RUNOFF, INFILTRATION AND SOIL ERODIBILITY STUDIES IN THE OTUTIRA CATCHMENT

by

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PREFACE

The work described in this thesis was undertaken in an attempt to discover the causes of erosion in areas of yellow-brown pumice soils in the central part of the North Island of New Zealand. This erosion appears to have become more wide-spread during the last thirty-five years in which intensive pastoral farming has gradually spread over the area.

Detailed studies have been confined to the laboratory and to the Otutira catchment which is one of the International Hydrological Decade Experimental Basins controlled by the Ministry of Works.

I am indebted to Professor C. Duncan for supervising the first half of the work and to Professor J. D. McCraw for supervising the second half. Dr. P. Hosking gave me advice on statistical analysis of the data and arranged for use of the University of Auckland I.B.M. 1130 computer. A number of students and friends have given me help in the field and the laboratory and to them I extend my thanks. Financial support was provided by the University Grants Committee.

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CONTENTS

FIGURES

TABLES

ABSTRACT

Yellow-brown pumice soils cover a large area of the central North Island of New Zealand. In the Waikato River basin these soils occupy over 7,000km^2. Since land development started in the mid-1930s approximately 4,000km^2 have been converted from the native vegetation to exotic forests (1,243km^2) and pasture (2,740km^2), and a further 500km^2 could be developed.

Since about 1959 gully erosion has become more common and widespread. The causes of this erosion were not known, although many hypotheses attempting to account for erosion have been put forward. The research reported in this thesis was undertaken in an attempt to isolate the most important causes of erosion.

Three experiments have been completed.

(1) A study of runoff from plots placed in areas of pasture grass, ungrazed grass and scrub vegetation has been made. Climatic, soil, vegetation, and slope variables were studied and as a result of statistical analysis it is concluded that surface water runoff is greater from developed land in pasture and less from areas covered by scrub and ungrazed grass vegetation. The major causes of runoff from pastures are very intense rainfall on a soil with low moisture content.

(2) Infiltration studies with an infiltrometer, designed and built for the purpose, reinforce the conclusions drawn from runoff studies. They also show that modifications of soil properties, especially compaction caused by animals and vehicles, decrease infiltration and hence promote runoff.

(3) Flume studies of the erodibility of pumice soils indicate that soil particles are easily entrained by running water, but that plant roots inhibit this process.

Analysis of data from the three experiments indicates that land development should be carried out so that:
(a) a close vegetation cover is kept on all soils;
(b) channel development is avoided; (c) vulnerable areas such as valley floors and steep valley sides are kept as water absorption areas; (d) animals and vehicles are excluded from water absorption areas to prevent soil compaction; (e) plants with strong and dense root systems are used to protect surface soils.

CHAPTER 1

EROSION IN AREAS OF YELLOW-BROWN PUMICE SOILS OF THE CENTRAL NORTH ISLAND

Extensive areas of the central North Island of New Zealand have yellow-brown pumice soils formed in a parent material of rhyolitic Taupo Pumice Ash beds of paroxysmal origin, erupted about 130 A.D. (Taylor, Pohlen and Scott, 1968; Healy, Vucetich and Pullar, 1964). This region extending southwards from Rotorua and Tokoroa to the mountains of Tongariro National Park had, at the time it was visited by the first Europeans in the 1840s, a considerable Maori population around the shores of its numerous lakes, along the Waikato River and close to the edges of the forests (Cooper, 1851). European settlement began in the 1880s in the Kaingaroa Plains but only in the Reporoa district was it very successful. Bush sickness caused losses of animals, and the poor feed provided by the native grasses, the depredations of wild dogs and the high transport costs combined to keep the area thinly settled and largely undeveloped (Vaile, 1939; Ward, 1956).

Much of the effort to develop the pumice lands during the 1930s was put into forestry. The discovery in 1936 that top-dressing pastures with cobaltised superphosphate prevents bush sickness, and the assumption of the responsibility for land development by the government allowed considerable settlement before development ceased at the outbreak of World War II. Land development commenced again in 1947 and large areas of land have been brought into pasture. Table 1-1 summarises the type of vegetation cover and percentage of land under the various classes of vegetation on the yellow-brown pumice soils of the Waikato River basin.

TABLE 1-1. Vegetation, in the Waikato River basin, on yellow-brown pumice soils (source: Waikato Valley Authority)

Cover Type	Present Cover		Percentage of area physically capable of further development	Remarks
	Area (km^2)	Percentage of Waikato Basin pumice land		
Bare rock, ice, permanent snow	184	3	0	
Tussock	370	5	100	Mainly in gazetted National Park
Tussock/scrub associations	842	12	Probably up to 95	Current figures include 285km^2 in East Taupo Forestry proposals
Indigenous forest, including cutover forest	1,632	23	30	Difficult country, mainly in the Kaimanawa & Hauhungoroa Ranges. Economics probably the limiting factor to development.
Pasture	2,740	39		Already developed
Exotic forest	1,243	18		Already developed
Total	7,011	100		

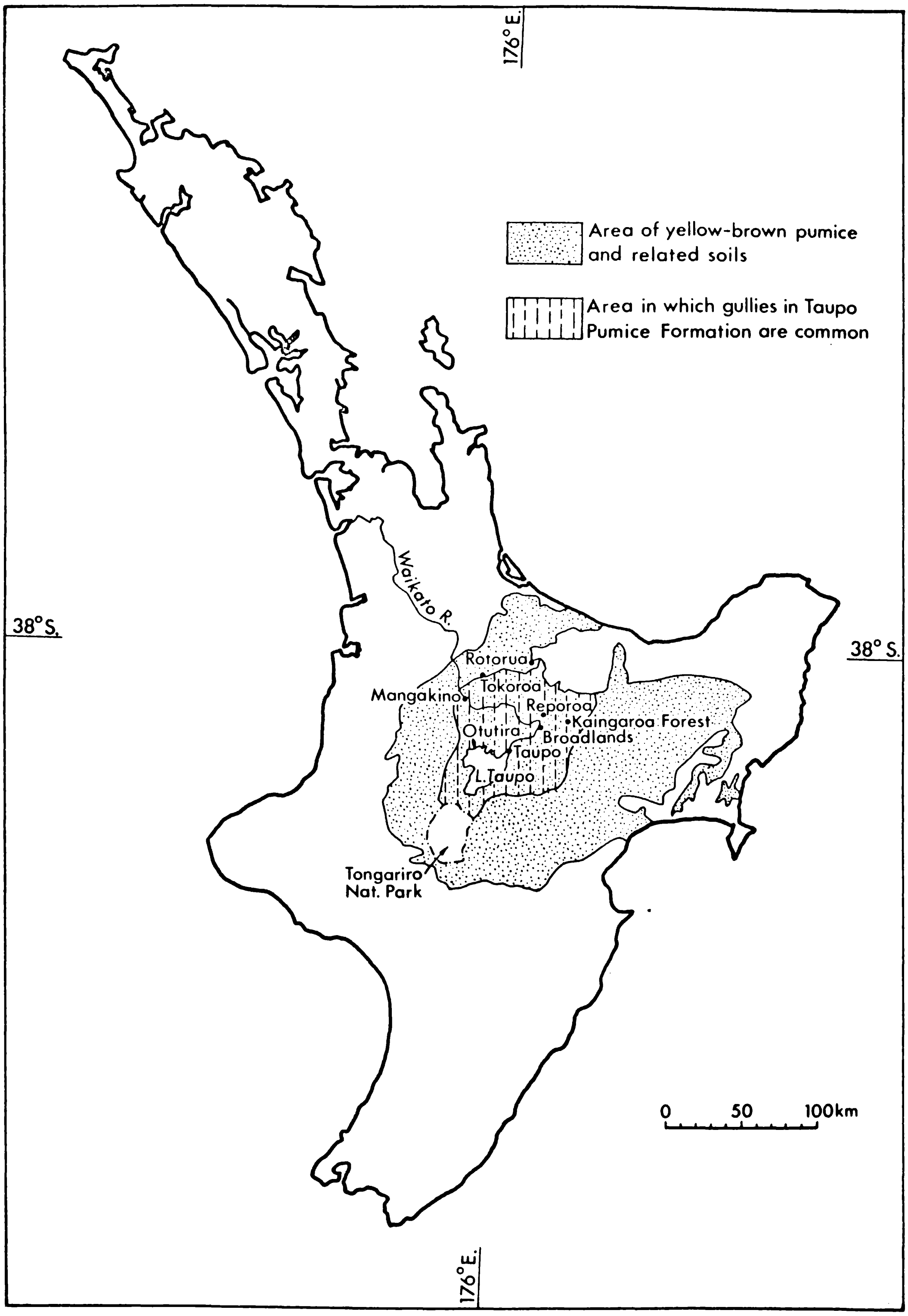

Fig. 1-1. Areas with yellow-brown pumice soils (after N.Z. Soil Bur. Bull. 26(1),) and with common gully erosion.

Methods of land development

Most of the central North Island was covered with scrub or tussock grassland and only the ranges were occupied by forests. The scrub is usually a shrub association of manuka (*Leptospermum scoparium*) and bracken fern (*Pteridium esculentum*) but introduced broom (*Cytisus scoparius*) is an important member in a few places.

The scrub is cut or crushed with large flanged rollers towed behind crawler tractors. The debris is left to dry for three or four months and then burned. After the burn the land is disced with giant discs and then harrowed. The whole cultivated area is then rolled twice to compact the seed bed. Finally the land is sown, usually from the air, with a seed mixture of 30lbs (13.6kg) and a dressing of 3cwt (152kg) of cobaltised superphosphate per acre (0.4ha) (Ward, Parkes, Grainger and Fenton, 1966). The seed mixture has the following composition:

15lb	ryegrass (*Lolium perenne*)
5lb	H1 ryegrass (*L.perenne* 'Manawa')
4lb	cocksfoot (*Dactylis glomerata*)
3lb	white clover (*Trifolium repens*)
2lb	red clover (*T. pratense*)
1lb	crested dogstail (*Cynosurus cristatus*)

Soil erosion

The morphology of soil erosion in the pumice lands is closely controlled by the geology and topography of the region. Over large areas sheets of plateau-forming ignimbrites are cut by narrow or gorge-like valleys. This landscape has been coated with a number of volcanic ash showers, the last of which came from the 130 A.D. eruptions. Many of the valleys were partly filled with thick deposits of airfall, nuée ardente, lahar and colluvial pumice. Some valleys were partly re-excavated soon after the 130 A.D. eruptions but others retained much of the pumice which was gradually colonised by plants. In these pumice-filled valleys most water seeped through the porous deposits and there were few surface streams. An example of the resulting landscape is shown in figure 1-2. The first noticeable recent erosion of the valley infills occurred at Broadlands about 1959, but the first large scale features were produced in 1962 when nearby Rotorua had a rainfall of 2580.6mm which is nearly twice the annual rainfall of 1384mm (Healy, 1967). Erosion was also first noticed in other parts of the pumice lands, especially at Reporoa and around Mangakino, at the same time. In all areas it appeared to coincide with the first unusually wet season occurring after land development.

The nature of the erosion has been described by Healy (1967) and by Selby (1967a). In a few areas sheet erosion has occurred on steep slopes, but far more common and of greater geomorphological and economic significance are the large gullies which have re-excavated the remaining pumice infill of the ignimbrite valleys and gorges. Some of the largest gullies are 30m wide, 30m deep and several kilometres long. They have dissected the land of several farms, destroyed culverts, farm bridges and fences and the outwash debris from them has been left as an infertile deposit on lower ground, or washed into the lakes of the Waikato River system where it has endangered the production of hydro-electric power. A typical gully is shown in figure 1-3.

The gullies have been described by Blong (1965, 1966, 1970) Healy (1967) and Oliver (1969). Oliver has also studied the sediments of gully heads near Mangakino. The causes of gully erosion have been subjectively assessed but, as yet, no quantitative data have been published. Hypotheses put forward suggest that an increase in surface water flow has caused the gullies, and that the increased surface water flow is a result of:

(1) Short duration high intensity rainfalls (Robertson, 1963; Blong, 1965).

(2) Resistance to wetting of pumice soils when unsaturated (Van't Woudt, 1954; Packard, 1957; Glass and Drost, 1962).

(3) Organic matter accumulation in the upper horizons of pumice soils (Dixon and Jackman, 1954; Jackman, 1964).

Fig. 1-2. A typical ignimbrite plateau with pumice filled valleys, near Mangakino.

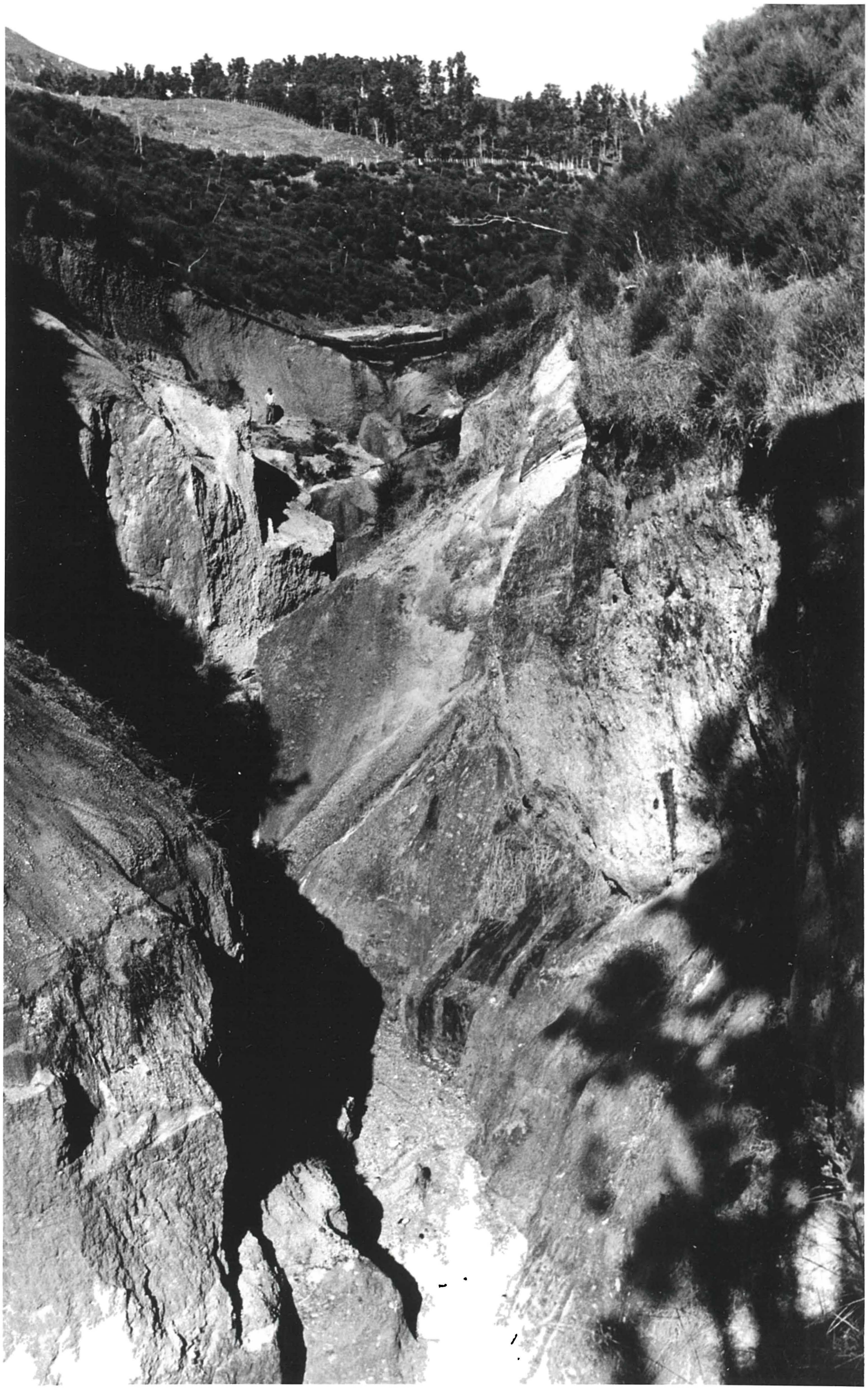

Fig. 1-3. A large gully near Mangakino.

(4) Soil compaction as a result of consolidation by heavy machinery and stock (Packard, 1957; Campbell, 1965).
(5) The absence of earthworms and the build up of a dense root mat (Bailey, 1953).
(6) High seasonal rainfall soon after land development (Healy, 1967).
(7) Lower infiltration rates into grass root mats than into soil and roots of scrub areas (Selby, 1967b).
(8) Reduction of flow-restricting vegetation (Oliver, 1969).

Many of these hypotheses overlap, but they fall into two classes:

1) those concerned with the effects of prolonged or intense rainfalls;
2) those concerned with the influence of the physical properties of the soils upon infiltration and hence upon runoff. The first class can be tested by studies of runoff under naturally occurring rainstorms and the second class less directly by measuring appropriate soil properties and correlating them with observed runoff. The soil properties to be measured must include all those likely to influence infiltration - especially, organic matter content, particle size, aggregation, bulk density, compaction and porosity.

Construction

It is evident in many places that the building of roads and culverts has locally caused surface water flow which has left pumice deposits on pastures, the grasses of which have then died and the runoff from later storms has washed over bare, unprotected soil. Tracks cut by farm machinery, animals and foresters have also left many areas of soil unprotected and prone to the formation of rills which can rapidly turn into gullies, once a stream cuts down into the pumice infills. Oliver (1969) has classified these possible causes into: 1) those which increase stress on soils; and 2) those which reduce soil strength.

Whilst it is clear that local causes such as inappropriate siting of farm tracks, fences and roadworks can be avoided and so reduce or prevent gully initiation, it is also clear that these obvious causes cannot account for the origins of all gullies. Reliable quantitative information on the effects of climate, soils and vegetation on runoff are essential before conservation practice and erosion prediction can be put onto a reliable basis.

Otutira experiments

The object of the research reported in this thesis is to provide information on the variables which influence runoff from yellow-brown pumice soils. It was evident that a study at the catchment level would not provide the detailed information needed on a large number of variables, and it was decided therefore to install a series of plots in a suitable catchment so that runoff from small areas under different kinds of vegetation and land use could be studied. Much of the accessible land had already been cleared of its original vegetation when this study started in 1967, and the choice was restricted to areas where land development was in progress. Because the main government developing agency -- the Department of Lands and Survey -- does not undertake forward planning, and works on an annual budget and plan, it could not be guaranteed that plots put into an undeveloped area would be left undisturbed for several years. It was decided, therefore, to place all of the experiments in one catchment at Otutira.

The Otutira catchment had been chosen by the Ministry of Works Hydrological Survey as one of New Zealand's International Hydrological Decade Experimental Basins. In this basin land use is controlled for research purposes. Part of the catchment was already established in pasture and the majority of the land was in its original scrub-covered state. The catchment is described in chapter 2.

Information derived solely from runoff plots could not provide detailed data on the infiltration of water into the yellow-brown pumice soils because water falling onto plots may be lost by initial surface detention and then by evaporation or transpiration. Furthermore, the information from small plots cannot be extrapolated to whole catchments and the Otutira results could not be used extensively (the reasons for this statement are discussed in chapter 3). It was decided, therefore, to include an independent study of infiltration in the research programme. Similarly it was unlikely that plots would provide information on soil erosion, so a flume study of the erodibility of soils was also included in the programme. Both the infiltration and flume tests can be applied readily to areas outside the Otutira catchment and Otutira results can then be used as benchmark data.

The whole research programme is seen, not as a study of physical processes, but as a contribution to the selection of the major factors influencing runoff and hence gully erosion. The results will apply only to the Otutira catchment but if a few important variables can be isolated then these may be tested and studied in other parts of the pumice country.

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CHAPTER 2

THE OTUTIRA CATCHMENT

The Otutira catchment is an elongated basin which discharges into Kawakawa Bay (38^{o} 39'S, 175^{o} 50'E) of Lake Taupo. It is 22km west of Taupo township and 32km south of Mangakino (figure 2-1). The basin has an area of 299.3ha. It slopes, from a high point of 585m a.s.l., gently towards the lake.

The research described in this thesis was all carried out in the northern part of the catchment, in an area of about 14 ha, and the following detailed maps and comments apply only to that area.

Relief

The thalweg of the catchment runs, from its high point in the north, southwards to Lake Taupo. The valley sides face approximately east and west. The general nature of the relief is shown in figures 2-2 and 2-3. The valley floor slopes southwards at an angle of 1^{o} to 2^{o} and the east and west facing slopes have angles of from 5^{o} to 35^{o}. The slopes are smooth and broken by small terracettes only in the area of pasture grasses. The entire surface is covered by soils and vegetation.

Geology

The geology of the catchment has been described by Rishworth (1970). The uppermost beds are Taupo Ash, which here consist of pumice sand with some lapilli. On the slopes the tephra is air-fall but on the floor of the valley much of it is rewashed colluvium. The Taupo Ash is up to 6m thick on the relatively flat areas but only 0.5 to 1.3m thick on the slopes.

The Taupo Ash is underlain by up to 1.2m of yellowish-brown Tirau Ash. This rests upon up to 4.5m of brownish-yellow sandy loam which is probably late Pleistocene

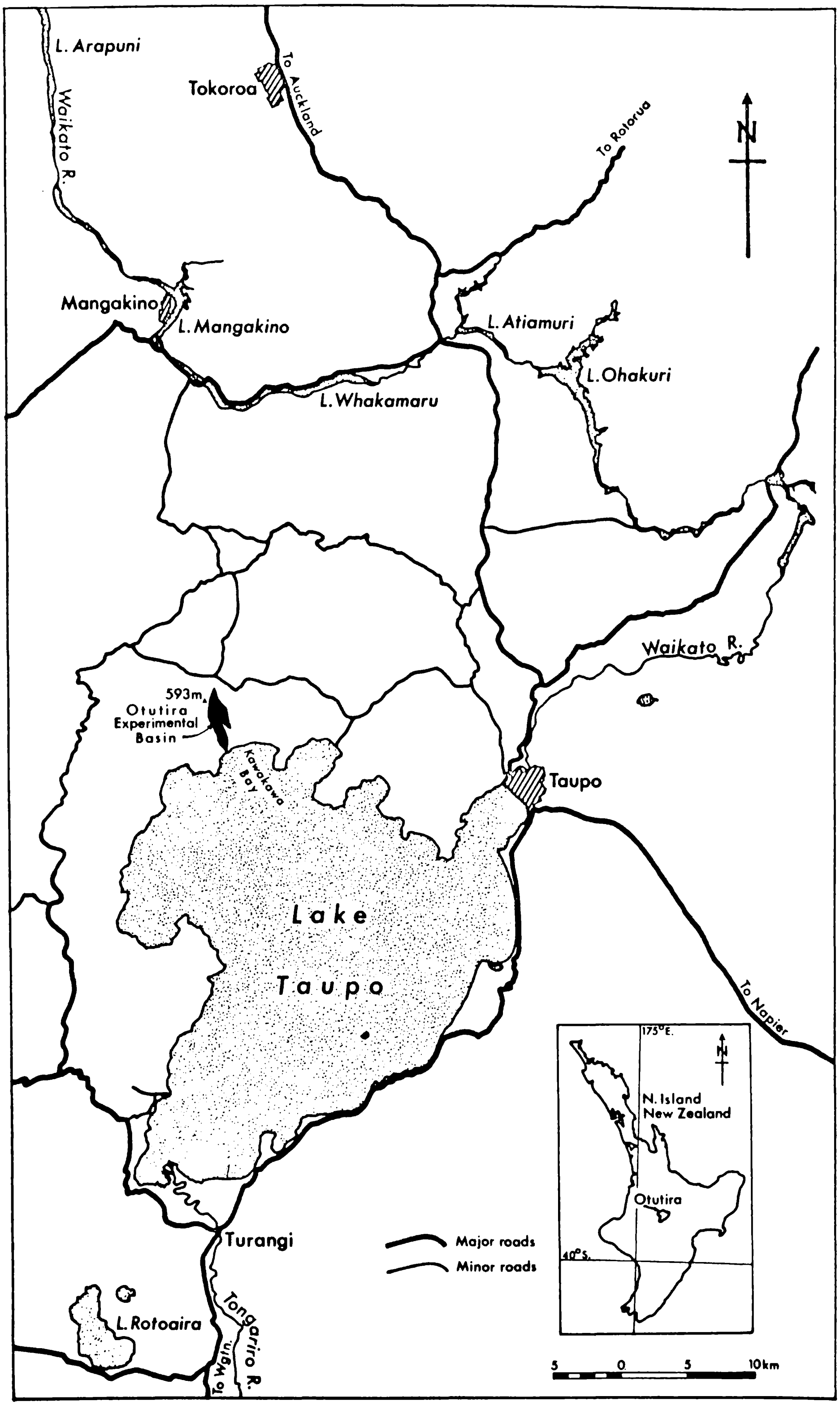

Fig. 2-1. Location of the Otutira catchment.

Fig. 2-2. The northern part of the Otutira catchment.

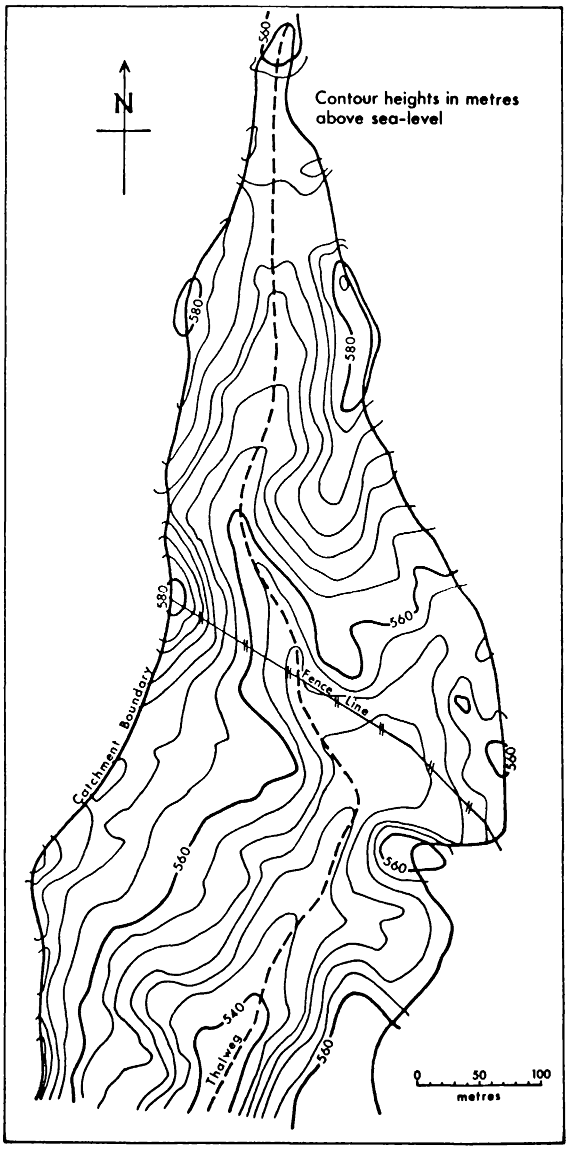

Fig. 2-3. Relief of the northern part of the Otutira catchment.

volcanic ash. This has not yet been studied in detail. Beneath the ashes is a pumice lapilli tuff of unknown thickness and extent. Outcrops in the valleys to the east and west of Otutira indicate that the whole basin is underlain by subhorizontal to gently dipping fissured Mokai ignimbrite. The stratigraphy of the area is complex and will only be understood when more borehole data become available. The hydrological significance of these beds is that they are all permeable and the groundwater table is very low. A borehole drilled to 62.5m from 30m below the catchment boundary failed to reach groundwater (Rishworth, 1968).

Soils

The soils of the catchment have been mapped by Cowie and Campbell (unpublished, undated, report) and are shown in figure 2-4. Over all the study area the soils are derived from Taupo Ash overlying Tirau Ash, except in the floor of the valley where colluvial, and possibly alluvial, Taupo Ash has accumulated and forms the parent material. The soils from Taupo Ash on Tirau Ash have been named Oranui Sand Soils which are classed as rolling phase, strongly rolling phase, and Oranui Hill Soils. The soils from reworked pumice are called Waipuhihi Sand Soils. Typical profiles are given below.

1) Oranui Sand Soil under pasture grasses:

12 to 20cm	black (10YR 2/1) sand with many fine pumice gravels; very friable; weakly developed fine nutty and granular structure; distinct irregular boundary,
7.5 to 10cm	brown (10YR 4/3) sand; friable; very weakly developed medium nutty structure; some fine pumice gravels; indistinct boundary,
23cm	pale yellow (near 2.5Y 5/4) sand with some fine pumice gravels; friable; very weakly developed medium nutty structure; distinct boundary,

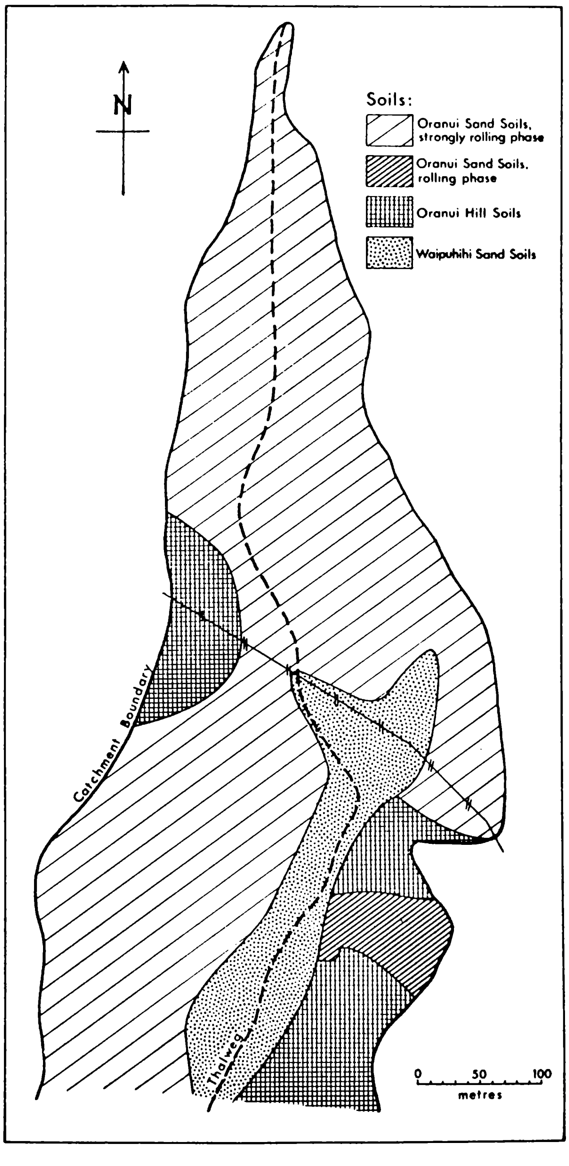

Fig. 2-4. Soils of the northern part of the Otutira catchment (after Cowie and Campbell, undated report).

35cm	pale yellowish brown (2.5Y 6/4) coarse sand with much rhyolite; slightly firm; distinct boundary, (Rhyolite Block Member)
23cm	yellowish brown (10YR 5/4) loam, greasy; friable; weakly developed medium nutty structure; indistinct boundary,
on	brown (10YR 5/6) loam; very greasy; friable.

This rests on yellowish brown non-greasy sandy loam which overlies sandy breccia with rhyolite stones.

In many places a thick A_2 horizon of greyish brown (10YR 5/2) sand occurs, associated with a dark reddish brown (5YR 3/3) iron/humus pan in the subsoil. These are "eggcup" in form and probably represent the effect of individual podsolizing trees such as rimu.

In a few places, generally on eroded ridge tops, the Taupo Ash is absent and the soil is formed directly on the Tirau Ash.

Oranui sand soils beneath scrub have similar profiles to those beneath pasture except that the scrub soils have a 1cm reddish brown litter layer on the surface, and a weakly developed crumb structure rather than the fine nutty and granular structure of the pasture soils.

2) Waipuhihi Sand Soil beneath ungrazed exotic grasses:

12cm	black (7.5YR 2/1) sand; extremely friable; very weakly developed crumb structure; few pumice gravels; distinct irregular boundary,
2.5 to 10cm	dark brown (7.5YR 3/2) sand; very friable; very weakly developed crumb structure; very irregular boundary,
20cm	yellowish brown (10YR 5/6) sand; friable to slightly firm; few darker brown mottles around roots; very weakly developed medium blocky structure; distinct boundary,
18cm	pale yellow (2.5YR 7/4) sand with many pumice gravels; very firm; massive; sharp boundary,

35cm	grey coarse rhyolitic sand with fine gravels; loose; single-grained; few pumice gravels,
on	greyish brown gritty sandy loam; slightly greasy with few reddish mottles. This grades down to a yellowish brown greasy sandy loam.

In many profiles the second horizon is deeper and darker in colour (10YR 3/4), and in some profiles there are traces of a bleached subsurface horizon.

Vegetation

The vegetation of the catchment has been described by Radcliffe (unpublished report) and the distribution of the major communities is shown in figure 2-5. There are two main types of vegetation: 1) pasture grass and clover communities; 2) scrub communities in which the dominant species are manuka (*Leptospermum scoparium*), kanuka (*Leptospermum ericoides*), bracken (*Pteridium esculentum*), five-finger (*Neopanax arboreum*), kamahi (*Weinmannia racemosa*) with *Coprosma* sp. and kohuhu (*Pittosporum tenuifolium*). In the areas of intense research described in this thesis the dominant shrub species is always manuka with either *Erica lusitanica* and *Hebe stricta* or bracken as an understory. The ground layer in the scrub is composed of mosses and herbs.

The scrub communities have very few species and seldom have a height greater than 3m. Local inhabitants believe that the last fire to sweep through the area occurred in 1937 and there is no record of any disturbance to the scrub since that time. The plants appear to be little affected by animal browsing, although wild pigs are common in the catchment.

The northernmost part of the basin was cleared for pasture and sown in, or about, 1960 by the Department of Lands and Survey. It is now grazed sporadically by sheep and beef cattle.

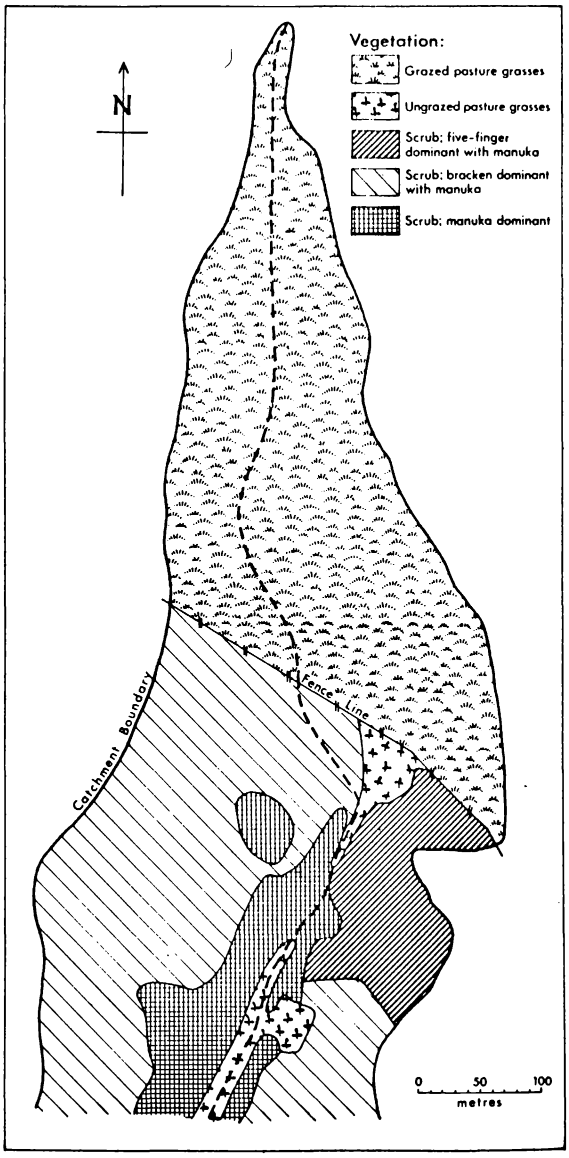

Fig. 2-5. Distribution of the major plant communities in the northern part of the Otutira catchment (after Radcliffe, 1967).

Climate

A meteorological recording station was established in the extreme northern end of the catchment in 1967. The record of climatic data is therefore short. The area usually has a warm dry summer with localised, high intensity, rainfalls and cool wet winters. Precipitation from autumn to spring is normally from prolonged frontal rain of low intensity. Rainfall is about 1500mm per year with a ten year variation thought to be around ± 20 per cent. Frosts are common during the winter and spring, and snow is infrequent but neither have been observed to have any hydrological significance.

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CHAPTER 3

RUNOFF PLOT STUDIES IN THE OTUTIRA CATCHMENT

Hydrological research may be conducted at two distinct levels: that of whole drainage basins; and also at the level of small plots, either natural or artificial. The object of drainage basin studies is to obtain an understanding of the relationships between rainfall and runoff (Linsley, 1967) and the effects of the many components of the drainage basin -- vegetation, soils, lithology, geometry, etc. -- can seldom be evaluated. The value of runoff plots is that they are usually small (between 2 and $1000m^2$ in area) and have homogeneous characteristics so that in experimental or laboratory conditions one variable can be held constant while each of the others is manipulated. In this way runoff plot studies can be used to evaluate the effect of individual variables upon runoff. Runoff plots established under field conditions are used for the selection of variables which influence runoff. Each of these variables must be described quantitatively and statistical analysis is then used to assess the significance of each variable. The correct selection of the variables to be measured presupposes a considerable knowledge of their likely effect, and experience with the collection and analysis of the data.

Runoff plot studies have frequently been criticised because the data from them have been misused. It has been pointed out by Burton (1966) that, no matter how perfect the experimental design of runoff plot studies, the results from them cannot be extrapolated to whole catchments because the routing effects of channel storage completely mask the overland flow effects measured on the plots. It might be added also that plot studies cannot take into account the effects of interflow and groundwater movement to springs. Burton's contention is supported by the experimental work of Foster, Huggins and Meyer (1968) on runoff from plots, by the theoretical studies of Horton (1945), and the experimental work of Emmett (1970) on runoff from slopes.

Plot studies at Otutira have been designed to provide information on the relationships between runoff and climatic, soil, vegetation and relief characteristics. No attempt has been made to extrapolate this information to larger areas. The object is to distinguish the chief factors influencing runoff so that the physical processes of runoff and erosion can then be studied. The plot studies are regarded as the first step in an investigation which will lead to an understanding of these processes.

RUNOFF PLOTS

Runoff plots have been in use for studies of soil loss and runoff since at least 1917 (Hayward, 1968). Hayward (1967, 1968) has reviewed the literature and described the construction and uses of plots and the problems of interpreting data from them.

All plots consist of an area of soil surrounded by a border of wood, metal or concrete which is both raised above and set into the soil a few centimetres. At the downslope end of the plot is a device for collecting runoff water and sediment. Plots vary greatly in size from 0.743m^2 (Duley, 1939) to more than 1,000m^2 (Van Doren, Stauffer and Kidder, 1950). Observational or field studies have used relatively small plots: Costin, Wimbush and Kerr (1960) used 5.34m^2 plots and the New Zealand Forest Service 4.45m^2 plots (Eiselstein, 1966; Soons and Rainer, 1968).

Defects of Runoff Plots

Many of the defects of runoff plots relate to their use for runoff and sediment collection, and to the extrapolation of these data to whole catchments. Most theories of overland flow hold that velocity and depth of runoff water increase with distance downslope and therefore the capacity of water to entrain sediment also increases downslope (Horton, 1945). Runoff plots will therefore tend to underestimate runoff and sediment yield.

Leakages into and out of the plot can be a considerable source of error. Leakages into the plot occur at the upslope end when water seeps under the border and comes to the surface inside the plot. Leakages at the downslope end take place under the runoff collector. Tests for such leaks were carried out at Otutira using Gentian Violet dye placed outside the upslope and side border, and inside the plot upslope of the rim of the collecting trough. In tests the dye was either washed vertically downwards into the soil with infiltrating water, or washed into the trough: no leaks were detected.

Interference with the microclimate by plot borders and troughs has been observed by Hayward (1969) who was working on bare soils in the South Island mountains. Direct capture of rain in the collection trough was tested for, at Otutira, by raising one trough two inches above ground level. At no time did this trough receive a measurable quantity of water. The plot sides also did not appear to interfere with airflow at the plot border, because the grass and other vegetation round them was usually higher above the ground surface than the timber of the frame. Frost heave was not observed at Otutira, and the soil surface and slope were not changed by washing of sediment from the upper to the lower part of the plot. The plot frames and troughs appeared to have no effect upon the microclimate.

EQUIPMENT USED AT OTUTIRA

The design of equipment used for studying runoff and sub-surface water movement is shown in figure 3-1. All climate recording instruments are of standard design.

Runoff Plots

Each of the runoff plots encloses an area of $4m^2$. The design of the plots is based on those used by the New Zealand Forest Service Experiment Station in the Craigieburn Range (Soons and Rainer, 1968), but the Otutira plots are rather narrower because it was found that the

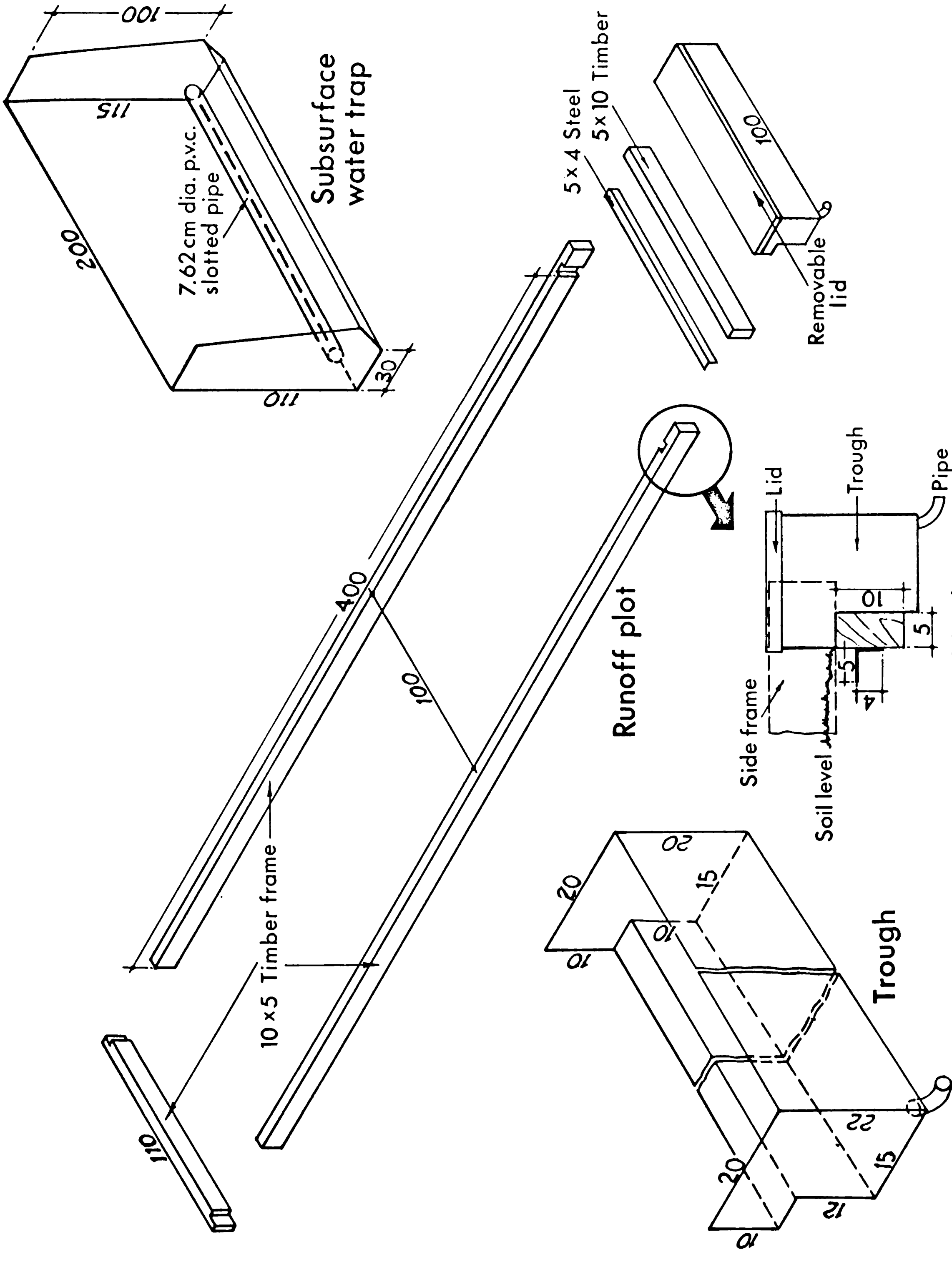

Fig. 3-1. Designs for runoff plots and subsurface water traps.

ground was too uneven for a plot wider than 1m to be fitted flush with the soil surface. Accordingly the plots are 1m wide and 4m long. The frame of the plots is made of 10 x 5cm tanalised pine and the collecting trough of galvanised sheet iron. The frame is aligned down the line of steepest slope and sunk about 8cm into the ground. The board at the lower end is sunk into the ground so that when the collecting trough is fitted onto it, the lip of the trough is slightly below the ground surface. A piece of galvanised iron is fastened to the board beneath the lip of the trough so that water cannot seep down the face of the board rather than flow into the trough. All of the joints between the trough and the frame are sealed with putty. The outlet from the trough is through a 1cm diameter pipe (a 2cm diam. would probably be more suitable, if sediment were washed off the plot, as it would be less likely to become blocked). A lid is fitted to the collection trough to prevent precipitation falling into it. The runoff is delivered through the pipe to a 22 litre polythene container which is inside a 72 litre polythene drum buried downslope from the plot. In most conditions the 22 litre container is adequate to collect the runoff of an observation period and the 72 litre drum is only an overflow receiver. Twenty runoff plots were used in the experiment. Three of the runoff plots are coupled to modified Lambrecht automatic raingauges. The runoff water is led into the orifice of the gauge and this has proved to be a satisfactory way of measuring the period and rate of runoff from the 3 plots -- numbers 8 and 9 in the pasture area and number 17 in the scrub.

Raingauges

Storage raingauges with a 200cm^2 orifice were placed alongside each group of runoff plots. In the pasture area the gauges were placed in five pairs. One of each pair was tilted so that it was normal to the slope and one was used as a vertical check gauge alongside the tilted gauge. In the scrub and ungrazed grass areas two vertical gauges only were used, as the scrub round them impeded the catch of tilted raingauges. Two Lambrecht automatic gauges, also with 200cm^2 orifices, were placed in the pasture area. Gauge number 1 was treated as the master gauge. Rainfall on the plots was estimated from the tilted gauges.

Thermometers

Soil and air temperatures were recorded with a Lambrecht three-probe distance thermograph housed in a shelter alongside automatic raingauge number 1.

Subsurface Water Traps

Six traps were set into the ground normal to the slope so that they collect the subsurface water flowing into an area 2m wide and 1m deep (figure 3-1). The traps are made of galvanised sheet iron and the water is collected when it flows into the trap and descends to the bottom of the trough, where a slotted 7.62cm diameter PVC pipe conducts it out of the trap into another pipe which leads downslope into a 72 litre drum. The PVC pipe is covered with a layer of gravel chips to prevent the slots being blocked by soil. This trap is similar to that used by Whipkey (1965).

INSTALLATION OF EQUIPMENT

The installation of both runoff plots and subsurface water traps disturbs the soil and they must therefore be put in position and left for the soil to consolidate. The plots and traps were therefore put into the ground in March and April 1967 in the hope that they would be ready for use in the following spring -- October 1967. It was found, however, that the soil around the plots in the scrub had not been recolonised by plants and that there was leakage around the edge of the plots. Tests were carried out on the plots every few months until it was clear that leakage was no longer occurring. Usable data could not be obtained from the plots until February 1969. Measurements commenced in February 1969 and were concluded in March 1971. During this time runoff and other variables were measured after each major storm or wet period. Forty-four storms or wet periods occurred during the two years.

Location of Runoff Plots

In any experiment in which statistical analysis of the data is to be used, an adequate design in which the tests are replicated and randomised is essential. In the 50 plot studies, reviewed by Hayward (1968), 46 did not replicate and randomise their treatments.

In the Otutira studies the aim has been to study runoff in relation to variations in soil properties, vegetation cover, slope, aspect, surface roughness and precipitation. It was considered that 20 was the largest number of plots which could be tended by one observer and the distribution of the plots was at first attempted in a purely random fashion for the whole study area. The result was a distribution which placed many across vehicle tracks, fence lines, irregular slopes and other unrepresentative places. The second attempt was more satisfactory: the study area was mapped into areas which were suitable and unsuitable for plots using subjective criteria; in effect this produced three suitable areas in the pasture, two in the scrub and one in the ungrazed grass. Large parts of the study area were eliminated because of disturbance by vehicles, fence lines and other experiments. Within each of the six areas it was decided to place a minimum of two plots. The eight remaining plots were then divided amongst the six areas by using a random selection with a deck of cards. This gave a total of fourteen plots to the pasture, four to the scrub and two to the ungrazed grass areas. Location of the plots within the five selected areas was made by covering each area with a $10m^2$ grid and selecting the squares from a table of random numbers. The plot was then placed against the north margin of the grid square and orthogonal to the slope.

The result of this procedure has been to give minimum replication -- with only two plots in the area of ungrazed grass -- but a random distribution which effectively samples the slopes, soils, aspects and variations within the two major types of vegetation. The location of the plots and other instruments is shown in figure 3-2.

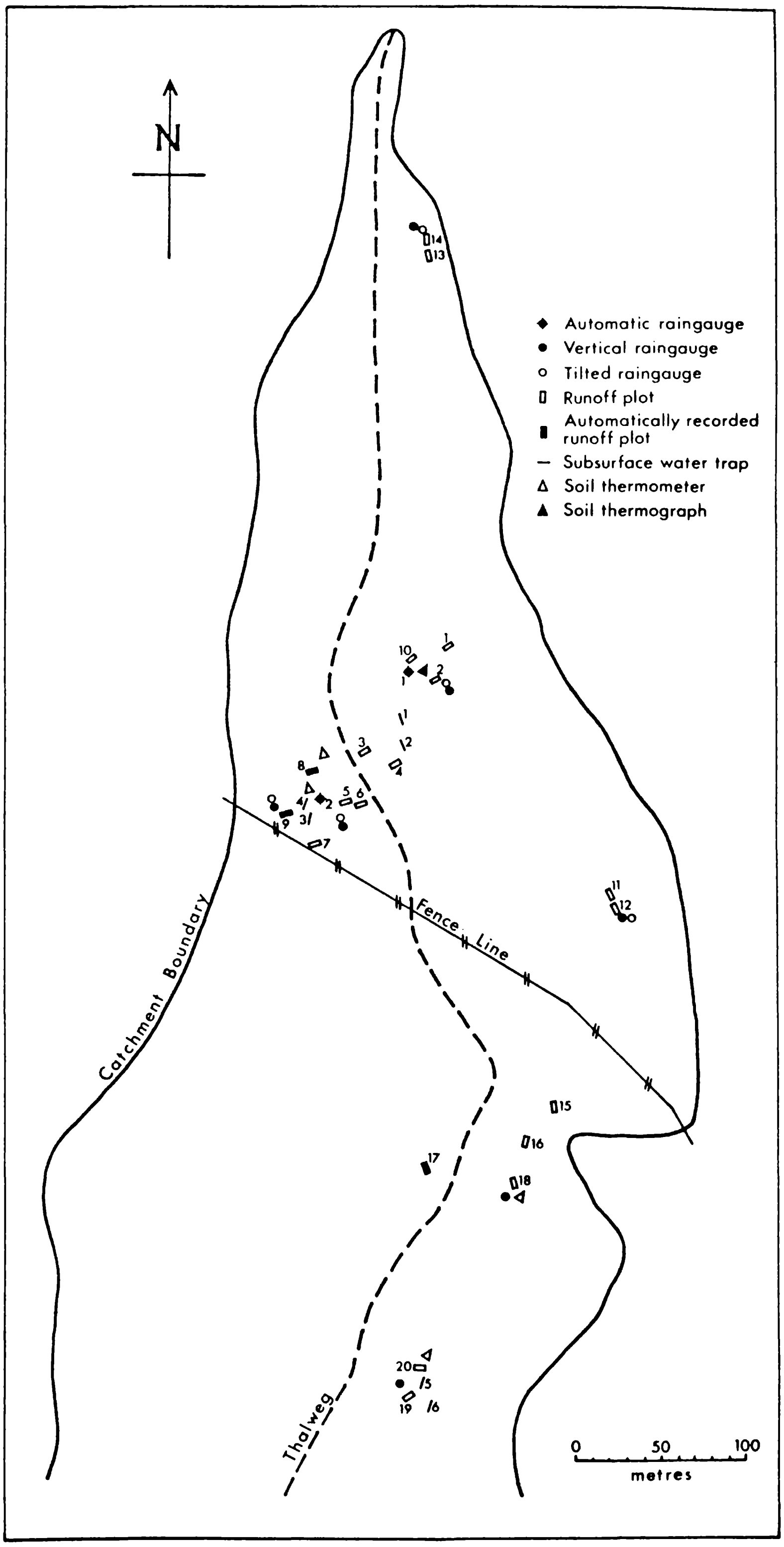

Fig. 3-2. Location of instruments in the Otutira catchment.

VARIABLES MEASURED

Thirty-six variables were selected to characterise each of the twenty plots. Runoff is the dependent variable for which explanation is sought and the other thirty-five variables fall into four classes: 1) precipitation; 2) temperature; 3) plot characteristics; 4) soil properties.

1. Precipitation Variables. Rainfall characteristics were divided into eleven variables: all were measured for each of the forty-four observation periods. Rainfall on each plot was measured in a tilted raingauge and expressed as a depth of water in mm. The aim of subdividing precipitation into variables is to give a measure of the duration, frequency and intensity of rainfall.

X_1 Total precipitation falling in the observation period.
X_2 Maximum precipitation occurring in 24 hours.
X_3 Maximum precipitation in 12 hours.
X_4 Maximum precipitation in 6 hours.
X_5 Maximum precipitation in 1 hour.
X_6 Maximum precipitation in 0.5 hour.
X_7 Number of storms in the observation period. A storm is defined as a period of continuous rain separated from another period of rain by at least two hours.
X_8 Total precipitation for the maximum storm in the observation period. This is the storm with the highest total rainfall.
X_9 Total duration of precipitation, measured in hours.
X_{10} The total duration of rainless time, in hours.
X_{11} Time, in hours, since the last storm of the previous observation period.

2. Temperature Variables. Five temperature variables were used to give a measure of seasonality and potential evapotranspiration. Data available were not sufficient for calculating a measure of evapotranspiration and temperature variables and rainfall periodicity have been relied on to give an indication of water losses to the atmosphere.

Temperatures are given in degrees Celsius.

X_{12} Mean maximum daily air temperature since the last storm of the previous observation period.

X_{13} Maximum air temperature in the observation period.

X_{14} Mean air temperature of the observation period.

X_{15} Minimum air temperature of the observation period.

X_{16} Mean soil temperature, at a depth of 10cm, for the observation period.

3. Plot Characteristics. Most of the characteristics remained constant for the two years of observation. Vegetation and soil compaction, however, were measured for each observation period.

X_{17} Dry weight of vegetation. This was measured by taking ten point samples of vegetation length in areas of grass and converting this value to a dry weight equivalent. The scrub is evergreen and as far as could be detected did not vary in dry weight during the two years of observation. (This absence of growth is attributable to a 'blight' which infected the manuka).

X_{18} Soil penetration resistance was measured with a Proctor penetrometer and the reading in lbf/in^2 converted to kiloNewtons per square metre (kN/m^2). Penetration resistance is closely correlated with soil moisture, but it is also related to soil compaction and it is used to give a measure of compaction caused by animal trampling.

X_{19} Angle of slope of the plot, in degrees.

X_{20} Aspect of the plot measured in degrees from geographical north.

X_{21} Roughness ratio, which is the ratio of plot length in a direct line to plot length measured over the ground surface.

4. Soil Characteristics. All soil characteristics were taken to be constant throughout the two years of observations. Values for each plot are arithmetic means of three

samples. Methods of analysing the samples are given in the appendix. Computer code names are given here and in the appendix.

X_{22}	Percentage, by weight, of the total soil sample with diameters greater than 6.35mm (PTC 1).
X_{23}	Percentage, by weight, of the total soil sample with diameters 0.635 to 6.35mm (PTC 2).
X_{24}	Percentage, by weight, of the total soil sample with diameters 0.063 to 0.635mm (PTC 3).
X_{25}	Percentage, by weight, of the total soil sample with diameters less than 0.063mm (PTC 4).
X_{26}	Percentage, by weight, of the total sample which did not pass the 0.63mm sieve at the end of 10 minutes sieving, but which did pass it after a further 10 minutes sieving (AGG 1).
X_{27}	Percentage, by weight, of that part of the sample too large to pass the 0.63mm sieve after 10 minutes sieving but which did pass it after a further 10 minutes sieving (AGG 2).
X_{28}	Percentage weight of organic matter which passed the 0.635mm sieve, expressed as a percentage of the total material passing that sieve (ORG 1).
X_{29}	Total weight of all organic matter in the sample expressed as a percentage of the weight of the total sample (ORG 2).
X_{30}	Thickness of the root mat, in mm (VEGS).
X_{31}	Bulk density, in g/cm^3 (BULK).
X_{32}	Particle density, in g/cm^3 (PART).
X_{33}	Total porosity, that is the non-solid volume of the sample expressed as a percentage of the total sample volume (PORO).
X_{34}	Macroporosity, that is the volume of the macropores as a percentage of the volume of the total sample (MAC 1).
X_{35}	Macroporosity, that is the volume of macropores as a percentage of the total pore space (MAC 2).

Table 3-1. Properties of each runoff plot.

Plot Number	Angle of Slope (degrees)	Aspect (degrees)	Roughness Ratio	Particle Size				Organic Matter		Aggregation		Thickness of root mat (cm)	Density		Porosity		Macroporosity as % of Total Pore Space
				>6.35(mm)	0.635 to 6.35(mm)	0.063 to 0.635(mm)	<0.063(mm)	%Fine Org. Mat.	Wt. of Org. Mat. as % of Sample	Fines	Total		Bulk	Particle	Total Porosity	Macroporosity as % of Total Sample Vol	
1	15	320	1.02	7.1	24.1	52.4	16.5	13.5	11.4	27.5	18.6	2.3	0.67	2.07	67.2	2.7	4.3
2	12	335	1.01	3.8	21.5	56.3	18.4	16.6	15.1	24.5	18.3	1.7	0.61	1.95	69.6	2.0	3.0
3	10	355	1.01	4.4	27.4	57.0	10.8	13.5	10.9	16.9	11.7	1.7	0.79	2.12	61.5	2.2	3.7
4	25	345	1.03	4.0	21.4	63.7	11.0	16.6	15.1	30.2	22.5	2.2	0.63	6.40	69.6	2.5	1.6
5	26	135	1.03	1.6	16.8	70.5	11.2	23.6	20.8	33.1	26.9	2.0	0.58	2.07	73.0	2.5	3.6
6	10	140	1.01	1.9	30.3	61.2	6.6	13.3	10.7	15.1	10.2	2.7	0.75	2.19	65.9	1.8	3.0
7	16	110	1.01	1.6	25.3	66.6	6.6	15.2	13.1	18.2	13.3	2.0	0.76	2.23	63.2	4.2	7.0
8	20	165	1.02	1.7	21.0	68.9	8.5	21.9	18.8	22.3	17.1	1.5	0.60	2.07	70.2	3.3	5.0
9	33	115	1.06	1.7	9.9	76.3	12.2	13.0	12.8	23.1	20.4	1.3	0.74	2.24	66.6	4.3	6.8
10	7	335	1.01	3.7	22.9	56.2	17.2	17.0	13.6	25.8	19.1	1.3	0.64	2.12	70.0	2.7	4.1
11	13	295	1.02	1.5	18.6	68.1	11.9	12.8	11.5	21.2	17.2	1.8	0.72	2.17	67.3	4.0	6.1
12	22	300	1.03	2.8	18.4	63.6	15.2	12.4	10.6	12.6	9.9	0.5	0.69	2.10	66.7	3.4	5.4
13	12	75	1.02	2.1	14.4	70.8	37.9	17.3	16.3	32.3	26.9	1.5	0.66	2.05	67.1	2.8	4.4
14	22	55	1.02	2.0	10.6	70.0	17.3	16.4	16.8	32.6	28.4	1.7	0.69	2.17	66.8	3.2	5.2
15	28	260	1.01	3.9	14.6	68.6	13.0	14.1	12.8	21.3	16.8	0.5	0.52	2.04	72.9	7.4	10.8
16	20	290	1.02	3.7	24.5	60.5	11.0	16.9	13.3	38.2	27.6	1.2	0.49	2.01	77.0	11.0	15.0
17	7	205	1.02	3.7	21.9	61.4	12.9	13.7	11.1	18.4	13.7	1.0	0.58	1.97	72.1	7.0	10.1
18	7	305	1.02	10.2	27.4	51.1	11.3	13.5	9.4	19.5	12.2	1.1	0.54	1.95	72.1	7.8	11.4
19	11	280	1.06	5.7	23.1	58.8	11.3	20.3	15.7	21.6	15.3	2.2	0.60	2.05	70.1	5.8	8.6
20	25	285	1.05	7.1	28.8	53.9	10.1	19.6	16.0	35.9	23.0	3.5	0.52	2.00	73.7	7.3	10.3

Y <u>Runoff</u>. The runoff from each plot was measured in a graduated cylinder and expressed as a total, in ml.

The properties of each plot are given in table 3-1.

DATA COLLECTION

Ideally data from the instruments should have been collected after each major storm. In practice this was not always possible but visits were made to Otutira at least once a fortnight for the two years of the observations. In both years there were considerable periods without rain and the total number of observation periods from which useful data were obtained was 44. Observations began on 14 February 1969 and finished on 1 March 1971. There was only one break in the record, caused by faulty automatic raingauges, and that was from 21 February 1969 to 6 March 1969.

EXPERIMENTAL ERRORS AND DEFICIENCIES

It has been suggested above that the Otutira runoff plots did not cause errors of the kind which have occurred in the work carried out in the South Island (Hayward, 1969). Other possibilities of error arise because it was necessary to obtain a measure of soil compaction and grass length for each observation period and also to take samples for soil analysis. It was clear that pushing a penetrometer needle into each plot ten times and cutting grass off the plot to obtain a $0.25m^2$ sample would soon render the plots useless. The necessary measurements and samples were therefore obtained from the area immediately around the plot.

Ten penetrometer readings were taken round each plot in a random fashion and the mean value obtained.

Vegetation was measured by stretching a string diagonally across the plot and measuring the length of the grass at ten points along it. These measurements were then converted to a dry weight equivalent using data given in the graph of figure 3-3. These data were obtained by cutting the vegetation off 23 plots from the pasture and ungrazed grass areas and oven drying it for a week. The weights were plotted against the height.

Soil samples were obtained from three points around the plot: A) top right hand corner, B) centre left, C) bottom right hand corner, as the observer faces upslope.

These rather indirect measurements will all have introduced some measure of inaccuracy into the data but the alternative would have interfered with the plot itself.

The inability to measure soil moisture accurately gave rise to another deficiency in the measurements. Several methods were tried but failed, possibly because of the hysteresis effect. Neither Bouyoucos gypsum blocks nor an Aquatron moisture meter gave results which could be used to derive a calibration curve when their readings were plotted against values obtained from gravimetric samples. The most accurate method of measuring soil moisture is the gravimetric method (Johnson, 1962) but this would require at least five samples from each plot each observation period, because soil moisture is known to vary considerably over short distances (Hills and Reynolds, 1969). It was evident that taking several core samples from each plot, or the area around it, would soon damage the area round the plots and interfere with runoff measurements. Soil moisture indications have, therefore, to be obtained from climatic data. This is an unsatisfactory situation for it has been shown (Philip, 1957) that antecedent soil moisture can have a most important influence on runoff.

The value of the runoff plot observations would have been increased if finance had made it possible to record the runoff from all plots automatically and to place an automatic raingauge alongside each plot. It would then have been possible to study runoff from each phase of each storm, but as this was impossible the automatic gauges available could only be used to give an indication of the general relationships between runoff and precipitation.

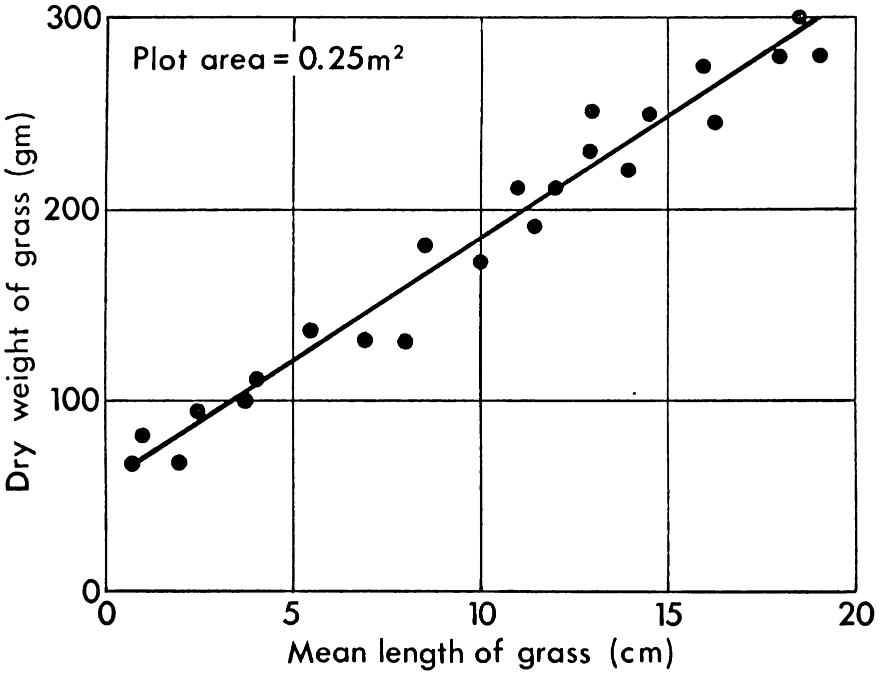

Fig. 3-3. The relationship between length and dry weight of grass.

Fig. 3-4. A runoff plot in the scrub.

Fig. 3-5. Runoff collectors for plot 6 (the lid of the drum has been removed).

Fig. 3-6. An automatic raingauge and an automatic recorder for runoff.

Fig. 3-7. Some of the instruments in the pasture area.

The two automatic raingauge records have been used to modify the data from the storage raingauges on a proportional basis to provide a measure of rainfall intensity on each plot. This means that intensity figures are only correct for plots alongside the two automatic gauges but the error for the other plots is probably small.

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CHAPTER 4

THE CAUSES OF RUNOFF IN THE OTUTIRA CATCHMENT

Analysis of data collected in the 44 observation periods and from sampling the soils on each of the 20 runoff plots was carried out in order to answer the following questions:

(1) Are there significant differences in the properties of the runoff plots (i.e. their climate, soils, vegetation and runoff) from each of the three vegetation types?

(2) Are the differences between the properties of the runoff plots such that those on the areas of scrub and ungrazed grass can be regarded as belonging to the same statistical population for comparison with those in the pasture area?

(3) To what extent is the runoff from the runoff plots of each of the three vegetation types related to the measured plot properties?

(4) Which of the runoff plot properties contribute to the measured runoff and to what extent?

Analysis of variance

Analysis of variance was carried out (Croxton, 1953) among the three vegetation types for the soil, vegetation, rainfall, and runoff sets of data. Only 27 variables were used in the analyses because all of the others, such as temperature, are derived from the data from plot 10. The results are summarised in table 4-1. It will be seen that the precipitation received on the plots was different, but only at a moderate significance level (F value - 0.05), except for the maximum precipitation in 6 hours. Runoff, a vegetation measure, penetration resistance, one measure of macroporosity and the largest soil particles were all

Table 4-1. Results of analysis of variance among plots in three vegetation types for 27 variables.

Variable	Pasture Grass		Ungrazed Grass		Scrub		$\underline{F}$
	$\bar{X}$	$\underline{n}$	$\bar{X}$	$\underline{n}$	$\bar{X}$	$\underline{n}$	
Slope	17.357	14	15.500	4	18.00	2	0.311
Aspect	220.000	14	265.000	4	282.500	2	1.985
Roughness	1.021	14	1.017	4	1.055	2	0.288
PTC 1	2.850	42	5.375	12	6.400	6	9.046***
PTC 2	20.899	42	22.100	12	25.950	6	2.160
PTC 3	64.399	42	60.400	12	56.350	6	0.954
PTC 4	14.378	42	12.050	12	10.700	6	0.611
ORG 1	18.607	42	17.575	12	19.150	6	0.091
ORG 2	23.957	42	24.350	12	28.750	6	0.585
AGG 1	15.935	42	14.550	12	19.950	6	3.449**
AGG 2	14.107	42	11.650	12	15.850	6	2.965*
VEGS	1.729	42	0.950	12	2.850	6	2.450*
BULK	0.681	42	0.532	12	0.560	6	3.366**
PART	2.425	42	1.992	12	2.025	6	1.166
PORO	67.477	42	73.525	12	71.900	6	3.738**
MAC 1	2.971	42	8.300	12	6.550	6	0.822
MAC 2	4.514	42	11.825	12	9.450	6	66.483***
Runoff	6751.058	616	1895.199	176	1837.387	88	25.091***
Total Pp	45.485	616	53.963	176	53.982	88	3.754**
Max. Pp - 24 hr.	24.812	616	29.249	176	29.264	88	4.457**
Max. Pp - 12 hr.	19.995	616	23.528	176	23.536	88	4.547**
Max. Pp - 6 hr.	14.845	616	17.491	176	17.498	88	5.143***
Max. Pp - 1 hr.	6.733	616	7.977	176	7.982	88	4.303**
Max. Pp - 0.5 hr.	4.999	616	5.902	176	5.907	88	3.000*
Total Pp for max. storm	23.127	616	27.300	176	27.309	88	3.910**
Dry Wt. of Vegetation	2108.186	616	17104.253	176	4773.296	88	1565.171***
Penetration Resistance	4632.260	616	3191.836	176	3138.558	88	114.646***

N.B. Soil property code names are explained in the appendix
$\bar{X}$ is the mean, $\underline{n}$ is the number of samples, Pp is precipitation.

Critical $\underline{F}$ values: α = 0.10, Symbol*, α = 0.05, Symbol **, α = 0.01, Symbol ***.

Table 4-2. Results of analysis of variance among plots in developed and undeveloped areas.

Variable	Pasture Grass		Ungrazed Grass & Scrub		*F*
	$\overline{X}$	*n*	$\overline{X}$	*n*	
Slope	17.357	14	16.333	6	0.210
Aspect	220.000	14	270.833	6	3.672*
Roughness	1.021	14	1.030	6	0.418
PTC 1	2.850	42	5.717	18	17.414***
PTC 2	20.899	42	23.383	18	3.027*
PTC 3	64.399	42	59.049	18	1.385
PTC 4	14.378	42	11.600	18	0.651
ORG 1	18.607	42	18.100	18	0.002
ORG 2	23.957	42	25.816	18	0.478
AGG 1	15.935	42	16.350	18	0.118
AGG 2	14.107	42	13.050	18	0.671
VEGS	1.729	42	1.583	18	0.645
BULK	0.681	42	0.542	18	44.601***
PART	2.425	42	2.003	18	2.262
PORO	67.477	42	72.983	18	7.462***
MAC 1	2.971	42	7.717	18	1.519
MAC 2	4.514	42	11.033	18	118.811***
Runoff	6751.058	616	1875.928	264	40.921***
Total Pp	45.485	616	53.969	264	7.516***
Max. Pp - 24 hr.	24.812	616	29.254	264	8.914***
Max. Pp - 12 hr.	19.995	616	23.530	264	9.094***
Max. Pp - 6 hr.	14.845	616	17.493	264	10.286***
Max. Pp - 1 hr.	6.733	616	7.979	264	8.636***
Max. Pp - 0.5 hr.	4.999	616	5.904	264	6.040**
Total Pp for max. Storm	23.127	616	27.303	264	7.823***
Dry wt. of vegetation	2108.186	616	12993.934	264	1095.266***
Penetration resistance	4632.260	616	3174.076	264	229.431***

N.B. Soil property code names are explained in the appendix. $\overline{X}$ is the mean, *n* is the number of samples, Pp is precipitation.

Critical *F* values: α = 0.10, Symbol*, α = 0.05, Symbol**, α = 0.01, Symbol***.

different at a high level of significance (F value - .01). Most of the soil properties were not significantly different.

When the percentage of precipitation collected as surface runoff is calculated for each runoff plot for the 44 observation periods and the results displayed (figure 4-1) it is shown that the pasture plots yielded considerably greater runoff than those in the ungrazed grass and scrub areas. The mean runoff from the pasture plots was 4.6 percent with a standard deviation of 1.46 percent. The scrub plots yielded a mean runoff of 0.89 percent and the ungrazed grass a mean of 0.67 percent. This suggests that the scrub and ungrazed grass plots can be treated as belonging to the same statistical population so that all developed areas (pasture) can be compared with all undeveloped areas (ungrazed grass and scrub). It is shown below (figure 4-2) that this is true for very wet periods as well as for periods of mean conditions. Analysis of variance between developed and undeveloped area plots confirms the above conclusion. The results are summarised in table 4-2. It can be seen that the level of significance of the differences between the precipitation for the two areas has increased beyond that for the three vegetation types. The differences between the soils also become clearer with five properties being different at a highly significant level - penetration resistance, macroporosity as a percentage of total porosity, total porosity, bulk density and the coarsest particles. It is also clear that runoff from the pasture is greater, at a high level of significance, than that from the undeveloped areas.

RUNOFF FROM PASTURE AREAS

Correlation analysis

Simple linear correlations were determined between each of the independent variables and the dependent variable (runoff). The summarised results in table 4-3 show that only precipitation variables are closely correlated with runoff, and that the degree of correlation rises with the increasing intensity of the rainfall.

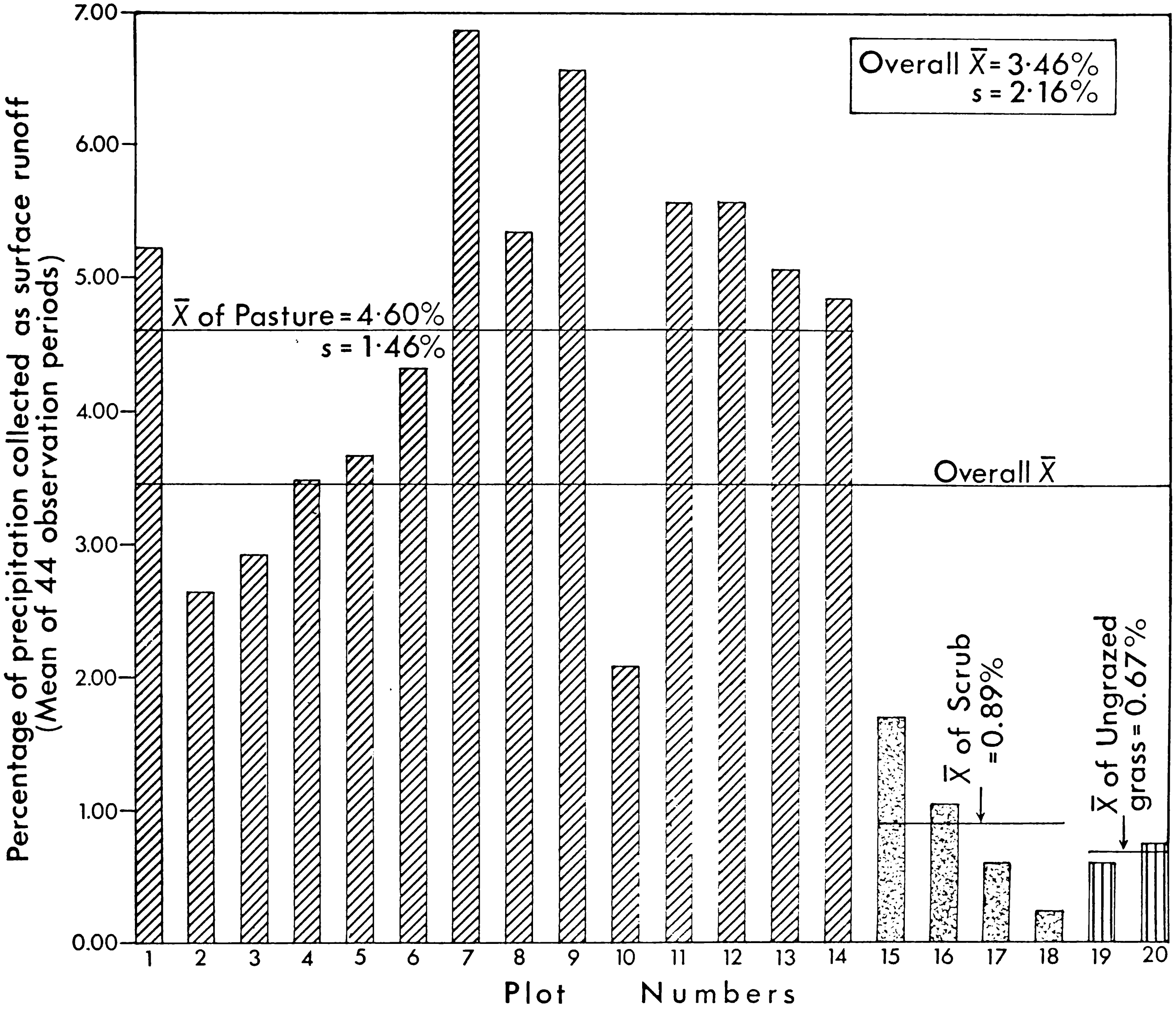

Fig. 4-1. Mean runoff from all plots for all observation periods.

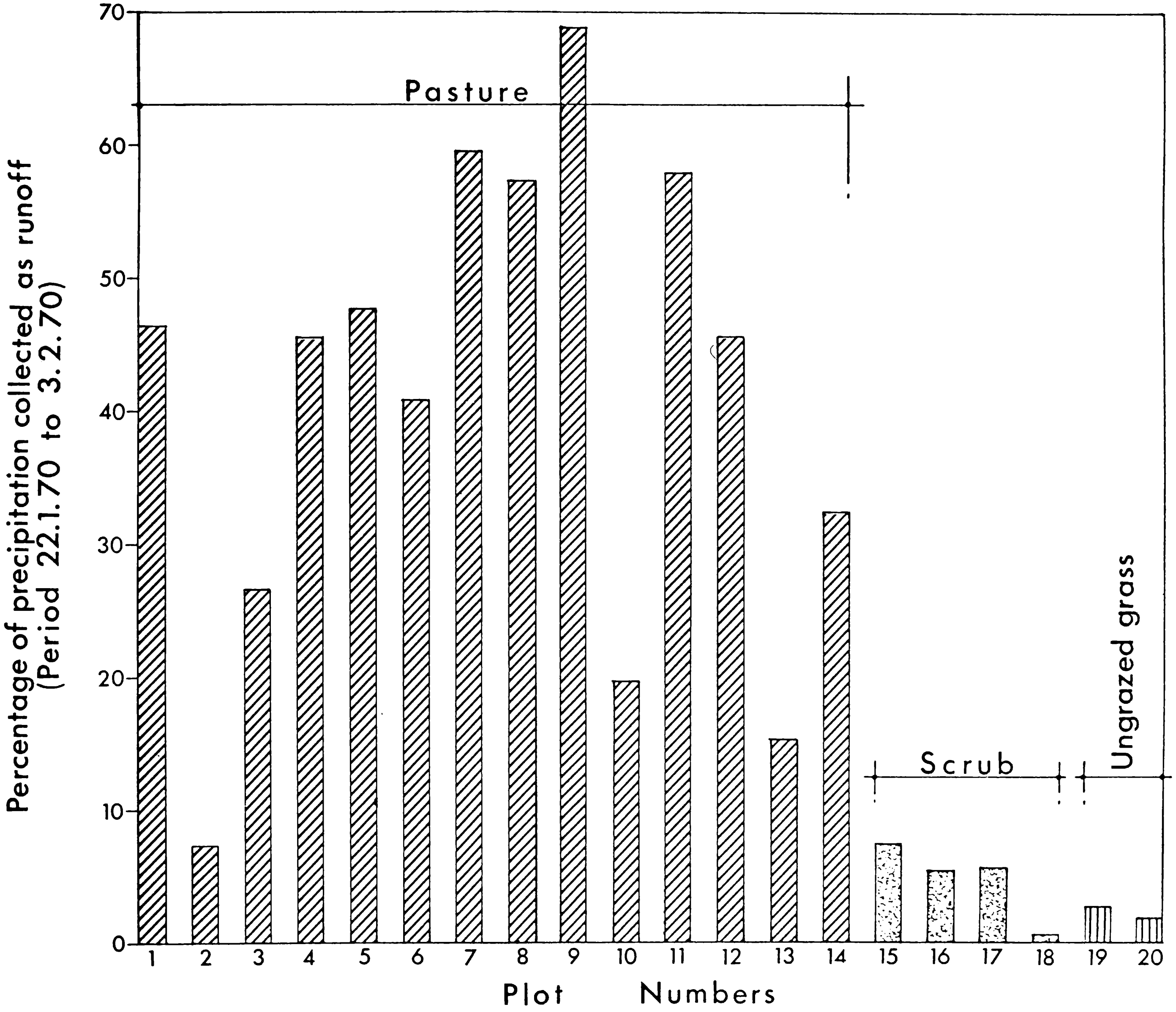

Fig. 4-2. Runoff from all plots for one period of heavy rainfall (22.1.70 - 3.2.70).

Table 4-3. (Part 1) Simple linear correlations between runoff and all variables.

Independent Variable		Correlation coefficients with dependent variable - Runoff		
		Pasture Grass 14 plots x 44 periods	Ungrazed Grass & Scrub 6 plots x 44 periods	Overall 20 plots x 44 periods
	Slope	0.042	0.297	0.070
	Aspect	-0.034	-0.067	-0.084
	Roughness	0.033	-0.077	-0.039
	PTC 1	-0.005	-0.218	-0.144
	PTC 2	-0.023	-0.263	-0.072
	PTC 3	0.032	0.288	0.118
	PTC 4	-0.018	0.127	0.026
	ORG 1	-0.031	0.109	-0.009
	ORG 2	-0.037	0.055	-0.049
	AGG 1	-0.045	0.013	-0.050
	AGG 2	-0.035	0.137	0.013
	VEGS	-0.013	-0.056	0.006
	BULK	0.044	-0.123	0.180
	PART	-0.019	0.246	0.026
	PORO	-0.050	0.074	-0.174
	MAC 1	0.085	0.010	-0.167
	MAC 2	0.086	0.007	-0.155
Estimated Proportionally	Total Pp.	0.187	0.501	0.167
	Max. Pp. - 24 hr.	0.207	0.490	0.180
	Max. Pp. - 12 hr.	0.333	0.555	0.284
	Max. Pp. - 6 hr.	0.446	0.592	0.370
	Max. Pp. - 1 hr.	0.710	0.656	0.584
	Max. Pp. - 0.5 hr.	0.733	0.624	0.604
	Total Pp. for Max. Storm	0.195	0.488	0.171
	Dry Wt. Vegetation	-0.095	0.195	-0.150
	Penetration Resistance	0.141	-0.096	0.196

Table 4-3. (Part 2).

Independent Variable		Correlation coefficients with dependent variable - Runoff		
		Pasture Grass	Ungrazed Grass & Scrub	Overall
		14 plots x 44 periods	6 plots x 44 periods	20 plots x 44 periods
From climate Station at Plot 10	Total Pp.	0.182	0.492	0.184
	Max. Pp. - 24 hr.	0.195	0.479	0.194
	Max. Pp. - 12 hr.	0.319	0.534	0.298
	Max. Pp. - 6 hr.	0.431	0.574	0.392
	Max. Pp. - 1 hr.	0.726	0.645	0.637
	Max. Pp. -0.5 hr.	0.745	0.620	0.650
	Number of storms	0.003	0.199	0.018
	Total Pp. for max. storm	0.181	0.472	0.182
	Duration of Pp.	-0.067	0.162	-0.042
	Duration rainless time	0.249	0.214	0.218
	Time since last storm	0.025	-0.070	0.015
	Mean max. daily temp.	0.337	0.126	0.282
	Highest air temp.	0.354	0.157	0.299
	Mean air temp.	0.350	0.142	0.294
	Minimum air temp.	0.361	0.180	0.306
	Mean soil temp.	0.371	0.162	0.312

Table 4-4. Prediction equations of runoff from pasture plots.

First Step
Predicted runoff = -2965.118 + 1736.470*** (Max. precipitation in 0.5 hour) (where R^2 = 0.554)

Second Step
Predicted runoff = -13896.941 + 1646.915*** (Max. precip. 0.5 hr) + 568.878*** (Highest temperature) (where R^2 = 0.612)

Third Step
Predicted runoff = -16596.516 + 1586.105*** (Max. precip. 0.5 hr) + 589.993*** (Highest temp.) + 7.171*** (Duration of rainless time) (where R^2 = 0.627, F : 343.084***)

Multiple regression

Multiple regression analysis in stepwise form (Draper and Smith, 1966) gives the order of importance of the variables and the extent to which they 'explain' the dependent variable. The results of such an analysis are given in table 4-4. The maximum rainfall falling in 0.5 hour explains 55.4 percent of the runoff. The addition of the highest maximum air temperature increases the explanation to 61.2 percent and the further addition of the duration of rainless time increases the explanation to 62.7 percent. The addition of further variables adds little to the explanation and the prediction equations in table 4-4 are not carried beyond this step. The highest air temperature of the period is positively correlated with runoff ($\underline{r}$ = 0.354) and hence the higher the temperature the greater the runoff. The duration of rainless time is also positively correlated with runoff ($\underline{r}$ = 0.249), hence the longer the rainless time the greater the runoff. This implies that runoff is greatest when pre-existing soil moisture is least. Comment on the causes of runoff will be made below.

RUNOFF FROM UNGRAZED GRASS AND SCRUB

Correlation analysis

Table 4-3 shows that the same pattern of correlation values occur in the undeveloped areas as in the pasture, but that the importance of total precipitation is increased and that of short duration intense rainfall is decreased. The temperature correlations are also lower.

Multiple regression

The prediction equations in table 4-5 show that the levels of explanation are less than those for pasture with only 43 percent of the runoff being explained by the one variable of maximum precipitation in one hour, and with 61 percent explained by four variables - maximum precipitation in one hour, angle of slope, total precipitation and soil particles of 0.63-6.35mm diameter. The latter is the only soil variable so far noted that is important and then in a negative sense. Its correlation with runoff is -0.263 and hence it is an infiltration controller rather than a runoff maker.

OVERALL ANALYSIS OF RUNOFF

When an overall analysis, grouping the data for the pasture, ungrazed grass and scrub plots, was attempted the same general pattern of correlations and explanations emerged - tables 4-3 and 4-6 - but the percentage explanation fell and penetration resistance emerged as an important variable even though it has a correlation with runoff of only 0.196. The low level of explanation achieved indicates that although the causes of runoff in developed and undeveloped areas are similar the data from the two classes should not be grouped if a reliable prediction of runoff is required.

In the three analyses to determine simple linear correlations (table 4-3) precipitation measurements, other than total precipitation for the period, were entered in two forms. The first form was a calculation of the rainfall received by each plot for a given period. This calculation used the rainfall intensity records from the two automatic raingauges to modify data from the storage gauges at each plot so that the rainfall intensities at each plot were proportional to the total rainfall. This method gave a lower level of correlation with runoff than that achieved by the second method which took all rainfall intensities from the master climate station alongside plot 10. Plot 10 apparently represented rainfall intensities for the whole area unexpectedly well.

CAUSES OF RUNOFF

The variables contributing highly to the explanation of runoff are listed below.

(a) Intense precipitation, especially that occurring as

Table 4-5. Prediction equations of runoff from ungrazed grass and scrub plots.

First Step — Predicted runoff = $-374.676 + 282.075^{***}$ (Maximum precipitation in one hour) (Where $R^2 = 0.430$)

Second Step — Predicted runoff = $-1916.866 + 282.161^{***}$ (Max. precip. 1 hr.) $+ 94.378^{***}$ (slope angle) (Where $R^2 = 0.519$)

Third Step — Predicted runoff = $-2370.493 + 232.345^{***}$ (Max. precip. 1 hr.) $+ 94.385^{***}$ (Slope) $+ 15.768^{***}$ (Total precipitation) (Where $R^2 = 0.576$)

Fourth Step — Predicted runoff = $508.341 + 232.400^{***}$ (Max. precip. 1 hr.) $+ 75.463^{***}$ (Slope) $+ 15.769^{***}$ (Total precip.) -109.920^{***} (Particle size 0.63 - 6.35 mm d.) (Where $R^2 = 0.608$, $F : 100.478^{***}$)

Table 4-6. Prediction equations of runoff from all plots.

First Step Predicted runoff = -2042.439 + 1310.194*** (Max. precipitation in 0.5 hr) (Where R^2 = 0.422)

Second Step Predicted runoff = -8889.022 + 1328.324*** (Max. precip. 0.5 hr) + 1.608*** (Penetration resistance) (Where R^2 = 0.471)

Third Step Predicted runoff = -12776.527 + 1280.303*** (Max. precip. 0.5 hr.) + 1.258*** (Pen. res). + 279.955*** (Maximum temperature) (Where R^2 = 0.488, F : 278.504***) the maximum precipitation in 0.5 hour or 1 hour, gives rise to overland flow because the precipitation rate exceeds the infiltration rate only for the short periods in which rainfall is very intense. This finding is in accordance with what has already been demonstrated in other environments by numerous workers (Selby, 1970) and was suggested by Robertson (1963) for pumice soils. In conditions of very high rainfall in short periods the percentage of runoff is very much greater than the mean values of the 44 observation periods. This is demonstrated by comparing figures 4-1 and 4-2.

During the period 22.1.70 to 3.2.70, when 30.2mm of rain fell, runoff from all pasture plots was about ten times higher than the mean runoff for the two years of observations and reached 68 percent of precipitation on plot 9 and exceeded 10 percent on all pasture plots except number 2 (<u>c.f.</u> mean for pasture plots of 4.6 percent). The ungrazed grass and scrub plots had approximately five times as much runoff as their mean. The greater significance of intense rainfall in pasture areas than undeveloped areas is demonstrated by the correlation coefficients. For pasture areas the correlation of the maximum precipitation in 0.5 hour with runoff is 0.733 and for 1 hour 0.710, but for the undeveloped areas the coefficients are 0.624 for 0.5 hour rainfalls and 0.656 for 1 hour rainfalls.

(b) <u>The highest air temperature</u> in the observation period is a reflection of the rate of evapotranspiration but probably more importantly of soil moisture content before rainfall commenced. This conclusion is reinforced by the third variable (c) <u>duration of rainless time</u> which is also a measure of soil moisture. Positive correlations of highest air temperature and duration of rainless time indicate that runoff increases as soil moisture decreases. This finding also supports the conclusion of Van't Woudt (1954) and Packard (1957) that pumice soils exhibit a resistance to wetting once they have dried out. This phenomenon, which is widely known in other soils (Le Bano and Letey, 1969), has not yet been fully investigated in pumice soils.

(d) Total precipitation is of greatest importance in the areas of ungrazed grass and scrub. It is probable that this is because soils are less compacted and retain their moisture more readily in the undeveloped areas than in the pasture. This is indicated by the highly significant differences between (e) penetration resistance among the three vegetation types (table 4-1), and by the correlation coefficients of total precipitation with runoff. From the undeveloped area the correlation coefficient is 0.501 but from the pasture area is 0.187.

(e) Penetration resistance is not correlated with runoff at any but a low level (0.196 in the overall analysis) but in the multiple regression analysis it emerges as the second most important variable in the overall analysis. From this it may be concluded that the importance of many soil properties - each only slightly correlated with runoff - is subsumed in the penetration resistance.

(f) Soil particles of 0.63 - 6.35mm diameter enter the multiple regression equation for the undeveloped area at the fourth step. This variable is negatively correlated with runoff indicating that runoff decreases as the proportion of this coarse sand to fine gravel fraction in the soil increases. This is presumably because the presence of this fraction increases soil permeability.

(g) Slope angle occurs as the second most important variable in the undeveloped areas. Its correlation coefficient with runoff is 0.297 which is lower than that of several other variables, but these other variables interact and their effect is subsumed in the two major precipitation variables and in the coarse sand to fine gravel variable. Slope presumably behaves largely independently of other variables and, because slope is positively correlated with runoff, runoff increases with slope angle. In pasture areas slope is unimportant, having a correlation coefficient of only 0.042 with runoff.

RATE OF RUNOFF

The rate of runoff was measured at only three plots - plot 17 under scrub and plots 8 and 9 under pasture. The runoff from the plots in relation to rainfall is indicated in figures 4-3 and 4-4 for two periods. These periods were chosen as being representative. In both periods May 7-10, 1970 (figure 4-3) and September 24-26, 1969 (figure 4-4) the pattern of runoff was approximately the same. Runoff began first under the scrub but at a very slow rate. The maximum rate of runoff on all plots approximately coincided with the most intense rainfall although on plot 9, which has a very steep slope of 33°, the maximum runoff rate occurred earlier than on the other plots. In the May storm runoff from the pasture plots was prolonged even when rainfall intensity had declined to a low value.

The runoff for the period 9-10 May 1970 also shows that runoff from the scrub is more nearly instantaneous than that from pasture, and that it closely follows the rainfall intensity pattern. The amounts of runoff during low intensity precipitation on scrub are rather greater than amounts from the pasture plots. This supports the general conclusion already drawn from the simple correlation analysis and multiple regression analysis that from soils under scrub the lower intensity rainfalls and total rainfall are more important causes of runoff than under pasture where intense rainfalls are more important.

LOSSES OF EXPLANATION

The percentage of explanation of runoff achieved in the multiple regression analyses is 63 percent for the pasture areas, 61 percent for the undeveloped areas and 49 percent when all plots are combined. This rather low level of explanation requires comment.

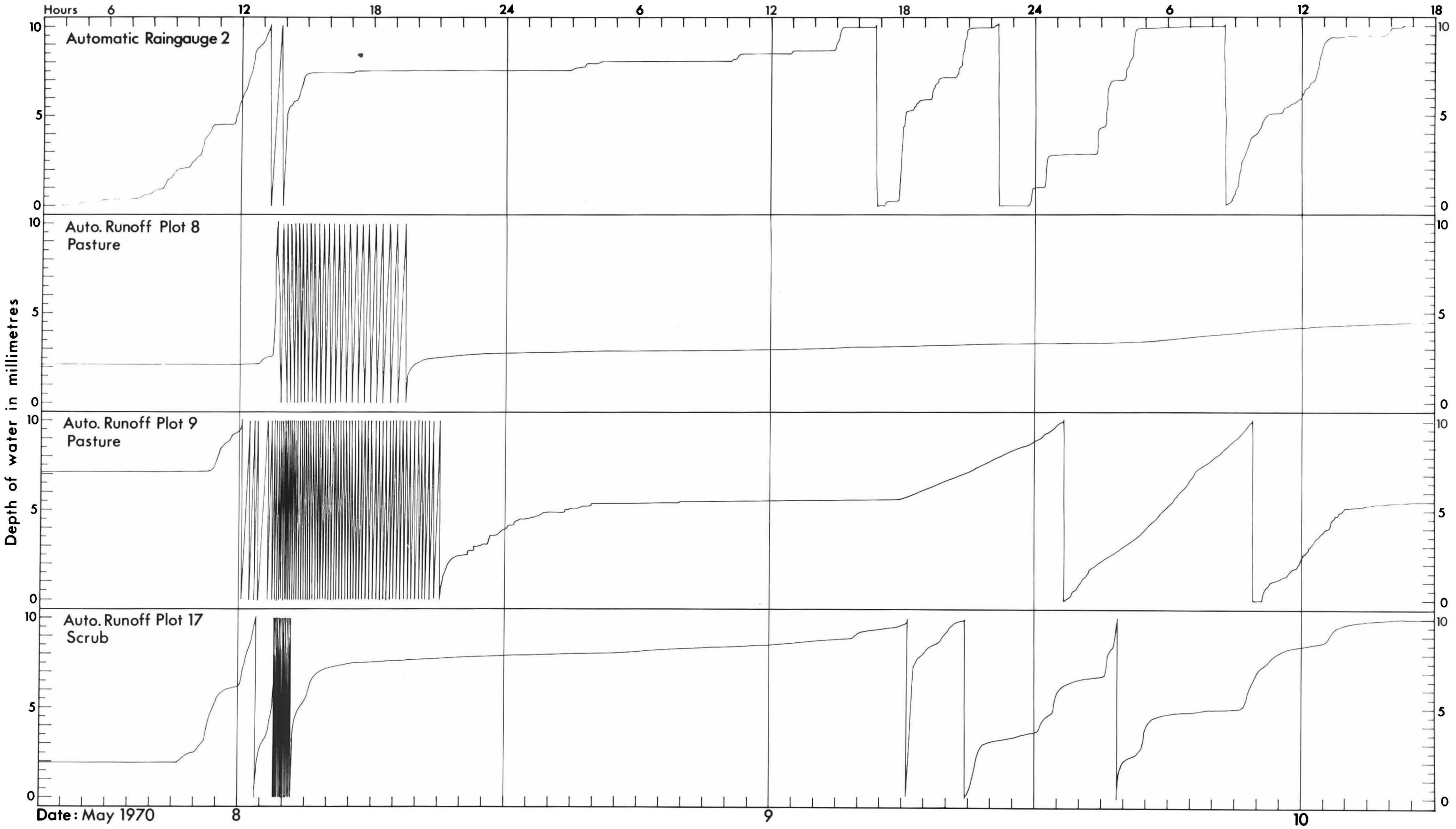

Fig. 4-3. Runoff and precipitation during the period 7-10 May, 1970.

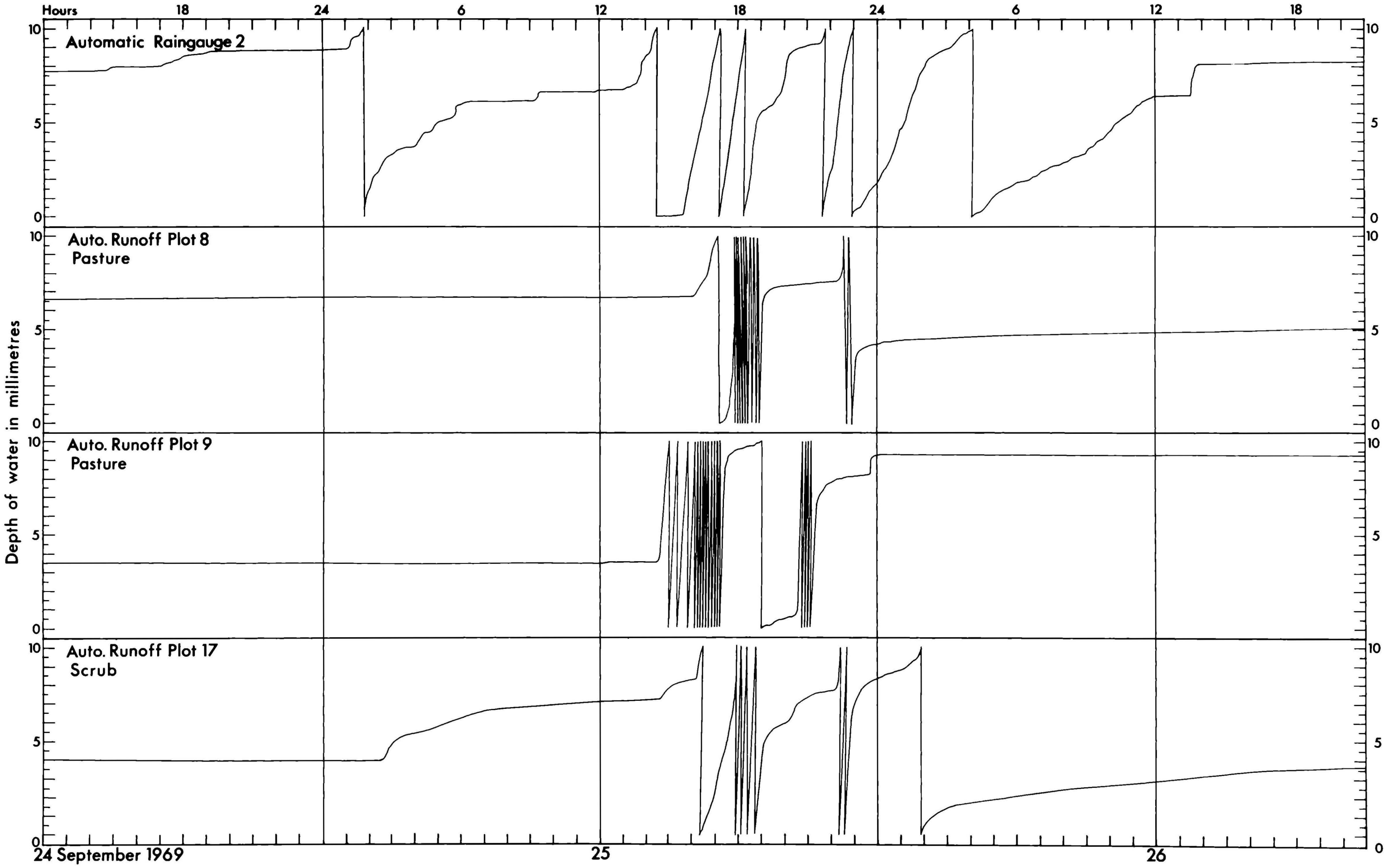

Fig. 4-4. Runoff and precipitation for the period 24-26 September, 1969.

Scatter of the data

When runoff as a percentage of precipitation falling on a plot is graphed against the depth of precipitation (figures 4-5, 4-6, 4-7, 4-8) it is readily seen that there is a great scatter of the data such that no line or curve could represent the relationship, and that no transformation of the data, such as a logarithmic transformation, would greatly improve the fit of a curve. The causes of this scatter no doubt lie in the great number of variables which have some, albeit small, influence on runoff. Most of the soil properties are only slightly correlated with runoff - some negatively and some positively - but because of the seasonal significance of such important variables as the highest temperature and penetration resistance (partly measuring soil moisture) it must be expected that any soil property will change its relationship to runoff with seasonal and other conditions. It is the changing influence of many contributing factors and the great variety of climatic conditions under which rain fell which induces such scatter and reduces the level of explanation achieved. This scatter could be decreased if instead of agglomerating data for all observation periods and for the three vegetation types the data were split either for analysis by storm type or by individual plots. A higher level of explanation would then be achieved. Soons (1970) achieved explanations ranging from 54 to 93 percent of the variance by analysing her data, for 6 plots using 15 variables, in this form. Such methods however do not give an understanding which is relevant to the conditions occurring in the plots of a whole catchment and their applicability to a general situation is thereby reduced.

Sampling

In order to obtain soil data it was necessary to take three cores from around each plot, and similarly penetration resistance was measured around each plot, and vegetation cover point sampled across each plot. Such methods give data which are only partly representative of the whole plot and the results of such methods reduce the degree of

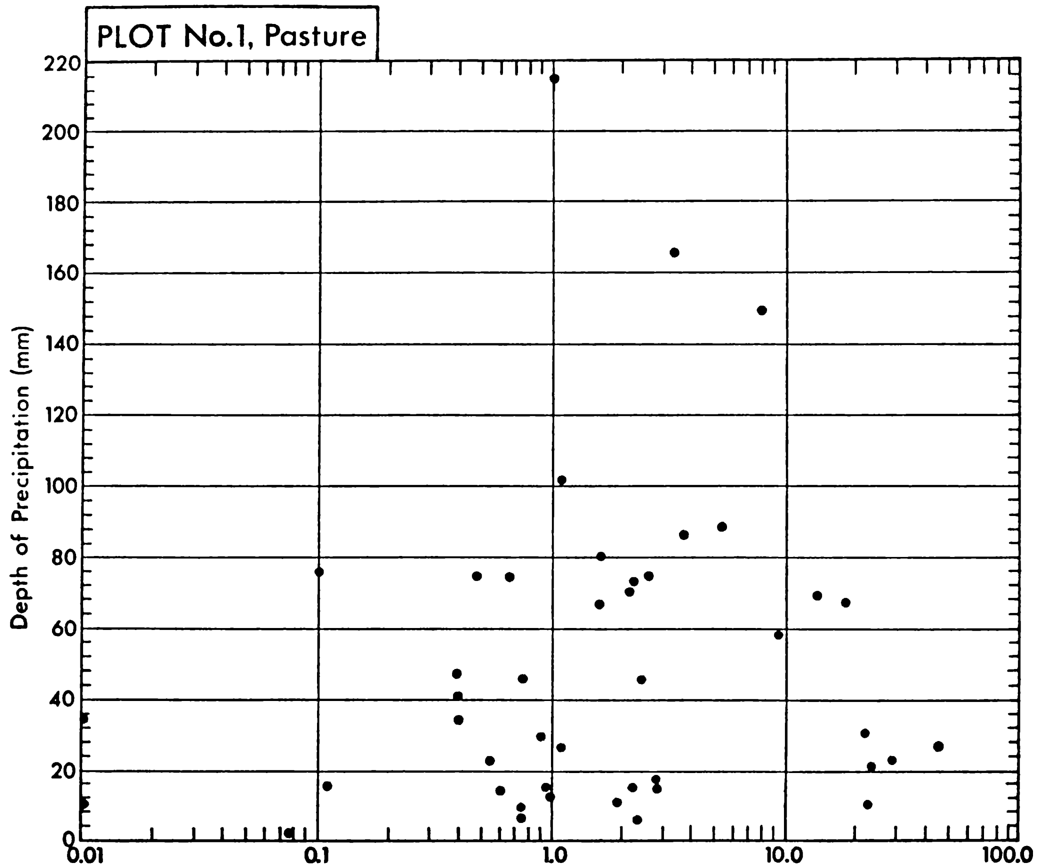

Fig. 4-5. A plot of runoff against precipitation for each of the observation periods.

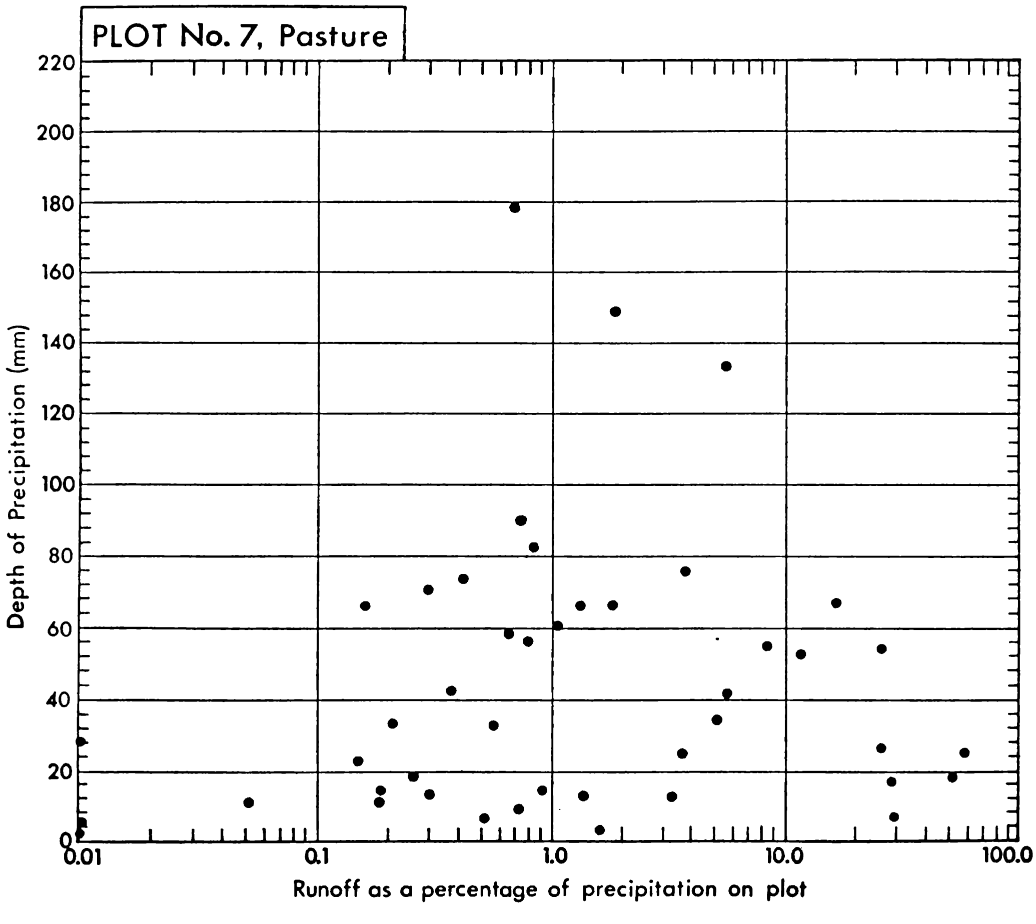

Fig. 4-6. A plot of runoff against precipitation for each of the observation periods.

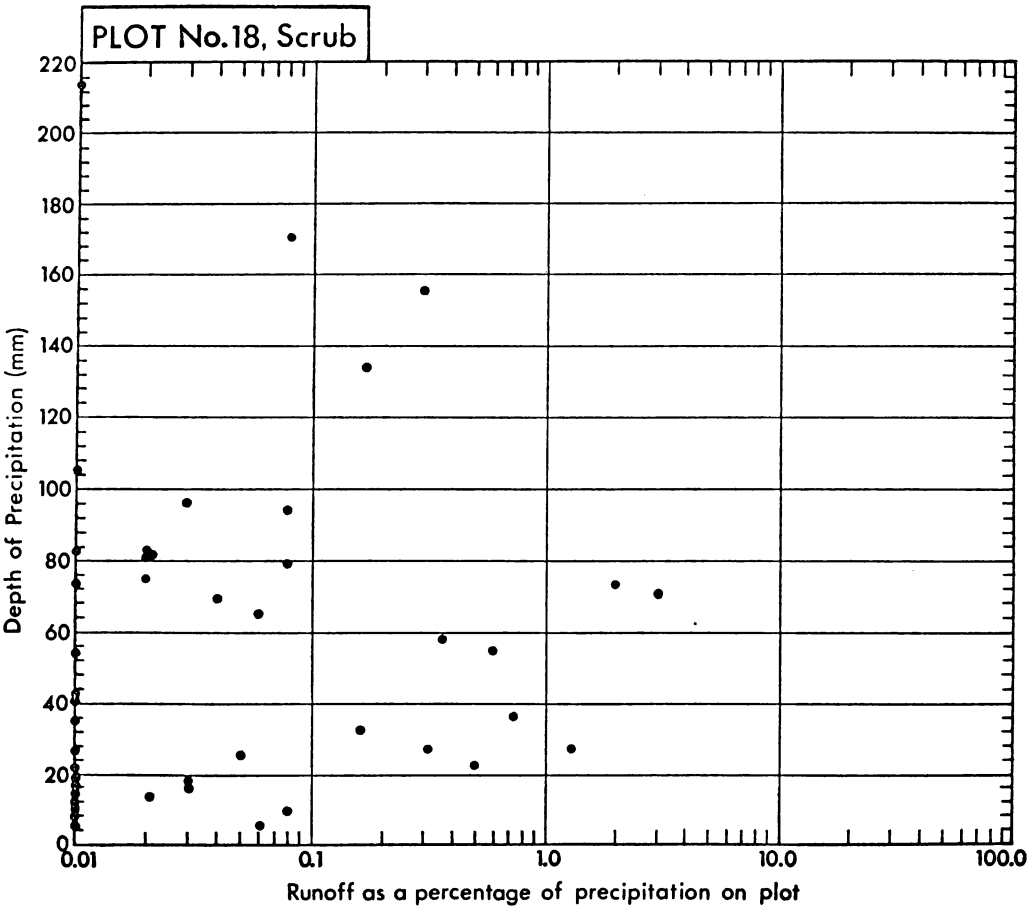

Fig. 4-7. A plot of runoff against precipitation for each of the observation periods.

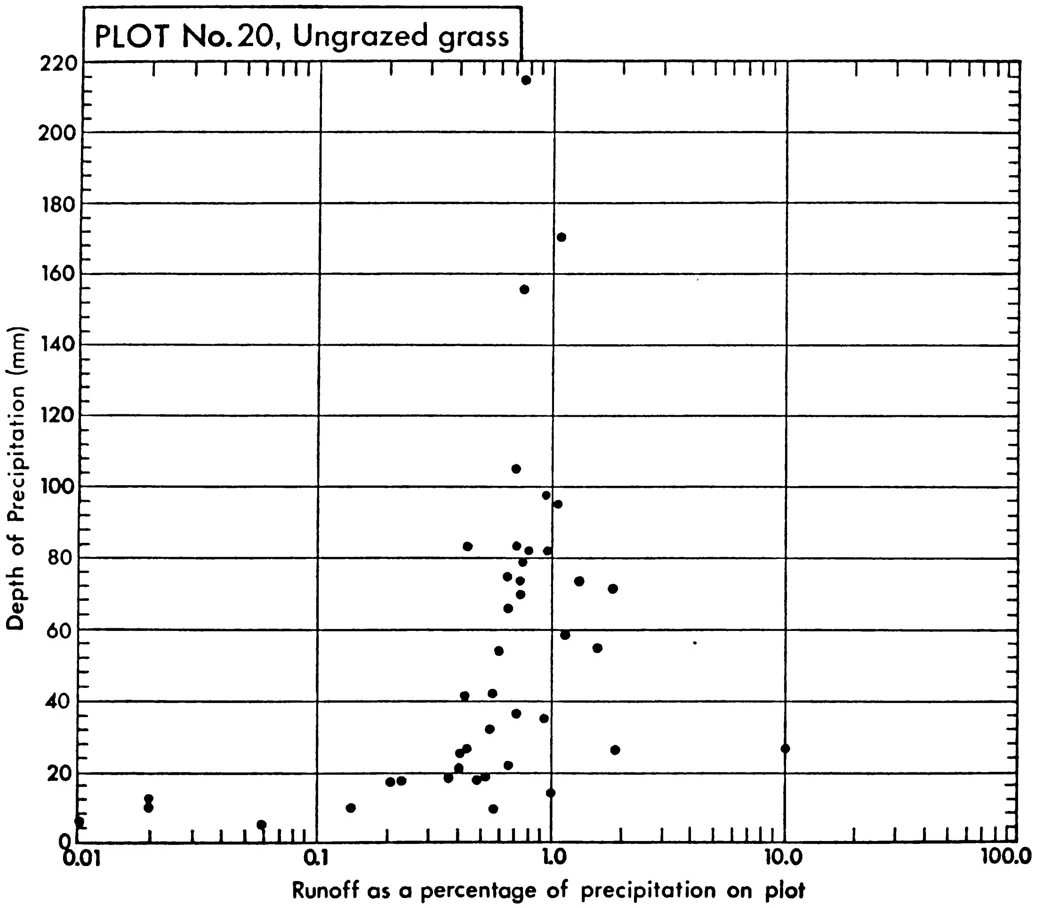

Fig. 4-8. A plot of runoff against precipitation for each of the observation periods.

explanation achieved. Beckett and Webster (1971) have pointed out the high degree of variability of soil properties within $1m^2$ of soil. Experimental errors also cause uncertainties in the data.

Methods of analysis

It has been pointed out by Mead (1971) that although multiple regression analysis is valid even when the so-called independent variables are correlated, and hence not truly independent, internal correlations make multiple regression less efficient in the sense that standard errors of the estimated regression coefficients will, in general, be larger than with uncorrelated independent variables. In either case the estimated regression coefficients give unbiased estimates of the true coefficients. Some loss of explanation may, however, be caused by the method of analysis.

SUBSURFACE WATER FLOW

Subsurface water was found in the six subsurface water traps only at the end of a prolonged period of rain towards the end of each winter in the two years of observations. It appears then that subsurface lateral water flow and high water tables do not contribute to runoff from the area under study. This justifies the confinement of this research to overland flow.

CONCLUSIONS

The aim of this study was not to develop a prediction equation for basin runoff because it has already been shown in chapter 3, that runoff from plots cannot be used to predict runoff from catchments, but rather to discover if runoff is significantly different among the three vegetation areas and to what causes runoff may be attributed. The analyses described above have successfully answered these questions, and the levels of explanation achieved in the multiple regression analyses in no way detract from these conclusions which are listed below.

(1) Runoff from each of the three vegetation areas is different from the other areas at a high level of significance and is greatest from areas of pasture.

(2) Vegetation density (as measured by dry weight), penetration resistance and soil coarse gravel content are the only three plot properties which are different at a high level of significance.

(3) For purposes of analyses it is reasonable to group undeveloped areas with scrub and ungrazed grass together, and to compare them with developed areas under pasture.

(4) The variables which explain runoff in undeveloped areas are: maximum precipitation occurring in one hour, angle of slope, total precipitation and soil particles of coarse sand to fine gravel sizes; these together explain 61 percent of the runoff.

(5) The variables which explain runoff in pasture areas are: maximum precipitation in 0.5 hour, the highest temperature of the period and the duration of rainless time in the period. The last two variables are measures of pre-existing soil moisture and indicate that low pre-existing soil moisture increases runoff. These three variables together explain 63 percent of the runoff.

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CHAPTER 5

DESIGN OF A HAND-PORTABLE RAINFALL-SIMULATING INFILTROMETER

Methods used to measure infiltration rates of water into soils have usually been one of three types: (1) a watershed hydrograph analysis which utilises rainfall and runoff data from a watershed; (2) a cylinder or ring, inserted into the soil, which impounds water at the surface; (3) a sprinkling device to simulate a rainstorm on a plot.

The watershed hydrograph method is often valuable in large area studies but it is useless for separating the numerous variables which affect infiltration within a catchment such as vegetation, soil type, soil characteristics, slope and stocking rates. The ring method is simple and cheap but insertion of the ring, which is essentially a short length of metal tubing, disturbs the soil, air is easily trapped in the soil column, seepage occurs at the interface of the metal ring and the soil, lateral movement occurs below the level of the ring, and the application of water in a flood does not represent the events of a storm. Sprinkling infiltrometers can overcome most of the defects of these two methods (Parr and Bertrand, 1960).

Most sprinkling infiltrometers attempt to simulate rain falling on a known area of ground and to measure the water applied and that which runs off the plot. The differences between the two figures are the amounts of water which have infiltrated into the soil. A number of sprinkling infiltrometers have been developed and are in use (Rowe 1940a; 1940b; Packer, 1957: Bertrand and Parr, 1960: Meyer and Mannering, 1960: Powell and Beasley, 1967). These instruments are all large and usually require a large vehicle to carry them. Even if they are portable, they need a water supply far exceeding the capacity of a man to carry it, and a motor pump to supply water to the sprinklers. Such instruments can therefore only be used in areas well served by roads. In addition most cannot be used in closely planted forests, on rough ground or steep slopes.

A small hand-portable instrument has been used by Melton (1957, p.9) but this has a ring rather than a plot and hence is likely to be inaccurate. Adams, Kirkham and Nielsen (1957) developed a similar instrument using a plot rather than a ring and McQueen (1963) has made some improvements to their design.

Many of the components used in McQueen's (1963) design were not available in New Zealand and his instrument was thought to be insufficiently rugged for use in remote undeveloped country in New Zealand. Furthermore his instrument could only be used on horizontal ground, whereas it is often essential to be able to compare infiltration rates on soils at a wide range of slope angles. Nevertheless the principles developed by McQueen are sound and have been used to produce an instrument suitable for New Zealand conditions.

Principles

Natural raindrops hitting the soil surface dislodge soil particles and move some of them into soil pores. Simulated rainfall should therefore duplicate the type and intensity of natural storms. The energy of natural rainfall is extremely variable during a storm and computation of infiltration rates from a variable application rate would be difficult, so a constant rainfall intensity, having a constant kinetic energy within the energy levels naturally occurring, should be simulated.

The kinetic energy of a falling body is equal to one half the mass times the square of the velocity so for a given amount of precipitation the energy is a function of velocity. Laws and Parsons (1943) have shown that the average diameter of raindrops in a storm having an intensity of 25.4mm/h is 2.25mm. A drop of this size would require a free fall of 10m to reach a terminal velocity of 7m/s (Laws, 1941). A drop of 5mm diameter falling 3m would have the same velocity and therefore the same energy per unit of rain. Neither the drop size distribution nor the energy of natural rainfall can be practically duplicated, but a larger drop falling a shorter distance has the same energy per unit of rain and therefore a similar erosive force.

Soil particles are removed in suspension in water running off the soil surface or carried in drops of water splashed from the plot. It is therefore desirable to collect runoff and splash separately and to be able to measure the sediment moved.

Expansion of some clay minerals during hydration reduces the volume of soil pores and, therefore, the infiltration rate. Ions from salts dissolved in water may influence the expansion of clay minerals. In general sodium will increase swelling and calcium may reduce it. Water used in the infiltrometer should therefore be of nearly the same chemical composition as rainwater. Filtered de-ionised or distilled water is therefore used.

The accuracy of infiltrometer measurements is influenced by the size and shape of the plot. Shapes most often used are rectangular or circular. Increased infiltration leading to erroneously high measured rates generally occurs at the plot boundary as a result of capillary underflow or as accelerated flow rates through disturbed soil. The relative magnitudes of these errors are a function of the ratio of boundary length to plot area, and the ratio should therefore be as small as possible. The smallest possible ratio will be achieved by a circular plot. Size of the plot is determined by the need for the instrument to be portable by hand (McQueen, 1963).

Because there is a wide range of soil conditions in even small areas accurate average infiltration rates can only be obtained by statistically adequate sampling of point values distributed through a drainage basin.

Requirements for the design

The infiltrometer is required for use in a wide range of types of country, with variable slopes, and vegetation cover ranging from forest to pasture, as well as on bare soils. The instrument must have: (1) an accuracy at least equal to that of other infiltrometers in use; (2) it should be hand-portable by one man; (3) water requirements should be small; (4) it should not disturb the surface structure of the soil during installation or operation; (5) it should prevent lateral movement of water beyond the boundary of the plot; (6) it should provide for collection and measurement of water and sediment splashed out of the plot separately from water and sediment accumulating on the plot; (7) the energy of simulated rain should correspond with the average energy level of natural storms; (8) rainfall intensity should be controllable over a wide range and should be stable at any given intensity; (9) installation and operation of the instrument should be rapid and convenient; (10) data obtained should require little computation; (11) the instrument should operate efficiently even in adverse conditions - such as in high winds; (12) it must be able to operate on a wide variety of slopes; (13) it must be constructed of materials readily available in New Zealand.

DESIGN OF THE INFILTROMETER

The infiltrometer is shown in figure 5-1 and the details of construction in figures 5-2 and 5-3. The instrument has five main units: (1) a reservoir and control; (2) a raindrop maker; (3) a windshield with its supporting tripod; (4) a base unit; (5) two tubes for measuring runoff and splash with the associated sediment. The details of this design are given in Selby (1970).

The reservoir and control unit has three functions: (1) it supplies water to the raindrop maker; (2) it measures the quantity of water supplied; (3) it controls the hydraulic head and hence the rate of application of

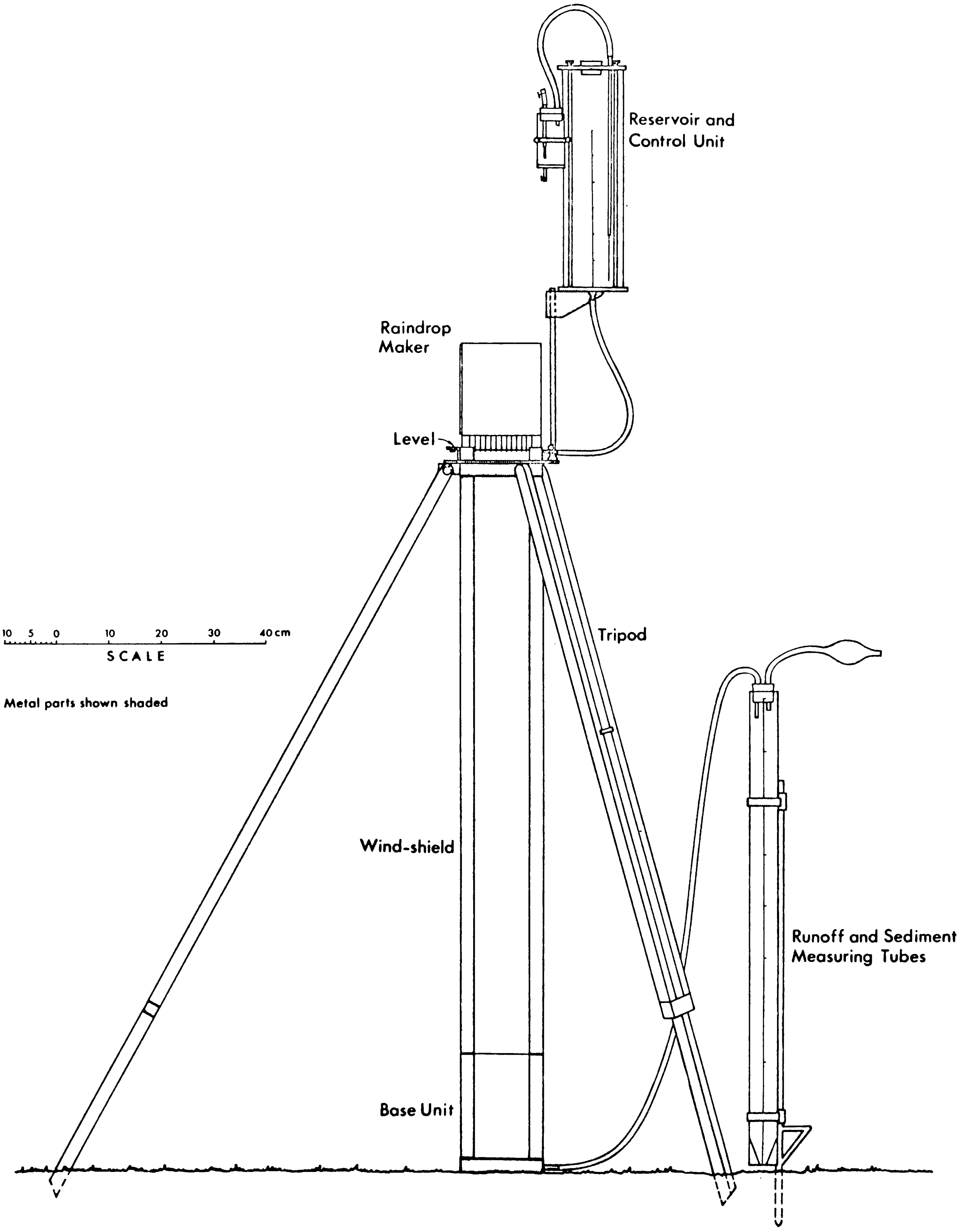


Fig. 5-1. Components of the infiltrometer with a horizontal base unit.

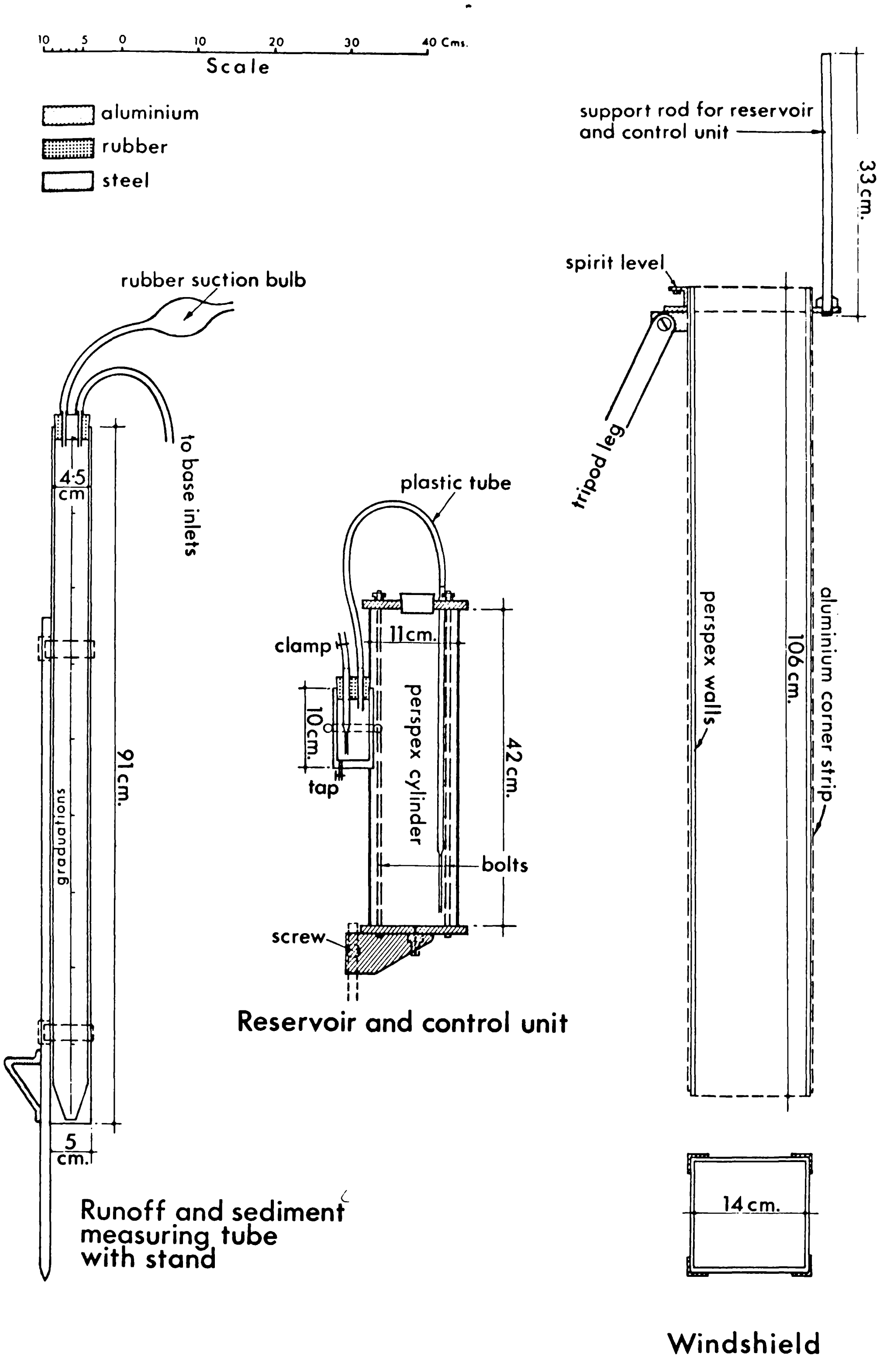
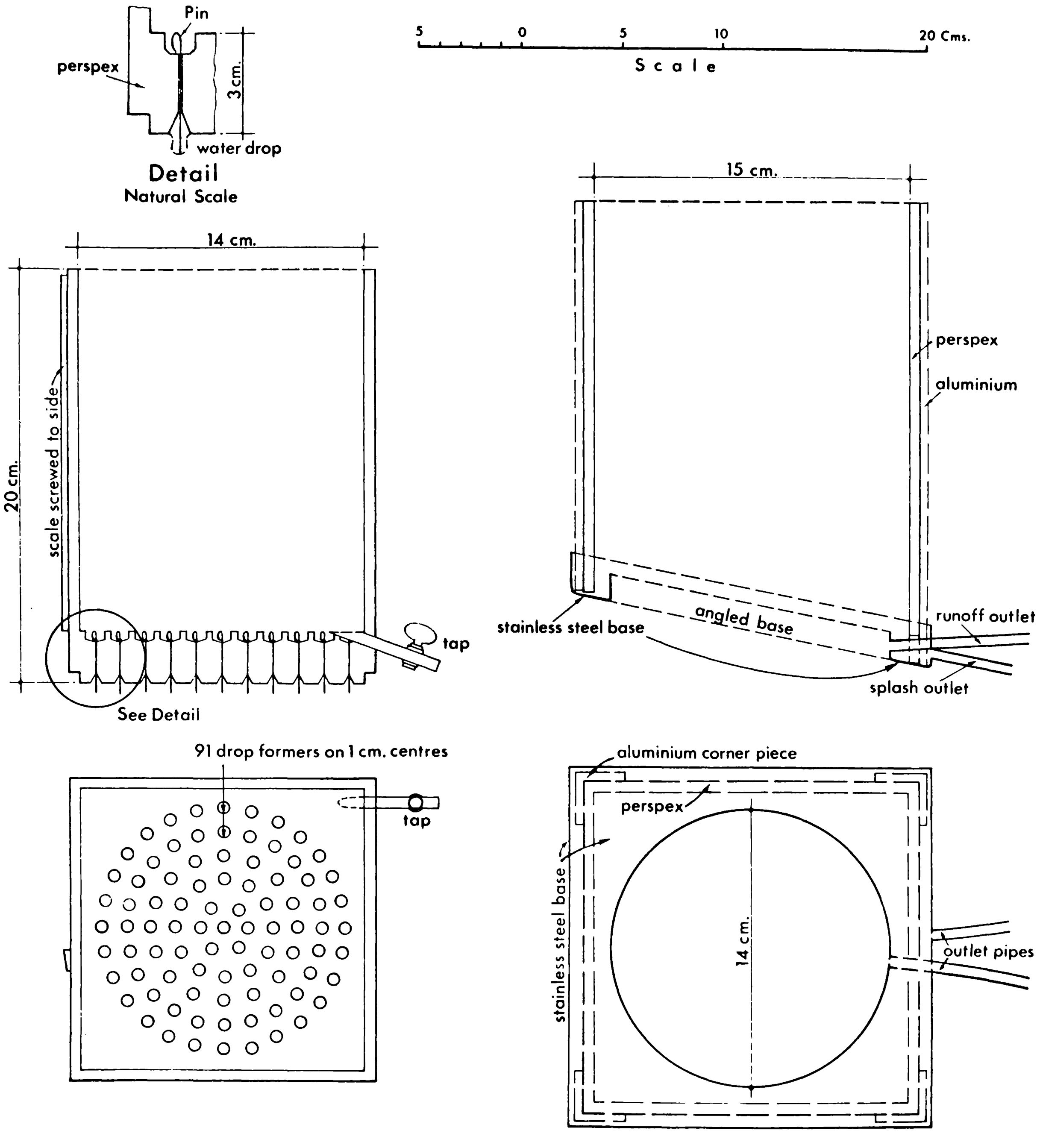


Fig. 5-2. Details of the construction of the measuring tubes, reservoir and windshield.



Raindrop Maker

Base for Runoff and Splash Collection

Fig. 5-3. Details of the raindrop maker and bases.

raindrops. The reservoir is a cylinder of 3mm thick perspex with an internal diameter of 11cm and a length of 42cm (figure 5-2). Aluminium end-plates, 1cm thick, have grooves machined into them and the cylinder fits into these. Rubber gaskets ensure an airtight fit. The control unit is a perspex bottle. The control operates by allowing air to bubble through the control bottle and into the reservoir thus controlling the rate at which water drains into the raindrop maker. The reservoir is calibrated to measure the depth of water applied to the plot area. The spacing of the calibration marks is computed from the ratio of the square of the plot diameter to the square of the diameter of the reservoir. In this case $14^2/11^2 = 1.62$. Therefore 1.62mm on the reservoir represents 1mm of precipitation.

<u>The raindrop maker</u> is a perspex box with a 3cm thick bottom drilled with a number 60 drill (diameter 1.016mm) to take 91 pins of chromium-plated brass wire. The bottom of each hole is countersunk to give a cone-shaped recess, with a height of 2mm and diameter of 5.7mm, which acts as the raindrop former. It was found on testing that one set of pins did not give an adequate range of precipitation and two sets were therefore made with pins of diameter 0.91mm and 0.68mm. The head in the raindrop maker can be varied between 50 and 150mm and gives a range of available precipitation between 20 and 3000mm/h. The raindrop maker sits on the windshield.

<u>The windshield</u> has walls of 3mm thick perspex reinforced at the corners with aluminium channelling. The tripod is a standard kind used with plane tables, and the level is a standard circular one.

<u>The base unit</u> is also made of perspex and aluminium channelling except for the base plate which is of stainless steel (figure 5-3). Ten base units have been made with the angle of the base ranging from the horizontal to 45° at 5° intervals. The circle and the ellipses for all the bases were cut from the same 18 gauge B.S.W. stainless steel tube. One flexible tube through which runoff water and sediment can be sucked off is let into the stainless steel ring, and

a second tube is let into the perspex. Through the second tube splash water and sediment can be removed. The base unit is sealed to the soil surface with montmorillonitic clay.

Runoff and sediment tubes. Two perspex graduated tubes collect runoff and splash water with their associated sediments. Suction bulbs of the type common to medical equipment are used to draw off the water. The perspex tubes must be rigid. Their bases are cones machined from solid blocks of perspex and then stuck to the tubes with adhesive. The cone is not really necessary and could be dispensed with. The tubes may either be calibrated directly to give a measurement of the depth of water removed from the plot, or scale marks put on them, and then a conversion factor used to convert tube units to runoff units.

FIELD USE

In the field the infiltrometer is most useful in comparing adjacent soils under different types of land use or vegetation. Comparisons carried out by the United States Geological Survey show that this type of infiltrometer is more accurate than many larger instruments and does not give the excessively high infiltration rates of instruments which disturb the soil.

Lateral flow of water away from the plot through the soil may be a source of considerable error (Marshall and Stirk, 1950) in obtaining infiltration rates. It is therefore desirable to surround the plot by a wetted buffer zone. This is most readily done by inserting a steel ring into the ground round the plot and spraying water onto the buffer zone at such a rate that water is just prevented from ponding on the surface of the ground. In order to prevent soil disturbance the steel ring should be at least 20cm from any part of the plot. When this is done on sloping plots it is desirable to have a reservoir, upslope of the plot, from which at least two pipes lead to small spray nozzles which wet the entire buffer zone. A siphon can drain water ponding on the lower edge of the buffer zone.

When the instrument is set up vegetation has to be clipped off around the circle or ellipse of the plot. The base unit is then sealed to the ground with clay so that the excess water from the plot will flow only into the drain tubes. The rest of the instrument is assembled, water is put into the reservoir and its level in the raindrop maker adjusted to give the intensity required. The control unit is then set to maintain the level. The raindrop maker can then be positioned over the windshield and base unit. Timing is started when the first drops hit the plot surface. As water accumulates on the plot and in the base unit it is drawn off. The water level in the accumulation tube is recorded at 1, 3, 5, 7, 9, 11 and 15 minutes and thereafter at 5 minute intervals. The record sheet should have columns for time (T min), runoff (R in tube units), splash (S in tube units), $\frac{R + S}{T}$, precipitation rate (Pr in tube units), infiltration rate ($Pr - \frac{R + S}{T}$ in tube units), and infiltration rate (Ir in mm/min) where:

$$Ir = (Pr - \frac{R + S}{T})24.8$$

(Note: the multiplier, 24.8, is the number of mm representing one unit on the accumulation tubes for runoff and splash divided by the ratio of the area of the accumulation tube to the area of the plot).

Total infiltration (mm) = (Total precipitation (tube units) - Total R + S (tube units))24.8

Sediment is collected from the accumulation tubes at the end of the test.

LABORATORY USE

Because only about three tests can be run by one man in one day it may be more efficient to collect large undisturbed samples of soil and to run the infiltration tests on them in the laboratory. Stainless steel rings, of 3mm thick steel with a diameter of 30cm and height of 20cm, and a slide-on base and lid have been found very successful for collecting samples. Such a method has the advantage that the angle of slope of the soil surface and the pre-existing soil moisture can both be readily modified to test a wide range of conditions that cannot be readily controlled in the field. In addition direct suction can be applied to the accumulation tubes and the suction bulbs need not then be used.

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CHAPTER 6

INFILTRATION INTO SOILS OF THE OTUTIRA CATCHMENT

The only published figures for infiltration rates in yellow-brown pumice soils, which have been traced, are those given by Campbell (1965, p.9), Anaru (1967, p.9) and Selby (1967). Campbell says: "Infiltrometer measurements made by the writer and D. Nordbye showed that various pumice soils absorbed rainfall at a greater rate than 4 inches per hour (101.6mm/h) under natural conditions of grass, scrub or forest, but on pastures the rate was less than half an inch per hour (12.7mm/h)". Campbell gives no details of the method, location or site characteristics of his measurements nor does he indicate if they were part of the earlier work (1951) carried out by Nordbye with a North Fork Constant Head Infiltrometer.

Anaru gives infiltration rates of 3.70 inches per hour (94.0mm/h) for areas in scrub compared with 1.85 inches per hour (47mm/h) for a 5-year old pasture. Selby, using infiltration rings, obtained values ranging from 36.75 inches per hour (933mm/h) under *Pinus radiata* forest to 1.11 inches per hour (28mm/h) under pasture. In this work only 10 trials were carried out to obtain an indication of the variations likely to be found in areas of yellow-brown pumice soils.

OTUTIRA TESTS

Six sample sites were chosen at random using a deck of cards and a grid system, from those areas of the Otutira catchment in which disturbance of the ground would not interfere with other experiments: their location is shown in figure 6-1. Two of the sites were under manuka (*Leptospermum scoparium*) or manuka with bracken (*Pteridium esculentum*): two were under ungrazed long grass, and two

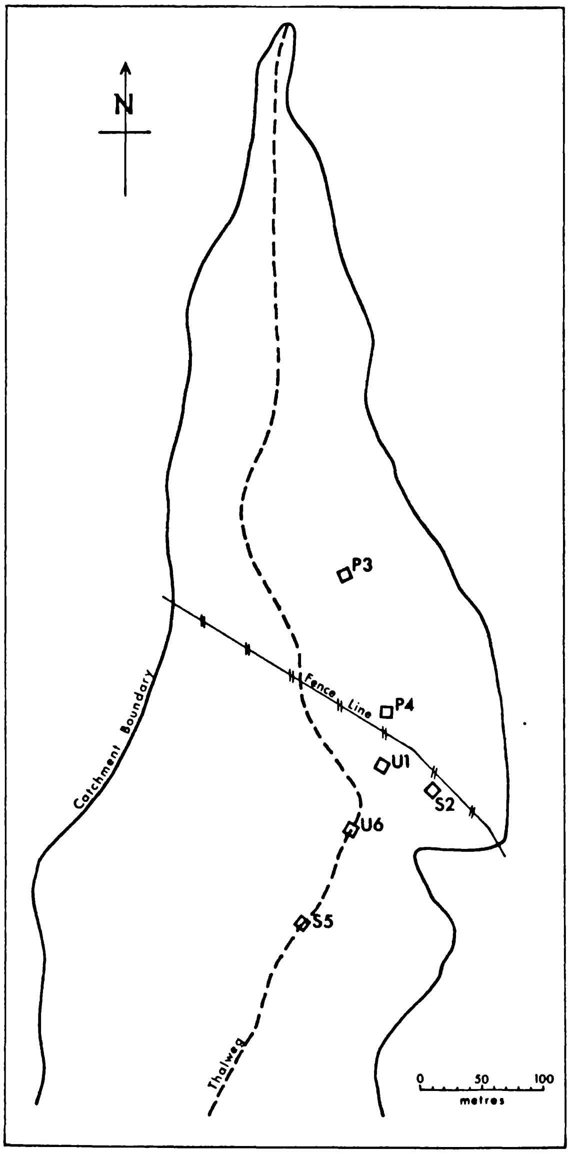


Fig. 6-1. The six sample sites for infiltration studies. P - pasture; U - ungrazed grass; S - scrub.

under pasture. The most common grasses in the ungrazed area were cocksfoot (Dactylis glomerata), Yorkshire fog (Holcus lanatus) and ryegrass (Lolium perenne). In the pasture the most important plants were white clover (Trifolium repens), suckling clover (T. dubium) and ryegrass. Each site, of about $4m^2$, was homogeneous within itself and flat. From each site 18 undisturbed samples were removed in steel boxes for infiltration measurements in the laboratory. The boxes are the larger of those used in the flume test (figure 7-2) - chapter 7. Of the 18 tests 6 were run at a slope of 0^o, 6 at 15^o and 6 at 30^o. Because many of the tests were carried out during the summer of 1969-70, which was exceptionally dry, one half of the samples were soaked in rainwater for two weeks and then allowed to drain freely for at least two days before infiltration measurements were carried out on them. This treatment gave samples with a wide range of pre-existing soil moistures.

Tests were carried out as indicated in the section 'Laboratory Use' of chapter 5. Each test lasted for one hour and a rate of precipitation was used which gave a small runoff from the plot. The tests showed that the infiltrometer gives remarkably smooth infiltration curves, but because it is very sensitive to even small variations in the head of water in the raindrop maker it is necessary for the operator to be constantly vigilant and to prevent variations in head by using the inlet tap as a regulator if necessary. The instrument is also very sensitive to blockage of the pinholes by dirt, and it was found to be necessary to filter all water used and to record the level of water in the reservoir at frequent intervals as a check on the precipitation rate. On the samples taken from the manuka and bracken scrub the outlet pipes were easily blocked by loose fragments of vegetation and the orifice had to be protected by a fine wire mesh. Each sample was examined before the tests and approximately 5 per cent were rejected, because cracks in the sample might have produced unnaturally high infiltration rates.

RESULTS

The results of the tests are summarised in figures 6-2, 6-3, 6-4 and 6-5. It is evident that infiltration rates are less, and have less variation, in the soils beneath pasture grasses than those beneath either the scrub or ungrazed grass, and that, in general, soils with high pre-existing soil moisture have a higher infiltration rate. The influence of slope angle does not appear to have been as important as might have been expected. In many of the tests a steady state was attained within ten minutes of starting the test, and there was a tendency for earlier attainment of steady state in the pasture plots. In area 6 beneath long ungrazed grass many of the plots showed a falling infiltration rate for about the first ten minutes and then a rising rate until steady state was attained at times ranging from 40 minutes to more than one hour.

Soil analysis

In an attempt to develop an understanding of the properties of the soil which influence infiltration soil samples were taken for laboratory analysis. Thirty core samples were taken from each of the six sample sites. Because the infiltration samples themselves could not be sampled without destroying their usefulness for infiltration studies the 30 samples were taken from 10 positions, chosen by a random method with a deck of cards and a quadrant frame, around the site from which the infiltration samples were taken.

STATISTICAL ANALYSIS

Statistical analyses were carried out in an attempt to provide answers to the following questions:-

1. Are the differences in mean infiltration under the three vegetation types statistically significant?
2. Do the soil properties differ significantly from one vegetation type to another?
3. To what soil properties is infiltration related?

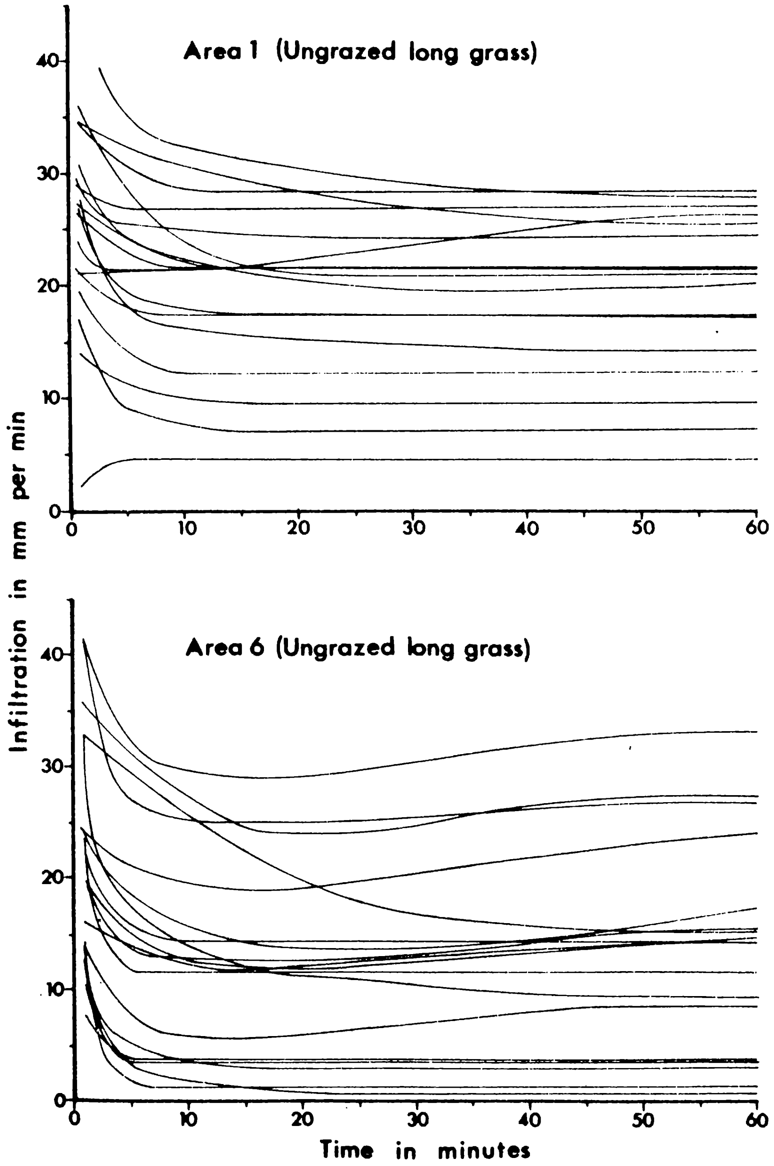


Fig. 6-2. Infiltration curves for two areas with ungrazed long grass.

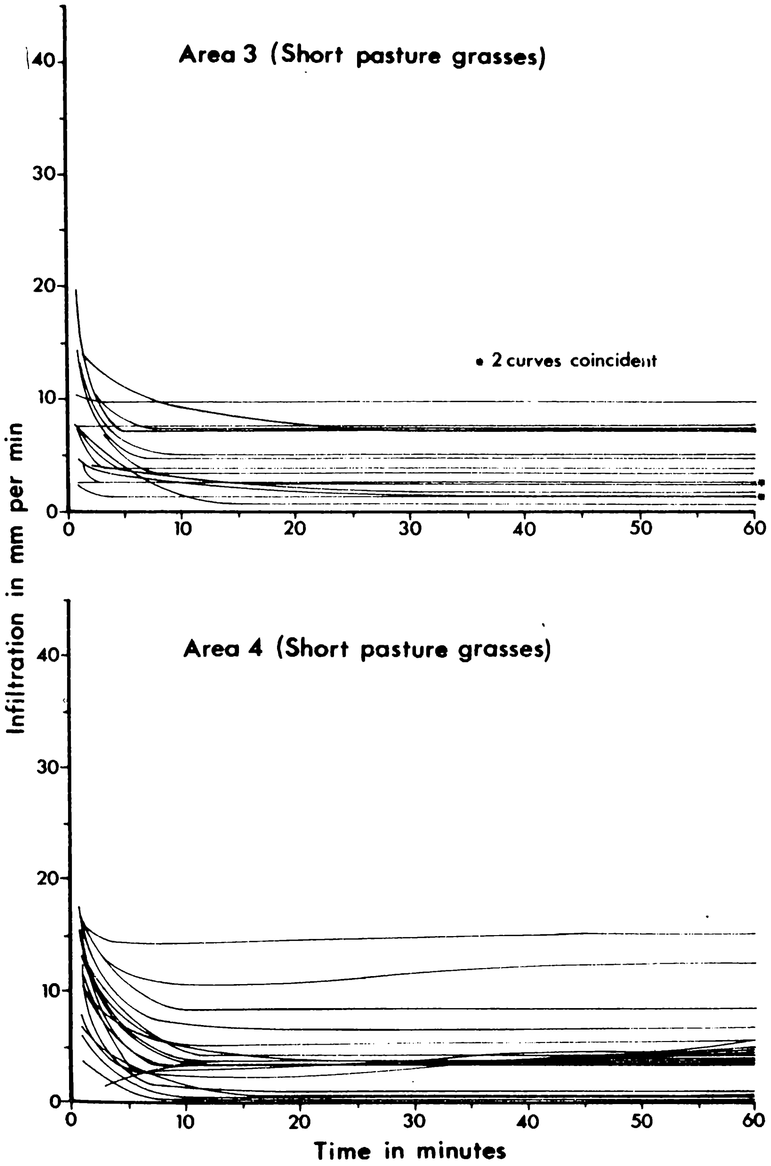
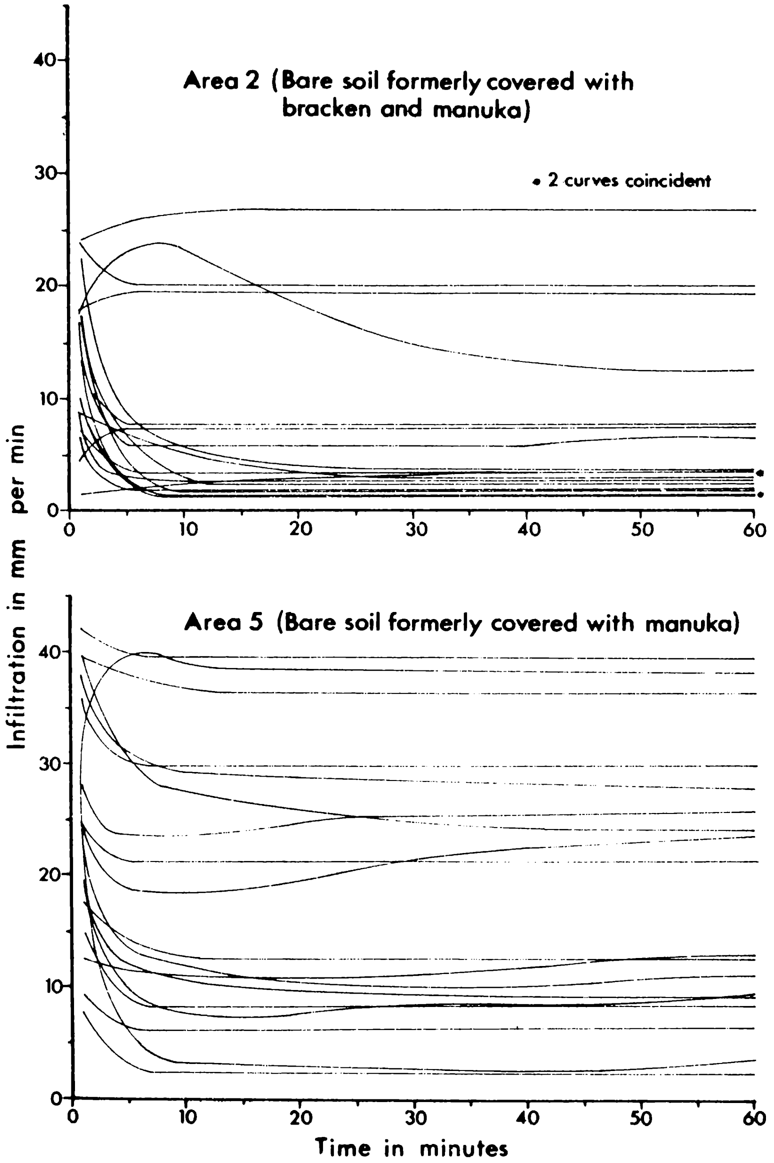


Fig. 6-3. Infiltration curves for two areas with short pasture grasses.



ig. 6-4. Infiltration curves for two areas with bare soil which was formerly covered with manuka scrub.

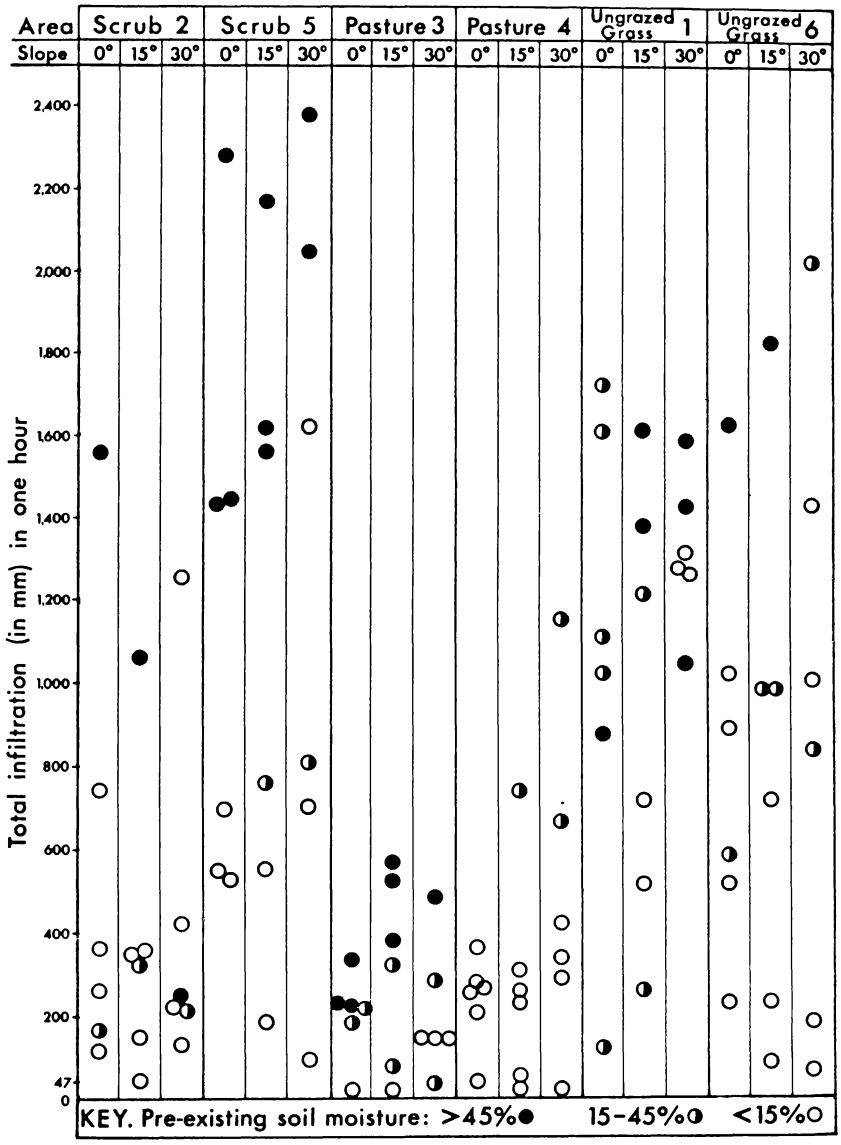


Fig. 6-5. The distribution of total infiltration in one hour under varying conditions of vegetation, slope and pre-existing soil moisture. The three classes of soil moisture are based upon a frequency distribution histogram of the pre-existing moisture.

4. Is it possible to provide a satisfactory prediction of infiltration rates by measuring easily determined soil properties?

In an attempt to answer these questions, analyses of variance, and linear regressions were carried out on the infiltration and soil variables. Details of soil analyses and explanation of the coding used in the statistical analyses are given in the appendix.

Analysis of Variance

The results of the analyses of variance of sample means are given in table 6-1. It can be seen that both infiltration and the various soil properties (with one exception) have significantly different sample means. Pre-existing soil moisture and angle of slope were experimentally controlled to give a range of values and their sample means therefore are of little consequence. Because vegetation length for scrub could not be obtained directly from measurement on the small sampled plots an index value based on dry weight equivalent had to be used. This also, then, invalidates any comparison of variance about the mean.

Correlation and stepwise multiple regression analysis

The simple linear correlations between all variables are given in table 6-2. It is evident that infiltration is not highly correlated with any single variable. Only pre-existing soil moisture (MOIS) and aggregation (AGG1, AGG2) stand out as being closely correlated with infiltration. This conclusion is reinforced by the stepwise multiple regression (table 6-3). Pre-existing soil moisture (MOIS) explains 18.8 percent of the infiltration and the addition of aggregation (AGG1) increases the explanation to 36.6 percent. The third variable root density (VEGS) increases the explanation to 51.9 percent but the addition of further variables adds little to our understanding and 8 variables provide only a 61 percent explanation. The best prediction equation which can be produced, with all variables contributing significantly, therefore has only a low level of explanation:

Table 6-1. Results of analysis of variance for infiltration and soil properties among three vegetation types.

Soil Properties		Pasture		Ungrazed Grass		Scrub		Overall Mean	F Value
		Mean	Sample Size	Mean	Sample Size	Mean	Sample Size		
Total of 108 Samples	INFL	289.72	36	1002.42	36	820.92	36	-	17.292***
	MOIS	22.52	36	22.00	36	26.08	36	-	0.429
	VEGN	4.28	36	12.92	36	(92.0)	-	-	-
	SLOP	(15)	3	(15)	3	(15)	3	-	-
	COMP	4594.25	36	4529.08	36	3024.50	36	-	12.237***
	SHER	32.241	36	37.432	36	12.578	36	-	88.106***
Properties of soils of each vegetation area	PTC1	4.2	20	4.8	20	2.8	20	3.93	4.768***
	PTC2	23.2	20	25.6	20	23.7	20	24.17	0.793
	PTC3	64.8	20	58.2	20	61.7	20	61.57	4.521**
	PTC4	7.8	20	11.0	20	11.8	20	10.20	7.722***
	AGG1	25.6	20	22.6	20	15.6	20	21.27	4.402**
	AGG2	34.5	20	32.1	20	21.1	20	29.23	5.709***
	ORG1	14.8	20	18.4	20	12.5	20	15.23	4.145**
	ORG2	14.6	20	16.4	20	11.4	20	14.13	4.300**
	VEGS	2.2	20	3.4	20	1.0	20	2.20	14.212***
	BULK	0.74	20	0.66	20	0.62	20	0.67	6.175***
	PART	2.18	20	2.09	20	2.01	20	2.09	4.277**
	PORO	66.4	20	68.4	20	69.1	20	67.97	2.600*
	MAC1	4.4	20	4.3	20	6.8	20	5.17	10.227***
	MAC2	6.8	20	6.6	20	10.0	20	7.80	8.957***

Confidence levels α=0.10(*), α=0.05(**), α=0.01(***)

N.B. Values for VEGN for scrub areas are an index. Values for MOIS and SLOP are manipulated to give a range.

Table 6-2. Matrix of simple linear correlation coefficients between infiltration and properties of yellow-brown pumice soils.

Dependent Variable		INFL	MOIS	VEGN	SLOP	COMP	SHER	PTC1	PTC2	PTC3	PTC4	AGG1	AGG2	ORG1	ORG2	VEGS	BULK	PART	PORO	MAC1	MAC2
Independent Variables	INFL	-	.433	.184	.058	-.165	-.035	.091	.158	-.328	.243	-.359	-.341	.004	-.075	.182	-.124	.089	.223	-.102	-.119
	MOIS	.433	-	.103	-.111	-.652	.189	.007	-.346	.137	.213	.137	.068	-.030	.082	.035	-.320	-.117	.410	.245	.219
	VEGN	.184	.103	-	-.000	-.439	-.753	-.833	-.131	-.004	.587	-.688	-.769	-.540	-.737	-.662	-.496	-.482	.407	.696	.694
	SLOP	.058	-.111	-.000	-	.119	-.042	-.000	-.000	-.000	-.000	-.000	-.000	-.000	-.000	-.000	-.000	-.000	-.000	-.000	-.000
	COMP	-.165	-.652	-.439	.119	-	.027	.289	.301	-.043	-.472	.036	.106	.086	.098	.294	.536	.428	-.525	-.553	-.534
	SHER	-.035	.189	-.753	-.042	.027	-	.797	-.075	-.104	-.138	.714	.755	.614	.827	.648	.014	.171	.107	-.350	-.369
	PTC1	.091	.007	-.833	-.000	.289	.797	-	.306	-.392	-.259	.503	.620	.781	.846	.638	.231	.414	-.060	-.658	-.684
	PTC2	.158	-.346	-.131	-.000	.301	-.075	.306	-	-.781	-.148	-.424	-.217	.472	.063	-.134	.428	.234	-.499	-.549	-.533
	PTC3	-.328	.137	-.004	-.000	-.043	-.104	-.392	-.781	-	-.424	.255	.076	-.697	-.346	-.049	.170	.195	-.105	.190	.192
	PTC4	.243	.213	.587	-.000	-.472	-.138	-.259	-.148	-.424	-	-.097	-.124	.168	.073	-.131	-.939	-.845	.830	.746	.735
	AGG1	-.359	.137	-.688	-.000	.036	.714	.503	-.424	.255	-.097	-	.976	.470	.792	.439	-.150	-.153	.152	.035	.029
	AGG2	-.341	.068	.769	-.000	.106	.755	.620	-.217	.076	-.124	.976	-	.628	.876	.447	-.073	-.117	.059	-.089	-.091
	ORG1	.004	-.030	.540	-.000	-.086	.614	.781	.472	-.697	.168	.470	.628	-	.877	.252	-.135	-.138	.122	-.247	-.261
	ORG2	-.075	.082	-.737	-.000	.098	.827	.846	.063	-.346	.073	.792	.876	.877	-	.551	-.168	-.086	.212	-.220	-.236
	VEGS	.182	.035	-.662	-.000	.294	.648	.638	-.134	-.049	-.131	.439	.447	.252	.551	-	.108	.293	.016	-.472	-.472
	BULK	-.124	-.320	-.496	.000	.536	.014	.231	.428	.170	-.939	-.150	-.073	-.135	-.168	.108	-	.848	-.932	-.841	-.820
	PART	.089	-.117	-.482	.000	.428	.171	.414	.234	.195	-.845	-.153	-.117	-.138	-.086	.293	.848	-	-.601	-.865	-.879
	PORO	.223	.410	.407	-.000	-.525	.107	-.060	-.499	-.105	.830	.152	.059	.122	.212	.016	-.932	-.601	-	.690	.648
	MAC1	-.102	.245	.696	-.000	-.553	-.350	-.658	-.549	.190	.746	.035	-.089	-.247	-.220	-.472	-.841	-.865	.690	-	.997
	MAC2	-.119	.219	.694	.000	-.534	-.369	-.684	-.533	.192	.735	.029	-.091	-.261	-.236	-.472	-.820	-.879	.648	.997	-

Significance levels: $\alpha=0.10$, $r=.344$; $\alpha=0.05$, $r=.404$; $\alpha=0.01$, $r=.515$

Table 6-3. Results of stepwise multiple regression, with infiltration as the dependent variable.

Independent Variable	Step Number	R^2	Beta Coefficient
MOIS	1	.188	0.6149***
AGG1	2	.366	-1.1605***
VEGS	3	.519	0.1565
ORG2	4	.575	-
SLOP	5	.588	0.1011
SHER	6	.596	-0.0576
COMP	7	.601	0.1906*
BULK	8	.610	-0.6422***

F value: 19.38*** R^2: .610

Confidence level, t,, α=0.10*,
α=0.05**, α=0.01***

$$\text{Predicted INFL} = 557.36 + 15.44\,(\text{MOIS}) - 938.88\,(\text{AGG1}) + 172.17\,(\text{VEGS}) + 99.07\,(\text{ORG2})$$

with $\underline{F}$: 34.83*** and R^2 : .575

CONCLUSIONS

The range of infiltration rates on all yellow-brown pumice soils from Otutira is large, but there is a highly significant greater mean infiltration under scrub than under pasture grass vegetation. Ungrazed grass samples showed an even higher mean infiltration than scrub but lower extreme values. This suggests that the change of vegetation alone is not responsible for decreasing infiltration but that it is land use practices which are most important. The soil property which pastoral farming might be expected to modify most readily is soil compaction. Compaction is shown in table 6-2 to be negatively correlated at a high level of significance with total porosity (-.525) and macroporosity (-.553 and -.534) indicating that as compaction increases porosity decreases. It may reasonably be concluded therefore that the change of land use from scrub to pastoral farming has decreased infiltration rates.

The sampling and measurements required to calculate infiltration rates and curves are tedious and time consuming. Analysis of soil properties is evidently not a short-cut to direct measurement because of the low degree of explanation achieved. It is evident that the yellow-brown pumice soils of the Otutira catchment are exceedinly heterogeneous in their properties, as might be expected of soils derived from coarse pumice and ash deposits which have had relatively little time in which to weather. The great range of infiltration rates in a small area, even with the same vegetation suggests that prediction of runoff from infiltration alone is unlikely to be reliable. It would seem, therefore, that predictions should be made from catchment runoff analysis into which the infiltration variations are naturally integrated.

It appears that, because of the very variable nature of the infiltration, water running off one small area is likely to infiltrate into another area of the soil and that much runoff is not to be expected from a drainage basin. In figure 6-5 only 8 of the 108 test plots are shown to be incapable of absorbing a rainfall of 47mm/h. This figure is the maximum rainfall intensity to be expected at Taupo, the nearest meteorological station with long records, in a 50 year period (Robertson, 1963). A tentative conclusion may be that high runoff, and with it the liability to rapid erosion, is likely to be associated only with very high intensity rainfalls, especially when they fall on pastures of low pre-existing soil moisture.

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CHAPTER 7

A FLUME FOR TESTING THE RELATIVE ERODIBILITY OF SOILS AND SEDIMENTS

The erodibility of soils and sediments may be assessed either by isolation of certain soil properties as indices of erodibility, or by direct measurement of erosion under known conditions. The first or indirect method has been attempted most commonly because it is most easily carried out, as indices are normally derived from soil analytical data and require little special equipment.

Indices of erodibility

The initial work on soil erodibility was carried out by Bennett (1926) who was impressed by the apparent direct relationship between erosion and the silica to sesquioxide ratio in the lateritic soils of Cuba. Middleton (1930) devised indices of erodibility which were essentially measures of soil aggregation or soil properties affecting aggregation. Bouyoucos (1935) attempted to define the dispersion properties of soil in terms of the clay ratio or binding properties of the soil. Many other workers followed the lead of Middleton and Bouyoucos in their studies of dispersion and aggregation, and the most important studies have been reviewed by Bryan (1968-69). Other studies used dispersion and water transmission as the main indices (Middleton, 1930; Baver, 1933; Lutz, 1934; Voznesensky and Artsruui, 1940). Nearly all of these indices were developed for applications to bare or cultivated soils. After a critical examination and comparison of these indices, using 90 samples from 36 profiles from the Peak District, England, Bryan (1968-69) concluded that none of the proposed indices conform to the requirements for such an index: that it be simple to measure, reliable in operation and capable of universal application.

Direct measurements

By far the most common type of direct measurement of erosion is runoff plot studies. These have the disadvantage of being costly and time consuming. Such studies are also most useful on soils from which there is a high sediment yield which is caused by sheet erosion. Runoff plot studies have been reviewed by Hayward (1968, 1969), and the conclusions derived from them by Smith and Wischmeier, (1962) and Selby (1970a).

Pumice Soils

Development of an index of the erodibility of yellow-brown pumice soils has to overcome two problems. Firstly sediment yield from pumice soils with a good vegetation cover, which nearly all such soils in New Zealand have, is virtually nil. Secondly the dominant type of erosion is not sheet erosion but gully formation. Accordingly a flume has been devised which will simulate gully erosion of soils. Details of the flume have been published (Selby, 1970b).

THE FLUME

The flume consists of four main components, shown in figure 7-1 as A, B, C, D, a reservoir and a collecting basket for sediments. Details of the construction are shown in figure 7-2. Each of the components A, B, C, D is fabricated from 2mm thick galvanised sheet steel. Box A has a removable bottom and removable sliding lid, and half of one end is open. Box D is smaller and one end is completely open; it too has a sliding lid. The box B is designed to fit on the upper rim of A when the sliding lid of A is removed. It has two plates which fit inside A between the side of the box and the soil sample. The bottom of B is angled at 5° (see figure 7-1). The stilling box C has four inlets for water at the back and a baffle plate to reduce turbulence. The water flows down the inclined chute. The reservoir used in the experiments so far is a 4,500 litre tank with four 25.4mm diameter gate valves at the bottom. Pipes from the valves lead into the stilling tank. The reservoir may be fitted with ball-

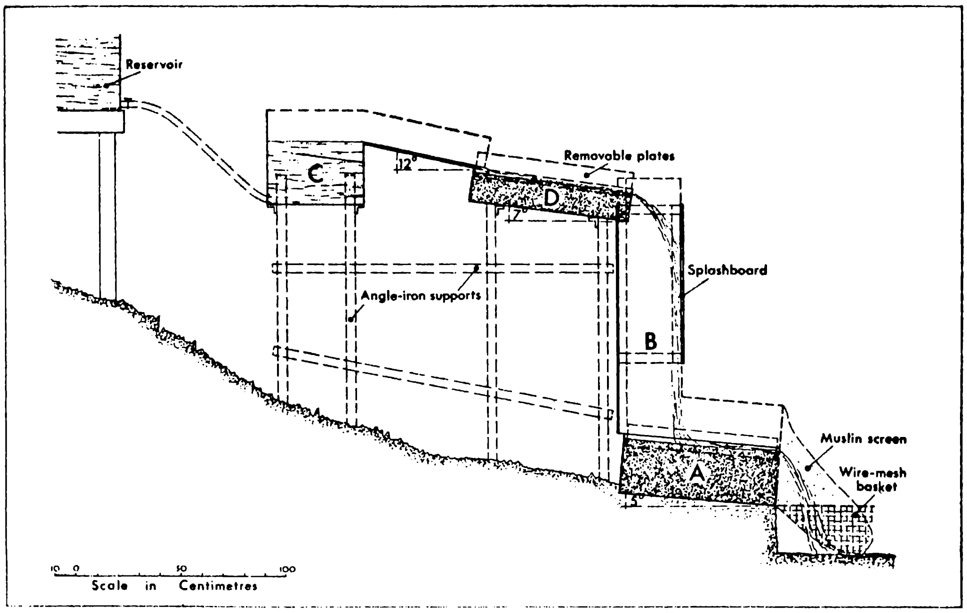
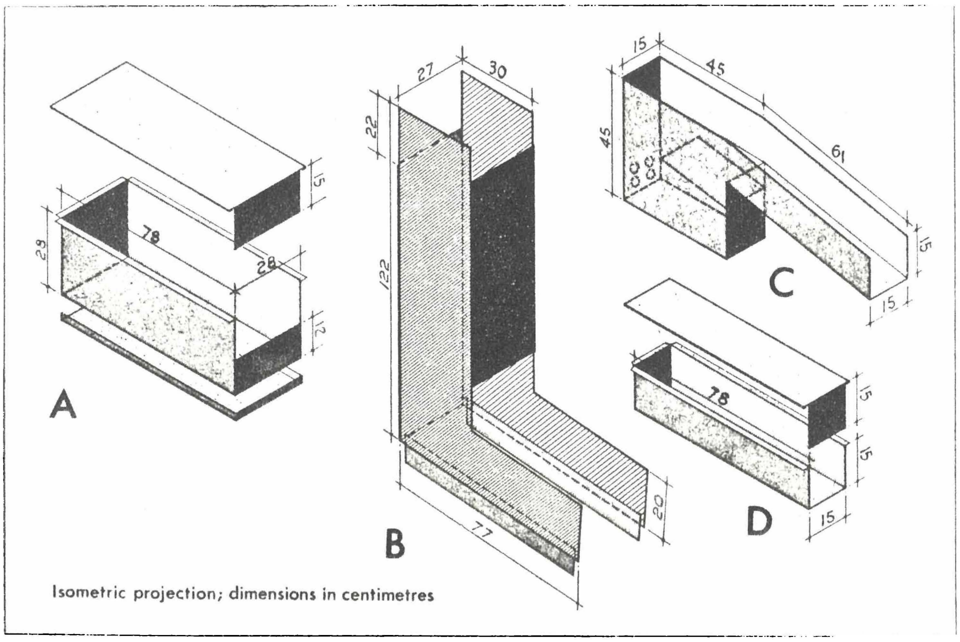


Fig. 7-1. The assembled components of the flume.



Isometric projection; dimensions in centimetres

Fig. 7-2. Details of construction of components of the flume.

cocks at the inlet so that it can be kept full during the experiments. The sediment trap is a stainless steel wire-mesh basket with a mesh of 100μ which contains a linen or muslin bag in which sediment is trapped. The flume may be assembled in a laboratory or in the open. The assembled units are shown in figure 7-1, supported by a slotted angle-iron frame. A larger tank (22,500 litres) is used to keep a constant head in the reservoir.

Sample collection

To collect soil or sediment samples box A is placed on the ground with the bottom removed. A trench is then dug round the box and the box eased downwards as soil is cut away from its edge with a flexible long-bladed knife. It is important not to deform the box or shake the sample by hitting it. When the sample surface is just below the rim of the box the soil beneath the box is dug away and the lid and bottom slid on. The weight of a full box may be about 100kg. To fill box D the lid is removed, the box is placed on the soil, a trench dug around it and the box then pushed horizontally into the resulting 'slice' of soil as the spare soil is cut away with a knife. The sliding lid is then replaced.

Tests

For running a test the boxes of soil are placed in the frame and the sliding lids removed. The box B acts as a wind shield and as a deflector to keep the water falling onto the same part of the sample in A -- as would happen in a waterfall in nature --, and to make it fall as a sheet rather than a column of water. Removable plates are then fitted to the rim of box D to prevent loss by splashing. Box D has a slope of 7° and box A one of 5° as these are slopes commonly occurring respectively above and below the heads of gullies in the areas of pumice gully erosion which are being investigated. The angle of 12° on the chute provides sufficient velocity for scour to occur on the surface of the sample in D. The reservoir has four outlets which thus provide four set discharges, and measurements of discharge are therefore not necessary once

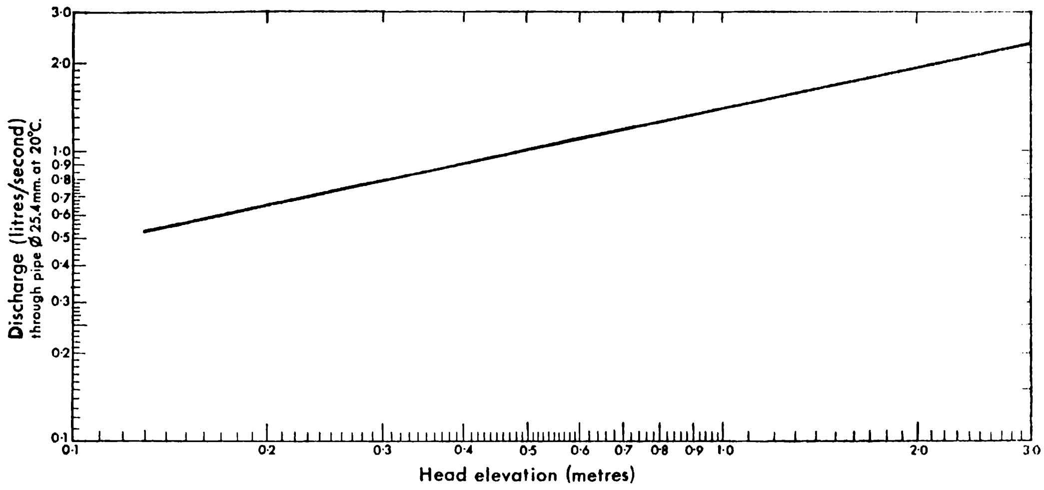


Fig. 7-3 Discharge from one 25.4mm diameter outlet pipe for various heads.

the discharge from the tank has been calculated. The discharge occurring at one outlet for different heads is shown in figure 7-3. It is desirable to keep a constant head because a 4,500 litre tank with four valves open and a head of 2m will only discharge for 18 minutes, which is not long enough to significantly erode a soil sample bonded by grass roots.

The test gives measures of channel erosion and lip erosion on A and D and plunge-pool erosion on A. The total weight of sediment removed is measured.

When samples are collected it is necessary to take core samples alongside the box samples because the box samples are destroyed in the test, and analyses of their physical properties cannot then be made.

Preliminary tests show that the flume can be used on a wide range of soils, with textures varying from clays to fine gravels, and from pastures and forests. Fluvial, and colluvial deposits can also be studied. The information gained can be extended in the field by determining the value of soil characteristics which are shown, by correlation analysis, to have a high significance for erosion.

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CHAPTER 8

FLUME TESTS ON OTUTIRA SOILS

From the same six areas used for the infiltration studies four pairs of samples were taken in the steel sample boxes described in chapter 7. In each pair one box was large and one was small. The samples were either air dried, or soaked for two weeks and then left to reach field capacity or a drier state, according to a random choice so that there was a wide range of contained moisture values obtained from the samples. So that the scrub samples could be fitted into the flume the vegetation had to be cut off these samples. For purposes of analysis however an index length of 92cm (obtained by averaging the length of vegetation naturally occurring) was used. Immediately before each test the following measurements were made on each sample: vegetation length, compaction, shearing resistance, soil moisture.

Each sample was then run in the flume, for 20 minutes, at a constant discharge of 7.2 litres/s. The sediment was collected in the trap, dried, weighed and then sieved into 4 fractions:

(1) Organic matter > 0.635mm, as a percentage weight of the eroded material
(2) Mineral matter > 0.635mm, as a percentage weight of the eroded material
(3) Organic matter < 0.635mm, as a percentage weight of the eroded material
(4) Mineral matter < 0.635mm, as a percentage weight of the eroded material.

Immediately after each 20 minute run a cylindrical cutter was pushed into the soil beneath the waterfall and all soil to a depth of 10cm was removed. The hole that remained simulated a post-hole or any other hole from which the topsoil and root matter had been removed; this had the effect of exposing the B horizon material. The intention of making such a hole was to gauge the effect on erosion of interfering with the vegetation and topsoil.

The flume was then allowed to run for a further 10 minutes at the same discharge. The sediment was again collected, dried, weighed and sieved into four fractions as before. This procedure gave 8 20 minute tests on the topsoil of each of the three vegetation types and 8 tests of 10 minutes on the subsoil of each vegetation type. The length of the tests was controlled by the water available but 20 and 10 minute runs were found to be satisfactory.

A typical test is shown in figure 8-1. A scrub sample is shown in figure 8-2 and the results of a 20 minute run are shown in figures 8-3 and 8-4. It can be seen that considerable lip erosion has occurred on the edge of the upper sample, but that the lower sample is mainly affected by plunge-pool erosion which has washed much of the soil out of the pool and left only a network of roots. Surface wash has removed loose litter from the soil surface but lip erosion is slight. Thirty soil samples for correlation analysis were taken by corer from each of the vegetation areas. The samples were located by a random method using a deck of cards and a quadrat frame divided into $10cm^2$ units. Analysis of the thirty samples gave 10 values for each soil property. The methods used are described in the appendix.

STATISTICAL ANALYSIS

Statistical analysis was carried out in an attempt to answer the following questions:

(1) Are there significant differences in the amounts of sediment eroded from the samples taken from the three vegetation types?

(2) Are there significant differences in the properties of the soils of the 6 areas?

(3) To what extent are the fractions of the eroded sediments related to each other and to the soil properties?

(4) Which of the measured soil properties contribute to the erodibility of the soil and to what extent?

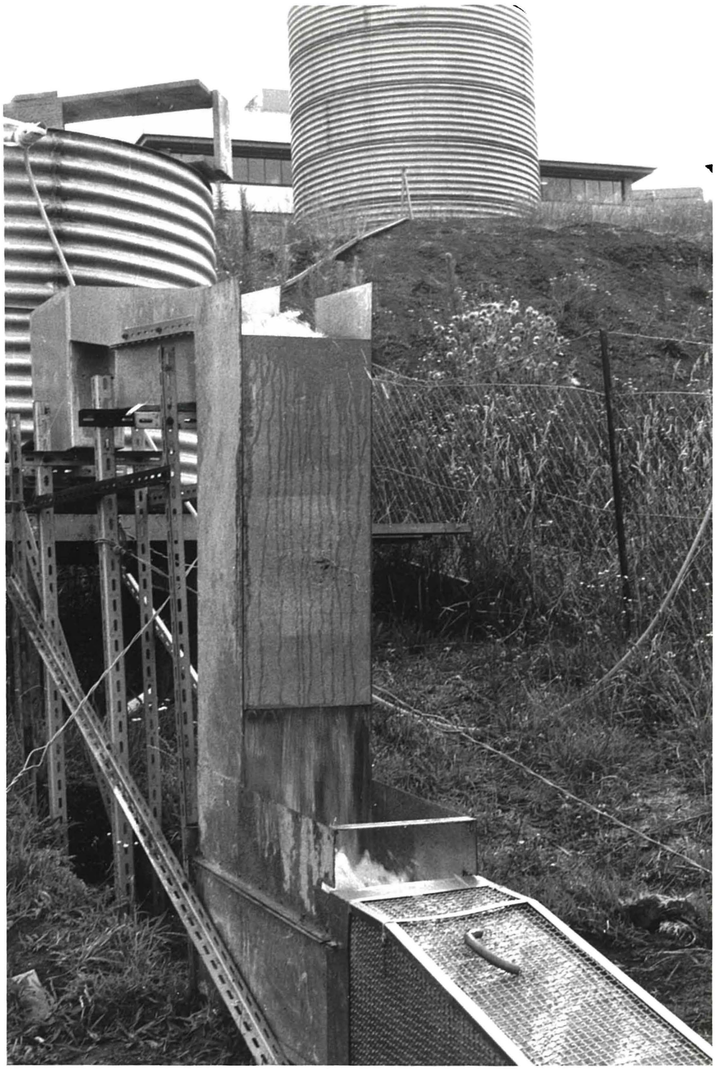

Fig. 8-1. The flume during a test run.

Fig. 8-2. A scrub sample in a large sample box before a flume test.

Fig. 8-3. A scrub sample after a test. The root system has been exposed by the erosion of the soil beneath the waterfall.

Fig. 8-4. Lip erosion on a scrub sample in the upper sample box.

Analysis of variance

Analysis of variance was first carried out on the sediments eroded from the 8 samples taken from each of the 3 vegetation types. The results are given in table 8-1. It is shown that for all 4 fractions in the sediment from the 20 minute tests there were highly significant differences between the three vegetation types. For the total sediment on this 20 minute test the differences have a very high level of significance. In the 10 minute tests the water in the flume was falling into the hole bored into the large soil block and therefore hitting the soil below a level at which the vegetation - and man and animals - create the greatest differences in the soil properties. The differences in the properties of the sediments from the B horizons thus have differences with little statistical significance.

When the weights of sediments from the 20 and 10 minute runs are added together the differences between the yield from the 3 vegetation groups still has a high significance.

The sediment yields have been plotted on the histograms shown in figure 8-5. This figure shows that for the 20 minute runs there is a wide range in yield and this is reflected in the high standard deviation ($\underline{s}$). The scrub samples yielded the greatest quantities of sediment, and scrub yields are always around or above the mean values ($\underline{\bar{X}}$) for all sediments combined. The pasture and ungrazed grass samples yielded less sediment, and the pasture area values were generally lower than those of the ungrazed grass. Observations made during the flume tests suggested that the lower compaction of the scrub and ungrazed grass samples and the less dense root mat in the scrub samples partly accounted for this distribution.

The 10 minute runs showed a slightly different pattern. Scrub values are still generally high but the differences between the three areas are less and the standard deviation is lower. This reinforces the conclusion, already drawn, that vegetation, man and animals have less influence on the

Table 8-1. Results of analysis of variance for sediment fractions from three vegetation types (eight observations for each vegetation type).

Test (min)	Sediment Fraction (mm)	Pasture Mean(g)	Ungrazed Grass Mean (g)	Scrub Mean(g)	Overall Mean(g)	F value
20	>0.635 Organic	6.60	18.52	79.87	35.00	12.974***
20	>0.635 Mineral	34.34	35.30	212.08	93.91	11.861***
20	<0.635 Organic	7.40	20.02	68.75	32.06	14.759***
20	<0.635 Mineral	47.59	42.41	239.33	109.78	12.119***
10	>0.635 Organic	2.45	4.25	5.68	4.13	3.134*
10	>0.635 Mineral	120.49	64.07	84.83	89.80	0.526
10	<0.635 Organic	12.10	10.80	18.89	13.93	3.390*
10	<0.635 Mineral	100.19	66.62	119.05	95.29	0.787
20+10	>0.635 Mineral	9.05	22.76	85.54	39.12	13.093***
20+10	>0.635 Organic	154.82	99.36	296.90	183.69	3.205*
20+10	<0.635 Mineral	19.50	30.82	87.64	45.99	13.700***
20+10	<0.635 Organic	147.78	109.04	358.37	205.06	6.017***
20	All Sediments	95.94	116.25	600.00	270.73	15.591***
10	All Sediments	235.19	145.82	228.38	203.38	0.612
20+10	All Sediments	331.12	262.08	828.37	473.86	6.980***

Significance Levels: $\alpha=0.10$ Symbol*, $\alpha=0.05$ Symbol**, $\alpha=0.01$ Symbol***

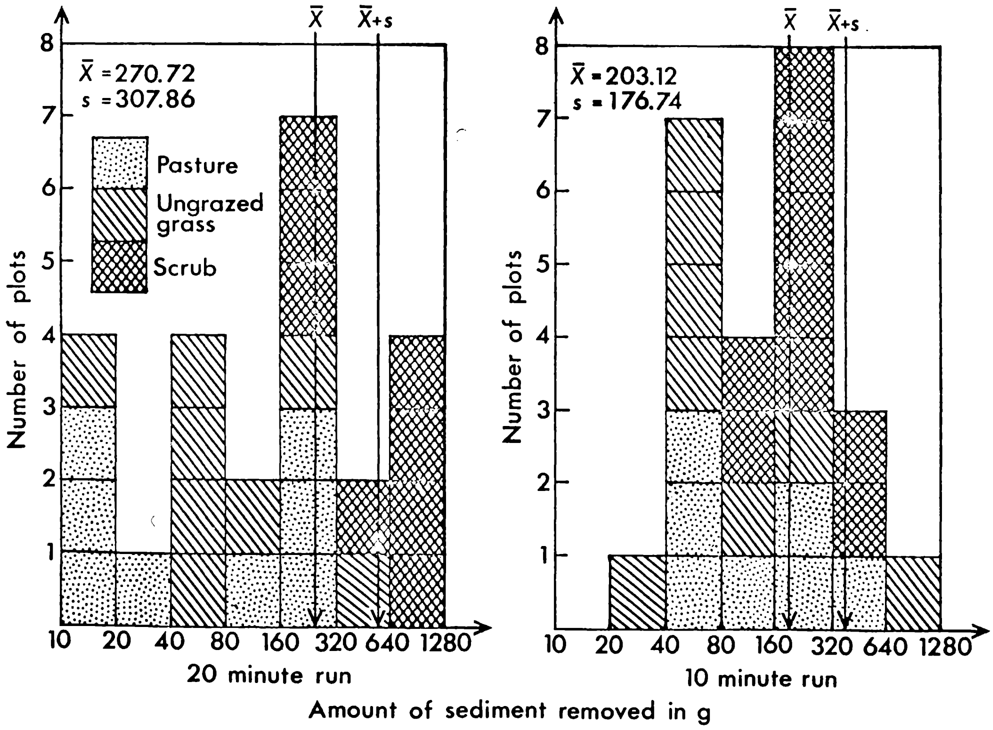

Fig. 8-5. Histograms showing sediment removed in each test.

B than the A horizons of the soils.

Differences between the soils of the 6 areas studied are reflected not only in their erodibility but in virtually all their measured properties. Analysis of variance of the properties has yielded the results summarised in table 8-2. Variance amongst the vegetation types could not be measured because of the index value used for the scrub samples. Soil moisture was artificially manipulated to give a spread of values but all other soil properties except the coarse sand fraction (PTC2) and the total porosity (PORO) were found to have a significant or highly significant difference. The soils are therefore not homogeneous and their properties must always be measured when research related to them is being carried out.

All of the analyses outlined above were also carried out for the 6 areas treated individually rather than grouped into 3 vegetation types. The results are so similar to those for the 3 groups that they are not described here.

Correlation analysis

Analysis to produce the simple linear correlation coefficient of one sediment fraction against each of the others yielded the data for a correlation matrix (table 8-3). As would be expected the correlations between the fractions eroded in the 20 minute test are all high. This indicates that the erosion process simulated in the flume is not a selective one and therefore in this characteristic at least the flume experiment does faithfully simulate gully erosion. The 10 minute test showed lower correlations and some inverse correlations indicating that the flume was less successful in simulating scouring of a ready made hole, but the combined values for the 20 + 10 minute runs still gave good correlations.

Correlations among soil properties and sediment fractions (table 8-4) show that high correlations occur only between sediments produced in the 20 minute tests and the soils. This is clearly because the properties of the B horizon, which was eroded in the 10 minute test, are not

Table 8-2. Results of analysis of variance for soil properties among three vegetation types.

Soil Properties		Pasture		Ungrazed Grass		Scrub		Overall Mean	F Value
		Mean	Sample Size	Mean	Sample Size	Mean	Sample Size		
Total of 24 Samples	VEGN	6.38	8	16.88	8	(92.0)	1	38.42	-
	COMP	5856.5	8	5598.1	8	3531.2	8	4995.3	4.800**
	SHER	53.37	8	47.22	8	24.74	8	41.78	6.167***
	MOIS	28.84	8	30.21	8	36.94	8	32.00	0.583
Properties of soils of each area	PTC1	4.2	20	4.8	20	2.8	20	3.93	4.768**
	PTC2	23.2	20	25.6	20	23.7	20	24.17	0.793
	PTC3	64.8	20	58.2	20	61.7	20	61.57	4.521**
	PTC4	7.8	20	11.0	20	11.8	20	10.20	7.722***
	AGG1	25.6	20	22.6	20	15.6	20	21.27	4.402**
	AGG2	34.5	20	32.1	20	21.1	20	29.23	5.709***
	ORG1	14.8	20	18.4	20	12.5	20	15.23	4.145**
	ORG2	14.6	20	16.4	20	11.4	20	14.13	4.300**
	VEGS	2.2	20	3.4	20	1.0	20	2.20	14.212***
	BULK	0.74	20	0.66	20	0.62	20	0.67	6.175***
	PART	2.18	20	2.09	20	2.01	20	2.09	4.277**
	PORO	66.4	20	68.4	20	69.1	20	67.97	2.600*
	MAC1	4.4	20	4.3	20	6.8	20	5.17	10.227***
	MAC2	6.8	20	6.6	20	10.0	20	7.80	8.957***

Critical F values α=0.10 Symbol*, α=0.05 Symbol**, α=0.01 Symbol***

N.B. Values of VEGN for scrub areas are an index.

Table 8-3. Matrix of simple linear correlation coefficients between sediment fractions.

Particle size variation from 0.635mm diam		20 min test				10 min test				20+10 min tests				20 min	10 min	20+10 min
		>O	>M	<O	<M	>O	>M	<O	<M	>O	>M	<O	<M	Totals all Sediments		
20 min test	>O	-	.798	.827	.863	.531	-.014	.381	.237	.999	.524	.792	.702	.901	.128	.735
	>M	.798	-	.872	.840	.207	.207	.578	.431	.784	.795	.866	.774	.944	.359	.868
	<O	.827	.872	-	.945	.306	.189	.646	.474	.818	.699	.990	.866	.958	.373	.885
	<M	.863	.840	.945	-	.267	.232	.593	.513	.850	.704	.933	.922	.967	.415	.910
10 min test	>O	.531	.207	.306	.267	-	-.237	-.017	-.214	.575	-.008	.255	.087	.301	-.235	.126
	>M	-.014	.207	.189	.232	-.237	-	.354	.597	-.028	.758	.229	.430	.195	.911	.542
	<O	.381	.578	.646	.593	-.071	.354	-	.848	.363	.605	.745	.792	.595	.661	.736
	<M	.237	.431	.474	.513	-.214	.597	.848	-	.215	.658	.568	.806	.466	.874	.731
20+10 min tests	>O	.999	.784	.818	.850	.575	-.028	.363	.215	-	.505	.780	.684	.889	.109	.718
	>M	.524	.795	.699	.704	-.008	.758	.605	.658	.505	-	.720	.783	.750	.804	.915
	<O	.792	.866	.990	.933	.255	.229	.745	.568	.780	.720	-	.900	.944	.446	.906
	<M	.702	.774	.866	.922	.087	.430	.792	.806	.684	.783	.900	-	.878	.682	.958
20 min	Totals all Sediments	.901	.944	.958	.967	.301	.195	.596	.466	.889	.750	.944	.878	-	.370	.915
10 min		.128	.359	.373	.415	-.235	.911	.661	.874	.109	.804	.446	.682	.370	-	.713
20+10 min		.735	.868	.885	.910	.126	.542	.736	.731	.718	.915	.906	.958	.915	.713	-

O = Organic, M = Mineral

Significance levels: α=0.10, r=±.344; α=0.05, r=±.404; α0.01- r=±.515.

Table 8-4. Matrix of simple linear correlation coefficients between soil properties and sediment fractions.

Particle size variation from 0.635mm diam.		20 min test				10 min test				20+10 min test				20 min	10 min	20+10 min
		>O	>M	<O	<M	>O	>M	<O	<M	>O	>M	<O	< M	Totals all sediments		
Soil Properties	VEGN	.740	.717	.749	.716	.440	-.056	.457	.165	.742	.444	.737	.569	.763	.069	.606
	COMP	-.362	-.423	-.483	-.424	.037	.121	-.492	-.290	-.347	-.207	-.511	-.424	-.445	-.083	-.372
	SHER	-.566	-.612	-.710	-.680	-.134	-.243	-.592	-.551	-.555	-.559	-.728	-.718	-.678	-.438	-.702
	MOIS	.168	.061	.280	.209	.128	-.208	.259	.113	.170	-.088	.291	.195	.166	-.062	.099
	PTC1	-.770	-.779	-.697	-.763	-.345	-.097	-.407	-.290	-.765	-.580	-.682	-.658	-.804	-.219	-.702
	PTC2	-.117	-.015	.067	.013	-.073	.418	.223	.372	-.118	.249	.099	.177	-.010	.442	.184
	PTC3	-.039	-.013	-.178	-.008	-.148	-.020	-.133	-.057	-.047	-.021	-.180	-.031	-.035	-.047	-.047
	PTC4	.613	.451	.570	.397	.501	-.439	.163	-.219	.623	-.029	.527	.175	.490	-.360	.214
	AGG1	-.303	-.392	-.432	-.448	-.160	-.275	-.398	-.370	-.303	-.432	-.450	-.476	-.428	-.364	-.481
	AGG2	-.352	-.426	-.447	-.480	-.184	-.205	-.377	-.317	-.351	-.411	-.459	-.474	-.463	-.295	-.477
	ORG1	-.305	-.352	-.232	-.376	-.081	-.115	-.133	-.174	-.300	-.306	-.226	-.340	-.362	-.160	-.342
	ORG2	-.444	-.533	-.461	-.571	-.150	-.272	-.374	-.379	-.438	-.524	-.470	-.565	-.557	-.365	-.579
	VEGS	-.524	-.605	-.595	-.615	-.166	-.211	-.567	-.380	-.517	-.534	-.622	-.596	-.629	-.336	-.621
	BULK	-.532	-.355	-.447	-.295	-.439	.548	-.072	.342	-.541	.103	-.403	-.049	-.385	.490	-.078
	PART	-.769	-.622	-.660	-.535	-.496	.309	-.218	.086	-.773	-.224	-.616	-.331	-.645	.214	-.395
	PORO	.272	.106	.217	.075	.315	-.620	-.038	-.460	.282	-.314	.183	-.156	.135	-.597	-.157
	MAC1	.762	.641	.644	.581	.452	-.351	.253	-.110	.764	.210	.608	.351	.668	-.251	.396
	MAC2	.791	.672	.667	.608	.462	-.324	.261	-.083	.793	.247	.630	.382	.698	-.221	.431

Significance levels: $\alpha=0.10$, $r=\pm.344$; $\alpha=0.05$, $r=\pm.404$; $\alpha=0.01$, $r=\pm.515$.

reflected in the soil analyses which sampled only the upper 10cm of the soil profile. The relationships indicated in the matrix of table 8-4 will be discussed below.

Stepwise multiple Regression

Multiple regression provides the obvious technique for seeking explanation of the erosion in terms of soil properties but its formulation initiates a number of problems: (1) soil properties were not measured on each sample used in the flume; (2) there would be 18 independent variables in the analysis, which is too many for a realistic regression equation, especially when only 24 samples were used; (3) the variables should be independent, but table 3 indicates that many are closely correlated. To reduce the number of independent variables a stepwise multiple linear regression routine was used.

Stepwise regressions were produced for each of the sediment fractions for the 20 minute and 10 minute flume tests, for the combined 20 and 10 minute tests and for the totals of the 20, 10 and combined 20 and 10 minute tests with the sediment as the dependent variables and all soil properties as independent variables.

Table 8-5 shows that high levels of explanation of the erosion of the sediment particles were achieved. The soil variables with which correlations were achieved were, however, so varied that no clear understanding of the processes involved could be seen. In table 8-6 are shown the results of the stepwise regression analysis for the 20, 10 and 20 + 10 minute flume tests. This table shows that the sediment yield can only be explained by the operation of several variables.

Flume test on topsoil (20 minute run)

In the 20 minute run the first variable - particles of mineral matter exceeding 6.35mm diameter (PTC1) - explained 64.6 percent of the sediment loss and the addition of the fine organic matter fraction (ORG1) increased the explanation to 82.9 percent. Both of these explanations

Table 8-5. Summary of the results of stepwise multiple regression analyses.

Run	Sediment fraction variation from 0.635 mm diam.	F value & significance level	R^2	Number of Steps
20 min	> O	25.87***	.878	5
	> M	13.37***	.877	8
	< O	9.62***	.837	10
	< M	8.78***	.756	6
10 min	> O	4.57***	.709	8
	> M	1.67	.471	10
	< O	3.41**	.546	8
	< M	5.54***	.606	7
20+10 min	> O	21.02***	.881	6
	> M	2.88**	.650	9
	< O	9.96***	.813	11
	< M	6.98***	.711	7

O = Organic, M = Mineral matter

Significance levels $\alpha=0.10$, Symbol*, $\alpha=0.05$, Symbol**, $\alpha=0.01$, Symbol***

Table 8-6. Results of stepwise multiple regression analyses of soil properties against sediment yields.

	Soil Properties	Dependent Variables								
		20 min tests			10 min tests			20+10 min tests		
		Beta coefficient	Step Number	Multiple R^2	Beta coefficient	Step Number	Multiple R^2	Beta coefficient	Step Number	Multiple R^2
Independent Variables	VEGN	-	-	-	-	-	-	0.5856	8	.770
	COMP	-0.2526	6	.865	-0.3744*	3	.535	-0.3223*	4	.765
	SHER	-	3	.850	-	2	.510	-	-	-
	MOIS	-0.0827	10	.871	-	-	-	-	6	.768
	PTC1	-1.8155***	1	.646	-	-	-	-0.7683	1	.493
	PTC2	-	-	-	-	-	-	0.5418	2	.668
	PTC3	-	-	-	-0.2022	5	.578	-	-	-
	PTC4	-	-	-	-	-	-	-	-	-
	AGG1	-	-	-	-	-	-	-	-	-
	AGG2	-	-	-	-	-	-	0.6419	3	.712
	ORG1	1.0038***	2	.829	-	-	-	-	-	-
	ORG2	-	5	.861	-	-	-	-	-	-
	VEGS	0.2208	4	.860	-0.1657	4	.559	0.1489	5	.768
	BULK	-	-	-	-	-	-	-	-	-
	PART	-	-	-	-	-	-	-	-	-
	PORO	-	-	-	-0.8615***	1	.356	-0.3491	7	.769
	MAC1	-	-	-	-	-	--	-	-	-
	MAC2	-0.2655	7	.869	0.1248	7	.583	-	-	-
		F value 19.09***; R^2, .871			F value 5.03***; R^2, .583			F value 7.63***; R^2, .770		

are highly significant. The addition of 8 more variables brought the explanation to 87.1 percent. The correlations in table 8-4 help to explain the way in which these soil properties achieve their effect. The coarse mineral particles (PTC1) are negatively correlated with all of the sediment fractions. The highest negative correlations are with the sediment from the topsoil (20 minute tests) and those with the subsoil sediments (10 minute tests) are lower. Observations during the flume test indicate that the roots of the vegetation grow into the vesicular pumice particles and so prevent them being washed away. The root content of the subsoil is lower than that of the topsoil, especially under grasses. The greater the proportions of coarse particles in the soil which can be held by the roots, therefore, the less the degree of erosion. Where the roots are deficient, as in the subsoil, the large particles of pumice, because of their low density, will tend to float and erosion will then be greater.

The fine organic matter in the soil (ORG1) has a negative but lower degree of correlation with all sediments, suggesting that a soil with low organic matter content is readily eroded. It is probable therefore that the organic matter has a positive effect on aggregation of particles and helps the aggregates to cohere.

The third variable, shearing resistance (SHER) is closely related to the fourth - the thickness of the root mat (VEGS) - and the fifth - total weight of organic matter (ORG2). The plant roots have a strong binding effect on the soil particles, which is measured by the shearing resistance, and their effect is to inhibit erosion of topsoil. The remaining variables add little further explanation. Of them compaction and macroporosity are probably also measures of cohesion. It may be reasonably concluded that plant roots and their associated soil properties explain at least 86.1 percent of the resistance of the topsoil to erosion, at a high level of significance.

Flume test on subsoil (10 minute run)

All soil analyses were carried out on the topsoil to a depth of 10cm only. The 10 minute flume tests were carried out with the upper 10cm of soil removed from the plunge-pool in the lower sample. Hence it should be expected that there would be a much lower level of explanation of sediment yield by topsoil properties. Table 8-6 indicates that this is so. The first variable, total porosity (PORO), explains 35.6 percent of the erosion at a high level of significance. It is shown in table 8-4 that porosity is negatively correlated with all sediments except coarse organic matter (which is largely roots), and therefore that low cohesion assists high erosion rates. Shearing resistance increases the explanation to 51 percent but has little significance and is later dropped out of the equation. With a low level of explanation it is doubtful if more useful conclusions can be drawn from the results of this section of the analysis.

Flume test combined results

Table 8-6 shows that the total sediment yield from the 20 and 10 minute flume tests can be explained primarily by the variables which have already been mentioned in the discussion of the 20 minute test. The explanation from the combined data is less than with the 20 minute test data and the order of importance of the variables is changed. Four variables explain 76.5 percent of the erosion and the addition of four more variables only increases the explanation to 77.0 percent. The accumulated explanation to the 77 percent level is highly significant but the explanation at each step is much less significant.

Prediction

Multiple regression analysis has its greatest value when it can be used for prediction. The 'best explanation' equations given in table 8-7 show the value of the constants, the percentage of explanation achieved and its statistical significance when the most important soil properties are measured. These equations only apply to the surface soils

Table 8-7. Prediction equations of erosion, derived from stepwise multiple regression analyses for the 20 minute test on the surface 10cm depth of soil.

First Step Predicted erosion = 1240.714 - 246.606***(PTC1)
(where $\underline{R}^2 = 0.646$)

Second Step Predicted erosion = 998.881 - 410.462***(PTC1)
+ 58.118***(ORG1)
(where $\underline{R}^2 = 0.829$)

Third Step Predicted erosion = 1023.085 - 358.356***(PTC1)
+ 50.819***(ORG1)-2.800(SHER)
(where F:37.905*** and R^2=0.850)

Table 8-8. Component structure derived by varimax rotation.

	Component				
	1	2	3	4	5
VEGN	.550	-.754	.022	.114	.320
COMP	-.301	.307	-.100	-.850	-.111
SHER	-.046	.462	.273	-.497	-.577
MOIS	.244	.057	.135	.923	-.022
PTC1	-.303	.628	-.432	-.052	-.543
PTC2	-.395	-.148	-.870	-.159	.183
PTC3	-.171	.019	.978	.037	.079
PTC4	.936	-.118	-.266	.158	-.019
AGG1	.098	.950	.270	-.059	-.097
AGG2	.024	.989	.073	-.098	-.069
ORG1	.094	.675	-.706	-.083	-.099
ORG2	.103	.881	-.329	-.052	-.315
VEGS	-.164	.385	.001	-.002	-.772
BULK	-.978	-.066	.010	-.186	.044
PART	-.873	-.127	.066	-.046	-.397
PORO	.882	.044	.044	.247	-.316
MAC1	.860	-.094	.311	.137	.368
MAC2	.845	-.097	.311	.121	.404
Percent variance explained	40.449	26.233	15.411	8.365	5.627
Total **variation** explained = 96.085 percent					

studied at Otutira but the variables which give explanation of the erosion are so easily measured compared with the direct measures achieved in the flume test that it would be very worth while to take samples for flume tests and soil property analysis from other areas of yellow-brown pumice soils and to compare their properties with those of Otutira soils to see if these prediction equations have a wider application.

Factor analysis

One of the objectives of factor analysis is to reduce a large number of variables to a smaller number of factors within which associated variables are subsumed. Interpretation of the meaning of that factor may then give the observer a deeper insight into the processes underlying the phenomena he is investigating. In studies of soil and hydrological phenomena measurements are made of commonly recognised properties but in reality these properties may not be truly 'causal' but may only be components or contributions to a 'cause'. Factor analysis may help to indicate the true nature of the cause. This type of analysis has been used in watershed hydrology by a number of investigators including Anderson (1965); Anderson, Duffy and Yamamoto (1966); Snyder (1968); Wallis (1965, 1968) and Wallis and Anderson (1965).

Factor analysis of the sediment and soil data has yielded 5 principal components which together explain 96.085 percent of the total variation in the 18 variables (table 8-8). The first component, accounting for 40.449 percent of the variance, shows that the fine soil particles - of silt and clay sizes - the porosity and low density of the soil particles are all highly correlated with this component. This suggests that the erosion is attributable to the inherent properties of the pumice soils rather than to any particular effect of water flow or landuse. The factor may be distinguished as being one of high porosity and low density of pumice. These are features which contribute to the ease with which pumice is entrained and transported by running water.

The second component adds 26.233 percent of the total variation. The variables most highly correlated with this factor are aggregation and total weight of organic matter. This factor indicates, therefore, the importance of vegetation in modifying soil properties and hence the response of the soil to erosive forces.

The remaining three factors each contribute relatively little to the explanation. The third component is difficult to interpret but appears to be associated with soil mineral organic particle sizes. The fourth component is related to soil moisture content and compaction and the fifth component to plant root density and its effect on shearing resistance.

Factor analysis has produced generalised statements which confirm the order of importance of the variables distinguished by the stepwise multiple regression analysis and allows the general statement that erodibility of the yellow-brown pumice soils is controlled by the ease with which pumice particles are entrained and that this is modified by the binding effects of the vegetation.

CONCLUSIONS

Analysis has shown that erosion is significantly higher under the scrub than under pasture grass vegetation when the same volume of water washes over the surface of the ground in each test. Ungrazed grass is slightly less effective in protecting soil than grazed grass. This effect is largely to be explained by the binding effect of plant roots and organic matter on the soil particles. Gully erosion of pumice soils is attributable to the low density and easy entrainment of the soil particles.

It must be emphasized, however, that this conclusion applies only where surface water has the same effective erosive power in each case. Analyses of infiltration and runoff under the three vegetation types must be combined with those of erosion before valid conclusions can be drawn about natural conditions.

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CHAPTER 9

CONCLUSIONS

Causes of erosion

In the preceding chapters experiments have been described from which a number of conclusions about the causes of erosion of pumice soils may be derived.

It has been shown that surface water runoff is greater from developed areas in pasture and less from areas covered by scrub and ungrazed grass vegetation. The major causes of runoff from pastures are very intense precipitation falling on a soil with low moisture content. Infiltration studies support this conclusion.

Infiltration is relatively low under pasture grass vegetation and greater under scrub and ungrazed grass. The high infiltration under ungrazed grass indicates that it is not grass vegetation alone which causes low infiltration rates but modifications of the soil by land use practices. An important effect is the compaction by machines and animals which reduces soil porosity.

Where an equal shear stress is placed on soils beneath scrub and pasture vegetation, scrub soils are more easily eroded. Shear stresses are, however, probably never equal in natural conditions for runoff is always greater, in intense storms, from pasture areas. Erosion of pumice soils is attributable to the low density and easy entrainment of the soil particles. The binding effects of plant roots and organic matter in the soil reduce the liability to erosion.

Prevention of erosion

Analysis of the causes of erosion indicates that a number of land use practices may assist in the prevention of erosion.

The land must be protected against the effect of very intense storms, particularly those which occur when soil moisture content is very low. Such storms are most likely to occur after long dry periods during the summer. Field experience suggests that the maintenance of a close grass sward and the avoidance of overstocking are most effective in protecting the soil. Maintenance of a close grass sward on pumice soils during a dry summer is extremely difficult (Mr. J. H. Young, Chief Soil Conservator, Waikato Valley Authority, personal communication) and vulnerable areas should, therefore, be left in scrub or planted with trees. Vulnerable areas are valley floors and steep slopes.

High infiltration rates may be promoted by leaving valley floors as water absorption areas from which vehicles and animals are excluded so that the soil is not compacted. The vegetation cover may be scrub, forest or ungrazed grass but it is to be expected that farm forestry will be the most economical use for such areas. Absorption areas should be effective because it is short duration high intensity rain that they must temporarily impound and allow to infiltrate rather than prolonged rain.

Soil stability may be maintained by keeping a complete vegetation cover on the land and by promoting a vegetation with a strong dense root system. This will, at the same time, increase the proportion of organic colloids in the soil. All forms of activity which cause soil exposure, and especially the formation of ruts and channels must be avoided.

The experiments undertaken were not designed to provide information on the effectiveness of such practices as contour furrowing or terracing. Field evidence, however, suggests that they should only be used in carefully selected experimental areas, because indiscriminate use could result in the formation of local rills and channels, and subsurface pipes. Land development is likely to be most successful where the vegetation and land use allow the vegetation and soils to be highly absorbent of water and where plant root systems bind the soil. Increased runoff from roads and building sites must be routed to prevent it breaking the vegetation cover.

APPENDIX

PROCEDURES FOR DETERMINING THE PHYSICAL PROPERTIES OF SOILS

The procedures used in the analysis of soils are based upon the recommendations of Black, Evans, Ensminger, White and Clark (1965). They have been modified slightly so that large numbers of samples could be studied at one time, and also to accommodate the unique properties of soils with pumiceous parent material. Yellow-brown pumice soils present two problems to the analyst: (1) the dominant clay is allophane which has a very small particle size, and is also very difficult to disperse (Birrell and Fieldes, 1952); (2) mechanical dispersion and prolonged dry sieving treatment of the sand fraction of the soils causes physical breakdown of included pumice particles (McDonald, 1955). To avoid these problems separation of the soil fractions has been limited to that obtainable by the dry sieving method.

All samples for analysis were collected in stainless steel corers 10cm long with an internal diameter of 6cm. All measurements are thus of whole samples of the upper 10cm of the soil. All vegetation was clipped off the surface of the sample.

ANALYSIS OF PARTICLE SIZE, AGGREGATION AND ORGANIC MATTER

Particle Size Analysis

Dry, clean and weigh each sieve (6.35, 0.635, 0.063mm) to be used. Place the whole air-dried sample in the top sieve and break it up sufficiently for the lid to be placed on the top sieve. Shake the sieve nest on a mechanical shaker for ten minutes. Weigh each sieve with its retained material. Extract all root matter and charcoal from the aggregates retained in the 6.35mm and 0.63mm sieves and weigh them. Gently break up all aggregates on the sieves and replace the nest on the shaker for a further 10 minutes. Weigh each sieve and the retained material. These measurements give 4 measures of particle size.

Aggregation

The measure of aggregation is derived from the material which at the end of 10 minutes sieving is retained above the 0.63mm sieve but which has passed through the 0.63mm sieve by the end of a further 10 minutes sieving (in a soil not containing pumice the period of sieving could be extended to 30 minutes).

Organic Matter

Root matter separated by hand from the 6.35 and 0.63mm sieves is weighed.

To determine fine organic matter the contents of the 0.063mm sieve and the receiver are mixed together. A 50gm sample of this mixture is oven-dried at 105°C for 8 hours to check that no moisture has been absorbed. From the 50gm sample a 5gm sample is taken and placed in a furnace at 400°C for 14 hours. The loss of weight during furnace treatment is a measure of the fine organic matter content (higher temperatures are likely to cause explosion of vesicles in the pumice and loss of water of crystallisation).

SOIL POROSITY AND DENSITY MEASUREMENTS

Core samples of the surface soil are collected in 10cm corers. The corers are sealed with tape and metal caps, numbered and stacked carefully to reduce disturbance during transport.

In the laboratory the base caps are removed and each corer is placed vertically on a filter paper and 1.58mm balsa wood porous plate in an empty bath. When 20 cores have all been placed in the bath, and the lids have been removed, water is added up to the 9.8cm level (with special care being taken not to submerge any of the cores). The cores are then left to soak from the base for 48 hours, with the water level being raised to 9.8cm periodically to compensate for losses caused by saturation of the samples and by evaporation.

When the samples have soaked for 48 hours the procedure for each core is to seal the upper surface with a lid, then remove the corer and base plate rapidly from the bath, invert it, and weigh it immediately. This weight is a measure of the weight of the sample (plus corer) when it is completely saturated, and thus provides a measured total porosity when the dry weight of the solid material is obtained. It is assumed that the only contained air is within the pumice blocks in the soil.

The corer is then removed from the balance and placed on the wetted surface of a tension table with minimum disturbance of the filter paper and plate.

When the 20 corers are in position on the tension table the outlet of the pipe from the table is positioned, facing upwards, at a point 20cm below the centre level of the cores. Plastic sheeting is then laid over the apparatus to reduce evaporation.

Following the cessation of flow from the samples, as indicated by a drop in the level of water at the outlet, each corer (with filter and plate) is removed from the table and weighed. With the pumice soil samples tested, flow ceased before 20 hours in every case.

When the corers have been weighed the moist soil is transferred from the corers to open dishes and each sample is then quartered. The quartering technique consists of splitting the sample in half down its longest axis with a sharp knife, repeating this procedure on one of the halves, and then retaining one of the final quarters. From the retained quarter of the sample, which is presumed to have a representative moisture content, a 50gm longitudinal sample is taken and is oven dried at 105°C. (Generally 24-48 hours drying time is required).

The oven-dry samples are placed in a dessicator or are weighed while still warm.

(N.B. From the measurements taken to this stage the total porosity, macro- and micro-porosity, and bulk density can be determined, and the particle density can then be calculated from these results. However, as a control, further measurements are made to determine the particle density and then calculate a second total porosity.)

Following the weighing of the samples after oven-drying the containers are sealed, or a 10gm subsample is immediately and carefully weighed into a pycnometer (250ml flask), which has already been dried and weighed.

Distilled water is then added to the samples (care being taken not to blow out fine particles of soil) and the ten pycnometers in each test group are heated in a water bath until the water has boiled for approximately four minutes. The flasks are removed from the bath and agitated with a horizontal spinning motion to release entrapped air, and are then permitted to cool to room temperature.

Because of both condensation in the neck of each flask and the presence of some soil particles above the 250ml line the flasks should be filled to the top for weighing. A hypodermic pipette provides an accurate control for adding the last few drops of distilled water. After weighing, the water temperature is recorded to 0.5°C with the thermometer bulb in the centre of the flask.

The flasks are then emptied, washed and dried, and then are weighed again containing only distilled water (at approx. 20°C), and the temperature of this water is also recorded.

N.B. This measurement of the flask and water was made very carefully at the start of the tests and was repeated several times. Variations in the volume of water were generally in the order of 0.03% or less, and one reading had a maximum variation of 0.1%. Thus, the best value was taken and used throughout the series of tests. Similarly the weight of each dry flask was carefully measured and recorded so that the 10gm samples could be inserted before the flasks were completely dry. This technique is quite important as there is no loss of accuracy but the time-saving over 50-100 samples is very considerable.

Results

The results obtained from this test procedure are: Total porosity (M), macro- and micro-porosity (M), bulk density (M), particle density (C), and then particle density (M), and total porosity (C).

where (M) indicates a result determined from direct measurements, and (C) indicates a result calculated from two or more measured results.

For statistical analysis the laboratory measurements provide 3 values for bulk density which are averaged, 2 values of particle density and 2 values of total porosity which are also averaged. The macroporosity is calculated from the averaged total porosity. The differences between calculated and measured values are increased as the percentage of pumice blocks increases. Averaging the values reduces this source of error.

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APPENDIX

CODE NAMES FOR SOIL PROPERTIES

In the computer analyses soil properties are distinguished by code names. These same names have been used in tables. The names are listed below.

VEGN	Vegetation length
COMP	Compaction
SHER	Shearing resistance
MOIS	Pre-existing soil moisture
PTC1	Particles $>$ 6.35mm diameter
PTC2	Particles 6.35 to 0.635mm diameter
PTC3	Particles 0.635 to 0.063mm diameter
PTC4	Particles $<$ 0.063mm diameter
AGG1	Aggregation as a percentage of the total sample
AGG2	Aggregation as a percentage of the sample exceeding 0.635mm diameter
ORG1	Percentage of fine organic matter in the sample
ORG2	Total weight of organic matter as a percentage of the sample
VEGS	Thickness of the root mat
BULK	Bulk density
PART	Particle density
PORO	Total porosity
MAC1	Macroporosity as a percentage of total sample volume
MAC2	Macroporosity as a percentage of total pore space