclusions can be made from the analyses of soil permeability.

i) In both land use catchments, a pronounced seasonal change in permeability occurs in the three soil horizons examined, including the forest organic litter layer.

ii) In both land use catchments, soil permeability decreases with soil depth by about half an order of magnitude per horizon in the mineral soils. However a larger permeability difference was apparent between the forest organic litter horizon and the upper mineral soil horizon.

iii) Differences in soil permeability between the two forms of land use are restricted to the surface soil horizons. The organic litter horizon in the forest catchment is about 100 to 1000 times more permeable that the 'A' horizon in the pasture catchment. These differences are caused by the obvious differences in soil horizon morphology. With the data available, no differences in the permeability of the B_2 and B_3 soil horizons could be detected between the two land use catchments.

iv) Soil permeability varies with geomorphic position (sub-catchment unit) in each land use catchment. However, these differences are consistent only in the B_2 soil horizon. In both land use catchments, the B_2 soil horizon is generally more permeable in the midslope and spur sub-catchment units, than in the riparian catchment areas.

Relationships were examined between the soil permeability of the mineral soil horizons and several co-variates that described the soil, topographic and vegetation characteristics of the land use catchments.

Note: the permeability measurements made within the experimental cells measure the maximum potential for saturated macro-pore flow in unsaturated soil conditions. No satisfactory models were found in the literature surveyed that could be used in place of Darcian flow theory to describe water flow in structured field soils. The estimates of permeability derived in this study are, however, similar to those expected for clay-rich soils.

In the mineral soil horizons, soil permeability appears to be determined by only those variables that interact in some way with the soil moisture regime and the particle size distribution of the catchment soils. The importance of these variables suggests that interactions, between the clay fraction and soil moisture, determine the seasonal and spatial variations of soil permeability in both catchments. Field observations made during this study support this hypothesis.

In the mineral soil horizons, the seasonal and spatial variations of soil permeability can be explained by variations in soil structure. These, in turn, appear to be induced by the spatial and seasonal variations of soil moisture observed in the two land use catchments. Spatial and seasonal soil moisture variations can influence soil structure by causing the expansion and contraction of the soil matrix, that is reflected in small, but hydrologically important changes in the soil macro-porosity. The presence of dessication cracks also appears important in determining the spatial and seasonal variations in soil permeability in the two land use catchments. Dessication cracks form most readily in the midslope and spur sub-catchment units in the pasture catchment. The presence of root channels and other structural fissures appear to be important factors in determining soil permeability in the B_2 soil horizon in the forest catchment.

The absence of large differences between the permeabilities of the lower mineral soil horizons (B_2 and B_3) in the two land use catchments can be explained by several factors.

The pasture soils exhibit a greater structural development compared with the soils in the forest. This suggests that the pasture soils should be more permeable than those in the forest. However, the forest soils are characterised by a greater number of root channels and other biogenic channels. In addition, the soils in the forest catchment are characterised by larger quantities of a clay type with a greater likelihood for volume change, than the soils in the pasture catchment.

Thus, the forest soils are more likely to exhibit greater soil permeability variations in response to seasonal soil moisture variations. However, this effect appears to be offset by the greater seasonal moisture variations observed in the pasture catchment. The net effect of all these variables can account for the similar soil permeabilites observed in the two land use catchments.

No independent variables were determined to explain the spatial and seasonal variations of permeability observed in the forest organic litter horizon. However, field observations provided evidence to suggest that seasonal variations of soil moisture are important in determining the permeability differences observed in the forest organic litter horizon.

Non-Darcian flow in soil structural fissures and in biogenic channels is also suggested by the analyses of soil permeability. However, the net rainfall regime in the experimental catchments appears incapable of initiating macro-pore flow in unsaturated soil matrix conditions, except in the largest storms.

In both land use catchments, non-Darcian flow mechanisms are therefore likely to be restricted to areas where subsurface saturation develops. However, the soil structures necessary for rapid macro-pore flow occur less frequently in these areas because the antecedent soil moisture conditions are consistently high.

6.4 HYDROLOGIC IMPLICATIONS OF SOIL MOISTURE REGIMES AND THE SOIL PERMEABILITY OBSERVED IN THE TWO LAND USE CATCHMENTS

Few comprehensive land use studies have been completed since partial and variable source areas hypotheses have become accepted. Consequently, little is known about the differences between the soil moisture and soil permeability characteristics of forest and pasture vegetation. In New Zealand, some inferences about the relationships between soil permeability, soil moisture, hillslope runoff processes and vegetation type have been made from detailed studies of single forms of land use (e.g. McDonald, 1961; Jackson, 1972, 1973; Webster, 1977). However, the data should not be extrapolated from one environment to another because of the variability of the results obtained from the different land use environments studied (Lynch, 1975).

In this section, the hydrologic implications of the observed spatial and seasonal variation of soil moisture and soil permeability are examined for the two land use catchments studied.

6.4.1 SURFACE RUNOFF PROCESSES

The relationships between soil permeability, soil moisture and surface runoff processes are examined for their role in determining infiltration-excess overland flow and saturation overland flow in the two catchments.

In the following analyses, overland flow velocities are assumed to be about 10 m h^{-1} in the pasture catchment (see Emmett, 1978). Overland flow velocities in the forest catchment are assumed to be restricted by the permeability of the organic litter layer. The mean transformed soil permeabilities of the organic litter horizon are equivalent to untransformed soil permeabilities of about 4.0 m h^{-1} for summer soil conditions, and about 2.0 m h^{-1} for winter soil conditions (table 6.7b).

6.4.1.1 Infiltration-excess overland flow

An estimate of the percentage of time that infiltration-excess overland flow is likely to occur in each land use catchment was made by comparing the untransformed soil permeabilities of the surface mineral soil horizons in each catchment, with the rainfall intensity-duration characteristics (c.f. table 6.8a and b and figure 5.6 and 5.7). In the forest catchment, interception losses prevent direct comparisons from being made between the gross rainfall intensities and soil permeability. For this vegetation type, comparisons were made between the gross rainfall intensities and the median surface mineral soil permeabilities, corrected for an assumed mean intra-storm evaporation rate of 0.81 mm h^{-1} (see section 5.3.2.2).

Table 6.12a and 6.12b show median untransformed surface soil permeabilities in each land use catchment, for summer and winter soil conditions. Also included in these tables are the results of a Duncan's multiple range test for the permeabilities of the surface mineral soils in each land use catchment and the per cent time these permeabilities are equalled or exceeded by catchment rainfall intensities. The Duncan's multiple range tests show those sub-catchment units in which no statistically significant differences could be detected between the permeabilities of the surface mineral soil horizons ($p = 0.05$).

In the pasture land use catchment, rainfall intensities seldom exceed the surface soil permeabilities when the catchment soils are dry (table 6.12a). Assuming 6 mm is the minimum rainfall depth required to fill depression storages in the pasture catchment (see Horton, 1935), infiltration-excess overland flow will occur only for storm durations of 0.5 to 1 h. Thus, if infiltration-excess overland flow does occur, overland flow paths will tend to be short and contributions to storm runoff restricted to the riparian sub-catchment unit (assuming the overland flow velocities presented in 6.4.1). Overland flow generated from the upslope catchment areas is likely to infiltrate the permeable soils in lower slope areas, either during intra-storm rainless periods or when rainfall ceases.

During winter soil conditions, greater yields of infiltration-excess overland flow generation are likely in the pasture catchment (table 6.12a). Infiltration-excess overland flow is likely to occur in the riparian sub-catchment unit, for durations as short as 15 minutes and for as long as 12 hours.

P A S T U R E

	SUMMER			WINTER		
	Spur	Riparian	Midslope	Riparian	Midslope	Spur
Sub-catchment unit mean permeability ($\log_{10}$ m s^{-1})	-5.308	-5.215	-5.084	-5.841	-5.419	-5.208
Duncans multiple range test	--------	--------				
Sub-catchment unit median permeability (mm h^{-1})	17.71	21.94	29.67	5.19	13.72	23.30
	Rainfall intensity-duration characteristics Per cent time surface soil permeability is equalled or exceeded					
Event duration	Spur	Riparian	Midslope	Riparian	Midslope	Spur
5 min	1.51	0.87	0.41	12.01	2.45	0.62
15 min	0.68	0.42	0.18	8.73	1.43	0.32
30 min	0.43	0.21	0.08	6.42	0.80	0.19
1 h	0.20	0.04	-	3.78	0.44	0.04
2 h	0.06	-	-	1.95	0.18	-
6 h	-	-	-	0.86	-	-
12 h	-	-	-	0.36	-	-
24 h	-	-	-	-	-	-

Table 6.12a : Mean surface soil permeabilities for the pasture sub-catchment units; Duncan's multiple range test, and the per cent time soil permeabilities are equalled or exceeded for the specified rainfall event durations

FOREST

	SUMMER			WINTER		
	Riparian	Spur	Midslope	Riparian	Midslope	Spur
Sub-catchment unit mean permeability ($\log_{10}$ m s^{-1})	-5.837	-5.254	-4.880	-6.079	-5.771	-5.697
Duncans multiple range test					--------	--------
Sub-catchment unit median permeability (mm h^{-1})	5.24	20.01	47.46	3.00	7.00	7.23
	Rainfall intensity-duration characteristics					
	Per cent time surface soil permeability is equalled or exceeded *					
Event duration	Riparian	Spurs	Midslope	Riparian	Midslope	Spurs
5 min	11.31	1.11	0.12	17.27	6.55	6.01
15 min	8.47	0.42	0.02	14.21	4.75	4.08
30 min	6.15	0.26	-	10.65	3.11	2.74
1 h	3.54	0.04	-	7.01	1.55	1.39
2 h	1.88	-	-	4.41	0.82	0.76
6 h	0.85	-	-	1.39	0.10	0.05
12 h	0.34	-	-	0.68	-	-
24 h	-	-	-	-	-	-

* - corrected for a 0.81 mm h^{-1} intra-storm evaporation rate from the forest canopy

Table 6.12b : Mean surface soil permeabilities for the forest sub-catchment units; Duncan's multiple range test, and the per cent time soil permeabilities are equalled or exceeded for the specified rainfall event durations

Smaller responses are suggested from the upslope sub-catchment units.

Similar analyses were completed for the development of infiltration-excess overland flow above the forest mineral soils. The same assumptions were used about the surface detention storage requirements, as no better estimates were found in the literature surveyed.

During both wet and dry soil conditions, infiltration-excess overland flow from the forest riparian sub-catchment unit are suggested for storm durations of 15 minutes - 12 hours (table 6.12b). Only small contributions of overland flow from upslope positions are probable in either season. During summer, the soils are too permeable to allow widespread infiltration-excess overland flow. During winter, the slow flow velocities through the organic litter horizon may prevent overland flow contributions from reaching the stream channel, in time to contribute to storm runoff.

The lower soil permeabilities in the B_2 soil horizon in the forest riparian sub-catchment unit increase the likelihood for infiltration-excess overland flow from these catchment areas, compared with similar areas in the pasture catchment. However, the lower flow velocities through the organic litter horizon act to retard and diminish the total response. Thus, it is probable that similar surface runoff responses will occur from the riparian sub-catchment units in both land use catchments. In both land use catchments, the largest responses of infiltration-excess overland flow are likely to occur from high intensity rainfall 'bursts' associated long duration storms because the surface detention storages will have been pre-filled by previous storm rainfall (see chapter 5; section 5.3.2.1).

Partial, but variable source areas of infiltration-excess overland flow are suggested for both the land use catchments. During winter, spatially variable soil permeabilities restrict the development of infiltration-excess overland flow to the riparian catchment areas.

During summer, surface permeabilities are too large to enable widespread overland flow to develop in either land use catchment. For these reasons infiltration-excess overland flow is likely to be restricted to variable areas marginal to the stream channel.

Depending on antecedent soil moisture conditions, long duration storms capable of sustaining infiltration-excess overland flow may saturate the soil profile and generate return flow and saturation overland flow.

6.4.1.2 Saturation overland flow

The likelihood for saturation overland flow in riparian areas of the land use catchments was estimated for the antecedent soil moisture conditions shown in figure 6.6 and figure 6.7. These results are based on an analysis of rainfall intensity-duration characteristics and available soil moisture storage. In both land use catchments, areas capable of producing saturation overland flow are restricted closely to the riparian sub-catchment units by the large soil moisture storage available in the midslope and spur regions (figure 6.10 and 6.11). However, saturation overland flow may occur infrequently in the pasture midslope positions during winter. Table 6.13a (pasture) and 6.13b (forest) show the results of these analyses for the riparian catchment areas in the two land use catchments.

In both land use catchments, saturation overland flow is likely to occur most often in long duration storm events. Interception losses in the forest catchment reduce the likelihood of saturation overland flow, compared with the pasture.

A comparison between table 6.12 a,b and table 6.13 a,b shows the relative importance of infiltration-excess overland flow and saturation overland flow in each land use catchment. In both catchments, the predominance of the two mechanisms of surface runoff production is dependent on storm characteristics.

PASTURE

	Per cent time available moisture storage is equalled or exceeded for selected soil moisture profiles				
Event duration	Maximum	Upper quartile	Mean	Lower quartile	Minimum
5 min	-	-	-	-	-
15 min	0.02	-	-	-	-
30 min	0.13	-	-	-	-
60 min	0.56	0.04	-	-	-
2 h	1.30	0.24	-	-	-
6 h	4.71	1.18	0.05	0.01	-
12 h	9.56	3.90	0.68	0.34	0.17
24 h	19.52	6.95	2.41	1.34	0.53
Available soil moisture storage in the upper 1.0 m of soil (mm depth)	12.22	24.94	45.94	58.26	70.93

Table 6.13a : Estimates of the per cent time the available soil moisture storage in the upper 1.0 m of soil of the riparian sub-catchment unit is equalled or exceeded and saturation overland flow is possible in the pasture catchment

FOREST

	Per cent time available moisture storage is equalled or exceeded for selected soil moisture profiles				
Event duration	Maximum	Upper quartile	Mean	Lower quartile	Minimum
5 min	-	-	-	-	-
15 min	-	-	-	-	-
30 min	0.13	-	-	-	-
60 min	0.44	-	-	-	-
2 h	0.94	-	-	-	-
6 h	2.56	0.10	-	-	-
12 h	3.75	0.68	-	-	-
24 h	3.74	1.33	-	-	-
Available soil moisture storage in the upper 1.0 m of soil (mm depth)	12.91	39.98	59.76	78.20	99.56

* - corrected for a 0.81 mm h^{-1} intra-storm evaporation rate from the forest canopy

Table 6.13b : Estimates of the per cent time the available soil moisture storage in the upper 1.0 m of soil of the riparian sub-catchment unit is equalled or exceeded and saturation overland flow is possible in the forest catchment

Short duration, high intensity, storms are capable of initiating infiltration-excess overland flow, but do not provide the volumes of water adequate to saturate the soil profile. For the longer duration, low intensity storms, the reverse is true. However, overland flow, generated by either flow mechanism, is likely to occur most often when the available soil moisture storage and surface permeabilities are reduced during wet, winter conditions.

The estimates of the likelihood of surface runoff mechanisms shown in table 6.12 and 6.13 are comparative only, as they do not include an assessment of the effects of intra-storm drainage. Drainage will act to reduce the occurrence of both surface runoff mechanisms.

6.4.2 SUBSURFACE RUNOFF PROCESSES

The following discussion is restricted to saturated soil conditions. Soil saturation appears necessary for rapid contributions of subsurface flow, by either Darcian, or non-Darcian flow mechanisms (Klute, 1972; Anderson and Burt, 1978a; Dunne, 1978; Mosley, 1982). Thus, in both land use catchments, rapid subsurface flow will be restricted to the riparian catchment areas (see figure 6.10 and 6.11).

Subsurface flow can contribute hydrologically important flow volumes to the stream channel only in catchments with the most permeable soils (Freeze, 1972b; Beven, 1982). Based on the information provided in a model study by Freeze (1972b; see case 11b, p. 1281), the soil permeabilities observed in the experimental catchments are generally 2 - 4 orders of magnitude too impermeable, to enable subsurface flow to reach the stream channel in time to contribute to storm runoff. Instead, the soil permeabilities are likely to create conditions suitable for the generation of saturation overland flow.

Despite the comparatively impermeable catchment soils, small volumes of subsurface flow are likely to occur in both land use catchments. Subsurface flow volumes from the forest catchment will probably be smaller than those from the pasture catchment, because of the different permeabilities of the B_2 and B_3 soil horizons in the riparian areas of both catchments. However, the small differences in subsurface flow between the two land use catchments may be hydrologically unimportant. These aspects are considered further in chapter 7.

6.4.3 SUMMARY

The results of the preceding sections in this chapter verify only some of the traditional hypotheses about the soil moisture and soil permeability characteristics of forest and pasture vegetation. The extreme hydrologic sensitivity of the pedologic-topographic-vegetation continuum is suggested by the close relationships between, soil moisture, soil permeability, the net rainfall regime and hillslope runoff.

Estimates of the likelihood of infiltration-excess overland flow show that this mechanism will occur preferentially in both land use catchments, when the soils are wet and relatively impermeable. Infiltration-excess overland flow is more likely in the forest than in the pasture because the surface mineral soils in the forest are less permeable than the surface soil in the pasture. However, the slower overland flow velocities inferred in the forest suggest that the source areas of infiltration-excess overland flow will be similar in both catchments.

In both land use catchments, storm rainfall volumes are generally inadequate to establish widespread, steady state infiltration-excess overland flow. Consequently, for most storm events, overland flow paths are probably short. Variable source area contributions of infiltration-excess overland flow are thus likely to be restricted to the riparian sub-catchment units in each land use catchment. However, widespread infiltration-excess overland flow may occur in both catchments in response to high intensity rainfall 'bursts', that are associated with long duration storms.

Saturation overland flow is also likely to be restricted to the riparian sub-catchment units in both land use catchments. The available soil moisture storage in the riparian areas of each catchment are similar in wet soil conditions. However, considerable differences in net rainfall input (chapter 5) will probably cause saturation overland flow to be generated less frequently in the forest, compared with the pasture catchment.

Areas of subsurface flow are restricted to the riparian sub-catchment units in each land use catchment. However, the soils of the experimental catchments are probably too impermeable to enable hydrologically important contributions of subsurface flow to storm runoff, even during dry soil conditions, when rapid macro-pore flow is more likely to occur. Instead, soil permeabilities are more likely to enhance the formation of profile saturation and the development of saturation overland flow.

The relationships between the water storage and transmission characteristics of the catchment soils and characteristics of the catchment rainfall, show the extreme sensitivity of the rainfall-runoff mechanisms to small changes in soil characteristics. This suggests that the interactions between the rainfall regime and soil hydraulic properties should be studied in greater detail in future studies of source area hydrology.

Physical estimates of surface and subsurface components of the hillslope runoff regime are presented in chapter 7.

ERRATA: VOLUME ONE

Page	
6	Line 18: "has' should read: 'have'.
22	Table 2.1: 'Corbett and Sopper, 1975' should read: 'Corbett <u>et al</u>., 1975'.
37	Line 22: 'source runoff' should read: 'source area runoff'.
56	Line 4: 'forth' should read: 'fourth'.
110	Table 4.5: 'Pelton and Korven (1965)' should read: 'Pelton and Korven (1969)'.
119	Line 20: 'sub-objective' should read: 'sub-objectives'.
121	Line 5: 'influence' should read: 'influence on'.
171	Figure 6.2c: '% by moisture' should read: '% by volume'.
181	Line 25: 'variation of' should read: 'variation'.
213	Line 23: 'have' should read: 'has'.
244	Line 28: '6.8a' should read: '6.7'.
245	Line 20: '0.5' should read: '0.25. Note: this analysis and the similar analyses presented on pages 248 - 249 are based on the assumption that 6mm is the minimum rainfall depth required to fill depression storages before infiltration-excess overland will commence.'

STUDIES OF SOURCE AREA HYDROLOGY UNDER INDIGENOUS FOREST AND PASTORAL AGRICULTURE IN THE HAPUAKOHE RANGE, NORTH ISLAND, NEW ZEALAND

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VOLUME TWO

CHAPTER 7 - 10

TABLE OF CONTENTS

VOLUME ONE

Page

VOLUME TWO

LIST OF FIGURES, TABLES, PLATES AND APPENDICES

LIST OF FIGURES

VOLUME ONE

FIGURE

Page

VOLUME TWO

Page

LIST OF TABLES

VOLUME ONE

TABLE

Page

VOLUME TWO

LIST OF PLATES

VOLUME ONE

PLATE

LIST OF APPENDICES

VOLUME TWO

APPENDIX

CHAPTER SEVEN

CATCHMENT HILLSLOPE FLOW PROCESSES

CONTENTS

7.1 INTRODUCTION

In humid temperate environments, most research on source area hydrology has shown that rainfall-runoff processes on vegetated slopes are described adequately by the variable source area model of hillslope hydrology. However, some recent studies have shown that a greater range of rainfall-runoff processes occur in humid temperate environments, particularly where soil conditions are close to the critical values that determine the predominance of surface or subsurface flow mechanisms (eg. Pilgrim, 1976, 1983; Bonell and Gilmour, 1978; Bonell _et al_., 1981). Thus, detailed analyses of the relationships between soil physical properties and hillslope runoff mechanisms appear necessary in all catchments studied.

An analysis of the hillslope runoff components observed in the two land use catchments is presented in this chapter. Emphasis has been given to the relationships between hydrologically important soil physical properties and the hillslope runoff regimes observed in the two land use catchments. In this way, the controlling processes of hillslope runoff can be established for both forms of land use.

The data collection and analyses of hillslope runoff components were completed to achieve the following sub-objectives:

i) to establish the spatial distribution of surface and subsurface hillslope runoff components in the two land use catchments;

ii) to establish the factors that determine these runoff processes;

and iii) to make inferences about the relationships between hillslope runoff components and stream flow.

The hydrologically important runoff producing areas in each land use catchment can be identified with the experimental design outlined in chapter 4. The importance of surface and subsurface flow mechanisms in generating stream flow can also be identified with the experimental design. However, in this study, only qualitative assessments can be made about the linkage between hillslope runoff and stream flow because of slope and channel routing effects.

7.2 SURFACE RUNOFF

7.2.1 INTRODUCTION

An examination of surface runoff processes formed the basis of most rainfall-runoff studies completed before the development of the partial and variable source area concepts (Betson, 1964; T.V.A., 1964; Hewlett and Hibbert, 1967). Most early studies were restricted to an examination of the processes generating Hortonian overland flow and its role in sediment entrainment. Many studies of this type were completed (see the summary by Dunne (1978)) and were effectively culminated by the studies by Emmett (1970).

The number of studies that examined surface runoff processes declined following the development of the partial and variable source area models: greater emphasis was placed on subsurface flow and on the spatial variability of soil conditions necessary to generate the newly identified flow processes. However, surface runoff processes are now being examined in more detail (for example, see the studies by Bonell and Gilmour, 1978; Yair *et al.*, 1978, 1980; Bren and Turner, 1979; Bonell *et al.*, 1981).

The increased interest in surface runoff mechanisms has occurred because it has become recognised that there are stringent limitations on the importance of subsurface flow processes in generating the stream hydrograph, even in forested catchments (Dunne, 1969; Freeze, 1972b, 1980; Bren and Turner, 1979). Interactions between rainfall, soil and topographic characteristics cannot be assumed, therefore, and must be examined carefully in each catchment studied.

7.2.2 THE DATA SET, NETWORK PRECISION AND DATA ANALYSIS

7.2.2.1 The data set

In this study, quantitative estimates of surface runoff[1] were made from small plots, located in each sub-catchment unit of the two land use catchments. Within each sub-catchment unit, these data have been used to provide information on the relationships between surface runoff, rainfall, soil, vegetation and topographic characteristics. In the past, plot studies have been criticised because the data have been extended to make inferences about catchment runoff processes, without regard to slope and channel routing processes (Burton, 1966). In this study, data from the runoff plots are used to make inferences about hillslope runoff processes operating within the sub-catchment units of each land use catchment. However, no attempt has been made to use these data quantitatively to predict discharge from larger catchment areas.

The experimental design, plot location and instrumentation are discussed in chapter 4. Measurements of accumulated surface runoff were made weekly from the runoff plots in each land use catchment.

---

[1] Surface runoff is defined in chapter 4.

Note: In this chapter, hydrologic flow volumes and discharges are expressed as mm depth equivalents and as specific discharges (mm h^{-1}) respectively.

Surface runoff from half the runoff plots was recorded continuously. During the two year study, data were lost during several short duration, high intensity storms, when the surface runoff plots were flooded by widespread infiltration-excess overland flow. In these storms, infiltration-excess overland flow was generated over the entire slopes of the pasture catchment and most of the slopes in the forest catchment.

The final data set comprised 104 weekly observations from the 20 plots distributed among the sub-catchment units of the two land use catchments (see chapter 4; figure 4.4).

7.2.2.2 Estimation of network precision

The precision of the surface runoff sampling network is discussed in chapter 4. No suitable model for estimating the probable variance of surface runoff from the sub-catchment units was found in the literature surveyed. Thus, an a posteriori estimate was made with the data collected, to provide an estimate of network precision for surface runoff, averaged over each sub-catchment unit, for observations made at a given time:

$$\text{i.e. } \bar{x}_T = 1/L \sum_{I=1}^{L} x_{IT} \qquad (1)$$

where x_{IT} is the surface runoff at plot (I) at time (T) in each sub-catchment unit of the two land use catchments, with L the number of surface runoff plots in each sub-catchment unit.

The standard error of x_T is $s\bar{x}_T$. The maximum and minimum standard errors for x_T are defined below:

$$s\bar{x}_{T\ max} = \max\ (s\bar{x}_{T_1},\ s\bar{x}_{T_2},\ \ldots.\ s\bar{x}_{T_{104}})$$

$$s\bar{x}_{T\ min} = \min\ (s\bar{x}_{T_1},\ s\bar{x}_{T_2},\ \ldots.\ s\bar{x}_{T_{104}})$$

Table 7.1 shows the minimum and maximum standard errors for estimating plot surface runoff ($s\bar{x}_{T\ min}$ and $s\bar{x}_{T\ max}$) observed during the two year period of intensive observations. Also presented in table 7.1, are the sub-catchment unit mean surface runoff ($\bar{x}_T$) and the 95 % confidence intervals[2] (95 % C.I.), expressed as a percentage of the sub-catchment mean surface runoff.

PASTURE

	$s\bar{x}_{T\ min}$			$s\bar{x}_{T\ max}$		
	$s\bar{x}_{T\ min}$	$\bar{x}_T$	95 % C.I.	$s\bar{x}_{T\ max}$	$\bar{x}_T$	95 % C.I.
Riparian	0.58	8.13	14.07	0.21	0.016	259.35
Midslope	0.01	0.22	7.25	0.16	0.130	254.96
Spur	0.28	2.60	20.95	0.50	0.610	160.11

FOREST

	$s\bar{x}_{T\ min}$			$s\bar{x}_{T\ max}$		
	$s\bar{x}_{T\ min}$	$\bar{x}_T$	95 % C.I.	$s\bar{x}_{T\ max}$	$\bar{x}_T$	95 % C.I.
Riparian	1.60	10.87	28.89	0.01	0.003	226.32
Midslope	0.01	0.55	5.02	0.17	0.120	277.18
Spur	0.01	0.26	7.43	0.01	0.005	278.32

$s\bar{x}_{T\ min}$, $s\bar{x}_{T\ max}$, $\bar{x}_T$, 95 % C.I. as defined in the text

units (mm depth)

Table 7.1 : $S\bar{x}_{T\ min}$'s, $s\bar{x}_{T\ max}$'s, $\bar{x}_T$'s and the 95 % C.I. (expressed as a percentage of $\bar{x}_T$) for surface runoff observations in the sub-catchment units of the land use catchments

The standard errors of sub-catchment unit mean surface runoff ($s\bar{x}_T$) are highly variable. For small storms, the standard errors are generally large, but decrease and become less variable as storm size increases.

---

[2] The 95 % confidence intervals are defined in chapter 6, section 6.2.1.1.2.

Consequently, the 95 % confidence intervals for estimates of mean sub-catchment unit surface runoff ($\bar{x}_T$) are large for many small storms (i.e. > +/- 100 %). However, in both experimental catchments, estimates of the sub-catchment unit mean surface runoff are made to within about +/- 40 % for most large rainfall inputs.

The large errors associated with estimating surface runoff may preclude hydrologically important differences from being detected among sub-catchment units in both land use catchments.

7.2.2.3 Data analysis

Conventional statistical techniques were used to analyse surface runoff in the two land use catchments. Serial correlation is present only in the surface runoff data obtained from the pasture riparian sub-catchment unit. Spatial correlation (table 7.2), non-normality and inequality of variances are also features of the surface runoff data set. A logarithmic transformation was not successful in normalising the data and stabilising the variances of the data from all the sub-catchment units.

		PASTURE			FOREST		
		Rip	Mid	Spr	Rip	Mid	Spr
Pasture	Rip	---					
	Mid	0.313 **	---				
	Spr	0.235 *	0.926 **	---			
Forest	Rip	0.715 **	0.560 **	0.533 **	---		
	Mid	0.457 **	0.767 **	0.787 **	0.763 **	---	
	Spr	0.389 **	0.741 **	0.753 **	0.701 **	0.947 **	---

rip - riparian mid - midslope spr - spur
* - significant at p = 0.05 ** - significant at p = 0.01

Table 7.2 : Correlation matrix for sub-catchment unit surface runoff for both land use catchments showing the spatial correlation between each sub-catchment unit

Consequently, non-parametric statistics were used instead. Where analyses were restricted to data observed from single sub-catchment units, the transformed data series were used with parametric techniques.

7.2.3 SURFACE RUNOFF IN THE LAND USE CATCHMENTS

Two aspects of the surface runoff are considered in this section. Firstly, the spatial distribution of surface runoff is examined. Secondly, the factors that determine surface runoff (characteristics of rainfall, soil, vegetation and topography) are examined, to identify the principal mechanisms of surface runoff in the sub-catchment units of each land use catchment.

7.2.3.1 General characteristics

Figure 7.1 a,b,c (pasture) and figure 7.2 a,b,c (forest) show the weekly rainfall depths and mean sub-catchment unit surface runoff depths ($\bar{x}_T$) observed in the two land use catchments.

A seasonal pattern of surface runoff is apparent in all the sub-catchment units in the pasture catchment and in the riparian sub-catchment unit of the forest catchment. During winter, large yields of surface runoff are generated in the riparian areas of both land use catchments. However, during summer, considerably smaller yields of surface runoff are generated from the pasture riparian areas. In contrast, the reverse is true in the pasture midslope and spur sub-catchment units. In these areas, the greatest yields of surface runoff occur more often during summer, than at other times of the year. The surface runoff yields from the forest midslope and spur sub-catchment units show no discernible seasonal variation. These catchment areas produce only small yields of surface runoff throughout the year.

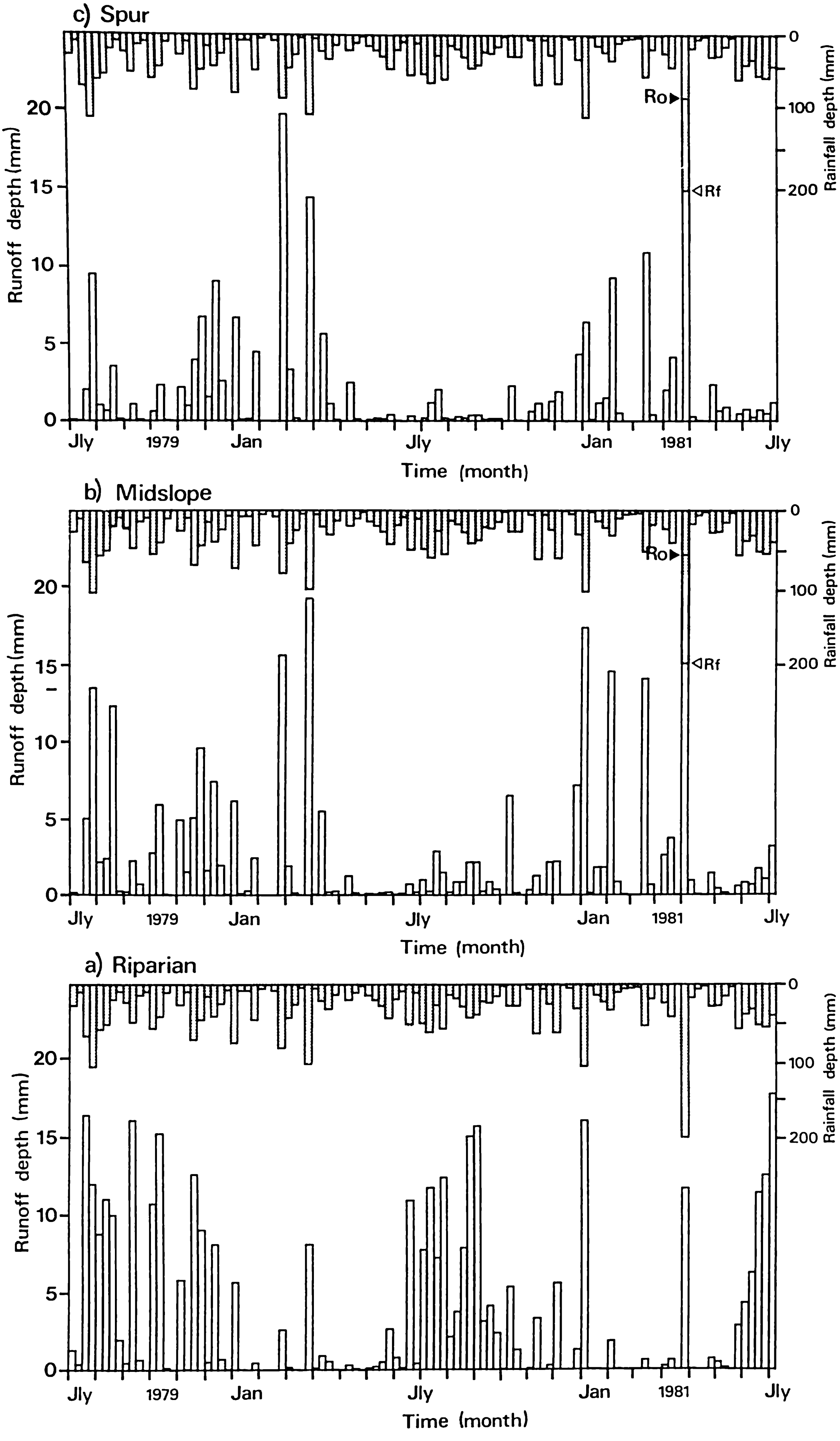


Figure 7.1: Weekly rainfall and surface runoff depths from the pasture sub-catchment units

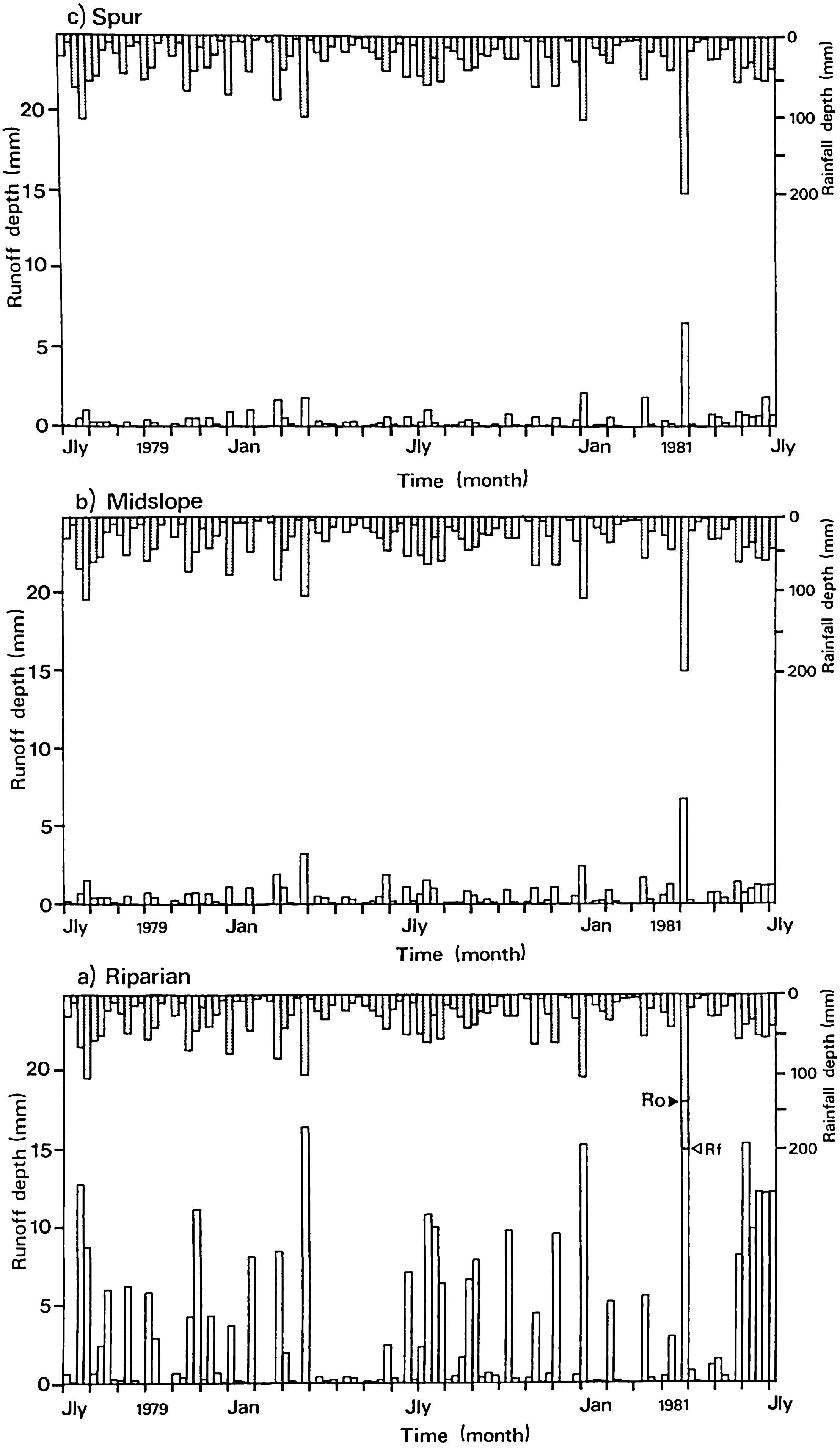


Figure 7.2: Weekly rainfall and surface runoff depths from the forest sub-catchment units

The seasonal patterns of surface runoff shown in figure 7.1 and 7.2 suggest that the mechanisms determining surface runoff are neither consistent within the two forms of land use, nor between them. For this reason, surface runoff from the summer and winter seasons are considered separately in the following analyses.

7.2.3.2 Spatial distribution of surface runoff in the land use catchments

Figure 7.3 (pasture) and figure 7.4 (forest) show the frequency distributions of surface runoff observed in each sub-catchment unit in the two land use catchments, for summer and winter storm events. The spatial distribution of surface runoff is shown clearly in the forest, but it is less apparent in the pasture. However, figure 7.3 shows the seasonal reversal of surface runoff production in the pasture catchment.

A non-parametric analysis of variance (Kruskal-Wallis) was used initially to examine the spatial distribution of surface runoff in the land use catchments (Ho: that the surface runoff yields are equal in the three sub-catchment units (strata) in each land use catchment; i.e. $\mu_{rip} = \mu_{mid} = \mu_{spr}$).

Table 7.3a shows the results of this analysis for surface runoff yields recorded in each land use catchment during summer. In both catchments, a non-significant Kruskal-Wallis test statistic was obtained for surface runoff generated in response to summer storms. Thus, given the data available, there is no evidence to suggest that mean surface runoff differs significantly between the sub-catchment units in either land use catchment. Nevertheless, the size of the differences shown between some sub-catchment units appear hydrologically important (e.g. the differences between the forest riparian areas and those further upslope). This suggests that the data collection network was inadequate to estimate the spatial distribution of surface runoff generated during summer.

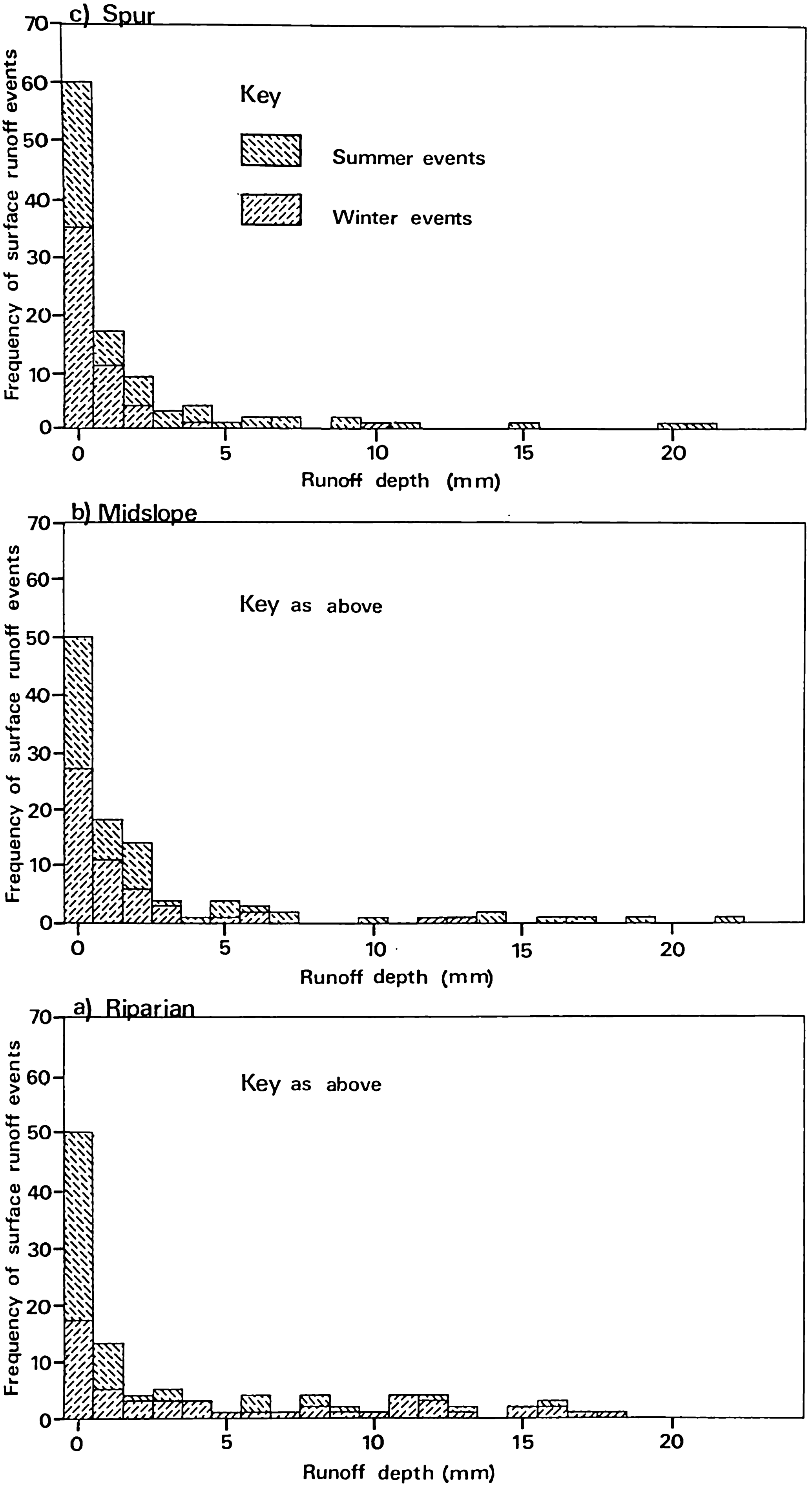


Figure 7.3: Frequency distributions of weekly surface runoff depths for summer and winter events from the pasture sub-catchment units

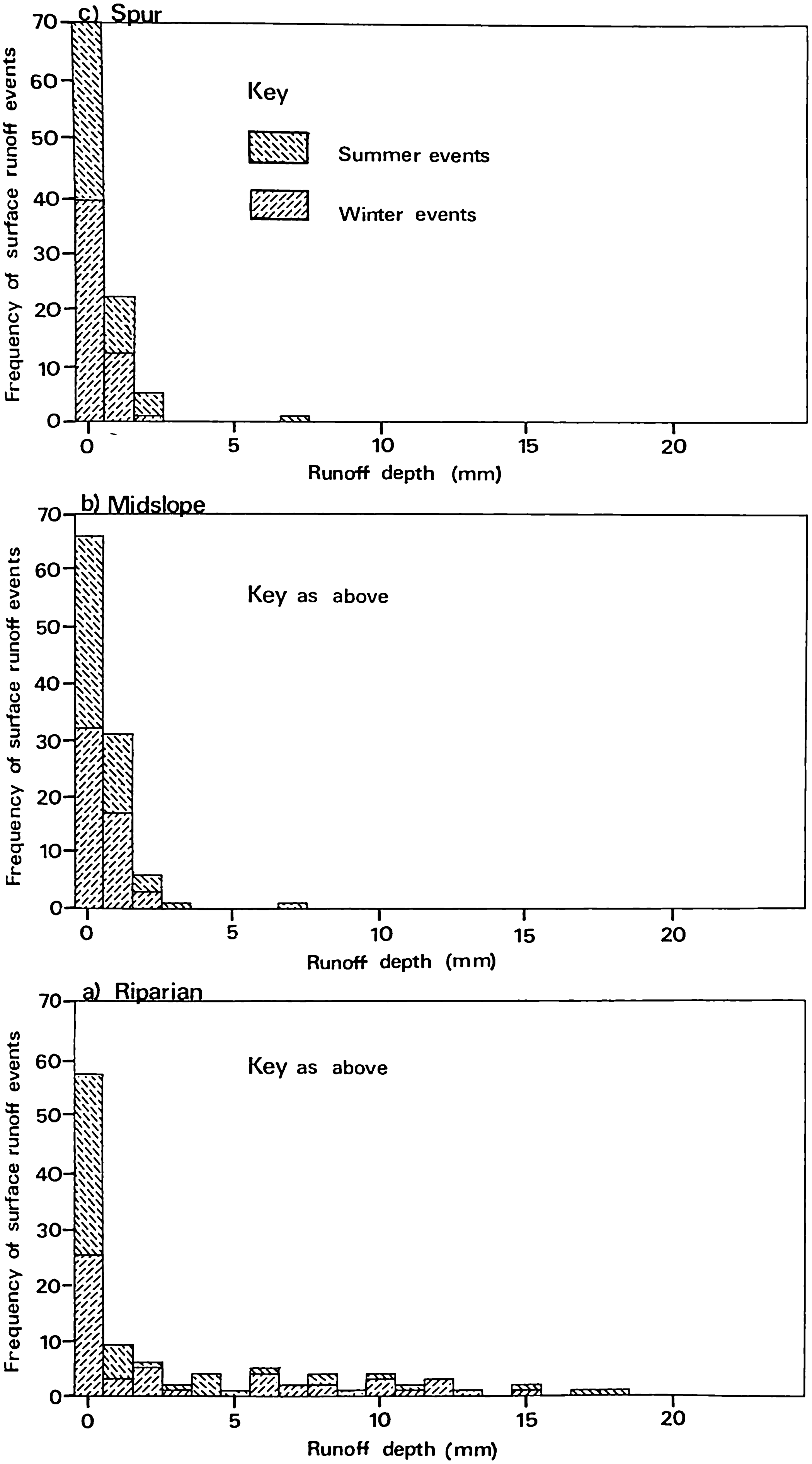


Figure 7.4: Frequency distributions of weekly surface runoff depths for summer and winter events from the forest sub-catchment units

Table 7.3b shows the Kruskal-Wallis test results for surface runoff yields observed in each land use catchment during winter. In both land use catchments, a significant Kruskal-Wallis test statistic was obtained. This implies that different surface runoff responses are generated in the three sub-catchment units of each land use catchment, in response to winter storms.

	Pasture				Forest			
Stratum	n	mean	std dev	rank sum	n	mean	std dev	rank sum
Riparian	53	1.86	3.01	3771.0	53	2.40	4.44	4728.0
Midslope	54	3.39	5.12	4683.0	53	0.59	1.10	4146.5
Spur	54	2.93	4.75	4587.0	53	0.46	1.02	3845.5
Kruskal-Wallis test statistic	3.63 ns				3.64 ns			

n - number of samples std dev - standard deviation
mean - sub-catchment unit plot surface runoff (mm depth)
ns - not significant at p = 0.05

Table 7.3a : Kruskal-Wallis test results for sub-catchment unit mean surface runoff from summer storms in the land use catchments

	Pasture				Forest			
Stratum	n	mean	std dev	rank sum	n	mean	std dev	rank sum
Riparian	52	5.35	5.76	5149.0	52	3.62	4.56	5117.0
Midslope	51	1.49	2.73	3767.0	52	0.48	0.50	3871.5
Spur	51	0.69	1.45	3019.0	53	0.31	0.37	3257.5
Kruskal-Wallis test statistic	21.05 **				16.96 **			

n - number of samples std dev - standard deviation
mean - sub-catchment unit plot surface runoff (mm depth)
** - significant at p = 0.01

Table 7.3b : Kruskal-Wallis test results for sub-catchment unit mean surface runoff from winter storms in the land use catchments

Wilcoxon signed ranks tests were completed to examine in more detail, the differences in the seasonal surface runoff responses within and between the two land use catchments (table 7.4a; summer events: table 7.4b; winter events).

In the pasture land use catchment, significantly different runoff responses to summer storms were found between the riparian sub-catchment unit and both the upslope sub-catchment units (table 7.4a). However, no significant differences were found between the two upslope areas (table 7.4a). The size of the differences in surface runoff from the midslope and spur catchment areas is probably not hydrologically important, particularly since surface runoff from these sites may not reach the stream channel in time to contribute to storm runoff. Thus, in the pasture land use catchment during summer, less runoff occurs from the areas marginal to the stream channel than from the midslope and spur sub-catchment units.

The seasonal pattern of surface runoff is reversed in the pasture land use catchment during winter. Statistically significant differences in storm runoff yields were found between all the sub-catchment units (table 7.3b). Surface runoff generation is greatest in the near channel areas and is inversely related to the distance from the stream channel.

A seasonally alternating pattern of runoff was not found in the forest land use catchment (c.f. table 7.3a and 7.3b). For all storm rainfall inputs, surface runoff yield decreases with increasing distance from the stream channel. The size of the differences in surface runoff yields, observed from the three sub-catchment units, are all statistically significant ($p = 0.01$; table 7.4b). However, the difference in surface runoff production from the two upslope sub-catchment units are considered too small to be of hydrological importance. Surface runoff generated in these areas is likely to be infiltrated in lower slope positions.

The spatial and seasonal patterns of surface runoff can be used to make inferences about the mechanisms of surface runoff production in each land use catchment. These factors are discussed in section 7.2.4.

		PASTURE			FOREST		
		Rip	Mid	Spr	Rip	Mid	Spr
Pasture	Rip	---					
	Mid	0.000**	---				
	Spr	0.004**	0.126ns	---			
Forest	Rip	0.035*	0.001**	0.027*	---		
	Mid	0.055ns	0.000**	0.000**	0.000**	---	
	Spr	0.007**	0.000**	0.000**	0.000**	0.000**	---

rip - riparian mid - midslope spr - spur
* - significant at p = 0.05 ** - significant at p = 0.01
ns - not significant

Table 7.4a : Level of significance of Wilcoxon signed ranks (two tailed) for sub-catchment unit mean surface runoff from summer storms in the land use catchments

		PASTURE			FOREST		
		Rip	Mid	Spr	Rip	Mid	Spr
Pasture	Rip	---					
	Mid	0.000**	---				
	Spr	0.000**	0.000**	---			
Forest	Rip	0.001**	0.000**	0.000**	---		
	Mid	0.000**	0.004**	0.806ns	0.000**	---	
	Spr	0.000**	0.000**	0.041*	0.000**	0.000**	---

rip - riparian mid - midslope spr - spur
* - significant at p = 0.05 ** - significant at p = 0.01
ns - not significant

Table 7.4b : Level of significance of Wilcoxon signed ranks (two tailed) for sub-catchment unit mean surface runoff from winter storms in the land use catchments

7.2.3.3 Determinants of surface runoff in the land use catchments

An analysis of the factors that determine surface runoff was necessary to establish the mechanisms of this flow process in each land use catchment. A number of independent variables, which describe the environmental characteristics of each runoff plot site, were measured during the two year observation period. Stepwise linear regression analysis was used to establish the important environmental characteristics that determine surface runoff in each land use catchment.

An analysis of this type is seldom simple. A correct choice of an initial set of explanatory variables presupposes considerable knowledge of their interactions with the dependent variable. Having measured an appropriate suite of independent variables, the raw data sets do not often satisfy the assumptions underlying this analysis technique (Box, 1966; Mark and Church, 1977).

7.2.3.3.1 Variable selection.

The independent variables measured at each runoff plot site fall into four main categories:

i) precipitation characteristics;
ii) soil physical properties;
iii) topographic characteristics;
iv) vegetation characteristics.

Table 7.5a and table 7.5b show the values of these variables for each runoff plot in the pasture and forest catchments, respectively. The rationale for the selection of these variables is presented in chapter 4 and appendix B. The observed values for the weekly rainfall variables are presented in appendix H.

	Runoff plot											
	1	2	3	4	5	6	7	8	9	10	11	12
site	1	2	3	4	5	6	7	8	9	10	11	12
stratum	1	1	1	1	2	2	2	2	3	3	3	3
aspect	180	150	105	125	310	150	300	143	160	160	320	160
slope	14	9	7	25	30	29	30	24	29	27	32	32
rough	1.05	1.03	1.09	1.08	1.10	1.04	1.08	1.05	1.04	1.07	1.16	1.02
cond (s)	-7.087	-7.168	-6.421	-8.933	-6.604	-5.912	-8.334	-7.553	-8.098	-7.742	-7.675	-6.949
cond (w)	-8.413	-8.593	-8.708	-9.250	-7.436	-7.102	-8.237	-8.716	-7.401	-7.747	-7.243	-7.160
sand	50.50	47.25	56.00	47.00	37.00	30.50	37.50	47.00	37.50	42.00	42.25	44.50
silt	22.00	25.25	20.50	32.75	28.50	23.00	36.75	35.50	31.75	32.50	33.00	34.50
clay	27.50	27.50	23.50	20.25	34.50	46.50	25.25	17.50	30.75	25.50	24.75	21.00

site - site number
stratum - sub-catchment unit: 1 - riparian; 2 - midslope; 3 - spur
aspect - plot orientation (degrees)
slope - slope angle (degrees)
rough - surface roughness (m m^{-1})
cond (s) - summer hydraulic conductivity ln (m s^{-1})
cond (w) - winter hydraulic conductibity ln (m s^{-1})
sand - per cent sand in the surface mineral soil horizon
silt - per cent silt in the surface mineral soil horizon
clay - per cent clay in the surface mineral soil horizon

Table 7.5a : Characteristics of the surface runoff plots in the pasture land use catchment

	Runoff plot							
	1	2	3	4	5	6	7	8
site	1	2	3	4	1	2	1	2
stratum	1	1	1	1	2	2	3	3
aspect	160	230	070	130	260	150	230	180
slope	15	25	24	25	34	36	35	27
rough	1.05	1.06	1.09	1.07	1.09	1.05	1.06	1.07
cond (s)	-7.709	-9.192	-8.506	-8.621	-6.041	-7.222	-7.892	-7.092
cond (w)	-9.276	-10.370	-9.817	-9.419	-8.468	-8.899	-8.547	-8.476
sand	43.50	39.00	47.50	40.75	31.00	31.00	32.25	27.75
silt	40.00	27.25	24.25	29.00	29.50	30.25	27.75	29.00
clay	16.50	33.75	28.26	30.25	39.50	38.75	40.00	43.25
canopy	5.61	2.42	5.16	4.14	5.27	6.03	4.22	4.02

site - site number
stratum - sub-catchment unit: 1 - riparian; 2 - midslope; 3 - spur
aspect - plot orientation (degrees)
slope - slope angle (degrees)
rough - surface roughness $(m\ m^{-1})$
cond (s) - summer hydraulic conductivity $\ln(m\ s^{-1})$
cond (w) - winter hydraulic conductibity $\ln(m\ s^{-1})$
canopy - % of clear sky above each surface runoff plot
sand - per cent sand in the surface mineral soil horizon
silt - per cent silt in the surface mineral soil horizon
clay - per cent clay in the surface mineral soil horizon

Table 7.5b : Characteristics of the surface runoff plots in the forest land use catchment

7.2.3.3.2 Analysis procedure and results

Stepwise linear regression models were determined for each of the 20 runoff plots in the experimental catchments: 12 in the pasture; 8 in the forest. The analyses followed the 'robust' procedures for variable selection and model development outlined by Hocking (1976). Data for all variables used in the analyses were logarithmically transformed to standardise the data.

The results of the linear regression analyses are presented in table 7.6a (pasture) and in table 7.6b (forest). For each plot, only variables with significant regression coefficients have been included. In both land use catchments, only some of the independent variables available for selection appear as factors important in determining surface runoff. Thus, while surface runoff yields vary considerably between sites in each catchment, the responses can be explained by variation in only a few independent variables.

7.2.4 DISCUSSION

7.2.4.1 Spatial variability of surface runoff in the two land use catchments

The results presented in section 7.2.3.1 show that the seasonal and spatial patterns of runoff generation conform only partially to the hillslope hydrological models considered applicable in humid temperate environments. Partial area contributions of infiltration-excess overland flow (Betson, 1964) or contributions from varying source areas of saturation overland flow can explain the spatial patterns of surface runoff observed in the pasture land use catchment, during wet antecedent conditions. The same models can explain the spatial pattern of surface runoff observed in the forest catchment throughout the year.

RIPARIAN SUB-CATCHMENT UNIT

Plot	1		2		3		4	
Coefficients and variables								
a	-25.244		-24.981		-17.680		-11.711	
b_1	2.336	raintot	1.757	raintot	1.927	raintot	1.925	raintot
b_2	-2.258	cond	-2.401	cond	-1.487	cond	2.051	ante
	n	77	n	77	n	80	n	69
	r^2	0.761	r^2	0.743	r^2	0.733	r^2	0.684
	$s_{y.x}$	1.164	$s_{y.x}$	1.224	$s_{y.x}$	1.252	$s_{y.x}$	1.210

MIDSLOPE SUB-CATCHMENT UNIT

Plot	1		2		3		4	
Coefficients and variables								
a	-5.377		8.477		-115.820		-5.331	
b_1	2.318	halfint	2.102	halfint	2.411	halfint	2.312	halfint
b_2	-	-	2.222	cond	-13.343	cond	-	-
	n	82	n	85	n	78	n	75
	r^2	0.668	r^2	0.658	r^2	0.679	r^2	0.655
	$s_{y.x}$	1.053	$s_{y.x}$	1.241	$s_{y.x}$	1.107	$s_{y.x}$	1.119

SPUR SUB-CATCHMENT UNIT

Plot	1		2		3		4	
Coefficients and variables								
a	-19.567		-1811.406		-34.095		-51.701	
b_1	2.301	halfint	2.424	halfint	2.422	halfint	2.399	halfint
b_2	-1.807	cond	215.536	cond	-3.823	cond	8.158	cond
	n	83	n	84	n	79	n	78
	r^2	0.752	r^2	0.746	r^2	0.828	r^2	0.828
	$s_{y.x}$	0.934	$s_{y.x}$	1.989	$s_{y.x}$	0.735	$s_{y.x}$	0.735

coefficients - regression coefficients
raintot - weekly rainfall total $\log_e$ (mm)
cond - hydraulic conductivity of the surface mineral soil horizon $\log_e$ ($m\ s^{-1}$)
halfint - weekly maximum half hour rainfall intensity $\log_e$ ($mm\ h^{-1}$)
n - number of non-censored non-zero data points
r^2 - coefficient of determination
$s_{y.x}$ - standard error of y about the regression line $\log_e$ (mm)

Table 7.6a : Linear regression models for the pasture overland flow plots. In all cases runoff is the dependent variable, a is the y intercept, b_1 is the regression coefficient for the first independent variable (x_1) and b_2 is the regression coefficient for the second independent variable (x_2)

RIPARIAN SUB-CATCHMENT UNIT

Plot	1	2	3	4
Coefficients and variables				
a	-9.363	-7.175	-9.165	-4.963
b_1	2.418 raintot	1.983 raintot	2.711 raintot	1.570 raintot
b_2	- -	0.371 vmax	- -	0.265 vmax
n	82	67	71	73
r^2	0.628	0.636	0.630	0.708
$s_{y.x}$	1.418	1.206	1.412	0.815

	MIDSLOPE SUB-CATCHMENT UNIT		SPUR SUB-CATCHMENT UNIT	
Plot	1	2	1	2
Coefficients and variables				
a	-5.704	-5.808	-7.166	-6.298
b_1	1.467 raintot	1.306 raintot	1.629 raintot	1.488 raintot
b_2	- -	- -	- -	- -
n	78	83	76	78
r^2	0.743	0.682	0.744	0.664
$s_{y.x}$	0.657	0.740	0.729	0.797

Abbreviations - as in table 6.6a

Table 7.6b : Linear regression models for the forest overland flow plots. In all cases runoff is the dependent variable, a is the y intercept, b_1 is the regression coefficient for the first independent variable (x_1) and b_2 is the regression coefficient for the second independent variable (x_2)

Partial area contributions of infiltration-excess overland flow appear to be the only viable mechanism for surface runoff production in the pasture land use catchment, during dry antecedent conditions.

The transition between saturation overland flow and infiltration-excess overland flow is common in many forms of agricultural land use (Dunne, 1978). However, in forest catchments, the transition between subsurface flow and saturation overland flow is more usual.

Soil permeabilities are close to the critical values that determine the likelihood of surface or subsurface flow mechanisms in the two land use catchments used in this study. Consequently, the importance of seasonal variations of soil permeability is suggested as important in determining the distribution of hillslope runoff components (see section 6.4.1.1). The hydrologic implications of seasonal soil permeability variations have seldom been considered in the recent studies of source area hydrology, particularly those completed in forested catchments.

In both land use catchments, the spatial pattern of surface runoff observed during wet antecedent conditions is related inversely to the observed spatial variability of soil permeability (c.f. table 6.12 and table 7.3).

However, the relationships between runoff and surface soil permeability are less obvious in the forest catchment, particularly during dry antecedent conditions. Nevertheless, the largest surface runoff responses were observed from the forest riparian areas, where the soils are the least permeable. Only small yields of surface runoff occur from the more permeable, upslope areas in the forest catchment.

Little association was found between surface soil permeabilities and surface runoff in the pasture catchment, during dry antecedent conditions (c.f. figure 7.1 and table 6.12a). In the next section, the relationships between the seasonal variations in soil permeability and the seasonal variations of surface runoff from the pasture catchment are considered in more detail.

7.2.4.2 Determinants of surface runoff in the pasture land use catchment

In the pasture land use catchment, four variables were shown by the regression analyses to be important factors determining the development of surface runoff (see table 7.6a).

At all riparian sites, total weekly rainfall is the primary independent variable entered in the regression models. This variable explains about 45 - 55 % of the observed variation of surface runoff. At all sites, large weekly rainfall inputs are associated with large surface runoff volumes. In 3 of the 4 riparian sites, seasonally variable soil permeability is the second independent variable entered in the regression models. This variable explains between 10 % and 20 % of the variation of surface runoff. At all sites, greater soil permeabilities are associated with decreased surface runoff. At the fourth riparian site, antecedent soil moisture is the second independent variable. At this site, greater surface runoff volumes are suggested during wet antecedent soil moisture conditions.

Both, saturation overland flow and infiltration-excess overland flow, are suggested by the independent variables included in the regression models for the riparian areas in the pasture catchment. Infiltration-excess overland flow is suggested at sites 1 - 3 by the inclusion of the soil permeability variable. Saturation overland flow mechanisms are suggested by the inclusion of antecedent soil moisture at riparian site 4. However, the occurrence of saturation overland flow appears to be restricted to catchment areas with physical characteristics highly conducive for the development and maintenance of high antecedent soil moisture conditions. These characteristics are described below.

Riparian site 4 is located at the head of a small ephemeral stream, in a position similar to pasture piezometer 7 (figure 6.8a). The site encompasses several of the characteristics described by Kirkby and Chorley (1967) as precursors for the development of saturation overland flow. These include, a strongly concave hillslope shape, both in form and plan, the occurrence of high water table elevations, and low soil permeabilities. The other runoff plots in the riparian sub-catchment unit (sites 1 - 3) are located on shallower, less concave foot slopes, with more freely draining alluvial and colluvial soils.

The mechanisms of surface runoff production suggested by the regression analyses support the inferences derived in section 6.4.1. The combined evidence from the regression models and from section 6.4.1 suggests that saturation overland flow occurs only in restricted areas of the riparian sub-catchment unit. These areas are generally adjacent to ephemeral streams or in strongly concave valley profiles: both areas are characterised by high antecedent soil moisture conditions.

Interactions between rainfall intensity and soil permeability appear to dominate surface runoff processes in both the pasture midslope and spur sub-catchment units. At all sites in these areas, the weekly maximum half hour rainfall intensity appears as the primary independent variable of surface runoff. This variable explains about 50 - 60 % of the observed variation in surface runoff. At all sites, the regression coefficients show that increased rainfall intensity is associated with increased surface runoff volumes.

At all the spur sites, but at only two midslope sites, seasonally variable surface soil permeability enters the regression models as the next most important factor determining surface runoff. Clearly, there is strong evidence for infiltration-excess overland flow mechanisms determining surface runoff generation in the midslope and spur sub-catchment units. These results also verify the mechanisms of surface runoff inferred from the soil moisture and permeability analyses presented in section 6.4.1.1 (table 6.12).

The results from the regression models provide some evidence to explain the apparently anomalous reversal in the spatial distribution of surface runoff in the pasture catchment (see section 7.2.3.2). In the midslope and spur sub-catchments units, the sign of the regression coefficients for soil permeability is positive at some sites and negative at others. At midslope site 2 and spur sites 2 and 4, greater yields of surface runoff are associated with increased soil permeability. At the remaining sites where soil permeability appears as an important independent variable (M3, S1, S3), the usual relationships between surface runoff and soil permeability are shown (i.e. decreased runoff is associated with greater soil permeability). At these 3 sites, the soil permeabilities show a seasonal trend opposite to those observed at all other sites (i.e. the surface soil permeabilities are lower during summer, than in winter; see table 7.5a). Both these factors suggest that complex interactions occur at these sites, between soil moisture, changes in soil structure and other unidentified soil physical characteristics.

Field observations, made during summer storms, suggest that dry soil conditions in the midslope and spur sites cause the soil to become water repellent. At these sites, rivulets of overland flow appeared to travel rapidly over dry exposed soil and among the partially decayed vegetation detritus. High contact angles (>90 degrees) were also observed between the surface runoff and the soil and vegetation surfaces. Some of this flow was intercepted by large soil cracks exposed at the surface, but small cracks (about 1 mm) were bridged by the flowing rivulets.

The processes and physical conditions required to induce water repellency in clay-rich soils have been described by McGhie and Posner (1980, 1981). They found that organic residues from pasture induced water repellency more readily, than similar residues from most other agricultural crops. Water repellency is most pronounced when the organic coatings are concentrated in the pore openings. In clay-rich soils, the effects of water repellency are magnified by increased porosity, that is induced by soil drying and a concomitant shrinkage of soil aggregates (McGhie and Posner, 1980). Such a mechanism may be operating in the strongly aggregated clay-rich 'A' horizon in the midslope and spur areas of the pasture land use catchment.

The development of water repellency at the midslope and spur catchment areas can explain the spatial pattern of surface runoff observed at these sites. These mechanisms can also explain the inconsistent seasonal variations of soil permeability observed in the upslope catchment areas. Although evidence for the development of water repellency is indicated only at some sites, this does not invalidate the proposed hypotheses because of two main factors.

Firstly, considerable spatial variability in the development of water repellency has been reported in other studies (e.g. McGhie and Posner, 1980). Secondly, the permeability measurements made in this study are based on flow rates integrated throughout the whole 'A' horizon. Thus, water repellency will be indicated in the permeability estimates only if it has developed sufficiently to influence water flow through a large part of the horizon.

Water repellency, developed only at the soil surface, can also account for the reversal in the spatial distribution of surface runoff observed in the pasture land use catchment.

7.2.4.3 Determinants of surface runoff in the forest land use catchment

In contrast with the complexity of surface runoff production shown for the pasture catchment, only two independent variables appear as important factors determining surface runoff in the forest land use catchment. At all sites in the forest, the total gross weekly rainfall appears as the primary independent variable entered in the regression models. This variable explains about 60 - 75 % of the observed variation of surface runoff. At two of the riparian sites in the forest, the volume of rain that falls at the observed weekly maximum rainfall intensity (vmax; see appendix.H and table 7.7) appears as the second most important independent variable of surface runoff (table 7.6b).

This variable is interpreted as evidence to suggest that infiltration-excess mechanisms of surface runoff predominate at these sites. The vegetation, topographic and soil characteristics of these sites offer no suggestions why a measure of rainfall intensity should be important only in these catchment areas (table 7.5b). Notably, the independent variables included in the regression models provide no evidence to suggest the development of saturation overland flow in the riparian areas of the forest catchment.

The regression analyses of surface runoff substantiate only partially the inferences made in section 6.4.1.1, that show clearly the importance of infiltration-excess mechanisms at all sites in the forest. The lack of evidence for infiltration-excess overland flow in the forest land use catchment could be due to a number of factors.

i) The intensity-duration characteristics of gross rainfall may be modified by interception processes, so that precise relationships cannot be established between surface runoff and the gross rainfall characteristics.

ii) The weekly rainfall totals are correlated significantly with the intensity-duration characteristics of rainfall (table 7.7). Consequently, the inclusion of this variable incorporates some of the characteristics of rainfall intensity.

iii) Evidence from the data sets obtained from all plot sites suggest that the infiltration-excess mechanisms of surface runoff may be modified by characteristics of the forest litter horizon. Evidence for this hypothesis is presented below.

In all sub-catchment units in the forest, some surface runoff develops for almost all rain events (see figure 7.2). In small storms, surface runoff occurs even though the surface soil permeabilities and the available soil moisture storage are not exceeded by the net rainfall. Bren and Turner (1979) have described similar observations on other steep (25 - 30 degree) forested slopes. They suggested that the downslope movement of rain splash can account for the small volumes of surface runoff that occurs, when storm conditions are inadequate to generate either, infiltration-excess overland flow, or saturation overland flow. In addition to rain splash, preferential flow can occur along twigs and undecayed leaf surfaces in the organic litter horizon.

	Raintot	Rtime	Maxint	Vmax	Halfint	Aveint
Raintot	--					
Rtime	0.571**	--				
Maxint	0.618**	0.410**	--			
Vmax	0.397**	0.104ns	0.430**	--		
Halfint	0.680**	0.210*	0.585**	0.854**	--	
Aveint	0.447**	-0.143ns	0.458**	0.622**	0.746**	--

raintot - total weekly rainfall (mm)
rtime - total weekly rain duration (h)
maxint - weekly maximum rain intensity (mm h^{-1})
vmax - depth of rainfall during the period of maximum intensity (mm)
halfint - weekly maximum half-hour intensity (mm h^{-1})
aveint - average weekly intensity (mm h^{-1})
** - significant at p = 0.01 * - significant at p = 0.05
ns - not significant

Table 7.7 : Correlation matrix for the weekly rainfall characteristics used in the multi-variate analyses of surface runoff. The weekly rainfall characteristics are presented in appendix H

Both these mechanisms may account for much of the surface runoff observed in the forest in response to small storms and may mask any important relationships between surface runoff and intensity-duration characteristics of gross rainfall. While infiltration-excess mechanisms were validated at only 2 of the 8 runoff sites, this does not mean that they do not occur at all sites in the forest. The soil moisture and permeability data provide strong evidence that infiltration-excess overland flow mechanisms are likely to predominate at all forest sites. Infiltration-excess overland flow is also suggested to account for the large yields of surface runoff observed from the forest riparian sub-catchment unit (see section 6.4.1.1 and 6.4.1.2).

7.2.4.4 Surface runoff and vegetation type

Infiltration-excess mechanisms have often been implied as the dominant mechanisms of surface runoff for different forms of agricultural land use (Dunne, 1978). The occurrence of infiltration-excess overland flow in the forest catchment is unusual, but this anomaly can be explained simply in this case. The permeabilities of the surface mineral soil in the forest catchment are typically 2 - 3 orders of magnitude lower than observed commonly in other forest environments as measured, for example, by Harr (1977), Bonell and Gilmour (1978), Mosley (1979, 1982), and Talsma and Hallam (1980). Only Gaiser (1952) has reported low permeabilities for a forest environment comparable with those observed in this study.

The relationships between surface runoff production and different forms of land use have been well established by many researchers (e.g. Kitteridge, 1948; Selby, 1971). However, the variability of the results obtained from the many different studies show that it is seldom possible to extrapolate this type of information from one environment to another (Lynch, 1975).

Table 7.3a and 7.3b show the influence of land use type on the yields of surface runoff production in the experimental catchments. The descriptive statistics for surface runoff show that the effect of vegetation type on the yields of surface runoff is dependent on geomorphic position and possibly other environmental characteristics (c.f. table 7.3a (pasture) and table 7.3b (forest)).

During summer, the differences in surface runoff observed between the two land use catchments can be explained by differences in the surface soil permeabilities observed in each area (c.f. table 6.12 a,b and table 7.3 a,b). This result suggests that the spatial variability of soil permeability dominates the effects of vegetation type, in determining the yields of surface runoff from the two land use catchments. However, the relationships between surface runoff yields and soil permeability vary greatly between the respective sub-catchment unit pairs of the two land use catchments. This variation may be caused by the influence of other environmental characteristics that determine surface runoff.

During winter conditions, changes in soil permeability alone, cannot explain the differences in surface runoff yields from the two land use catchments. Table 7.3a shows that greater volumes of surface runoff occur from the riparian areas of the pasture catchment, compared with similar areas in the forest catchment. This occurs despite the surface mineral soils of the forest riparian areas being less permeable.

The larger yields of surface runoff from the riparian areas in the pasture catchment may be caused by the increased likelihood for saturation overland flow from these areas, compared with similar areas in the forest (see table 6.12a and 6.12b). In addition, overland flow velocities are likely to be about 5 times lower in the forest than in the pasture (see section 6.4.1). These factors, in addition to the different net rainfall in each catchment, appear to dominate the effects of soil permeability in determining surface runoff from the two catchments.

The different overland flow velocities and net rainfall observed in the two catchments can also explain the larger volumes of surface runoff that occur from the pasture midslope and spur sub-catchment units, compared with similar areas in the forest. In these areas, evidence from the soil permeability data suggests that the reverse should occur.

In both land use catchments, the percentage of net rainfall recorded in the surface runoff plots varies greatly in each sub-catchment unit. Table 7.8 shows various statistics of the yields of net rainfall appearing as plot runoff, for both land use catchments. The mean percentage yields from the pasture catchment fall within the range reported from small plots for a variety of different forms of agricultural land use (see Dunne, 1978).

	PASTURE				FOREST			
	n	medn	mean	std dev	n	medn	mean	std dev
Rip	85	4.6	10.4	11.7	88	3.0	7.7	9.4
Mid	88	3.6	7.0	9.7	83	1.4	1.6	1.0
Spr	86	1.8	5.1	6.5	83	0.8	1.1	0.8

Rip - riparian
Mid - midslope
Spr - spur
n - number of samples
std dev - standard deviation
mean - mean % yield (events >0.0)
medn - median % yield (events >0.0)

Table 7.8 : Descriptive statistics of the percentage yield of storm rainfall appearing as surface runoff in each sub-catchment unit in the land use catchments

Few studies of surface runoff processes in forested catchments were found in the literature surveyed. The surface runoff yields from the forest riparian sub-catchment unit are considerably greater than those reported by Bren and Turner (1979) for forest vegetation, or for those reported for scrub vegetation on pumice soils by Selby (1971). However, the yields from the midslope and spur sub-catchment units in the forest catchment are similar to those reported in the two studies cited above.

The relationships between surface runoff and stream flow are considered in more detail in section 7.4 and in chapter 8.

7.3 SUBSURFACE FLOW

7.3.1 INTRODUCTION

Much of the recent research on source area hydrology has concentrated on subsurface flow mechanisms (Whipkey, 1965; Ragan, 1968; Weyman, 1970, 1973; Anderson and Burt, 1977a, 1977b, 1978a, 1978b; Mosley, 1979, 1982; Anderson and Kneale, 1980, 1982; Pierson, 1980). Most studies have sought to monitor the dynamics of the areas of subsurface and surface saturation at the base of hillslopes and relate subsurface discharge to stream flow. Generally, these investigations have been confined to two-dimensional slope forms, but more recently the effects of three dimensional slope form (contour convergence-divergence) have been examined (see Anderson and Burt, 1977a, 1977b, 1978a, 1978b; Anderson and Kneale, 1980, 1982).

The importance of subsurface discharge in contributing to stream runoff has been described in several of the studies cited above. Most have inferred relationships, between stream flow and subsurface flow, from the similarity of the time distributions of the two flow processes. However, only in a few recent studies have the quantities of subsurface flow been compared directly with the observed storm hydrographs (see Dunne, 1969; Weyman, 1970; Anderson and Burt, 1978b; Mosley, 1979; Anderson and Kneale, 1982). The results of these field studies suggest that subsurface flow can contribute to stream flow, but only in catchments with extremely permeable soils.

In environments with less permeable soil, the role of subsurface flow is more restricted. Models of hillslope flow processes show that subsurface flow does not contribute large volumes to the stream hydrograph, for the range of soil permeabilities found commonly in humid temperate environments (Freeze, 1972b, 1980). Instead, subsurface flow is more likely to influence the yields and time distribution of stream flow indirectly, by creating soil moisture conditions suitable for the formation of saturation overland flow.

In this section, the relationships between subsurface discharge and stream flow are examined. The spatial variability of subsurface flow mechanisms is not considered because the evidence presented in chapter 6 suggests that rapid subsurface flow is likely to be restricted to the areas of subsurface saturation in each land use catchment. The spatial variability of subsurface saturation is considered in chapter 6, where the relationships between slope form and plan, and the extent of basal slope saturation are discussed.

7.3.2 THE DATA SET AND DATA ANALYSIS

In each land use catchment, estimates of subsurface flow were made with the soil moisture and permeability data obtained from the intensively instrumented first-order basins (see figure 6.8; section 6.2.1.1). These data satisfy most of the requirements for a detailed analysis of subsurface flow from hillslopes (see Anderson and Burt, 1978b). However, only two recordings of saturated soil moisture conditions were made within these basins for each observation period. These observations were the maximum water table elevation during the preceding week, and the water table elevation at the time of the recording. Consequently, the time distribution of subsurface flow in both land uses can not be examined in detail.

Estimates were made of subsurface flow issuing from the stream bank draining each first-order basin. These estimates were made using the the mean soil permeability for each soil horizon at the stream bank (incorporating the seasonal variations described in appendix B) and the mean water table slope, determined from the first three rows of piezometers in each first order basin (see figure 6.8). A technique similar to that used by Weyman (1970) and Anderson and Burt (1978b) was used to estimate subsurface flow for the two data series recorded. Return flow was estimated in a similar manner, where the water table rose above the soil surface. Figure 7.5 shows the stream bank cross section of each first order basin, the physical dimensions of each soil horizon and the maximum possible water table elevation predicted for each sub-catchment (refer to section 6.2.2.3).

Several simplifying assumptions were incorporated in the analysis procedure. These included the assumption of spatial homogeneity of soil permeability; the use of general permeability estimates to represent lateral soil permeability; and the assumption that Darcian flow mechanisms are applicable in the catchment soils.

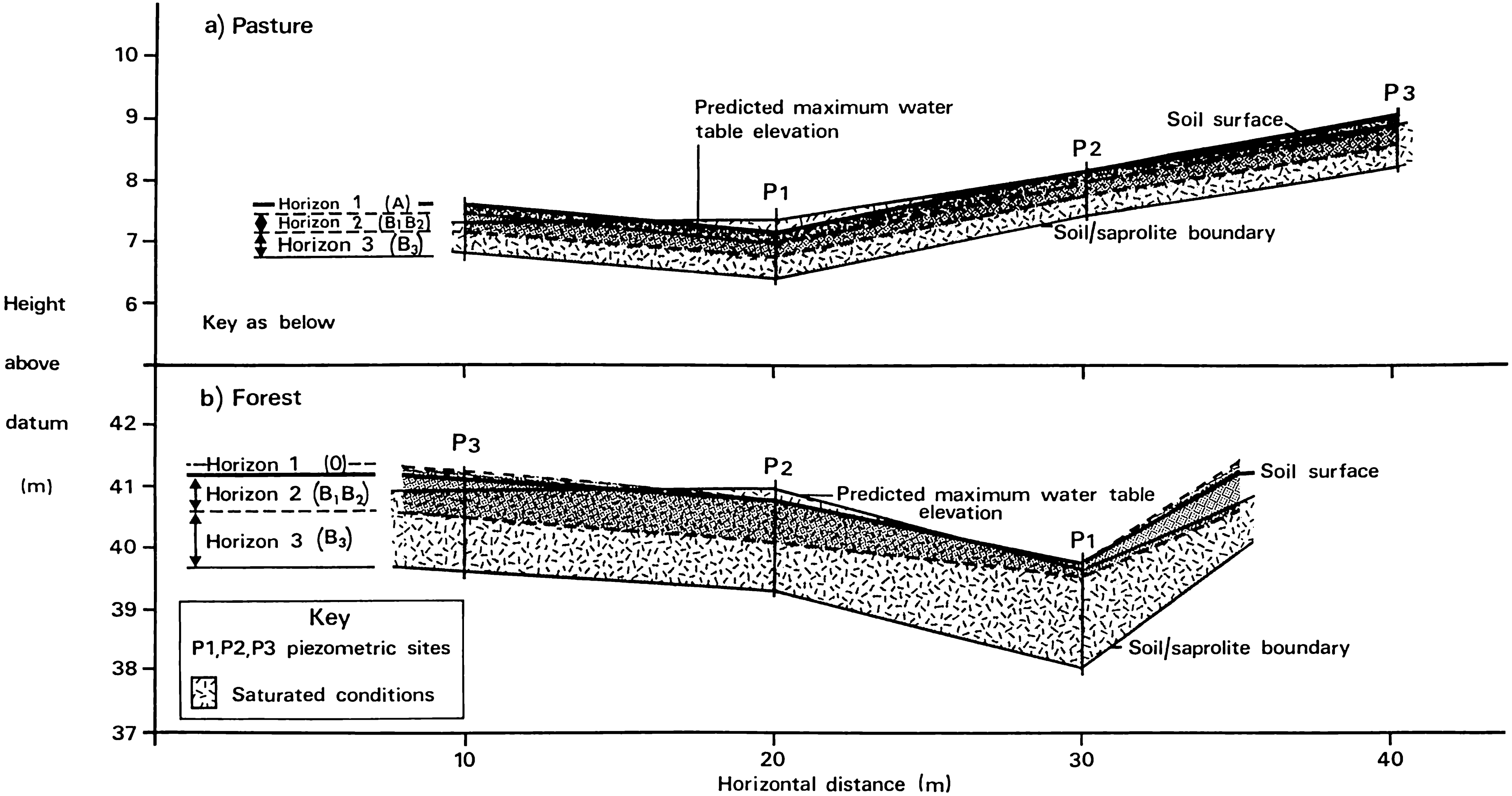


Figure 7.5: Cross sections of the two instrumented first order basins adjacent to the main stream channel showing the predicted maximum water table elevation

The use of these assumptions is to introduce only small errors to the analysis procedure. Estimates of the errors associated with the subsurface flow are not possible because the effect of these variables is unknown.

The subsurface flow data set comprised 104 observations of estimated weekly peak subsurface flow and 102 observations of subsurface flow made during conditions of stream flow recession.

7.3.3 SUBSURFACE FLOW IN THE LAND USE CATCHMENTS

7.3.3.1 General characteristics

The general characteristics of the estimated weekly maximum subsurface flow and the subsurface flow rates estimated for conditions of stream flow recession are shown in figure 7.6a and 7.7a, for the pasture land use catchment. Figure 7.6b and 7.7b show the same data for the forest catchment. A comparison between these figures shows that subsurface flow rates are generally larger and more responsive to rainfall inputs in the pasture, than in the forest catchment.

Return flow occurred as a component of the weekly maximum subsurface flow rate for 11 of the 104 observation periods in the pasture land use, but was not observed in the forest. Figure 7.6c shows the importance of return flow as a component of subsurface flow generation in the pasture catchment. In large storms, return flow can contribute more than 50 % of the aggregated subsurface flow response from the pasture. Thus, the large differences in total subsurface flow rates observed between the two catchments can be explained by the large differences in yields of return flow from each vegetation type (c.f. figure 7.6c and 7.7b). Additional contributions of direct precipitation on to saturated areas magnify further the differences in the total flow response attributable to subsurface flow mechanisms.

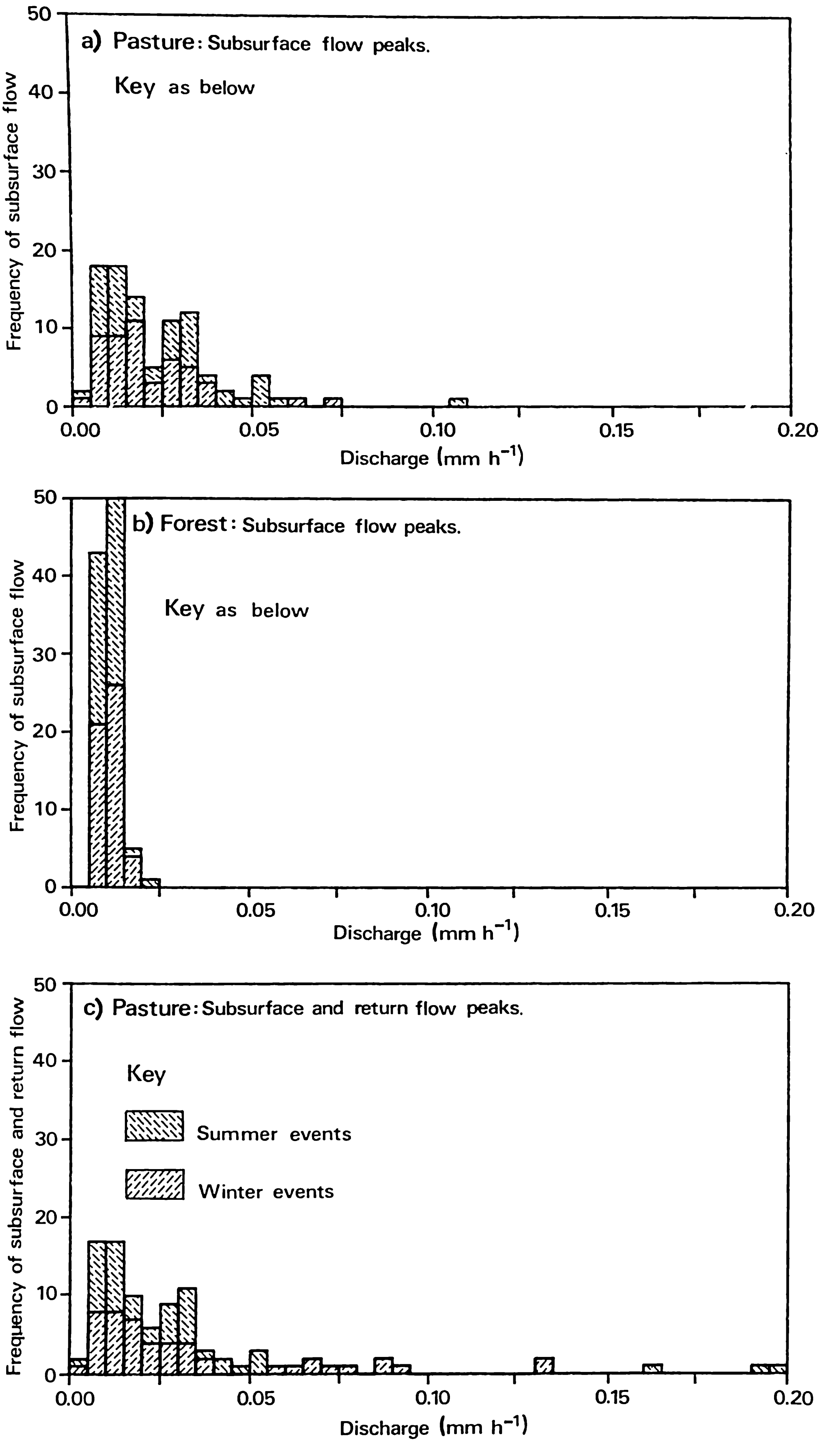


Figure 7.6: Frequency distributions of weekly peak subsurface flows from the forest and pasture land use catchments.
Note: return flow occurs only rarely in the forest land use and does not produce hydrologically important flow volumes

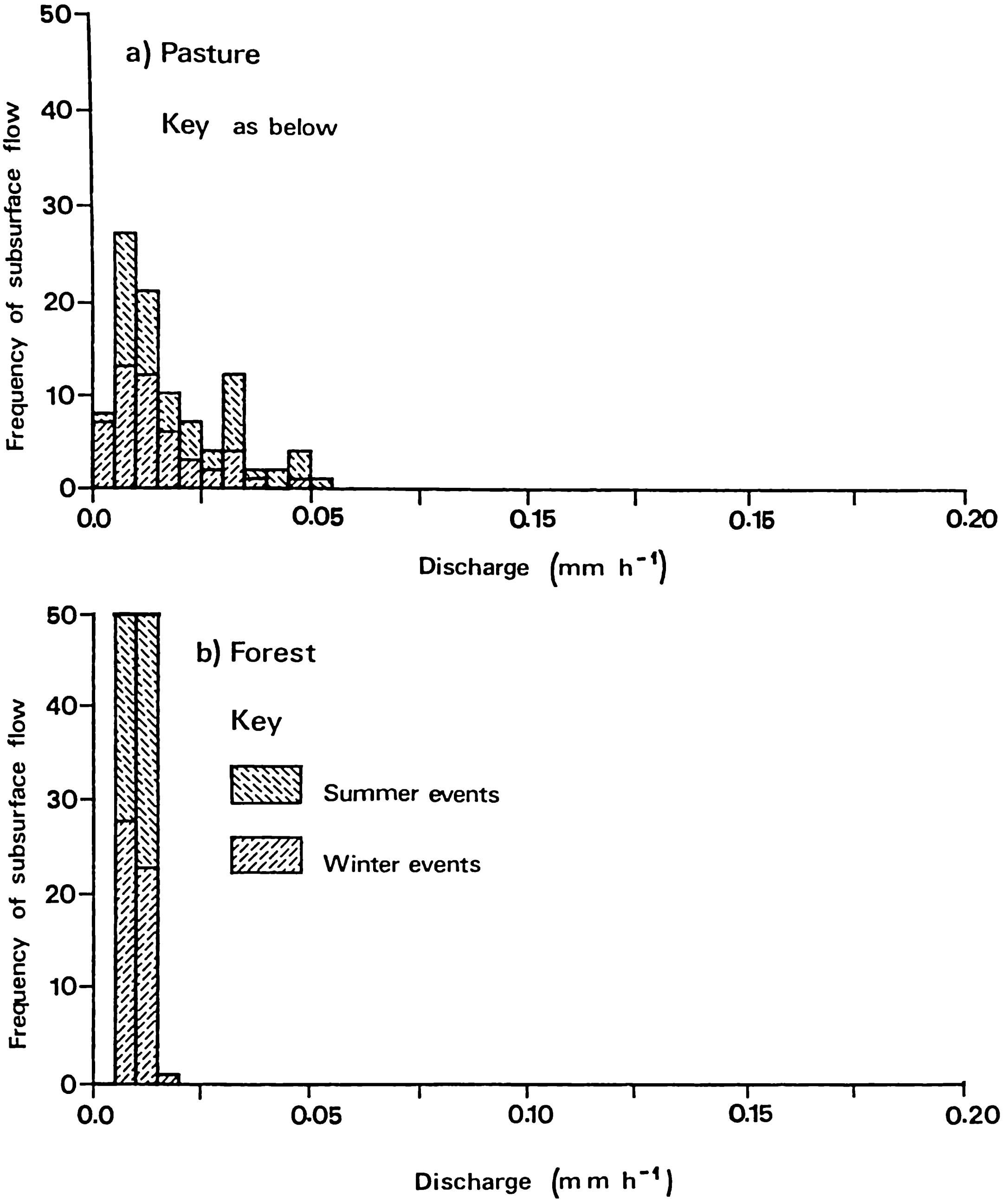


Figure 7.7: Frequency distributions of subsurface flow rates (recession flow conditions) from the pasture and forest land use catchments

7.3.3.2 Determinants of subsurface flow

Some of the factors that determine subsurface flow in the two land use catchments were examined by an analysis of correlations between:

i) the subsurface flow rates observed in each catchment;

ii) selected rainfall characteristics (see appendix H);

and iii) antecedent soil moisture conditions.

The examination was necessarily brief because of the limited subsurface flow data available.

Surrogate variables were required to describe the antecedent soil moisture conditions in the catchments because of the numerous failures of the neutron probe. The subsurface flow rate, observed during recession flow conditions in a given week, was used as a measure of antecedent soil moisture conditions for the two subsurface flow estimates made during the following week (i.e. the weekly maximum subsurface flow rates and the subsurface flow estimates made during recession flow conditions). The correlation coefficients, between antecedent soil moisture conditions and the weekly maximum subsurface flow rates, were estimated from an analysis of cross-correlations (lag = -1) between the two variables. Auto-correlation functions (lag = 1) were used to estimate the correlation coefficient between antecedent soil moisture and the subsurface flow rates observed during stream recession conditions. Table 7.9 shows the results of the correlation analyses.

In the pasture land use catchment, weekly peak subsurface discharges are strongly dependent on the weekly rainfall total ($r = 0.701$). Other rainfall variables are correlated significantly with the subsurface flow response. However, the variance explained by these variables is small, compared with 49 % variance explained by total weekly rainfall. Nevertheless, these results suggest that rainfall intensity-duration characteristics are also important in determining the weekly peak subsurface flow rates in the pasture catchment.

In the forest catchment, the results for weekly maximum subsurface flow rates are in contrast to those from the pasture. Antecedent soil moisture is the dominant explanatory variable, accounting for about 43 % of the observed variance in the data. Compared with the pasture, rainfall characteristics are less important in determining subsurface flow responses from the forest catchment.

	Pasture peak subsurface flow and return flow		Forest peak subsurface flow		Pasture subsurface flow: recession conditions		Forest subsurface flow: recession conditions	
Raintot	0.701	**	0.284	**	-0.142	ns	0.096	ns
Rain time	0.298	**	0.088	ns	-0.110	ns	0.000	ns
Maxint	0.264	**	0.087	ns	-0.188	ns	0.033	ns
Vmax	0.082	ns	0.050	ns	-0.065	ns	-0.046	ns
Halfint	0.370	**	0.252	*	-0.041	ns	0.123	ns
Aveint	0.247	*	0.174	ns	-0.048	ns	0.063	ns
Ccf (lag = -1)	0.056	ns	0.737	**	-----------		------------	
Acf (lag = 1)	---------		---------		0.654	**	0.879	**

raintot - weekly rainfall (mm)
maxint - weekly maximum rainfall intensity (mm h^{-1})
halfint - maximum half hour rainfall intensity (mm h^{-1})
ccf - cross correlation function
** - significant at p = 0.01
ns - not significant

raintime - duration of weekly rainfall (h)
vmax - volume of rainfall at maxint (mm h^{-1})
aveint - average weekly rainfall intensity (mm h^{-1})
acf - auto correlation function
* - significant at p = 0.05

Table 7.9 : Correlations between observed subsurface flow rates and selected independent variables for each flow population

In both land use catchments, antecedent soil moisture is the only explanatory variable correlated significantly with the subsurface flow rates observed during conditions of stream flow recession ($p = 0.01$).

7.3.4 DISCUSSION

The general characteristics of subsurface flow (section 7.3.3.1) conflict with the accepted hypothesis of hillslope runoff for the two forms of land use (see Dunne, 1978). However, the results presented in figure 7.6 and 7.7 are consistent with the soil moisture and permeability observations presented in chapter 6, for each land use catchment. The relationships found between the subsurface flow regimes, the characteristics of the rainfall input and the antecedent soil moisture conditions, all suggest that two primary factors explain the differences in subsurface flow observed between the two land use catchments. These factors are:

i) the large interception losses in the forest catchment that reduce the net rainfall by about 42 % in this vegetation type (see chapter 5);

and ii) the soils in the forest riparian catchment areas have a slightly larger available soil moisture storage than similar areas in the pasture land use catchment (see appendix G).

These two factors reduce the likelihood of subsurface saturation forming in the forest catchment and explain the importance of rainfall characteristics in determining subsurface flow in the pasture. These two factors also explain why antecedent soil moisture conditions are important in determining subsurface flow peaks in the forest. The soils in the forest riparian areas are also slightly less permeable than those in similar areas in the pasture catchment. This factor will also act to reduce the subsurface flow responses from the forest, compared with the pasture catchment.

The correlation analysis also suggests that the subsurface flow rates during stream recessions are independent of preceding storm characteristics. This evidence implies that the subsurface flow responses of both land use catchments are transient and that saturated areas drain rapidly. The relationships between subsurface flow and stream flow are considered in section 7.4.

7.3.4.1 Subsurface flow and vegetation type

No recent studies were found in the literature surveyed that compare directly the subsurface discharge from forest and pasture vegetation. Compared with pasture vegetation, greater subsurface flow rates have been implied for forested catchments for several reasons.

i) Subsurface runoff is often observed in forest catchments (e.g. Whipkey, 1965, 1969; Ragan, 1968; Mosley, 1979, 1982).

ii) Forest soils are generally more permeable than pasture or other agricultural soils (Selby, 1967a).

iii) Surface flow mechanisms are observed rarely in forest environments (Dunne, 1978).

However, the likelihood of smaller subsurface flow rates has been implied for forested catchments by evidence from comparative soil moisture studies of forest and pasture vegetation (e.g. Rowe and Reinman, 1961; Holmes and Colville, 1968). Thus, there is considerable uncertainty and a general shortage of conclusive evidence on the relationships between soil physical properties, soil moisture conditions and subsurface flow from forested and non-forested catchments.

Source of information	Vegetation	Soil textural class	Subsurface flow discharge
Whipkey (1965)	forest	silt loam	5.1×10^{-1}
T.V.A. (1966)	forest	clay loam	1.1×10^{-4}
Ragan (1968)	forest	sand	1.4×10^{-2}
Dunne (1969a)	pasture	sandy loam	3.1×10^{-2} to 4.2×10^{-3}
Whipkey (1969)	forest	sandy loam	2.5×10^{-2}
Hewlett and Nutter (1970)	forest	sandy loam	1.2×10^{-2}
Weyman (1970)	rough pasture, bracken	sandy loam	3.0×10^{-3}
Knapp (1973a)	rough pasture, bracken	peaty podzol	1.4×10^{-2} to 2.4×10^{-2}
Wilson and Ligon (1973)	pasture	sandy loam	1.7×10^{-2}
Anderson and Burt (1978b)	pasture	loam	7.1×10^{-3}
Mosley (1979)	forest	silt loam	1.3×10^{-2} to 2.5×10^{-2}
Bonell *et al*. (1981)	forest	clay	6.9×10^{-2} to 2.4 (site 2)
Anderson and Kneale (1982)	pasture	clay loam	1.6×10^{-2}
Pasture land use catchment			
(subsurface flow only: 0.11 mm h^{-1})*		clay loam	5.4×10^{-4}
(return flow included: 0.53 mm h^{-1})*			2.6×10^{-3}
Forest land use catchment			
(subsurface flow only: 0.02 mm h^{-1})*		clay loam	1.3×10^{-4}

Units: discharge - mm $s^{-1}m^{-1}$ (discharge per metre width of hillside)
* - specific discharge

Table 7.10 : A comparison between subsurface discharges observed in the two land use catchments and other published data

Table 7.10 shows a comparison of published subsurface flow data with the subsurface flow rates observed in the two land use catchments used in this study. No consistent patterns are apparent between the subsurface flow rates for forested and non-forested catchments or for the major soil textural classes. Of the studies cited in table 7.10, only in the catchments studied by Anderson and Burt (1978b) and Mosley (1979), have the observed subsurface flow rates been capable of generating all the storm flows observed in the stream channel. The subsurface flow rates observed in the two land use catchments are low compared with most of the other studies shown in table 7.10. Based on this information, subsurface storm flow is unlikely to contribute hydrologically important flow volumes to storm runoff, in either of the two land use catchments in the Mangawhara Valley.

The relationships between subsurface flow and stream flow are considered in section 7.4.3.

7.4 HILLSLOPE RUNOFF - STREAM FLOW LINKAGE

7.4.1 INTRODUCTION

The linkage, between hillslope runoff processes and the integrated catchment response observed in the stream channel, is intuitively obvious, but difficult to define and measure in practice. Thus, field studies of catchment hydrology have tended to be concentrated on either, the mechanisms of hillslope runoff processes (i.e. 'plot' scale experiments), or on 'catchment' scale experiments, where the analyses are based primarily on characteristics of the stream flow record. Examples of the former are the studies by Whipkey (1965), Dunne (1969), Emmett (1970), Weyman (1970, 1973) and Anderson and Burt (1978b). Examples of the latter include the studies by Dickinson and Whitely

(1973) and Pearce and McKerchar (1979).

Several factors have been described in the literature that suggest the relationships between hillslope runoff and channel processes are difficult to determine and will not be linear or time invariant. These factors include:

i) difficulties in sampling the spatial variability of surface and subsurface components of hillslope runoff (Foster, _et al_., 1968; Hayward, 1968; Emmett, 1970; Knapp, 1973, 1974; Atkinson, 1978);

ii) the complex interactions between the processes controlling hillslope runoff components;

iii) the additional complications of other catchment characteristics (e.g. catchment physiography) (e.g. Vorst and Bell, 1977; Pilgrim _et al_., 1982);

and iv) the effects of surface, subsurface and channel routing.

In the following sections, _qualitative_ assessments are made of the linkage between hillslope runoff processes and the characteristics of the stream hydrograph, for both the land use catchments.

7.4.2 SURFACE RUNOFF - STREAM FLOW LINKAGE

Two aspects of surface runoff-stream flow linkage are examined for both land use catchments. Firstly, the relationships between the yields of surface runoff and stream flow are considered; secondly, the time distribution of surface runoff and stream flow are examined.

7.4.2.1 Relationships between the yields of surface runoff and stream flow

7.4.2.1.1 Results

Figure 7.8 a,b shows a comparison between weekly unweighted mean sub-catchment unit surface runoff (i.e. the average of the surface runoff estimated in each of the three sub-catchment units in the two land use catchments) and weekly direct runoff totals for each land use catchment. The Hewlett and Hibbert (1967) separation procedure was used to estimate direct runoff for each week. Direct runoff includes precipitation into the stream channel and saturated near channel areas. In most storms, direct precipitation yields insignificant amounts of direct runoff (<1 %).

For most small runoff events, estimates of mean plot runoff can account for all the direct runoff from both land use catchments. However, the surface runoff plots under estimate direct runoff for storm events yielding more than about 6 mm of direct runoff, by an amount that increases with the size of the event (see figure 7.8a,b).

7.4.2.1.2 Discussion

The relationships between storm size, plot runoff and direct runoff are consistent with theoretical and field studies of infiltration-excess overland flow (e.g. Horton, 1936; Emmett, 1970). Overland flow velocities and depths tend to increase proportionally with overland flow path lengths. In large storms, the under-estimate of direct runoff is caused by overland flow paths being shorter (< 5.0 m) inside the plots, than outside. The fact that the surface runoff plots do not under estimate direct runoff for small storms, suggests that overland flow alone, will probably account for most of the direct runoff in both land uses, regardless of storm characteristics.

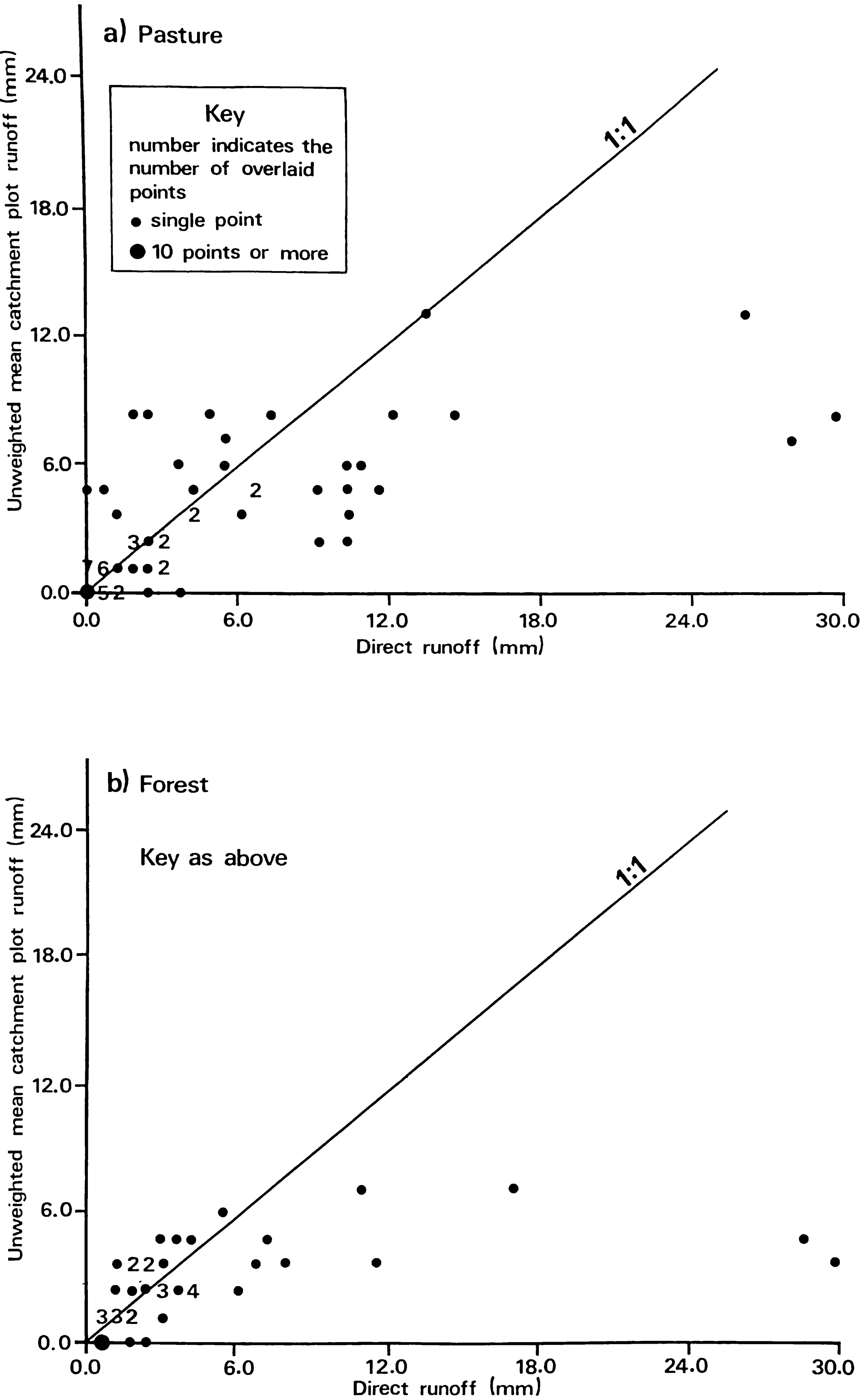


Figure 7.8a,b: The relationship between weekly unweighted mean sub-catchment unit plot runoff and weekly direct runoff totals from the pasture (a) and forest (b) land use catchments. Note: the surface runoff plots under estimate direct runoff in large storm events

Assumptions of similar contributions to direct runoff from each sub-catchment unit may not be valid for small storms, particularly in the forest land use catchment. However, surface runoff from the forest riparian sub-catchment unit can account for all direct runoff for about 50 % of storm events yielding less than 6 mm of direct runoff (figure 7.8b). In the pasture, surface runoff from the riparian sub-catchment unit can account for all direct runoff for about 35 % of storms yielding less than 6 mm of direct runoff. In the remaining storms, contributions of surface runoff may occur from the upslope sub-catchment units. Larger volumes of surface runoff, generated from the upslope sub-catchment units, are likely to reach the stream channel in the pasture catchment compared with the forest, because of greater overland flow velocities.

During the two year period of intensive observations, several visits were made to the catchments during periods of heavy rain. During these storm events, surface runoff was observed to be channelled rapidly into topographic hollows and re-entrants. The rapid channelling of surface runoff effectively increased the drainage network, so that overland flow paths were generally less than about 25 metres. As a result of channelling, opportunities for infiltration of surface runoff derived from upslope areas were reduced and contributions of surface flow from upslope positions were able to reach the stream channel more rapidly.

The field observations also showed that the slope areas contributing surface runoff were dynamic and spatially variable and depended on the extent of overland flow development. The effects of the spatial variability of soil permeability on the spatial distribution of surface runoff (see section 6.4.1) were not detected during these visits to the catchments.

7.4.2.2 Relationships between the time distribution of surface runoff and stream flow

7.4.2.2.1 Data collection, data analysis and results

Surface runoff was recorded continuously from half the plots in each land use catchment. The recording equipment and plot layout are described in chapter 4. Unfortunately, complete, usable, data sets were obtained for only a few observation periods because of mechanical or electrical failures in the recording system. Consequently, data from only one large storm are examined in this section. The storm chosen shows the characteristics typical of a range of storm inputs.

Figure 7.9 and 7.10 show the hyetograph and plot runoff from the sub-catchment units in the forest and pasture land use catchments, for the period 27 - 28 August 1980. Only small differences were found between the time distribution of plot runoff from the sub-catchment units in both the land use catchments. Figure 7.11 shows the stream flow for each land use catchment for the same period.

No formal estimate of the effect of slope routing could be obtained with the experimental network installed in the land use catchments. However, during the period 27 - 28 August 1980, some surface runoff plots in each catchment were flooded by channellised surface runoff. These plots were located in steep re-entrants near the main stream channel and thus provided an estimate of the time distribution of slope runoff. The relationships, between the time distribution of plot surface runoff, slope drainage and stream flow, are presented in figure 7.12. Table 7.11 shows the lag time between the centroids of rainfall and the three flow processes shown in the associated figures.

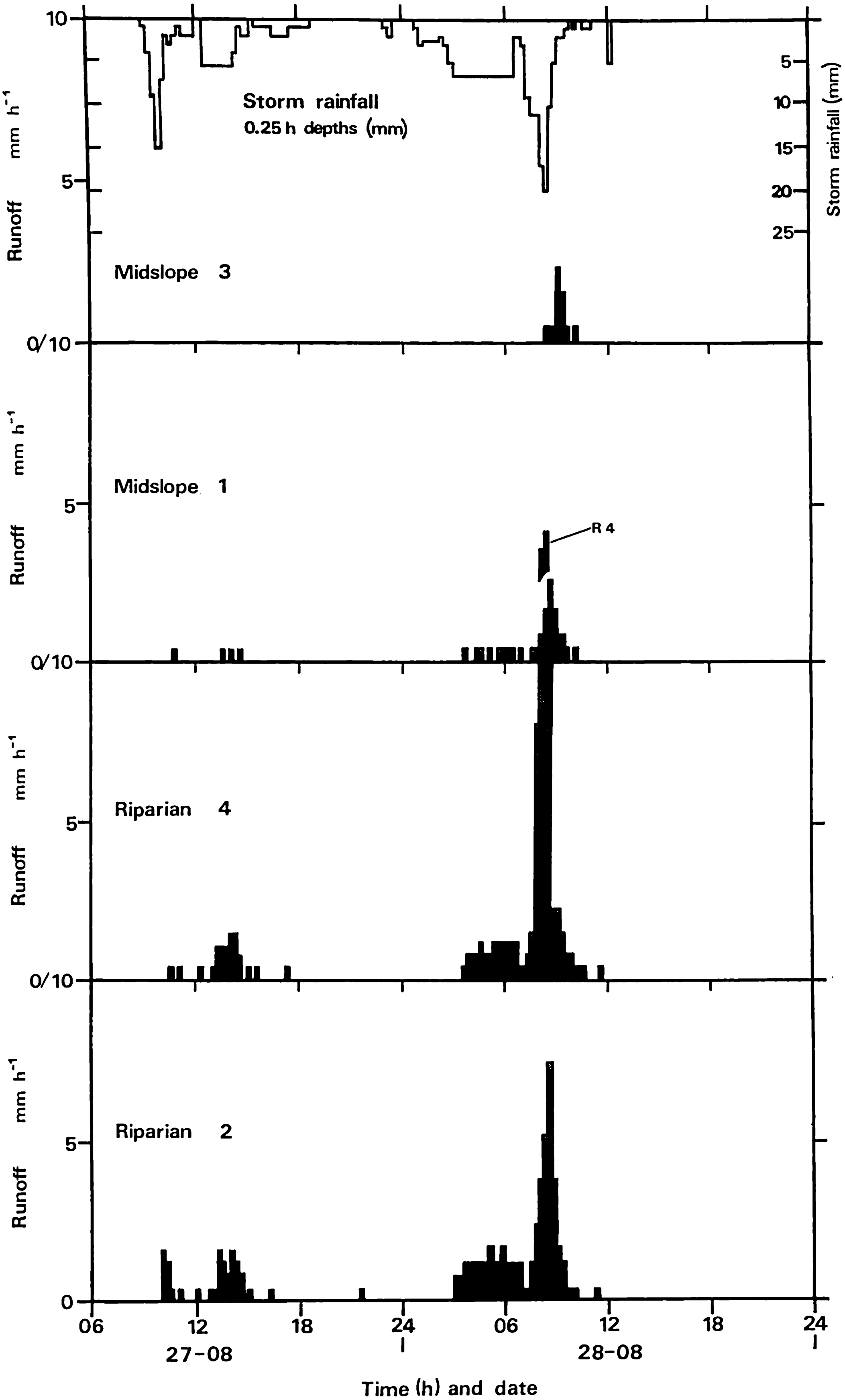


Figure 7.9 : The hyetograph and plot surface runoff in the pasture land use catchment for the 27-28th August 1980

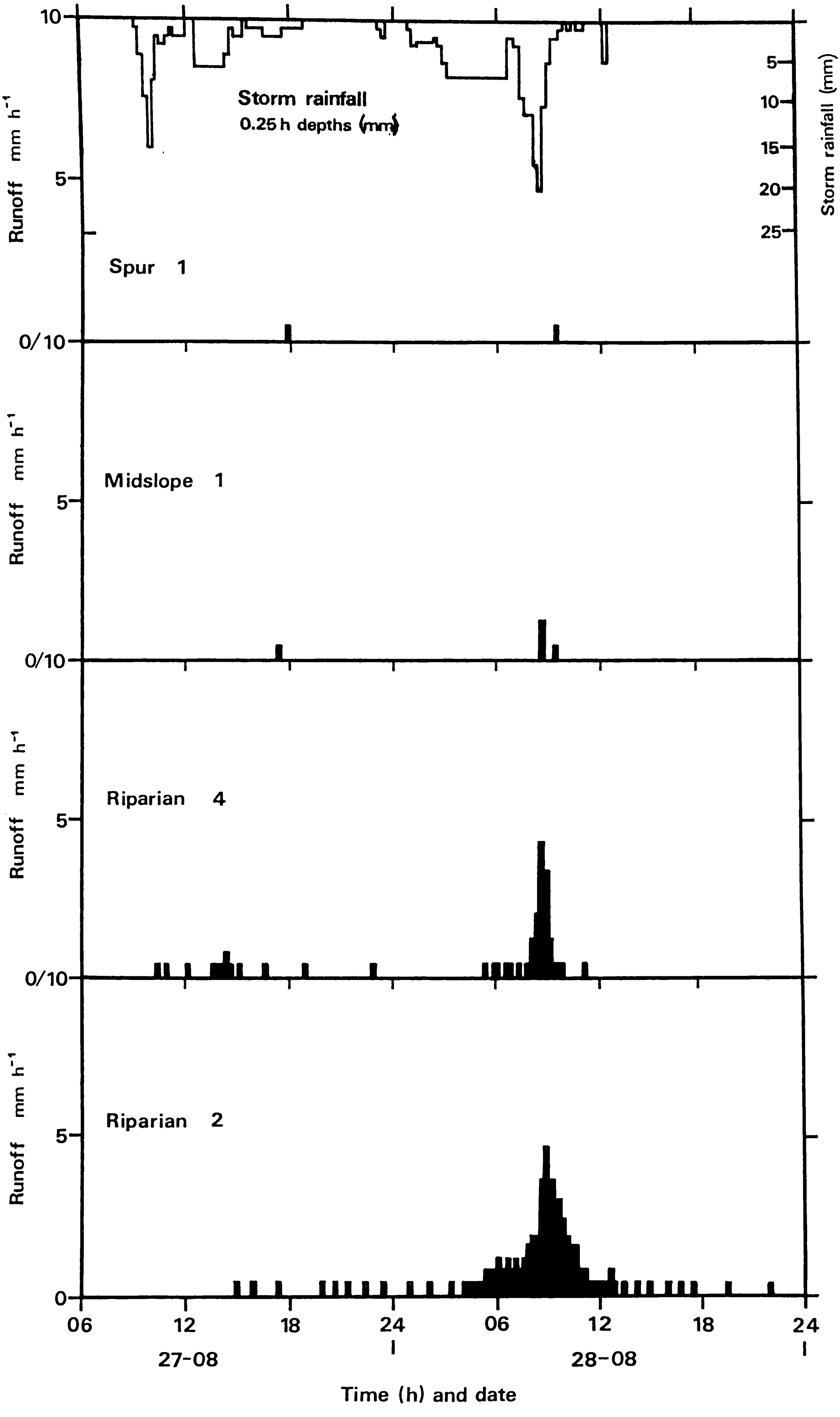


Figure 7.10 : The hyetograph and plot surface runoff in the forest land use catchment for the 27–28 th August 1980

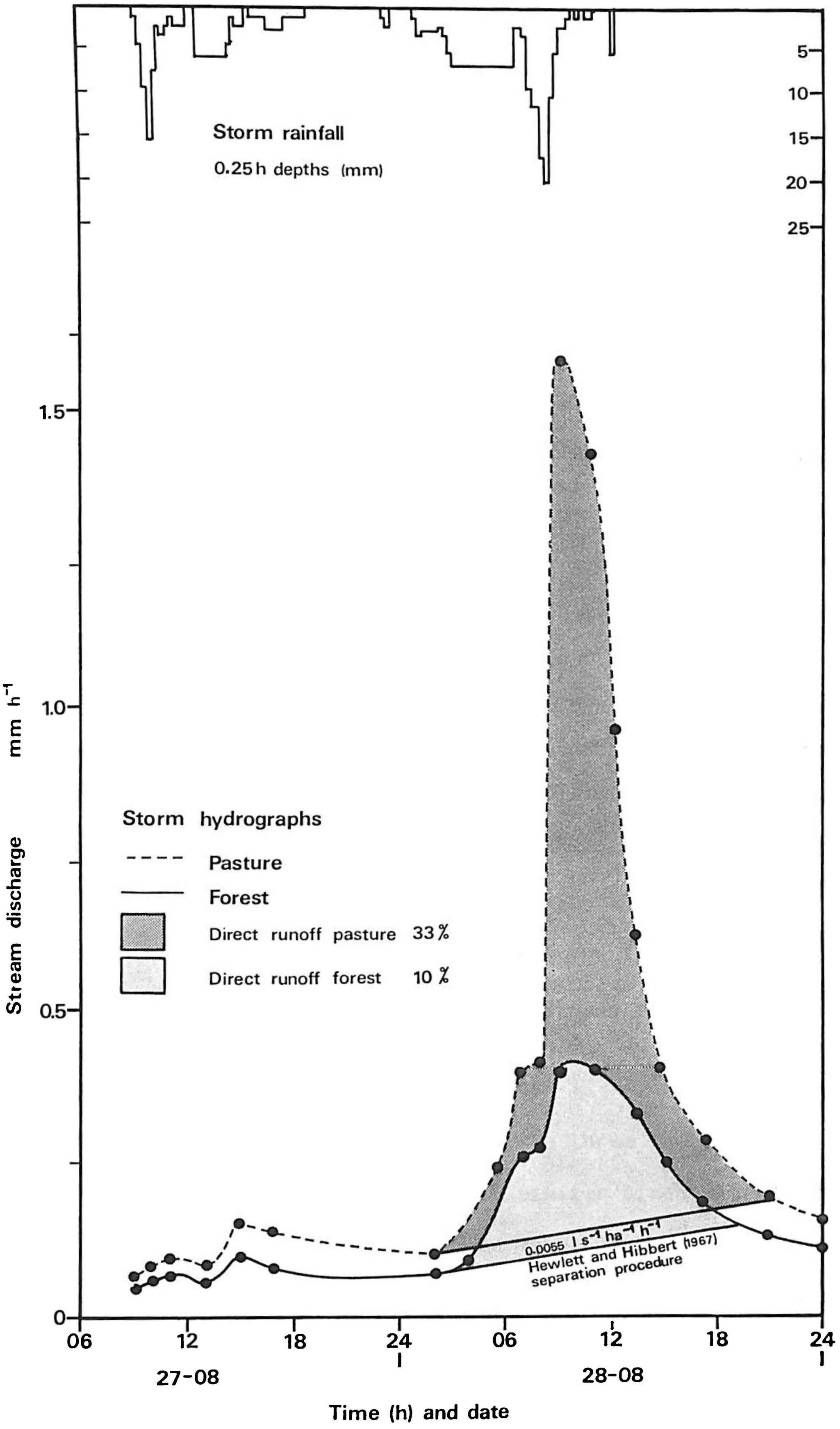


Figure 7.11 : The hyetograph and storm hydrographs for the two land use catchments for the 27-28th August 1980

7.4.2.2.2 Discussion

The data presented in table 7.11 allow comparisons to be made of the time distribution of rainfall, plot surface runoff, slope drainage and stream flow. While the absolute lag times between these three flow processes depend on storm characteristics and antecedent catchment conditions, the data in table 7.11 are typical of a range of storm inputs.

	PASTURE		FOREST	
Flow processes	Lag time (h)			
Surface runoff	Storm 1	Storm 2	Storm 1	Storm 2
Riparian a	0.75	2.25	*	2.75
Riparian b	0.75	2.25	1.5	2.75
Midslope a	1.25	2.50	*	*
Midslope b	1.25	2.75	-	-
Spur a	-	2.75	*	*
Spur b	-	*	-	-
Slope drainage	-	4.00	-	3.75
Stream flow	2.50	4.75	2.25	4.75

- no plot runoff

* storm yield too small to estimate the centroid

Table 7.11 : Lag times (h) between centroids of rainfall, plot surface runoff and stream runoff

The lag times between rainfall and the three flow components are large compared with those estimated for similar sized catchments supporting equivalent forms of land use (e.g. Toebes _et al_., 1968; Bonell _et al_., 1979; Scarf, 1973). These authors found that lag times, between rainfall and stream flow, were generally about 15 - 30 minutes. Differences in lag times between catchments can be caused by differences in surface detention (Scarf, 1973). The large lag times shown in table 7.11 suggest that surface detention storage is large, compared with the intermittent storm rainfall inputs that are typical of the Upper Mangawhara Valley (chapter 5). The uneven micro-topography of the pasture sward at the Mangawhara Valley is likely to result in greater surface detention storages, than for improved pasture sites. Lag times, similar to those observed in this study, have been reported for other rough pasture swards (see Selby, 1971).

The storm hydrographs show most of the characteristics expected for the two forms of land use (figure 7.11). Greater peak flows, greater base flows and greater direct runoff, all occur from the pasture catchment, compared with the forest. Also, the time to flow peaks and the lag times between rainfall and direct runoff are both similar in each land use catchment. These results verify the results of recent studies of stream flow characteristics from forest and non-forest vegetation (e.g. Hewlett and Helvey, 1970; Pearce and Rowe, 1979; Duncan, 1980). These studies suggest considerable differences between direct runoff yields and flow peaks from forest and other forms of land use. Only in a few studies have differences in lag times been reported between different forms of land use (e.g. Scarf, 1973).

A comparison between figure 7.9, 7.10 and 7.11 show that stream rises are initiated shortly after the development of overland flow in the surface runoff plots. Overland flow from the riparian sub-catchment units must reach the stream channel rapidly and generate the rising limb of the stream hydrograph. The slope of the rising limb of the forest stream flow hydrograph is less than that for the pasture, and can be explained by the lower overland flow velocities in this land use catchment. In both experimental catchments, the time distribution of direct runoff suggests that flow contributions from upslope sub-catchment units must be considerably delayed by slope and channel routing.

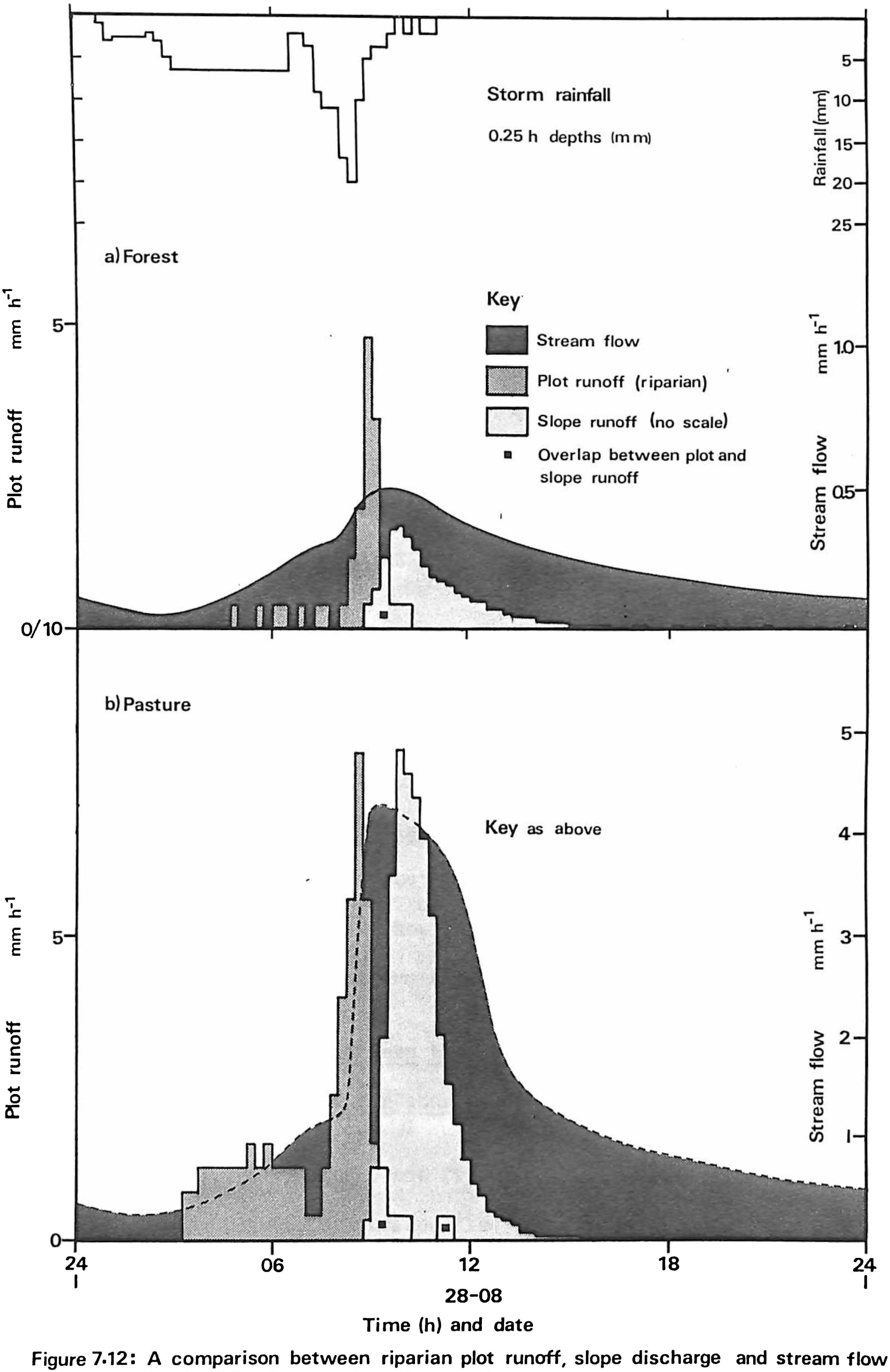


Figure 7·12: A comparison between riparian plot runoff, slope discharge and stream flow for the 28th August 1980 showing the time distribution of each flow component

In both land use catchments, slope drainage occurs for several hours following the end of rain and can contribute to the hydrograph recession (figure 7.12a,b). Lower overland flow velocities delay slope drainage in the forest, compared with the pasture catchment. Slope routing accounts for about 80 % of the time lag between rainfall and direct runoff in the two catchments (table 7.11 and figure 7.12a,b). The effects of channel storage and routing will also determine the time distribution of storm runoff from both land use catchments. These effects may be slightly larger in the pasture because of the higher discharges from this catchment. However the combined effects of slope and channel routing appear to be similar in each catchment (table 7.11).

7.4.3 SUBSURFACE FLOW - STREAM FLOW LINKAGE

The limited data available on subsurface flow processes restricts the detail with which the linkage between subsurface flow and stream flow can be examined. The relationships between subsurface flow and stream flow are considered for observations made during conditions of stream flow recession. Little information is likely to be gained from an analyses of peak subsurface flow rates and stream flow. The data presented in section 6.3.2 show that subsurface flow is unlikely to be important in determining storm flow from either land use catchment.

7.4.3.1 Relationships between the yields of subsurface flow and stream flow for conditions of flow recession

Figure 7.13a (pasture) and figure 7.13b (forest) show the relationships between subsurface flow and stream flow during conditions of flow recession. In the forest catchment, subsurface flow rates are smaller than stream flow for most conditions of recession flow. The ratio, of stream flow discharge to subsurface flow, varies from 1:1 (large subsurface flow rates) to about 50:1. In pasture land use catchment, similar results were observed. In both catchments, the specific discharges of subsurface flow and stream flow are similar, only when stream flow is low and the water table elevations are high. These conditions occur most frequently in summer, when the catchments' soils are most permeable.

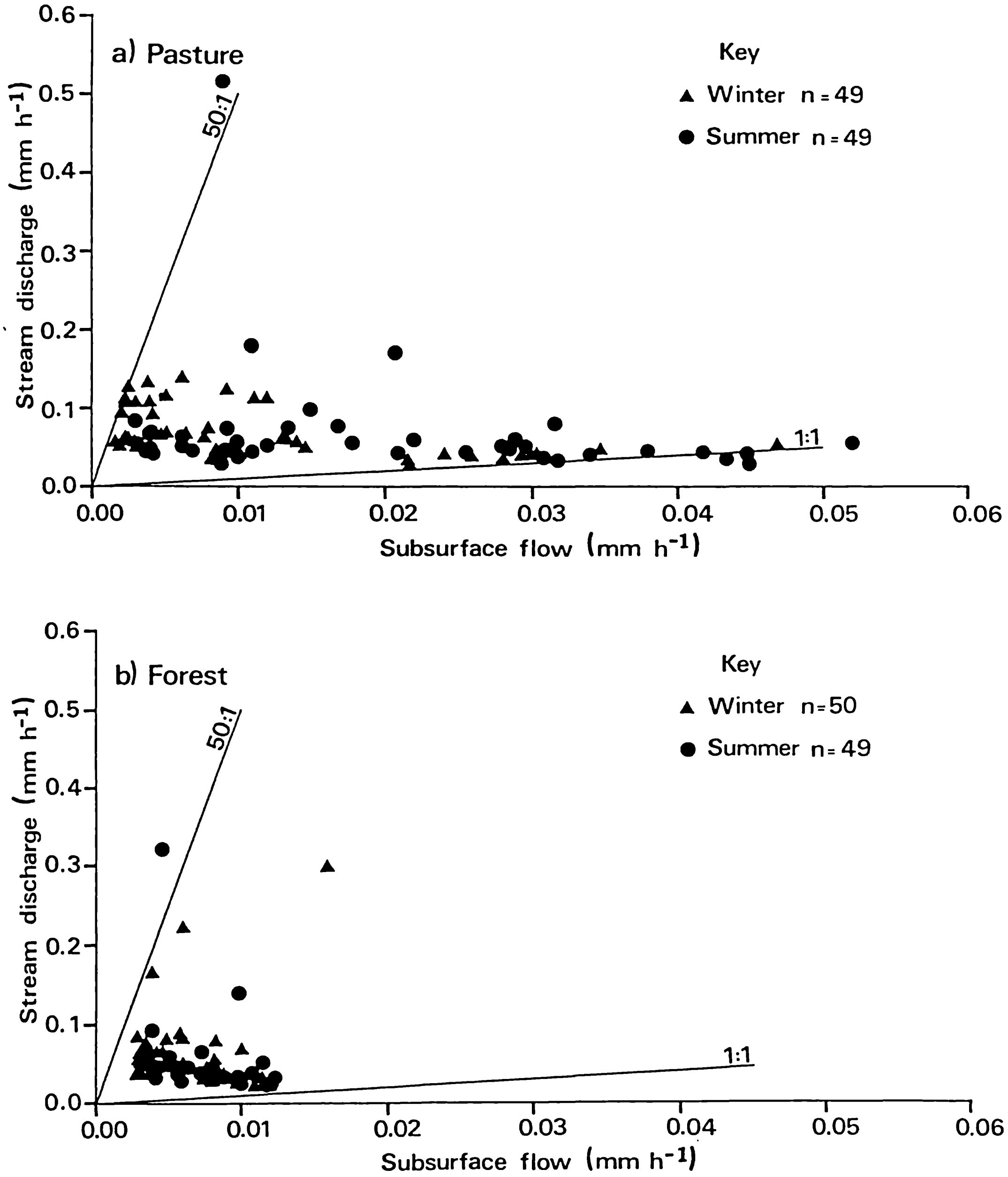


Figure 7.13a,b: The relationships between subsurface flow and stream discharge from the pasture (a) and forest (b) land use catchments (recession flow conditions)

As subsurface flow through the soil matrix can contribute all the stream flow only when the stream flows are very low, additional sources of flow are necessary to sustain flow during medium stream flows (i.e.

0.05 - 0.2 mm h^{-1}), when surface runoff has ceased.

7.4.3.2 Contributions of point sources of seepage to stream discharge

In both catchments, the additional sources of flow necessary to sustain stream flow during medium and low flow conditions appear to be derived from numerous seepage heads, that occur along the main stream channels and ephemeral stream lines. Point sources of seepage flow appear evenly distributed in both land use catchments, at locations that are independent of topographic features (i.e. hillslope hollows).

Figure 7.14 shows the relationships between stream flow and seepage flow recorded from the two first order basins, which were used for observations of saturated soil moisture conditions (see figure 6.8). In both land use catchments, specific discharges from the seepage heads draining the first order basins are greater than those in the main stream channel. However, the relationships between these flow components vary considerably with discharge. Together with subsurface flow through the soil matrix, seepage flow can account for all medium and low flows from each land use catchment.

Complex relationships are apparent between the flow from the seepage heads and flow from the saturated soil at the base of the two first order basins. Field observations provide little evidence of the relationships between these two flow processes. Undoubtedly there must be a strong linkage between the two flow regimes during low flow conditions.

Phipps (1982) analysed the water chemistry of these two flow processes in the two land use catchments. These analyses provide evidence to suggest that these two flow components are hydrologically distinct, with only a slow transfer of soil water from the soil matrix to deep seepage flow. The solute load of the flow from seepage heads is generally independent of storm rainfall inputs.

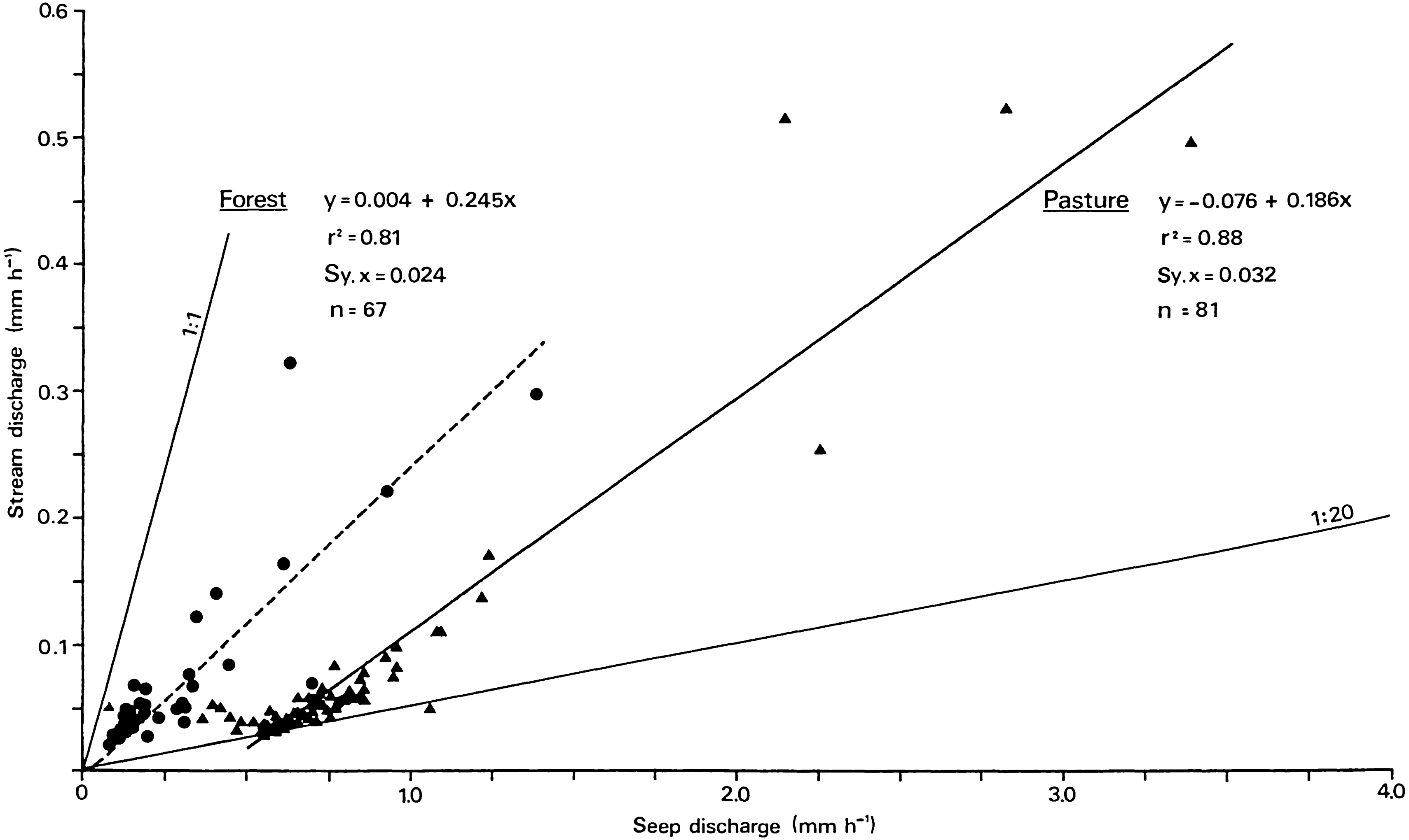


Figure 7.14: The relationships between seep discharge from the instrumented first order basins and streamflow from the forest and pasture land use catchments

Nevertheless, a slight seasonal reduction in the solute load occurs during the winter months, when soil moisture and vertical drainage from the regolith are at a maximum.

The water chemistry of subsurface flow through the soil matrix is considerably more variable. During periods of no rainfall, the solute load of the subsurface flow through the soil matrix increases to a level found in the seepage flow from point sources. During rain, the solute load decreases toward that of the incident rainfall, after an initial period of solute flushing (Phipps, 1982). These observations suggest that the seepage heads are linked to the permanent ground water table. These observations also suggest that the subsurface flow, and flow from the seepage heads, act as hydrologically distinct flow processes during rainfall.

Phipps (1982) also compared the variations of the dissolved silica concentrations of the seepage flow from point sources and stream flow, for several storm events. These comparisons showed that flow from the seepage heads is an important component of stream flow only during low flow conditions. Unfortunately, the chemical data does not provide sufficient information for an accurate estimate of the increases in ground water flow rates during storm conditions. Nevertheless, figure 7.14 shows that large deviations in the relationship between stream flow and seepage flow occur at stream flow discharges over about 0.2 - 0.25 mm h^{-1}. These discharges are similar to the lower limits of direct runoff for each land use catchment (see figure 7.11). The deviations shown in figure 7.14 suggest that seepage flow contributions are diluted by surface runoff components at higher stream discharges.

The analyses of stream water chemistry provided no information on the likely increase of subsurface flow rates during storm conditions. However, compared with the stream flow data presented in chapter 8, the data presented in figure 7.13 show that subsurface flow is unlikely to be important in determining storm flows from the two land use catchments.

Thus, both subsurface flow and seepage flow appear unlikely to be major contributors to storm runoff, in either the forest, or pasture land use catchment. Nevertheless, they appear to be important in determining stream flow volumes during base flow conditions.

7.4.3.3 Relationships between the time distribution of subsurface flow components and stream flow

Only limited data were available on the time distribution of subsurface flow components. On two occasions during the 2 year observation period, recordings of water table elevations were completed immediately following rainfall and the associated stream rise. These data suggest that subsurface storm flow peaks at about midway during the stream flow recession, followed by a decrease to the pre-storm discharge. During these storms, the upslope piezometers were observed to recess more rapidly than those near the stream channel, indicating a net downslope movement of infiltrated rain water.

The results described above suggest that the subsurface flow response is much slower and less important in determining the stream hydrograph in the two land use catchments, than reported in other studies of similar forms of land use (e.g. Bonell et al., 1979; Mosley, 1979; Pearce and McKerchar, 1979). However, the results are consistent with the differences between the soil permeabilities and soil moisture conditions reported in this study and those described in the studies cited above.

7.5 CONCLUSIONS

7.5.1 SURFACE RUNOFF COMPONENTS

The seasonal pattern of surface runoff varies within and between the two land use catchments. For all storm events, the spatial pattern of surface runoff production from the forest catchment conforms with hillslope runoff models inferred commonly for humid temperate climates. Greatest yields of surface runoff occur from the riparian sub-catchments, with proportionally less occurring from the upslope catchment areas.

In the pasture catchment, the spatial distribution of surface runoff production varies seasonally. During winter, the largest yields of surface runoff are derived from the riparian catchment areas. During dry antecedent conditions, the greatest yields of surface runoff are derived from the midslope and spur sub-catchment units. The development of water repellency, in the midslope and spur sub-catchment units during summer, can explain the increased yields of surface runoff from these catchment areas, compared with the damper riparian areas. Thus, this hypothesis can explain the seasonal reversal in the spatial distribution of surface runoff production found in the pasture land use catchment. However, direct evidence for this hypothesis was found in only a few sites.

The spatial distribution of surface runoff production from both land use catchments can be explained by partial area contributions of infiltration-excess overland flow. Characteristics of rainfall and soil permeability determine the volumes of surface runoff observed at most sites in the land use catchments. The spatial distribution of surface runoff production is related generally to the spatial variability of surface soil permeability. Evidence for saturation overland flow was found only in restricted areas of the riparian sub-catchment unit of the pasture catchment. The areas that produce saturation overland flow are characterised by high antecedent soil moisture contents and a strongly concave hillslope form.

Direct evidence for infiltration-excess overland flow was found at only 2 sites in the forest catchment. However, the soil permeability data and characteristics of the rainfall regime provide strong evidence for infiltration-excess overland flow as the dominant mechanism of surface runoff production in the forest catchment. Modification of the net rainfall regime by interception processes, and characteristics of the organic litter layer, are both thought to mask relationships between the catchment rainfall and surface runoff observed in the forest catchment. No evidence for saturation overland flow was found in the forest catchment.

7.5.2 SUBSURFACE FLOW COMPONENTS

In both land use catchments, the spatial distribution of subsurface flow conforms closely to that suggested by the variable source area concepts. Subsurface flow is seasonally variable, being dependent on variations in water table elevations and soil permeability. Insufficient data were available to determine the spatial distribution of non-Darcian subsurface flow. Evidence from the soil permeabilities suggest that this process is quantitatively unimportant, compared with other hillslope runoff processes occurring in each catchment.

Subsurface flow in the pasture was found to be greater and more responsive to rainfall, than in the forest. A correlation analysis was used to establish the degree of association between subsurface flow components and a suite of explanatory variables. Total weekly rainfall is the variable most highly correlated with subsurface flow peaks in the pasture catchment, while antecedent soil moisture is the variable most correlated with subsurface flow peaks in the forest. These results conflict with the accepted generalisation that subsurface flow occurs more readily in forested catchments. Compared with the forest catchment, the greater subsurface flow discharges from the pasture can be explained by several factors. These factors are:

i) the greater net rainfalls in the pasture catchment compared with the forest;

ii) the generally lower available soil moisture storage in the pasture riparian areas, compared with similar areas in the forest;

and iii) the slightly greater soil permeabilities in the pasture riparian catchment areas.

In addition to subsurface flow through the soil matrix, ground water flow contributes to low and medium flows during periods of stream flow recession.

7.5.3 HILLSLOPE RUNOFF - STREAMFLOW LINKAGE

Surface runoff is suggested as the main source of most of the direct runoff from both land use catchments. Subsurface flow through the soil matrix is too slow to contribute large volumes of storm runoff to the stream channel. Subsurface flow is sufficient to maintain low flows in the stream channel, but only when water table elevations are high, or when the catchment soils are permeable (dry antecedent soil conditions). In addition to subsurface flow through the soil matrix, ground water discharge, through a network of seepage zones, can maintain low and medium flows in the stream channel. Although subsurface flow and ground water flow appear closely linked in the field, the water chemistry of each component suggests that they are hydrologically distinct flow regimes.

The time distribution of direct runoff is similar for the two land use catchments. Both catchments exhibit a slow response to storm rainfall, compared with other catchments of similar size. About 80 % of the lag time between the centroids of storm rainfall and direct runoff results from slope routing processes. This suggests that the surface detention storage is large in each land use catchment. In combination with intermittent rainfall inputs, the large surface detention storage may cause the unusually slow storm flow response in the catchments, even though hillslope runoff is dominated by infiltration-excess overland flow mechanisms.

In both land use catchments, the spatial variability of the 'effective' source areas of surface runoff production are similar to those found commonly in humid temperate environments. However, the detailed examination of hillslope runoff processes shows that the mechanisms of surface runoff production are different to those inferred commonly for vegetated catchments in humid temperate climates. The principal reason, for the predominance of infiltration-excess overland flow in both the land use catchments, is the low permeability of the catchments' soils.

These results suggest that the spatial distribution of runoff mechanisms alone, may not indicate the appropriate model of hillslope runoff. Consequently, land management decisions may be in error if they are made on assumptions implied by observations of the spatial distribution of hillslope runoff. Detailed analyses of all aspects of the hillslope runoff regime thus appear necessary for all studies of source area hydrology

CHAPTER EIGHT

STREAM FLOW PROCESSES AND THE CATCHMENT WATER BALANCE

CONTENTS

8.1 INTRODUCTION

An examination of stream flow characteristics and water balance components has formed the basis of most catchment scale experiments established for hydrologic research. These studies have been established, mainly to compare rainfall-runoff mechanisms between different catchments (eg. Walling, 1977; Pearce and McKerchar, 1979), or to evaluate the influence of land use change on stream flow regimes (eg. Hewlett and Helvey, 1970; Swank and Helvey, 1970; Pearce and Rowe, 1979; Bosch and Hewlett, 1982).

Several researchers have criticised the use of data from catchment scale experiments for making inferences about hydrologic processes, because analyses of stream flow can not identify the mechanisms of hillslope runoff processes (Slivitsky and Hendler, 1965; Ackermann, 1966; Ward, 1971). The critics of catchment scale experiments suggest that process studies are more suitable as an experimental technique, because they are more rapid, less expensive, and no less accurate than traditional catchment experiments (Pearce, 1980).

In this study, an integrated approach has been emphasised, comprising both hillslope process studies and some catchment scale studies. This chapter describes an analysis of the stream flow characteristics of the two land use catchments. It is presented as a complement to the process-oriented studies of hillslope runoff components, described in chapter 6 and 7.

The principal sub-objectives of this chapter are:

i) to examine the discharge characteristics of each land use catchment;

and ii) to estimate the water balance components for each land use catchment.

8.2 THE DATA SET AND DATA ANALYSIS

8.2.1 THE DATA SET

Stream flow from each vegetation type was measured with the data collection network described in chapter 4. Flow records were manually digitised for the period of intensive observations. As the two forms of land use are contiguous areas within a single catchment, the estimates of discharge from the pasture 'area' (catchment) were obtained by difference (i.e. the discharge recorded at the forest site was subtracted from the discharge observed at the pasture site to provide an estimate of stream flow from the pasture 'area' (catchment) (see chapter 4)). Linear interpolation was used to estimate discharge for the pasture catchment when the flow recordings from the two sites were not concurrent. Missing records from each site were estimated from a non-linear, best fit relationship derived between the two flow sites. Missing records formed only a small percentage of the total record observed for each land use catchment.

The final data series comprised concurrent discharge estimates for each land use catchment, for the period July 1979 to July 1981.

8.2.2 DATA ANALYSIS

The analysis of stream flow characteristics is considered in two sections. Firstly, the general flow characteristics from each land use catchment are examined by an analysis of flow frequencies, and weekly flow maxima. Conventional techniques were used for these analyses. An EV II distribution was fitted to the weekly flow maxima recorded from each catchment, following the procedures described in section 6.2.2.1.2. Using the notation of Johnson and Kotz (1970), the EV II distribution function is defined:

$$P_{(x \leq x)} = \exp -\left(\frac{x - \xi}{\theta}\right)^{-c} \quad (x \geq \xi) \qquad (1)$$

where ξ is the location parameter (upper bound),

θ is the scale parameter,

and c is the shape parameter.

Secondly, unit hydrographs are used to evaluate the influence of land use type on the storm flow response from each catchment.

Unit hydrograph techniques have been used successfully in assessing the effects of increasing urbanisation in predominately rural catchments (Rao and Delleur, 1974). However, they have seldom been used for comparing storm runoff characteristics from different forms of rural land use. Unit hydrograph techniques have considerable advantages for this purpose, compared with statistical and more complex process-oriented models (Rao _et al_., 1979) that have been used more commonly (eg. Toebes _et al_., 1968; Hewlett and Helvey, 1970; Scarf, 1973; Langford and McGuiness, 1976; Harr and McCorison, 1979; Swift and Swank, 1981).

Unit hydrograph analyses are considerably more flexible than statistical techniques, as they are not necessarily restricted by the requirements of homogeneity of variance and independence of successive observations. Unit hydrograph techniques also allow the whole storm hydrograph to be described simply, instead of just a single feature (eg. flow peaks).

Unit hydrograph methods are simpler than most complex process-oriented models (eg. those described by Boughton, 1966, 1968; and Holtan _et al_., 1975): they are less prone to problems of parameter estimation and interpretation (Chapman, 1975), and to difficulties in accommodating process-response thresholds accurately within the model structure (McKerchar, 1980a).

Unit hydrograph methods may have some disadvantages when used to evaluate the hydrologic effects of different forms of land use (Rao *et al.*, 1979). The influence of different forms of land use on catchment storm responses may be detected only in small catchments and for small rain events. In large catchments, channel routing effects may attenuate the differences in the storm hydrograph response attributable to land use type. In large storm events, the effect of different interception losses, available soil moisture storage and other soil properties may be small, compared with the total storm output recorded from each catchment.

The assumption of linear, time invariant relationships, between net rainfall and the consequent runoff response, is also a limitation of unit hydrograph theory. These problems are most apparent in small catchments.

8.3 GENERAL FLOW CHARACTERISTICS OF THE LAND USE CATCHMENTS

8.3.1 RESULTS

Differences in the general flow characteristics from the two land use catchments occur throughout the range of discharges recorded (figure 8.1, 8.2 and 8.3).

The flow duration curves (figure 8.1) are truncated at a specific discharge of 1.0 mm h^{-1} (277.78 l s^{-1} km^{-2}), because stream discharges greater than this value occur infrequently (e.g. 0.46 % of the time in the pasture and 0.42 % of the time in the forest). The flow duration curves show that discharge from both vegetation types is characterised by long periods of low flow, punctuated by large, short duration stream rises in response to rainfall.

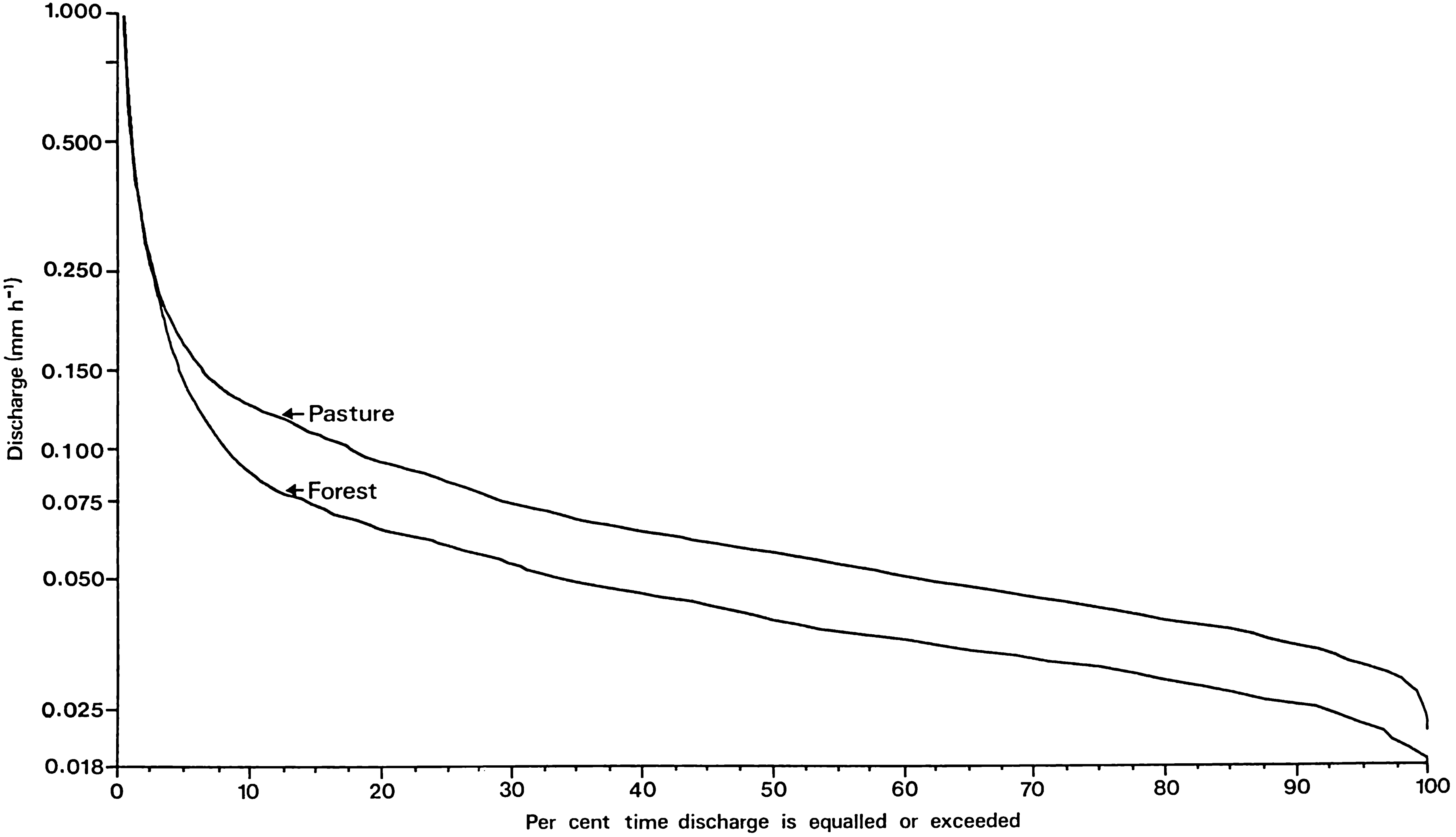


Figure 8.1: Flow duration curves for the forest and pasture land use catchments, Upper Mangawhara Valley

For about 95 % of the time, flow is less than an order of magnitude from the minimum recorded in each land use catchment (0.022 mm h $^{-1}$, pasture; 0.018 mm h $^{-1}$ forest).

The largest differences in flow frequency distribution occur below 0.2 mm h $^{-1}$ (55.6 l s $^{-1}$ km $^{-2}$), when contributions of subsurface and ground water flow are large and surface runoff components are small or non-existent.

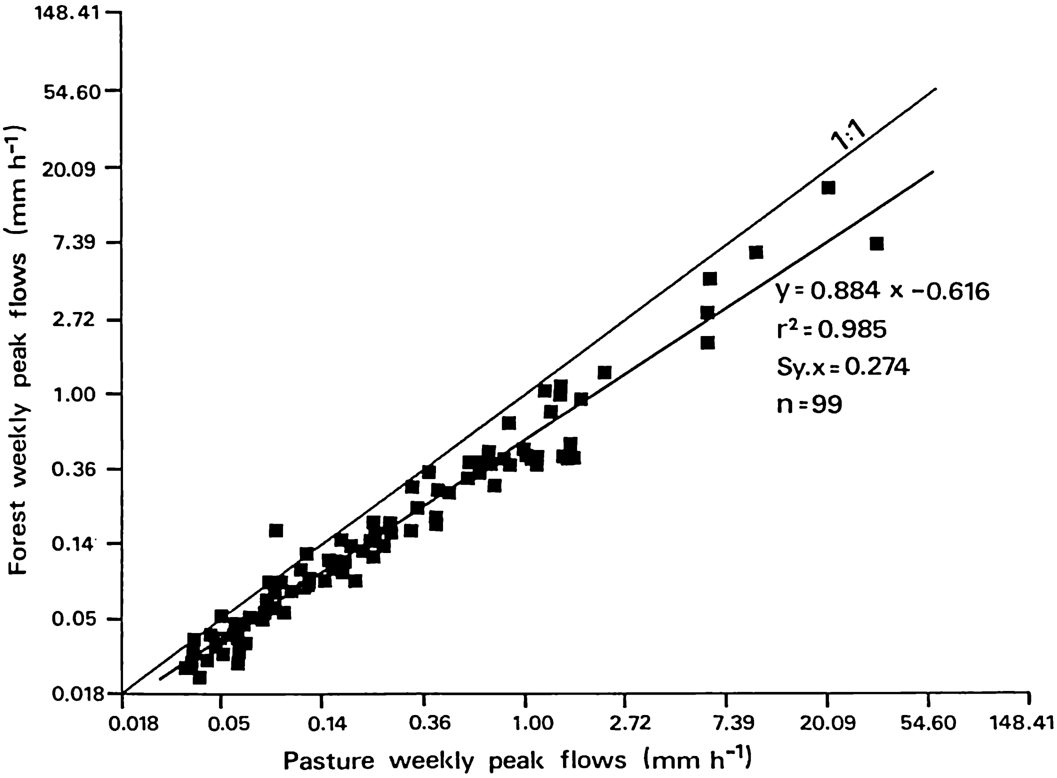


Figure 8.2: The relationships between the weekly peak stream discharges from the forest and pasture land use catchments, Upper Mangawhara Valley (log/log scale)

Figure 8.2 shows a comparison of the weekly peak flows from each land use catchment. The distributions of weekly peak flows from the two catchments are shown by the fitted EV II density functions (figure 8.3). For all storm events, peak flows for selected return periods are larger in the pasture, than in the forest. Table 8.1 shows the predicted discharges from each land use catchment for selected return periods.

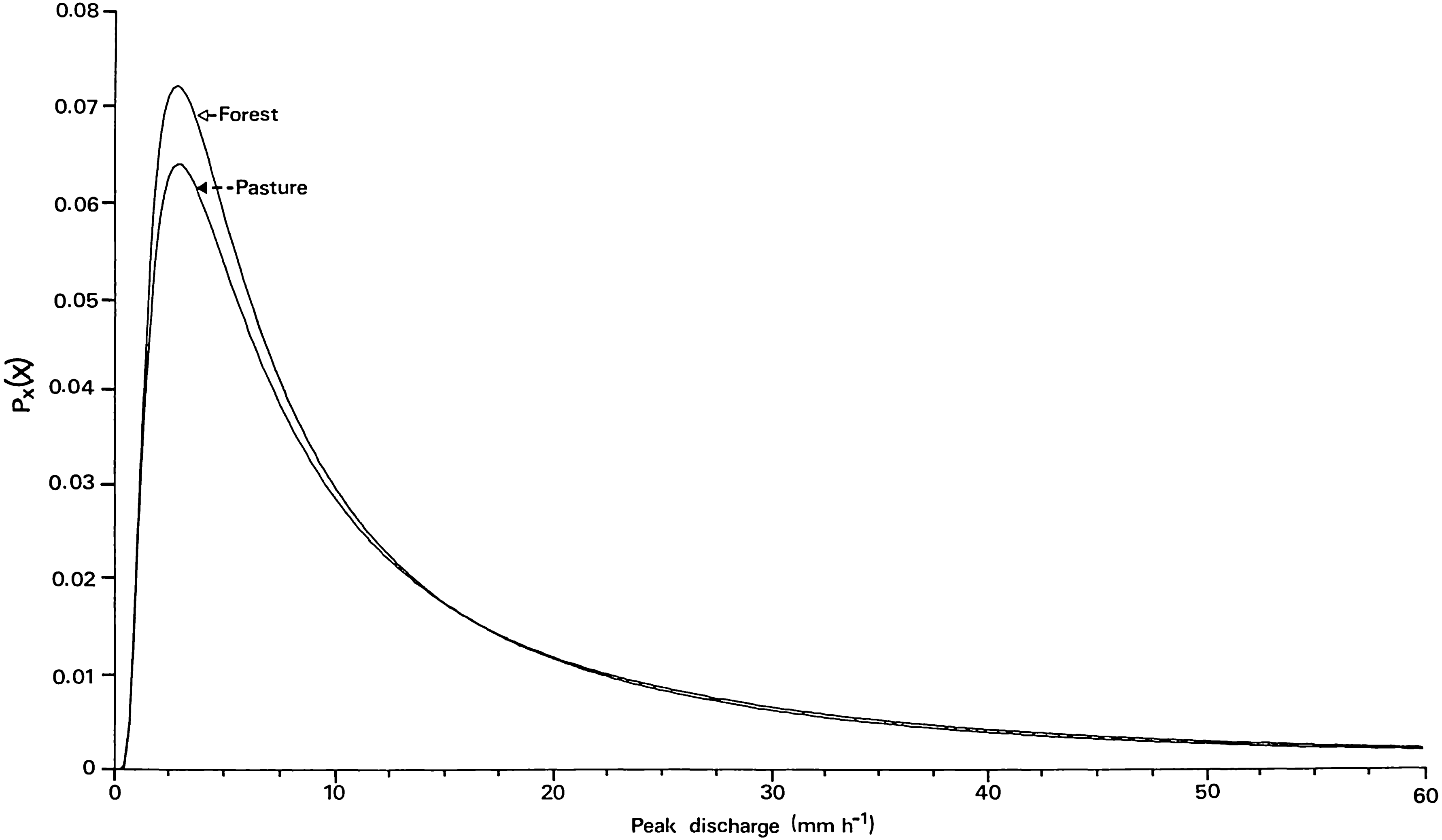


Figure 8.3: EV II probability density functions for weekly peak discharges from the forest and pasture land use catchments, Upper Mangawhara Valley

Return period (weeks)	Discharge (mm h^{-1}) Pasture	 Forest
2	13.12	11.28
4	40.47	32.60
26	520.00	361.00
52	1285.00	845.00

Table 8.1 : Estimated weekly peak discharges from the land use catchments for selected return periods

The discharge estimated for the '26' and '52' week return periods may be under-estimated, as some of the largest events recorded over-topped the flow recording structures and were not included in the analysis.

8.3.2 DISCUSSION

8.3.2.1 General flow characteristics

The flow frequency distributions for each catchment are typical of catchments with clay-rich soils. The low soil permeabilities, combined with the large total soil moisture storage, can cause the sharp division in surface and subsurface flow processes shown in figure 8.1 (see also table 6.7, section 6.2.1.3.1; appendix.F). The sharp inflection in the flow duration curves (0.10 - 0.15 mm h^{-1}) suggests that a gradual transition between subsurface and surface flow mechanisms does not occur in either land use catchment. This result implies that variable source area flow mechanisms do not predominate in the two catchments examined.

The general flow characteristics described in section 8.3.1 are typical of each vegetation type in similar steepland environments. The plot of the log transformed weekly peak flows, from each land use catchment, shows surprising linearity (figure 8.2). However the slope of the best fit line (log/log scale) shows that the relationship between the untransformed data sets is non-linear: the larger the storm event, the greater the difference between the peak discharges from the two catchments. However, the proportional differences between peak flows from each land use catchment tend to decrease with increasing storm size. In successively larger storms, the difference in antecedent catchment conditions becomes less important between the two catchments. This result is similar to those reported in other comparative land use studies (e.g. Hewlett and Helvey, 1970; Pearce et al., 1980a).

8.3.2.2 General flow characteristics and land use type

Several factors explain the different flow frequency distributions and weekly peak flows observed from the two land use catchments. Compared with the forest, the greater peak flows and low flow discharges in the pasture can be explained by the greater yields of surface and subsurface flow that occur in this land use type (chapter 7). Differences in these hillslope flow processes are, in turn, caused by the larger net rainfall input in the pasture catchment and by differences in the water storage and transmission properties between the catchments' soils.

The different non-storm flow characteristics from each land use catchment can be explained by smaller subsurface/ground water discharges from the forest, compared with the pasture (section 7.4.3). These, in turn, are determined by the differences between average available soil moisture storage, soil permeabilities (chapter 6) and ground water elevations found in the riparian areas of each catchment.

The rapid transition, from low flow conditions to storm flow conditions, appears to coincide with the development of infiltration-excess overland flow in each land use catchment. The flow frequency characteristics from each catchment are similar for medium flow ranges (0.2 - 0.25 mm h^{-1}). These are probably caused by the similar annual overland flow discharges derived from riparian areas in each catchment (see table 7.3, section 7.2.3.2).

In large storms, surface runoff from midslope and spur sub-catchment units are more likely to reach the stream channel in the pasture catchment, than in the forest (section 7.4.2.1.2). Additional contributions from these areas may explain the differences in weekly flow maxima for each land use catchment (figure 8.2, 8.3; and table 8.1).

The relationships, between the surface and subsurface runoff regimes and the soil physical properties of the catchment soils (chapter 6 and 7), may also explain the differences between the stream flow characteristics of the catchments described here and those reported for other similar sized catchments and vegetation types in New Zealand (eg. Pearce et al., 1976, 1982; Herald, 1979; Duncan, 1980).

8.4 UNIT HYDROGRAPH ANALYSIS

The development, assumptions and methods of unit hydrograph analysis have been described by many authors (eg. Nash, 1960; Natural Environment Research Council (N.E.R.C.), 1975; Dooge, 1979; Boorman and Reid, 1981). A representation of unit hydrograph theory is presented in figure 8.4. There are, however, some difficulties in estimating accurately unit hydrographs from small catchments.

8.4.1 CATCHMENT NON-LINEARITIES

Non-linear rainfall-runoff processes are most apparent in small catchments (Pilgrim, 1976). Rao et al. (1972) suggest that there may be no unique catchment unit hydrograph and that derived unit hydrographs may vary from storm to storm. The lack of uniqueness of unit hydrographs derived from different storms is attributed usually to inconsistences in the input data (Mawdsley and Tagg, 1981), or to inadequacies of unit hydrograph theory for approximating non-linear rainfall-runoff processes (Diskin and Boneh, 1975).

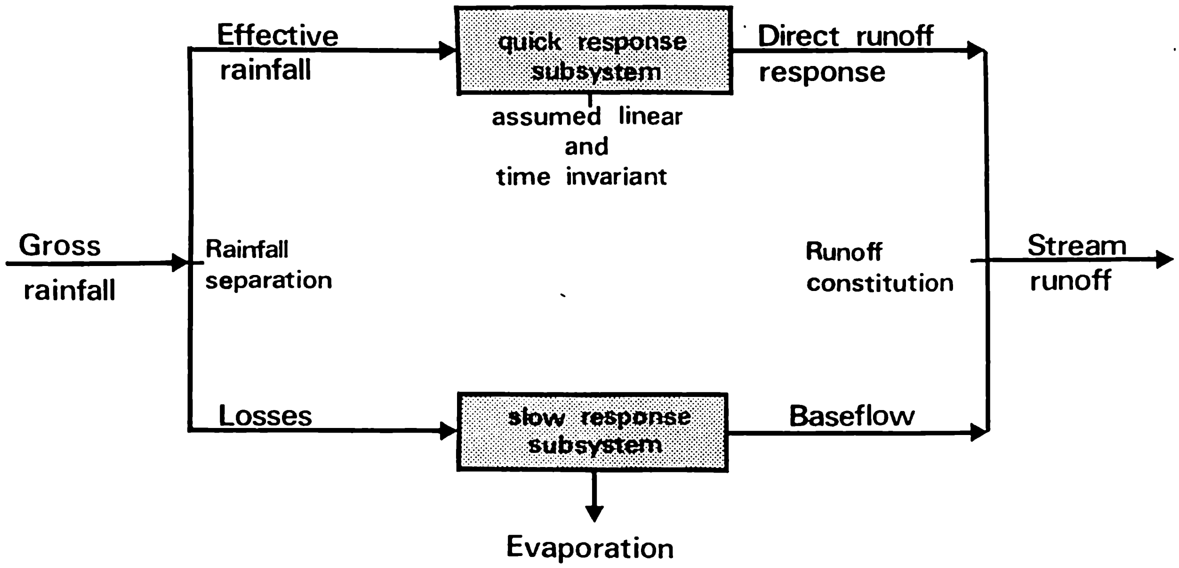


Figure 8.4: A system representation of the unit hydrograph approach (after Boorman and Reid, 1981)

The recognition of possibly non-linear, but more often, inconsistent relationships between catchment rainfall-runoff processes (N.E.R.C., 1975) has led to the estimation of catchment average unit hydrographs from multiple events (Diskin and Boneh, 1975; Boorman and Reid, 1981; Mawdsley and Tagg, 1981). There is, however, little information available on the relative merits of unit hydrographs derived from single or multiple events: Mawdsley and Tagg (1981) suggest slightly improved estimations for analyses based on up to 8 events.

It has been suggested that deficiencies, in both the estimation of effective net rainfall and storm flow separation, account for the difficulties described above. Boorman and Reid (1981) suggest that the rainfall separation procedure is the most important component of the unit hydrograph analysis, as it determines the estimated volume of surface runoff. They consider the hydrograph separation techniques are less important. However, Rao et al. (1979) suggest hydrograph separation procedures must be standardised, if unit hydrographs are used to evaluate the hydrological effect of different forms of land use.

8.4.2 THE CHOICE OF A PROBABILITY DENSITY FUNCTION TO DESCRIBE CATCHMENT UNIT HYDROGRAPHS

Unit hydrographs are specified often in terms of some probability distribution. These techniques are used for their simplicity and ease of interpretation and because all the information of the storm runoff response is summarised in a few parameters. Generally, the parameters of an appropriate probability density function are optimised by an iterative procedure and appropriate fitting criterion.

The gamma distribution appears to be the most popular of a variety of suitable distributions (Croley II, 1978; Haan and Barfield, 1978). However, the gamma distribution is unable to describe unit hydrographs for catchments with runoff responses characterised by short times to peak flow, high peak flows and rapid initial rates of recession (Bardsley, 1983).

The inverse Gaussian distribution has been suggested as being more appropriate in these situations, because the peak discharge of an inverse Gaussian hydrograph can be up to 4.7 times the centroid discharge, compared with only 2.0 in the case of the Gamma distribution. The physical justification of the inverse Gaussian distribution is about the same as for the Gamma distribution (Bardsley, 1983).

The inverse Gaussian distribution is used in the unit hydrograph analyses described here because it can describe more accurately the storm runoff responses from the land use catchments.

8.4.3 THE APPROACH

The non-linear hillslope runoff responses, described in chapter 7, suggest that the integrated catchment storm runoff responses will also be non-linear. Consequently, a non-linear rainfall separation procedure was incorporated in the unit hydrograph analysis, so that the hydrological effect of the two forms of land use could be determined accurately. In this way, non-linearity was introduced simply into the gross rainfall-stream flow system (figure 8.4), while retaining the simplicity of linear unit hydrograph theory. This procedure does not violate the assumptions of linearity in general unit hydrograph theory: linear relationships still exist between effective rainfall and the unit hydrograph.

In the non-linear rainfall separation procedure, effective rainfall is defined to be dependent solely on the gross rainfall input. Some limitations in this procedure are recognised. The separation of effective rainfall does not take into account the effects of different antecedent catchment conditions and preceding storm inputs.

The soil permeability analyses (chapter 6) show that steady-state infiltration rates are established quickly in both land use catchments, for given antecedent catchment conditions. Thus, changes in soil permeability during storm rainfall are probably small and generally independent of successive rainfall inputs. However, seasonal changes in antecedent catchment conditions do cause large changes in soil permeability. For this reason, unit hydrographs were estimated separately for summer and winter storm events.

The unit hydrographs for each vegetation type and season were estimated by a simple iterative procedure, incorporating the inverse Gaussian distribution to describe the form of the unit hydrograph, and a non-linear relationship that partitioned gross rainfall into effective rainfall and losses. All available gross rainfall and stream flow records were used in the derivation of the unit hydrographs, to reduce the problems described by Rao et al. (1972) and Mawdsley and Tagg (1981) (see section 8.4.1).

8.4.3.1 Data treatment

The rainfall and stream flow data series for the two year observation period were reduced to half hour time increments. A half hour interval was chosen because longer intervals were incapable of describing adequately the rising limb of storm hydrographs from each land use catchment.

Storm flow was separated from the total stream flow record using the Hewlett and Hibbert (1967) separation procedure. This procedure is arbitrary, but objective: no causal relationships are implied between the resultant flow components (Hewlett and Hibbert, 1967). The procedure is used widely and was chosen so that the results from this study would be comparable directly with other rainfall-runoff studies. Storm events were concantenated by removing all long periods of non-storm flow to reduce computer processing time (Diskin and Boneh, 1975; Boorman and Reed, 1981).

The remaining data set was checked for inconsistencies. Storm events with missing records (rainfall or stream flow) were removed, as were sections of the data series where the stream flow and rainfall records were obviously not concurrent. The remaining data series comprised between 10000 and 13000 concurrent estimates of rainfall and discharge made at half hour intervals. Unit hydrographs were derived from the 1100 - 1300 non-zero rainfall increments remaining in each data series.

Murray (1973) has suggested that models of this type should be developed from a sub-set of the total data series and then used to predict the remainder of the data set. In this way, it is possible to estimate the model's predictive ability. However, split record testing was not attempted in this study because the main use of this analysis was to compare the rainfall-runoff response from the two land use catchments. The prediction of storm runoff, given the catchment rainfall input, was not an objective of this analysis.

8.4.3.2 Derivation of the unit hydrograph

Using the notation of Johnson and Kotz (1970), the inverse Gaussian density function is defined:

$$f(x) = [\mu\phi / 2\pi x^3]^{0.5} \exp\left[- \frac{\phi x}{2\mu} + \phi - \frac{\mu\phi}{2x}\right] \qquad (2)$$

where μ and ϕ are the scale and shape parameters respectively, and the random variable x can be considered as the arrival time of an arbitrary water particle at the catchment outfall.

The inverse Gaussian density function was used to describe the form of the unit hydrograph. Figure 8.5 shows the standard inverse Gaussian density functions for selected values of ϕ.

Individual density functions for each half hour increment of rain were summed to form the predicted storm hydrographs. A simple iterative procedure was used to obtain a 'best fit' between the predicted and observed data series. These procedures are described below. Two assumptions were incorporated in this analysis.

i) Storm runoff from the individual density functions was assumed to cease after 2 weeks (672 time increments). This cutoff point was necessary because the inverse Gaussian density function tends to infinity. The 2 week cutoff point was based on the characteristics of the observed storm hydrographs: direct runoff from large storms did not continue beyond two weeks.

ii) Rainfall increments of less than 0.001 mm were assumed to be hydrologically ineffective and removed from the data series. In both land use catchments, an effective rainfall increment of 0.001 mm is small compared with the effective rainfall volumes required to initiate storm runoff.

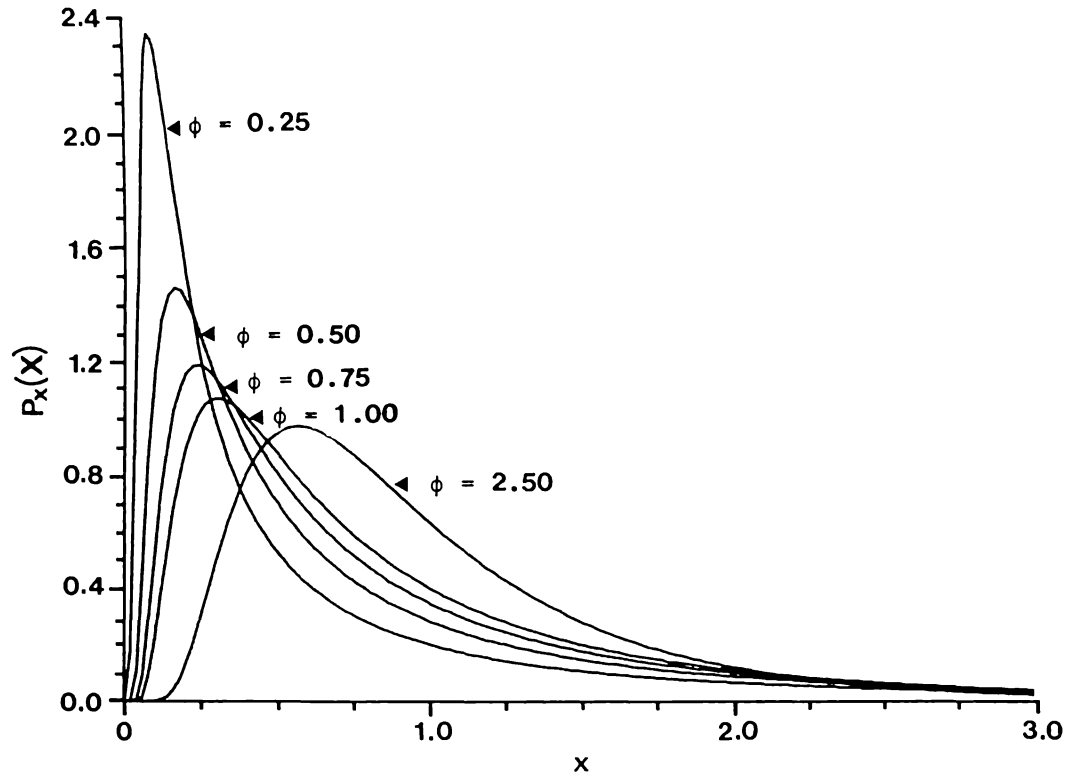


Figure 8.5: Standard inverse Gaussian density functions (scale $\mu=1$) for selected shape (ϕ) parameters

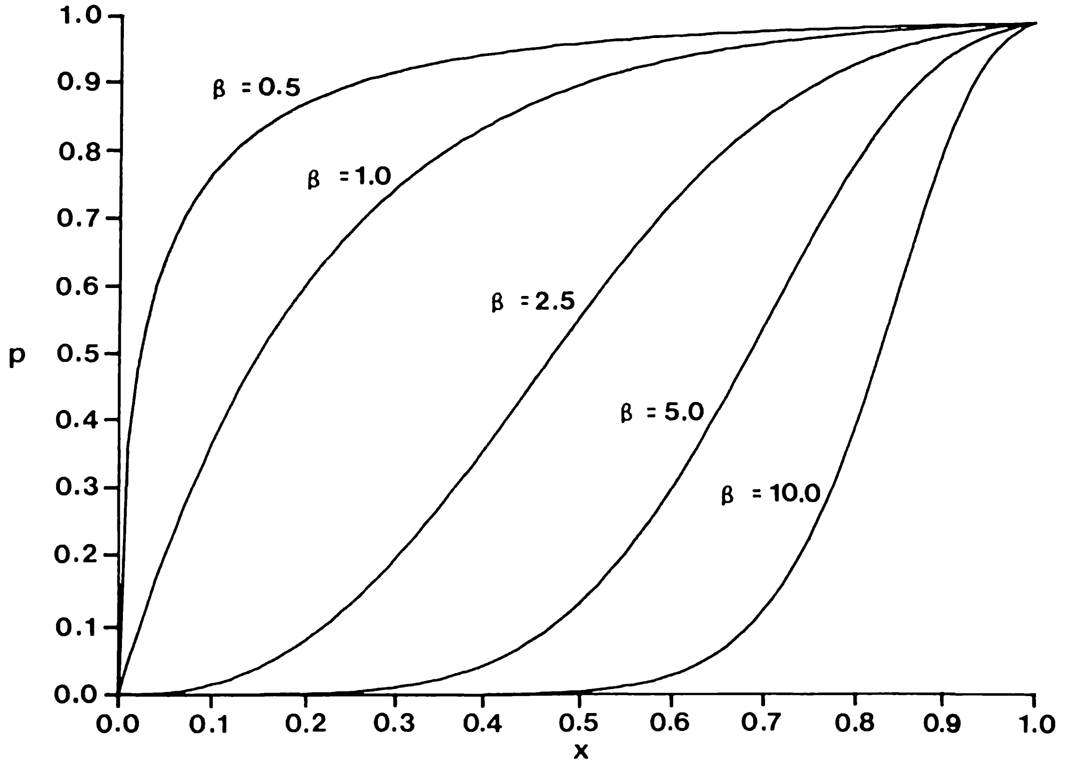


Figure 8.6: The relationship between p and x in $p = x \left(1-\exp^{-(x/\alpha)^{\beta}}\right)$ for selected values of β given $\alpha = 1$

Initially, the effective rainfall (p) was obtained as a function of gross rainfall through the relation:

$$p = x \left(1 - \exp^{-x/\alpha}\right) \qquad (\alpha > 0) \qquad (3)$$

where p is the half hour effective rainfall increment,

x is the half hour gross rainfall increment and

α is a scale parameter.

This relationship proved satisfactory, but a more flexible form of (3), below, yielded a considerable reduction in the residuals between predicted and observed runoff.

$$p = x \left(1 - \exp^{-(x/\alpha)^{\beta}}\right) \qquad (\alpha, \beta > 0) \qquad (4)$$

where p, x and α are as in (3), and β is a shape parameter.

The term in brackets in equation (4) approximates the form of the Weibull cumulative distribution function. Figure 8.6 shows the standard form of equation (4) ($\alpha = 1$) for selected values of β. Other functions could be used to achieve a non-linear division of effective rainfall, but these were not examined as part of this study.

The inverse Gaussian parameters, μ and ϕ, and the parameters describing the relationships between gross and net rainfall, α and β, were obtained by minimising the fitting criterion:

$$f(x)_{\min} = \sum_{i=1}^{n} (\hat{Q}_i - Q_i)^4 \qquad (5)$$

where $\hat{Q}_i$ is the predicted discharge at time i, Q_i is the observed discharge at time i and n is the total number of rainfall-discharge pairs in the concantenated data series. $\hat{Q}_i$ was obtained from the product of f(x) in (2) and the effective rainfall derived from (4). Note: the half hour effective rainfall increments (P_i) were multiplied by 2 to convert them to rainfall intensities (mm h^{-1}) so discharge $\hat{Q}_i$ (mm h^{-1}) could be estimated directly.

Several fitting criteria were examined during the development of the unit hydrographs. These included minimising the absolute value of the residuals (predicted minus observed discharge), and the residuals raised to the second, fourth and sixth power. A comparison of the fitting criteria was made to avoid biasing the optimised unit hydrographs to a particular range of flow (i.e. flow peaks). The minimisation of the residuals raised to the fourth power was chosen as the most appropriate fitting criterion because it appeared to yield the most even distribution of residuals over the range of flow observed in the land use catchments.

8.4.4 RESULTS

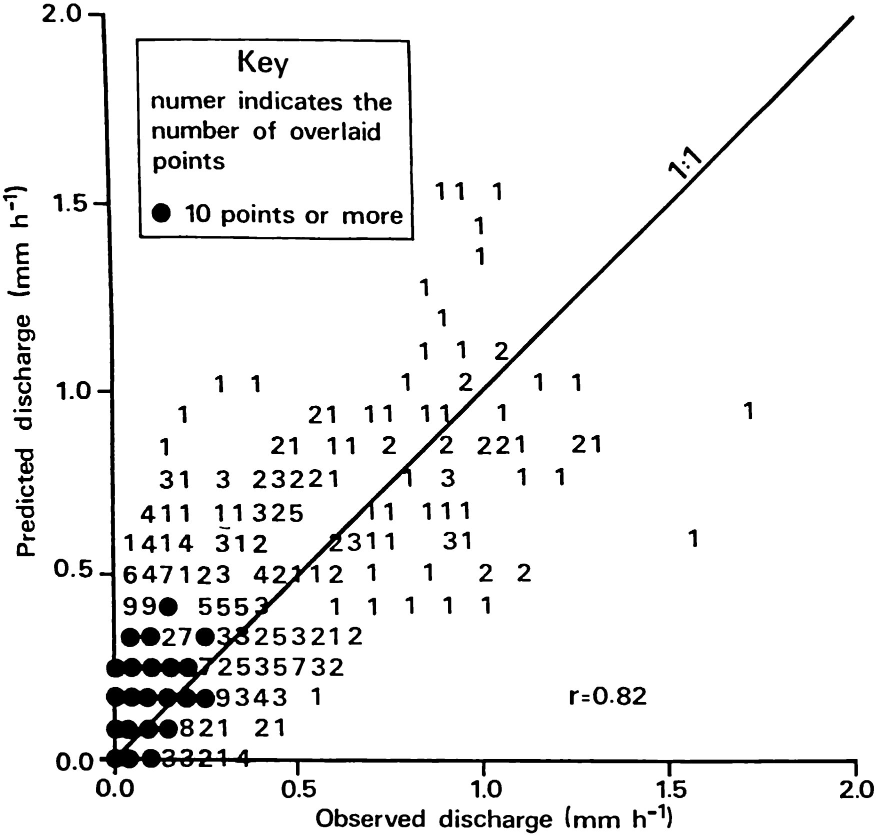
Table 8.2 shows the optimised values of the parameters describing the unit hydrograph, for each combination of vegetation type and antecedent catchment conditions studied. Larger values of both ϕ (shape parameter) and μ (scale parameter) describe less peaked unit hydrographs, with longer times to peak flows and slower recessions. However, the differences in ϕ and μ (table 8.2) yield only small differences in the form of the unit hydrograph (see figure 8.10).

		Inverse Gaussian distribution parameters		Gross rainfall separation parameters	
		μ	ϕ	α	β
Pasture:	summer	50.490	0.275	10.190	1.156
	winter	43.641	0.282	3.779	0.686
Forest:	summer	41.914	0.281	25.166	0.959
	winter	52.733	0.257	10.521	0.916

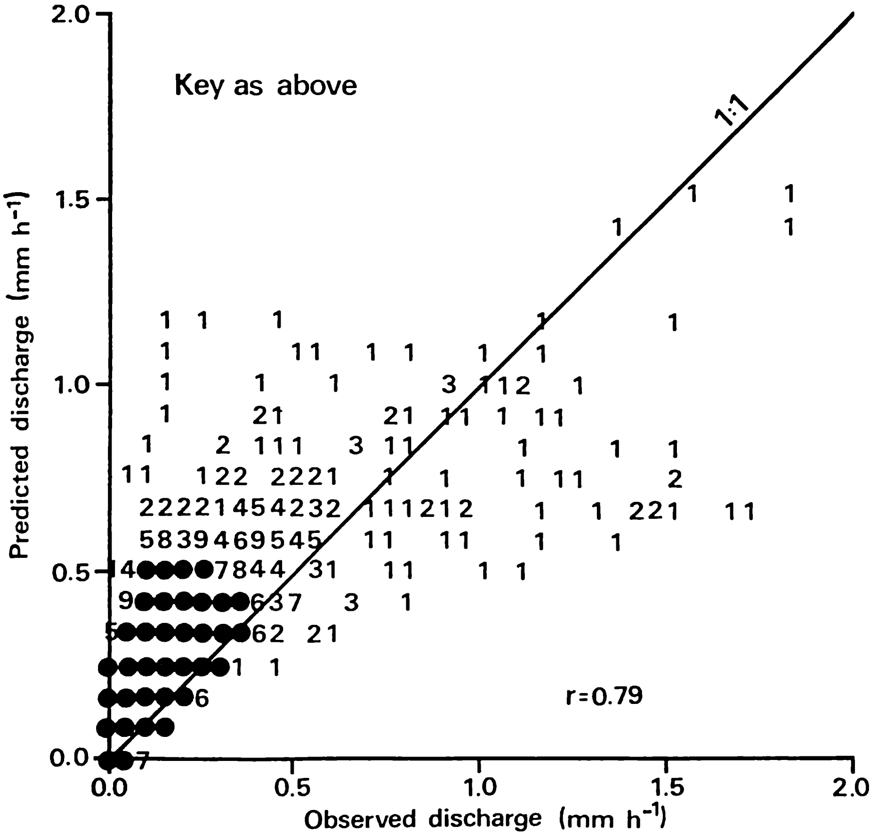
Table 8.2 : Optimised values of μ, ϕ, α, β for the two land use catchments, during summer and winter conditions

Figure 8.7 a,b and figure 8.8 a,b show the predicted and observed discharges associated with the 'best fit' unit hydrographs. Large correlations coefficients (used as a measure of 'goodness of fit') are shown in each case, but some scatter is apparent between the predicted and observed discharges. It must be appreciated that each unit hydrograph was derived from the direct runoff hydrograph for two six months periods, using half hourly comparisons between predicted and observed discharge. These results show clearly that unit hydrographs are likely to be inaccurate, if derived from only one, or at the most, a few similar storms.

Figure 8.7 and 8.8 show that, in winter conditions in both land use catchments, small events tend to be over-estimated, while large events tend to be under-estimated. This suggests that a slightly different form of the unit hydrograph is required to describe more accurately the rainfall-runoff response from the two catchments. For example, the shape and scale parameters describing the form of the unit hydrographs could be linked non-linearly to effective storm rainfall. Runoff responses from small storms would then be less peaked, while more peaked responses would be generated for larger storms. This aspect of the unit hydrograph analysis was not examined in this study.

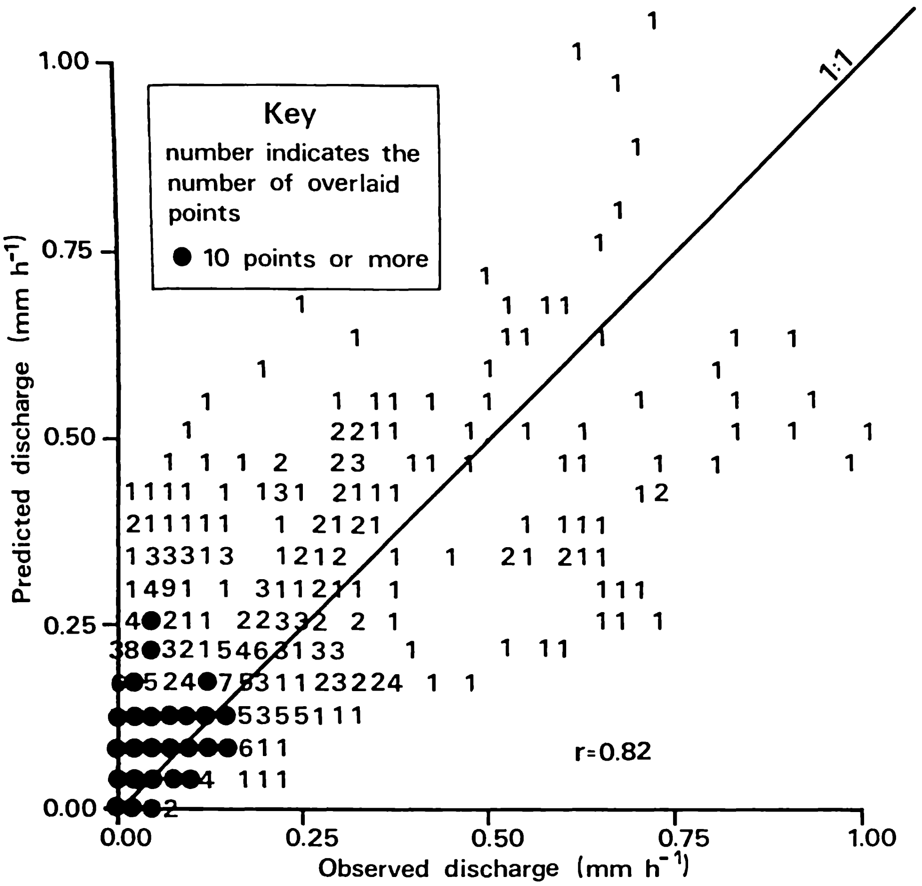


a) Summer storm events

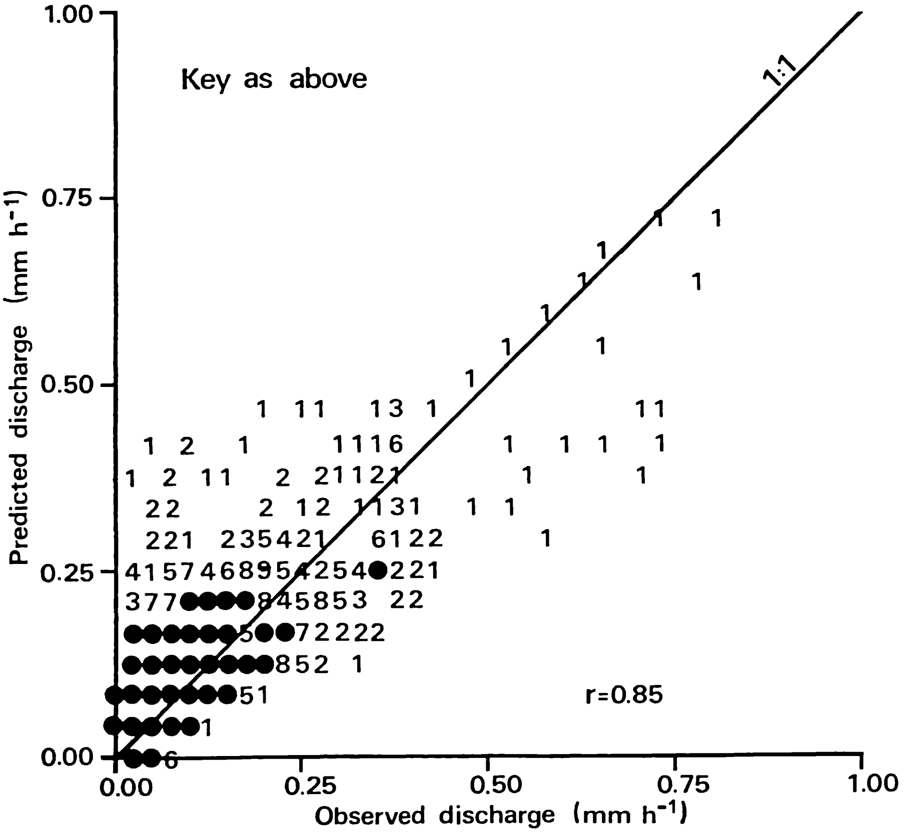


b) Winter storm events

Figure 8.7 : Predicted and observed discharge from the best fit unit hydrographs for the pasture land use, Upper Mangawhara Valley



c) Summer storm events



b) Winter storm events

Figure 8.8: Predicted and observed discharge from the best fit unit hydrographs for the forest land use, Upper Mangawhara Valley

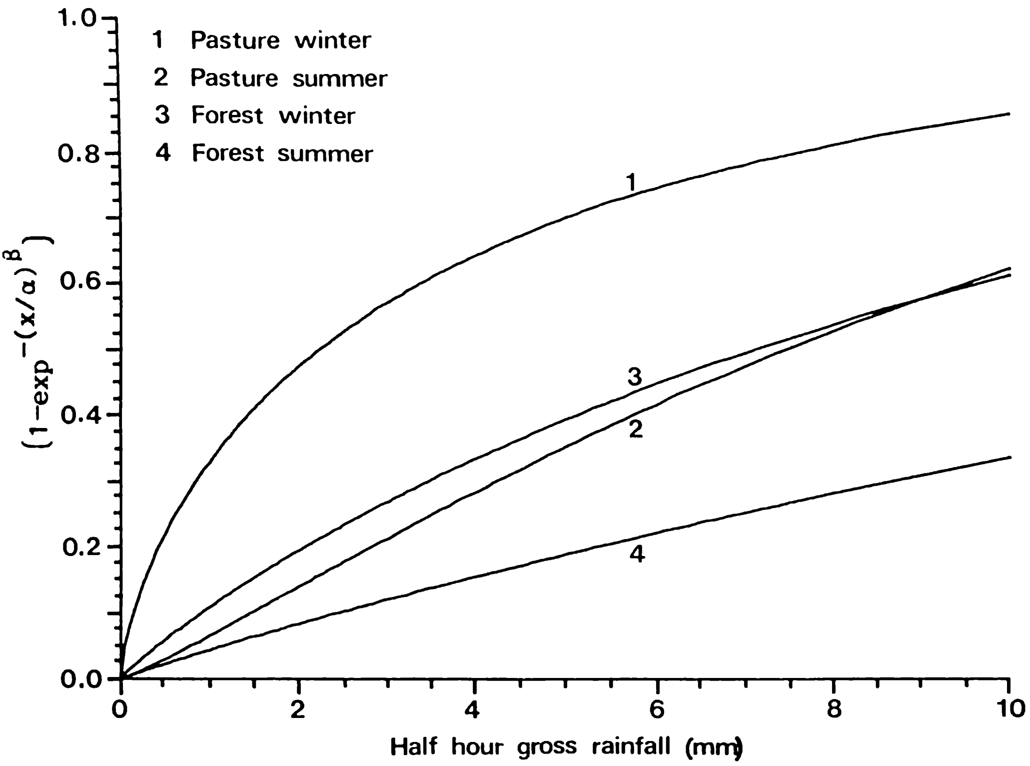


Figure 8.9a: The ratio of gross rainfall / net rainfall (equation 4) versus gross rainfall depth for the 'best fit' unit hydrographs

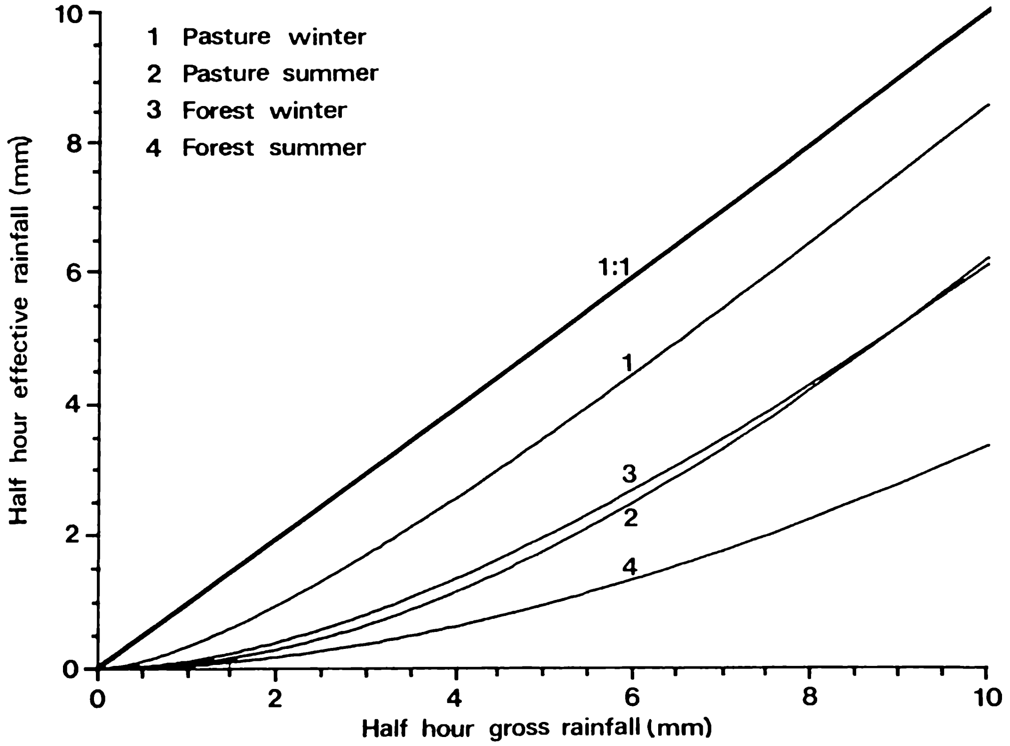


Figure 8.9b: The relationships between effective rainfall and gross rainfall for the 'best fit' unit hydrographs

Table 8.2 shows that the 2 unit hydrographs derived for each land use catchment are dominated by the differences in the rainfall separation procedure. Figure 8.9a shows that the proportion of gross rainfall appearing as effective rainfall (i.e. the term in brackets in (4)) varies considerably with land use, antecedent catchment conditions and gross rainfall. In all cases, the proportion of effective rainfall increases non-linearly with increasing gross rainfall.

Figure 8.9b shows the resultant relationships between effective rainfall and the gross rainfall input. Different relationships between effective and gross rainfall were found for each vegetation type, for both summer and winter storm events. However, the differences in the relationship between forest and pasture are similar, regardless of season. These results show the effect of the different interception characteristics of the two vegetation types and suggest that interception processes are independent of season (c.f. section 5.3.2.2).

Figure 8.10 a,b shows the unit hydrographs derived for each land use catchment for a single half hour rainfall increment of 1.0 mm. In the following sections, the relationships between the unit hydrographs, and gross and effective rainfall are discussed.

8.4.5 DISCUSSION

The results presented in section 8.4.4 show clearly the differences in the direct runoff response between the two forms of land use, for summer and winter storm events. The unit hydrographs summarise conveniently the complete storm response. However, in the discussion following, the unit hydrographs are examined for their influence on three characteristics of the storm runoff response: the general hydrograph shape; direct runoff yields; and peak flows.

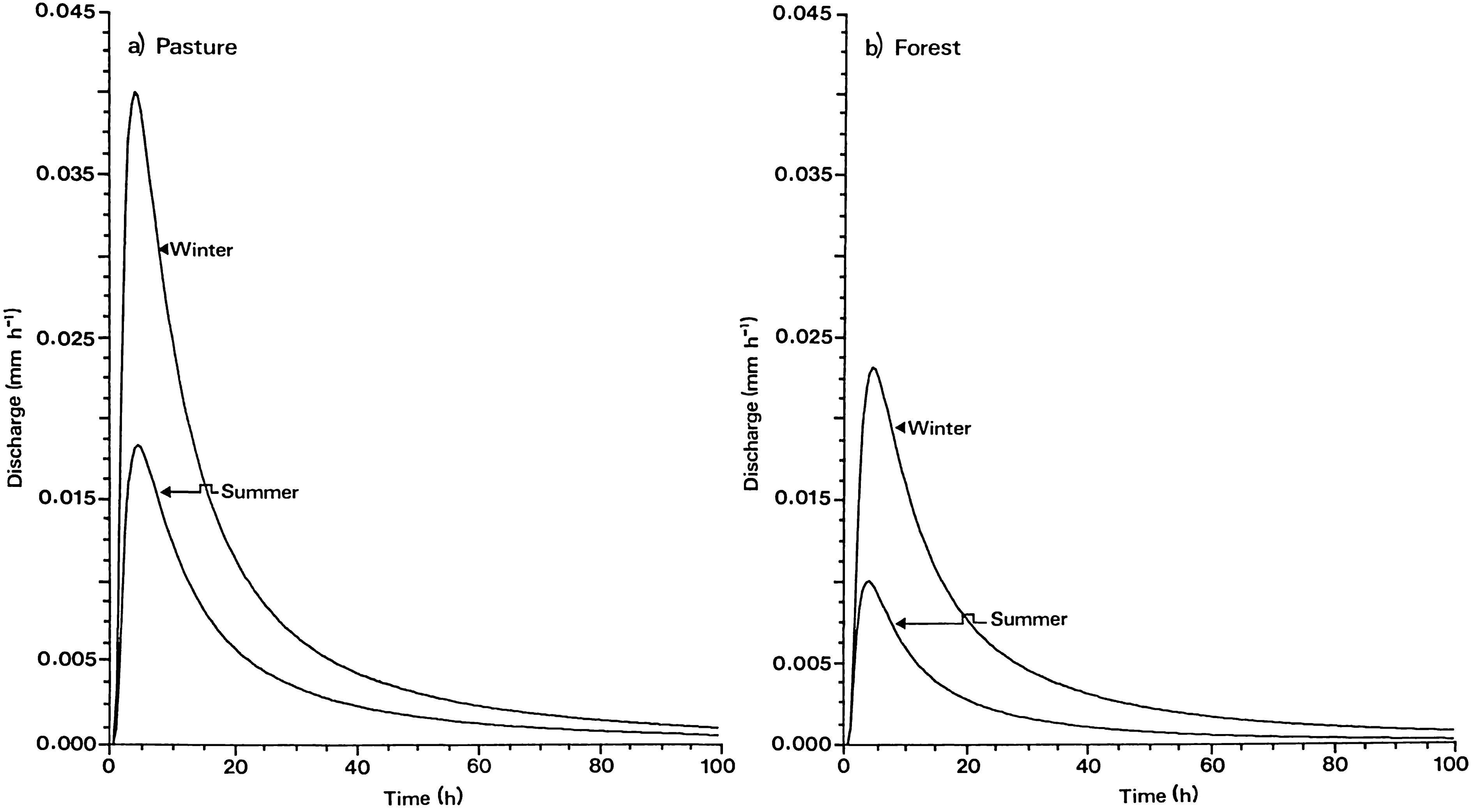


Figure 8.10a,b : Unit hydrographs for the forest and pasture land use catchments, for winter and summer storm events, Upper Mangawhara Valley

The derived unit hydrographs show few differences in their form, either between vegetation type, or between antecedent catchment conditions (table 8.2; figure 8.10 a,b). The time to flow peaks varies between 4.0 h (pasture winter and forest summer) and 4.5 h (pasture summer and forest winter). These differences do not appear hydrologically important, compared with the general shape of the unit hydrographs. Other characteristics of the hydrograph shape (i.e. the hydrograph recession) also appear similar. These results provide further evidence that similar hillslope runoff producing mechanisms occur in each land use catchment.

The principal differences between the derived unit hydrographs are restricted to differences in direct runoff yields and the hydrograph peaks. Direct runoff yields and the hydrograph flow peaks vary considerably, between both vegetation types, and within each vegetation type in response to antecedent catchment conditions.

Direct runoff varies in response to increasing gross rainfall, in exactly the same way as effective rainfall (figure 8.9b). For gross rainfall inputs larger than about 5 mm, the proportional differences in direct runoff yields from the two catchments tend to decrease as storm rainfall inputs increase. Over the range of storm inputs shown (figure 8.9a,b), this effect is most pronounced in winter conditions, when the catchments' soils are the least permeable.

For each unit hydrograph, the relationships between peak flow and gross rainfall also vary in the same way as direct runoff. Thus, similar comments about the relationships between direct runoff and gross rainfall inputs also apply to the unit hydrograph peak flows, for the two land use catchments.

The relationships between the observed unit hydrographs, vegetation type and antecedent catchment conditions can be explained by the differences in hillslope runoff yields observed in the two catchments (chapter 7). However, larger differences in the direct runoff response from the two catchments are suggested by the unit hydrographs, compared with the plot data on hillslope runoff processes (table 7.3). This result suggests the contributions of surface runoff from the midslope and spur areas in the pasture catchment are larger than those suggested by the runoff plot data.

The characteristics of stream flow, shown by the unit hydrographs, are similar to the results from several recent catchment studies of forest and non-forested catchments. Most of these studies report considerable differences in direct runoff yields and in peak flows for forested and non-forested catchments (e.g. Hewlett and Helvey, 1970; Luckman and Duncan, 1978; Pearce _et_ _al_., 1980a). Only a few studies have reported differences in lag times between contrasting forms of land use (e.g. Scarf, 1973).

The preceding discussion shows that unit hydrograph analyses are capable of describing differences in the storm runoff response from contrasting forms of rural land use. However, similar analyses must provide for non-linear rainfall-runoff responses. The non-linear rainfall separation procedure, developed in this study, describes adequately the non-linear relationships between _gross_ rainfall and stream flow found in the two catchments examined. Also, in future similar analyses, as many storm events as practicable should be used. The scatter in figure 8.7 and 8.8 shows that unit hydrographs showing a high degree of fit, but derived from one or just a few carefully chosen storm events, are not likely to describe accurately the general catchment response to storm rainfall.

8.4.6 SUMMARY

Stream flow processes from the two experimental catchments have been examined by analyses of the flow durations, peak flows and unit hydrographs derived for summer and winter storm events.

The flow frequency distributions show that discharge from each land use catchment is characterised by long periods of low flow, punctuated by large, short duration stream rises in response to rainfall. This result suggests a sharp division between surface and subsurface hillslope runoff regimes. Most of the differences in flow durations in the two land use catchments occur below 0.2 mm h^{-1}, with the largest absolute differences occurring when subsurface flow and ground water flow are at a maximum.

For all storm rainfall inputs, peak flows from the pasture catchment are larger than from the forest. However, the proportional differences, between the peak flows from each vegetation type, become smaller as storm size increases.

Unit hydrographs were derived for each land use catchment for summer and winter storm events. The form of the catchment unit hydrographs is similar for both forms of land use and antecedent catchment conditions. Differences in the unit hydrographs are restricted, instead, to differences in direct runoff and flow peaks.

The stream flow characteristics from each catchment can be explained by the relative contributions of hillslope runoff generated in each land use catchment. The different contributions of hillslope runoff are, in turn, caused by different interception characteristics in the two land use catchments, and by the differences in hydrologically important soil physical properties in each catchment (see chapter 6).

8.5 THE WATER BALANCE

An analysis of water balance components is used often to evaluate the effect of land use change on water yield behaviour. The results of many of the comparative land use studies have been summarised by Bosch and Hewlett (1982). Unfortunately, most of these studies have been established to evaluate the effects of various methods of forest removal: few examine specifically the differences in water yield behaviour between contrasting vegetation types. Even fewer studies describe the changes in water yield behaviour following the conversion of indigenous forest to pastoral agriculture, although this has been the predominant land use change in New Zealand.

The disparate literature, describing changes in water yield behaviour following conversion of forest vegetation to pastoral agriculture, is reviewed in chapter 2. This section describes the water balance components estimated for the two vegetation types studied.

8.5.1 WATER BALANCE COMPONENTS

Water balance components: gross rainfall and runoff in the pasture catchment; and gross rainfall, interception loss, and runoff in the forest catchment; were estimated using the data collection systems described in chapter 4 for the period July 1979 to July 1981. Data for these components are presented for both water years in the following sections (section 8.5.1.1 - 8.5.1.5). In section 8.5.2, the catchments' water balance are presented as an average of the two water years.

8.5.1.1 Gross rainfall

Estimated catchment rainfall for the two water years are 1497 mm (July 1979 - July 1980) and 1546 mm (July 1980 - July 1981). These values are within one standard error (174 mm) of the 26 year mean estimated from N.Z.M.S. site B 75441, at Hoe-o-Tainui. Figure 8.11a and 8.12a show estimates of weekly gross rainfall for the two year observation period.

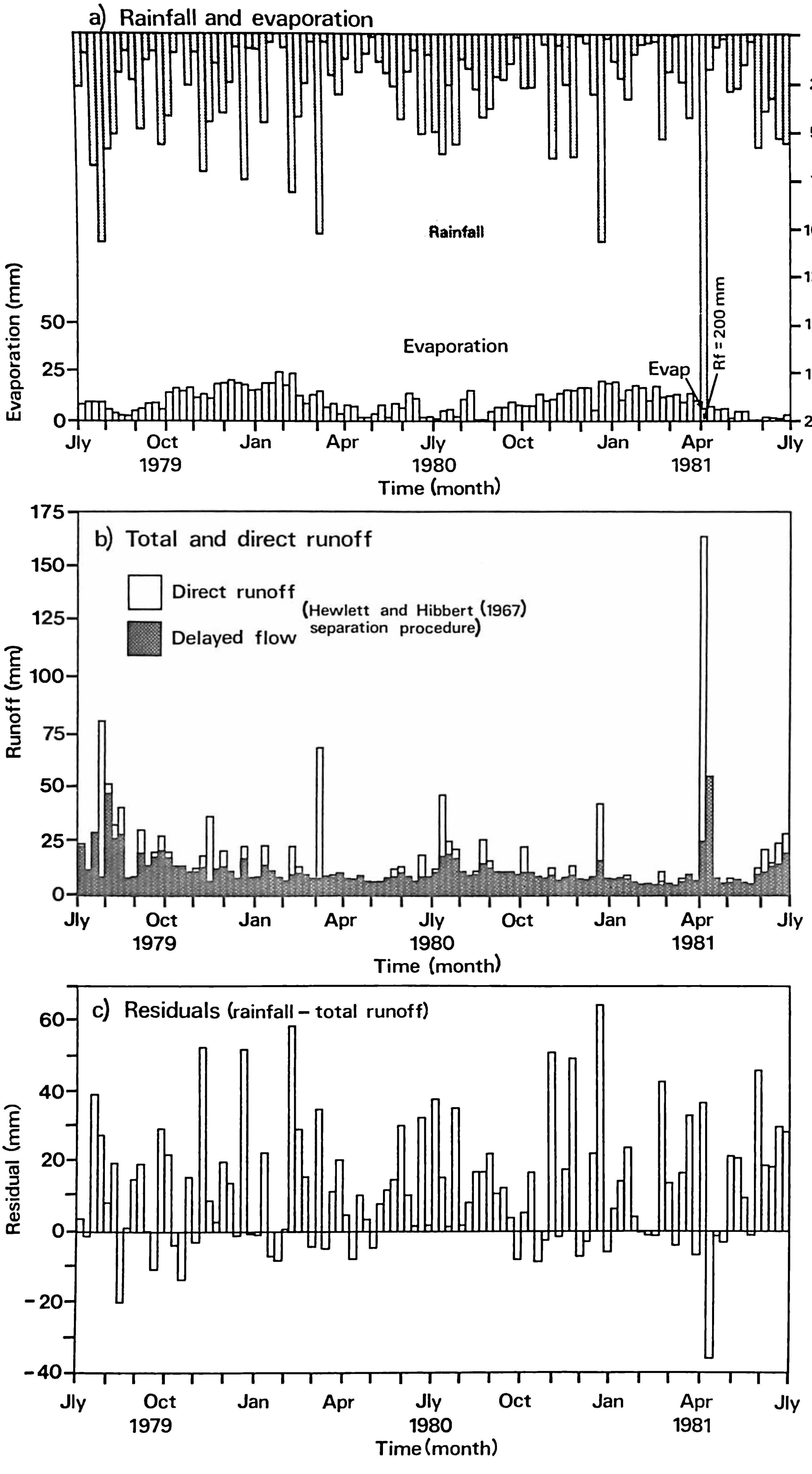


Figure 8.11a,b,c: Weekly estimates of water balance components for the pasture land use during the two year study period (July 1979 – July 1981)

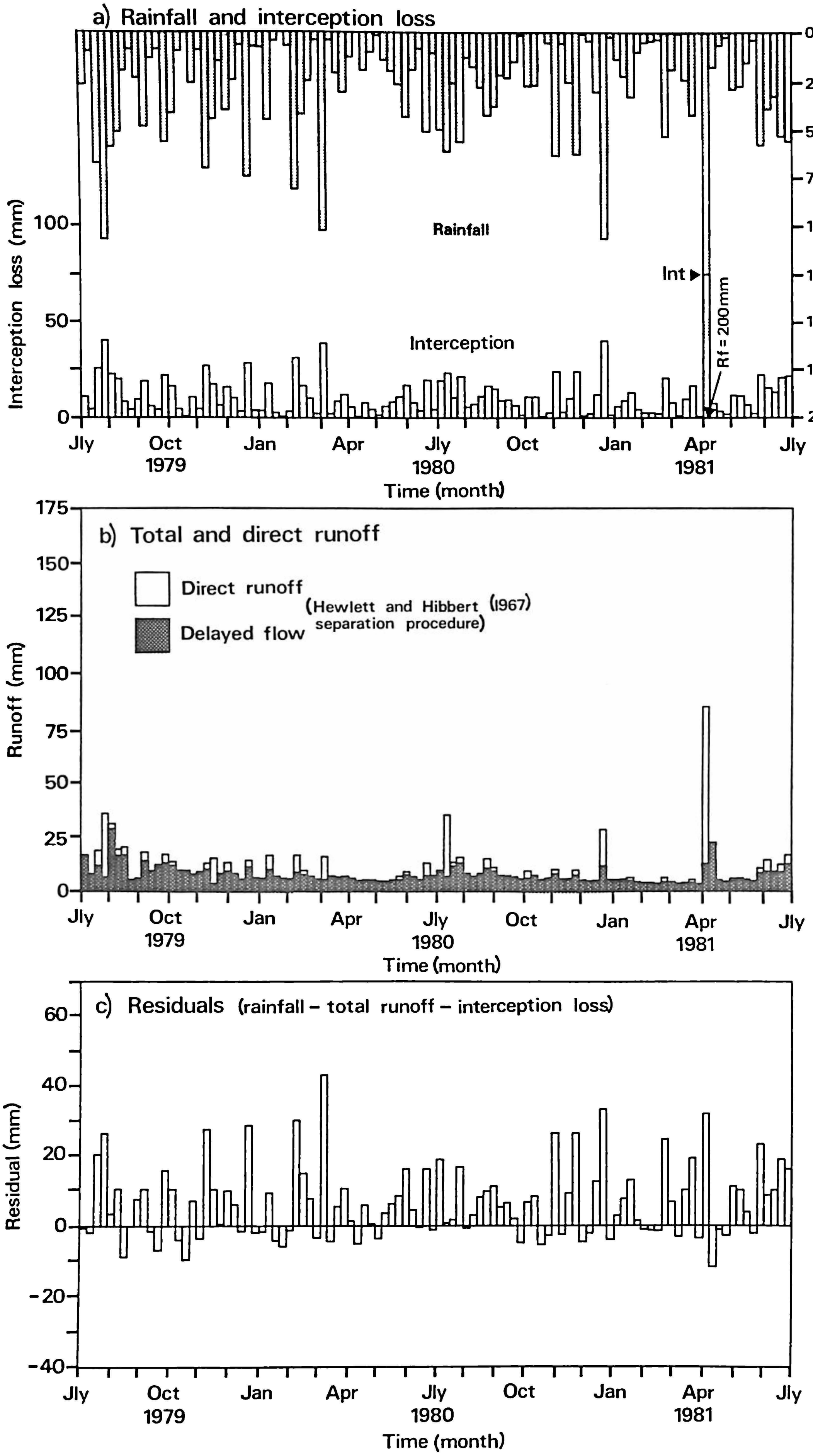


Figure 8.12a,b,c: Weekly estimates of water balance components for the forest land use during the two year study period (July 1979 – July 1981)

8.5.1.2 Interception

The relationships between gross and net rainfall, described in chapter 5, were used to estimate interception losses from the forest catchment. Interception losses for each water year are 42 % of gross rainfall, 629 mm (July 1979 - July 1980) and 649 mm (July 1980 - July 1981). Figure 8.12a shows the weekly estimates of interception loss and gross rainfall for the two water years. No estimate of the errors associated with estimating annual interception loss was possible because of the method used to calculate these data (see section 4.4.1.2).

8.5.1.3 Runoff

Weekly estimates of total and direct runoff (Hewlett and Hibbert (1967) separation procedure) were derived from the continuous stream flow record for each land use catchment: these are presented in figure 8.11b (pasture) and 8.12b (forest). Annual runoff totals for the pasture are 914 mm (July 1979 - July 1980) and 840 mm (July 1980 - July 1981). For the forest, these are 554 mm (July 1979 - July 1980) and 520 mm (July 1980 - July 1981). Annual runoff totals for two water years account for 61 and 54 % of the gross rainfall in the pasture, and 37 and 34 % in the forest.

Weekly direct runoff totals are related closely to the storm rainfall inputs in both land use catchments, but for most observation periods, direct runoff accounts for only a small proportion of total runoff (figure 8.11b and 8.12b). Direct runoff from the pasture (289 mm (July 1979 - July 1980); 293 mm (July 1980 - July 1981)) accounts for only 32 and 35 % of total runoff for the two water years, respectively. In the forest, quick flow (118 mm (July 1979 - July 1980); 162 mm (July 1980 - July 1981)) accounts for even smaller yields of total runoff, being 22 and 31 % for the two water years. In each land use catchment, delayed flow shows a slight seasonal pattern, reflecting the seasonal variations of the catchment soil moisture regimes.

The errors associated with estimating stream runoff are unlikely to be smaller than those described in chapter 4. As a result of widespread mass wasting, initiated by a large storm in March 1979 (see chapter 3), considerable quantities of sediment accumulated behind the weirs during some subsequent large storm events. Parts of the stream flow recession were lost during these large storm events and had to be filled using a 'best fit' relationship between the two flow recording sites. Consequently, the accuracy of the discharge measurements during these storms is probably reduced.

8.5.1.4 Ground water losses

The Mesozoic greywacke underlying the two experimental catchments has a low porosity and is only slowly permeable (Schofield, 1956; Kear, 1967). Losses to ground water in the land use catchments are therefore probably small. However, some ground water may move through fissures in the shattered greywacke basement.

The estimated annual loss to deep ground water is about 3 - 30 mm per year, assuming a permeability of between 1×10^{-9} and 1×10^{-10} m s^{-1} for the 'C' horizon of the catchment soils (Pender, 1971; Rogers, 1978). The upper value of 30 mm is suggested for the pasture catchment. An estimate of 15 mm is proposed for the forest catchment, because of the lower seasonal moisture regimes and the restricted areas of subsurface saturation observed in this vegetation type. Estimated annual ground water losses are small compared with the errors involved with estimating other components of the water balance.

8.5.1.5 Evapo-transpiration and transpiration

Evapo-transpiration in the pasture, and transpiration in the forest were estimated from the residual in the catchments' water balance. This method has the advantage of providing an integrated estimate of evaporative losses for each land use catchment, although the estimates include all errors in the water balance.

Estimates of the evapo-transpiration in the pasture are 553 mm (July 1979 - July 1980) and 676 mm (July 1980 - July 1981). Estimates of transpiration in the forest are 629 mm (July 1979 - July 1980) and 649 mm (July 1980 - July 1981). Figure 8.11c (pasture) and 8.12c (forest) show the seasonal variation in the weekly residuals.

Estimates of potential evaporation were made during the two water years from weekly observations of pan evaporation, using a correction factor of 0.69 (Finkelstein, 1973). Errors involved in these measurements are likely to be larger than those reported by Finkelstein (1961, 1973), because the observations were not made in accordance with standard hydrological procedure. Consequently, these data are not used in the estimate of the catchment water balances. However, they are presented in figure 8.11a for sake of completeness and for comparison with the water balance residuals estimated for each land use catchment.

8.5.2 THE WATER BALANCE OF THE LAND USE CATCHMENTS

The annual water balance was estimated as an average for the two water years (July 1979 - July 1981). A separate analysis for the two water years is not presented because of possible undetected changes in the catchment soil moisture store: soil moisture data for the winter of 1980 are not available.

The catchment soil moisture data (chapter 6; figure 6.4) show that soil moisture was similar in the pasture catchment at the beginning (July 1979) and at the end (July 1981) of the two year observation period. Similar information was not available in the forest catchment, but it was assumed that the catchment soil moisture was similar at the beginning and at the end of the study period. Based on the data from the pasture catchment, only small errors in the catchments' water balance are likely to result from the differences in soil moisture observed during July 1979 and July 1981.

Table 8.3 shows the water balance for each land use catchment, averaged over the two water years.

8.5.2.1 Discussion

The water balance for each land use catchment (table 8.3) is typical for the soil, vegetation, topographic and rainfall characteristics of the Hapuakohe Range. The water balances are also similar to those from other catchments with similar vegetation (e.g. Jackson, 1973; Pearce and McKerchar, 1979; Pearce and Rowe, 1979; Pearce *et al.*, 1982). In the two catchments studied, runoff and evapo-transpiration processes dominate losses from the water balance: losses to ground water are small.

8.5.2.1.1 Runoff yields

High yields of net rainfall appear as total runoff from both catchments, yet direct runoff accounts for only a small proportion of total runoff (table 8.4). These results can be explained by interactions between:

i) the intermittent, low intensity, rainfall;

ii) the generally large, catchment average soil moisture storage;

and iii) the low permeabilities of the catchments' soils.

Most storm rainfall inputs are inadequate to generate widespread overland flow in either land use catchment. Much of the surface runoff, generated in upslope catchment areas by small storms, is re-infiltrated in lower slope positions. However, subsurface storm flow responses are not possible from these events because of the low soil permeabilities. Widespread overland flow, is however, generated in each land use catchment by intense bursts of rainfall associated with long duration storm events (chapter 5). Large volumes of overland flow from these storms reach the stream channel and contribute to the few, large stream rises.

PASTURE

Rainfall (mm)	=	direct runoff (mm)	+	delayed flow (mm)	+	ground water loss (mm)	+	evapo-transpiration (mm)
1521	=	291	+	586	+	30	+	614

FOREST

Rainfall (mm)	=	direct runoff (mm)	+	delayed flow (mm)	+	ground water loss (mm)	+	interception (mm)	+	transpiration (mm)
1521	=	140	+	397	+	15	+	639	+	330

Table 8.3 : Water balance data for the pasture and forest catchments averaged over two water years (July 1979 - July 1981)

a) PASTURE CATCHMENTS

Catchment	size (ha)	infiltration capacity (mm h^{-1})	gross rainfall (mm)	total runoff / gross rainfall %	direct runoff / total runoff %	total runoff / net rainfall %
Mangawhara	8.2	10-40	1521	58	33	72
Pukewaenga	38.9	42	1266	48	44	60
Manakau	30.1	20	1300	36	20	45
Makara 11	7.4	50	1230	27	41	34
Moutere 5	8.2	11- 3	1110	25	40	31

b) FOREST CATCHMENTS

Catchment	size (ha)	infiltration capacity (mm h^{-1})	gross rainfall (mm)	total runoff / gross rainfall %	direct runoff / total runoff %	total runoff / net rainfall %
Ngahere	52.0	150	2630	64	25	85
Maimai	1- 5	250	2610	58	64	77
Mangawhara	24.0	5-40	1521	35	26	61
Big Bush 1-3	5- 8	180	1480	36	36	51

Data sources: Pukewaenga, Manakau, Makara 11, Moutere 5, Ngahere, Maimai; Pearce and McKerchar (1979) and Pearce and Rowe (1979). Big Bush 1-3; Pearce et al. (1982). Mangawhara; this study.

Table 8.4 : Yields of total runoff and direct runoff for selected New Zealand experimental catchments

Table 8.4 shows comparative data on the estimated total and direct runoff from other New Zealand pasture and indigenous forest catchments. Few generalisations are possible about the causes of the relationships between rainfall and total runoff for the catchments in the different regions. However, there appears to be a positive relationship between net rainfall and total runoff for both forest and pasture vegetation types (table 8.4), and a non-linear relationship between soil permeability and yields of direct runoff.

Freeze (1980) has provided theoretical evidence to show that the largest direct runoff yields occur in either, the most permeable, or the least permeable soils, albeit by different mechanisms. Smallest direct runoff responses (e.g. the Mangawhara catchments, Manakau, and possibly Ngahere) arise from soils with permeabilities barely able to support subsurface flow, without allowing the development of saturation overland flow or widespread infiltration-excess overland flow. However, the simple effects of these relationships are complicated further by the different soil and topographic characteristics in each catchment.

8.5.2.1.2 Evapo-transpiration

The estimated actual evapo-transpiration (ET) from the pasture catchment (614 mm) is less than the potential evaporation estimates (PE) of the three nearest N.Z.M.S. evaporation pans (c.f. table 8.3 and 8.5).

location	altitude	period of observation	potential evaporation
Ngatea	2 m	1966 - 1970	716 mm
Ruakura	40 m	1956 - 1969	714 mm
Rukahia	66 m	1956 - 1970	769 mm

Data source: Finkelstein (1973)

Table 8.5 : Potential evaporation estimates for the Waikato region

The soil moisture data (chapter 6) suggest that soil-plant-water conditions in both land use catchments are unlikely to satisfy the requirements for ET/PE = 1 (Penman, 1948). The ratio between ET (table 8.3a) and PE (table 8.5) varies between 0.80 - 0.86. This suggests a correction factor of 0.50 - 0.59 for estimating ET in the pasture catchment from pan evaporation measurements.

Blake (1972) has estimated that interception losses for pasture vegetation are about 20 % of annual gross rainfall. If these estimates are applicable to pasture vegetation in the Mangawhara, the estimated annual interception loss from the pasture catchment is about 304 mm. By difference, the estimated annual transpiration loss from the pasture catchment is about 310 mm. This is similar to the transpiration losses suggested for forest vegetation in other areas of New Zealand (see below).

The total evaporative losses from the forest catchment in the Mangawhara are considerably greater than those for similar indigenous forest types in other areas of New Zealand (e.g. Aldridge and Jackson, 1974; Pearce and Rowe, 1979; Pearce et al., 1982). However, average transpiration losses estimated from this study (330 mm) are similar to those suggested similar forest types in other areas of New Zealand (e.g. the Maimai catchments in Westland (350 mm) (Pearce and Rowe, 1979); and the Big Bush catchments in Nelson (330 - 360 mm) (Pearce et al., 1982)). Transpiration losses for similar tree species thus appear independent of location and climatic conditions. Similar results have been observed in Great Britain (T.M. Roberts; cited in Pearce and Rowe (1979)).

The net interception loss is considerably larger in the Mangawhara (42 %) than at either Big Bush (29 %), or at the Maimai catchments (26 %). These differences may be caused by the different rainfall depth-duration-frequency characteristics of each region, and by differences in the evaporation rates from the canopy following rain. Greater evaporation rates from the forest canopy (0.76 - 0.93 mm h^{-1} (chapter 5)) were observed in this study, compared with those observed at Maimai (0.37 mm h^{-1}). No comparisons are possible between the rainfall intensity-duration characteristics of each region.

8.5.2.2 Water balance components in the Mangawhara catchments

The water balance data show that estimated transpiration rates between the two vegetation types are similar (330 mm (forest); 310 mm (pasture)). Consequently, water yield differences between the two catchments must be caused largely by differences in the interception characteristics of each vegetation type. Some small differences in losses to ground water may occur between the two catchments.

Table 8.6a shows the absolute differences between the water balance components of the two land use catchments. Table 8.6b shows the same data as percentage differences. A Wilcoxon signed ranks test shows that weekly yields of direct runoff and delayed runoff from both land use catchments can be considered different ($p = 0.05$).

Few data are available that can be compared directly with the results obtained in this study, because few comparative studies of the water balance of indigenous forest and pasture vegetation have been completed in New Zealand. Jackson (1972) presented water balance data, from a similar comparative land use study (indigenous forest - pasture comparison), that suggest there are only small differences in the annual water balance of the two vegetation types. These results appear anomalous, when compared with the results from this study, and those from the other experimental, theoretical and catchment studies of forest and pasture vegetation cited in this thesis.

Comparative land use studies, that describe the hydrologic implications re-afforestation of pasture by pine (Pinus radiata), show that the differences in water yield behaviour between the two vegetation types are similar to those observed in this study. After canopy closure, the typical annual reductions in water yield from re-afforested pasture range from 22 - 50 %, depending on the prevailing climatic regime (Dons, 1980; Duncan, 1980; Waugh, 1980).

rainfall (mm)	=	direct runoff (mm)	+	delayed flow (mm)	+	ground water loss (mm)	+	evapo-transpiration (mm)
0	=	151	+	189	+	15	-	355

Table 8.6a : The difference (pasture - forest) between the water balance components of the forest and pasture land use catchments in the Upper Mangawhara Valley

Water balance component	Per cent difference (forest -> pasture)		
direct runoff	+ 108 %		
delayed runoff	+ 48 %	total runoff	+ 63 %
ground water loss	+ 100 %		
evapo-transpiration loss	- 37 %		

Table 8.6b : The percentage difference (forest -> pasture) between the water balance components of forest and pasture land use catchments in the Upper Mangawhara valley

The results observed between the two land use catchments in the Mangawhara (37 %) are thus typical for forest and pasture vegetation, despite the obvious differences in vegetation type, catchment conditions and climate.

8.5.3 SUMMARY

The annual water balance for each land use catchment was estimated as an average for two water years (July 1979 - July 1981). Runoff and evapo-transpiration dominate losses from the water balance in each catchment: losses to ground water are small.

High yields of net rainfall appear as total runoff from both land use catchments, although relatively small yields of direct runoff occur. In each catchment, these results can be explained by interactions between the net rainfall regime and the water storage and transmission characteristics of the catchment soils. The same interactions are suggested as the cause of the differences in water yield behaviour, observed between the two study catchments and other similar sized catchments in New Zealand.

Actual evapo-transpiration from the pasture vegetation is less than the average potential evaporation estimates for the Waikato region. Soil moisture data show that conditions for ET/PE = 1 are unlikely in either land use catchment. Estimates of annual transpiration losses from the pasture land use are 310 mm, assuming an annual interception loss of about 20 %.

Total evaporative losses (transpiration and evaporation of intercepted water) for the forest vegetation are greater than those reported for similar forest types, in other regions of New Zealand. The large interception losses in the Mangawhara appear to be caused by high evaporation rates from the wet forest canopy. Only small differences were found between the estimates of transpiration made in this study and those from other areas.

The water balance data, for the two catchments examined in this study, confirm other experimental, theoretical and field evidence about the general water yield behaviour from forest and pasture vegetation. Differences in water yield behaviour from the two vegetation types are dominated by differences in interception characteristics and not by differences in transpiration rates.

CHAPTER NINE

SUMMARY AND IMPLICATIONS FOR LAND MANAGEMENT

CONTENTS

9.1 HISTORICAL PERSPECTIVE AND SYNOPSIS OF THE STUDY RATIONALE

During the early part of this century the continued expansion of pastoral agriculture into marginal steepland areas led quickly to conflicts of land use. The removal of indigenous vegetation and the subsequent deterioration of plant cover was associated with downstream problems of flooding and sediment deposition. Early remedial measures to ameliorate these problems were based on overseas evidence, because the necessary hydrologic data were not available locally. Land management decisions were thus based on the premise that hillslope runoff processes were spatially uniform and could be controlled by improving the vegetation cover of the land. Re-afforestation was the principal method of improving the vegetation cover. Most of these management procedures were successful where applied.

However, the continued agricultural development of marginal steepland areas and the recent expansion of production forestry into similar regions, have led again to widespread conflict between the two forms of land use. Multiple use by these two forms of land use, with adequate provision for the protection of land and water resources, has been suggested as a management objective for marginal steepland areas.

The development of the new problems of land use conflict have been coincident with a significant development in the understanding of source area hydrology in humid, temperate climates. Hillslope runoff processes have been shown to result from complex interactions between soil, topographic, rainfall, and vegetation characteristics. The integrated hillslope runoff response is derived from contributions of surface and subsurface flow components. These processes are dynamically variable in space and time. The terms 'partial and variable source area models' have been used to describe these concepts and processes.

The new concepts of runoff generation have fundamental implications for the development of effective land management procedures. However, these concepts have not been applied widely to land management problems. The information necessary to interpret the hydrological effects of land use, within the framework of the new models of source area hydrology, is again unavailable for many areas where land use conflict occurs. Quantitative estimates of the spatial variability of hillslope runoff mechanisms must be obtained for a wide variety of land use environments, so that rational land management decisions can be made.

This type of information is largely unavailable for many regions in New Zealand, because most hydrologic studies have been conducted on either a 'catchment' scale or on a 'plot' scale. Catchment scale experiments provide no information on the hillslope runoff processes operating within the catchment boundary. Studies on a plot scale have been generally qualitative and provide no information on the linkage between processes observed on hillslopes, and the integrated result observed in the stream channel. Comprehensive studies, integrating both catchment and plot scale experiments, are thus necessary to provide information suitable for the assessment of the hydrologic consequences of different forms of land use for many areas of New Zealand.

9.2 EXPERIMENTAL

The experimental design developed for this study is based on the partial and variable source area concepts that have been shown to be applicable throughout humid temperate environments. The experimental catchments were sub-divided into three geomorphically distinct sub-catchment units (riparian, midslope and spur regions) so that quantitative estimates of the spatial variability of surface and subsurface hillslope runoff components could be made within each land use catchment. The sub-catchment units were delineated on the basis of a preliminary survey of the spatial distribution of soil moisture.

The use of the experimental design has enabled this study to expand the previous work on hillslope runoff processes by quantifying the qualitative observations made in most other studies. The experimental design also provided the potential to examine in detail the hydrologic implications of land use and to interpret them within the framework of the partial and variable source area models. Few similar studies have been reported.

9.3 RESULTS

The principal results of this study show the spatial variability and complexity of hillslope runoff processes for indigenous forest and pastoral agriculture, in the Upper Mangawhara Valley. Despite the complexity of the hillslope runoff processes, the integrated stream flow responses from each land use catchment are less variable, and show the differences expected for the two vegetation types.

A general summary of the results of this study is presented in the following sections. The main components of hillslope runoff in the two land use catchments are summarised in figure 9.1a,b[1] (upper section) as many of the interactions between the hillslope runoff components are complex. In addition, figure 9.1a,b (lower section) shows a summary of the relationships between hillslope runoff components and their determinants, together with the relationships between hillslope runoff processes and the catchment stream flow regime.

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[1] Additional copies of figure 9.1 can be found in the pocket inside the rear cover of this volume, for use while reading these sections.

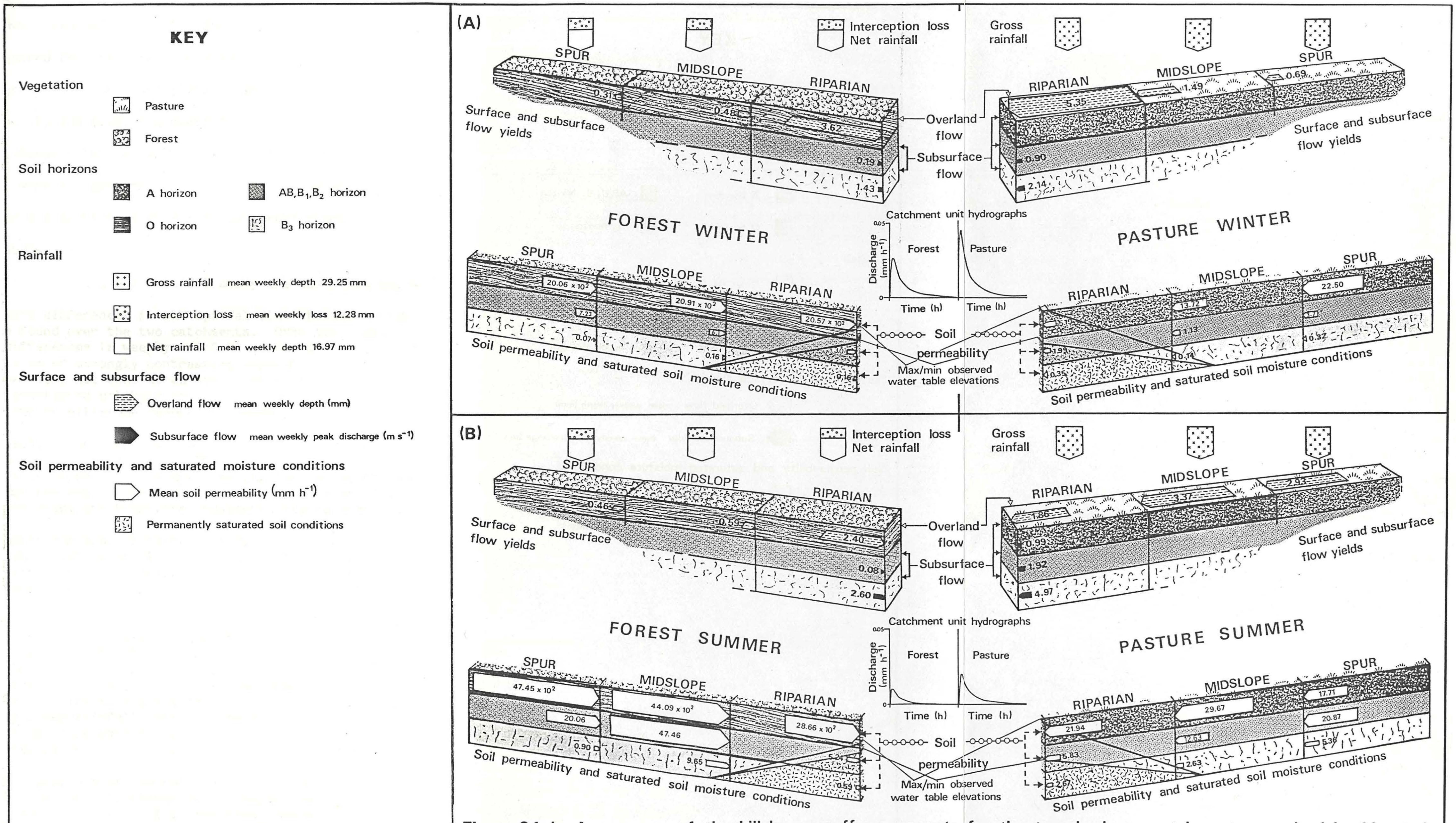

Figure 9.1a,b: A summary of the hillslope runoff components for the two land use catchments examined in this study

9.3.1 GROSS RAINFALL

Estimates of gross rainfall were required for both land use catchments as the basic hydrologic input. An estimate of interception losses was also required for the forest catchment, to describe differences in water balance and water yield behaviour between the two land use catchments. In addition, the spatial distribution, the intensity-duration characteristics, and the micro-periodicity of the catchment rainfall, were all examined as a precursor to determining the spatial distribution and mechanisms of hillslope runoff production in the two land use catchments.

The main findings of the gross rainfall study are described below.

i) No important differences in the spatial distribution of rainfall were found over the two catchments. Over the 2 year period, differences in weekly rainfall totals averaged about 4 % for sites of strongly contrasting exposure. These differences were not considered hydrologically important, and were considered unlikely to influence greatly the spatial distribution of hillslope runoff processes.

ii) A comparison, between the rainfall observed during the two year observation period and the 26 year record at an adjacent N.Z.M.S. site, shows that rainfall during the two years was typical for the area. The rainfall-runoff processes observed during this study are therefore considered representative.

iii) The intensity-duration characteristics of the catchment rainfall show that rainfall is generally intermittent and of low intensity. Few high intensity falls occur, even for the shortest event durations.

iv) An analysis of the micro-periodicity of rainfall events shows that most of the rain falls during long duration, low intensity, storms. No significant relationship between rainfall intensity and rainfall event duration was found. However, the highest average intensities tend to occur in the longer duration events and are thought to be associated with intra-storm rainfall bursts. The hillslope runoff response from these events will be proportionally greater, than if they occurred in isolation.

v) The serial structure of the rainfall input confirms the few, long duration rain storms as the major runoff producing events. Over 50 % of the total annual rainfall occurs in 10 % of the rainfall events. These events are all of 2 hours or longer duration.

Interception data show that the intensity-duration characteristics, the micro-periodicity, and the serial structure of the net rainfall impinging on the forest floor are not the same as those observed above the forest canopy. Short duration, low intensity storms appear to be affected considerably. In large storms, the intensity-duration characteristics appear to be relatively unaffected once the forest canopy is saturated. However, in large storms, the total rainfall depth is reduced considerably (see section 9.3.2, below).

The rainfall data suggest that infiltration-excess overland flow is probably rare in both land use catchments, but will occur preferentially on the pasture catchment following short duration, high intensity events (assuming typical published values of infiltration capacities i.e. 20 - 40 mm h^{-1} for the pasture catchment and >100 - 200 mm h^{-1} for the forest catchment). Subsurface flow and saturation overland flow are suggested as more probable than infiltration-excess overland flow, because rainfall intensities are low and the rainfall pattern is intermittent for most storm events.

9.3.2 INTERCEPTION PROCESSES AND NET RAINFALL

An estimate of interception losses from the forest experimental catchment was made, in an attempt to explain the differences in water balance components between the vegetation types, and to explain the anticipated differences in the components of the hillslope runoff regime. Throughfall only was measured: stem flow for similar forest types has been shown to be only a small (1.5 %) component of total net rainfall.

The principal results of the analyses of forest interception processes follow.

i) Interception losses for summer and winter storms are similar. For large storms, about 36 % of gross rainfall is intercepted and re-evaporated back to the atmosphere. The canopy storage component is estimated to be about 1.4 mm, but varies considerably between summer and winter seasons.

ii) Annual gross interception losses are 49 %, considerably greater than 36 % estimated for large storms. This situation occurs because much of the rainfall input occurs in intermittent events of similar size to the canopy storage capacity. Rainfall in this form is evaporated quickly from the canopy surface and lost.

iii) Net interception losses are estimated to be about 85 % of gross interception loss, because half the annual rainfall occurs during the day, when transpiration losses are suppressed by evaporation from the wet canopy. Therefore, annual net interception losses are about 42 % of gross rainfall, but may range between 39 and 48 %. Contributions of unrecorded stem flow will reduce this estimate slightly.

iv) Evaporation rates from the forest canopy are considerably greater than those reported in other New Zealand and overseas studies. This difference is attributed to higher net radiation fluxes for the Mangawhara Valley, greater aerodynamic roughness induced by the rough terrain, and to advective enhancement above the forest. The data show that high evaporation rates from the canopy surface can occur during rain, although a greater opportunity for evaporation exists during the many intra-storm rainless periods.

The combination of high inter- and intra-storm evaporation rates and the intermittent rainfall input, acts to cause the large interception losses observed in the forest land use catchment. Figure 9.1a,b shows these losses. The large interception losses are reflected in the different water yield behaviour and in the hillslope runoff processes observed in the two land use catchments.

9.3.3 SOIL PHYSICAL PROPERTIES

Quantitative analyses of soil moisture and permeability characteristics were completed for the experimental catchments, within the experimental design described in chapter 4. The fundamental interactions between the rainfall input, soil physical properties, and hillslope runoff processes required an examination of the variation of soil moisture and soil permeability in space and through time. The physical factors affecting soil permeability were also examined, because field observations suggested that hydrologically important changes in soil permeability occurred during each season. The spatial distribution of saturated soil moisture conditions were also examined, because of their importance in determining the surface runoff response from the two land use catchments.

The results of these analyses are presented below.

9.3.3.1 Soil moisture: unsaturated conditions

i) Hydrologically important soil moisture gradients occur between the sub-catchment units of both land use catchments, but these are most obvious in the pasture. Riparian areas in both land use catchments have the highest mean profile moisture content. In the pasture, soil moisture decreases progressively towards the catchment ridge, but in the forest, upslope areas tend to have nearly uniform soil moisture and tend to be drier than riparian areas.

The spatial variability of soil moisture in both catchments provides direct evidence to suggest that partial or variable contributions of storm runoff occur in both vegetation types.

ii) A seasonal pattern of catchment average soil moisture is apparent in both land use catchments, but this is less obvious in the forest. Soil moisture contents are greater in the pasture than in the forest, except during the summer months. Comparatively different hydrologic responses between the two land use catchments can therefore be expected throughout the year.

iii) Few consistent relationships were found between the seasonal moisture variations of the sub-catchment units within each catchment, or between similar sub-catchment units of both the catchments. The seasonal moisture variations at individual soil depths in the sub-catchment units also show few similarities within and between the two land use catchments.

iv) The results described in sections i - iii show that different processes control the spatial and seasonal variability of soil moisture in the two land use catchments. The magnitude of these processes is variable in time and space, and between each vegetation type.

Despite the apparent complexity of the soil moisture patterns within and between the two land use catchments, the variation described can be explained simply by considering interactions between the catchment soil regime and:

a) the proximity of a site to the stream channel and hence the transient water table;
b) lateral and vertical drainage;
c) the net rainfall regime of the two vegetation types;
and d) different evaporation rates from the soil surface of both vegetation types.

The interactions between these factors and the catchments' soil moisture regime are complex, but they are described briefly below.

v) The low seasonal moisture variations in pasture riparian areas can be explained by their proximity to the main stream channel. Capillary rise from the transient water table, and downslope drainage from the midslope sub-catchment unit act to maintain moisture contents near saturation in the riparian areas.

The comparatively large profile moisture variations, found at all depths in pasture midslope areas, suggest that these areas are zones of transient hydrologic activity. Large moisture variations at the soil profile base can be explained by temporary extensions of saturated soil conditions from the riparian areas.

Profile soil moisture variations in the spur regions of the pasture land use catchment are characterised by decreasing soil moisture variability with depth. Much of this variability is attributed to additions and withdrawals of moisture at the soil surface. The formation of dessication cracks in the spur areas enhance evaporative losses from the soil profile and delay moisture recharge, thus contributing to the large moisture variations observed in the near surface soils.

vi) Similar interactions describe the seasonal variations of profile soil moisture in the forest, although these are modified considerably by the reduced net rainfall input.

Compared with the pasture, greater seasonal moisture variations occur in the forest riparian areas because the seasonal water table is lower and responds more slowly to rainfall inputs. Also the downslope movement of soil moisture is reduced. Consequently, the soils in riparian areas in the forest tend to dry more in periods of low rainfall input.

Variations in the profile soil moisture are smaller in the midslope and spur sub-catchment units of the forest, than in the pasture land use catchment. The very low seasonal moisture variations in the forest spur and midslope areas suggest a balance between the net rainfall inputs, downslope soil moisture movement, and transpiration losses from the forest vegetation.

9.3.3.2 Soil moisture: saturated conditions

i) For most storm events, saturated moisture conditions are restricted to the riparian areas in each land use catchment. In both catchments, subsurface saturation develops initially in areas of low elevation and extends to upslope areas of contour convergence.

Contour convergence dominates the effect elevation potential in determining the spatial distribution of saturated conditions in each catchment, because the first order basins are deeply incised. The effect of contour convergence is most pronounced in areas with shallow slope angles.

Small areas of surface saturation, caused by rises in the water table to the ground surface, were recorded in the pasture catchment following some large storm events. Surface saturation was not recorded in the forest.

ii) Weekly peak water table elevations are generally lower in the forest compared with the pasture. These results agree with observations of unsaturated soil moisture conditions in each catchment. Compared with the pasture, the smaller areas of saturation in the forest catchment are caused by several factors. Most important among these are:

    a) the lower net rainfall;
    and b) the slightly larger available soil moisture storage in the forest riparian areas, compared with the pasture.

    Categorical statements are not possible about causes of the different water table elevations observed in the two vegetation types, because of unavoidable differences in the morphology of the two first order basins studied.

iii) Weekly peak water table elevations appear spatially uncorrelated at most sites in each land use catchment, despite the consistent expansion and contraction of saturated soil moisture conditions implied by the previous results (i - ii) (based on a simple probability analysis of weekly peak water table elevations).

    The apparent spatial independence of the short term water table fluctuations at individual sites is ascribed to changes in the size of small, but hydrologically important soil structural fissures. The importance of these features is more pronounced in the drier catchment areas where few significant correlations were recorded between individual sites. Root channels and other biogenic fissures also contribute to the highly variable piezometric responses observed at individual sites in the forest catchment.

The unsaturated and saturated soil moisture regimes observed suggest that variable source area contributions of hillslope runoff occur in both land use catchments, but that the hillslope runoff response will differ considerably between the two land use catchments. However, widespread surface saturation in the riparian areas does not occur in either catchment, despite evidence from the unsaturated soil moisture regimes that suggests this should occur regularly.

This anomaly suggests that the soil permeabilities are either low, and much of the storm rainfall runs off as infiltration-excess overland flow, or that the soils are extremely permeable so that most of the storm rainfall leaves the catchment by subsurface routes. In either case, only small net additions to soil moisture would occur and thus prevent widespread saturation of the riparian areas in each catchment.

The soil moisture results also show that uniform differences in soil moisture cannot be expected in contrasting vegetation types in the Hapuakohe Range, and probably not in other similar steepland environments. Consequently, inferences about changes in the mechanisms and spatial distribution of hillslope runoff cannot be inferred from changes in water yield data alone, despite the claims made often for comparative catchment scale experiments.

Figure 9.1a,b shows the maximum and minimum water table elevations observed in the two land use catchments during the observation period.

9.3.3.3 Soil permeability

i) Soil permeability varies seasonally in all soil horizons in both land use catchments, including the forest litter horizon. Soil permeabilities are typically 3 - 5 times lower in winter, when antecedent soil moisture conditions are high.

ii) Hydrologically important changes in soil permeability occur between the soil horizons identified in each land use catchment. Soil permeabilities decrease with increasing soil depth, by about half an order of magnitude per soil horizon. A larger permeability difference (2 - 3 orders of magnitude) occurs between the organic litter horizon and upper mineral soil horizon in the forest.

iii) Hydrologically important differences between soil permeability in the two land use catchments are restricted to the surface soil horizons: the 'A' horizon in the pasture, and the 'O' horizon in the forest. Differences, in the permeability of the 'B_2' and 'B_3' lower soil horizon, could not be detected between the two land use catchments with the data collected ($p = 0.05$). Therefore, these results support only partly the differences in soil physical properties inferred commonly for these two vegetation types.

iv) Horizon soil permeabilities are independent of geomorphic position, except in the B_2 mineral horizon. In both catchments the permeability of this horizon is greater in the upslope sub-catchment units.

v) Spatial and seasonal permeability variations, within the mineral soil horizons in the land use catchments, appear to be controlled by interactions between soil moisture and the clay fraction of the catchment soils. Seasonal changes in soil permeability result from changes in the soil macroporosity caused by soil structural changes induced by seasonal moisture variations.

Within each land use catchment, the relationships between soil moisture and permeability vary considerably between individual soil horizons. However, these relationships are similar for the respective mineral soil horizons in each catchment, despite the different clay mineralogies and soil moisture regimes observed between them.

The similarity of these relationships suggests compensatory interactions between several factors. These are:

a) the presence or absence of structural fissures and biogenic channels in each land use catchment;
b) the degree of structural development of the mineral soils in each catchment;
c) the clay mineralogy of the soils in each catchment;
and d) the catchment soil moisture regimes.

vi) Seasonal variations were also observed in the permeability of the forest litter horizon. Field observations suggest that these result from seasonal changes in the morphology of the litter horizon that are, in turn, induced by seasonal soil moisture variations.

The soil moisture and permeability results provide information that is of fundamental importance for interpreting the rainfall-runoff mechanisms in each land use catchment. The results from this study substantiate only some of the hypotheses accepted commonly about the influence of land use on soil moisture and soil permeability, and show others to be inappropriate in this case.

Evidence from the analyses of the rainfall regime, soil moisture and soil permeability suggests that both infiltration-excess overland flow and saturation overland flow will occur in each land use catchment during wet soil conditions (see figure 9.1a,b). Smaller contributions of both these mechanisms occur in the forest because of the lower net rainfall, the lower overland flow velocities and the slightly greater available soil moisture storages observed in this land use catchment. During summer, greater soil permeabilities and greater available soil moisture storages result in smaller contributions of both infiltration-excess overland flow and saturation overland flow from each catchment.

Areas of saturated subsurface flow are restricted closely to the riparian areas of each land use catchment (see figure 9.1a,b). However, the soils of the experimental catchments are so slowly permeable, that hydrologically important contributions of subsurface flow to storm runoff are not possible, even when the soils are dry and more permeable.

9.3.4 HILLSLOPE RUNOFF PROCESSES

Hillslope runoff components were estimated, for the two land use catchments, to provide information on the relative importance of surface and subsurface flow mechanisms in each catchment. The linkages between hillslope runoff processes and stream flow were also examined, to relate the processes observed on the 'plot' scale to those observed on a 'catchment' scale.

9.3.4.1 Surface runoff

i) A general seasonal pattern of surface runoff is apparent in most sub-catchment units of each land use catchment. In riparian areas of both the forest and pasture catchments, greater yields of surface runoff occur during winter when soil moisture is high, than in summer when the soils are dry.

The reverse is true in the pasture midslope and spur sub-catchment units. In these areas, the largest yields of surface runoff occur when the soils are dry.

The forest midslope and spur sub-catchment units show no discernible seasonal variation in surface runoff yields: only small yields are produced throughout the year.

ii) Hydrologically important differences in the spatial distribution of surface runoff were identified between the sub-catchment units in each land use catchment for summer and winter conditions.

In both land use catchments during winter, the greatest yields of surface runoff are generated in the riparian sub-catchment units. Surface runoff yields become progressively smaller in the upslope sub-catchment units.

A similar pattern of surface runoff occurs in the forest during dry antecedent catchment conditions. However, in the pasture when soils are dry, less runoff occurs from the riparian areas than from both the upslope sub-catchment units.

iii) In both catchments when the soils are wet, the spatial pattern of surface runoff is related inversely to the spatial variation of soil permeability.

In the forest when the soils are dry, the relationships between the spatial variability of surface runoff and soil permeability are less obvious. However, the highest surface runoff yields are associated with the areas with the lowest soil permeability.

In the pasture catchment during dry soil conditions, there appears to be little association between the spatial variability of surface runoff production and soil permeability.

iv) Few environmental characteristics determine the yield and spatial distribution of surface runoff in each land use catchment.

Infiltration-excess overland flow is the dominant mechanism of surface runoff in the pasture land use catchment. However, saturation overland flow occurs in some riparian areas, but only where conditions are most favourable for its formation.

In upslope areas of the pasture catchment, the development of water repellency during summer can explain the anomalously large contributions of surface runoff, and the weak relationships between the spatial variation of soil permeability and surface runoff.

v) Infiltration-excess overland flow is shown conclusively to occur at only two sites in the forest catchment. However, for several reasons, infiltration-excess overland flow mechanisms are indicated as being the principal surface runoff producing mechanism in the forest. These reasons are:

a) infiltration-excess overland was observed in the forest catchment for both large and small storms;
b) soil permeabilities of the upper mineral soil horizons are similar to those in the pasture catchment, and between 2-3 orders of magnitude lower than those assumed commonly for forest environments;
c) the relationships between the catchment soil permeabilities and the rainfall intensity-duration characteristics suggest that infiltration-excess overland flow will occur;
and d) there is little evidence to suggest saturation overland flow does occur in the forest.

vi) The differences in surface runoff between the two land use catchments vary with season and sub-catchment unit. Both variations in soil permeability and net rainfall regimes are the principal determinants of the relative yields of surface runoff from each catchment.

During summer, the relative yields of surface runoff appear to be determined by differences in the catchments' soil permeability, rather than by differences in net rainfall. However, the reverse is true in winter, when the soils are relatively impermeable.

vii) For each land use catchment, the seasonal differences in surface runoff production between the sub-catchment units are all hydrologically important.

9.3.4.2 Subsurface flow

i) Compared with the forest catchment, subsurface flow discharges in the pasture catchment are larger and more responsive to rainfall. These results conflict with the accepted hypotheses of hillslope runoff for both forms of land use. However these results can be explained by the different soil moisture and permeability characteristics in each catchment.

ii) Return flow is an important component of subsurface discharge in the pasture catchment, but it was not observed in the forest catchment. Return flow in the pasture catchment was observed during about 10 % of the observation periods, and in some storms contributed about 50 % of the total subsurface discharge.

iii) In the pasture catchment, weekly peak subsurface discharges are dependent on weekly rainfall totals, and to a lesser extent on the rainfall intensity-duration characteristics. In contrast, the forest weekly subsurface discharge peaks are generally independent of rainfall characteristics, but are instead, determined by antecedent soil moisture conditions.

In both land use catchments, antecedent soil moisture conditions are the sole explanatory variable for subsurface discharges during non-storm conditions.

These results suggest that the subsurface flow responses are transient in each land use catchment, and that subsurface flow rates decline rapidly to a value determined by the seasonal variations in the catchments' soil moisture and soil permeability characteristics.

iv) In the forest catchment, the large interception losses and the slightly lower permeabilities of the riparian sub-catchment unit both act to reduce the likelihood of subsurface flow in this vegetation type.

9.3.4.3 Hillslope runoff and stream flow linkage

i) Surface runoff appears to account for most of the direct storm runoff in each land use catchment. In most small storms, much of the direct runoff can be accounted for by contributions of surface flow from riparian areas only. Field observations provide the principal evidence for the importance of surface runoff contributions to direct runoff for large storms, because the surface runoff plots provide biased estimates of hillslope runoff in these events. Widespread overland flow occurs for large storm events over all the slopes in the pasture, and over most of the slopes in the forest catchment.

ii) In both land use catchments, contributions of subsurface flow through the soil matrix are too small and too slow to contribute large volumes to storm runoff. For most catchment conditions, a combination of ground water flow from seepage heads, and subsurface flow accounts for the base flow observed in the stream channel.

iii) In both land use catchments, large lag times were observed between rainfall, surface runoff, and the direct runoff response observed in the stream channel. Slope routing appears to account for about 80 % of the lag time between rainfall and direct runoff in each catchment. The uneven micro-topography and large surface detention storage are suggested as the cause of the delayed flow responses.

The limited data on the time distribution of subsurface flow suggest this mechanism peaks at about mid-way during stream flow recession, followed by a decrease to the pre-storm discharge.

The spatial distribution of hillslope runoff conforms with the patterns described by the partial and variable source area models. However, the mechanisms of surface runoff and the causes of the spatial distribution of these processes are not well described by these models.

In both land use catchments, the spatial distributiion hillslope runoff is described best by partial, but variable source areas of infiltration-excess overland flow. The spatial distribution of surface runoff is dependent on the spatial variability of soil permeability in each catchment that is, in turn, determined by variations in soil moisture in space and time. Subsurface discharges are less important in determining the stream hydrograph in the two land use catchments studied, than reported in other studies of similar forms of land use (figure 9.1a,b).

9.3.5 STREAM FLOW PROCESSES AND CATCHMENT WATER BALANCE

An examination of stream flow processes and water balance data was completed to provide an analysis of the integrated runoff response from the two land use catchments. The influence of land use on the stream flow regime was examined by a comparison of flow durations, weekly flow maxima and unit hydrographs derived for each catchment.

9.3.5.1 General flow characteristics

i) The flow frequency distributions of each land use catchment are typical of catchments with clay-rich soils. Discharge from both catchments is characterised by long periods of low flow, punctuated by large, short duration stream rises. The generally low soil permeabilities, yet large total soil moisture storage in each catchment appear to cause a sharp inflection in the flow duration curves at 0.10 - 0.15 mm h^{-1}. This suggests a sharp transition between surface and subsurface hillslope flow processes.

The greatest absolute differences in the flow frequency occur at 0.10 mm h^{-1} (forest) and 0.13 mm h^{-1} (pasture), when subsurface and ground water discharges are at a maximum in each catchment.

ii) Estimated weekly peak flows for all storm events are greater in the pasture, than in the forest. For increasing storm size, the difference in flow maxima recorded from the two catchments becomes proportionally smaller.

iii) The differences in flow frequency and weekly flow maxima observed between the two land use catchments can be explained by:

a) differences in the net rainfall regime of the two vegetation types;
b) differences in the soil moisture and permeability characteristics of the catchments' soils;
and c) differences in size of the surface and subsurface components of hillslope runoff.

9.3.5.2 Unit hydrograph analysis

i) Unit hydrographs were estimated from most of the stream flow record from each land use catchment, for both summer and winter storm events. The form of the derived unit hydrographs was described by an inverse Gaussian distribution. A non-linear rainfall separation procedure was incorporated to determine effective rainfall for each storm event.

ii) The unit hydrographs show only small differences in the catchments' storm runoff response, either between each land use catchment, or within each catchment in response to antecedent soil moisture conditions.

iii) Principal differences in the unit hydrographs are, instead, restricted to differences in direct runoff yields and flow peaks, for each combination of vegetation type and antecedent catchment conditions examined.

9.3.5.3 Catchment water balance

i) The water balance for the two land use catchments was estimated as an average for the two year observation period.

The estimated water balances are:

PASTURE

Rainfall (mm)	= Direct runoff (mm)	+ Delayed flow (mm)	+ Ground water loss (mm)	+ evapo-transpiration (mm)
1524	291	586	30	614

FOREST

Rainfall (mm)	= Direct runoff (mm)	+ Delayed flow (mm)	+ Ground water loss (mm)	+ Interception (mm)	+ Transpiration (mm)
1521	140	397	15	639	330

ii) The water balance of the land use catchments are similar to those observed in other similar sized catchments supporting equivalent vegetation in New Zealand. In both the catchments studied here, runoff and evapo-transpiration dominate losses from the water balance: losses to ground water are small.

iii) High yields of net rainfall appear as total runoff in both land use catchments, yet relatively small yields of direct runoff occur. The intermittent, low intensity rainfall, the generally large available soil moisture storage, and the low permeabilities of the catchment soils are suggested as being responsible for these results.

The differences, in stream flow characteristics and water yield behaviour observed for the two land use catchments examined, are similar to those reported in other comparative studies of forest (various species) and pasture vegetation.

Compared with the forest, greater stream discharges occur from the pasture catchment for all flow regimes. However, the form of the storm runoff response appears to be independent of vegetation type or antecedent catchment conditions. These results are consistent with those from the analysis of hillslope runoff (chapter 7), that show the predominant mechanisms of hillslope runoff are independent of land use type. Instead, only the frequency and size of the storm runoff response differ between the two land use catchments.

The principal differences in the water balance components between each land use catchment are caused by differences in interception losses: transpiration rates are similar for the two vegetation types.

9.4 CATCHMENT MANAGEMENT PROCEDURES AND THE CONTROL OF WATER YIELD BEHAVIOUR

Chapter 1 and 2 show that early attempts to ameliorate land use conflicts in New Zealand relied heavily on overseas research. Consequently, most remedial measures used in New Zealand have been based on the following assumptions:

i) that hillslope runoff processes are spatially uniform within catchments;

and ii) that water yield behaviour, stream stabilisation and erosion can be controlled by improving soil infiltration capacities.

In most cases, improved infiltration capacities were achieved by establishing forests over entire catchments.

Significant advances in explaining the processes of hillslope runoff generation have been made in the last decade (see chapter 2). Several recent studies in New Zealand have interpreted catchment responses based on the partial and variable source area concepts (e.g. Hayward, 1976, 1978; Pearce and McKerchar, 1979; Cooke and Dons, 1982; Dell, 1982). Despite the recognition of their important implications for land and water management, these concepts have not been applied widely to land management programmes.

Confusion, about the effectiveness of remedial land management practices proposed for sensitive steepland areas, has been exacerbated by a shortage of information about the relationships between the processes governing water yield behaviour and land use change. These problems have been compounded by the recognition of the applicability of the partial and variable source area models to many areas in New Zealand.

Before the advent of the partial and variable source area models, the effects of land use change on water yield behaviour were explained simply by:

i) changes in net rainfall regimes;

ii) changes in transpiration rates;

and iii) changes in the frequency and size of surface runoff processes.

Now, the following additional information is required to understand fully the consequences of land use change:

i) the spatial variability of surface and subsurface flow processes in each form of land use;

ii) the probable changes in soil moisture regimes following land use change;

and iii) probable changes in soil physical properties following land use change.

Information of this type is not available for most sensitive steepland areas of New Zealand where land use conflict occurs.

The information on hillslope and stream flow processes, provided by this study, can be used in the development of rational land management procedures that are applicable to the Hapuakohe Range and other areas of similar lithologies.

9.4.1 A FRAMEWORK FOR THE INTERPRETATION OF THE RESULTS OF THIS STUDY

The development of appropriate land management procedures for the Hapuakohe Range requires the transfer of research results from the two experimental catchments, to a wider area. This procedure is of obvious practical importance, but few studies have been reported that consider the problem of data transfer from one catchment to another, on the basis of field evidence of hydrological processes (Pilgrim, 1983).

The transfer of data from research catchments appears to occur at two distinct levels. Hydrological data may be transferred to catchments of similar size and similar morphometric characteristics, within a single region. Alternatively hydrologic data are transferred to catchments with different morphometric characteristics, and often to regions with completely unrelated hydrologic and geomorphic characteristics. The transfer of data to similar sized catchments, within a region, can be accomplished generally with a minimum loss of information (Baron et al., 1980). However, the transfer of data from small catchments to large catchments has been only moderately successful (Vorst and Bell, 1977), while the accurate transfer of data to unrelated regions appears to be impossible (Pilgrim, 1983).

Baron et al. (1980) have reviewed the problems of data transfer from one catchment to another. Principal, among several factors, are the effects of variations in storm runoff processes, the spatial variability of these processes within catchments, and the effects of land use. The full understanding of storm runoff processes and the location of source areas of runoff has been suggested as necessary for the prediction and transfer of hydrologic data from small catchments to larger areas (Vorst and Bell, 1977; Baron et al., 1980). An improved estimation of these factors will lead to improved structures in the distributed catchment models that are used commonly for hydrologic data transfer (Pilgrim, 1983).

Thus, the extension of hydrologic data from small experimental catchments to wider areas appears to be a two stage process. The first stage requires the mechanics and spatial variability of hillslope runoff processes to be verified in small catchments. The second stage requires the improvement of catchment models already in use, to extend data from small catchments to wider areas. The calibration of these model structures requires a high quality data base from nested catchment studies, that monitor simultaneously the rainfall-stream discharge relationships for small catchments within successively larger catchments (Baron et al., 1980; Pilgrim, 1983).

This study has contributed to the first requirement described above. However, the development of techniques to extend data obtained from the two experimental catchments to make inferences about the hydrologic responses of a larger area (i.e. the whole of the Mangawhara Valley), is beyond the scope of this study. Attempts to generalise data obtained from small catchments to larger areas must be considered to be inappropriate until the hydrological consequences of 'scale', on both the yields and time distribution of catchment runoff processes, are understood more clearly (Pilgrim, 1983).

9.4.2 THE LAND USE PROBLEM IN THE UPPER MANGAWHARA VALLEY

Since 1920, about 2000 ha of native forest has been converted to pastoral agriculture in the Upper Mangawhara Valley. This land use change, particularly in the steep catchments containing low order stream channels, has been associated with continuing problems of downstream flooding, high sediment yields, and general channel instability (Bennett, 1975; Selby, 1976; W.V.A., 1977). Further information on specific details of the land use problems are described by these authors. Re-afforestation of about 1700 ha of the head waters of the Upper Mangawhara Valley has been proposed to control the downstream problems of excess storm water yields and excess sediment supply to the stream channel (W.V.A., 1977).

Low flow regulation was not suggested as an urgent management goal for the Upper Mangawhara Valley (W.V.A., 1977). However, the continued development of horticulture within the Waikato basin suggests that the requirement for adequate summer low flows will become more important, and should, therefore, be evaluated in a discussion of the hydrological implications of land management procedures.

9.4.3 SELECTIVE CATCHMENT MANAGEMENT AND STREAM FLOW CHARACTERISTICS

The analyses of hillslope runoff processes described in this study show the importance of partial area contributions of infiltration-excess overland flow, in both the forest and pasture land use catchments. Two hydrologically distinct response units can be identified within the two land use catchments studied. For most storm events, the hydrologically active areas are restricted to the riparian and re-entrent areas. These results suggest the possibility of selective management of riparian areas for the control of general water yield behaviour, storm flow characteristics, and low flow regulation. However, for large storm events, widespread overland flow is likely to develop over entire catchment areas supporting pastoral agriculture, and over most of the slopes in forest covered catchments.

In the following sections, the data obtained from this study are used to make inferences about the hydrologic effectiveness of selective catchment management. The discussion is restricted to the hydrologic implications of selective re-afforestation of riparian areas of predominantly pasture catchments, for two main reasons. These reasons are:

i) following canopy closure, stream flow characteristics and catchment water balances of completely re-afforested pasture catchments are likely to be similar to those observed for the forest catchment studied;

and ii) the complete conversion of indigenous forest catchments to pastoral agriculture will likely cause yield changes similar to those observed between the two catchments examined in this study.

These yield changes are summarised in table 9.1. Several assumptions are incorporated in this table and in the following discussion.

i) Changes in stream flow characteristics are considered to be independent of forest species, provided that they are evergreen. This assumption is well supported by the many field, experimental and theoretical studies of interception processes from forest canopies (see chapter 5);

ii) Changes in stream flow characteristics aand changes in the catchment water balance following the re-afforestation of pasture riparian catchment areas will be similar, in the long term, to those likely to occur from the continued removal of native forest and development of pastoral agriculture in upslope catchment areas.

iii) The implications discussed below are restricted to basins of similar size to the ones studied, i.e. basins containing stream channels of order three, or less, because of the difficulties in transferring data to larger areas (section 9.4.1).

The implications of selective catchment control are considered on the premise that the present catchment conditions require improvement. Selective management of riparian catchment areas is not proposed to reduce runoff components from the pasture catchment to a level typical of completely forested catchments. Instead, selective catchment management is suggested as a way of improving flow characteristics from pasture areas, so that the downstream problems will be reduced to more acceptable or manageable levels, while multiple use of the land and water resources of the area is maintained. Principally this requires the reduction of peak flows and general water yields, while adequate low flow regimes are maintained.

Land management procedures to reduce the problems of sediment supply to the stream channels are not considered, although the problems of sediment supply and water yield behaviour are related.

9.4.3.1 Selective catchment management and general water yield control

Any general water yield change derived from a partial change of land use in the Mangawhara Valley, will result from changes in catchment average interception characteristics, because the differences in transpiration rates from forest and pasture vegetation are likely to be small.

The water balance data presented in chapter 8 suggest that catchment water yields are sensitive to partial land use change. A 10 % change in land use will result in a similar sized change in total annual water yield, equivalent to about 34 mm. This value is similar to those observed in other regions in New Zealand (e.g. Dons, 1980; Duncan, 1980; Waugh, 1980).

Thus, re-afforestation of pasture riparian catchment areas, generally about one third of total catchment area, is likely to reduce annual water yields from pasture catchments by about 100-110 mm. However, the hydrological effects of riparian treatment are likely to be considerably greater than the average value estimated above. Both direct runoff and delayed flow are generated by hillslope runoff processes operating preferentially from riparian catchment areas. Consequently, general water yields are likely to be influenced more by riparian treatments than by treatment of other catchment areas. These factors are considered in the following sections. Estimates of the likely yield changes following re-afforestation of pasture riparian catchment areas are presented in table 9.1.

9.4.3.2 Selective catchment management and flood control

Land treatments for the control of direct runoff yields and flood peaks must be applied to reduce the quantities of infiltration-excess overland flow. Saturation overland flow mechanisms appear important only in restricted areas of the riparian sub-catchment units of pasture catchments.

Estimates of the likely reduction in direct runoff yields, following re-afforestation of pasture riparian catchment areas, can be made from the estimates of the spatial variability of surface runoff production in the pasture catchment, and from the observed differences in direct runoff from the two land use catchments examined.

Vegetation cover	Water balance components								
	Rainfall (mm)	=	direct runoff (mm)	+	delayed flow (mm)	+	ground water loss (mm)	+	evapo-transpiration (mm)
Pasture	1521	=	291	+	586	+	30	+	614
Riparian areas forested	1521	=	225	+	524	+	20 *	+	752
Forest	1521	=	140	+	397	+	15	+	969

* estimated

Table 9.1 : Estimated annual water balance data for catchments supporting a complete pasture cover, riparian forest cover with pasture in the upslope catchment areas, and complete forest cover in the Upper Mangawhara Valley. Note: these data are considered applicable for only small catchments containing channels of order three or less

Table 9.1 shows that the average annual difference in direct runoff from the two catchments studied is about 151 mm: about 45 % of this depth occurs during the winter months, the remainder during the summer months.

During winter, yields of direct runoff from the pasture catchments are derived mostly from riparian areas. Consequently, the re-afforestation of pasture riparian catchment areas will be effective in controlling direct runoff yields. Direct runoff yields will be reduced, primarily because of a reduction of net rainfall input. The development of a litter horizon will also reduce surface runoff contributions from these areas, by retarding the downslope movement of overland flow and thus promoting a greater opportunity for infiltration. For similar reasons, the likelihood for saturation overland flow will be also reduced.

About 71 % of the total surface runoff is derived from riparian areas in the pasture experimental catchment during winter (see table 7.3). Thus, following re-afforestation of pasture riparian catchment areas, and once the canopy has closed, direct runoff yields during winter are likely to be reduced by about 48 mm (71 % of 45 % of the 151 mm difference in annual direct runoff between forest and pasture land use catchments). This estimate is likely to be conservative, because plots in the riparian areas tend to under-estimate hillslope runoff more than the plots from the upslope sub-catchment units (see chapter 7).

During summer, the relative specific contributions from pasture riparian areas are smaller (22 % of the total plot runoff) than during winter: greater proportions of storm runoff are derived from upslope sub-catchment units during summer (see table 7.3). Consequently, the re-afforestation of these areas will be less effective in reducing direct runoff. The estimate of the reduction in direct runoff, following treatment of the pasture riparian catchment areas, is about 18 mm for storm events occurring during the summer (22 % of 55 % of 151 mm, the difference in annual direct runoff between the two land use catchments).

This estimate is not consistent with the data obtained from the surface runoff plots in the two catchments examined. The plot data suggest that surface runoff may increase from riparian areas as a result of re-afforestation, because of a smaller seasonal change in soil permeability. This may occur, but the slower transmission of surface runoff by the forest litter layer will act to reduce storm runoff peaks and direct runoff yields by reducing the contributions of surface runoff from the upslope catchment areas.

Following re-afforestation of pasture riparian catchment areas, and canopy closure, a reduction of 66 mm in the annual direct runoff yields is indicated, based on the data presented in this study and the assumptions described above.

However, it must be appreciated that riparian treatments will be less effective in very large storms as the hydrologic influence of vegetation type decreases with increasing storm rainfall inputs, even with complete forest cover.

9.4.3.3 Selective catchment management and low flow regulation

Land management for low flows is linked closely with the management of general yield and flood control, because any treatment designed to reduce these problems must necessarily reduce low flow stream discharges.

The flow duration analyses (chapter 8) show that low flows are smaller under forest vegetation compared with those under pasture, although the rates of recession from each vegetation type are very similar. These conditions arise because the catchment soils are relatively impermeable and have a large soil moisture holding capacity. Changes, in low flow conditions following land use treatment, are thus determined mainly by changes of the catchment average soil moisture.

The need for low flow regulation must be balanced against the needs of general yield and flood control. Assuming that adequate flood control can be achieved by riparian planting, the trade off, between further general yield reductions and the maintenance of low flows, depends on the the total catchment area treated.

Re-afforestation of pasture riparian catchment areas will reduce the yields of delayed flow by reducing net rainfall and so inducing lower water table elevations than would occur normally. For this analysis it is assumed that the reduction in low flows will be proportional to the area of the catchment treated. This estimate is likely to be conservative. Compared with re-afforestation of riparian areas, similar treatments applied to upslope catchment areas will be less effective, because the treatment effects will be attenuated by the intervening slope segments.

Using the assumptions above and a procedure similar to the one used in section 9.4.3.2, re-afforestation of pasture riparian catchment areas should cause an annual reduction of delayed runoff of 62 mm (33 % of 189 mm, the difference in delayed runoff between the two land use catchments examined).

9.4.4 SUMMARY

The findings of this study have important implications for the future land management of the Upper Mangawhara Valley, the Hapuakohe Range and other areas with similar environmental characteristics. The preceding discussion suggests that the management of water yield, flood control and summer low flows appear to be realistic objectives for land management in the study area.

The estimated changes in the water balance components of pasture catchments following the re-afforestation of riparian catchment areas are summarised in table 9.1. Included in this table are the water balance components for catchments supporting complete covers of the two vegetation types examined. The data presented in table 9.1 suggest that selective re-afforestation of riparian catchment areas will cause a greater proportional reduction in direct runoff compared with delayed flow. The net effect of these reductions is a more equable flow regime: low flows are reduced, but not to the same extent as peak flows.

These results suggest that land and water managers should give a greater emphasis to treating the hydrologically active areas within catchments. Considerable control of stream flow characteristics can be achieved by selective re-afforestation of riparian areas of low order channels in the Upper Mangawhara Valley, and the wider Hapuakohe Range, that are presently under pasture vegetation. However, the degree to which riparian re-afforestation causes a satisfactory change in stream flow characteristics, depends entirely on the objectives of the land management practices proposed for a given catchment.

In addition to the control of stream flow characteristics, the selective management of riparian areas in the Upper Mangawhara Valley should also yield considerable improvements in stream water quality. Riparian treatment will not reduce the incidence of mass wasting in the area, but will help prevent much of the detritus from reaching the stream channel and so improve downstream channel stability.

As data cannot yet be transferred accurately from small catchments to larger areas, practical applications of selective catchment management are the only true test of this management strategy, for effective water yield control for complete, large catchments. If adequate control of land and water resource problems can be achieved by selective catchment management, then considerable benefits from multiple use of the regions land and water resources should be derived.

CHAPTER TEN

CONCLUSIONS

CONTENTS

10.1 CONCLUSIONS

The objectives of this study are outlined in chapter 1. By considering these objectives the study has contributed to three general areas of process and land use hydrology.

10.1.1 HILLSLOPE FLOW PROCESSES

The study has shown that the hillslope runoff mechanisms inferred commonly for vegetated catchments in humid temperate environments (a varying mix of saturation overland flow and subsurface flow) are not appropriate for most storm inputs in the catchments studied, even though the spatial distribution and behaviour of many of the components of hillslope runoff are described well by the hillslope runoff models considered applicable in these environments. The single most important factor responsible for this apparent anomaly is the low permeability of the soils in the two land use catchments studied. This finding illustrates the problems inherent in the growing tendency to extrapolate findings from one region to another, without adequate verification.

The results of this study show the importance of a detailed analysis of the spatial variability of soil moisture and soil permeability within catchments, and the importance of a detailed analysis of interactions between these soil properties and the intensity-duration characteristics of the incident rainfall. Not only do interactions between rainfall inputs and soil physical properties influence the yields, the mechanisms and the spatial variability of hillslope runoff production, they also determine the water yield behaviour and stream flow characteristics of the two land use catchments studied.

This study has also provided field evidence to support the several recent model studies of hillslope runoff processes, that show the extreme sensitivity of the hillslope runoff regime to interactions between soil physical properties, the rainfall input, and slope form.

10.1.2 LAND USE CHANGE

The results from this study show that the differences in water yield behaviour and stream flow characteristics, for native forest and pasture vegetation, result mainly from the differences in evaporative losses from vegetation surfaces, when they are wet. The estimated transpiration losses are similar for the two vegetation types. These results thus confirm those described in the many recent comparative land use catchment studies reported in the literature.

The process studies of hillslope runoff, which were completed within the sub-catchment units of each land use catchment, have extended considerably the understanding of the relationships between vegetation type, surface and subsurface hillslope runoff, and hydrologically important soil physical properties. Interactions between these variables are shown to be, neither consistent among the individual sub-catchment units within a single vegetation type, nor between similar sub-catchment units within the two vegetation types examined. Also, this study has shown these interactions to be more complex than recognised generally.

Despite these complexities, the relative contributions of hillslope runoff from the two vegetation types can be explained by differences in the frequency and yields of 'Hortonian' overland flow developing above the mineral soil horizon in each catchment.

Although the differences in hillslope runoff can be explained simply in the two catchments studied, the relationships between the soil moisture distribution and the processes and yields of hillslope runoff should be examined carefully in all environments. This is particularly important in regions where the catchment soils are permeable and soil moisture variations influence directly the yields and mechanisms of hillslope runoff. In these areas, detailed examinations of hydrologically important soil physical properties are necessary because different forms of land use may be associated with different mechanisms of hillslope runoff.

10.1.3 THE APPLICATION OF HILLSLOPE HYDROLOGIC MODELS TO LAND USE MANAGEMENT

In the past, the partial and variable source area models of hillslope hydrology have not been applied widely to land management problems. This has occurred because few studies of source area hydrology have included quantitative assessments of the spatial variability of hillslope runoff components.

In this study, quantitative estimates were made of the spatial variability of surface and subsurface hillslope runoff components. These estimates show that two hydrologic response units can be identified in each land use catchment: the greatest yields of hillslope runoff occur from riparian areas in both the forest and pasture catchments. Selective management of riparian catchment areas is suggested as a method of enabling adequate control over water yield behaviour and flow frequency distribution: peak flows should be reduced more than low flow discharges by riparian re-afforestation. However, the estimates, of the effectiveness of riparian treatments made in this study, are likely to be conservative because inferences about the responses of whole hillslopes have been made from data derived from small plots. The deficiencies of the use of small plots for this purpose are outlined elsewhere in this thesis. Ultimately, the extent to which the treatment of riparian catchment areas provides satisfactory control of water yield behaviour depends on the objectives of land and water resource management in each area considered.

Catchment scale experiments are suggested as the most appropriate research method to determine the effectiveness of selective management treatments over large catchment areas. This suggestion is made because at present, it is not possible to transfer data accurately from small research catchments to larger areas. However, spatially distributed process studies must also be incorporated in future, large scale catchment experiments, to monitor induced changes in hydrologically important components of hillslope runoff.

10.2 SUGGESTIONS FOR FUTURE RESEARCH

Several areas to which future research should be directed are suggested by the sensitive relationships found in this study, between hillslope runoff, the net rainfall input and the soil moisture and permeability characteristics of the catchment soils.

The fundamental interactions between the rainfall input, soil physical properties and hillslope runoff processes, requires a greater emphasis on quantitative estimates of these variables and their variability in space and through time. Not only is this information required to understand the details of hillslope runoff, it is also necessary to enable data collection networks to be established on a sound statistical design.

Additional research is required to determine the role of non-Darcian flow in unsaturated field soils. Particularly, non-Darcian flow should be examined for the rainfall intensity-duration characteristics found under natural conditions. Inferences derived from data obtained from irrigation studies are not likely to be applicable to studies of source area hydrology.

Further research is necessary on the hydrologic implications of water repellency in clay-rich soils. Few studies have been reported on the conditions for the development of water repellency or on its general occurrence in New Zealand catchments, despite field evidence to suggest this phenomenon occurs frequently and over large areas of some catchments.

The influence of vegetation type on hydrologically important soil physical properties are not well established for many steepland environments where land use conflict occurs. Consequently, little is known on the implications of different forms of land use on the processes of source area hydrology in these areas. Comprehensive, integrated studies of the hydrological effect of contrasting land use regimes are thus required. These could be achieved by developing process studies within comparative land use studies that are already established. In addition, process studies should be incorporated in future catchment scale studies established to evaluate the hydrologic effectiveness of selective catchment management.

The delicate relationships between the rainfall input, hydrologically important soil physical properties and hillslope runoff shown in this study, suggests that results from hydrologic studies are not transferable, except within very similar environments. Consequently, future studies of hillslope runoff processes should be sufficiently detailed to establish clearly the predominant processes of hillslope runoff, without resort to inferences derived from similar studies in other areas.

Together, with more work on the quantitative estimates of hillslope runoff processes, improved catchment model structures are required to allow the information derived from small catchments to be applied to larger catchments areas, and if possible to catchments in other environments.

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APPENDIX A

SOIL MOISTURE CALIBRATION CURVES

Calibration of the neutron probe access tubes followed the procedures outlined by Eeles (1969) and Watt and Jackson (1981). Calibration curves for access tubes in individual sub-catchment units were derived from data obtained from individual sites at the time of installation. This method is similar to the 'extended field method' discussed by Williamson and Turner (1980). Soil moisture was determined gravimetrically from samples taken at 10 cm depth intervals and plotted against the count ratio measured at each depth. Additional calibration data were obtained for the surface soil layers, and at some sites for the whole profile, to supplement the initial calibration curves and calibrate the sites for a wide range of moisture contents.

The 'sphere of importance' (Olgaard, 1965), necessary for the interpretation of the data obtained by neutron moderation, was determined from a trial site within the experimental catchments. The results showed the sphere to vary slightly in diameter, being approximately 20 cm in wet soil and 25 cm in dry soil conditions. These results are very similar to those obtained by Williamson (1979) for a clay soil.

Shields for surface measurements were not used, instead a separate calibration curve was derived for the 10 cm depth for each of the sub-catchment unit, and for the 20 cm depth where the calibration curve differed significantly from that for the remaining soil profile. Presented on the following page are the regression equations describing the calibration curves, the coefficients of determination, and the standard errors of the estimate of soil moisture, given the count ratio.

Calibration curves

Pasture riparian plots: 10 cm depth

volumetric moisture percent = 107.848 x count ratio - 1.268
r^2 = 0.85 $s_{y.x}$ = 2.999

Pasture riparian plots: 20 cm to the base of the access tubes

volumetric moisture percent = 24.101 x count ratio + 23.067
r^2 = 0.67 $s_{y.x}$ = 3.231

Pasture midslope plots: 10 cm depth

volumetric moisture percent = 98.485 x count ratio + 9.500
r^2 = 0.83 $s_{y.x}$ = 3.449

Pasture midslope plots: 20 cm depth

volumetric moisture percent = 24.841 x count ratio + 22.610
r^2 = 0.51 $s_{y.x}$ = 3.506

Pasture midslope plots: 30 cm to the base of the access tubes

volumetric moisture percent = 47.889 x count ratio - 3.605
r^2 = 0.83 $s_{y.x}$ = 2.345

Pasture spur plots: 10 cm depth

volumetric moisture percent = 153.590 x count ratio - 16.718
r^2 = 0.962 $s_{y.x}$ = 3.367

Pasture spur plots: 20 cm to the base of the access tubes

volumetric moisture percent = 29.828 x count ratio + 12.884
r^2 = 0.86 $s_{y.x}$ = 3.448

Forest riparian plots: 10 cm depth

volumetric moisture percent = 47.227 x count ratio + 21.233
r^2 = 0.89 $s_{y.x}$ = 1.933

Forest riparian plots: 20 cm depth

volumetric moisture percent = 52.203 x count ratio + 8.614
r^2 = 0.84 $s_{y.x}$ = 3.396

Forest riparian plots: 30 cm to the base of the access tubes

volumetric moisture percent = 48.352 x count ratio - 5.466
r^2 = 0.88 $s_{y.x}$ = 1.967

Forest midslope and spur plots: 10 cm depth

volumetric moisture percent = 55.547 x count ratio + 11.687
r^2 = 0.75 $s_{y.x}$ = 3.630

Forest midslope and spur plots: 20 cm to the base of the access tubes

volumetric moisture percent = 20.725 x count ratio - 22.101
r^2 = 0.84 $s_{y.x}$ = 3.004

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* volumetric moisture percent: units m^3 m^{-3}
r^2 coefficient of determination
$s_{y.x}$ standard error of the estimate of moisture given the count ratio.

APPENDIX B

A SUMMARY OF THE ADDITIONAL SITE VARIABLES USED TO EXPLAIN COMPONENTS OF THE HILLSLOPE RUNOFF REGIME

The following variables are discussed in chapter 4, chapter 6 and chapter 7. They were measured at the runoff plot sites and are independent variables used to explain components of the hillslope runoff regime.

Precipitation variables

Precipitation characteristics were described by 6 variables, selected to give a measure of the intensity-duration characteristics of the weekly catchment rainfall. The variables were estimated from the rainfall record for the 104 observation periods. Weekly estimates of the 6 precipitation variables are presented in appendix H.

Soil variables

Seven variables were chosen to describe the soil physical properties at each plot site. Three variables were chosen to describe the particle size distribution at each site: (% clay, % silt and % sand; international classification). Two samples were taken for each soil horizon at the 20 observation sites in the experimental catchments. Estimates of these variables were made using the hydrometer method, in accordance with the New Zealand Standard N.Z.S. 4402 P. These three variables were assumed to remain constant during the period of observation.

The surface soil permeability at each site was described by 3 variables. Two of these variables, the summer and winter surface permeabilities, were assumed constant for their respective seasons. A third permeability variable was generated to describe the inferred seasonal permeability variations at each site. A cosine function was fitted through the mean surface permeability observed at each site, for summer and winter soil conditions. The continuous permeability variable was then generated for each surface runoff plot, for each of the 104 observation periods.

The choice of an appropriate soil moisture variable proved difficult. The observations of soil moisture, made at each site by neutron moderation, could not be used as the primary soil moisture variable because only 37 complete observations were made during the two year study period.

Several moving average antecedent precipitation indices were examined, but all were inadequate to model the seasonal variation of catchment soil moisture. Instead, the stream discharge immediately preceding the major weekly storm event was used as a surrogate variable for antecedent soil moisture. This variable represents the drainage component of the integrated catchment soil moisture regime. The principal disadvantage of the use of antecedent stream flow, as a surrogate variable, is that it does not account for the different seasonal moisture variations observed in the sub-catchment units. However, field observations made during this study suggested that antecedent stream flow and antecedent moisture conditions were linked closely in the riparian sub-catchment units. Thus, this variable was considered to provide an adequate estimate of seasonal soil moisture variation, at least for the areas where soil moisture was most likely to determine the hillslope runoff mechanisms directly (i.e. the riparian catchment areas).

Topographic variables

The topographic characteristics of each site were described by four variables; all were assumed to be constant throughout the 104 observation periods.

The slope angle of each site was determined by Abney level. The mean of three measurements was expressed to the nearest degree.

The aspect of each site was measured in degrees from geographical north, from a position below the plot facing upslope.

The surface roughness of each site, expressed as the ratio of the plot length in a direct line to the plot length along the ground, was determined from three measurements along the plot width.

The fourth variable was a discrete variable that described the geomorphic position of the site (i.e. riparian, midslope and spur).

Vegetation variables

The dry weight of vegetation adjacent to each site in the pasture catchment was estimated from twenty point samples of vegetation length, converted to a dry weight equivalent. Measurements of vegetation length were made every two weeks, but ceased when it became apparent that dry matter varied little under the grazing management used by the land owner. The results were not used in the analysis of surface runoff.

An estimate of canopy density above the runoff plots in the forest catchment, was made by expressing as a percentage, the area of clear sky from photographs taken vertically upward from identical positions in the plots. A grid was placed over the each photograph and the number of intersections in clear sky were counted and expressed as a percentage of the total number (100) of grid intersections.

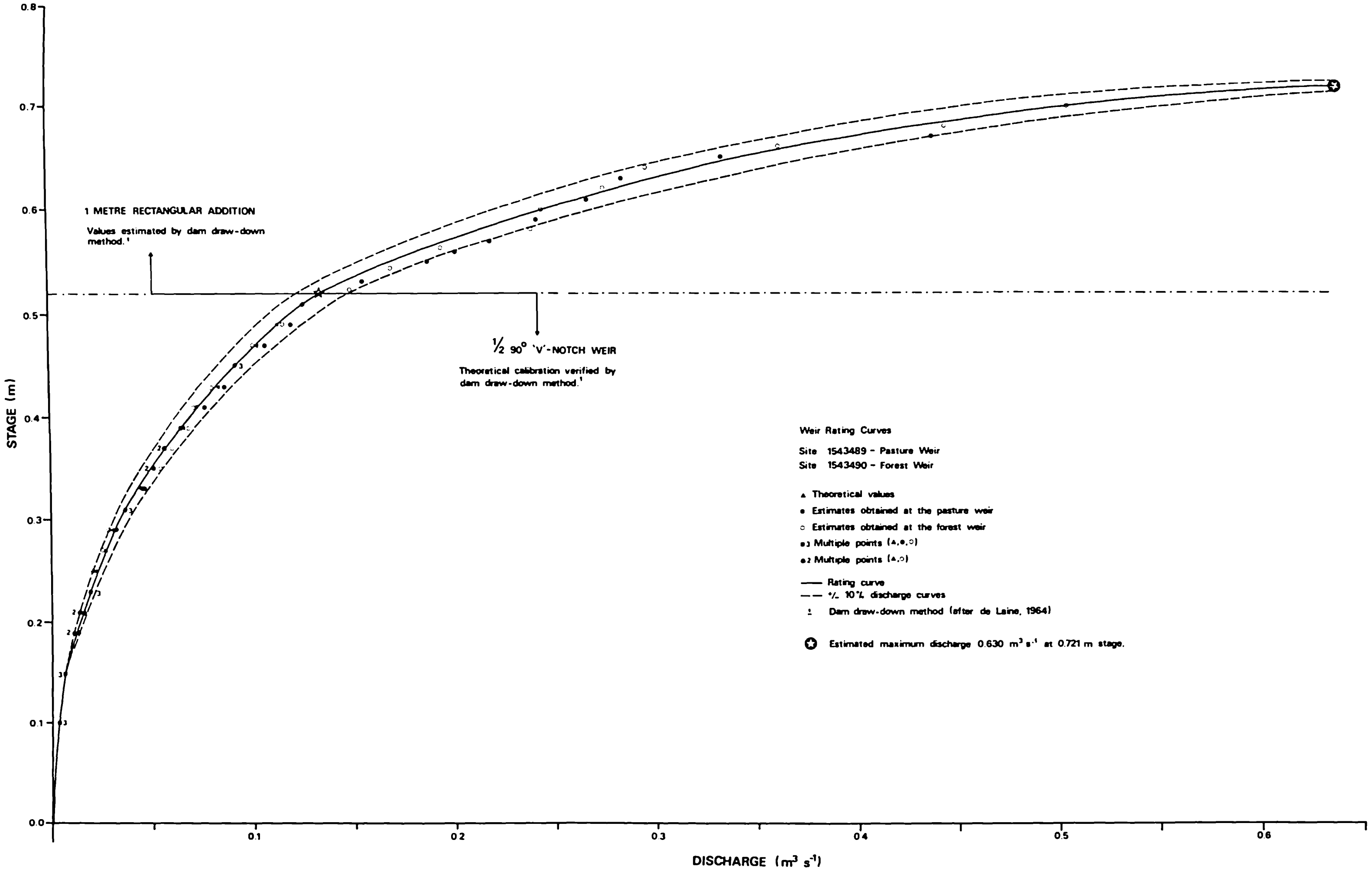
The litter layer depth was estimated from twenty depth measurements made within the surface runoff plot at each site.

APPENDIX C

STAGE DISCHARGE RELATIONSHIPS FOR THE MANGAWHARA WEIR SITES

MANGAWHARA WEIR RATING CURVES II 09.02.81

Site Numbers 1543489, 1543490



APPENDIX D

A LIST OF THE MAIN COMPUTER PROGRAMS WRITTEN FOR THIS RESEARCH PROGRAMME

Program name Function

Rainfall

Dur.for : Calculates intensity-duration curves for durations up to 24 hours; the micro-periodicity of rainfall and rainless events and the serial structure of the rainfall input.

Soil moisture

Neuton.for : Calculates soil moisture from the base data and the calibration curves (appendix a); outputs soil moisture data for individual sites and sub-catchment units and plots graphs for this output.

Subsurface flow

Sub.for : Calculates subsurface flow discharges for weekly observations of water table elevation. Calculations are based on Darcian flow theory using water table elevations and permeability estimates.

Streamflow

Weekrno.for : Calculates flow duration curves, total weekly runoff and weekly direct runoff using the Hewlett and Hibbert (1967) separation procedure.

Rbasflo.for : Removes base flow from flow data (based on the Hewlett and Hibbert (1967) separation procedure).

Unit hydrograph analysis

Unit.for : Determines the catchment unit hydrograph using and inverse Gaussian distribution and non-liner rainfall separation procedure. Calls Nag (Numerical Algorithms Group, 1981) routines to minimise the function describing the unit hydrograph and rainfall separation procedure.

Unitdata.for : Repacks serial rainfall and stream flow data to half hour intervals for unit hydrograph analysis by unit.for.

Invgaus.for : Generates inverse Gaussian density functions for the optimised parameters from program unit.for.

Generate.for : Reads observed rainfall and stream flow data and generates the predicted stream flows from the rainfall input (half hour increments) and the optimised parameters from program unit.for. Outputs data suitable for time series plots of predicted and observed discharge.

General

Gum.for : Generalised analysis of extreme value data. The correct extreme value distribution is chosen by the procedure described by van Montfort (1970). Parameters of the extreme value distribution are estimated using standard graphical procedures.

Prob.for : Generates probability density functions for the extreme value distributions (EV I, II, III).

APPENDIX E

SUB-CATCHMENT UNIT MEAN SOIL MOISTURE CONTENTS: DESCRIPTIVE STATISTICS AND WILCOXON SIGNED RANK TEST RESULTS

depth (m)	vegetation	sub-catchment unit	n	mean	s.d	Wilcoxon signed rank test results					
						Pasture			Forest		
						rip	mid	spr	rip	mid	spr
0.1	Pasture	riparian	36	46.36	5.32	--					
		midslope	36	44.56	5.29	**	--				
		spur	36	32.03	8.84	**	**	--			
	Forest	riparian	36	42.78	1.94	**	*	**	--		
		midslope	36	30.29	3.06	**	**	ns	**	--	
		spur	36	29.59	2.95	**	**	ns	**	**	--
0.2	Pasture	riparian	37	40.98	2.49	--					
		midslope	37	36.26	2.91	**	--				
		spur	37	25.24	3.99	**	**	--			
	Forest	riparian	37	46.32	2.06	**	**	**	--		
		midslope	37	29.85	1.22	**	**	**	**	--	
		spur	37	30.64	1.25	**	**	**	**	**	--
0.3	Pasture	riparian	37	47.88	1.93	--					
		midslope	37	38.45	5.09	**	--				
		spur	37	35.29	3.69	**	**	--			
	Forest	riparian	37	45.81	2.16	**	**	**	--		
		midslope	37	34.71	1.57	**	**	ns	**	--	
		spur	37	37.30	1.05	**	ns	**	**	**	--
0.4	Pasture	riparian	37	48.43	1.52	--					
		midslope	37	42.84	3.86	**	--				
		spur	37	39.42	2.76	**	**	--			
	Forest	riparian	37	46.63	2.06	**	**	**	--		
		midslope	37	36.64	1.37	**	**	**	**	--	
		spur	37	40.33	0.86	**	**	*	**	**	--

n - number of samples

s.d - standard deviation

* - significant at p = 0.05

** - significant at p = 0.01

mean - sub-catchment unit mean soil moisture content (% by volume)

ns - no significant differences between sub-catchment unit mean soil moisture

rip - riparian

mid - midslope

spr - spur

depth (m)	vegetation	sub-catchment unit	n	mean	s.d	Wilcoxon signed rank test results					
						Pasture			Forest		
						rip	mid	spr	rip	mid	spr
0.5	Pasture	riparian	37	48.98	1.24	--					
		midslope	37	47.23	2.85	**	--				
		spur	37	43.55	2.12	**	**	--			
	Forest	riparian	37	49.45	2.07	*	**	**	--		
		midslope	37	38.57	1.30	**	**	**	**	--	
		spur	37	43.56	0.94	**	**	ns	**	**	--
0.6	Pasture	riparian	37	49.59	1.16	--					
		midslope	37	48.38	2.96	**	--				
		spur	37	45.03	2.19	**	**	--			
	Forest	riparian	37	49.88	2.17	ns	**	**	--		
		midslope	37	40.21	1.24	**	**	**	**	--	
		spur	37	44.00	1.14	**	**	**	**	**	--
0.7	Pasture	riparian	37	49.93	1.14	--					
		midslope	37	49.55	3.18	ns	--				
		spur	37	46.53	2.39	**	**	--			
	Forest	riparian	37	50.35	2.30	ns	**	**	--		
		midslope	37	41.82	1.13	**	**	**	**	--	
		spur	37	44.65	1.42	**	**	**	**	**	--
0.8	Pasture	riparian	37	50.31	1.10	--					
		midslope	37	50.06	2.81	ns	--				
		spur	37	47.01	1.95	**	**	--			
	Forest	riparian	37	50.25	2.26	ns	ns	**	--		
		midslope	37	43.09	0.90	**	**	**	**	--	
		spur	37	44.87	1.17	**	**	**	**	**	--

n - number of samples

s.d - standard deviation

* - significant at p = 0.05

** - significant at p = 0.01

mean - sub-catchment unit mean soil moisture content (% by volume)

ns - no significant differences between sub-catchment unit mean soil moisture

rip - riparian

mid - midslope

spr - spur

depth (m)	vegetation	sub-catchment unit	n	mean	s.d	Wilcoxon signed rank test results					
						Pasture			Forest		
						rip	mid	spr	rip	mid	spr
0.9	Pasture	riparian	37	50.72	1.15	--					
		midslope	37	50.24	2.90	ns	--				
		spur	37	47.17	1.57	**	**	--			
	Forest	riparian	37	50.17	2.35	*	ns	**	--		
		midslope	37	44.36	0.80	**	**	**	**	--	
		spur	37	45.10	0.97	**	**	**	**	**	--
1.0	Pasture	riparian	37	50.86	1.22	--					
		midslope	37	49.56	3.00	**	--				
		spur	37	47.00	1.45	**	**	--			
	Forest	riparian	37	51.42	3.02	ns	**	**	--		
		midslope	37	44.64	0.91	**	**	**	**	--	
		spur	37	45.02	0.94	**	**	**	**	**	--
1.0 +	Pasture	riparian	74	51.07	1.33	--					
		midslope	74	52.75	2.89	**	--				
		spur	74	45.23	1.59	**	**	--			
	Forest	riparian	74	50.49	2.46	*	**	**	--		
		midslope	74	43.82	0.97	**	**	**	**	--	
		spur	74	43.30	1.50	**	**	**	**	**	--
Whole profile	Pasture	riparian	37	48.86	3.43	--					
		midslope	37	46.89	6.16	**	--				
		spur	37	41.58	7.63	**	**	--			
	Forest	riparian	37	48.77	3.34	ns	**	**	--		
		midslope	37	39.34	5.31	**	**	**	**	--	
		spur	37	40.98	5.47	**	**	**	**	**	--

n - number of samples

s.d - standard deviation

* - significant at p = 0.05

** - significant at p = 0.01

mean - sub-catchment unit mean soil moisture content (% by volume)

ns - no significant differences between sub-catchment unit mean soil moisture

rip - riparian

mid - midslope

spr - spur

APPENDIX F

ESTIMATES OF BULK DENSITY AND SATURATED MOISTURE CONTENT FOR SOILS IN THE LAND USE CATCHMENTS

PASTURE

depth	Rip 1	Rip 2	Rip 3	Rip 4	mean	std err	n	sat moist
0.10	1.070	1.098	1.145	0.910	1.0558	0.1020	4	60.16
0.20	1.230	1.276	1.245	1.279	1.2525	0.0473	4	52.55
0.30	1.254	1.292	1.308	1.257	1.2778	0.0265	4	51.78
0.40	1.256	1.279	1.307	1.269	1.2778	0.0217	4	51.78
0.50	1.254	1.315	1.301	1.266	1.2840	0.0287	4	51.55
0.60	1.251	1.294	1.310	1.260	1.2788	0.0279	4	51.75
0.70	1.253	1.312	-	1.256	1.2737	0.0352	3	51.94
0.80	1.269	1.304	-	1.269	1.2807	0.0202	3	51.67
0.90	1.261	1.305	-	1.258	1.2780	0.0236	3	51.77
1.00	1.259	1.310	-	1.264	1.2777	0.0281	3	51.79
1.10	1.254	1.308	-	1.272	1.2780	0.0250	3	51.77
1.20	1.250	1.287	-	1.248	1.2517	0.0220	3	52.39
1.30	1.247	-	-	1.243	1.2460	0.0042	2	52.98

depth	Mid 1	Mid 2	Mid 3	Mid 4	mean	std err	n	sat moist
0.10	1.057	1.066	1.051	1.112	1.0640	0.0358	4	59.85
0.20	1.235	1.106	1.281	1.246	1.2170	0.0766	4	54.08
0.30	1.234	1.134	1.288	1.255	1.2278	0.0063	4	53.67
0.40	1.248	1.124	1.291	1.258	1.2303	0.0732	4	53.58
0.50	1.249	1.103	1.275	1.247	1.2185	0.0780	4	54.02
0.60	1.251	1.150	1.275	1.287	1.2408	0.0623	4	53.18
0.70	1.250	1.186	1.274	1.281	1.2478	0.0433	4	52.92
0.80	1.247	1.196	1.270	1.275	1.2486	0.0378	4	52.88
0.90	1.242	1.189	1.271	1.270	1.2430	0.0384	4	53.09
1.00	1.233	1.197	1.268	-	1.2327	0.0383	3	53.48
1.10	1.233	1.197	-	-	1.2150	0.0255	2	54.15
1.20	1.230	1.205	-	-	1.2175	0.0177	2	54.06
1.30	1.229	1.201	-	-	1.2150	0.0198	2	54.15
1.40	1.224	1.208	-	-	1.2135	0.0148	2	54.21
1.50	1.226	1.208	-	-	1.2170	0.0127	2	54.08

depth	Spr 1	Spr 2	Spr 3	Spr 4	mean	std err	n	sat moist
0.10	1.050	0.920	1.020	1.040	1.0075	0.0597	4	61.98
0.20	1.218	1.176	1.170	1.180	1.1860	0.217	4	55.25
0.30	1.256	1.236	1.245	1.230	1.2418	0.0113	4	53.14
0.40	1.251	1.236	1.237	1.260	1.2460	0.0116	4	52.98
0.50	1.267	1.243	1.239	1.240	1.2473	0.0133	4	52.93
0.60	1.263	1.246	1.245	1.280	1.2820	0.0611	4	51.62
0.70	1.253	1.246	1.239	1.380	1.2795	0.0672	4	51.72
0.80	1.260	1.248	1.240	1.310	1.2645	0.0316	4	52.28
0.90	1.262	1.251	-	1.320	1.2777	0.0371	3	51.79
1.00	1.251	1.253	-	1.290	1.2647	0.0220	3	52.28
1.10	-	1.247	-	1.302	1.2745	0.0392	2	51.91
1.20	-	1.249	-	1.305	1.2770	0.0396	2	51.81
1.30	-	1.248	-	1.302	1.2800	0.0453	2	51.70
1.40	-	1.289	-	-	1.2890	-	1	51.38
1.50	-	1.288	-	-	1.2880	-	1	51.40

mean - sub-catchment unit mean bulk density (kg m $^{-3}$)

std err - standard error n - number of samples

sat moist - estimated saturated moisture content (% by volume)

rip - riparian mid - midslope spr - spur

FOREST

depth	Rip 1	Rip 2	Rip 3	Rip 4	mean	std err	n	sat moist
0.10	1.190	1.169	1.210	1.216	1.1963	0.0213	4	54.86
0.20	1.210	1.190	1.230	1.213	1.2108	0.0164	4	54.31
0.30	1.270	1.230	1.250	1.240	1.2475	0.0171	4	52.92
0.40	1.320	1.240	1.230	1.230	1.2550	0.0436	4	52.04
0.50	1.320	1.210	1.220	1.220	1.2425	0.0519	4	53.11
0.60	1.300	1.200	1.230	1.210	1.2350	0.0451	4	53.40
0.70	1.290	1.210	1.190	1.210	1.2250	0.0443	4	53.80
0.80	1.300	1.210	1.190	1.200	1.2250	0.0507	4	53.80
0.90	1.290	1.200	1.200	-	1.2300	0.0520	3	53.58
1.00	1.260	1.190	1.180	-	1.2100	0.0436	3	54.34
1.10	1.250	-	1.210	-	1.2450	0.0495	2	53.02
1.20	1.300	-	1.210	-	1.2550	0.0636	2	52.64
1.30	1.310	-	1.220	-	1.2650	0.0636	2	52.26

depth	Mid 1	Mid 2	mean	std err	n	sat moist
0.10	1.010	-	1.0100	-	1	61.89
0.20	1.120	-	1.1200	-	1	57.74
0.30	1.150	1.179	1.1645	0.205	2	56.06
0.40	1.170	1.167	1.1685	0.0021	2	55.59
0.50	1.230	1.179	1.2045	0.0361	2	54.55
0.60	1.280	1.221	1.2505	0.0417	2	52.81
0.70	1.280	1.230	1.2550	0.0354	2	52.04
0.80	1.286	1.240	1.2630	0.0325	2	52.34
0.90	1.283	1.249	1.2660	0.0240	2	52.23
1.00	1.290	1.248	1.2690	0.0297	2	52.11
1.10	1.289	1.242	1.2655	0.0332	2	52.25
1.20	1.292	1.242	1.2670	0.0354	2	52.19
1.30	1.294	1.241	1.2675	0.0375	2	52.17
1.40	1.298	1.241	1.2695	0.0402	2	52.09
1.50	1.294	1.238	1.2660	0.0396	2	52.23

depth	Spr 1	Spr 2	mean	std err	n	sat moist
0.10	0.870	-	1.8700	-	1	67.17
0.20	1.150	-	1.1500	-	1	56.60
0.30	1.220	1.260	1.2400	0.0283	2	53.21
0.40	1.230	1.280	1.2550	0.0354	2	52.64
0.50	1.260	1.282	1.2710	0.0172	2	52.04
0.60	1.240	1.279	1.2595	0.0276	2	52.47
0.70	1.285	1.286	1.2855	0.0007	2	51.49
0.80	1.288	1.286	1.2870	0.0014	2	51.43
0.90	1.289	1.284	1.2865	0.0035	2	51.45
1.00	1.288	1.289	1.2885	0.0007	2	51.38
1.20	1.280	1.287	1.2835	0.0049	2	51.57
1.20	1.282	1.288	1.2850	0.0042	2	51.51
1.30	1.279	1.284	1.2815	0.0035	2	51.64
1.40	1.284	1.284	1.2841	0.0000	2	51.55

mean - sub-catchment unit mean bulk density (kg m $^{-3}$).
std err - standard error n - number of samples
sat moist - estimated saturated moisture content (% by volume)
rip - riparian mid - midslope spr - spur

APPENDIX G

SOIL PARTICLE SIZE RESULTS FOR THE VEGETATION - SUB-CATCHMENT UNIT - HORIZON EXPERIMENTAL CELLS

PASTURE

Sub-catchment unit	Soil horizon	Clay			Silt			Sand		
		n	mean	s	n	mean	s	n	mean	s
Riparian	1	8	50.19	3.96	8	25.13	5.09	8	24.69	3.37
	2	8	48.19	6.71	8	23.63	3.69	8	28.19	3.97
	3	8	44.44	6.53	8	23.94	1.70	8	31.56	5.23
Midslope	1	7	38.14	6.84	7	31.29	6.54	7	30.57	12.57
	2	8	27.25	7.03	8	27.38	5.01	8	45.38	7.05
	3	8	26.00	4.71	8	27.31	5.13	8	46.69	6.07
Spur	1	8	41.56	3.27	8	32.94	1.74	8	25.50	3.95
	2	8	33.31	2.93	8	27.43	2.24	8	39.25	3.36
	3	8	27.94	3.35	8	27.06	4.70	8	45.00	4.50

FOREST

Sub-catchment unit	Soil horizon	Clay			Silt			Sand		
		n	mean	s	n	mean	s	n	mean	s
Riparian	1	4	42.12	2.10	4	34.50	6.46	4	23.38	7.95
	2	8	42.38	5.67	8	29.19	4.17	8	28.44	5.05
	3	8	45.27	9.48	8	26.56	2.67	8	28.44	7.91
Midslope	1	0	*	*	0	*	*	0	*	*
	2	4	31.00	0.82	4	29.87	2.17	4	39.13	1.44
	3	4	37.75	0.96	4	27.75	2.99	4	36.50	3.70
Spur	1	0	*	*	0	*	*	0	*	*
	2	4	30.00	3.44	4	28.38	1.03	4	41.63	3.28
	3	4	32.25	3.48	4	31.38	3.22	4	36.38	5.98

n - number of samples
s - standard deviation
mean - cell mean percentage of soil particles in the specified size fraction (international particle size classification)

APPENDIX H

WEEKLY RAINFALL PARAMETERS AND ANTECEDENT SOIL MOISTURE ESTIMATES

	Weekly rainfall parameters						Antecedent soil moisture	
Period	Raintot	Rtime	Maxint	Vmax	Halfint	Aveint	Pasture	Forest
1	27.4	22.17	28.57	2.40	7.25	1.24	3.003	2.580
2	10.3	10.00	7.20	0.60	2.60	0.87	2.937	2.534
3	67.7	32.08	26.51	2.20	13.05	2.11	2.818	2.534
4	107.1	17.75	32.00	8.00	23.08	6.03	3.072	2.885
5	59.3	33.16	12.31	4.10	8.66	1.79	3.580	3.082
6	51.8	26.58	74.34	6.20	12.40	1.95	3.396	2.901
7	20.0	*	*	*	*	*	3.479	2.885
8	9.2	5.19	3.46	4.70	3.96	1.77	3.416	2.996
9	23.9	14.83	11.99	2.00	5.47	1.61	3.252	2.960
10	49.2	27.58	9.99	3.30	8.66	1.78	3.020	2.827
11	13.8	6.25	16.87	2.80	5.60	2.21	3.228	2.960
12	9.2	13.00	2.28	1.00	2.28	0.71	3.477	2.827
13	56.9	46.08	22.75	3.00	10.16	1.23	3.666	3.030
14	42.0	35.63	18.40	4.60	14.13	1.18	3.299	3.190
15	10.0	10.42	13.09	1.10	2.70	0.96	3.141	2.803
16	0.0	0.00	0.00	0.00	0.00	0.00	2.974	2.708
17	26.6	11.92	14.39	1.20	9.16	2.23	2.984	2.625
18	9.6	6.17	12.00	2.00	5.92	1.56	2.831	2.557
19	70.8	39.83	68.40	5.70	11.10	1.78	2.998	2.534
20	45.1	5.50	39.73	29.80	39.73	8.20	3.165	2.708
21	15.1	4.42	16.80	5.60	12.20	3.42	2.773	2.646
22	40.8	12.50	22.32	18.60	22.32	3.26	2.730	2.493
23	25.1	6.06	35.73	6.70	13.40	4.14	2.891	2.557
24	6.9	11.08	6.00	1.00	2.19	0.62	2.888	2.451
25	74.7	17.25	25.20	4.20	18.00	4.33	2.757	2.282
26	7.7	3.00	10.79	0.90	4.40	2.57	3.012	2.862
27	7.8	3.00	10.01	0.90	4.70	2.60	2.606	2.262
28	45.7	110.33	48.02	4.00	9.00	0.41	2.607	2.262
29	4.6	2.19	8.00	0.50	2.60	2.10	2.825	2.262
30	0.0	0.00	0.00	0.00	0.00	0.00	2.819	2.262

appendix H cont../

	Weekly rainfall parameters						Antecedent soil moisture	
Period	Raintot	Rtime	Maxint	Vmax	Halfint	Aveint	Pasture	Forest
31	7.4	2.50	12.00	1.00	*	2.96	2.380	2.230
32	81.5	52.17	53.96	4.50	18.00	1.56	2.226	2.262
33	42.7	12.17	15.60	2.60	15.43	3.51	2.537	2.380
34	25.5	19.42	12.00	1.00	5.32	1.31	2.717	2.451
35	4.0	6.44	3.20	0.60	1.60	0.62	2.744	2.303
36	102.6	20.42	53.41	17.80	42.10	5.03	2.479	2.208
37	4.3	2.00	3.84	1.60	3.20	2.15	3.141	2.766
38	21.1	2.83	52.69	8.80	24.80	7.43	2.420	2.230
39	31.0	13.83	36.01	3.00	7.50	2.24	2.682	2.282
40	12.9	4.92	21.00	3.50	7.00	2.62	2.618	2.282
41	0.0	0.00	0.00	0.00	0.00	0.00	2.498	2.163
42	19.6	9.13	23.20	2.90	8.56	2.15	2.843	2.054
43	10.2	3.19	19.20	1.20	5.17	3.20	2.580	2.282
44	1.7	1.13	2.24	0.70	1.40	1.51	2.282	2.001
45	14.4	13.38	8.00	0.50	2.64	1.08	2.526	2.262
46	20.2	6.38	28.80	1.80	7.70	3.17	2.377	1.974
47	27.1	17.50	14.40	0.90	4.29	1.55	2.455	2.186
48	43.8	20.50	28.80	1.80	9.84	2.14	2.601	2.380
49	19.2	31.63	17.60	1.10	5.60	0.61	2.271	2.163
50	8.3	5.06	9.60	0.60	5.39	1.64	2.238	2.079
51	51.3	22.63	44.80	2.80	10.69	2.27	2.207	2.128
52	10.5	6.63	12.00	1.50	4.75	1.59	2.616	2.534
53	50.1	16.00	21.20	5.30	12.58	3.13	2.393	2.208
54	61.5	26.19	30.40	1.90	9.91	2.35	2.879	2.646
55	26.4	6.63	20.00	5.00	11.55	3.99	3.138	4.098
56	56.7	22.94	70.40	4.40	9.08	2.47	2.601	2.468
57	13.0	2.81	27.20	1.70	8.67	4.62	3.218	2.845
58	17.7	7.38	33.60	2.10	7.60	2.40	2.503	2.468
59	28.5	12.81	29.60	3.70	7.51	2.22	2.590	2.351
60	42.9	23.63	10.40	2.60	7.76	1.82	2.766	2.493

appendix H cont../

	Weekly rainfall parameters						Antecedent soil moisture	
Period	Raintot	Rtime	Maxint	Vmax	Halfint	Aveint	Pasture	Forest
61	38.5	23.44	28.80	1.80	8.65	1.64	2.742	2.398
62	22.0	6.94	40.00	2.50	8.43	3.17	2.750	2.603
63	23.6	8.31	27.20	1.70	8.18	2.84	2.761	2.351
64	15.1	7.81	16.00	1.00	7.70	1.93	2.847	2.332
65	1.7	4.00	1.60	0.10	1.20	0.38	2.784	2.262
66	27.7	11.25	30.93	5.80	18.71	2.46	2.703	2.208
67	27.5	11.88	24.00	1.50	6.45	2.32	2.982	2.332
68	0.0	0.00	0.00	0.00	0.00	0.00	2.738	2.262
69	5.3	2.50	12.80	0.80	4.00	2.12	2.639	2.163
70	63.8	18.06	30.40	1.90	10.00	3.53	2.468	2.128
71	5.6	4.38	4.00	1.00	3.42	1.28	2.481	2.282
72	25.9	12.75	52.80	3.30	9.52	2.03	2.348	2.128
73	63.1	18.81	65.60	4.10	11.71	3.35	2.497	2.186
74	0.8	1.44	1.60	0.10	0.00	0.56	2.730	2.351
75	4.4	3.75	4.80	0.60	2.27	1.17	2.688	2.054
76	30.9	8.63	44.00	5.50	15.37	3.58	2.438	2.001
77	106.7	22.56	57.60	14.40	36.27	4.73	2.661	2.128
78	2.3	1.75	5.60	0.70	2.81	1.31	2.489	2.128
79	14.1	4.13	11.20	0.70	7.70	3.42	2.483	2.163
80	22.9	17.94	9.60	0.60	5.76	1.28	2.565	2.028
81	33.3	11.31	41.14	18.00	36.00	2.94	3.224	2.827
82	10.3	7.13	8.00	0.50	4.56	1.45	2.305	1.974
83	5.3	10.81	6.40	0.40	2.16	0.49	2.196	1.917
84	4.7	9.88	8.00	0.50	2.37	0.48	2.279	1.856
85	3.7	1.75	10.40	1.30	3.93	2.11	2.258	1.887
86	53.9	10.31	35.20	2.20	14.82	5.23	2.010	1.740
87	19.4	11.31	19.20	1.20	4.67	1.72	2.179	1.887
88	0.8	0.38	4.80	0.30	1.00	2.13	2.211	1.946
89	24.8	9.50	20.80	2.60	11.20	2.61	2.180	1.740
90	42.9	9.06	65.60	4.10	22.52	4.73	2.321	1.740

appendix H cont../

Period	Weekly rainfall parameters						Antecedent soil moisture	
	Raintot	Rtime	Maxint	Vmax	Halfint	Aveint	Pasture	Forest
91	0.0	0.00	0.00	0.00	0.00	0.00	2.440	1.740
92	200.4	44.13	57.60	3.60	29.48	4.54	2.385	1.740
93	18.3	6.41	21.60	1.80	12.60	2.85	-	2.293
94	6.7	5.00	16.00	1.00	2.80	1.34	2.320	2.128
95	2.7	1.13	20.80	1.00	3.20	2.40	2.350	2.054
96	29.7	11.81	21.07	7.90	17.11	2.51	2.336	2.028
97	28.1	10.88	25.60	1.60	9.60	2.58	2.211	1.946
98	15.8	5.69	22.40	1.40	5.95	2.78	2.176	2.028
99	4.2	5.63	6.40	0.40	3.20	0.75	2.144	1.974
100	58.7	26.63	43.20	2.70	9.98	2.21	2.007	2.054
101	39.9	15.25	62.40	3.90	9.20	2.62	2.182	2.186
102	33.3	14.63	68.80	4.30	9.73	2.28	2.818	2.534
103	54.0	18.00	80.00	5.00	14.96	3.00	2.706	2.104
104	56.7	16.88	30.40	1.90	10.16	3.36	3.409	2.939
105	41.5	11.81	32.00	2.00	13.40	3.51	3.443	3.086

Abbreviations

Raintot - total weekly rainfall (mm)
Rtime - total weekly rain duration (h)
Maxint - weekly maximum rain intensity (mm h^{-1})
Vmax - depth of rainfall during the period of maximum intensity (mm)
Halfint - weekly maximum half-hour intensity (mm h^{-1})
Aveint - average weekly intensity (mm h^{-1})
Ante - antecedent stream flow $\log_e$ ($m^3 s^{-1} \times 10^{-3}$)

ERRATA: VOLUME TWO

Page	
273-4	Table 7.5a,b: '$m\ s^{-1}$' should read: '$cm\ s^{-1}$'.
276-7	Table 7.6a,b: '$m\ s^{-1}$' should read: '$cm\ s^{-1}$'.
276	Table 7.6a: Missing definition for variable 'ante'. 'Ante' is the antecedent stream flow ($\log_e m^3\ s^{-1} \times 10^{-3}$) that occurred before the largest storm in each of the 104 observations periods. The variable 'ante' was used as a surrogate variable for antecedent catchment soil moisture.
277	Table 7.6b: 'Table 6.6a' should read: 'Table 7.6a'. Missing definition for variable 'vmax'. 'Vmax' is the depth of rainfall that occurred during the period of maximum rainfall intensity in each observation period. See also appendix H.'
291	Line 1: 'is to' should read: 'is thought to'.
291	Line 2-3: 'with the subsurface' should read: 'with the estimates of subsurface'.
291	Line 29: '7.7b' should read: '7.6b'.
374	Line 38: 'soil regime' should read: 'soil moisture regime'
383	Table: '1524' should read: '1521'.
451	Appendix H: 'Antecedent stream flow is the variable 'ante' and is used as a surrogate for antecedent catchment soil moisture (see cols. 7-8).