HILLSLOPE FLOW PROCESSES IN AN UPLAND CATCHMENT IN S.E. SCOTLAND

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TO MY FATHER

Perfect knowledge alone can give certainty, and in Nature perfect knowledge would be infinite knowledge, which is clearly beyond our capacities.

We have, therefore, to content ourselves with partial knowledge, knowledge mingled with ignorance producing doubt.

W. STANLEY JEVONS

DECLARATION

I certify that this thesis has been composed by myself from the results of my own work, except where stated other- wise, and that it has not been submitted for any degree other than that of Doctor of Philosophy in the University of Edinburgh.

ABSTRACT

In this thesis the flow processes occurring in an upland catchment in South-East Scotland are studied. Also, a qualitative explanation of the conversion of rainfall to storm runoff in the study catchment is given. The literature relating to flow processes and storm runoff generation is reviewed and the conclusions that have been drawn concerning flow processes and storm runoff generation by various investigators are outlined and discussed. Specific reasons for choosing this particular study catchment are given and the type and installation of instruments and equipment used are described. Particular attention is given to the problems in choosing the right methods and equipment for studying flow processes.

The results obtained are presented in four sections relating to: a) weather conditions in the catchment during the two field seasons; b) response of the plots to natural rainfall; c) response of the plots to artificial rainfall and d) relationships between the response of the plots and the catchment as a whole to rain. These results indicate that the main flow process in the brown earth soil part of the catchment is lateral movement of infiltrated water through the soil horizons and mainly through the A horizon. The high water velocity computed indicates movement through structural and biological voids rather than through the soil matrix. Another important flow process in this part of the catchment is saturated litter flow. Also Horton "litter flow" and litter flow due to very dry soil conditions occurs in the same part of the catchment. However, these are localized

and are not important flow processes. As far as the peat soil area of the catchment is concerned, the main flow processes are saturated litter flow and pipe flow.

The results also show that areas near to the stream channel and those far from the stream channel both respond to rainfall and contribute to storm runoff. Therefore the concept of variable or partial source areas does not seem to be applicable in this catchment.

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CONTENTS

		Page No.
Declaration		i
Abstract		ii
Acknowledgements		iv
Contents		v
List of Figures		ix
List of Tables		xii
List of Plates		xvi
List of Maps		xvii
List of Appendices		xviii
PART I	INTRODUCTION	1
1.1	General Introduction	1
PART II	THE STUDY AREA	21
2.1	Location and Selection of the Study Area	21
2.2	Altitude and General Topography	23
2.3	Geology and Soils	26
2.4	Climate	27
	2.4.1 Winds	28
	2.4.2 Precipitation	28
	2.4.3 Temperature	31
	2.4.4 Evapotranspiration and Water Balance	31
2.5	Vegetation and Land-use	33
PART III	INSTRUMENTATION AND METHODS	35
3.1	Introduction	35
3.2	First Field Season's Experimental Work	36
	3.2.1 Installation of Equipment to Measure Catchment Rainfall and Runoff	36

Page No

3.2.1.1 Installation of a Raingauge Network 36

3.2.1.2 Installation of Hydrometric Station 43

3.2.1.3 Appraisal of the Rainfall and Runoff Data Collected During the First Field Season 46

3.2.2 Investigation of Flow Generation Processes 51

3.2.2.1 Overland Flow 52

3.2.2.1.1 General Considerations and Selection of the Locations for the Establishment of the Plots 52

3.2.2.1.2 Design and Construction of the Plots 58

3.2.2.2 Infiltration 66

3.2.2.2.1 Definitions 66

3.2.2.2.2 Trial for Infiltration Assessment with Cylinder Infiltrometers 67

3.2.2.2.3 Field Measurements with a Rainfall Simulator Infiltrometer and Modifications of the Instrument 77

Page No.

3.2.2.2.4 Selection of Locations for Infiltration, Litter Flow and Throughflow Measurements 89

3.2.2.3 Trial Throughflow Plot 101

3.2.3 Conclusions of the First Field Season's Experimental Work 109

3.3 Second Field Season's Experimental Work 111

3.3.1 Litter Flow Measurements in the Peat Soil 113

3.3.2 Infiltration Measurements 114

3.3.3 Selection of Locations and Construction of Runoff Plots 115

3.3.4 Application of Artificial Rainfall in the Runoff Plots 129

3.3.5 Determination of the Velocity of Flow Through the A Soil Horizon 131

PART IV RESULTS 135

4.1 Introduction 135

4.2 Rainfall and Runoff Conditions Experienced in the Catchment During the Course of the Study 139

4.3 Results Obtained from Natural Rainfall 145

4.3.1 Observed Litter Flows from the Triangular Plots in the Brown Earth Soil Area 146

4.3.2 Observed Litter Flows from the Triangular Plots in the Peat Soil Area 157

4.3.3 Observed Flows in the Rectangular Plots 163

4.3.4 Soil Hydrographs from the Rectangular Plots 180

Page No.

4.3.5 Discussion 188

4.4 Results Obtained from Artificial Rainfall 196

4.4.1 Calculated Infiltration Rates 196

4.4.2 Rainfall Intensities and Comparison with the Infiltration Rates 204

4.4.3 Observed Litter Flows and Throughflows from the Infiltration Locations 210

4.4.4 Application of Artificial Rainfall in the Runoff Plots 220

4.4.5 Discussion 229

4.5 Flow Velocity Through the A Soil Horizon 236

4.5.1 Results and Discussion 236

4.6 Response of the Catchment to Rainfall 244

4.6.1 Hydrograph Analysis 244

4.6.2 Minimum Contributing Area to Storm Runoff 252

4.6.3 Storm Runoff Generation 259

PART V CONCLUSIONS 271

REFERENCES 278

APPENDICES 287

LIST OF FIGURES

Page No.

Figure 1: Stream hydrographs showing the main types of runoff increase (after Horton, 1933) 4

Figure 2: Diagram showing the source of storm flow (direct runoff) from a forested watershed with uniform soil mantle (after Hewlett and Hibbert, 1967) 7

Figure 3: Relationship between discharge and gauge height 45

Figure 4: Details of the constructed cylinder infiltrometer 69

Figure 5: Cylinder infiltrometer and feeder bottle in operation 71

Figure 6: Rainfall simulator infiltrometer (after Boontawee, 1977) 78

Figure 7: The rainfall simulator infiltrometer after the modifications (not to scale) 87

Figure 8: Perspective view of the modified infiltrometer and guttering 90

Figure 9: Trial throughflow plot 104

Figure 10: Diagram showing the periods during which the different hydrological components were measured 137

Figure 11: Diagram showing daily rainfall and runoff during the two field seasons 141

Figure 12: Litter flows observed in the triangular plots in the brown earth soil area 147

Page No.

Figure 13: Litter flows observed in the triangular plots in the peat soil area 158

Figure 14: Observed flows in the rectangular plots 165

Figure 15: Two rain events of almost the same total rainfall that generated different amounts of litter flow 177

Figure 16: Soil hydrographs generated on 7/10/82 185

Figure 17: Soil hydrographs generated on 11/10/82 187

Figure 18: Diagram showing the separation of the amount of artificial rainfall in each site in various components 211

Figure 19: Hydrographs generated from artificial rainfall in each site of location 1 214

Figure 20: Hydrographs generated from artificial rainfall in each site of location 7 215

Figure 21: Median throughflow curves of the nine locations 217

Figure 22: Generated hydrographs in the rectangular plots from artificial rainfall 222

Figure 23: Generated hydrographs in plot 2 from artificial rainfall under dry (A) and wet (B) soil conditions 228

Figure 24: Hydrographs generated from natural and artificial rainfall 235

Figure 25: Hydrograph analysis by Barnes' method (after Chow, 1964) 247

Figure 26: Various methods of hydrograph separation (after Ward, 1975) 248

Page No.

Figure 27: Hydrograph analysis by Hewlett's method 251

Figure 28: Hydrographs generated from artificial rainfall in each site of location 2 292

Figure 29: Hydrographs generated from artificial rainfall in each site of location 3 293

Figure 30: Hydrographs generated from artificial rainfall in each site of location 4 294

Figure 31: Hydrographs generated from artificial rainfall in each site of location 5 295

Figure 32: Hydrographs generated from artificial rainfall in each site of location 6 296

Figure 33: Hydrographs generated from artificial rainfall in each site of location 8 297

Figure 34: Hydrographs generated from artificial rainfall in each site of location 9 298

LIST OF TABLES

Page No.

Table 1: Average monthly precipitation at West Hopes (1916-1950) 28

Table 2: Average mean temperature (°C). Period 1931-1960 32

Table 3: Water balance for West Hopes 33

Table 4: Weekly rainfall and runoff during the two field seasons 47

Table 5: Rainfall and runoff of a number of rain events during the first field season 49

Table 6: Land-use and characteristics of the locations selected for overland flow measurement 56

Table 7: Gradient and projectional area of the litter flow plots 62

Table 8: Observed amount of litter flow in the triangular plots on 22nd July 1981 rain event 63

Table 9: Observed litter flow in the triangular plots during 1981 65

Table 10: Computed infiltration capacities in the first selected location 74

Table 11: Computed infiltration capacities on 25th July 1981 75

Table 12: Computed infiltration capacities after bentonite was used 76

Table 13: Mean infiltration rate and litter flow with the application of artificial rainfall on 13th August 1981 81

Table 14: Mean infiltration rates and litter flow with the modified base unit 83

Page No.

Table 15:	"Infiltrometer data sheet" used to compute the infiltration rates in the study catchment on 19th September 1981	91
Table 16:	Characteristics of the locations selected for infiltration assessment	94
Table 17:	Mean infiltration rates, litter flows and throughflows recorded in October 1981 from the selected locations	97
Table 18:	Infiltration rates and infiltration capacities computed with the rainfall simulator and the cylinder infiltrometer, respectively	98
Table 19:	Occurrence of litter flow in the study catchment from artificial (A) and natural (B) rainfall	100
Table 20:	Data obtained from the trial throughflow plot in 1981	107
Table 21:	Characteristics of the triangular plots constructed at the peat soil	114
Table 22:	Monthly rainfall and runoff observed during the two field seasons in the study area	140
Table 23:	Mean monthly rainfall in the study area	142
Table 24:	Observed amounts of litter flow in the brown earth soil during the first field season	149
Table 25:	Rainfall intensities occurring during the nine time periods	153
Table 26:	Observed amount of litter flow in the peat soil	160
Table 27:	Rainfall intensities occurring during the 11 periods of the second field season	162

Page No.

Table 28: Observed flows from the four rectangular plots during the second field season 166

Table 29: Observed monthly flows in the rectangular plots 168

Table 30: Total observed flows from each plot during the 17 time periods 171

Table 31: Amounts and percentages of flows emerging from each soil segment in the four rectanular plots 174

Table 32: Hydrologic component of the four hydrographs generated in the rectangular plots 183

Table 33: Flow processes observed in field experiments throughout the world 192

Table 34: Mean infiltration rates of the two runs computed in the nine locations 197

Table 35: Mean infiltration rates of both runs in the nine selected locations 200

Table 36: Rainfall recorded in the study area from May to October (1981-82, in mm) cross-classified according to duration and intensity of fall. Numbers in cells are the total numbers of events in each class 206

Table 37: Two day rainfall intensities with a return period of once in five years for the study catchment 208

Table 38: Litter flow and throughflow emerging from each infiltration site 213

Table 39: Flows emerging from the rectangular plots from artificial rainfall 221

Page No.

Table 40: Observed flows in plot 2 from artificial rainfall under dry and wet soil conditions 227

Table 41: Values of flow velocity through the A horizon in the five selected locations 237

Table 42: Saturated hydraulic conductivity of soils in which subsurface stormflow has been measured (after Dunne et al., 1980) 240

Table 43: Characteristics of flood events during the two field seasons 255

Table 44: Contributing area values noted in the literature 258

Table 45: Initial infiltration rate of each site of the nine locations 288

Table 46: Final infiltration rate of each site of the nine locations 289

Table 47: Mean infiltration rate of each site of the nine locations 290

LIST OF PLATES

Page No.

Plate 1: General view of the study catchment 25

Plate 2: Recording raingauge, standard non-recording raingauges with standard and ground level exposure, and funnel gauge 42

Plate 3: Modified base-unit of the rainfall simulator infiltrometer 84

Plate 4: Runoff plot 1 124

Plate 5: Runoff plot 4 127

Plate 6: Saturated litter flow on the flood plain of the study catchment on 2nd October 1981 264

Plate 7: Saturated litter flow in the peat soil area of the study catchment on 6th October 1982 266

Plate 8: Litter flow at a sheep scar of a well-vegetated site of slope II of the study catchment 267

Plate 9: Flow through the A horizon demonstrated by inserting zinc guttering into the soil 268

LIST OF MAPS

		Page No.
Map 1:	Catchment where the work was carried out	22
Map 2:	Characteristics of the study catchment	24
Map 3:	Flood rainfall in East Lothian over period of continuous downpour (East Lothian County Council, County Planning Department)	30
Map 4:	Diagram showing how polygons were constructed for estimating weighted rainfall	40
Map 5:	Selected locations for overland flow plots construction	57
Map 6:	Selected locations for infiltration assessment in the brown earth soil	93
Map 7:	Location where the trial throughflow plot was constructed	102
Map 8:	Selected locations in the study area where the runoff plots were constructed	120
Map 9:	Study area showing the various plots and equipment	136
Map 10:	Computed infiltration rates in the various segments of the study area	205

LIST OF APPENDICES

Page No.

Appendix 1: Initial, final and mean infiltration rate of each infiltration site of the nine locations 287

Appendix 2: Hydrographs generated from artificial rainfall in each infiltration site of the locations 2, 3, 4, 5, 6, 8 and 9 291

PART I: INTRODUCTION

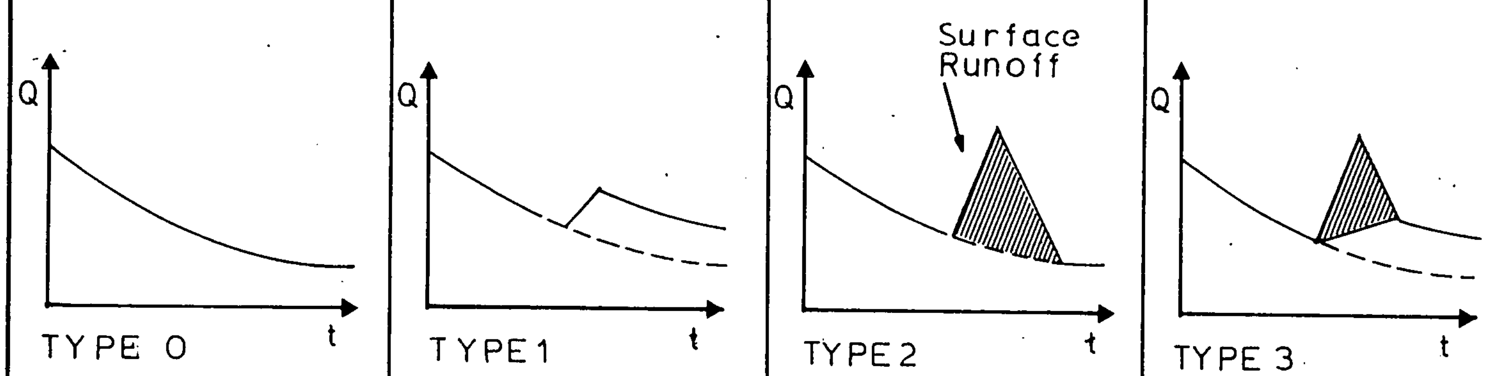
1.1 GENERAL INTRODUCTION

The flow processes which occur when the rainfall reaches the surface of the ground until it becomes streamflow are of great importance. Knowledge of these processes determines the uses to which land may be put and the necessary strategies required for wise land management and related water resources (Dunne and Leopold, 1978; Engman, 1974; Vries , 1978; Knisel and Sheridan 1983). In addition, these flow processes contribute to a better prediction of the amount of runoff generated by a rain event, and play a very important role in the understanding of the shaping of the landforms (Freeze, 1974). In the case of the occurrence of overland flow in a catchment, for example, the water flows very fast - 3,050 to 6,919 m/day - (Hewlett and Nutter, 1970)-and reaches the stream channel very fast. Hence it contributes to storm runoff and the lowlands may face flooding problems. The occurrence of overland flow may also result in soil erosion, thus preventing any profitable use of the land. Furthermore, overland flow may carry bacteria and pollutants to the stream channel (Dunne et al., 1975; Hewlett, 1982). Consequently, these areas require specific management in order to solve or minimize the problems mentioned above. Generally, as Dunne and Leopold (1978) stressed, "An appreciation of flow processes allows the planner to recognize present constraints, to predict the consequences of some form of development and to avoid possible problems." The importance of understanding flow processes has been long recognized, and much work has been devoted to achieving this.

Horton (1933), relying on his infiltration theory, developed the classical model of runoff. According to this model, the soil surface separates the rainfall into two different components which follow different courses in the hydrologic cycle. Horton stressed that "The surface of a permeable soil acts like a diverting dam and head-gate in a stream, where the head-gate can be opened to a certain width only, or closed so as to still leave a fixed opening. Similarly, with varying rain intensity, all the rain is absorbed for intensities not exceeding the infiltration capacity, while for excess rainfall, there is a constant rate of absorption as long as the infiltration capacity is unchanged. As in the case of the dam and head-gate there is usually some pondage which remains to be disposed of after the supply to the stream is cut off, so in the case of infiltration, surface detention remains after rain ends. Infiltration divides rainfall into two parts, which therefore pursue different courses through the hydrologic cycle. One part goes via overland flow and stream channels to the sea as surface runoff; the other goes initially into the soil and hence through groundwater flow again to the stream, or else is returned to the air by evaporative processes. The soil therefore acts as a separating surface and the author believes that various hydrologic problems are simplified by starting at this surface and pursuing the subsequent course of each part of the rainfall as so divided, separately."

The classification of stream rises according to Horton's theory is depicted in Figure 1. Type 0 runoff occurs when rainfall intensity is lower than infiltration rate and total infiltrated water less than field capacity. So, no surface runoff occurs, neither does any accretion to the groundwater occur. Hence the stream hydrograph has the form of a dry weather depletion curve. In type 1 runoff conditions, the rainfall intensity is again lower than the infiltration rate, but the total infiltrated water exceeds the soil moisture deficit. Hence groundwater flow increases, while surface runoff again does not occur. In type 2 conditions the rainfall intensity exceeds the infiltration rate, while the total infiltrated water is not enough to make good the soil moisture deficit. Consequently, surface runoff occurs, while there is no groundwater flow. In type 3 conditions, rainfall intensity and total infiltrated water are higher than infiltration rate and soil moisture deficit, respectively. So, increase in runoff results from surface runoff and groundwater flow. Horton's model on flood flow generation from surface runoff was widely accepted and as a result many hydrology text books presented diagrams showing that a hydrograph is composed of two main parts: surface runoff and groundwater flow:

At this point it is worthy of note that the movement of water through the soil was indicated as a primary source of storm runoff and especially from forested lands when Horton was crystallizing the opposite theory, i.e. that all storm flow was overland flow. Hursh (1936) and Hertzler (1939), for example, emphasized the importance of interflow as a contributor to the total stream flow, and later Hursh and



1 HYDROLOGIC PARAMETERS	2	3	4	5
RAINFALL INTENSITY	LESS THAN INFILTRATION RATE	LESS THAN INFILTRATION RATE	GREATER THAN INFILTRATION RATE	GREATER THAN INFILTRATION RATE
FIELD MOISTURE	TOTAL INFILTRATION LESS THAN FIELD CAPACITY	TOTAL INFILTRATION GREATER THAN FIELD CAPACITY	TOTAL INFILTRATION LESS THAN FIELD CAPACITY	TOTAL INFILTRATION GREATER THAN FIELD CAPACITY
SURFACE RUNOFF	NONE	NONE	YES	YES
FLOW INCREASE	NONE	GROUNDWATER ONLY	SURFACE RUNOFF ONLY	SURFACE RUNOFF AND GROUNDWATER

Figure 1. Stream hydrographs showing the main types of runoff increase (after Horton, 1933)

Brater (1941), Hoover and Hursh (1943) and Hursh (1944) demonstrated the need to account for interflow in explaining storm runoff, especially from forested upland catchments. Furthermore, Hursh and Fletcher (1942) stressed that the water may move very fast through the soil profile and hence it can reach the stream channel in sufficient time to contribute to storm hydrograph.

By the 1950s the views of hydrologists on the contributions of overland flow and throughflow to the storm hydrograph were quite diverse. Linsley (1949), referring to the diverse opinions concerning whether or not surface runoff contributes to the storm hydrograph, emphasized that the debate was a matter of rigorous definitions of surface runoff and interflow. In fact, he supported the view that some water flows to the stream channel by flowing over the ground in some places and through the soil in others. Hence, it was difficult for this water to be classified as surface runoff or interflow. While the debate on the source of storm runoff was continuing, Roessel (1950), from data he collected from different catchments, argued that true groundwater discharge may form the major part of flood flows with minor or no contributions from surface runoff.

Different concepts about flow processes and mechanisms of stream flow generation grew out of work by Hewlett in the Coweeta Hydrologic Laboratory. As he explained, the research started "chiefly because the low water flows and behaviour of Coweeta streams could not be explained logically by conventional concepts of groundwater hydrology." (Hewlett, 1961). From experimental work (Hewlett, 1961; Hewlett and

Hibbert, 1963) and field observations, the variable source area concept was developed. According to this concept the stream flow from a small catchment is due to a shrinking and expanding source area which is in contrast to Horton's ideas about stream flow generation. The variable source area model of runoff generation is described in detail by Hewlett and Hibbert (1967), Hewlett and Nutter (1970), Nutter (1973), Ward (1975) and therefore only the main ideas developed by Hewlett are mentioned below. These are:

1. Infiltration is seldom a limiting factor and therefore overland flow has to be treated as a special case instead of a typical case.

2. During a rainless period, unsaturated soil moisture from the slopes of the catchment moves down slope. As a result of this movement, saturated soil conditions occur in the areas near the stream channel and they are regarded as source areas of the base flow of the stream.

3. During a rain event the downhill movement of soil moisture increases, but despite this, it moves very slowly to contribute to storm runoff.

4. Replacement of the moisture near the stream channel from new rain coming downslope, and called translatory flow, is essential for the generation of storm runoff.

The above flow processes are depicted in Figure 2. Hewlett et al. (1970) postulated that "a crucial feature of the variable source area concept is the expanding channel network, since by this means the channel reaches out to tap subsurface flow systems, which for whatever reasons have overridden their capacity to transmit water beneath the surface."

The contribution of throughflow from only a part of a catchment to the stream hydrograph peaks was indirectly indicated by other investigators as well. Betson (1964), for

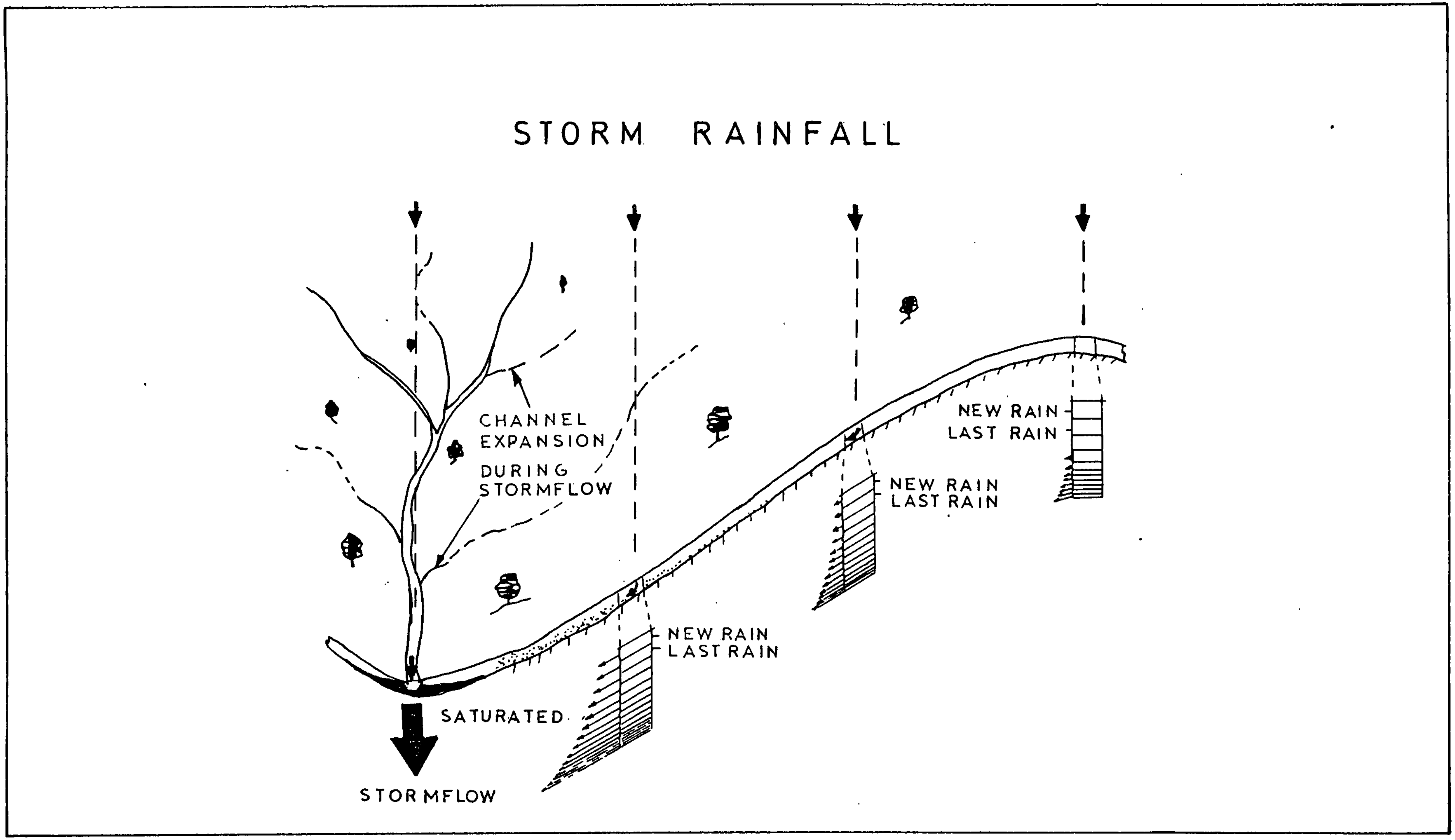


Figure 2. Diagram showing the source of storm flow (direct runoff) from a forested watershed with a uniform soil mantle (after Hewlett and Hibbert, 1967).

example, developed a model based on Horton's infiltration equation. Estimation of runoff in terms of rainfall infiltration and evapotranspiration losses indicated a persistent error and this could only be explained by assuming that only a small but consistent part of the catchment was contributing to the storm hydrograph. Betson called these areas "partial source areas" instead of "variable source areas" as they were called by Hewlett.

The theories about "partial and variable source areas" were indirectly supported by Tennessee Valley Authority (TVA, 1964), as well. When the area stream factor correlation pilot study failed (TVA, 1964), hydrologists referred to the concept of a "dynamic watershed" and concluded that "when rainfall starts after a dry period this dynamic watershed is very small, but as the rain continues and the slopes get wet, the watershed expands and more area contributes to runoff. This expansion is abrupt and large for intense bursts of rainfall, and it is slow for low intensity and prolonged rain. This dynamic watershed does not only grow, it also contracts" (TVA, 1964).

Amerman and McGuiness (1965) also indicated the existence of variable or source areas in a catchment when he discussed runoff from small catchments in Ohio. He suggested that "runoff producing areas were located in seemingly random fashion on ridge tops, valley slopes, and valley bottoms", and these areas were not necessarily connected to the valley stream by continuous surface streams.

The importance of variable and source areas and the dynamic watershed concept in management decision on water resources was soon recognized (Dunne et al., 1975; Engman, 1974). Field investigations were therefore suggested to test the theoretical studies with field data (Dunne, 1980; Pilgrim et al. 1978). The first field study was carried out by Ragan (1968) in Vermont. Ragan measured inflows in a 190 m reach of channel in a drainage area of 0.45 km^2. Eighteen storms were analysed during six months and the results showed that storm runoff was produced by direct rainfall into the main channels, by return flow, and direct rain onto saturated areas and subsurface flow from the valley floor when the water table was close to the ground surface at the beginning of the storm. No overland flow was observed. The area which produced storm runoff ranged from 1.2 to 3% of the catchment area and it was found that this area was a function of the storm duration and intensity, and also that it existed in the form of localized zones of intense contribution.

Dunne and Black (1970a, 1970b) carried out detailed work in the same area (Vermont) and studied flow processes and the existence of variable or partial source areas. Three continuous hillside plots, one with convex contours, one with concave contours, and another with straight contours, were instrumented. The runoff from each plot was measured at the ground surface, at the base of the root zone and at the perennial groundwater seepage level. The plots were used for two years and the runoff from each level of each plot was measured continuously. A number of artificial rainstorms of high return periods were also applied. Finally, periodic measurements of soil moisture, piezometric head, water table elevation and meteorological parameters were made. Dunne and Black (1970a, 1970b) drew the following conclusions from this work:

1. Hortonian overland flow did not occur in most storms except on roads and disturbed areas.

2. Significant amounts of storm runoff were produced from small areas of hillside where the water table reached the ground surface.

3. During large storms, subsurface storm flow occurred but was not an important contributor to the total storm runoff, despite the fact that the conditions were favourable for its existence.

4. The importance of an area of hillside in producing storm runoff depended on the ability to generate overland flow.

5. The findings were in general agreement with the partial area concept of Ragan (1968) and Betson (1964) and the area which contributed to storm runoff may have varied seasonably or throughout the year.

Betson and Marius (1969) studied runoff processes and the existence of partial source areas in a small agricultural catchment in a thin A horizon in western North Carolina using sub-plots, observation wells and piezometers. It was suggested that in the areas where the A horizon was thin, the water table reached the ground surface and storm runoff occurred infrequently. The areas which produced storm runoff were scattered around the catchment and whether this storm runoff reached the streams or not depended upon the capacity of some downslope soil to absorb the runoff. Corbett et al. (1975) also found that the dynamic watershed model was applicable by using artificial rainfall in a small (7.9 ha) catchment.

Freeze (1972) developed a deterministic mathematical model which supported the runoff generation mechanisms observed earlier by Ragan (1968), and Dunne et al. (1970a, 1970b) in field experiments. Freeze concluded that there are limitations for the occurrence of subsurface flow to be regarded as a runoff component. He stated that only on convex hillslopes that feed deeply incised channels, and then only when saturated soil conductivities are very large, is subsurface storm flow a feasible mechanism. On concave slopes with lower permeability, and on all convex slopes, hydrographs are dominated by very short overland flow paths from precipitation on transient near-channel wetlands. On these wetlands surface saturation occurs from below because of rising water tables that are fed by vertical infiltration rather than by lateral subsurface flow (Freeze, 1972).

The investigators mentioned above concluded that the dominant flow processes which contributed to storm runoff were overland flow which occurred where the water table reached the ground surface by one way or another, and direct precipitation into saturated zones and the main channel. However, a number of other investigators found that subsurface flow could contribute to storm runoff and have drawn different conclusions on the same subject.

Whipkey (1965)(b), for example, working in east central Ohio, presented a lot of information showing that subsurface flow could contribute to storm runoff. Whipkey's experimental work was carried out by applying artificial rainfall in a 17 x 1.44 m plot. Flows were measured from the ground surface and at depths of 56, 90, 120 and 150 cm. The artificial rainfall intensity varied from 17 to 51 mm/hour and was applied 24 times with dry and wet soil conditions. The total seepage for 24 hours ranged from 3-16% of the applied rain and it was higher with wet than with dry soil conditions.

The largest amount of the seepage occurred above the 90 cm because the silty loam layer at this depth served as a water-flow impeding layer. Very small and steady conditions of seepage were observed below this depth and also very small amounts of overland flow, especially at the beginning of the storm. Whipkey concluded that in coarse-textured soil the infiltrated water first travels downwards and when a finer textured layer is reached the water travels laterally over this impeding layer.

Whipkey (1969) drew the same conclusions about the existence and the quantities of subsurface storm flow especially as a contributor to storm runoff by using natural and artificial rainfall in plots which he constructed in forested slopes in the same area and in locations having a different soil type. One hundred and thirty simulated storms were made over a four year period with intensities varying from 12 to 76 mm/hr and duration varying from 60 to 150 minutes. Subsurface storm flow was observed in most of soil types and varied in silt and loam and in loam soil from 15 to 62% of the total rainfall. By contrast, no subsurface storm flow was observed from sandy soil. Another important conclusion from these studies was that subsurface storm flow came primarily from interconnected cracks and channels in layered fine-textured soils and was not a function of the hydraulic gradient and hydraulic conductivity of the soil in the forested catchment.

The fast movement of water through interconnected macro-channels formed by roots and animal burrows has also been stressed by other investigators (Gaiser, 1952; Aubertin, 1971;

Vries et al., 1978; German and Beven, 1981). Additional information on this process was obtained from the field work carried out by Beasley (1976). He set up two plots in the upper parts of the slopes of two forested catchments in the USA. One of them had an area of 540 m^2 and the other one of 680 m^2. Gutters were inserted to intercept overland flow and flows from the bases of the A and B horizons. During three years' study covering 36 storms, plot No. 1 which represented one-third of the total area of the first catchment generated 27% of the channel flow and plot No. 2 which represented one-third of the total area of the second catchment generated 26% of the channel flow. Beasley found that overland flow and flow through the A horizon were negligible, whereas most of the observed flow was generated from B horizon. The lag time was so short that the throughflow velocity exceeded 800 m/day. In order to explain this fast movement, Beasley proposed that water moved through macro-channels and not through the soil matrix.

Although the work mentioned so far has attributed little importance to the role of overland flow, it is worthy of mention that some investigators found this component to be significant for the storm hydrograph. Pierce (1967), for example, showed that overland flow did occur and that it contributed to the storm hydrograph. He analysed a summer storm hydrograph from a small mountain catchment and stressed that during the rain events, storm runoff as a result of overland flow may be occurring and therefore a closer examination of water disposal on the forest floor was necessary. New information on flow processes operating on a 18.3 x 44.8 m field plot at Stanford, California were obtained by Pilgrim et al. (1978). In the latter work radioisotope tracers were used and it was also found that in the same plot Hortonian and saturated overland flow, as well as rapid subsurface flow occurred simultaneously and made appreciable contributions to storm runoff.

In addition to studies in the USA, work on hillslope flow processes and storm runoff generation has also been carried out in many other countries around the world. In Canada, for example, a parametric study on rainfall/runoff relations for 38 storms in Eaton basin, southeastern Quebec, was carried out by Carson and Sutton (1971) between 1950 and 1966. This showed that saturated areas which developed near to the perennial channel network during the storms were extremely important in producing storm runoff in the ways suggested earlier by Hewlett and Hibbert (1967) and Dunne and Black (1970a,b). In Japan, subsurface flow, especially through macropores, was detected by Tsucamota (1961) who applied artificial rainfall in two small plots, while the runoff on litter's surfaces was negligible.

Important work has also been undertaken by Mosley (1979) in a small (0.3 ha) experimental forested catchment in New Zealand. He found that the dominant flow process was subsurface storm flow mainly through macrochannels (root channels). Mosley measured the flow velocities using a practical method (Mosley 1969, 1982) and found that they were much higher than the saturated hydraulic conductivity. Mosley's important finding, however, was that subsurface flow from all parts of the catchment contributed to storm runoff, even during very small storms. Mosley concluded that "stream flow is at almost all times dominated by subsurface flow and that runoff from partial and variable source areas contributes significant quantities of stream flow only during the rising limb of the stream flood hydrograph."

The field work carried out by Bonnel and Gilmour (1978) in Africa is another example which indicated that the variable source area concept was not valid in that particular catchment. Subsurface flow and especially saturated overland flow were the dominant flow processes which contributed to storm runoff. Storm flow was not generated from variable or partial source areas, but from widespread parts of the catchment. Despite the fact that the hydraulic conductivity of the upper 20 cm of the soil profile was high, the intensity of the rainfall was enough for the water to reach the ground surface and move as saturated overland flow after the occurrence of a perched water table.

Versfeld (1981), using small plots (0.07 ha) located in South Africa, tested the effect of treatment - such as burning or hoeing of fynbos and thinning of plantations - on the occurrence of overland flow. He found that the occurrence of overland flow before and after the treatment was negligible, even with large storms (>125 mm).

Some work on hillslope processes and their relation to the stream hydrograph, was carried out by Weyman (1970, 1973, 1974) in the UK. The catchment area was 0.21 km^2 and the upper part (0.11 km^2) was occupied by peaty podzol, while the slopes (0.1 km^2) were covered by brown earth soil. Weyman showed that runoff from the hillslopes in the form of saturated and unsaturated throughflow produced the main response of the basin to rainfall. The amount of runoff increased as saturated conditions extended uphill. However, this runoff could not be regarded as storm flow because the velocity was very slow. Also overland flow from the hill-slopes did not contribute to quick response in the stream. As far as the upper basin was concerned, Weyman found that the runoff processes were overland flow and flow near the surface of the ground. These runoff processes in the upper basin were responsible for the true storm hydrograph. Furthermore, the headwater and channel areas were emphasized as source areas for storm runoff.

Additional work in the UK has been carried out by Arnett (1974). He studied the environmental factors which affect the spatial and temporal speed and also the volumes of topsoil interflow. Arnett worked in two adjacent plots 6.5 and 4.5 ha in area. Flows from the A and B horizons and from nine and six sites of the first and second plots, respectively, were intercepted. He found that the annual volumes of each site showed a wide variability and that no increase of interflow was observed as a result of lengthening of catchment areas. The variability of interflow was attributed to the cracking of the topsoil combined with the lateral distribution of living and dead Bracken rhizomes.

Piping is another phenomenon which has attracted considerable attention in the UK. Jones (1971), considered the movement of water through the soil by pipes and stressed that, "Piping is clearly a widespread phenomenon in the British Isles and seems likely to be a characteristic of humid, temperate regions and of semi-arid areas, if not more so." Work on the rate of pipe flow in subsurface water movement has also been done by the Institute of Hydrology (1972) in an experimental catchment in central Wales. It was shown that ephemeral pipes carry large quantities of water during and after rainfall. It takes some time, however, before they start responding to rainfall until "a storage deficit has been satisfied". It was found that ephemeral pipes carry about 20% of the total rainfall measured in the catchment area and hence it was considered that pipe flow represents a dominant runoff process.

From the present review it is apparent that the flow processes which contribute to storm runoff are:

1. Hortonian overland flow, where the rainfall rate exceeds the infiltration rate of the soil and the excess rainfall flows over the ground surface.

2. Expansion of the channel system during storms to tap subsurface flow systems and permit overland flow from "variable source areas".

3. Saturation overland flow from "partial source areas" when the water table reaches the ground surface, often near channels and in areas with a thin A horizon.

4. Subsurface flow of infiltrated water moving through the soil mantle or through macropores towards the channel system.

The most important finding, however, seems to be the complexity of the various processes and the little information about the relation between them and the conditions under which each flow process is likely to occur. Some of the processes may occur in a given catchment and it is probable that different processes or groups of them may be dominant in different catchments especially when different climatological and geological conditions exist (Pilgrim et al. 1978). In addition, the areas of the catchment -

if not the whole catchment - which produce storm runoff, regardless of whether the term variable, partial or dynamic watershed has been used to describe, are clearly quite scattered. So, a number of investigators have questioned the different results obtained by other investigators who carried out field work in catchments with the "same" conditions. Also the variety of the observed flow processes urged many investigators to suggest additional field work on this subject. Dunne and Black (1970a), for example, questioned Whipkey's (1965) conclusions that lateral movement of water through the soil horizons can contribute to storm runoff. Dunne and Black found that subsurface flow was not important and moreover, their area was not "too different from that of Whipkey to invalidate comparisons". However, Dunne (1980) himself later admitted that "differences of emphasis between studies of runoff reflect the physical geology of the region where the studies were carried out and the various models of runoff are complementary and not contradictory". Furthermore, Kirkby and Chorley (1967) discussing the applicability of Horton's and throughflow model, stressed that "these ideas are proposed not to replace those by Horton, but rather to supplement them by providing the other end-member of a continuous spectrum of possible flow models". In addition, Pilgrim et al. (1978) when he found - as discussed earlier - that in the area of the same plot Hortonian and saturated overland flow - as well as rapid throughflow - occurred, reported that his results were in contrast to the findings of previous studies which were carried out for the most part in eastern USA, often with forest cover, or in the UK in areas with high total, low intensity rainfalls. Pilgrim concluded that "knowledge of the paths of water from precipitation on the ground surface to runoff in stream channels is still limited, despite growth of interest in the process involved" and that sweeping generalizations on runoff processes for a given area are not justified. Similarly, Ward (1974) considering the various locations of the observed "variable and partial source areas" in different catchments, concluded that "the work that has been done tends to confirm Hewlett's basic concepts, although it is to be hoped that further field work will be initiated in order to provide additional evidence about this problem".

As far as the UK is concerned, little work has been done on the flow processes occurring in individual mountain catchments (Weyman, 1970, 1973, 1974; Arnett, 1974) and the conclusions drawn, as discussed earlier, are at variance. In this context, it must be mentioned that the most intensive experimental work in the UK is being carried out in a catchment at Plynlimon in Wales by the Institute of Hydrology. It is worthy of note, however, that despite the fact that the two basins of the rivers Wye and Severn are essentially identical in geological and geomorphological terms (Kirby et al. 1974), one is covered with coniferous forest, while the other is used as sheep pasture. Hence the question arises as to their comparability. However, geology, vegetation and soils are not the same everywhere, and so it is not at all certain that the hydrologic conditions will be the same. Such information is very important because of pressure to change land-use in many upland areas partly for hydrological reasons. This is a pressing problem in Scotland where no work on upland flow processes has been published to date. The purpose of the rest of this thesis is to present the results of a study undertaken in an upland area in southern Scotland as a contribution towards achieving a better understanding of the hydrology of such an area. This presentation falls into four parts. It starts with a description of the study area. This is followed by a description of the instruments used and the modifications made to them to make them adaptable to the rugged terrain of the catchment and also an account of the experimental methods employed. A further section presents the results derived from the experimental work during two field seasons. Finally, the conclusions drawn from the study are presented and discussed.

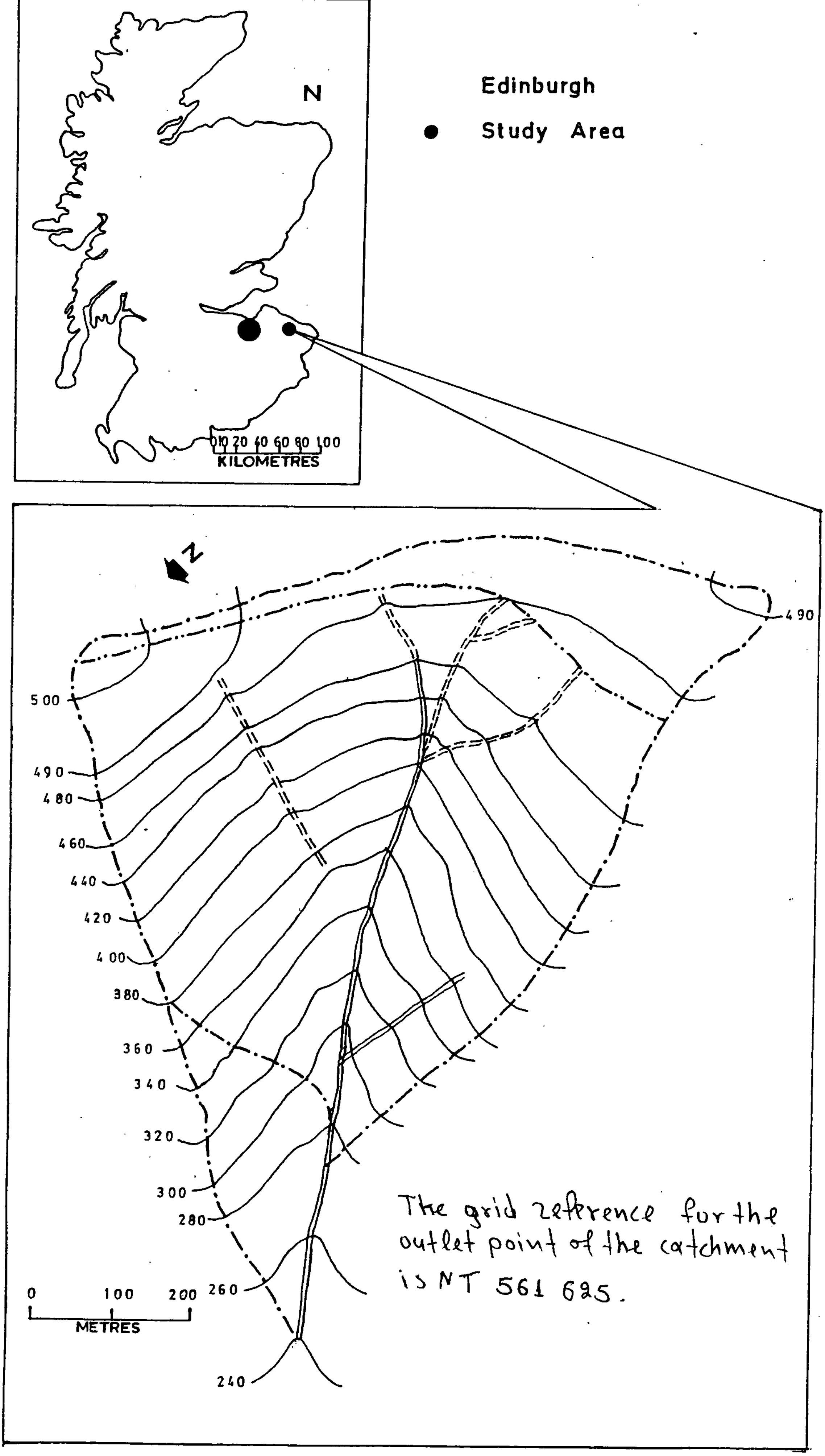
PART II: THE STUDY AREA

2.1 LOCATION AND SELECTION OF THE STUDY AREA

The work reported in this thesis was carried out in a first order upland catchment in the Lammermuir Hills, an area which is located in southeast Scotland about 40 km east of Edinburgh (Map 1). The area covered by the catchment lies between longitude 2° 41' 30" to 2° 42' 10" W and latitude 55° 50' 25" to 55° 51' 10" N.* The catchment was chosen for study for the following reasons:

1) It is an area where information on runoff generation processes would be useful locally. This is because the catchment is located in the headwaters of a river that frequently floods the town of Haddington further downstream. Many of the people who have been affected by these floods believe that they are caused by excessive overland flow during heavy storms in the headwater areas. It is believed that these areas are overburnt and overgrazed, and so if the land-use was changed, overland flow would be reduced and floods would be less damaging (East Lothian County Council, 1957).Up to now, however, there is no evidence to substantiate this claim and it is possible that overland flow may not be a problem at all.
2) The catchment is typical of many other upland areas in south Scotland in terms of relief and land-use, as they will be described later.
3) The catchment is not far from Edinburgh and offers easy access to an individual research worker based in the city.

*The grid reference for the outlet point of the catchment is NT 561 625.

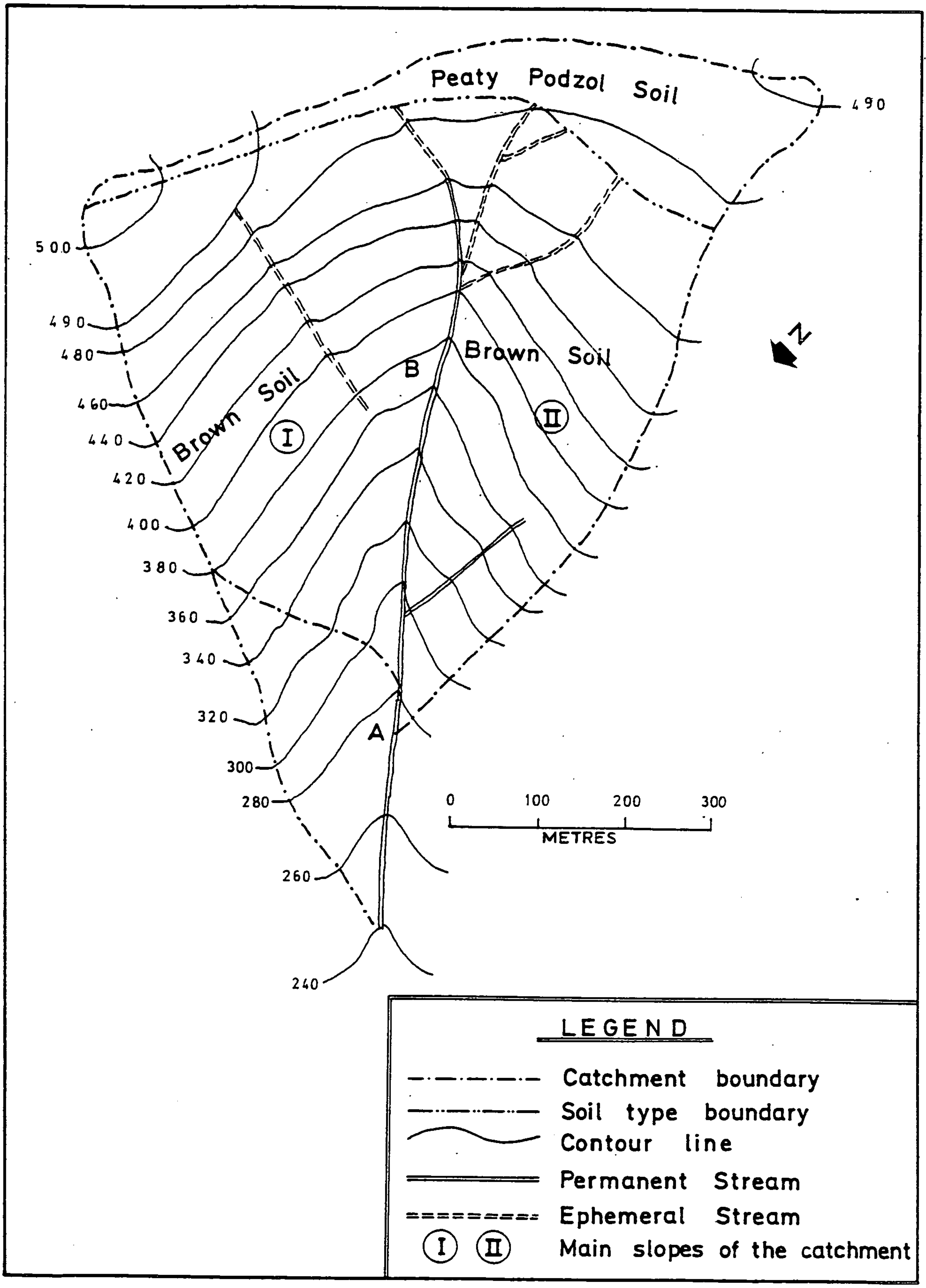


Map 1. Catchment where the work was carried out.

4) It was known that permission to work in the area would be given readily.
5) The catchment has a ready-made stream gauging site located at its outlet point. The importance of such features has been emphasized by Newson (1983).
6) The hillside is reasonably accessible for transportation of instruments, equipment and materials because of the existence of tracks built for farming and other purposes.

2.2 ALTITUDE AND GENERAL TOPOGRAPHY

The study area is approximately triangular (Map 2, Plate 1), and the altitude ranges from 275 to 510.00 m. The catchment occupies an area of 36.5 ha and consists of two main slopes (I and II). The aspect of slope I ranges from 280° to 325° and that of slope II from 325° to 355°. In both slopes and along the stream channel from points A to B (Map 2) there is a narrow zone with gradient ranging from 8° to 10°. Above that, the gradient increases generally from 30° to 33° up to approximately 480 m altitude, and then decreases gradually until at the top of the catchment the area is almost flat. It should be mentioned that the area of the slopes is not uniform, but there are locations with gradient lower than 30° and locations with gradient higher than 33°. At this point it is worthy of note that on slope I above the narrow zone along the stream channel, the surface is very stony and the stones may have been accumulated from the upper and steeper part of the slope. In addition, it must be emphasized that the lower part of the same slope has convex contours and the precipitation, regardless of whether



Map 2. Characteristics of the study catchment.

Plate 1: General view of the study catchment.

it moves as overland flow or throughflow, is diverted by the topography to the stream channel where, as was mentioned earlier, there is a ready-made site for installation of a water level recorder.

2.3 GEOLOGY AND SOILS

Ragg et al. (1967) and Jennings (1980) have given detailed descriptions of the geology and the soils of a wide area of East Lothian, including the catchment under study. In the catchment where the experiments in the present thesis were carried out, the solid rocks (Ashgill, Caradoc and Arening) are Ordovician sediments and the soils have been developed from stony drifts. On the side slopes of the catchment, a freely drained brown earth has been developed. This soil type occupies 28.5 ha or 78% of the study area. The A horizon is a dark reddish-brown loam with moderate organic content and abundant roots. The depth varies from 0-10 cm. Below the A horizon there is a clear change into a reddish-brown B horizon with low organic content, and having a depth of 10 to 25 cm. Below this depth there is a sharp change into the C horizon which consists of weathered material. The depth to the C horizon varies from 25 to 90 cm. A peaty podzol has been developed in the headwater area, having an average depth of 30 cm. This soil type occupies 5.7 ha or 16% of the catchment area. The B_1 horizon generally contains a thin iron pan, often continuous, which is impermeable to water and roots. The B_2 horizon is bright coloured, the B_3 is paler and there is little or no evidence of gleying in either horizon. It is worthy of note that there is no distinctive soil type formation in the area along the main stream channel and this flat valley bottom must be the result of floods which occurred in the past. This area represents c. 2.3 ha or 6% of the catchment area.

2.4 CLIMATE

At present, there are no meteorological memoranda for the specific upland catchment where the experiments were carried out. However, a description of the climate of the wider area of the catchment was given by Dight (1968).

The first half of the year is usually dry or very dry with spring tending to be prolonged and cool, as a result of the influence of haar and easterly winds blowing off the North Sea. April to June is the sunniest quarter of the year, but the late summer can be very wet. Autumn is frequently mild and warm, due to the westerly winds which predominate at this time of year. In addition to this general picture of the climate, information from the nearest lowland meteorological stations was used for the description of the elements of the climate. Rainfall is, of course, relevant to the subject of this thesis, but information on wind, air temperature and evapotranspiration is also necessary to complete the general picture of the climate in the catchment. The fact that the rainfall pattern is closely linked with the wind regimes, necessitates a description of the prevailing winds first.

2.4.1 Winds

Southwesterly winds are the dominant winds in southeast Scotland. However, the powerful funnelling effect of the Forth-Clyde valley alters the situation in the study area quite a lot. Warm south to southwesterly winds are not easily steered into the region, while the blustery, colder west-southwest to west-northwest winds which generally succeed them are normally funnelled in and are responsible for most of the strong winds and gales which occur mainly in autumn and winter. The wind speed usually varies from force 1 to force 6 [(2-6) to (46-57) km/h]. Apart from this annual picture, there is a pronounced seasonal pattern of winds. From April to June there is a marked predominance of winds from northwest to east, associated with high pressure to the north. Northerly winds during this period are rare, but when they occur they are frequently to gale force. Winds of force 7 to 12 [(59-70) to 141 < km/hr] occur from January to May, coming from the north and east (Johnson, 1952).

2.4.2 Precipitation

Average monthly precipitation from the rainguage at West Hopes which is very close to the study catchment and at an altitude of 247 m, is presented in Table 1.

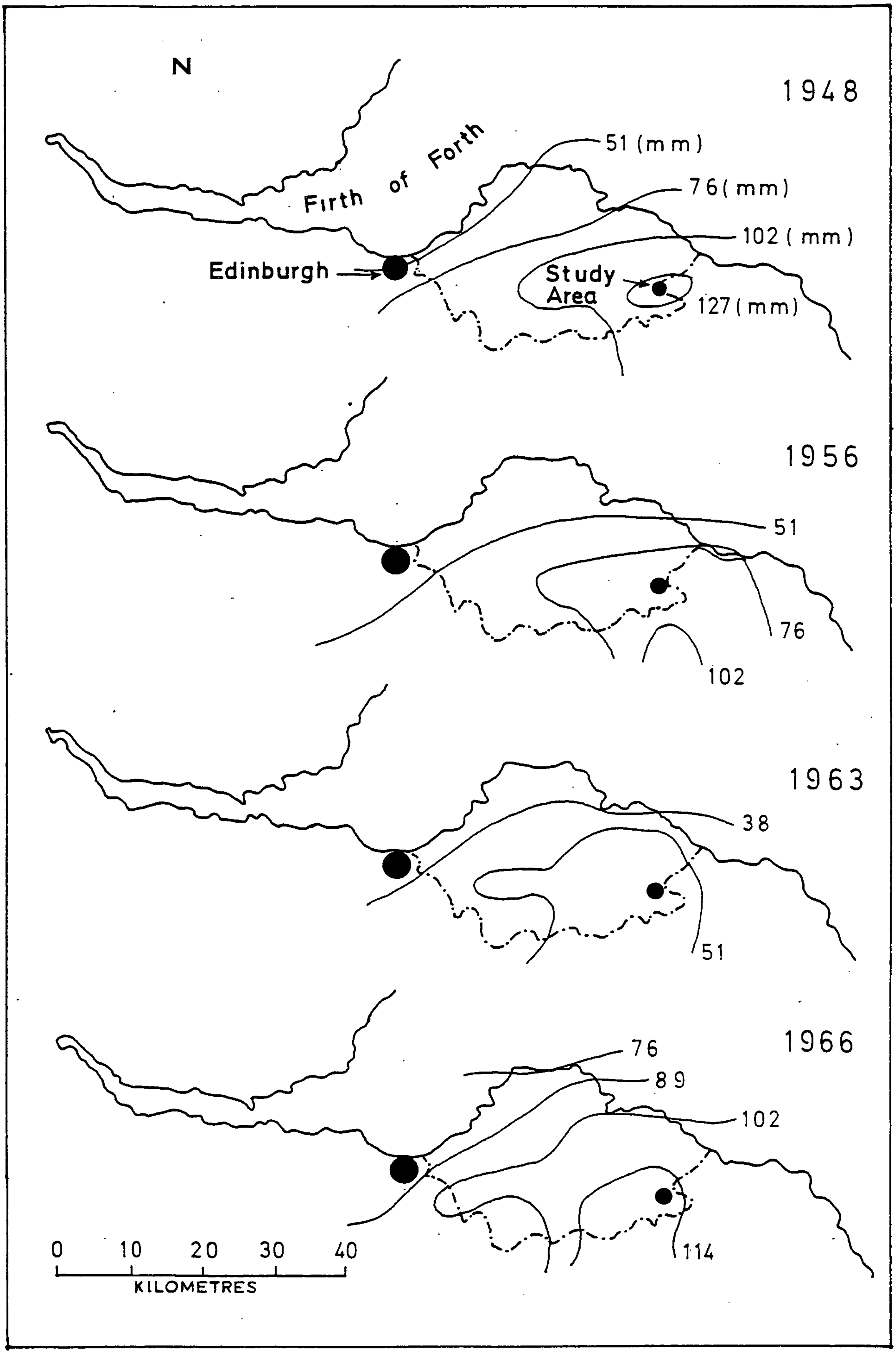
Month	J	F	M	A	M	J	J	A	S	O	N	D	Annual Total
(mm)	88	62	60	60	73	61	83	94	81	96	92	81	931

Table 1. Average monthly precipitation at West Hopes (1916-1950)

This shows that the area has a mean annual precipitation of just under 1000 mm.

March and April are the driest months, while August, October and November tend to be wetter than the mean monthly average (78 mm).

Despite the fact that the area is not particularly wet, it does from time to time experience intense and prolonged rain. This usually occurs when the polar front is very far south so that unstable maritime air streams southwards across the British Isles (Meteorological Office, 1964) and under such conditions non-frontal depressions tend to form off the west coast and hence give rise to heavy rainfall. Under such conditions, southeast Scotland also suffers the full force of orographic rainfall from onshore winds sweeping into the depression. As the depression moves across the British Isles, the heavy rain wheels anti-clockwise and continues to affect the same region for a long time (Learmonth, 1950; Rodda, 1970). These periods of heavy rainfall generally occur in August (Mossman, 1896). Map 3 shows a selection of these heavy rain events, most of which produced severe flooding problems in the lowlands and in the town of Haddington. The most severe event on record took place during the 6th to 12th August 1948, when heavy rain fell in the catchment under study and the surrounding areas and 140 mm of rain was recorded at Haddington. This amount represented 25% of the annual rainfall. Learmonth (1950) estimated that approximately 1,500 tonnes (150 mm) of water fell on each hectare of the study area during that storm. On several other occasions, the rainfall in the uplands has approached or exceeded 100 mm during such storms.



Map 3. Flood rainfall in East Lothian over period of continuous downpour. (East Lothian County Council, County Planning Department.)

2.4.3 Temperature

There are no temperature records for the study area and therefore records from the nearest meteorological stations will be used. For this purpose, the stations of North Berwick, Haddington, Marchmont and Whitchester were chosen to show the average monthly mean temperatures. These records are presented in Table 2. For the study area, however, the effect of altitude must be taken into account since the altitude ranges from 250 to 510 m. At Whitchester, for example, which is 255 m above sea level, the average minimum temperature for December, January and February was -0.1, -1.5 and -1.6 degrees Celcius, respectively, but for the study area the temperature during these months must have been much lower. Evanescent coverings of snow occur sometimes in the late autumn or early winter, but snow coverings are more common in late winter. The days of "snow lying" per year may range from 35 (at the bottom of the catchment) to 50 or more at the top (Ragg et al., 1967).

2.4.4 Evapotranspiration and Water Balance

The lack of any hydrologic information for the catchment under study makes description of the meteorological elements of the climate very difficult. However, the monthly evapotranspiration and water balance conditions can be computed by using the average monthly rainfall records from the nearest raingauge at West Hopes (Meteorological Office, 1964) and the mean monthly potential evapotranspiration (Ledger and Thom, 1977). This information is presented in Table 3.

MONTH	NORTH BERWICK (36 m)			HADDINGTON[1] (49 m)			MARCHMONT (152 m)			WHITCHESTER[2] (255 m)		
	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN
JANUARY	6.0	0.5	3.3	5.4	-0.8	2.3	5.1	-0.4	2.3	3.8	-1.5	1.2
FEBRUARY	6.6	1.0	3.8	6.3	0.1	3.2	5.8	-0.3	2.8	4.3	-1.6	1.4
MARCH	8.7	2.1	5.4	8.5	1.3	4.9	8.2	1.1	4.7	6.8	0.3	3.6
APRIL	11.5	3.7	7.6	11.7	3.1	7.4	11.0	2.9	6.9	10.4	2.0	6.2
MAY	13.9	5.9	9.8	14.2	5.2	9.7	14.1	5.2	9.7	13.5	4.4	9.0
JUNE	16.9	8.6	12.7	17.6	8.2	13.0	17.2	8.1	12.7	16.1	7.6	11.9
JULY	18.7	10.8	14.7	19.0	10.1	14.5	18.7	10.2	14.5	17.6	9.5	13.6
AUGUST	18.4	10.7	14.5	18.2	10.7	14.5	18.3	9.8	14.1	17.1	9.2	13.2
SEPTEMBER	16.5	9.0	12.7	16.5	8.1	12.3	15.9	8.0	14.9	15.0	7.4	11.2
OCTOBER	12.8	6.4	9.6	12.6	5.5	9.1	12.1	5.3	8.7	11.3	5.0	8.1
NOVEMBER	9.4	3.6	6.5	8.9	2.2	5.5	8.4	2.4	5.4	7.4	1.8	4.6
DECEMBER	7.3	2.1	4.7	6.5	0.8	3.7	6.3	1.0	3.6	6.6	-0.7	3.1
YEAR	12.2	5.4	8.8	12.2	4.5	8.3	11.8	4.5	8.1	10.8	3.6	7.3

Table 2. Average mean temperature ($^{\circ}$C). Period 1931-1960.

Notes: 1. Considerable weighting

2. Actual means 1946-1961

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean monthly precip. (mm)	88	62	60	60	73	61	83	94	81	96	92	81
Mean monthly pot. evap. (mm)	0	9	28	52	79	88	83	66	41	21	4	0
Difference (mm)	88	53	32	8	-6	-27	0	28	40	75	88	81
Cummulative deficit (mm)	-	-	-	-	6	33	33	-	-	-	-	-
Surplus precit. (mm)	88	53	32	8	-	-	-	28	40	75	88	81

Table 3. Water balance for West Hopes.

This shows that there is, on average, a period of soil moisture deficit from May until the end of July. Soil moisture is recharged again by the end of August when late summer rain begins. From October until the end of April precipitation is in excess of that required to bring the soil up to field capacity and may go as overland flow or through the soil to produce runoff or to replenish underground water supplies. It must be stressed, however, that potential moisture deficits for this part of Scotland, as Ledger and Thom (1977) indicated, may be much higher during dry years with less than average summer precipitation.

2.5 VEGETATION AND LAND-USE

The greater part of the catchment is covered by heather (Calluna vulgaris) and the area along the stream channels by bracken (Pteridium aquilinum). There are also a number of pasture grasses such as Agrostis tenuis, Festuca ovina, Festuca rubra and Vaccinium myrtillus was locally abundant on the peat. In slope II, from the outlet of the catchment and near the stream channel, there is a zone approximately 200 m in length and 50 m in width covered by broadleaved trees (beech, birch, ash and sycamore). The area is used to graze a large number of sheep (∿500). They live out on the hill all year round, and during bad weather conditions they have to make the most of whatever shelter they can find. Grouse shooting is another important use of the study area. The shooting begins in September and ends at the end of October. The combination of the two land uses - grazing and grouse-shooting - together with the burning of small patches of heather each year during May and June, makes the area look like a macro-mosaic of burned and green zones.

Taking into account the previously described geology, climate and land-use of the study area, it becomes apparent that the area is typical of the Lammermuir Hills as a whole and, indeed, other upland areas in southeast Scotland.

PART III: INSTRUMENTATION AND METHODS

3.1 INTRODUCTION

As was stated in the introduction, the purpose of the research reported in this thesis was to study hillslope flow processes in an upland catchment and also to explain qualitatively how the rain falling in it is converted to storm runoff. For the fulfilment of these purposes it was recognized from the beginning that data would be needed on:

a) the nature of the hydrographs of runoff from the catchment as a whole;

b) the processes in various parts of the catchment.

Also it was recognized that a number of constraints existed and were relevant to:

a) the lack of background information on the catchment's hydrology;

b) the work had to be done by one research worker with limited facilities and within two field seasons.

Furthermore, it was found impossible for any field work to be carried out in the winter because of problems of access and possible damage to equipment by frost.

Under these limitations it was decided that the first field season be spent on finding out as much as possible about the catchment and the techniques likely to yield the most useful results with the resources available; and the second field season following up the experience and findings of the early work.

3.2 FIRST FIELD SEASON'S EXPERIMENTAL WORK

3.2.1 Installation of Equipment to Measure Catchment Rainfall and Runoff.

It is apparent that in any study of the rainfall runoff response of a catchment area, accurate data are required on the rainfall input and runoff output of the area concerned. In the study catchment neither of these was already being measured. Thus, installation of equipment to do so was a necessary step in the investigation.

3.2.1.1 Installation of a Rainguage Network. The difficulties in measuring rainfall in rugged terrain have been long recognized and much work has been carried out (Fourcade, 1942; Hamilton, 1954; Aldridge, 1976; Sevruk, 1974; Hibbert, 1977; Sharon, 1980) in order to find suitable methods to overcome them. The difficulties are associated with the observed variations of the rainfluxes. The sources of the variations are the inclination of the rainfluxes falling on sloping ground and the uneven distribution of them before they reach the ground surface (Sharon, 1980). The latter source of variation of course affects the accuracy of the measurements on flat ground as well, but this problem is more serious in mountainous regions where storms are often accompanied by strong winds.

Since the topography of the study catchment was very complex and most of it was exposed to wind, rainfall measurement needed particularly careful consideration. One of the first problems to be resolved was whether to use inclined or vertical gauges. The use of vertical or inclined rainguages for sampling rainfall in sloping ground is a subject still under debate. Hamilton (1954),for example, who used vertical and tilted gauges in the mountains of southern California concluded that "Tilted gauges should be expected to provide a closer approach than vertical gauges to the true volume of precipitation sample of the various slopes and exposures existing in the drainage area study." Other investigators have given different reasons why they applied inclined rain-gauges and generally there is a diversity of opinions about the reliability and accuracy of them. Hayes and Kittredge (1949) for instance reported that inclined gauges provided the best measure of true rainfall because at some sites where vertical and inclined gauges were set up in pairs the inclined gauges caught more rainfall than the vertical. Hibbert (1977) characterized the measurements with inclined gauges as superfuous because many inclined gauges caught less than vertical ones at the same site.

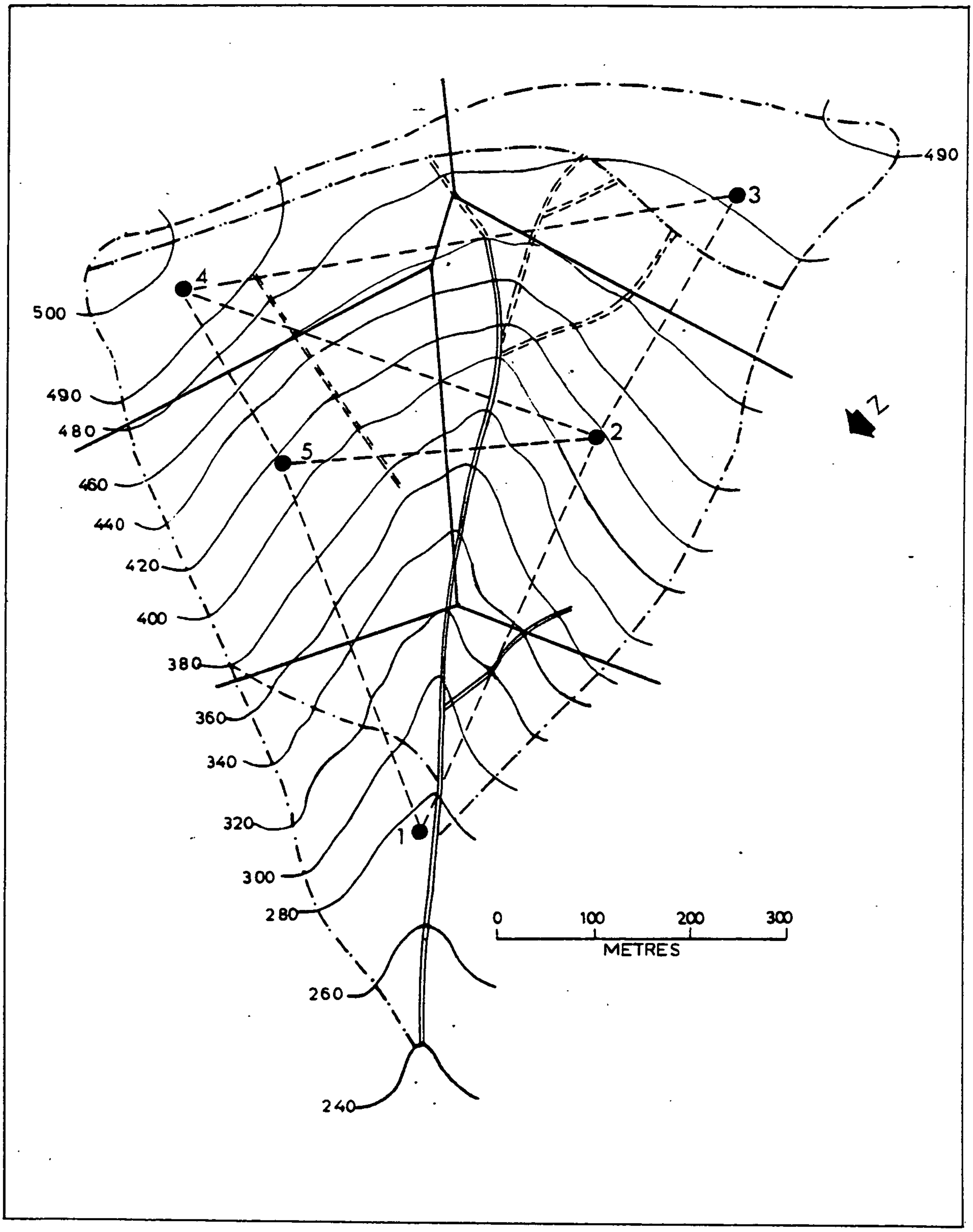
A recent detailed work with vertical and inclined gauges has been carried out by Sharon (1980) in Israel. He computed the rainfall of a catchment having rugged terrain using vertical raingauges by measuring a number of parameters relevant to the inclination and direction of the rainflux and by applying these measurements to a trigonometrical model. Direct measurements were also taken from inclined gauges and they were compared with the values obtained from the model. Sharon reported that the applicability of his model required accurate measurements of the rainfall inclination and direction. However, since the latter is rarely possible in mountainous regions he concluded that in rugged terrain "inclined gauges are often the easiest way to obtain accurate results".

As mentioned earlier, the other source of variation of the rainfall, especially in windy mountainous regions, is the distribution of the rainfall in the air before it reaches the ground surface. Variations of this type have been measured by Mink (1960), Hovind (1965), Aldridge (1975) and no satisfactory explanation for them has been given yet. Hovind (1965), for example, reported that when the air strikes a steep slope horizontally, a component of it moves upslope with less velocity than the original horizontal. The low velocity of this component affects the redistribution of the raindrops and specifically, drops having a small diameter do not reach the ground surface simultaneously with the largest ones but are deposited in a different place. It has been reported (Hovind, 1965) that windward slopes and high locations exposed to strong winds receive less rain than others which are better protected from winds. The height of the raingauge itself creates more problems and contributes to the redistribution of the raindrops, since turbulance and eddies are produced when the wind strikes it (Rodda et al., 1976). This means that some raindrops are blown away from the orifice of the gauge and the amount of rain which reaches the ground would be larger if the raingauge had not been there.

All the techniques used so far to overcome the effect of the wind in raincatching in exposed sites have been described in detail by Rodda (1976). Fences, for example, were used in the USSR and shields in the USA. Some raingauges were set in pits and a large number of comparisons in rain-catching were made between gauges lying with their rims at ground level. However, it was recognized that it was impossible to know the error between the rain reaching the ground and the rain caught in a gauge at a particular point. In general, however, it is now accepted by hydrologists that raingauges installed with their rims at ground level give the smallest error between true and measured rainfall. For this reason it was decided to adopt this method for the present study. Experiments carried out in the UK and in other countries suggest that this difference varies and is highest in windy mountainous regions. In the UK this difference has been found to vary from 3.2% (Green, 1970) to 6.6% (Rodda, 1967) for annual totals, but differences up to 20% (Rodda et al., 1976) have been reported in the literature for other areas.

The next step after the decision to use ground level raingauges was the installation of a network by which the mean rain over the catchment would be estimated accurately with manageably small number of gauges and a minimum of computing. In the light of the experience gained by the Institute of Hydrology at Plynlimon (pers. comm.) it was decided to design a network that would be suitable for analysis by the Theissen polygon method and would at the same time take account of the altitudinal and aspect differences in the catchment (Map 2) that could be expected to affect rainfall distribution in the area. The chosen raingauge network is shown in Map 4.

In each location a non-recording raingauge was installed



Map 4. Diagram showing how polygons were constructed for estimating weighted rainfall.

vertically with its rim 2 cm above the ground in order to avoid any problems of surface water moving downslope during heavy rain events. These were standard gauges (Meteorological Office mk 2) having a collecting funnel with an aperture of 127 mm in diameter. A rectangular frame made of zinc, 10 cm in height and 50 cm in length, was fixed around each gauge and was filled with soil covered with grass in order to avoid the problem of splashing (Plate 2, A,B). The grass was kept very short in the areas within the frame. Measurements were usually taken weekly, except in cases of heavy rain events when readings were taken after the rain stopped.

In addition to non-recording raingauges, locations 1 and 3 were also equipped with Casella Siphon type recording raingauges (diameter 203 mm) to record the variation of the intensity of the rainfall with time. These were chosen to provide data for the sites whose results were expected to differ most. In location 1 the recording gauge was installed with its rim 43 cm (17 inches) above the ground level. In location 3, which was highly exposed to winds, efforts were made to install the recording gauge at ground level, but the soil was stony below 30 cm making digging impossible below this depth. The gauge was therefore installed with its rim lying 13 cm above the ground level. The charts of the recording raingauges were changed every Monday when measurements were also taken from the non-recording raingauges.

Finally, it must be mentioned that in locations 1 and 3 a standard raingauge was installed with its rim 30 cm

(A)

(B)

Plate 2: Recording raingauge, standard non-recording raingauges with standard and ground level exposure, and funnel gauge, at (A) site 1, and (B) site 3.

above the ground level. The latter raingauges were installed to provide information on the difference in raincatch between raingauges with their rims 30 cm above ground level and those with their rims at ground level. With the exception of location 1, all other locations were fenced after the installation of the raingauges to prevent possible damage by sheep.

3.2.1.2 Installation of Hydrometric Station. As was indicated in Part II, one of the reasons for selecting the study area was that a ready-made gauging site already existed on the stream flowing from it. This consisted of a masonry-lined rectangular channel built to convey the stream to Hopes Reservoir which was approximately 1 km away. The channel was equipped with a Munroe vertical drum-type water level recorder. This was installed on 8th July 1981. The chart was checked weekly. Accumulation of gravel or soil at the site of the water level recorder was not a problem. This was due to the fact that the stream channel had a low gradient for some distance before the instrument and hence any amount of eroded gravel or mass of soil could be stopped in this area. However, the site was checked and cleaned frequently in case there was some accumulation of gravel or soil, especially after a rain event. This helped to avoid any systematic error in the stage readings.

A stage discharge relationship was established after 32 measurements had been made in a cross-sectional area very close to the water level recorder. Twenty-eight of the measurements were made using a current meter and another four were made with a collecting vessel of known volume and a stopwatch when the discharge was low during the summer. The experimental points were plotted on a Log-log paper and a best-fit line through the points was drawn using the least squares method (Figure 3). The stage discharge equation thus found was used to compute the flow rates from the stage records. Most of the measurements were made when the water stage was below 17 cm. Only on a few events did the water level rise higher than this, by far the most notable being on October 2nd 1981 when the height rose to 44.5 cm. One discharge measurement was made when the stage height was 33 cm on the 2nd October 1981, but unfortunately the highest discharge was not measured. Two reasons contributed to this misfortune. First, the stage rose during the night and second, the author was unable to visit the catchment as a result of an accident he had on the morning of the 2nd October 1981. Even at the stage height of 44.5 cm the flow was still contained within the rectangular artificial channel and there was no reason for supposing that any change in the gradient of the stage-discharge relationship occurred between this level and that of the highest gauged discharge. Extrapolation of the relationship to cover this high event could therefore be expected to produce a good estimate of its discharge. In addition, the good relation between discharge and water stage obtained for up to 33 cm (correlation coefficient $r = 0.99$ from Fig. 3) was taken into consideration for the extrapolation.

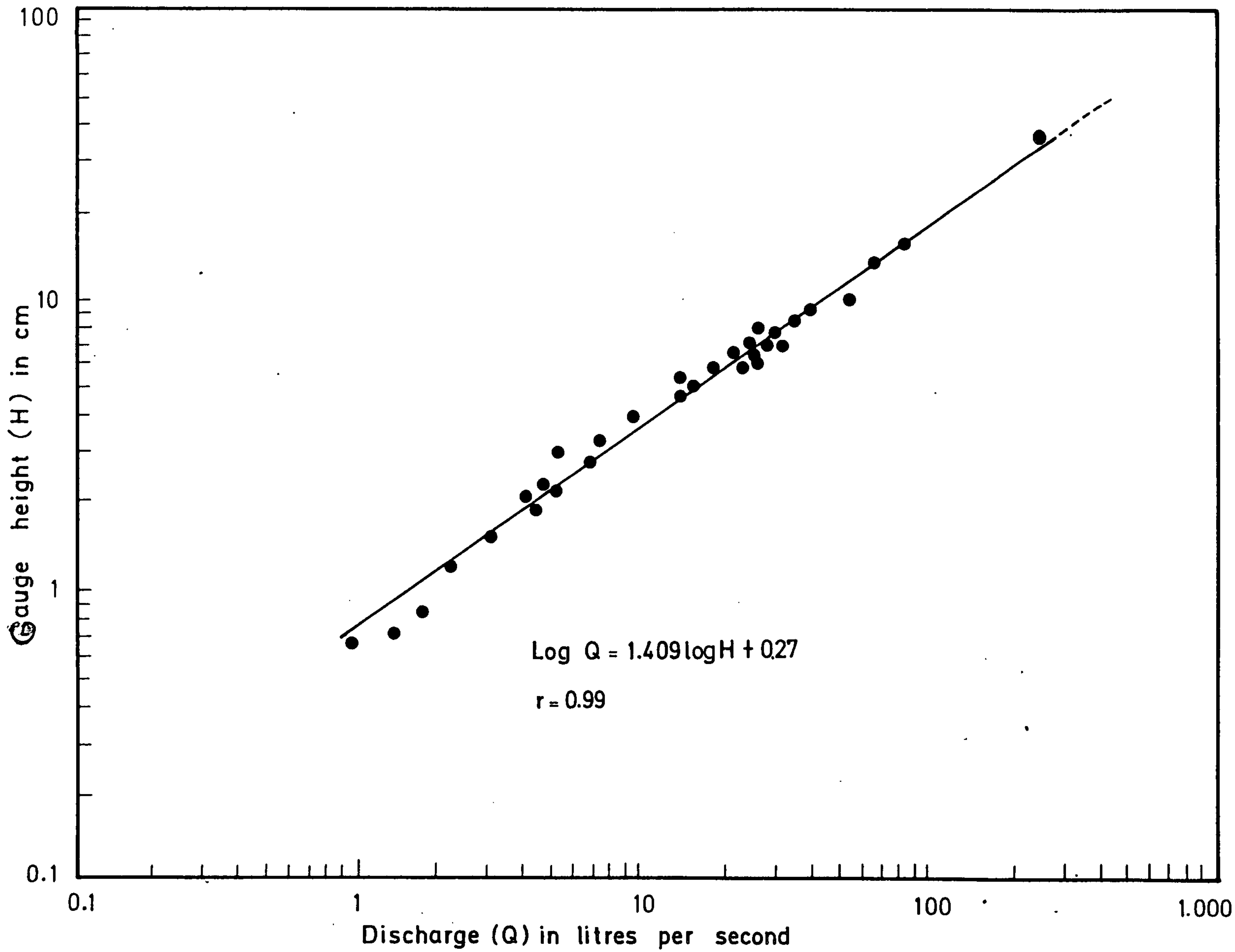


Figure 3. Relationship between discharge and gauge height.

3.2.1.3 Appraisal of the Rainfall and Runoff Data Collected During the First Field Season. Having described the installation of the raingauge network and the hydrometric station, it is now important to appraise the rainfall and runoff data obtained during the first field season. Table 4 shows the weekly weighted rainfall and runoff in mm from the beginning of July to the end of October 1981. Daily runoff for the first seven days of July was taken to be equal to the runoff on 8th July 1981. This was because, as mentioned in the previous chapter, the water level recorder was installed on 8th July 1981. This table shows that over the four months the rainfall totalled 374 mm and the runoff, 131 mm, or 35% of the rainfall. Thus, evapotranspiration losses during this period were 243 mm. Taking into account that Ledger et al. (1977) have estimated mean potential evapotranspiration for this period in East Lothian as 211 mm, as well as the fact that potential evapotranspiration from April to September was found to be 401 mm in the same area (Ministry of Agriculture, Fisheries and Food, 1967), the above amount of evapotranspiration (243 mm) seems reasonable. A consideration of the weekly values of rainfall and runoff reveals that runoff was smaller than rainfall for the largest part of this period. In fact it started decreasing gradually from the beginning of July and reached a minimum and almost constant value ($\sim$1 mm per week) at the beginning of August. For two weeks (from 26th August 1981 to 8th September 1981) there was no rain, but the amount of runoff was unchanged from that of the previous week. This implies that runoff during this period must have been generated only from

Dates	Rainfall (mm)	Runoff (mm)
1-7-81 7-7-81	5.1	3.35
8-7-81 14-7-81	5.1	2.9
15-7-81 21-7-81	12.0	1.7
22-7-81 28-7-81	41.0	5.8
29-7-81 4-8-81	5.6	1.5
5-8-81 11-8-81	6.0	1.0
12-8-81 18-8-81	5.2	1.1
19-8-81 25-8-81	9.6	1.0
26-8-81 1-9-81	0	1.1
2-9-81 8-9-81	0	1.0
9-9-81 15-9-81	22.1	1.9
16-9-81 22-9-81	45.9	2.9
23-9-81 29-9-81	72.4	19.4
30-9-81 6-10-81	81.8	61.3
7-10-81 13-10-81	37.0	10.3
14-10-81 20-10-81	5.3	5.6
21-10-81 27-10-81	3.6	5.6
28-10-81 31-10-81	16.1	3.2
TOTAL	374.0	131.0

Table 4. Weekly rainfall and runoff during the first field season

groundwater flow. Also, during a number of weeks when a small amount of rain fell, the flow of the stream was not affected at all. During the four-month period, runoff was larger than rainfall for only two weeks (from 14th to 27th October 1981) and this must have resulted from the large amount of rainfall the catchment received during the last days of September and the beginning of October. The weekly values of runoff ranged from 17% (12th to 18th August 1981) to 75% (30th September to 6th October 1981) of the rainfall.

The rainfall and runoff data presented here generally agree on a weekly basis and over a period of four months. However, the fact that rainfall and runoff amounts from specific events were very important for flood analysis, means that a comparison of them was necessary. Table 5 is presented here with weighted rainfall and runoff from four rain events that occurred during the first field season. Total runoff, as it will be explained in the results, was computed from the beginning of the rising limb of the hydrograph to the time storm runoff finished. Before comparing rainfall and runoff from these events it is important to consider the catch of the five gauges that were used for computing the weighted rainfall. This is because, for example, in two storms, gauges 2 and 3 which were situated at approximately the same altitude and gradient as guages 5 and 4 respectively (Map 4), but had a different aspect, caught significantly less rainfall than gauges 5 and 4. In fact, for the rain event of 22nd July 1981 the catch in gauges 2 and 3 was 56 % and 45% less than the catch in gauges 5 and 4 respectively. The corresponding figures

Storm Number	Date	Rainfall (mm)					Weighted Rainfall (mm)	Runoff	
		No. of raingauge						(mm)	%
		1	2	3	4	5			
1	22/7/81	47.1	24.2	31.1	56.2	55.5	41.6	2.6	6
2	19/9/81	33.9	34.0	39.3	42.5	34.6	36.4	0.8	2
3	25/9/81	46.6	46.1	55.1	56.5	45.9	49.4	14.0	28
4	1/10/81	94.8	55.7	65.1	108.2	108.1	84.4	48.8	58

Table 5. Rainfall and runoff of a number of rain events during the first field season

for the rain event of 1st October 1981 were 48% and 40%. On the other hand, for the other two rain events there was an increase of rain catch with altitude. An explanation for this difference can be seen if we take into account the fact that both of these rain events (No. 1 and 4) were accompanied by strong northerly winds. Thus, slope I, which was at the leeward side, must have received a larger amount of rain than slope II which was on the windward side. More details about the differences in raincatch would have been given if the windspeed had been measured. Due to the lack of this information the work which was done by Hovind (1965) in California and mentioned in section 3.2.1.1 seems to be important for this explanation. This is because Hovind worked in an area with slopes of 30° (like the present area) and the wind speed was measured. Also measured was the speed of the upward component of the wind when it struck the slopes and divided into two components. For example, with a wind speed of 12 m sec^{-1} or 43 km/hour, the upward speed was 7 m sec^{-1}. Hovind estimated that this speed was equal to the terminal speed of raindrops having a diameter of less than 0.23 cm. Thus, all drops with a diameter less than 0.23 cm were deposited at the leeward slope of the catchment. Finally, he concluded, that under these conditions less than 10% of the available rainfall would reach a windward slope. Thus, the weighted rainfall in the catchment must have been reasonably accurate. Comparison of the weighted rainfall and runoff of these storms reveals that runoff ranged from 2 to 58% of the rainfall. This figure was smaller when the catchment was dry and larger when wet soil conditions occurred in the catchment. Taking into account the total amount of rainfall and runoff for the four months, the weekly values, the values for the various storms, as well as the differences that were observed in rain caught in the various slopes, it becomes apparent that rainfall and runoff were measured reasonably accurately for the purpose of the present study.

3.2.2 Investigation of Flow Generation Processes.

It was indicated in the general introduction that determination of the flow processes by which rainfall from the catchment area reached the stream channel was the main objective of the study. Also it was explained earlier (section 2.1) that one reason for choosing this particular area was that it was believed to generate excessive amounts of overland flow during heavy rain events. Hence, installation of equipment to select and measure such flow was seen to be an important aspect of the work programme during the first field season. At the same time it was recognized that on the one hand only limited equipment was available for this work and on the other hand, overland flow might not occur at all during the study period because of the possible non-occurrence of heavy rain. Under these conditions it was decided also to undertake an infiltration measurement programme during this period to determine the infiltration capacities of the soils in the catchment, so that they could be related to the rainfall intensity. It was felt that these two approaches would provide much useful information on the area's hydrological characteristics and also would provide a sound basis on which to plan later work.

3.2.2.1 Overland Flow.

3.2.2.1.1 General Considerations and Selection of the Locations for the Establishment of Plots. Overland flow has been detected and measured by a number of research workers either by installing plots of various dimensions in the slopes of a catchment, or by inserting a guttering system in the banks of a stream. Emmett (1970), for example, in west-central Wyoming installed seven plots 2.1 m wide and 14 m long to determine the transfer value of the laboratory data to natural conditions. Hills (1968) applied steel triangular frames having 30 m long sides to detect any occurrence of overland flow which was generated in the area of the frames and which would move downhill. Also plots 35 feet long were used by Foster et al. (1968) in their simulation of overland flow.

In addition a number of other workers (Whipkey, 1965, 1969; Pilgrim, 1978; Versfeld, 1981) used plots of various dimensions to detect and measure overland flow and throughflow. Detection and measurement of overland flow has been made, as mentioned earlier, not only in the slopes of the catchment, but at the stream banks, as well. Weyman (1973), for example, carried out work on the downslope movement of water in a slope 670 metres in length by installing gutters at the bottom of the slope. Also Dunne et al. (1970a, b) collected overland flow by installing a guttering system in the stream bank. Generally, as the literature reveals, overland flow has been studied using plots of many different shapes and sizes. A review of plot design and construction (Hayward, 1967) indicated that each investigator believed that his design was satisfactory for his purpose.

Taking into account the way the various investigators detected and measured this hydrologic component, two things become apparent: first, some of them regarded as overland flow any amount of rainwater that reaches the stream channel moving over the ground surface, and second, some others any amount of rainwater moving over the ground surface regardless if it reaches the stream channel or not. Thus, the first group of research workers studied occurrence of overland flow as it was defined by Langbein and Iseri (1964). Specifically they stressed that overland flow is the flow of rainwater or snowmelt over the land surface toward the stream channel, or that part of the runoff which travels over the soil surface to the nearest stream channel, or finally that part of the runoff of a drainage basin that has not passed beneath the soil since precipitation. The same definition about overland flow was given by Hewlett and Nutter (1970) in their "variable source area model". They emphasized that "we take the liberty of defining overland flow (surface runoff) in our own terms as rainwater that fails to infiltrate the soil surface at any point on its way from the basin to the gauging station". However, the importance of any flow of rainwater over the ground surface generally, was recognized by hydrologists as well. Thus, many of them, as mentioned earlier, detected and measured it in plots installed in the slopes of a catchment. Another point that needs consideration is the infiltration rates of the soils of a catchment and the occurrence and detection of overland flow. This is because the literature reveals that infiltration rates vary even in a small area of a catchment. As a result overland flow may occur discontinuously in a slope during a natural rain event. So, it is debatable how certain a research worker may be about the occurrence of overland flow in the area of the plot when no water is collected at the bottom of the plot. Consequently the use of large or small plots for overland flow measurement is a dilemma for the research worker. Large plots would not detect the occurrence of overland flow if such flow failed to reach the "outlet" of the plot. On the other hand small plots would not detect the occurrence of overland flow if it did not occur inside their area. Random sampling is an obvious solution, but this method cannot be easily applied to a catchment (Tolbes et al., 1970).

I came with these ideas in mind when I had to decide about the type of the plots. Furthermore, it was considered important that the plots should be constructed and operated by one person, as well as the limited available material. Under these conditions it was decided to start with small and simple plots. The problems of access to the remote parts of the catchment were considered as well. Thus, it was decided to start the work from areas where access was easiest and so the operational problems could be tested with minimum waste of time. Examination of the catchment revealed that this could be done in the brown earth soil area. In addition this area of the catchment was larger than others occupied by different soil types. Hence, detection and measurement of overland flow in this soil type would show a flow process occurring in the largest part of the catchment.

For the selection of the locations in this segment of the catchment, where overland flow plots would be constructed, the existing land-use types were considered. This was because the soil type, gradient, etc. were the same and hence possible occurrence of overland flow may be affected by the land-use type. Specifically, they were: land covered with heather several years old, land covered with bracken, grass land and burnt land. Two types of burnt land were identified. Land where the burning took place the same year the fieldwork started, and land which was burnt one or two years earlier. The area occupied by bracken was very small in comparison to other areas and was situated only along the stream channel and in a few other hollow locations. Due to the small area occupied by bracken it was decided that no overland flow plots would be established in these locations. The remaining area was a mosaic of patches of heather, grassland and burnt land. Due to regular burning for grouse shooting it was impossible to work out the exact area occupied by each type. However, a rough estimation showed that 50% of the area was covered by heather, 20% by grass and the rest by burnt land. Given this situation of land uses, it seemed reasonable to regard all the patches and strips having a specific land-use type, e.g. heather or grass as a sampling stratum and each stratum as a population. It was decided to sample a small area from each population as representative of all areas having the same land-use type, simply because the existing locations and the available time prohibited sampling the total population.

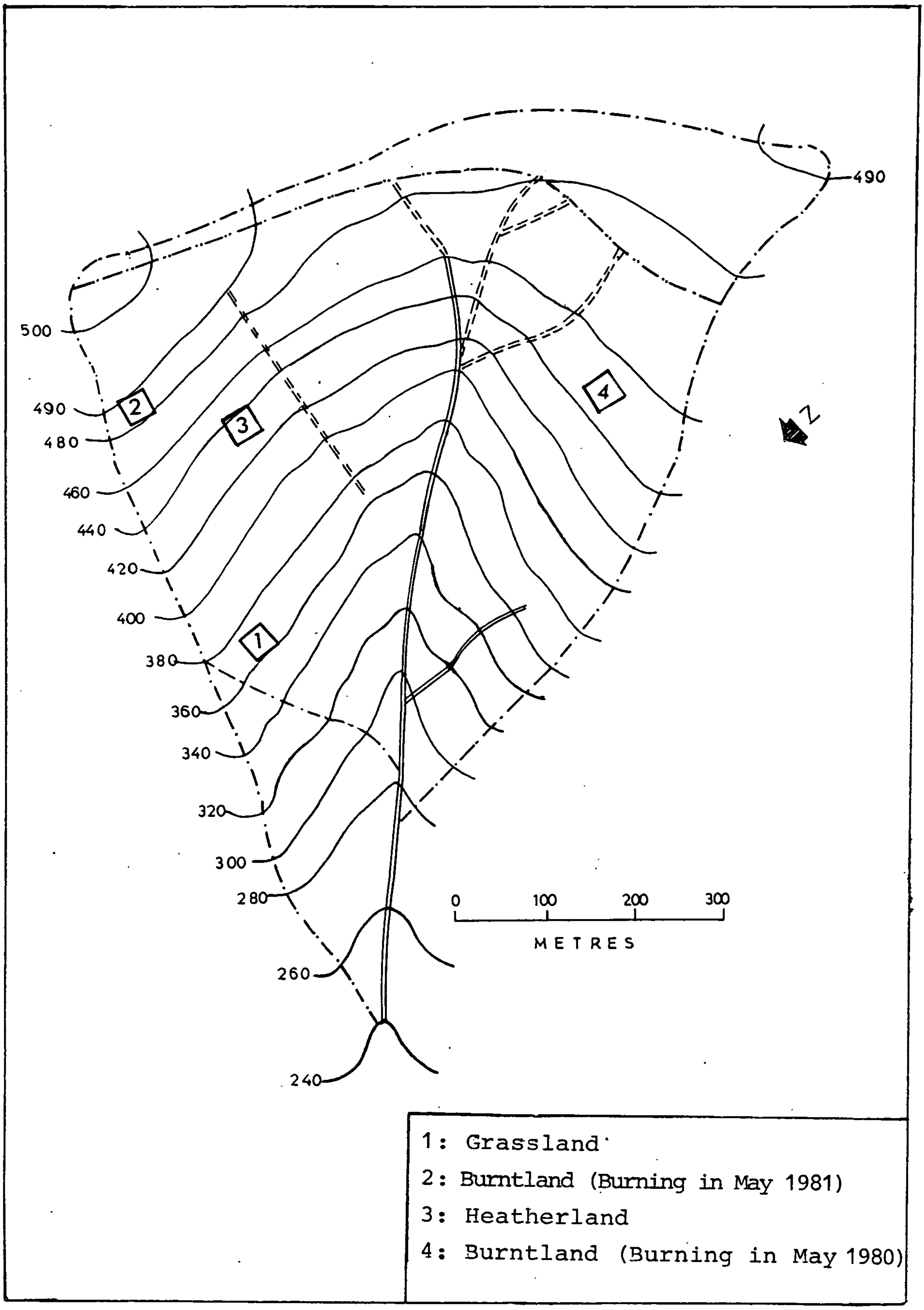
At this point it should be emphasized that this method of sampling was not the perfect one to evaluate statistically the mean for the whole population. It was applied however, for convenience and because the purpose of these plots was only to measure the possible occurrence of overland flow under certain conditions of soil type and land-use type during natural events.

The land uses where the possible occurrence of overland flow would be measured, after rejecting the locations covered with bracken, are shown in Table 6.

Soil Type	Land use	Location characteristics
Brown Earth	Grassland	Covered always with grass
	Burntland	Burning in May 1981
	Heatherland	Heather plants 5 years old
	Burntland	Burning in May 1980

Table 6. Land use and characteristics of locations selected for overland flow measurement.

Problems arose when a location of every land use had to be sampled as representative of the whole population (land-use). The patches and strips of each land-use type were not continuous, and their shape and size were also variable. An additional problem was the long distance of some possible locations from the road into the area. These had to be ruled out because the gradients were too steep to be negotiated by a single person when carrying equipment. As a practical solution to this problem a location approximately 40 x 40 metres was chosen for each land-use type since most of the existing patches had dimensions of this order. Map 5 depicts the selected"representative" locations and a general



Map 5. Selected locations for overland flow plots construction.

description of them is given below.

Location 1 was grassland and its gradient varied from 30° to 35° (67-78%). The depth of the A horizon was estimated from samples taken and it varied from 5-10 cm. No burning took place in the past and the location was always covered with grass.

Location 2 was burnt land and before burning it was completely covered with heather. The burning took place during May 1981, one month before the selection of the location. The gradient ranged from 20° to 35° (44-78%) and the depth of the A horizon varied from 10-15 cm. When the location was selected there was no vegetative cover at all.

Location 3 was heather land. The heather was quite young and about 15-20 cm in height. It had been burnt 5 years before. Its gradient varied from 20° to 30° (44-67%) and the depth of the A horizon was approximately 10 cm. The location when viewed from some distance looked to be completely covered with heather. However, careful examination revealed that under the crown of the heather the ground was bare except for the stems of the heather plants.

Location 4 was on land that had been burnt one year before. The ground was sparsely covered with grass and burnt stems of heather. The gradient ranged from 27° to 32° (60-71%) and the depth of the A horizon was approximately 10 cm.

3.2.2.1.2 *Design and Construction of the Plots.* After the selection of the locations, the size, shape and number of the plots that would be established in an area approximately 1,600 m^2 was considered. Taking into account that it had been decided to construct simple and small plots, for reasons mentioned earlier, it seemed convenient to reduce the area of the selected locations and to choose a smaller one 10 x 10 metres. The latter small areas were gridded and two to three small squares, 1.0 m^2 each, were selected randomly. The number of plots to be installed in each location was decided according to the portion of the catchment area occupied by each land use and the general opinion that overland flow occurs usually in bare soils. Therefore three plots were installed in heather and land burned in 1981 and two plots in grass and land burned in 1980.

In the middle of each square a small plot was installed in such a way that any occurrence of overland flow would converge on a single point where it could be easily collected. The collection was performed by isolating the area using a barrier which was a zinc frame. Zinc was preferred because it was cheap, flexible and very light and hence it could be easily carried in steep locations which were far from any road. Square zinc frames were first considered. The zinc frames could be driven into the soil in such a way that the two angles would be in the same downslope axis and thus offering the following two advantages:

1. Occurrence of overland flow outside the plot would not accumulate against the plot barriers.
2. Overland flow occurring in the area of the plot would be collected at the downslope angle.

In the end, however, triangular frames were chosen because they could be driven into the soil more easily, since they had only three instead of four sides. These frames were placed in such a way that their base was upslope and the apex downslope, since this arrangement helped the overland flow to converge on a single point.

The plots were installed in the sampled squares as follows: a triangle (50 cm long on each side) was drawn in the ground surface and the soil was cut 5 cm deep along the triangle sides with a hammer and a chisel. The frame was then driven into the soil and the gaps between the frame and the soil were sealed with bentonite. The edge of the frame was 5 cm above the ground surface to protect the surface of the plot from possible inflow of overland flow from outside. In addition a metal sheet was driven into the soil just outside the upslope site of each plot. This metal sheet protected the area of the plot from possible water movement which could appear as overland flow in the plot. The metal was driven into the soil as deep as the vertical distance between the upslope side and the downslope apex of the frame. A polythene vessel of known volume was placed in a pit 40 cm downslope from the apex to collect any overland flow. A gutter of zinc was used to connect the downslope angle of the frame and the polythene vessel.

At this point it should be mentioned that the surface of the ground was covered with litter and burned material, thus making the upper part of the A horizon loose. Hence it was difficult to determine the line between overland flow and throughflow. In agricultural or in pasture land the distinction between water movement over and immediately below the ground surface, i.e. the distinction between overland flow and throughflow may be practically possible.

However, in the study area, such a distinction between the two types of flow was found very difficult. It was, therefore, decided to insert the gutters 3-4 cm below the ground surface according to the specific surface conditions of each plot. Furthermore, it was decided to use the term "litter flow" instead of overland flow for any amount of water that was collected in the vessel. Ramsan and Tisctiendoff (Chorley, 1980) used the term "litter flow" for this type of flow. Ragan (1968) and Beasley (1976) seemed to have faced the same problem when they mentioned that they inserted gutters into the "litter layer" for overland flow collection.

Bentonite was used in the connection point between the soil and gutters to ensure that they would be watertight. In addition a polythene sheet was used to cover the gutters to prevent rain falling directly on them. Finally the plots were fenced to avoid damage by sheep. However, damage to the polythene sheets and the vessels by hares, rabbits and foxes was not uncommon. Care was taken to maintain the plots in a good condition in order to avoid errors due to damage by animals or other reasons.

Since the plots were constructed on sloping ground the effective area for the computation of the possible volume of "litter flow" was the projectional area. This area was computed from the gradient of the slope where the plot was constructed. The inclined area of each plot was the same and was equal to 0.11 m^2. Table 7 shows the gradient and the projectional area of each plot.

The rain which fell in each plot was calculated from the nearest raingauge. Specifically raingauge No. 1 was

Location No.	Plot No.	Plot gradient		Projectional area (cm²)
		Degrees	%	
1	1	33	73	908
	2	31	69	928
2	3	25	56	981
	4	23	51	997
	5	23	51	997
3	6	21	47	1,010
	7	31.5	70	923
	8	31.5	70	923
4	9	27	60	965
	10	31	69	928

Table 7. Gradient and projectional area of the "litter flow" plots.

used for plots 1 and 2, raingauge No. 5 was used for plots 3, 4, 5, 6, 7 and 8, and raingauge No. 2 was used for plots 9 and 10. The vessels were checked weekly, except when large rain events occurred when they were checked as soon as possible after the rain was over.

The plots were established during the first five days of July 1981. Between them and the 20th of this month the daily rainfall was not more than 5 mm. On the 21st the rainfall was 8 mm. The first large rain event occurred on the 22nd July 1981. The rain started at 10.00 hours and continued until 14.00 hours on the 23rd July. The vessels were checked on the 24th July and Table 8 shows the amounts of water collected. This event showed that a large percentage of the rainfall may have moved over or through the

Location No.	Plot No.	Rainfall (mm)	Volume of water observed in the vessel (cm^3)	Rainfall observed in the vessel (mm)	Percentage of total rain observed in the vessel
1	1	47.1	3,327	33.6	71
	2	47.1	2,073	20.5	44
2	3	55.5	1,850	20.4	37
	4	55.5	3,766	40.9	74
	5*	55.5	-	-	-
3	6	55.5	489	5.2	9
	7	55.5	3,804	41.2	74
	8	55.5	3,749	40.6	73
4	9	24.2	1,430	15.5	64
	10	24.2	-	-	-

* Disturbance in the plot.

Table 8. Observed amount of litter flow in the triangular plots on 22nd July 1981 rain event.

top 3-4 cm of the soil. No water accumulated in the vessels of plots 5 and 10. The polythene sheet in plot 5 was bitten by a hare or rabbit and the gutter of this plot was found moved from its correct position. This may have influenced the result. The lack of any accumulation of water in plot 10 was attributed to the existence of a thick litter layer. However, with the exception of plot 6 (gradient 21°), the percentage of accumulated water was considered to be very high. It was thought, therefore, that this volume could be litter flow or a mixture of litter flow and throughflow. To avoid this latter possibility the gutters were removed from their original depth of 3-4 cm and re-inserted 1.5 to 2 cm below the ground according to the conditions existing at each plot. The gutters were used in the latter depth until the end of October 1981.

The data obtained during the rest of the period of operation are presented in Table 9. This shows that litter flow was observed nine times during the first field season. Such flow occurred in most of the plots in the four locations. It was most frequent in location 2 plots and least frequent in location 3 plots. Litter flow was never observed in plot 10, location 4.

The main characteristic of the data presented here is the variability in the observed amount of litter flow, not only from one location to another but also from one plot to another in the same location. In location 1, for example, and for the nine times, 43.8% of the rain that fell was observed as litter flow in plot 1 and 15% in plot 2. In location 3 the corresponding figures for plots 6, 7 and 8

Location No.	Vegetative Cover	Plot No.	Gradient	Total amount of rain in mm(T), Observed litter flow in mm(O) and Percentage of rain becoming litter flow% — Time interval 1			2			3			4			5			6			7			8			9			TOTAL		
				Date: 19/8/81			10-11/9/81			14/9/81			16-20/9/81			23/9/81			24-26/9/81			1-4/10/81			5-9/10/81			28-31/10/81					
				T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%
1	Grassland	1	33°	10·5	3	28·6	15·1	8	53	7·4	1·5	20·3	39	12	30·8	14·5	0·5	3·4	55·8	28	50·2	94·8	64	67·5	37·6	10	26·6	19·6	2	10·2	294·3	129	43·8
		2	31°	10·5	—	—	15·1	—	—	7·4	—	—	39	4	10·2	14·5	—	—	55·8	13	23·3	94·8	26	27·4	37·6	1	2·7	19·6	—	—	294·3	44·0	15·0
2	Burntland (Burning May 1981)	3	25°	5·7	0·5	8·8	11·8	2·2	18·6	7·8	1·8	23·1	39·8	7·6	19·1	14·6	D	—	54·4	9·3	17·1	108·1	26·6	24·6	34·8	D	—	11·0	D	—	238·6	48·0	20·1
		4	23°	5·7	1	17·5	11·8	4·5	38·1	7·8	2·3	29·5	39·8	15·7	39·4	14·6	1·2	8·2	54·4	20·5	37·7	108·1	56·6	52·3	34·8	2·8	8·0	11·0	—	—	288·1	104·6	36·3
		5	23°	5·7	0·4	7	11·8	2·5	21·2	7·8	1	12·8	39·8	8·3	20·8	14·6	D	—	54·4	14·1	25·9	108·1	32	29·6	34·8	2	5·7	11	—	—	273·4	60·3	22·10
3	Heatherland	6	21°	5·7	—	—	11·8	—	—	7·8	—	—	39·8	1	2·5	14·6	—	—	54·4	3·4	6·2	108·1	14·8	13·7	34·8	—	—	11	—	—	288·1	19·2	6·7
		7	31·5°	5·7	—	—	11·8	—	—	7·8	—	—	39·8	3·9	9·8	14·6	—	—	54·4	6·6	12·1	108·1	16	14·8	38·4	—	—	11	—	—	288·1	26·5	9·2
		8	31·5°	5·7	—	—	11·8	—	—	7·8	—	—	39·8	6·6	16·6	14·6	—	—	54·4	10·9	20	108·1	25·4	23·5	38·4	—	—	11	—	—	288·1	42·9	14·9
4	Burntland (Burning May 1980)	9	27°	9·4	—	—	14·6	—	—	7·7	—	—	39·4	4·9	12·4	12·6	—	—	54·6	9·8	18·0	55·7	13·4	24	38·4	—	—	18·4	—	—	250·8	28·1	11·2
		10	31°	9·4	—	—	14·6	—	—	7·7	—	—	39·4	—	—	12·6	—	—	54·6	—	—	55·7	—	—	38·4	—	—	18·4	—	—	250·8	/	

Table 9. Observed litter flow during 1981 in the triangular plots.

D = disturbance in the plot.
Δ = Time interv. 5 and 8 are not included.
▲ = " " 5 is not included.

were 6.7%, 9.2% and 14.9% respectively. The largest total amount of litter flow for the nine times was observed in plot 1 (43.8%) and the smallest in plot 6 (6.7%). However, for single time intervals this figure ranged from 2.5% (plot 6) to 67.5% (plot 1).

In some time intervals a relatively small quantity of rain produced a large quantity of litter flow. In plot 1, for example, during time interval 2, 15.1 mm of rain produced 8 mm (53%) of litter flow. In plot 4, 11.8 mm of rain produced 4.5 mm (38.1%) of litter flow. These values may be attributed to high rainfall intensities and low infiltration capacities, or due to saturated soil conditions, or very dry conditions inhibiting the movement of water through the soil surface. However, the purpose of this chapter is not to find reasons for litter flow occurrence and quantity, but to show whether or not litter flow occurred in the study area and whether or not it was a phenomenon to which further attention would need to be paid during the second field season. The data presented show the answer to these questions to be yes.

3.2.2.2 Infiltration

3.2.2.2.1 *Definitions.* It is necessary at the beginning of this chapter to define some terms which will be used later. These terms are infiltration, infiltration capacity and infiltration rate. Infiltration has been defined by a number of research workers as the entry of water into the soil (Horton, 1933; Musgrave, 1935; Satterlund, 1972; Schwab et al., 1981; Hewlett, 1982). It has also been defined by other workers as not only the entry of water into the soil but also the vertical movement through it (Wisler et al., 1959; Dunne et al., 1978; Lee, 1980). The group of researchers mentioned first defined the vertical movement of water through the soil as percolation. In the present study the term infiltration means "the flow of water into the soil and in succession the flow through it vertically". The importance from the hydrological point of view, of the vertical and lateral movement of water and especially as mentioned in the general introduction, on sloping ground when it enters the soil was the reason why the above definition was adopted.

The terms "infiltration capacity" and "infiltration rate" need some clarification as well. Horton (1933) was the first to use the term infiltration capacity as the maximum rate at which the soil in a given condition can absorb water. The term can be used when the water is applied at a rate higher than that which can be absorbed by the soil. Infiltration rate is the rate at which water is being absorbed by the soil at any particular time and it can be equal to or less than the infiltration capacity.

3.2.2.2.2 *Trial for Infiltration Assessment with Cylinder Infiltrometers.* As mentioned in section 3.2.2 the purpose of the infiltration measurement programme that would be undertaken, was to determine the infiltration capacities of the soils in the catchment and to relate them with the rainfall intensities. Such a relationship would show if litter flow occurred in the study area due to rainfall intensities higher than the infiltration capacities.

There are two general approaches to the determination of infiltration capacity of the soil. The first is the analysis of hydrographs of runoff from natural rainfall on plots and catchments and the second is the use of infiltrometers with artificial application of water to enclosed sample areas. The infiltrometers are divided in two general groups: rainfall simulators and flooding type. Various kinds of equipment are in use of both types, and they vary in size, in the quantity of water that is required and in methods of measuring the water. The flooding infiltrometers are usually cylinders of variable dimensions and include one, two, or more cylinders (single, double and multi-cylinder infiltrometers). Both types of infiltrometers have been used to obtain infiltration data by previous investigators. Recent work by Hills (1968) and Tricker (1978), however, has suggested that a single cylinder infiltrometer is as good a method as any for obtaining data in British conditions. Hence, it was decided to use a simple cylinder in the study area to obtain the infiltration capacities of the soils.

For this purpose a steel tube 1.5 metres in length was cut into pieces and five infiltrometers were constructed. Details of dimensions and features of them are shown in Figure 4, A-B. The internal diameter of them was 13 cm and the wall thickness 4 mm. They had maximum and minimum height in two diametrical opposite points 28 and 20 cm. Thus, the cross-sectional area that would be driven into the soil had approximately the same gradient (30°) as most of the area of the catchment. Hence, the same depth of

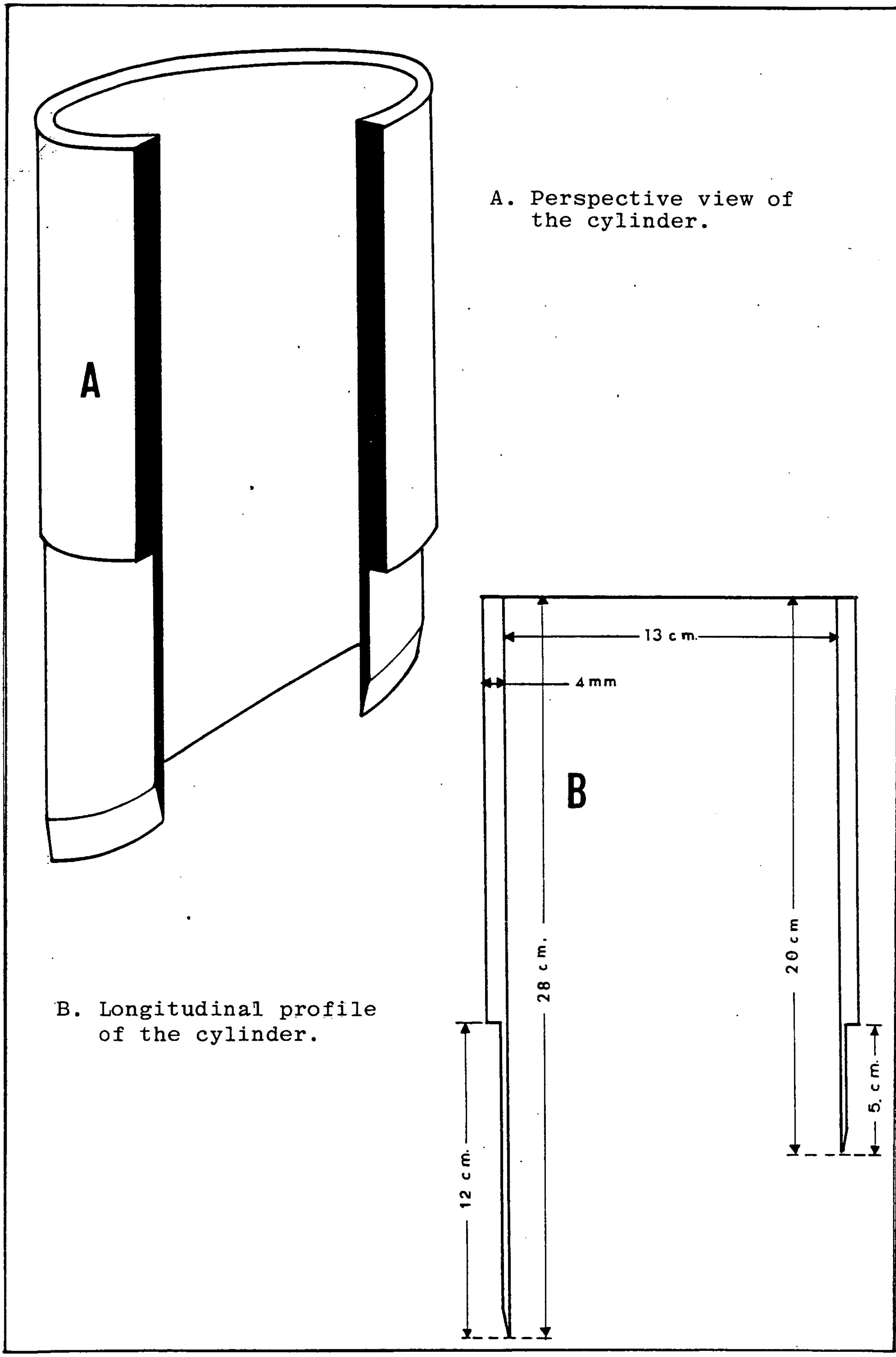


Figure 4. Details of the constructed cylinder infiltrometer.

insertion would be obtained along their circumferences, when the infiltrometer was inserted in the vertical position. For the determination of this depth, it was taken into account that other investigators who applied this technique found that 5 cm of insertion was adequate. Therefore, the latter depth was accepted as suitable in the present study and was refined to 1 mm in order to avoid as much as possible the disturbance of the soil. Specifically in the side of the cylinder that was 28 cm the lower 12 cm were refined for reasons of convenience in the construction of the cylinders. Cylinders with the referred dimensions were used because they were light enough to be carried around in the hilly terrain and to remote parts of the catchment. In addition, they were cheap, since only a small amount of material would be needed for the construction of the cylinders.

A 10 litre polythene bottle was used to feed each cylinder. The upper part of the bottle was flat so that it could be easily supported by the cylinder and also remain horizontal. In addition each bottle had two copper tubes fixed in a plastic stopper and projecting through its cap. The depth of water was of course higher in the downslope area enclosed by the cylinder as a result of the gradient of the ground. It was recognised that this unequal depth of water would be a source of an error in determining infiltration capacity, but this could not be avoided due to the topographic conditions. The bottles were graduated externally so that as the water level inside the cylinder fell, the fall in the head could be read directly on the scale of the bottle. Figure 5 depicts how the cylinder infiltrometer and the feeding bottle worked together.

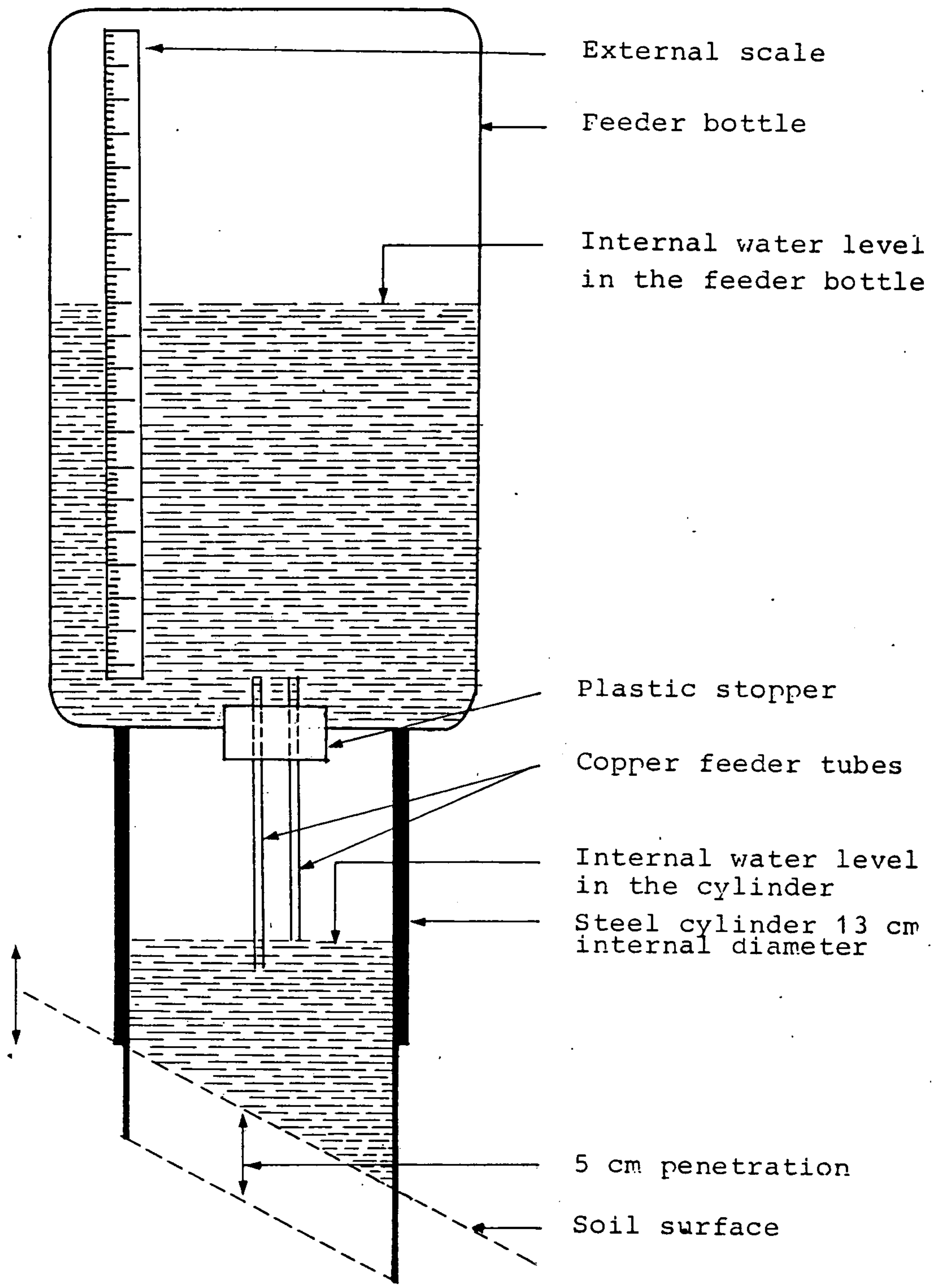


Figure 5. Cylinder infiltrometer and feeder bottle in operation.

When the cylinders were ready a location was selected on the 20th July to test the applicability of the technique and to measure the infiltration capacity of the location. It was a grassland area of c. 30 m^2 about 100 metres away from the stream channel with a gradient of 30°. It was decided to make ten measurements in this area. The vegetation at the selected points was shortened using a grass cutter. It was then decided to start the measurements at the down-slope points of the location in order to avoid any change in the initial moisture content of the location by down-slope movement of the infiltrated water. Efforts to insert the cylinders into the soil by hand failed. The soil was very hard and a hammer had to be used. A piece of wooden board was placed in the upper edge of the cylinder in order to prevent distortion and with gentle hits the five cylinders were driven 5 cm into the soil. The five feeding bottles full of water were placed on the cylinders and after a short settling period, readings of the fall of the water level were taken every five minutes. It soon became apparent that the entry of water into the soil was very fast and therefore it was difficult to maintain and control simultaneously five cylinders. Furthermore, one 10 litre bottle of water was not enough to feed the infiltrometer for very long. Hence, the feeding bottle had to be changed after a period of time and two to three such bottles were used for one hour's infiltration measurements. It took approximately 30 seconds to replace each bottle and during this time the head of water in the cylinder was absorbed by the soil. Additional water was therefore needed to maintain the new head. These problems were solved by reducing the number of infiltrometers working simultaneously from five to two. In addition three feeding bottles full of water were kept close to each infiltrometer in use, so that the replacement of the empty feeding bottle was as quick as possible. As a result of the problems encountered during the testing of the technique, the first selected location was abandoned and a new one was chosen close to the first.

In this second location ten infiltration measurements were made using two cylinders as described above. Each measurement lasted for one hour. At this stage it was necessary to consider how the mean infiltration capacity of each site and the mean infiltration capacity of the location should be expressed. It seemed reasonable to use the arithmetic mean of the twelve segment infiltration capacities (each of five minute duration) for the computation of the mean infiltration capacity of each infiltration site. The mean infiltration capacity of the location could be expressed by the arithmetic mean of the infiltration capacity of the ten measurements. It is worthy of note that the measured infiltration capacity was not corrected for possible lateral movement of water beneath the cylinder. It was considered reasonable to test first the technique in the field and then think about correcting any sources of error. The computed mean infiltration capacity of each site and that of the location are depicted in Table 10.

An examination of the infiltration capacities obtained for the ten sites reveals that they have great variability. Also the values are very high. Variability between sites

No. of site	1	2	3	4	5	6	7	8	9	10	Location
Infiltration capacity (cm/hr)	119	101	177	161	225	243	241	138	235	220	$\bar{x}$ = 186 ± 54

Table 10. Computed infiltration capacities in the first selected location.

has been observed by every other investigator who carried out work in the same field. The values, however, are unusually high, and possible sources of error needed to be considered. The disturbance of the soil seemed to be very relevant to the high infiltration capacities obtained despite the thinness of the lower part of the cylinders. The existence of old roots and stones - although small - in the soil made insertion very difficult and thus some disturbance was unavoidable.

As a result a gap was created between the cylinder and the soil and hence, it was very easy for the water to enter the soil. Another source of error affecting these measurements could be the possible lateral movement of the infiltrated water beneath the cylinders. It seemed, however, reasonable to tackle the error due to the disturbance of the soil before working out any method to estimate the amount of any laterally moved water.

While these problems were being considered, a rain event occurred on the 22nd July 1981, which produced litter flow in the overland flow plots even though its intensity was far less than the infiltration capacities being suggested by these cylinder measurements. The lack of any relation between the values of the infiltration capacities and the amount of litter flow observed in the plots raised considerable doubts about the validity of the cylinder method. Infiltration capacities ranging from 101-241 cm/hr (Table 10) were computed from the cylinder infiltrometer. On the other hand from the 41.6 mm of weighted rain (Table 8) that fell in 28 hours (mean intensity 1.45 mm/hr) a large amount (9 to 74%, Table 8) moved over the ground surface or through the upper 3-4 cm of the soil.

The results were so contradictory that it was decided to re-measure the infiltration capacity using the same technique in order to work out the possible error in the first ten measurements. Another location was selected and on the 25th July 1981 ten more measurements were made. The computed infiltration capacities are depicted in Table 11.

No. of site	1	2	3	4	5	6	7	8	9	10	Location
Infiltration capacity (cm/hr)	160	185	152	197	135	108	116	323	20	294	$\bar{x}$ = 169 ± 89

Table 11. Computed infiltration capacities on 25th July 1981.

This shows that the new infiltration capacities ranged from 20 to 325 cm/hr and had a mean value of 169 ± 89 cm/hr. Hence there was practically no change from the values computed previously. Some efforts were made, thereafter, to test the spatial variability of the infiltration capacity over a wider area of the study catchment. A number of locations were selected and 3-4 measurements were made in each of them as described previously. The computed infiltration capacities varied in each location, but they were as high as the values presented previously. It was then decided to take a new set of measurements, but to seal this time the gap between the cylinder and the soil with bentonite in order to avoid the easy entry of water into the soil. Table 12 shows the values for the infiltration capacity obtained after bentonite was used.

No. of site	1	2	3	4	5	6	7	8	9	10	Location
Infiltration capacity (cm/hr)	75	108	155	17	249	91	108	104	67	73	$\bar{x}$ = 105 ± 62

Table 12. Computed infiltration capacities after bentonite was used.

As can be seen in this Table the values obtained ranged from 17 to 249 cm/hr and had a mean value of 105 ± 62 cm/hr. The latter value is to be compared to the previously calculated mean infiltration capacities of 186 ± 54 and 169 ± 89 cm/hr (Tables 10 and 11). It appears that there was some reduction in the arithmetic mean of the infiltration capacity of the latter location. The mean infiltration capacity of the latter location was still very high and contradictory to the litter flow that occurred on the 22nd July rain event. Hence, the most serious source of error, the disturbance of the soil, seemed to be unavoidable. As a result the technique described in this section was abandoned and alternative methods for assessing the infiltration capacities of the study catchment were considered.

<u>3.2.2.2.3 *Field Measurements with a Rainfall Simulator Infiltrometer and Modifications of the Instrument.*</u> The reasons why the cylinder infiltrometer was not regarded as being suitable for assessing the infiltration capacities of the soil in the study area have been stated earlier. After the rejection of this equipment efforts were directed to finding another instrument that would not disturb the soil to such a degree and therefore would yield infiltration capacities closer to the actual infiltration capacities of the study catchment. One such instrument is, as mentioned in section 3.2.2.2.2, the rainfall simulator, and as such a simulator was readily available for use, it seemed logical to test its suitability for the present study. Details of this device are shown in Figure 6, and a full description has been given by Boontawee (1977).

The first trial with the infiltrometer was made on the 13th August 1981. The location selected was grassland and was close to the first location where the cylinder infiltrometers were used on 25th July 1981. It had an average gradient of 30°. Before transporting the instrument to the selected location the lower part of its base unit was cut off in such a way that its bottom edge had a gradient of 30°. The same had been done to the cylinder infiltrometers as stated earlier. At the selected location five infiltration sites (50 cm x 50 cm) were sampled systematically and the vegetation in them was shortened with a grass cutter. As before, the farthest downslope site was used first. The base unit was pressed gently, by hand, 1-2 cm into the soil and a spirit level used to check that it was horizontal and

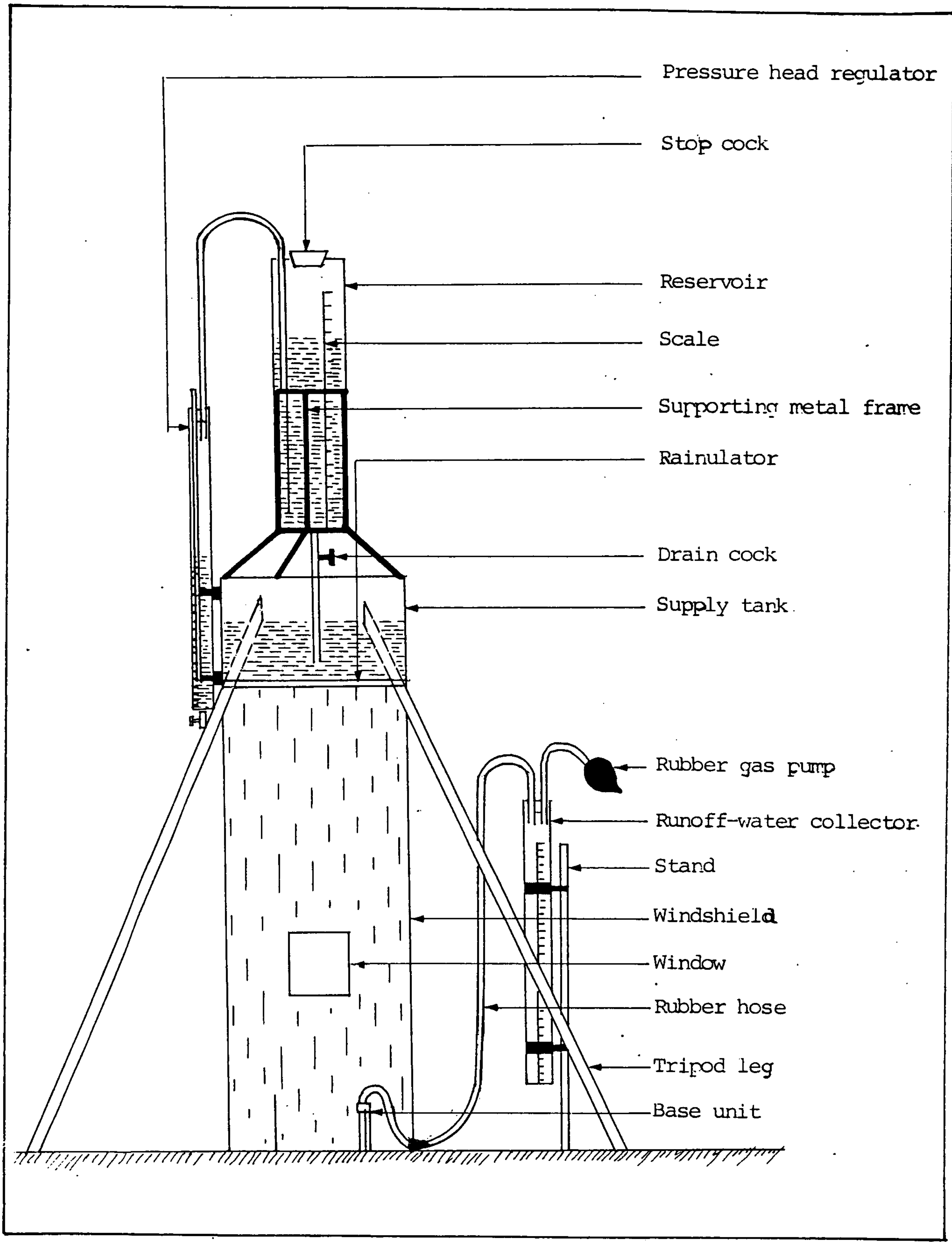


Figure 6. Rainfall simulator infiltrometer (after Boontawee, 1977).

the simulator was erected above it. At this point a decision had to be made as to the intensity of the artificial rainfall that would be applied. The instrument was capable of producing rainfall intensities ranging from 40 to 140 mm/hr. In this case an intensity of 50 mm/hr was regarded as adequate because it was a little higher than the minimum obtainable intensity and also it was not too high that the soil could be flooded. It was of course recognized that this intensity was much higher than the intensity of natural rain occurring in the British Isles. It was decided to take readings of the reservoir level every five minutes as was done with the cylinder infiltrometers.

When the instrument was put into operation it soon became apparent that the defined artificial rainfall intensity of 50 mm/hr was difficult to keep constant. In reality the water was dropping from the reservoir and the hydraulic head in the supply tank was rising because the falling of the drops through the rainulator was not regular. This was attributed to the vibrations of the water in the supply tank caused by wind and also to the possible entry of dust that may have blocked some holes of the rainulator. In other words, the established relationship between hydraulic head in the supply tank and intensity of artificial rainfall in the laboratory was not valid in the field. Furthermore, it was easy for the instrument to be overturned by the wind due to its height and also it was difficult to collect the water occurring as litter flow due to the nature of the ground surface.

Despite these constraints the instrument was operated for one hour and the arithmetic mean of the 12 infiltration rate readings made at five minute intervals was 40.8 mm/hr. Also a depth of 2.5 mm of water that fell in the infiltration site was observed as litter flow. The intensity of the rainfall was not constant for the whole hour for the reasons explained above. However, since a column of water 43.3 mm in depth passed through the rainulator in one hour, the intensity was recorded as 43.3 mm/hr. Three more measurements were made in the same way and the infiltration rates computed to be 40, 33 and 29 mm/hr. In two of these measurements a small amount of water was observed as litter flow.

The above measurements, despite the fact that they gave values much lower than the values obtained with the cylinder infiltrometer, were not regarded as being satisfactory since it was clear that they were affected by several sources of error. Therefore, another measurement was made. For this measurement the reservoir and the supply tank of the instrument were covered with a plastic sheet. Before the measurement was made, the rainulator was cleaned and the hydraulic head was appropriate for an intensity of 50 mm/hr. These precautions seem to have made some improvement as the intensity remained constant at 46.5 mm/hr. Also an amount of water was observed as litter flow.

In Table 13 the intensity of the applied artificial rainfall, the mean infiltration rate and the amount of water observed as litter flow for the selected location are shown.

No. of measurement	Intensity of artificial rainfall	Mean infiltration rate (mm/hr)	Observed litter flow (mm of depth)
1	43.30	40.80	2.50
2	40.00	40.00	-
3	34.00	33.00	1.00
4	33.90	29.0	4.90
5	46.50	38.0	8.50

Table 13. Mean infiltration rate and litter flow with the application of artificial rainfall on 13th August 1981.

The experience gained from the previous measurements was that a number of problems concerning the operation of the instrument had to be solved before it could be regarded as suitable for the terrain and the climatic conditions of the study area. These problems were:

1. The height of the instrument. The height of the rainulator with the accompanying reservoir and wind-shield was 1.9 m above the ground surface. As stated earlier, the catchment was very exposed to winds and therefore it was very easy for the instrument to be overturned by the wind, despite the tripod legs supporting it.
2. Vibrations in the water of the supply tank and entry of dust. As mentioned previously, during the operation of the instrument the water in the supply tank was moving. As a result, the established relationship between the hydraulic head in the supply tank and the intensity of the artificial rainfall did not remain constant. The entry of dust into the water and subsequently into the holes of the rainulator had the same effect on the relationship.

3. Difficulty in litter flow collection. It was noticed from the first measurements made on 13th August 1981 that the original construction of the base unit and the runoff water collector of the instrument (Fig. 6) was not suitable for collecting litter flow in the study area. This was because the upper part of the soil, as mentioned before, was very loose. It was observed that once litter flow accumulated in the downslope part of the base unit, it began to infiltrate and move downslope beneath the base unit. As a result of this infiltration, there was often no accumulation of litter flow to measure at the end of the five-minute sampling interval, even though litter flow had clearly occurred. This meant that the amount of water observed as litter flow in the previous five measurements might well have been higher if the base unit had had such a construction as to permit the continuous collection of litter flow.
4. Transportation of the instrument. The transportation of the instrument and all its components across long distances and up steep slopes, was also a problem. This was, of course, irrelevant to the accuracy of the measurements.

Of these problems collection of litter flow was regarded as the most serious problem and therefore improvements and modifications were started at the base unit of the infiltrometer. What was necessary was a base unit with such a construction as to permit a continuous collection of the litter flow without allowing it to accumulate in the base unit. This was achieved by drilling a number of holes in the lower part of the base unit and fixing a collector tube to lead away water flowing through these holes. Plate 3, A,B, clearly shows this modification. After this modification and covering the reservoir and the rainulator with a plastic sheet as before, a number of new measurements were made in the same location. The computed infiltration rates from these measurements seemed to be more accurate and closer to those expected. A set of measurements made after this modification are shown in Table 14.

No. of measurement	Rainfall intensity (mm/hr)	Mean infiltration rate (mm/hr)	Observed litter flow (mm of depth)
1	47	34	13
2	46	30	16
3	52	37	15

Table 14. Mean infiltration rates and litter flow with the mofified base unit.

At this point it should be mentioned that the modification of the base unit did not solve the litter flow collection problem completely. The reason was that soil litter, burnt material and eroded soil were transported in the curved tube. A stainless steel wire was used to clean the tube, but it was found to be ineffective. This was due to two reasons: firstly, it was time-consuming as it had to be done all the time, and secondly, the tube was curved and therefore difficult to clean. The author, having to deal with this new problem, as well as with the height of the instrument and the vibrations in the water of the supply tank, was forced to consider new modifications to the instrument. The following changes were considered:

(A)

(B)

Plate 3: Modified base-unit of the rainfall simulator infiltrometer.
(A) External view
(B) Internal view.

1. The digging of a shallow pit a short distance downslope of the infiltration site and the insertion of a gutter in the soil profile having a length longer than the diameter of the rainulator (31.4 cm) in order to collect litter flow directly.
2. The complete removal of the base unit and the assumption that the plot area for infiltration assessment equalled the area underneath the rainulator. The removal of the base unit would also mean the lack of a buffer zone around the area whose infiltration rate was under assessment. But while it was recognized that this might be a new source of error, the topographic conditions of the ground surface, necessitated taking this step.
3. The removal of the reservoir feeding the supply tank and the pressure head regulator and their replacement by a polythene bottle to feed the supply tank. In the top of this bottle would be a plastic stopper with two copper tubes having sufficient length to enable the appropriate hydraulic head in the supply tank to be obtained. The copper tubes could be moved up and down through the plastic stopper, so changing the hydraulic head and therefore the intensity of the artificial rainfall. It was felt that these modifications would convert the original rainfall simulator infiltrometer (Figure 6) into a type more suitable and adaptable to the topographic and climatic conditions of the study area. The instrument would become much simpler to operate, lower in height and therefore less sensitive to the effects of the wind. It would also become lighter and therefore

easier to transport over long distances and rough terrain. Furthermore, the problem of the dust entry could be avoided by covering the feeder bottle and the supply tank completely with a plastic sheet.

The instrument, after modification, is shown in Figure 7. The feeder bottle was 20 cm in diameter, 30 cm in height and had a capacity of approximately 9.5 litres. A wooden support was constructed and placed in the upper part of the supply tank where it held the feeder bottle firmly and vertically. The bottle had an external scale which was used to compute the volume of water passing through the rainulator by taking readings of water level at fixed time intervals. The copper tubes passing through the plastic stopper had an internal diameter of 8 mm and a wall thickness of 0.8 mm. The plastic stopper was a tapered fit (70 mm in diameter down to 60 mm in diameter) in the neck of the bottle which ensured a good seal and no leakage of water. The gutter used to collect litter flow was made of zinc alloy which was both hard and lightweight. It was 60 cm in length and 8 cm in width, and was bent along its length into a 60° V shape, the sides of the V having widths of 5 cm and 3 cm.

Another problem that had to be solved at this stage was how far downslope from the plot area the pit should be dug in which to place a gutter. If the pit was too near the plot, it might stimulate lateral movement of infiltrated water. On the other hand if the distance away was too far, then the results would be affected by water being absorbed into the soil before reaching the gutter. Considering these

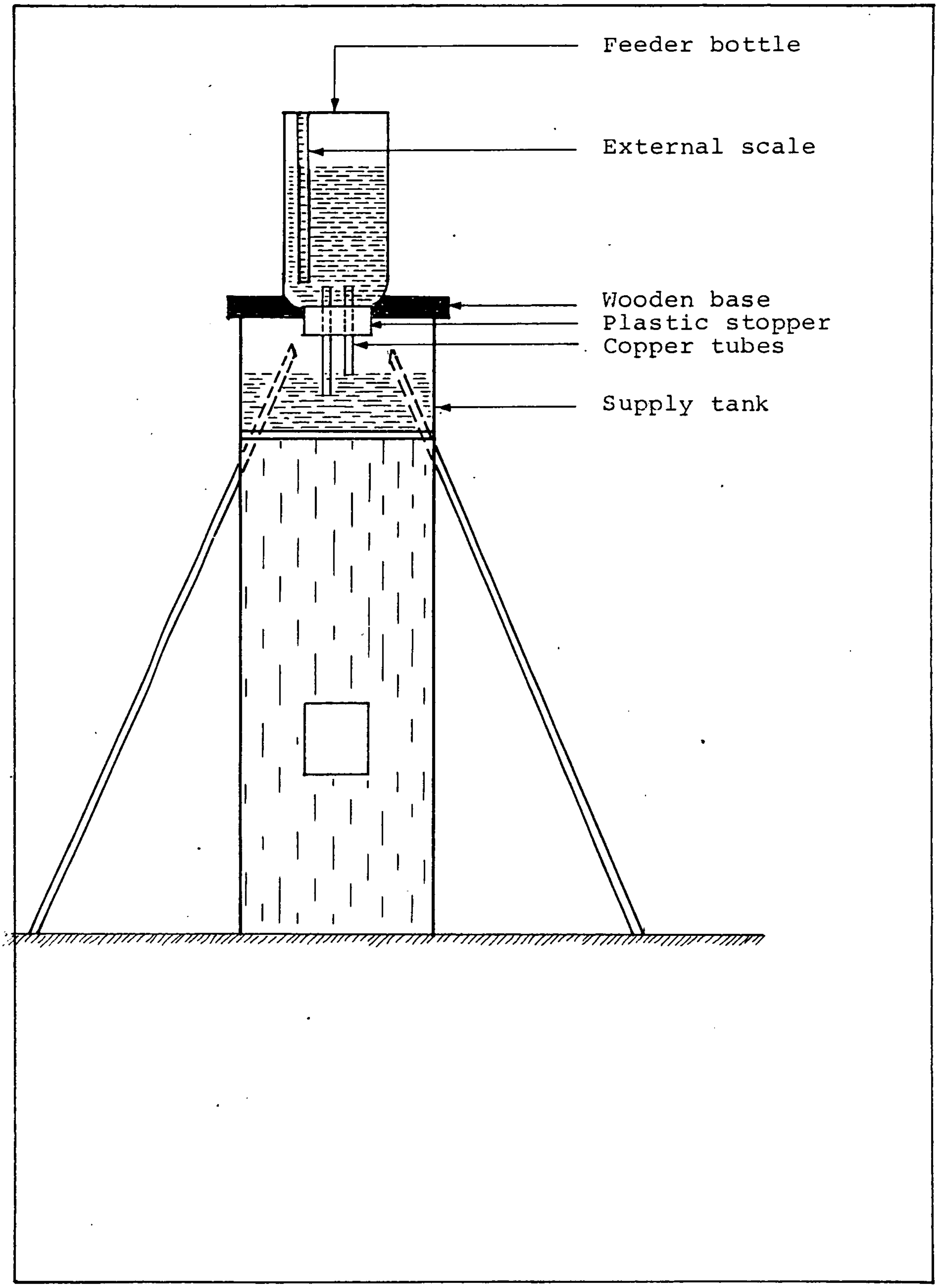


Figure 7. The rainfall simulator infiltrometer after the modifications (not to scale).

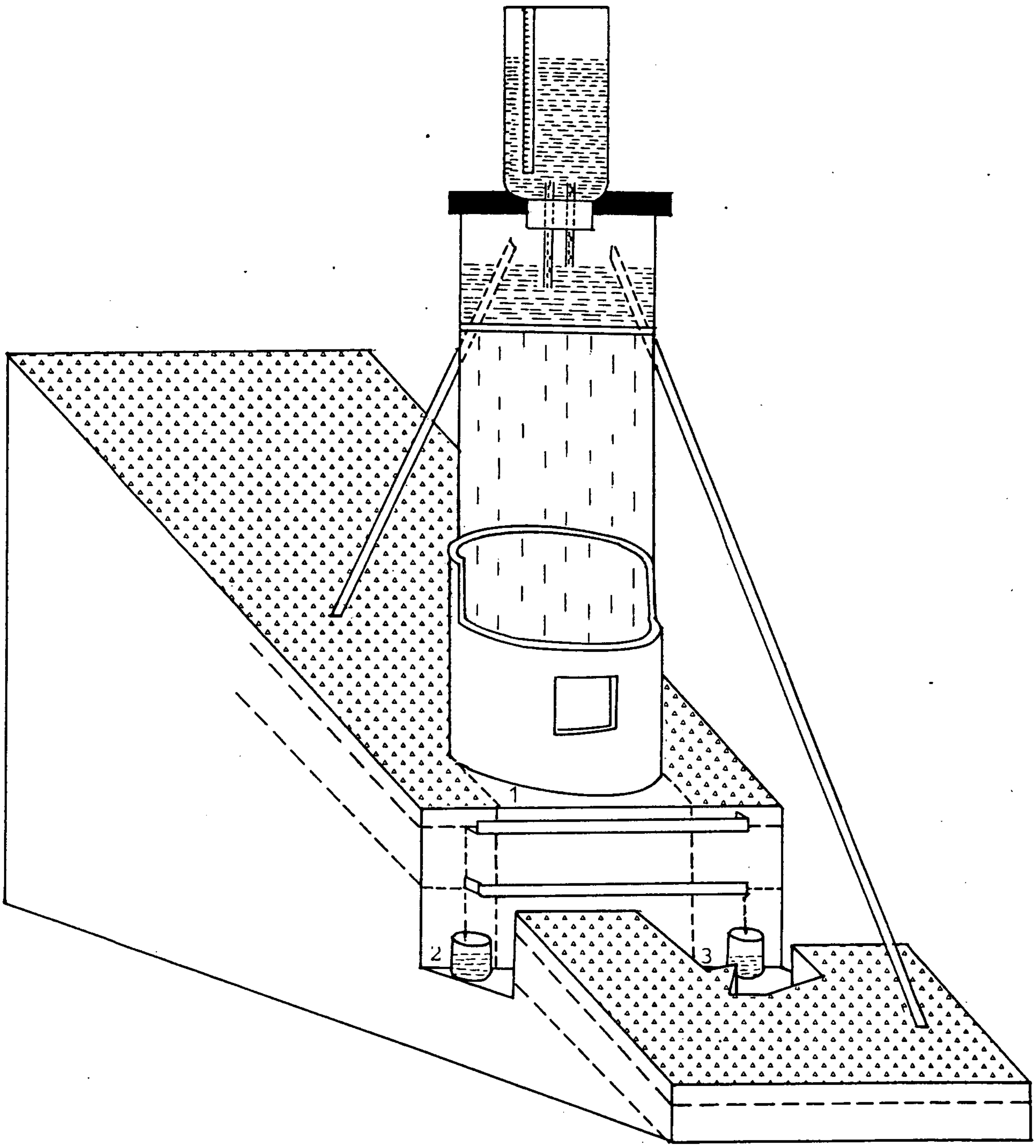
two aspects plus the fact that the gutter should be inserted 1-2 cm into the vertical soil face and 1-2 cm below the ground surface, a distance of 2-3 cm downslope of the plot area seemed to be a good compromise.

The modified instrument was then tested in the field. It worked very well except for some water leakage under the gutter. Bentonite was used to seal this water pathway under the gutter. The pit was approximately 65 cm in length, 15 cm in depth and 15 cm in width, so there was enough space for a small cup to be placed at the end of the gutter to collect litter flow. While the instrument was in use in the field, it became apparent that a large amount of the water entering the soil was moving laterally and was seeping out from the vertical face of the A horizon underneath the gutter. Hence it was thought a good idea to insert another gutter at the base of the A horizon to collect such water. It was felt that the use of two gutters would have two advantages:

1. It would enable the infiltration rate to be computed with a small error. This is because more of the fraction of the total water applied to the soil that moved laterally could now be measured and subtracted from the total. There was of course some lateral movement of the applied artificial rainfall through the deeper soil horizons. However, from a number of measurements made in the field it appeared that most of the water moving laterally travelled through the A horizon.
2. The measurement of the amount of litter flow and flow through the A horizon would yield information on the distribution of artificial rainfall after entry into the soil.

The modified infiltrometer as described above (Figure 7) plus the gutter system (Figure 8) to collect and measure litter flow and lateral flow were tested in the field on 9th September 1981 and produced sensible results (Table 15). Therefore, it was decided to embark on a programme of measurements using the instrument in this form.

3.2.2.2.4 *Selection of Locations for Infiltration, Litter Flow and Throughflow Assessment.* When the modified instrument was tested in the field and found to be working satisfactorily the permanent locations for the assessment of infiltration, litter flow and throughflow in the catchment were selected. Both soil type and land use were taken into account in the selection of these locations. It was also decided that in the first field season, measurements would not be made at the top of the catchment occupied by peat soil, but only on the slopes occupied by brown earth soil. The reasons for this were the same as those given earlier in relation to litter flow. In situ delineation and measurement of the area covered by each land use was not possible for reasons outlined previously. As a result locations for infiltration, litter flow and throughflow assessment were selected by the same method as that used for choosing the litter flow locations. Two locations of approximately 40 m x 40 m of each land use were selected as being representative for all areas having the same land use. The reason for selecting two areas of each land use was simply to cover a larger area of each type. They were selected in a way that ensured that they were distributed over the whole area



1. Zone not receiving water directly
2. Cup for litter flow collection
3. Cup for throughflow collection

Figure 8. Perspective view of the modified infiltrometer and guttering.

Time	Scale Reading		Water passed through the rainulator (cm^3)	Simulated Rainfall (mm)	Litter flow		Through flow		Infiltration		
	Feeder Bottle	Hydraulic head			cm^3	mm	cm^3	mm	cm^3	mm	mm/hr
1	2	3	4	5	6	7	8	9	10	11	12
13.10	0.00	3	-								
13.15	1.07	3	338.10	4.37	-	-			338.10	4.37	52.40
13.20	2.04	3	306.50	3.96	8	0.10	13	0.17	285.50	3.69	44.30
13.25	3.09	3	331.80	4.28	13	0.17	27	0.35	291.80	3.76	45.10
13.30	3,14	3	331.80	4.28	19	0.24	46	0.59	266.80	3.45	41.40
13.35	5.22	3	341.80	4.41	22	0.28	52	0.67	267.30	3.46	41.50
13.40	6.17	3	300.20	3.88	25	0.32	94	1.22	181.20	2.34	28.10
13.45	7.23	3	335.00	4.33	36	0.46	113	1.47	186.00	2.40	28.80
13.50	8.14	3	287.60	3.71	27	0.35	127	1.64	133.60	1.72	20.60
13.55	9.09	3	300.20	3.88	31	0.40	141	1.82	128.20	1.65	19.80
14.00	10.21	3	354.00	4.57	29	0.37	159	2.06	166.00	2.14	25.70
14.05	11.22	3	319.20	4.12	37	0.48	172	2.22	110.20	1.42	17.05
14.10	12.11	3	281.20	3.63	42	0.54	163	2.10	76.20	0.99	11.90

Notes:

1. Feeder bottle cross sectional area: 316 cm^2
2. Rainulator cross sectional area: 774 cm^2

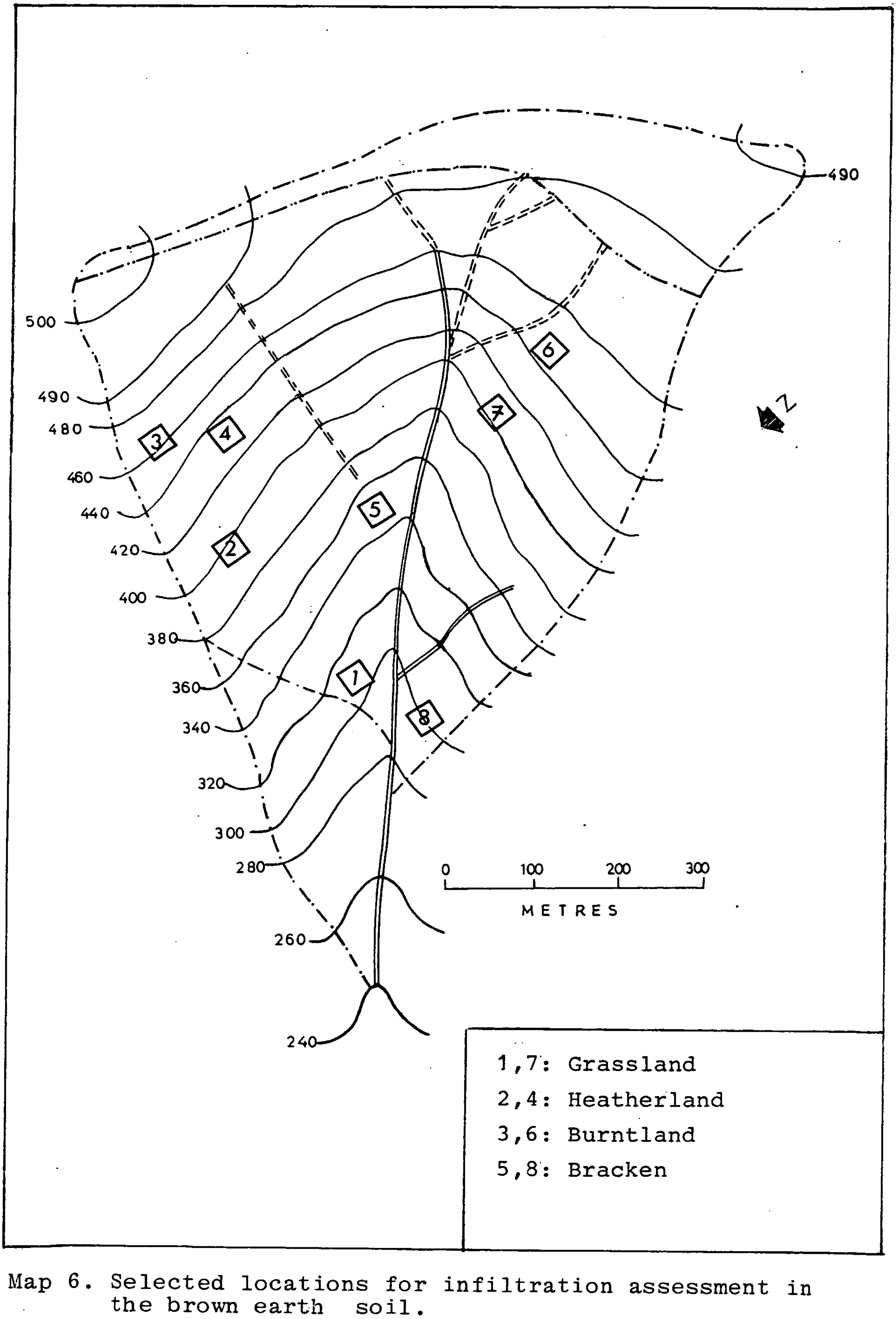
Table 15. "Infiltrometer data sheet" used to compute the infiltration rates in the study catchment on 9th Sept. 1981.

occupied by brown earth soil, while at the same time they were not more than 400 metres from the stream channel. This constraint being imposed to overcome the difficulty of transporting the instrument and water over long distance.

The locations selected are depicted in Map 6 and Table 16 shows their main physical characteristics.Locations 1 and 7 were both grassland and were on slopes (I) and (II) respectively. The vegetation in location 1 was not thick, and small areas of bare soil were visible. In contrast, location 7 was completely covered by grass. Locations 2 and 4 were covered with heather and differed in vegetation age and density. The heather of location 2 was seven or eight years old and very thick,whilst that of location 4 was five years old and contained within it small grassy or barren areas. Locations 3 and 6 were burnt land, the burning having taken place in 1981. At location 3 the ground was completely free of litter, while at location 6 the ground was covered with a litter layer consisting of burnt moss and small fragments of heather. Finally, locations 5 and 8 were both covered with bracken and were situated close to the stream channel. The selection of these locations close to the stream channel with their lack of distinctive soil horizons was unavoidable as the patches of bracken occurring further from the stream channel were not regarded as being representative of the whole land use type due to their small size.

With the locations now selected there were a number of details to be clarified before measurements could begin. These were:

a) The intensity of the simulated rainfall.



Map 6. Selected locations for infiltration assessment in the brown earth soil.

Location No.	Soil type	Land use	Average gradient	
			0^{o}	%
1	Brown earth	Grassland	33	73
2	"	Heatherland	28	62
3	"	Burntland	24	53
4	"	Heatherland	32	71
5	"	Bracken	11	24
6	"	Burntland	33	73
7	"	Grassland	31	69
8	"	Bracken	9	20

Table 16. Characteristics of the locations selected for infiltration assessment

b) The duration of each measurement.

c) The number of measurements that could be taken in each location in one day.

d) The size of the area in each location where the measurements would be made.

The intensity of the artificial rainfall could not be lower than 40 mm/hr because the instrument, as mentioned earlier, could not produce intensities lower than this. However, even the lower limit of 40 mm/hr far exceeds any natural rainfall rate normally experienced in Britain and it was therefore decided to use 50 mm/hr in order to avoid any operational problems of the instrument with the lowest rate.

Considering point (b), the total amount of rain that fell in the catchment and the surrounding areas which produced serious flooding problems in 1948 and 1956 was taken into account. Meteorological office data showed that this ranged from 100 to 150 mm in 2 days. Thus the mean intensity was 2 or 3 mm/hr. Comparison of the catchment reaction to 100 to 150 mm of natural rain falling in 2 days, and 100 to 150 of artificial rain falling in 2 or 3 hours would be of dubious value. However, with a lot of reservations it was decided to apply artificial rainfall for 2 hours with an intensity of 50 mm/hr as stated earlier. With this intensity, the sites would receive approximately the same amount of rain that falls naturally during long flood-producing events and some indication as to reaction of the soil to this amount of water might therefore be obtained. Detail (c) was the number of measurements that could be taken in each location in one day. This depended on the duration of each measurement, the time taken to transport the instrument and its water supply to the location and the time taken to set the instrument up before use. For four measurements the time taken added up to approximately twelve hours. In addition, two more hours would be used in travelling from Edinburgh to the study area and back again. Consequently, even if everything went well, it was not really possible to envisage making more than 4 measurements each day.

Finally a decision was taken concerning the size of the area in each selected location where the measurements would be made. This was done by choosing a rectangular area 6 x 5 metres inside each location, and dividing it into 0.25 m^2 squares (infiltration sites). A number of these squares chosen at random was used for measurements.

The procedure for the decisions taken and described above was time-consuming and therefore the locations were not selected until the end of September 1981. At that time of year at the latitude of the study area the daylight hours are short and consequently four measurements could not be made in each selected location in one day. As a result of this situation it was decided that in 1981 only two measurements would be made instead of four. These were undertaken in October 1981 and the data collected are shown in Table 17. The results demonstrate a wide range of mean infiltration rates for individual sites in the catchment. Mean infiltration rates recorded in two hours ranged from 5.5 mm/hr (location 6, site 1) to 47.30 mm/hr (location 5, site 1). The rates varied not only from one location to another but from one site to another in the same location. Visual appraisal

Location No.	Infiltration Site No.	Land-use	Gradient	Mean Infiltration rate (mm/hr)	Litter flow (mm of depth)	Through flow (mm of depth)
1	1	Grassland	33°	22.10	33.80	22.00
	2			32.00	12.60	23.40
7	1		31°	8.00	80.60	3.55
	2			5.70	88.50	-
2	1	Heatherland	28°	13.30	26.00	47.40
	2			11.40	50.25	26.95
4	1		32°	13.50	6.20	66.80
	2			7.40	77.10	8.10
3	1	Burntland	24°	12.30	57.10	18.30
	2			9.00	60.60	21.50
6	1		33°	5.50	86.90	2.10
	2			7.20	84.70	0.90
5	1	Bracken	11°	47.30	-	5.40
	2			44.90	-	10.20
8	1		9°	21.00	-	58.00
	2			30.20	2.10	37.50

Table 17. Mean infiltration rates, litter flows and throughflows recorded in October 1981 from the eight selected locations.

Infiltrometer Type	Infiltration site									
	1	2	3	4	5	6	7	8	9	10
Rainfall simulator infiltrometer Infiltration rate (mm/hr)	32.6	23.0	8.3	14.8	15.6	16.8	17.1	10.2	9.1	11.6
Cylinder infiltrometer Infiltration capacity (cm/hr)	119	101	177	161	225	243	241	138	235	220

Table 18. Infiltration rates and infiltration capacities computed with the rainfall simulator and the cylinder infiltrometer respectively.

of the data shows that higher infiltration rates were recorded in locations 5 and 8 (bracken) and lower in locations 3 and 6 (burnt land).

Infiltration rates were considerably lower than the infiltration capacities recorded with the cylinder infiltrometer. A comparative data sample is presented in Table 18. The first set of values ranged from 9.1 to 32.6 mm/hr and the second from 101 to 243 cm/hr (1,010 to 2,430 mm/hr). The large difference is obvious and one can reasonably claim that with the cylinder infiltrometer the values are higher because no laterally moving water was collected and subtracted from the total amount applied during the test. If the soil in the catchment had such high infiltration capacities, then no litter flow would be observed by applying artificial rainfall with an intensity of 50 mm/hr. However, as Table 17 shows, litter flow was observed at almost every site and it ranged from 2.1 to 88.5 % of the total water applied. Furthermore, such high infiltration capacities of the soil are not justified if we take into account that litter flow was observed in the triangular plots during natural rainfall with a lower intensity than the artificial rainfall.

Litter flow data from natural and artificial rainfall are presented in Table 19 and show that in some triangular plots the amount of natural rainfall observed as litter flow was very high. In plot 1 location 1, for example, in interval 7, 67.5% of the rain became litter flow. The data from both infiltrometers and the occurrence of litter flow from natural and artificial rainfall indicate that the

A

No. of location	No. of infiltration site	Land-use	Artificial Rainfall (mm) T	O	%
1	1	Grassland	93.30	33.75	36.00
	2		100	12.65	12.65
7	1		100	12.65	12.65
	2		100	80.60	80.60
2	1	Heatherland	100	88.50	88.50
	2		100	26.00	26.00
4	1		100	6.20	6.20
	2		100	77.15	77.15
3	1	Burntland	100	57.10	57.10
	2		100	60.55	60.55
6	1		100	86.90	86.90
	2		100	84.75	84.75
5	1	Bracken	100	-	-
	2		100	-	-
8	1		100	7.00	7.00
	2		100	2.10	2.10

T = Total applied rainfall on each plot or site.

O = Amount of rainfall which converted to litter flow.

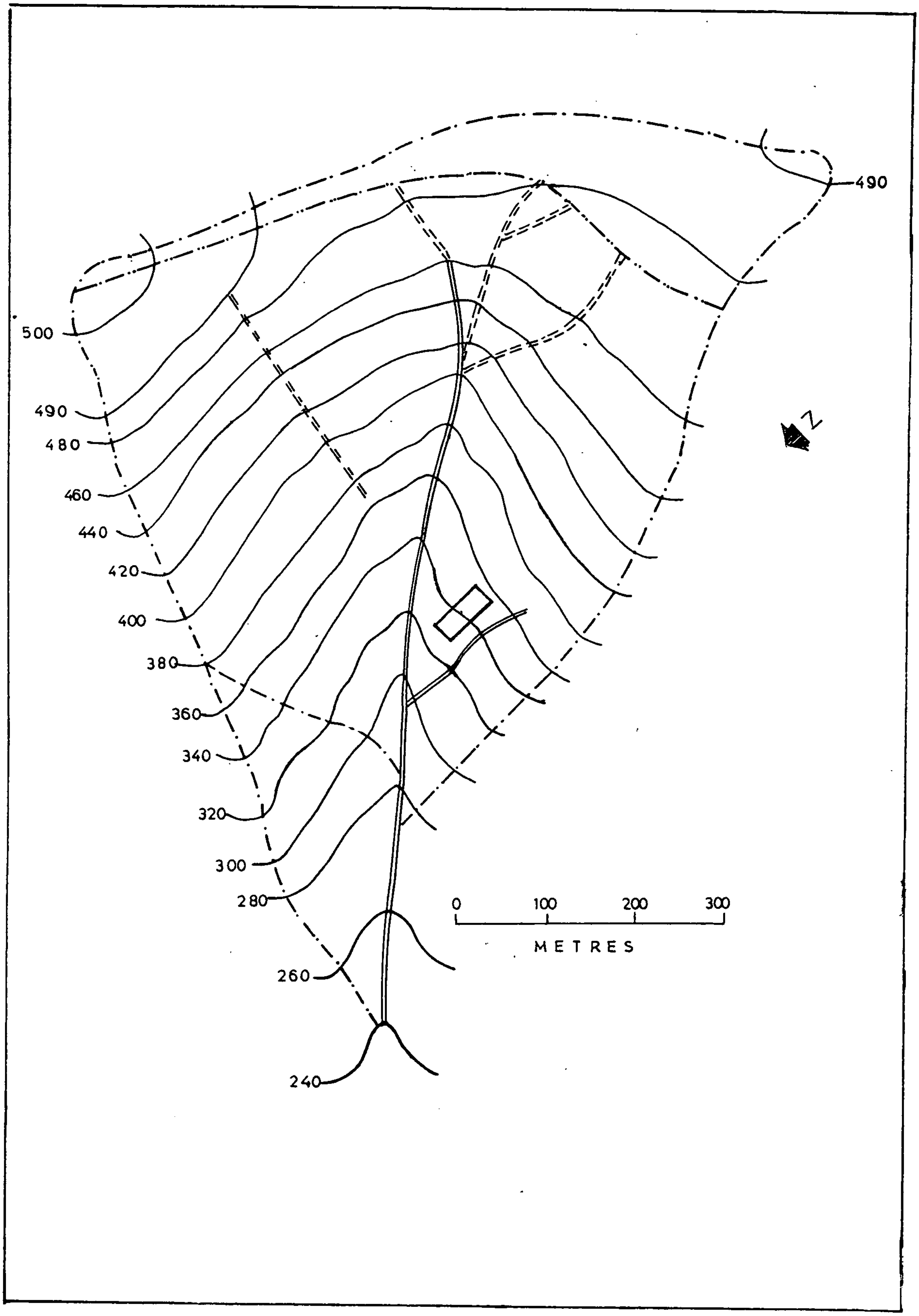
B

No. of location	Land-use	No. of plot	Natural Rainfall (mm)								
			Time interval								
			4			6			7		
			Date								
			16-20/9/81			24-26/9/81			1-4/10/81		
			T	O	%	T	O	%	T	O	%
1	Grassland	1	39	12	30.8	55.8	28	50.2	94.8	64	67.5
		2	39	4	10.2	55.8	13	23.3	94.8	26	27.4
2	Burntland	3	39.8	7.6	19.1	54.4	9.3	17.1	108.1	26.6	24.6
		4	39.8	15.7	39.4	54.4	20.5	37.7	108.1	56.6	52.3
		5	39.8	8.3	20.8	54.4	14.1	25.9	108.1	32	29.6
3	Heatherland	6	39.8	1	2.5	54.4	3.4	6.2	108.1	14.8	13.7
		7	39.8	3.9	9.8	54.4	6.6	12.1	108.1	16	14.8
		8	39.8	6.6	16.6	54.4	10.9	20	108.1	25.4	23.5
4	Burntland	9	39.4	4.9	12.4	54.6	9.8	18	55.7	13.4	24
		10	39.4	-	-	54.6	-	-	55.7	-	-

Table 19. Occurrence of litter flow in the study catchment from artificial (A) and natural (B) rainfall.

rainfall simulator infiltrometer gave results that could be regarded as being reliable, and closer in value to those resulting from natural rainfall than those using the cylinder infiltrometer. Furthermore, the simulator was regarded as adequate in the topographic and climatic conditions of the catchment after the modifications were made to it. The time spent developing the instrument seemed, therefore, to have been well worth while.

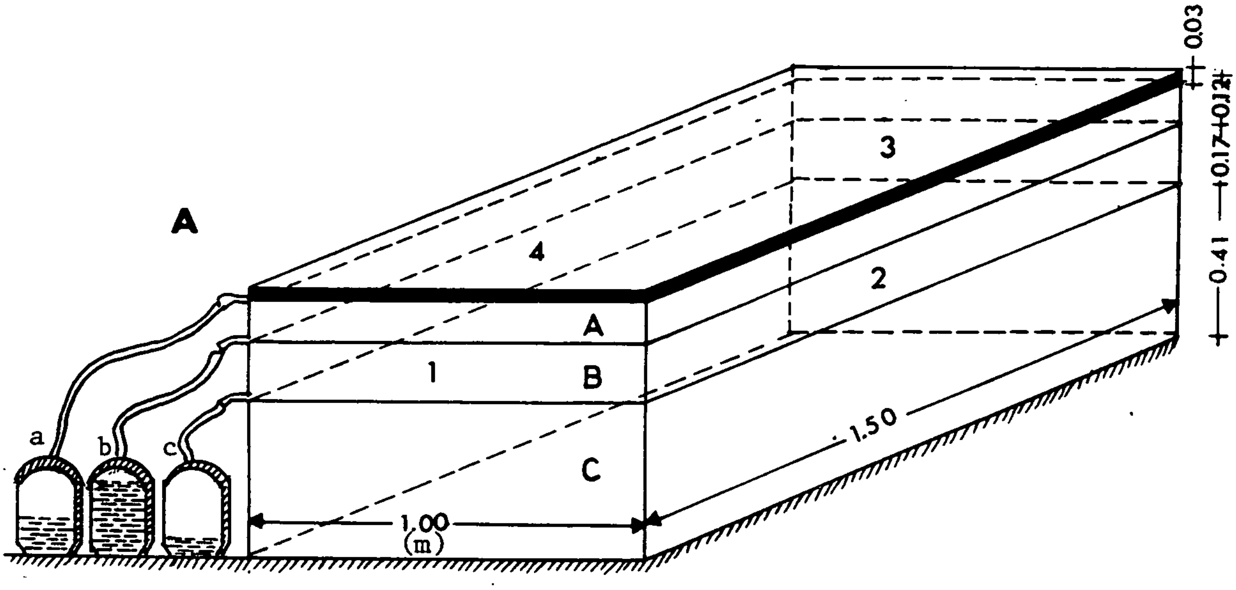
3.2.2.3 Trial Throughflow Plot. As was emphasized in the general introduction of the thesis a number of research workers found out that water movement through the various soil horizons and mainly through root channels and animal burrows was the dominant flow process in the areas they worked. Furthermore, they indicated that such water movement contributed to storm runoff. As far as the present study area is concerned, the work carried out with the triangular plots and the rainfall simulator infiltrometer up to the end of August 1981 indicated that litter flow and flow through the A horizon of the soil was important. It was recognized, however, that a fuller understanding of water movement through the upper and lower soil horizons could only be obtained by installing larger and more sophisticated plots than the triangular ones. It was decided that a plot 1.5 m in length and 1 metre in width would give some information about the existence and importance of water movements through the soil horizons. A location was selected at the beginning of September at the lower part of slope II approximately 60 metres from the channel of the main



Map 7. Location where the trial throughflow plot was constructed.

stream (Map 7). The location had an average gradient of 24° and a covering of grass. Installation of a plot without sealed boundaries would mean that it would receive drainage from area directly upslope of it rather than only its own area. Therefore, the sides of the plot had to be sealed to avoid water entering from outside. Other workers who have installed plots not covering the whole slope length (from the stream bank up to the ridge top) have used various techniques to protect them from water coming from external areas. Hewlett (1961, 1963) for example, built up in the middle of a slope a box made of cement which was then filled with soil. Whipkey (1965, 1969) in plots installed in a slope, applied artificial rainfall and therefore it was not necessary for the sides of them to be covered. However, in this part of the present study sealing of the plots' sides with cement or some other type of water-proof material was not considered necessary for the following reasons: Firstly, only the amount of water draining from the plot would be collected and measured and not its time distribution. Secondly, sealing the plot in this way was time-consuming and as its construction was not started until the beginning of September, it had to be completed quickly if any data were to be obtained before the end of the field season. With these problems in mind it was decided to dig a trench around the plot so that water draining directly from upslope would not affect the plot itself.

The construction of the plot is shown in Figure 9. Diagram A shows the construction with details and diagram B a plan view of the plot. The trench was 20 cm in width

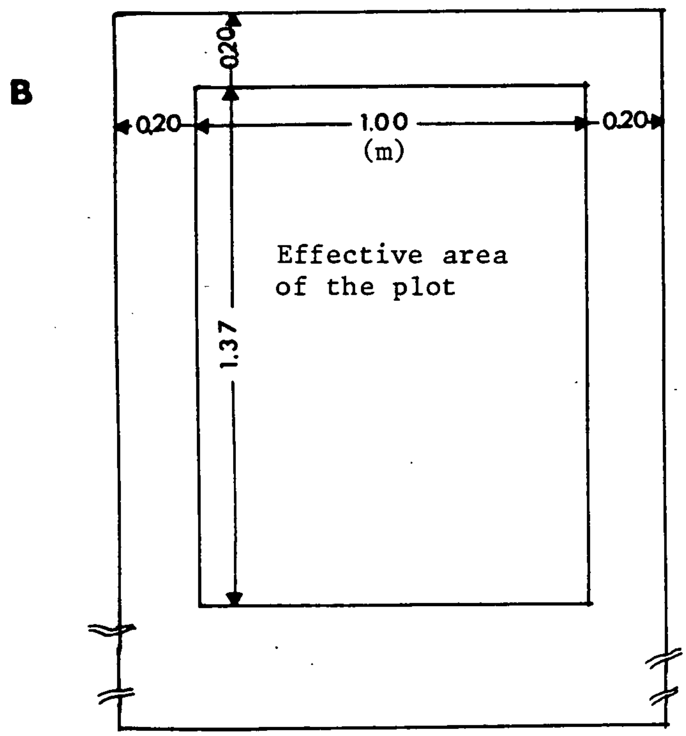


A. Perspective view of the plot

Litter layer

A,B,C Horizons of the soil

a,b,c Containers for collection of litter flow and flows from the A and B soil horizons respectively



B. Plan view of the plot

Figure 9. Trial throughflow plot.

which was considered enough for the insertion of gutters and collection of flow. The depth of the plot was 70 cm as the A, B and C horizons were 12, 17 and 41 cm respectively. Gutters were inserted on sides 1, 2 and 4. On side 3 any water loss was regarded as negligible due to the plot gradient. The gutters were made of light zinc and bent to an angle of 45°. They were inserted so that water flowing into the gutters on faces 2 and 4 would flow into the gutters on side 1 and from there into polythene containers. The first three gutters for litter flow collection were placed 3 cm below the ground surface and were driven 3-4 cm into the plot face. The next three gutters were inserted just below the A horizon and made watertight with a mixture of cement and mortar. In the same way a third set of gutters was inserted just below the B horizon. The installation of the fourth set of gutters for the collection of flow from the C horizon, however, proved to be impossible due to the hardness of the soil below the B horizon. Therefore, flows were collected and measured only from the A and B horizons and over the ground surface as litter flow. The water from these gutters being led into three 15 litre capacity plastic containers. When the construction was finished a roof was built to protect the gutters from direct rainfall.

The plot was operated until the end of October and the containers checked once a week. In the event of a long rain event they were checked when the rain stopped. For the computation of the amount of rain falling in the plot the arithmetic mean of the readings from gauges 1 and 2 was used. This is because the plot was situated approximately half-way between them (Map 4).

During September and October a small number of rain events occurred and various amounts of litter flow and flows from the A and B horizons were collected and measured. Three of these events have been chosen for analysis and discussion. They were selected firstly because the rainfall was continuous and as a result there was no doubt about the amount of rain that produced the observed volumes of litter flow and throughflow, and, secondly, because they also produced hydrograph rises in the stream draining the study area. Plot data for these events are shown in Table 20. The rain events on the 2nd and 4th October are not separate. In reality it started raining on the 1st October at 8.00 a.m. and finished on the 2nd October at 8.00 p.m. but the containers were checked twice, on the 2nd and 4th, and the observed flows are presented both, separately and combined. On the 26th September, and on the 2nd and 4th October the A horizon collection container was found to be full of water. The first time it was found full the author decided to replace it with a bigger one. Unfortunately before this could be done it started raining again and it was not possible to install a larger container until the 6th October. As luck would have it, the rainfall for the rest of the month was very low and the extra capacity was not needed!

During these three events 156 mm of rain fell on the plot area and of this amount 65.9 mm (42.3%) moved as litter flow and through the A and B horizons of the plot soil. Of the total rainfall 9.6% formed litter flow and 25 and 7.7% moved through the A and B horizons respectively.

Date	Average Rainfall (mm) Gauge $\frac{1+2}{2}$	Litter flow			Flow through A horizon			Flow through B horizon			Total		
		Litres	mm	%	Litres	mm	%	Litres	mm	%	Litres	mm	%
19/9/81	34	3.4	2.5	7	8	6	18	-	-	-	11.4	8.5	25
26/9/81	46.3	5.2	4	9	15*	11	24	2.8	2	4.5	23	17	36.8
2/10/81	47.4	8.5	6.2	13	15*	11	23	7.1	5.2	11	30.6	22.4	47.2
4/10/81	28	3	2.2	8	15*	11	39	6.4	4.7	17	24.4	17.3	64
4/10/81	75.4	11.5	8.4	11	30	22	29.2	13.5	10	13.3	55	40.4	53.6
Total	155.7	20.1	14.9	9.6	53	39	25	16.3	12	7.7	89.4	65.9	42.3

* The container was full.

Table 20. Data obtained from the trial throughflow plot in 1981.

The amount of rain that flowed through the A horizon must have been higher as the container was found to be full. Unfortunately the amount of water lost could not be estimated. The rain event on the 19th September produced only litter flow and flow through the A horizon; these amounts were 7 and 18% of the total rainfall (34 mm) respectively. The rain event on the 26th September produced flows from all three soil segments which were 9,24 and 4.5% of the total amount of rainfall (46.3 mm) respectively. During this rain event the water that seeped from the plot was 13% higher than that of the previous rain event. The A horizon container was found to be full of water and therefore the real amount of rain that moved through it was unknown. During the rain event of the 1st October 1981 the containers were checked twice, as has been mentioned earlier. The amount of litter flow was 6.2 mm and 2.2 mm, or 13% and 8% of the total rain that fell in the plot from 1st October (8.00 a.m.) to the 2nd October (9.00 a.m.) and from 2nd October (9.00 a.m.) to 8.00 p.m. of the same date respectively. The equivalent results for flow through the B horizon were 5.2 mm and 4.7 mm (11% and 17%). The results for both checks for the A horizon were 11 mm because the container was full of water. In reality there was an increase in the amount of rainwater flow through the A horizon from 23% to 39% of the total rainfall (47.4 and 28 mm). These figures would have been higher had a larger container been used.

From the data obtained during these events it can be concluded that movement of the rainfall over the ground surface or through the litter layer and through the A and

B horizons of the soil was considerable.

It was also recognized that plot experiments of this type were necessary if flow processes in the study area were to be fully investigated.

3.2.3 Conclusions of First Field Season's Experimental Work.

As was indicated in section 3.1, the first field season's experimental work had a preliminary purpose. Specifically it was designed to find out what flow processes occurred in the study catchment. It was also intended to test the suitability of instruments and equipment, and to throw light on the methods by which these flow processes could be measured. This work also gave valuable experience in making appropriate measurements.

The chapters devoted to the description of the experiments undertaken, and the data obtained during this period have shown that conclusions can be made concerning the measurement of rainfall and runoff, litter flow, infiltration and throughflow.

As far as rainfall and runoff are concerned the results show that the established network of five standard raingauges in the catchment and the water level recorder at the outlet of the catchment gave reasonably accurate data. However, it was recognized that there must have been some under-estimation of the measured rainfall, despite the use of standard raingauges at ground level. This was due to the variable gradients of the catchment slopes and the effect of wind on the rainfall distribution. As was stressed previously, (section 3.2.1.1) when the rain strikes a steep slope horizontally there is a redistribution of the raindrops. Specifically small diameter raindrops are deposited in different places from large diameter raindrops. Also small diameter raindrops do not reach the ground surface simultaneously with large diameter raindrops. Another source of error must have been the fact that not all the sub-slope aspects of the catchment were covered adequately by five-raingauge network. Runoff was measured reasonably accurately as well and the instrument operated well throughout the period.

The data obtained from the triangular plots during the period of operation indicated that litter flow occurred in almost every location. The observed amount varied from one location to another and from one plot to another in the same location. This variability was considered to indicate that the occurrence and importance of litter flow could have been studied with more precision if larger plots had been constructed. The observed amounts of litter flow were produced by rainfall events of various intensity and duration. Soil moisture conditions also varied. The maintenance of these plots was not an easy task, however, as damage caused by animals living in the catchment was very frequent. It was decided therefore, that they would not be used in the second field season. The first reason for this decision was that larger and more sophisticated plots than the triangular plots were considered better for litter flow detection. With more sophisticated plots the occurrence of throughflow could be studied in addition to litter flow. Secondly, it was difficult for the author to operate and maintain two different types of plots. However, despite the cessation of the operation of the triangular plots in the brown soil area, it was concluded that a number of plots of this type usefully be constructed in the portion of the catchment occupied by peat soil during the second field season.

The cylinder infiltrometer was used to determine infiltration capacity was clearly unsatisfactory. The modified rainfall simulator, on the other hand, gave good results and was convenient to use. Moreover, it enabled the movement of the infiltrated water through the soil to be studied.

Finally the work undertaken enabled conclusions to be made concerning litter flow and throughflow occurrence from natural rainfall by operating the trial throughflow plot. The operation of this plot, despite the short time available, showed that of the water absorbed by the soil, the greater part moved through the A horizon. It was felt, therefore, that better-constructed plots of this type would provide much vital information about the area in hydrological behaviour.

3.3 SECOND FIELD SEASON'S EXPERIMENTAL WORK

In the light of the comments made in the preceding sections it was decided that the following work should be undertaken during the second season:

1) Continued measurement of rainfall and runoff with the same instruments and equipment that were used in the first season. Thought was given to increasing the

intensity of the raingauge network, but in the end this was not followed up because of the extra time that would have been involved in making even more observations.

2) Selection of a location at the top of the catchment occupied by peat soil and establishment there of a number of triangular plots for litter flow collection and measurement. Measurements of litter flow on the slopes of the catchment occupied by brown earth soil by triangular plots would not be continued during the second field season for reasons mentioned earlier.

3) Continuation of infiltration measurement at the eight locations selected for study in season one in the brown earth soil, using the modified infiltrometer. Also selection of a new location in the peat soil area of the catchment for measurement of the infiltration rates of the peat soil.

4) Selection of a number of locations and establishment there, of larger and more sophisticated runoff plots than the triangular and the trial throughflow plots for detailed study of litter flow and flow through the soil horizons.

5) Supplementation of the data obtained from these larger plots by the application of artificial rain to them. This decision was taken because natural rainfall is unpredictable in terms of both time and space, and the runoff plots might not be in operation long enough for sufficient data to be collected from natural rainfall events alone.

6) Measurement of the flow velocity through the A soil horizon by applying artificial rainfall. This decision was taken because the infiltration measurements taken during October 1981 showed that water moved very quickly through the A horizon.

3.3.1 Litter Flow Measurements in the Peat Soil

Three triangular plots were installed in the peat soil area of the catchment in June 1982 and were operated until November 1982. It was recognized that this was a small number, but it was not feasible to install and maintain a larger number of such plots in so remote a part of the area. The plots were installed at a location chosen approximately 50 metres from the top of the catchment. It was covered with grass and its gradient ranged from 9° to 11°. The fact that the peat soil area of the catchment was covered with grass and heather was taken into account. However, as the largest part of it was covered with grass, it was considered reasonable to collect and measure any occurrence of litter flow in this vegetative cover. In the selected location a smaller one 10 x 10 metres was chosen and three plots with sides 50 cm in length were constructed in the way described earlier. The location was numbered 5, as the other locations selected in the first field season were numbered 1 to 4. Also the plots were numbered 11 to 13, as the first field season's plots were numbered 1 to 10. The specific gradient and the projectional area of each plot in cm^2 is given in Table 21.

Location No.	Plot No.	Gradient of plot		Projectional area in cm^2
		0°	%	
5	11	9	20	1,070
	12	9	20	1,070
	13	11	24	1,063

Table 21. Characteristics of the triangular plots constructed at the peat soil.

For the computation of the amount of rain falling in the plots the gauge 3 (Map 4) was used becuase it was very near to the location. The volume was measured once each week and in the case of a large rainfall it was measured during the rainfall or when it stopped. Measures were taken to protect the plots from damage and they remained in good conditions throughout the period of operation.

3.3.2 Infiltration Measurements

Infiltration measurements during the second field season were made as planned in the eight locations selected for study during the first year. Two sets of four measurements were made at each location. This was because each measurement lasted at least two and a half hours and therefore more than four measurements could not be made in one day under the same weather conditions. This frequency of measurement was smaller than the statistically desirable sample size, but for reasons stated earlier, there was nothing the author could do about this.

The work was carried out during July and August 1982. These months were chosen because this is the main flood season in this part of Scotland. The measurements at the various locations were not made on consecutive days, but at least every other day due to the difficulty of the work. The time for each set of measurements ranged from 12 to 15 hours depending on the distance that the instrument and the water had to be carried. When the first set of four measurements in each location was finished, the next set was started.

At this stage, it has to be added that in July 1982 a new location was chosen at the top of the catchment which was occupied by peat soil. On the 27th of this month eight hourly measurements were made. The short duration of these measurements was due to the distance the water had to be carried. Also in the same location on the 31st July 1982 two more measurements were made, each lasting for two hours in order to get some additional information about the response of the peat soil to a larger amount of artificial rainfall.

3.3.3 Selection of Locations and Construction of the Runoff Plots

The first problem to be solved in this part of the work for the second field season was the selection of the locations in which to install the runoff plots. From the catchment factors that affect the flow quantity such as soil type, land treatment, topography, lithology, etc. (Whipkey et al., 1980; Ward, 1975) only soil type and land treatment were taken into account for the selection of the locations. This is because it was very easy to identify these factors in the catchment and thus select locations. Topography was not taken into account because this is only important for very long plots (Whipkey et al., 1980) while in the present study, as will be explained later, the runoff plots were not very large. Lithology was not taken into account as it was uniform over the whole catchment (Ragg et al., 1967). Finally, it has to be emphasised that to consider all the factors that control throughflow would mean the establishment of a large number of runoff plots which would make the present study much more difficult.

Hence, it was hypothesised that any variations in flow rates would be greater between locations with different soil type and land treatment than between locations with the same soil type and land treatment. This is borne out by experience gained from the results of measurements in the first field season. However, these control factors are not enough to suggest that there would be variations in throughflow rates between two locations of differing soil type and land treatment. For example, the depth and structure of the soil may affect the throughflow rates and this has been stressed by a number of previous investigators. Amerman and McGuiness (1965) emphasised that "No watershed, large or small, is simply a two-dimensional, irregular leaky surface. It is three-dimensional. The mass or body of the watershed below the surface is composed of porous material which is often a complex, heterogeneous combination of layered soil and rocks". Also Betson and Marius (1969), when he found in an experimental catchment no direct relationship between plot and catchment runoff, stressed that "No matter how similar two areas may appear on the surface, variations in the composition and depth of various soil horizons can occur that may markedly influence how any particular area within a watershed contributes to storm runoff". Additionally, the same investigator (Betson et al., 1980) mentioned that "even single hillslopes are far from being simple homogeneous systems".

Despite these conclusions, the soil types and land treatments were taken into account for the selection of the locations simply because it was impossible to know, beforehand, the possible variations in the rates of throughflow that might be recorded by the plots. The existing soil types and land treatments in the study area have been described in the second part of this thesis.

Before selecting the locations it was necessary to consider the length of the plots since this could affect the choice of the locations. Plots having a length from the ridge top of the catchment to the bank of the stream channel may be good for the study of throughflow, but construction and running of a plot covering this length of slope is not easy. Therefore a number of previous investigators, as mentioned in the general introduction, measured direct throughflow seepage from the soil by a device fixed in an artificial soil profile in the middle of the slope and the length of the plot was shorter than the total length of the slope.

In this study the idea of constructed plots over the whole length of the slopes seemed not to be feasible for the following reasons:

1. The boundary between the peat soil occurring at the top of the catchment and the brown earth soil occurring on the lower slopes of it (Map 2) was such that it was not possible to find a strip of land from the top of the catchment to the stream banks that contained only one of these soil types. The collection of flow from two soil types would not show the separate response of either of them.
2. There was a possibility that the plot would not be drained solely from the area located directly upslope of it. This was due to the presence of a large number of animal burrows in the slopes of the catchment. The burrows led in different directions and therefore it would be possible for the plot area to receive water from areas other than directly upslope and also to lose water as burrows crossed the plot area.
3. The banks of the stream were completely covered with vegetation. This vegetation had to be removed for the insertion of the gutters which meant some disturbance of the soil. Therefore the advantages of inserting the gutters in an undisturbed natural soil profile would be lost. Also it would be difficult for flows to be collected and measured from each soil horizon as there was no distinctive formation of soil horizons present at the banks of the stream.
4. The drainage area of a plot having such a length would be very large and a water level recorder would be needed to measure the flows, the one available was used to measure the total stream flow at the outlet of the

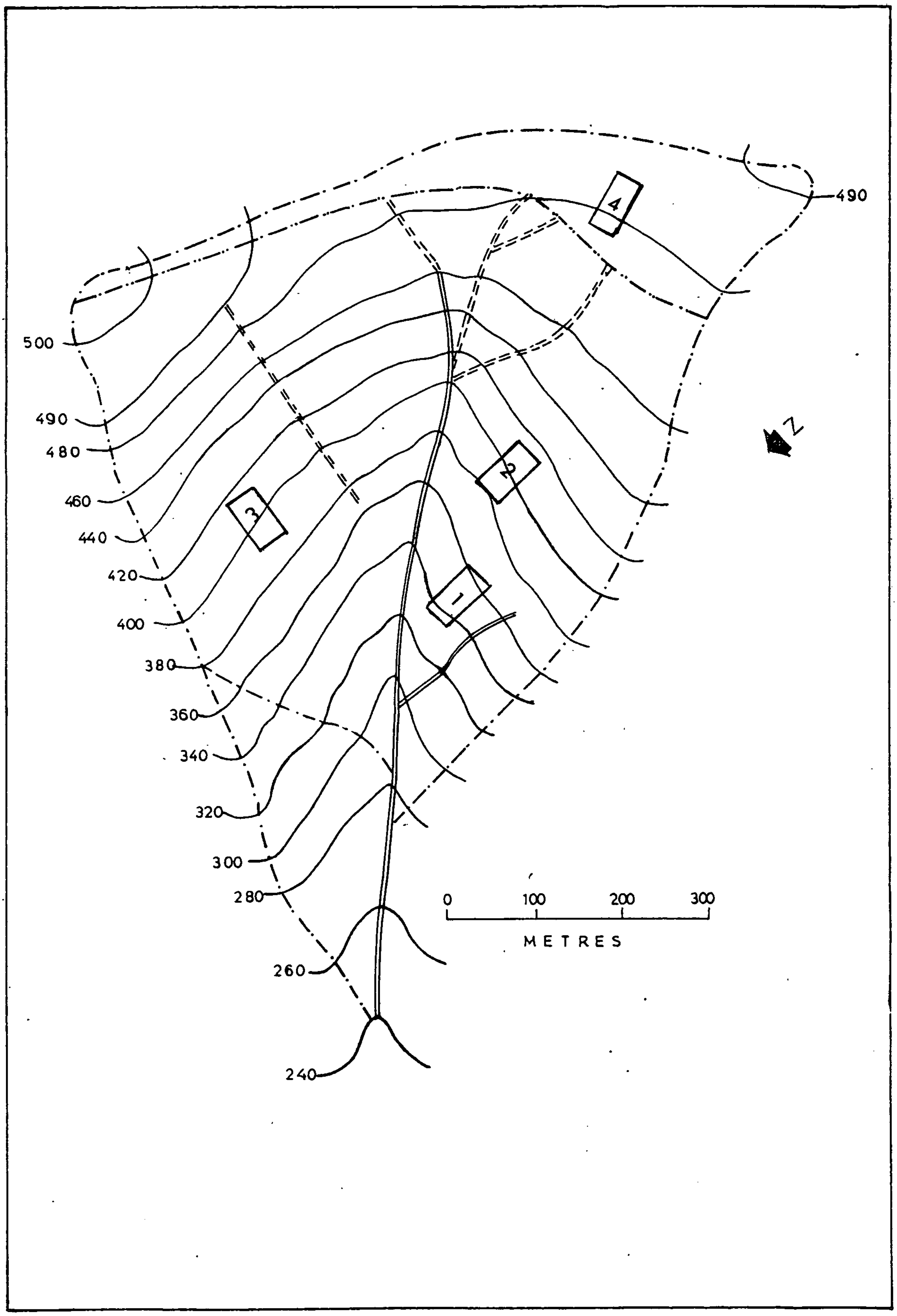
catchment. To collect flow from such a large area would require large containers which would be difficult to transport. It would also be difficult for one person using large plots to measure the time distribution of flows using a stopwatch and measuring cylinder.

5. There was a patchwork of differing vegetation over the catchment and a plot covering more than one type of vegetation. A long plot length covering more than one vegetation type would introduce an unnecessary variable.

These were the reasons for constructing a number of plots on the slopes of the catchment of a shorter length than the whole slope.

Three locations were selected on the slopes of the study area because three different land treatments occurred on the area of brown earth soil. In addition, one more location was chosen at the top of the catchment where peat soil occurred. These locations were selected in the same way as the locations for the establishment of the triangular plots. The total area of each location was approximately 1,500 to 1,600 m^2.

Location 1 was burnt land with an average gradient of 24°. The burning took place in May 1981 and when it was chosen in May 1982 some thin grass was growing there. Location 2 was grassland with an average gradient of 32°. Location 3 was heatherland with an average gradient of 31°. The heather was five years old. Finally, location 4 was chosen close to an artificial drainage pit and had a thick Vaccinium cover. Its average gradient was 11°. The selected locations are shown in Map 8.



Map 8. Selected locations in the study area where the runoff plots were constructed.

The decision that had been made to construct the plots on the slopes would not only mean digging a pit for the insertion of the gutters but also building artificial boundaries to avoid the influence of the water draining downwards from the area upslope of the plot. As a result, the soil would be disturbed to a large degree and as the land was private serious disturbance was not permitted. This was the first of the reasons why it was decided to construct only one plot in each location. The second reason was the amount of work involved for one person and the amount of money needed for construction materials which would be excessive. A sloping area within each plot of 1.5 m^2 was regarded as adequate for the study of water movement through the soil horizons. It was of course recognized that larger plots would be better for the examination of the runoff characteristics of the slope but the constraints mentioned earlier restricted the choice of plot size.

The width of the plots was 0.9 m as a number of plastic gutters 0.9 m in length were available from a previous research project. Re-use of those gutters was economically sensible. The sloping length of the plots was 1.7 m as the plot area was to be 1.5 m^2. As well as flow from each of the soil horizons, litter flow would be collected.

After these considerations, a rectangular area 1.7 x 0.9 m, representative of the whole location (1,500 - 1,600 m^2), was chosen; this is where the plots would be constructed. Before beginning the construction a decision had to be made as to what material to use for the boundaries of the plot. The idea of covering the plot sides with polythene or metal sheets was not adopted because there were doubts concerning their suitability. Whipkey (1965) found that polythene sheets did not form a good connection with the soil.

Alternatively, a mixture of cement and mortar was tested in a natural soil profile and worked perfectly. Firstly the soil face was wetted and then covered with the mixture. The connection was so good that any water movement between the soil and the material would be negligible. It was therefore decided to employ this method of sealing the plot boundaries.

Construction was started on May 10th, 1982 at plot 1. A rectangular frame of string with length of 1.7 metres and width of 0.9 metres was used to define the boundaries of the plot on the ground surface. Along the outer edge of the side boundaries a pit of 0.2 metres in width and a depth down the parent material was dug. The depths of the A, B and C horizons were 9, 12 and 45 cm respectively. The upslope end of the pit was 20 cm deeper than the downslope one in order to avoid any influence of water flowing downslope from areas outside of the plot. The exposed plot faces were then wetted and covered with the cement and mortar mixture to a thickness of between 1.5 to 2 cm. A polythene sheet was placed on the outside to support the mixture when wet. When the cement and mortar mixture had dried the pit was refilled with soil up to the ground surface. The downslope face of the plot, where the gutters were to be inserted was cut in such a way that each successively deeper soil horizon projected 3 cm further out than the one above to provide better support for the gutters. The installation of a gutter for litter flow collection in this plot was not regarded as being worthwhile as the A horizon was very loose and it was therefore difficult to separate litter flow from throughflow. Hence, only three gutters were installed to collect flow from the A, B and C horizons. They were installed in the following manner; the soil just below each horizon was cut using a chisel to form a groove which went into the plot a distance of 3 cm horizontally and had a vertical width of 1 cm, cement and mortar was then inserted at the downside of the groove into which the gutter was then placed. A polythene sheet was also inserted to cover the downside of the cutting and part of the gutter. This was to ensure that water flow from each horizon would enter the correct gutter (Whipkey, 1965). At the end of each gutter was a plastic tube which channelled the collected water into plastic containers, these were situated in a pit downslope of the plot at a distance of 4 metres from the plot. The capacity of the containers for the A and B horizons was 25 litres and for the C horizon it was 15 litres. This was done as the conclusions from the first year's work were that throughflow was reduced from A to B and C horizons. The faces of the plot where the gutters were inserted was covered with a nylon mesh to prevent soil falling into the gutters. Also a metal roof was erected to protect the gutters from natural rainfall. Finally the plot was fenced off to protect it from sheep.

The construction of plot 1 was completed in four days. The work was extremely difficult as the materials had to be transferred by hand over long and steep slopes. Plate 4 (A,B),

(A)

(B)

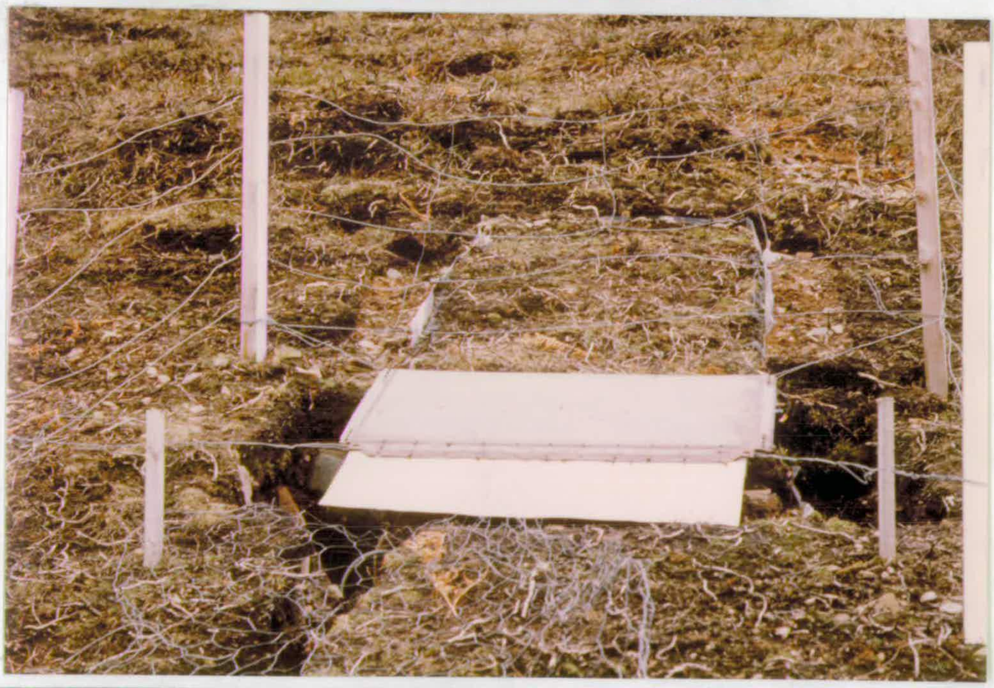


Plate 4: Runoff plot 1.
(A) Guttering system for collecting flows from the soil horizons.
(B) Roof of the plot to prevent rain falling directly on the gutters.

shows the plot after construction was complete. The picture was taken at the end of October 1982 when the area of the plot was covered with some vegetation.

A few days after work on the first plot was finished, the digging was started for the construction of the second plot. The A, B and C horizons were 11, 17 and 36 cm in depth respectively. Firstly the upslope side and secondly the left and right sides were dug and then covered completely with cement and mortar. Then the digging of the downslope side of the plot was started. When this digging had reached the B horizon a large stone was encountered, this stone covered half of the plot side and it proved very difficult to dig any deeper.

Meanwhile, as explained, the other three sides of the plot had already been dug and cemented and therefore half of the work on this plot was complete. To start again on another plot would have been a setback and as the land was private and any other disturbance of the land was not allowed, it was decided that in plot 2 one gutter would be fixed for litter flow collection and two gutters for flow collection from the A and B horizons.

The experience gained from the construction of this plot was that the work should start on the downslope side of the plot. In this case, if it proved difficult for any reason for the gutters to be installed then the plot could be abandoned with little wasted effort and not very serious ground disturbance.

After some time the work continued in constructing plot 3. The strong ground and the lack of distinctive horizons were the characteristics of the soil. Despite these conditions, the work continued and a pit 90 cm in depth was dug. In its downslope profile three gutters were inserted; the first 2 cm below the ground surface for litter flow collection, the second 18 cm lower than the first where the boundary between the A and B horizons occurred and where the C horizon may have been, this, as explained earlier being due to the lack of distinctive soil horizons. Finally, the third gutter was installed at the bottom of the pit.

A nylon mesh was used to protect the gutters from falling soil. Despite this precaution a lot of soil fell in the space of a few days, some of which was suspended in the net and some which accumulated in the third gutter. The first time this happened, the soil was removed and the gutter fixed in position again. The problem of soil accumulating in this third gutter persisted however, and so the gutter was removed completely and the pit was filled with soil until its depth was 30 cm. As a result of this only two gutters remained in plot 3.

The final plot was constructed at the top of the catchment. Flows were collected and measured only from the peat horizon. The reason that a deep pit was not constructed was the long distances and steep terrain over which the materials and especially the cement had to be transported. Plate 5 (A,B) depicts how this plot was constructed.

At this stage it must be stressed that the first three plots were constructed by the end of May 1982 and used from June to October 1982, whilst the fourth plot, due to

(A)

(B)

Plate 5: Runoff plot 4
(A) During construction
(B) After construction.

its position and the time and effort expended on the first three plots, was not constructed until the last ten days of July 1982 and was used from August to October 1982.

Furthermore, the problem the author faced with the destruction of the plastic tubing by rabbits and hares is worthy of note. These tubes were bitten many times and had to be replaced. The destruction continued and a solution was found only when the whole of the tubing was covered with a wire mesh.

From the constructed plots, except the measured amount of flows, the time distribution of plot flow was studied as well. Since the plots were not equipped with a water level recorder, the water flow rates had to be measured with a measuring cylinder and a stopwatch. For this purpose a caravan was sited approximately 1.5 km from the nearest outlet of the study area plot so that the author could stay there and reach the catchment in case of a rain event.

As luck would have it the summer of 1982 was very dry, and virtually no rain occurred in July and August. Even when it did occur, it fell at night when fieldwork was impossible. However, from the middle of September to the middle of October there were a number of wet days, this rainfall being characterised by short duration and uneven distribution in the catchment. During this period the author managed to calculate the time distribution of plot flow only for four rain events despite the fact that he stayed in the catchment for a number of days and nights. Because there were four runoff plots to operate and because the rain events were of short duration, the measurement of flow rates could only be done at one plot every five minutes. Plot 1 was chosen for these measurements because gutters had been inserted to the three soil horizons. From the three other plots only the total volume of flow was collected and measured when the rain ceased and the flow rates were very low.

The work on the time distribution of the plot flow was found to be very difficult and especially at night when a torch was necessary. Of the four rain events mentioned above, three occurred during the day and one occurred at night. Flow rates from some other measurements were not kept as they lasted for a short time (less than five minutes). This work revealed that measurements of this kind at night and under adverse weather conditions were extremely difficult to make.

3.3.4 Application of Artificial Rainfall in the Runoff Plots

A brief mention about the application of artificial rainfall in the runoff plots was made at the planning stage of the second field season's experimental work (see section 3.3). It was felt that the application of artificial rain to the plots would extend the usefulness of the data obtained from them, particularly if it did not rain much during the study period.

It was recognized, however, that the use of artificial rainfall might create some problems. Specifically, the water flows would wet an area of the ground that was a little larger than the area underneath the rainulator

(D = 31.4 cm) before the water seeped out and into the gutters. This disadvantage was due to the presence of the fence in the downslope face of the plot. Removal of the fence and replacement was not simple. As the area between the rainulator and the gutters of the plot was narrow it would become wet quickly and afterwards this would be a convenient method for collection and measurement of the flows, as well as for calculating their time distribution through the soil horizons by applying a large quantity of artificial rainfall and having fixed gutters just below each soil horizon.

At the beginning it was decided that two measurements would be made in each runoff plot at an applied rainfall rate of 50 mm/hr. One would be made in dry and one in wet soil conditions. This is because the movement of water through the soil is affected by the moisture content of the soil.

The discharge rates from the gutters would be monitored manually using a measuring cylinder and stopwatch. Measurements would be taken at five minute intervals.

In plot 1, artificial rainfall was applied on the 2nd July 1982 and in plot 2 on the 5th of the same month. Each of these measurements lasted for three hours. Measurements were made in plots 3 and 4 on the 12th July and 17th August and lasted for two and three hours respectively. The lack of distinctive horizons of the soil was the reason for the shorter duration of the measurement in plot 3. At the end it was decided not to make the next two measurements in plots 3 and 4 for the lack of distinctive soil horizons of the soil and the difficulty in carrying water to the top of the catchment respectively, but only to collect flows from natural rainfall. The above measurements were made under dry soil conditions.

Later, between the middle of September and the middle of October when rain had fallen in the catchment, the two planned measurements for plots 1 and 2 under wet soil conditions were decided to be made. In plot 2 artificial rainfall was applied on the 16th October 1982 for three hours. After this measurement was taken, and while the author was preparing to repeat the measurement in plot 1, it started raining and therefore flows from natural and artificial rainfall could not be separated. Unfortunately the second attempt at making measurements in plot 1 could not be made as a result of an illness to the author which prevented him staying in the catchment for the rest of October 1982.

3.3.5 Determination of the Velocity of Flow Through the A Horizon

It was mentioned in section 3.3 that one of the aims of the second field season's experimental work would be the determination of the velocity of flow through the A soil horizon. It was believed that this knowledge would yield information about the time the water needed to reach the stream channel from the various parts of the catchment.

The decision to measure the velocity was due to the fast movement of the water through the A soil horizon when measurements were made with the rainfall simulator infiltrometer. Specifically the infiltration measurements made during the first field season and up to the end of August in the second field season indicated that the first seepage of water from the vertical face of the A horizon appeared very quickly. In some of the infiltration sites this time was less than five minutes. This was a very short time for water movement through the soil matrix and existence of macropores in the A horizon of the catchment and the movement of water through them might explain the fast movement. This idea was considered following conclusions drawn from a number of other investigators (Aubertin, 1971; Mosley, 1979 and 1982; German et al., 1981; Gaiser, 1952) about the existence of macropores, mainly in forested and sloping ground, and the fast movement of water through them.

A macropore has been defined by Aubertin (1971) as a "large pore, cavity, passageway, tunnel or void in the soil through which water usually drains by gravity". The present study area was not forested. However, the existence of a thin and loose A horizon and the steep gradient of the slopes in conjunction with decayed roots of heather, bracken etc., and the large number of animals living in the catchment indicated favourable conditions for the creation of macropores. Defining the nature and extent of macropores was not the subject of this thesis. However, determination of the flow velocity through the A soil horizon, on a small scale by applying artificial rainfall seemed not to be impracticable.

Since movement of water through macropores is very rapid when the soil is saturated (Mosley, 1982) it was decided that measurements of velocity would be made after saturating the soil by applying artificial rainfall, or after a rain event large enough to saturate it. Furthermore, the fact that natural rain is unpredictable in terms of time and amount, it was decided that a number of measurements would be made with artificial rainfall and dry soil conditions.

For this purpose three locations were selected on slope II. One of them was burnt land and the other two were grassland. Their gradients were between 29° and 31°. Another location was selected on slope I, which was covered with heather.

In every location between three and five measurements were made between the beginning of September and the 20th September 1982. A small starting site (50 cm x 50 cm) was chosen in each location where the first measurement would be made. Then at 1.5 metres from the first site and on the same contour, the rest of the sites were chosen. The infiltrometer was set up in the first site and artificial rainfall with an intensity of 140 mm/hr was applied for one and a half hours. This time was thought to be sufficient for a strip of ground 1.5 to 2 metres downslope and in front of the infiltrometer to become completely saturated. Then the infiltrometer was removed and the strip was left for 30 minutes to drain. Meanwhile, a pit was dug 100 cm downslope of the site and two gutters, for litter flow and flow through the A horizon were inserted. Then the infiltrometer was again set up in the same site and artificial rainfall with an intensity of 50 mm/hr was applied. An amount of fluorescent dye (green pyramine) was added to the supply tank and the feeder bottle, so that the water would be visible at the vertical face of the pit. Using a stopwatch the time taken for the water to reach the gutters was measured. From the time and the downslope distance (1 m) to the gutters it was a simple task to compute the velocity of any occurrence of litter flow or throughflow. After the first measurement had been taken the supply tank and the feeder bottle were washed to remove the dye in order to be ready for the next measurement.

Apart from the measurements made with artificial rainfall in the four locations, another location on slope I was chosen in which five measurements were taken after the soil had been wetted by natural rainfall. These measurements were made on the 7th September 1982 and fluorescent dye was added to the supply tank and feeder bottle at the start. The artificial rainfall had an intensity of 50 mm/hr as for the other measurements. The number of measurements made in each location and the computed flow velocities will be presented and discussed in detail in the next part of this thesis.

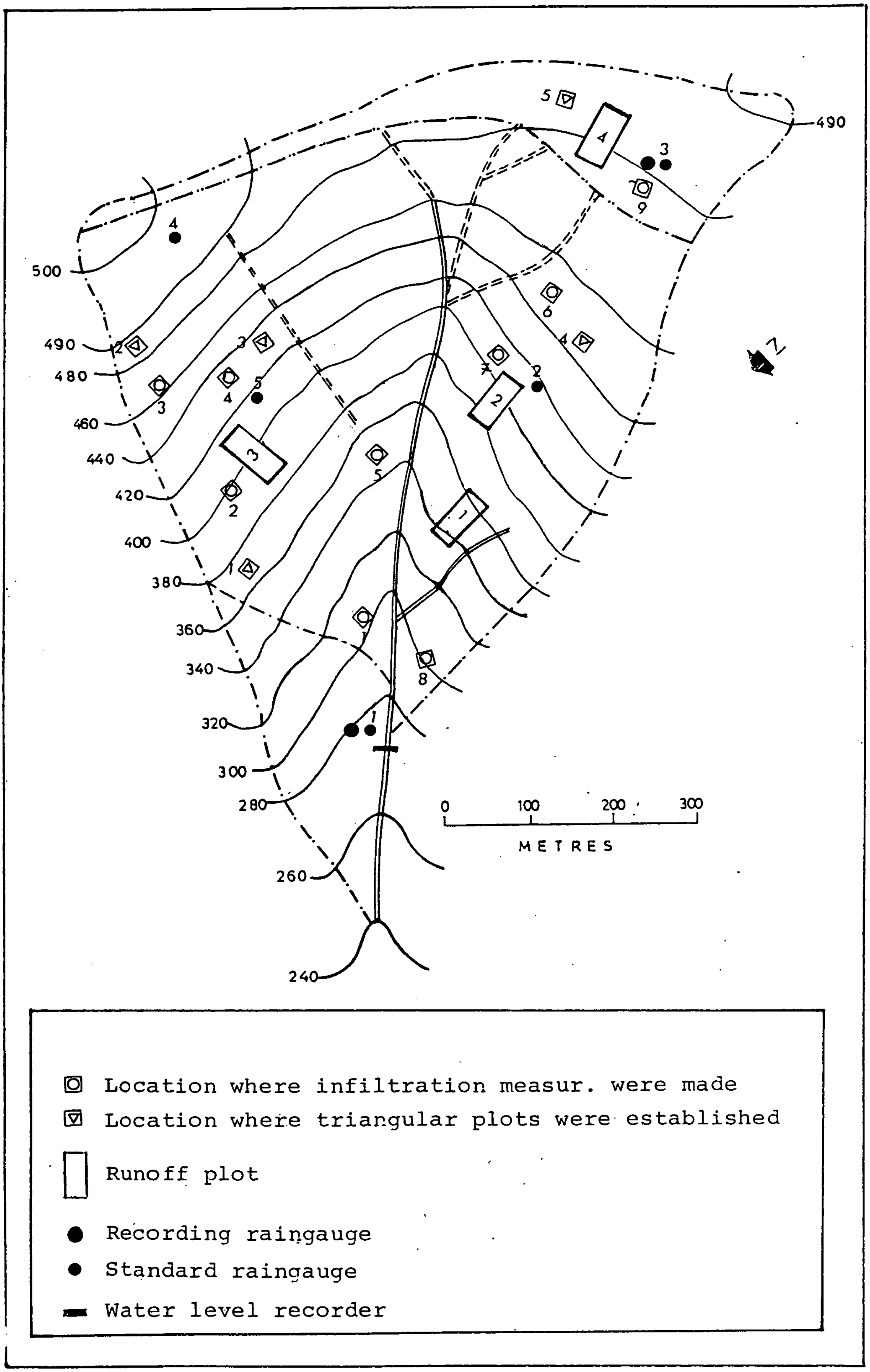
PART IV: RESULTS

4.1 INTRODUCTION

From the two seasons of fieldwork described in Part III, a large quantity of hydrologic data has been collected. The majority of the data collected resulted from the second season's fieldwork. This is because the work during the first season was aimed primarily at the identification of the various flow processes and the methods by which they could be measured. Before presentation of the results, it is useful to summarize the available data, when they were collected and how the results are to be presented.

Map 9 shows the locations where plots were established, where infiltration measurements were made and where the instruments and equipment were situated. In addition, Figure 10 shows diagrammatically the periods during which measurements were made.

During the first field season rainfall was measured from the beginning of May until the end of October 1981 at all five sites in the catchment, and at one site only until end December 1981. In the second field season, rainfall records are available from the beginning of May up to the middle of November 1982. Runoff was measured from 8th July to the middle of December 1981 and then again from 1st May to the middle of November 1982. Litter flow records from the triangular plots installed in the brown soil (Map 5) are available from the beginning of July to the end of October 1981, and from the beginning of June to the end of October 1982 in the peat soil. Volumes of flows from



Map 9. Study area showing the various plots and equipment.

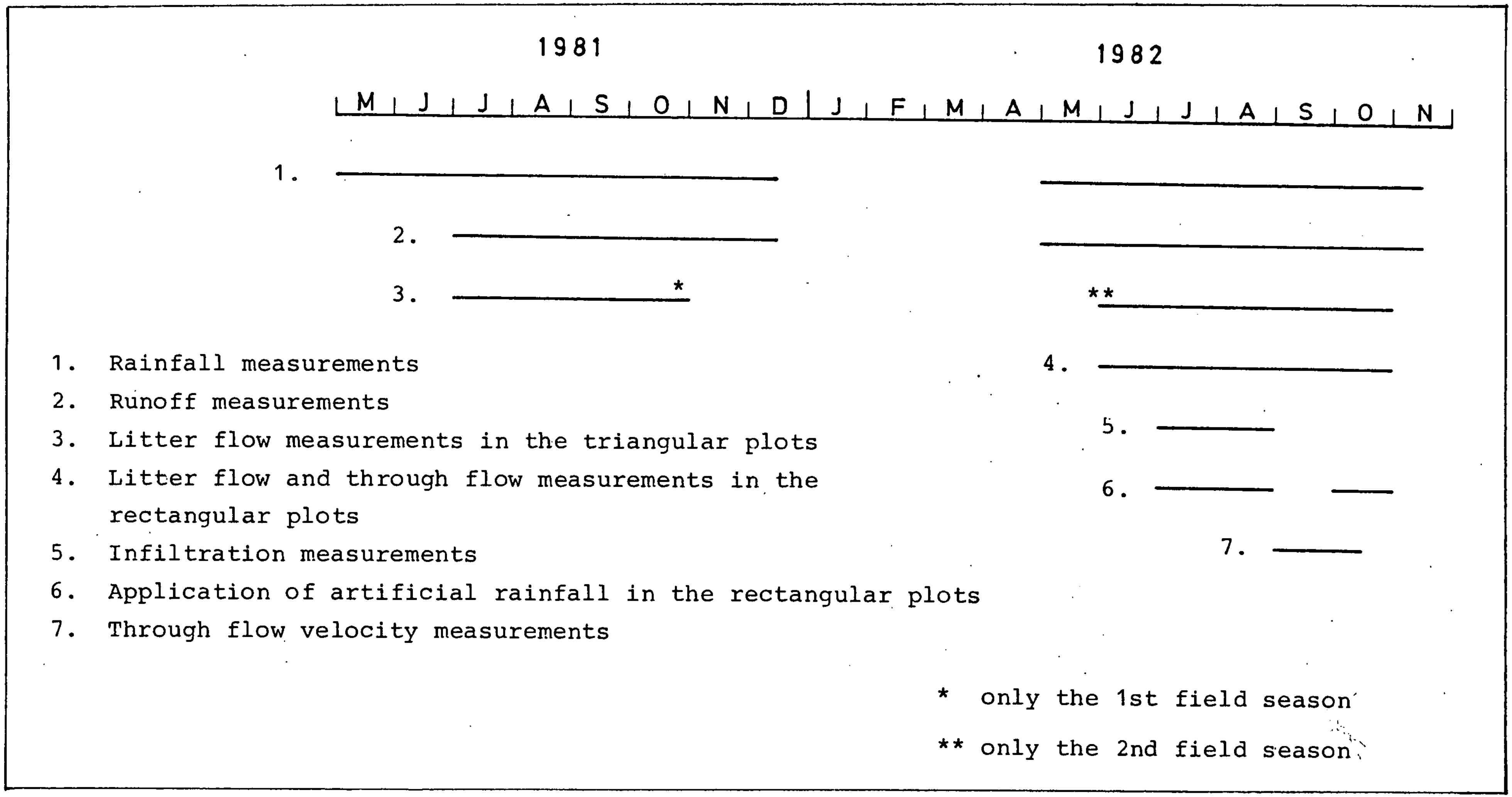


Figure 10. Diagram showing the periods during which the different hydrological components were measured.

the rectangular plots 1, 2, and 3 were measured from the beginning of June to the end of October 1982, and from plot 4 from the 1st August to the end of October 1982.

Eight locations chosen during the first season and one during the second season, were used for infiltration measurements during July and August 1982. Measurements with artificial rainfall, in order to test the response of the soil to a large amount of water using the rainfall simulator in the rectangular plots, were made during July, August and October 1982. Finally, measurements of the velocity of flow through the A horizon of the soil, with artificial rainfall, were made during September and October 1982.

Considering the data referred to above, and the fact that the purpose of this thesis was first, to find out what flow processes occurred in the catchment and second, to explain qualitatively how rainfall was converted to storm runoff, the following presentation of the results seemed reasonable and convenient.

1) Presentation of rainfall and runoff data of both field seasons. These data will show both the amount and distribution of rainfall with time, and the response of the catchment to rainfall.

2) Presentation and discussion of the results obtained from natural rainfall in the plots. This will be in two categories:

   a) results obtained from the triangular plots in the first and second field seasons;

   b) results obtained from rectangular plots (volume of flows and soil hydrographs).

3) Presentation and discussion of the results obtained from artificial rainfall. This will be in three categories:

   a) results obtained from the infiltration locations (infiltration rates, litter flows and flows through the A soil horizon);

   b) results obtained by applying artificial rainfall in the rectangular plots;

   c) results showing the flow velocity through the A soil horizon.

4) Examination of possible relationships between the flow processes observed from natural and artificial rainfall in the catchment, and the amount of rainfall converted to runoff. That is to say, how meaningful were the observed flow processes in terms of the amount of rainfall converted to runoff.

4.2 RAINFALL AND RUNOFF CONDITIONS EXPERIENCED IN THE CATCHMENT DURING THE COURSE OF THE STUDY

The rainfall and runoff data collected during the two field seasons are summarized in Table 22 and Figure 11. In addition to the data in Table 22, the average monthly and average total rainfall of the catchment are presented in Table 23.

During the first field season the catchment received 483 mm of rain and each of the months from May to October received 66, 43, 61, 27, 142 and 144 mm of rain, respectively. The total amount of runoff during the final four months of this field season (since the water level recorded was installed at the beginning of July) was 131 mm of rain and for each month from July to October it was 14, 5, 27 and

Month	Year 1981 Rain (mm)	Year 1981 Runoff (mm)	Year 1981 Rain-Runoff (mm)	Year 1982 Rain (mm)	Year 1982 Runoff (mm)	Year 1982 Rain-Runoff (mm)
May	66	Was not measured	-	60	17	43
June	43	Was not measured	-	99	15	84
July	61	14	47	48	11	37
August	27	5	22	55	8	47
September	142	27	115	103	9	94
October	144	85	59	189	90	99
Total	483 (374)*	131	243	554 (395)*	150 (118)*	404 (277)*

* Only for the last four months

Table 22. Monthly rainfall and runoff observed during the two field seasons in the study area.

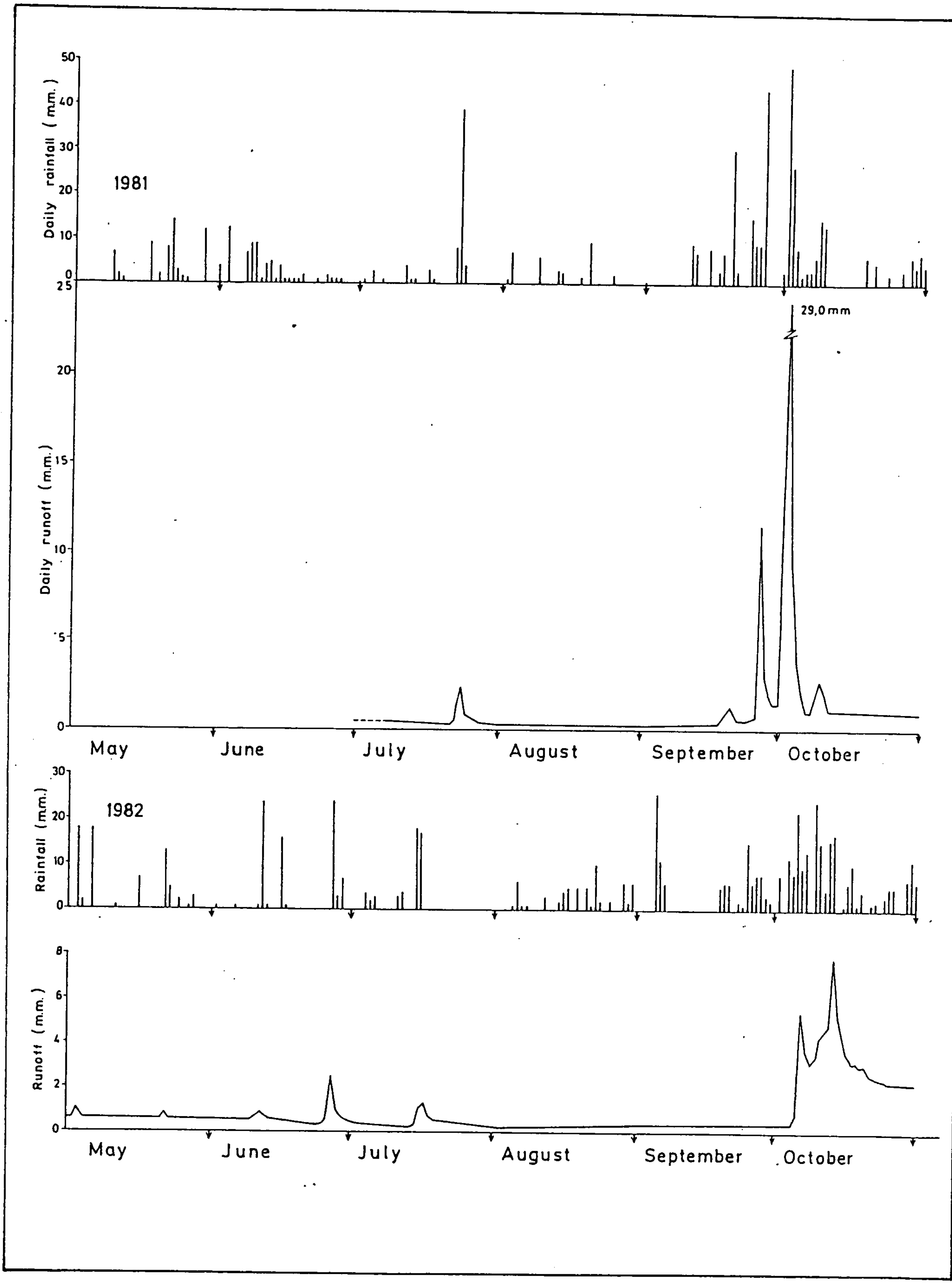


Figure 11. Diagram showing daily rainfall and runoff during the two field seasons.

Month	May	June	July	August	September	October	Total Rainfall (mm)
Average* rainfall (mm)	74	61	83	94	81	96	489
Rainfall in 1981 (mm)	66	43	61	27	142	144	483
± %	-11	-30	-26	-72	+75	+50	-1
Rainfall in 1982 (mm)	60	99	48	55	103	189	554
± %	-19	+62	-42	-42	+27	+97	+13

* Average monthly rainfall at West Hopes (1916-1950)

Table 23. Mean monthly rainfall in the study area

85 mm, respectively. This season can be characterized generally as dry, except for the last ten days of September and the first ten days of October. Specifically the amount of rainfall during May and June was lower than the average amount by 11 and 30%, respectively. For these months runoff records are not available, but it was observed by the author who was present in the catchment almost every day, that there was no significant change in the daily amount of runoff from that recorded on 8th July when the water level recorder was installed. The amount of rainfall was also lower than the average during July and August, by 26 and 72%, respectively. The daily amount of runoff during these months was low (∿0.5 mm) and almost constant, except for 22nd July when 42 mm of rain falling in 28 hours generated a significant hydrograph at the outlet of the catchment.

The dry conditions continued until 19th September and on that date and on the 26th, two other rain events of 36 and 49 mm, respectively, generated significant hydrographs at the outlet of the catchment. These two events contributed to the higher (+75%) amount of rain than the average the catchment received in September. The last four days of September were rainless, and it started raining again on 1st October. The rainfall on 1st October 1981 and the amount of runoff generated is worthy of note. This is because rain events like this are estimated to have a return period of ten years (R. Sargent, personal communication, 1981) and cause minor flooding problems in the town of Haddington. The rainfall started at 8.00 a.m. on 1st October 1981 and stopped at 8.00 p.m. the next day. The rain was accompanied by a strong wind and the weighted amount of rain in the 36 hours was 84.4 mm. Its intensity ranged from 1.7 to 5.2 mm/hr and the amount of runoff during the first three days of October was 14.3, 29 and 9.6 mm (63% of the total rainfall). On 2nd October 1981 the author was present in the catchment and the flow processes observed then will be described later.

After this rain-event two other smaller ones (26 mm) on the 8th and 9th of this month generated another hydrograph, while smaller amounts of rain fell in the catchment during the rest days of October and the daily runoff was low and constant. The total amount of rainfall (144 mm) in October was higher than the average by 50%.

Conditions during the second field season were not very different from those observed during the first field season. Specifically the total rainfall for the six months was 554 mm and each month from May to October received 60, 99, 48, 55, 103 and 189 mm of rain, respectively. Similarly, the total amount of runoff was 150 mm and for each month separately it was 17, 15, 11, 8, 9 and 90 mm respectively.

The rainfall in May was lower than the average amount of this month by 19% and the daily amount of runoff remained low and almost constant (∿0.5 mm). No distinctive hydrographs were generated during this month at the outlet of the catchment. The amount of rainfall during June in contrast to the previous month, was higher than the average by 62% and a distinctive hydrograph was generated on the 25th of this month from 3.9 mm of rain. The runoff for the rest of this month was low and constant. The rainfall in July and August was lower than the average by 42% and during September higher by 27%. The runoff during these months remaind low and constant as well, except for a hydrograph that was generated on 15th July from 33 mm of rain. October was very wet and the rainfall was almost double (+97%) the average amount of this month. High flows were observed at the outlet of the catchment after 6th of this month and on that date a distinctive hydrograph was generated from 23 mm of rain that fell in 6.5 hours. For the remaining days of this month the flows remained continuously high, but without distinctive hydrographs. This was because despite the large amount of rain during this month, it fell in the form of storm showers with dry spells between them. In fact, of the 31 days in October, only 8 were rainless and in the other 23, 76 showers occurred having dry spells of at least half an hour between them.

From the description of the rainfall and runoff conditions it becomes apparent that both field seasons were dry from May to late September, except for isolated rain events that generated small hydrographs at the outlet of the catchment. However, in late September and October during both field seasons, a number of rain events generated some significant hydrographs in the stream draining the catchment.

4.3 RESULTS OBTAINED FROM NATURAL RAINFALL

In this section only those results obtained by operating the various types of plots under natural rainfall conditions are presented and discussed. The results obtained from catchment rainfall and runoff measurements will be presented in a later chapter.

The natural rainfall results are divided into four subsections.

1) Observed litter flows from the triangular plots in the brown earth soil area.
2) Observed litter flows from the triangular plots in the peat soil area.
3) Observed flows from the rectangular plots.
4) Soil hydrographs generated from the rectangular plots.

4.3.1. Observed Litter Flows from the Triangular Plots in the Brown Earth Soil Area

The observed quantities of litter flow are shown in Fig. 12. The daily rainfall is the arithmetic mean of gauges 1, 2, and 5, because these were the gauges used for the computation of rainfall in the plots. The dotted and solid lines correspond to zero and positive litter flow readings, respectively. If there is more than one day in the same time period, then they are connected together, i.e. they are shown as only one line with the total rainfall.

The rain event on 22nd-23rd July, as explained in section 3.2.2.1.2, yielded a large amount of litter flow, and possibly throughflow, because the gutters had been fixed 3 to 4 cm below the ground surface. For this reason these data are not presented here.

Before discussing the results it should be kept in mind that the plots were constructed in four selected locations in the portion of the catchment occupied by brown soil. In each location, two or three plots were constructed

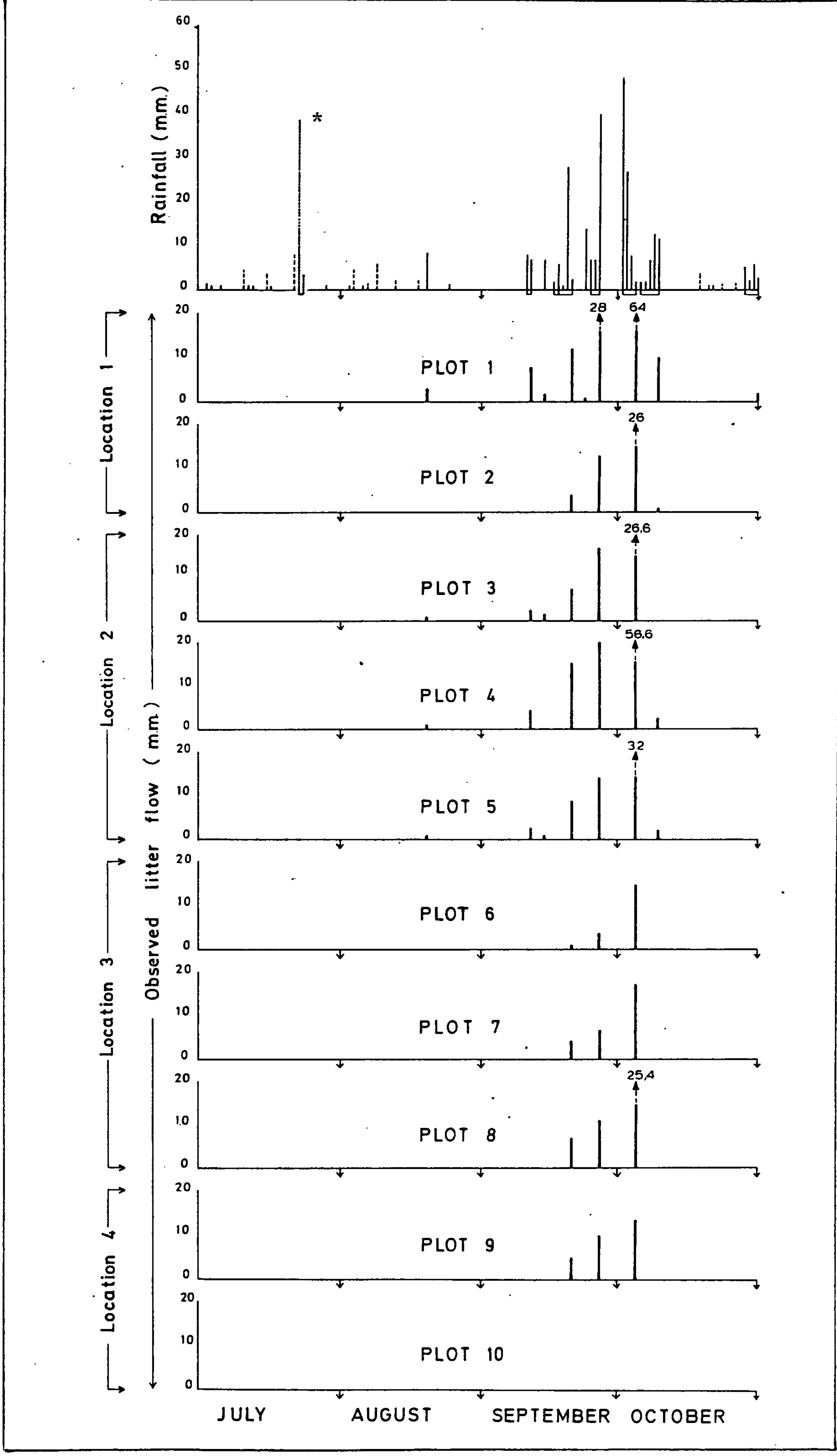


Figure 12. Litter flow observed in the triangular plots in the brown earth soil area. *Flows from this rain event are not included.

and were operated from the beginning of July to the end of October 1981. Efforts were made to collect and measure any occurrence of litter flow generated from a specific rain event. The time between two consecutive readings of the raingauges and the vessels was defined as 'time period'. A 'time period' may have included one, two or more days separated by a dry spell of at least five hours. Five hours was considered to be a suitable interval, not only for the litter layer, but for the deeper soil horizons to drain, because as will be mentioned later, the flows were measured from the deeper soil horizons as well as from the litter layer.

During July, with the exception of the above rain event, no litter flow occurred in any of the plots. During August, only one rain event yielded an amount of litter flow in some plots. September was wetter than the previous months and litter flow occurred in five time periods. Finally, in October, litter flow was observed in three time periods. So, over the period that the plots were in operation, litter flow occurred in nine time periods as shown in Table 24.

Most of the data in Table 24 were presented earlier in another context in Table 9. On this occasion, however, the Table also includes information about soil moisture conditions. Such information is useful, because as is well documented in hydrological literature, any water movement over or through the ground is affected by the soil moisture. This information is presented by means of antecedent precipitation index (API) as recommended by Kohler et al. (1951). Hence, a number of investigators have applied this

Location No	Vegetative Cover	Plot No	Gradient	Total amount of rain in m.m(T), Observed litter flow in mm(O) and Percentage of rain becoming litter flow%																											TOTAL		
				Time Period																													
				1			2			3			4			5			6			7			8			9					
				Date																													
				19/8/81			10-11/9/81			14/9/81			16-20/9/81			23/9/81			24-26/9/81			1-4/10/81			5-9/10/81			28-31/10/81					
				API(mm): 4			API(mm):0·04			API(mm): 9			API(mm):12			API(mm):23			API(mm):33			API(mm): 34			API(mm):59			API(mm): 4					
				T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%	T	O	%
1	Grassland	1	33°	10·5	3	28·6	15·1	8	53	7·4	1·5	20·3	39	12	30·8	14·5	0·5	3·4	55·8	28	50·2	94·8	64	67·5	37·6	10	26·6	19·6	2	10·2	294·3	129	43·8
		2	31°	10·5	–	–	15·1	–	–	7·4	–	–	39	4	10·2	14·5	–	–	55·8	13	23·3	94·8	28	27·4	37·6	1	2·7	19·6	–	–	294·3	44·0	15·0
2	Burntland (Burning May 1981)	3	25°	5·7	0·5	8·8	11·8	2·2	18·6	7·8	1·8	23·1	39·8	7·6	19·1	14·6	D	–	54·4	9·3	17·1	108·1	26·6	24·6	34·8	D	–	11·0	D	–	238·6	48·0	20·1
		4	23°	5·7	1	17·5	11·8	4·5	38·1	7·8	2·3	29·5	39·8	15·7	39·4	14·6	1·2	8·2	54·4	20·5	37·7	108·1	56·6	52·3	34·8	2·8	8·0	11·0	–	–	288·1	104·6	36·3
		5	23°	5·7	0·4	7	11·8	2·5	21·2	7·8	1	12·8	39·8	8·3	20·8	14·6	D	–	54·4	14·1	25·9	108·1	32	29·6	34·8	2	5·7	11	–	–	273·4	60·3	22·10
3	Heatherland	6	21°	5·7	–	–	11·8	–	–	7·8	–	–	39·8	1	2·5	14·6	–	–	54·4	3·4	6·2	108·1	14·8	13·7	34·8	–	–	11	–	–	288·1	19·2	6·7
		7	31·5°	5·7	–	–	11·8	–	–	7·8	–	–	39·8	3·9	9·8	14·6	–	–	54·4	6·6	12·1	108·1	16	14·8	38·4	–	–	11	–	–	288·1	26·5	9·2
		8	31·5°	5·7	–	–	11·8	–	–	7·8	–	–	39·8	6·6	16·6	14·6	–	–	54·4	10·9	20	108·1	25·4	23·5	38·4	–	–	11	–	–	288·1	42·9	14·9
4	Burntland (Burning May 1980)	9	27°	9·4	–	–	14·6	–	–	7·7	–	–	39·4	4·9	12·4	12·6	–	–	54·6	9·8	18·0	55·7	13·4	24	38·4	–	–	18·4	–	–	250·8	28·1	11·2
		10	31°	9·4	–	–	14·6	–	–	7·7	–	–	39·4	–	–	12·6	–	–	54·6	–	–	55·7	–	–	38·4	–	–	18·4	–	–	250·8	/	

D=disturbance in the plot

Table 24. Observed amounts of litter flow in the brown earth soil during the first field season.

index in field studies (Linsley, 1949; Kohler et al., 1951; Minshall et al., 1965; Weyman, 1974; Mosley, 1979).

This index is defined by an equation of the type

$$API = P_0 + P_1K + P_2K^2 + P_3K^3 + \dots + P_nK^n,$$

where P_0 refers to precipitation within 24 hours prior to the storm. P_1, P_2 and P_3 indicate precipitation 1, 2, 3 days prior to the storm and n denotes the number of days used to establish the index. K is a constant which is assumed to decrease with time according to a logarithmic recession (Linsley, 1949). The value of the constant K depends on the soil type (Minshall et al., 1965) and experience has shown that its value in Eastern and Central areas of the USA varies from 0.8 to 0.95 (Linsley, 1949). However, as the previous investigator stressed, the antecedent precipitation factor is only an index to moisture deficiency and the use of an approximate value of K does not seriously affect the results.

In the study catchment, observations have indicated that the soil, and mainly the A horizon, drained very quickly when the rain ceased. Therefore, a value of 0.8 was decided upon as a value of K. As far as the number of days is concerned, 30 was used by some investigators to establish the index. For this particular catchment, since a value of 0.8 had been chosen for the constant K, the number of days was decided at 20 because the index after the 20th day (K^{20}) would be very small. The same values of the coefficient (0.8) and the number of days (20) were used for both existing soil types.

In Table 9 it was shown that litter flow did occur in almost all of the plots and that the variability was observed not only between locations, but also between plots in the same location. It was also emphasized that litter flow occurred from relatively small and large rain events and with wet and dry antecedent soil conditions. In some time periods a large amount of litter flow was generated from a relatively small amount of rainfall. In addition, from Table 24 it is apparent that, in the plots in location 1 and 2, litter flow was observed during more time periods than in the plots situated in locations 3 and 4. In fact, in plots 1 and 2 of location 1, litter flow was observed in nine and four time periods; the totals, expressed as percentages of the total rainfall, being 43.8% and 15%, respectively. Almost all of the plots in location 2 generated litter flow in the first eight time periods. The total amounts for plots 3, 4 and 5 were 20.1%, 36.3% and 22.1% of the total rainfall, respectively. No flow was observed in plots 3 and 5 in time period 5, and in plot 3 in time period 8. This was due to damage to the plots. In the first eight time periods all undamaged plots of location 2 generated litter flow, and it is therefore reasonable to assume that had plots 3 and 5 not been damaged then they would also have generated litter flow during these periods. This assumption cannot be made for period 9 as the other two undamaged plots did not generate litter flow.

In locations 3 and 4, litter flow was observed only during time periods 4, 6 and 7. Plots 6, 7 and 8 of location 3 generated 6.7%, 9.2% and 14.9%, respectively of the total rainfall as litter flow during these three time periods and plot 9 of location 4, 11.2% of the total rainfall. In plot 10 at this location litter flow was never observed.

From these results, it is evident that litter flow occurred in all the chosen locations and was more frequent in land that had recently been burned and grassland. It was less frequent in heatherland and burnt land with thin grass.

The question that now arises is why litter flow occurred. Did it occur due to the rainfall intensity being higher than the infiltration capacity of the soil? Or was it due to very dry, or saturated, soil conditions? In answering these questions, using rainfall intensity data only, the following hypothesis was set: If litter flow occurred due to the first reason then the rainfall intensity during periods 4, 6 and 7 must have been higher than the rain intensities of the other periods. This is because in periods 4, 6 and 7 litter flow was observed in all the plots of all the locations, while in the other periods only the plots in locations 1 and 2 yielded litter flow. The intensities of rainfall in these two groups of periods (4, 6, 7 and 1, 2, 3, 5, 8, 9) were calculated and are presented in Table 25.

This table shows that the rain intensities in periods 4, 6 and 7 which yielded litter flow in all the plots, ranged from 0.9 to 6.0 mm/hr, 0.6 to 9.0 mm/hr and 1.7 to 5.2 mm/hr, respectively. It is reasonable to assume that litter flow was generated from the higher rainfall intensities. In time period 7, litter flow was generated by a maximum rainfall intensity of 5.2 mm/hr, so it is reasonable

Time period No.	Duration (days)	Rainfall intensities (mm/hr)	Total Rainfall (mm)
4	5	0.9, 1.0, 1.4, 1.5, 1.6, 2, 2.8, 3.2, 4.5, 6.0	39.6
6	3	0.6, 1.0, 1.8, 2.0, 2.5, 2.8, 5.6, 8.5, 9.0	54.7
7	4	1.7, 1.8, 2.1, 2.2, 2.3, 3.3, 3.9, 4.0, 5.2	95.0
1	1	0.6, 2.2	7.4
2	2	1.8, 2.1	13.0
3	1	1.0, 6.0	7.7
5	1	1.4, 4.2	14.2
8	5	0.5, 1.1, 1.5, 2.5, 2.7, 3.0, 3.3, 8.4	36.1
9	4	0.3, 0.5, 1.0, 1.9, 2.8, 8.0	14.2

Table 25. Rainfall intensities occuring during the nine time periods.

to assume that the higher maximum rainfall intensities encountered in periods 4 and 6 (6 and 9 mm/hr, respectively) would also produce litter flow. As the rain of maximum intensity in period 7 only lasted for 1.5 hours this would not be sufficient to account for the observed litter flow which ranged from 13.4 to 64 mm of the rainfall. Therefore, rain of a lower intensity during this period must have been converted to litter flow. Examining the intensity of rain of the other periods (1, 2, 3, 5, 8, 9) this last statement seems to be contradicted because rain intensities higher than the maximum of period 7, ranging from 6 to 8.4 mm/hr, only generated litter flow in the plots of locations 1 and 2. Consequently, the observed litter flow, at least in locations 3 and 4 was not the result of a rainfall intensity higher than the infiltration capacity of the soil.

Considering the plots in locations 1 and 2, it may be argued that litter flow occurred due to the rainfall intensities being higher than the infiltration capacity of the soil because it was observed in all time periods. However, this is not valid if we examine the low rainfall intensities that generated litter flow in time periods 1 and 2 (Table 25). In these periods, litter flow occurred with a rainfall intensity of approximately 2 mm/hr. If it was the result of intensity of rain being higher than infiltration capacity then during time periods 4, 6 and 7, which had higher intensities and larger durations, a larger amount of litter flow would have been generated than in periods 1 and 2. This did not happen and so litter flows must not have been generated in the catchment during the period of study due to the rainfall intensity being higher than the infiltration capacity of the soil. Therefore, saturated or very dry soil conditions must have been the reason for litter flow occurring. As far as time periods 1, 2, 3 and 9 are concerned, the following observations caused the author to conclude that litter flow must have occurred due to very dry soil conditions.

1) The total amount of rain during the above periods was very small and was not sufficient to saturate the soil.
2) The soil could not have been saturated at the beginning of the rain because the computed API was very small (Table 24).
3) It has been emphasized by a number of investigators (Osborn, 1964; Debano et al., 1966; Satterlund, 1972; Knapp, 1980) that dry soils are generally hydrophobic and that burned land gets wet with difficulty (Rowe, 1941; Debano et al., 1966).
4) The author tested the above view by dropping water onto the dry soil. It was observed that the water flowed down over the soil for between 3 and 5 metres without being absorbed.

For the other periods it is difficult to reach this conclusion because the computed API was high, so litter flow must have occurred due to saturated soil conditions. This is supported by the fact that the total amount of rainfall for the periods 4, 6 and 7 was higher than that for periods 1, 2, 3 and 9 and possibly sufficient to saturate the soil. The soil during time periods 5 and 8 must have been saturated from the rainfall of periods 4 and 7, respectively and not from the total rainfall of periods 5 and 8. This is inferred from the small amount of rainfall during period 5, which was not enough to saturate the soil, and from the fact that the total rainfall for period 8 fell in eight showers over a period of five days. In conclusion, the observed amount of litter flow was primarily due to saturated and secondly due to very dry and burnt soil conditions. Due to this second reason litter flow was observed only in recently burnt land and in only one grassland plot. It was difficult to provide a satisfactory explanation for the lack of litter flow in other plots. It may, for example, have been due to the surface conditions of each plot.

At this point, the importance of each type of litter flow that was observed should be emphasized. As mentioned before, and as hydrologic literature reveals, the second type is a phenomenon observed in very dry or burnt land and lasts as long as it takes for the soil to get wet. However, even if some of this type of litter flow does reach the channel it does not seem to be a significant component of storm flow. As for the first type of litter flow, its importance seems somewhat different from the others. This is because, first, as the three time periods (4, 6 and 7) have indicated, litter flow occurred in all the plots (except 10) at all the locations, regardless of vegetative cover, when the total amount of rainfall over the period was relatively high. Second, most of the plots, in all of the locations, generated more flow with an increase in total rainfall. Plots 3 and 4 are an exception as they generated in time period 6 less flow than in time period 4 which had less total rainfall (Table 24). This response was difficult to explain.

To draw any conclusions about the amount of flow observed for each type of vegetative cover was not easy, as all the plots yielded litter flow only three times during the period of operation. In addition, the task was made more difficult when the variability in observed amounts of flow in the plots of some locations was examined. Taking into account that widespread litter flow was generated in the catchment from a relatively high amount of rainfall, it is reasonable to assume that it reached the storm channel. Observations on runoff processes made by the author during rain events in the catchment, supported this opinion.

4.3.2. Observed Litter Flows from the Triangular Plots in the Peat Soil Area

It has already been explained (section 3.2.2.1.1) why litter flows in the peat soil area of the catchment were measured only during the second field season, and why only one location was selected. It was also stated that three plots, numbered 11, 12 and 13 were constructed and operated from the beginning of June until the end of October 1982. The daily rainfall during this period, computed from gauge 3 (Map 4), and the observed amounts of litter flow are shown in Fig. 13. Dotted and solid lines have the same meaning as they did in Fig. 12 in the previous section. Data from 27/9/82 to 4/10/82 are not reliable due to disturbance of the plots by people shooting in the area at that time.

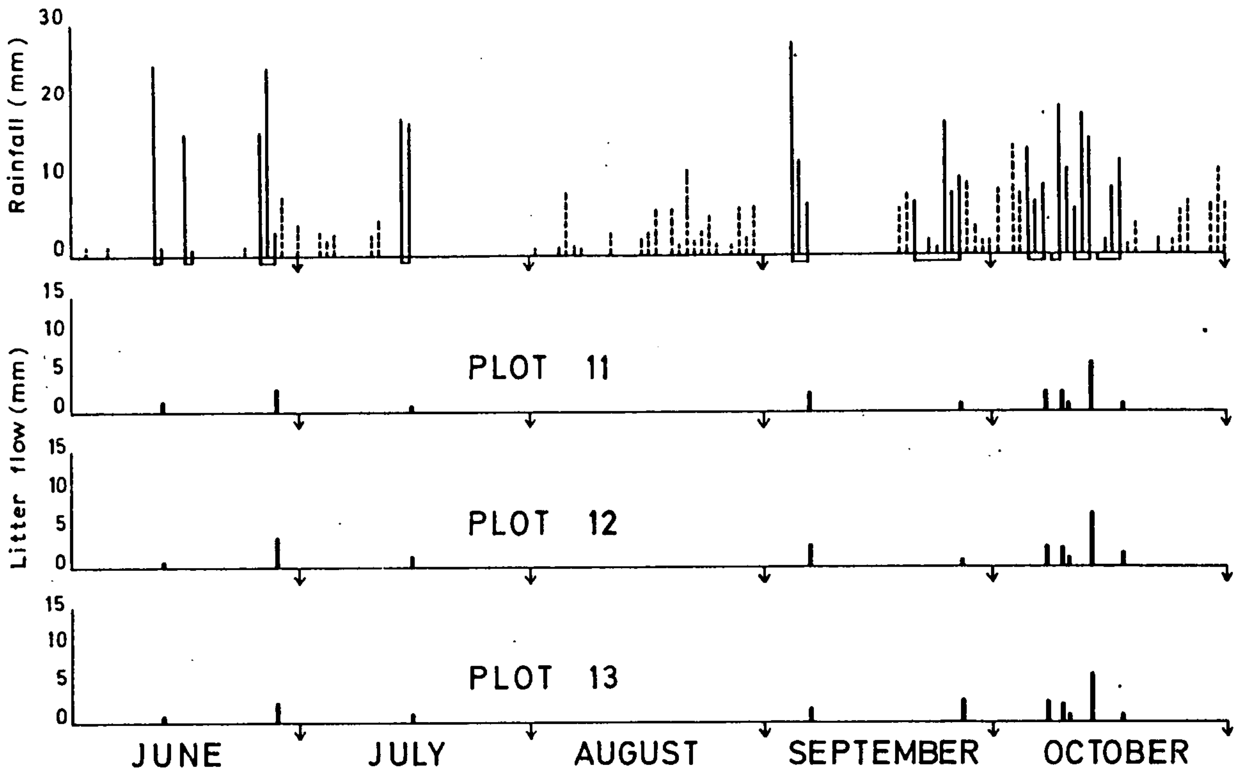


Figure 13. Observed litter flows from the triangular plots in the peat soil area.

Table 26 presents more details about the data collected. The terms API and time period are as defined earlier.

During the period of operation litter flow was observed over eleven time periods, in nine of which all the plots yielded litter flow. In the other two periods (2 and 6) litter flow was observed in only one and two of the three plots, respectively. The rainfall in the eleven time periods ranged from 11 to 45.6 mm, remembering that these amounts are not the result of one rain event in each period. The API ranged from 2 to 58 mm. The percentage of the total rainfall for the eleven periods converted to litter flow for plots 11, 12 and 13 was 6.2%, 7.4% and 5.3%, respectively. For individual time periods this percentage varied between 1-16% for plot 11, 0.6-18% for plot 12 and 0.9-14% for plot 13.

Visual appraisal of Table 26 reveals that the amount of litter flow was relatively small under dry antecedent soil moisture conditions in many time periods. For example, in the first six time periods, the percentage of rainfall converted to litter flow in periods 3, 4 and 5 ranged from 2-9% with a total rainfall of 43, 34.8 and 45.6 mm. In the other three periods (1, 2 and 6) this percentage was very small (0.6-1.0%). On the other hand, larger percentages of rainfall were converted to litter flow in time periods 7 to 11 with a small total rainfall and wet antecedent soil moisture conditions. In time periods 8 and 9, for example, the total rainfall was 19.2 mm and 11 mm and the API was 40 mm and 56 mm, respectively. The percentage of rainfall observed as litter flow ranged from 11-15% in period 8, and

Time Period No.	Date	API (mm)	Rainfall (mm)	Observed litter flow					
				Plot 11		Plot 12		Plot 13	
				(mm)	%	(mm)	%	(mm)	%
1	11-12/6/82	2	24.0	.3	1	.3	1	0.2	.9
2	15-16/6/82	17	15.5	-	-	.1	.6	-	-
3	25-27/6/82	4	43.0	3	7	3.7	9	2.5	6
4	14-15/7/82	6	34.8	1	3	1.4	4	.8	2
5	4-6/9/82	7	45.6	2.3	5	2.7	6	1.8	4
6	20-26/9/82	12	43.2	.5	1	.6	1	-	-
7	5-7/10/82	29	28.8	2.6	9	3	11	2.4	9
8	8-9/10/82	40	19.2	2.5	13	2.9	15	2.2	11
9	10/10/82	56	11.0	.9	8	1.2	11	1	9
10	11-13/10/82	56	38.8	6.2	16	6.9	18	5.5	14
11	14-17/10/82	58	22.9	.9	4	1.2	5	.75	3
	TOTAL		325.9	20.2	6.2	24.0	7.4	17.2	5.3

Table 26. Observed amount of litter flow in the peat soil.

8-11% in period 9. Consequently, the question that arises is why did this happen? In answering this question the reasons for litter flow must first be clarified. If we hypothesize that litter flow occurred due to rainfall intensities being higher than the infiltration capacity of the soil, then the intensity of the rainfall during the last five time periods must be higher than the first ones due to the observed amounts of litter flow. The rainfall intensities computed for each time period are presented in ascending order in Table 27. This shows that in the first six periods the intensities ranged from 0.5 to 7.4 mm/hr and in the last five from 0.6 to 8.0 mm/hr. These intensities are practically the same and so the hypothesis set out above must not be true.

We can reach the same conclusion if we examine carefully only the rainfall intensities of the first six time periods, and especially period 5. During this period litter flow was observed with rainfall intensities of 0.5-1.6 mm/hr. If this litter flow was generated due to the above reason, then all rainfall intensities in excess of 1.6 mm/hr should generate litter flow. However, this was not observed and so the hypothesis is rejected.

As this first reason for litter flow has now been excluded we can suppose as before that it must have been due to either very dry soil conditions or to saturated soil conditions. Which of these two types occurred in each time period cannot be answered directly because there were no data available concerning the amount of rainfall the soil needed to become saturated. However, by examining the API

Time Period No.	Duration (days)	Rainfall intensities (mm/hr)	Total Rainfall (mm)
1	2	0.5, 0.8, 1.1, 1,6, 2.1, 2.5	24.0
2	2	0.7, 1.8, 3.1	15.5
3	3	0.8, 0.9, 1.1, 1.4, 1.5, 1.6, 1.8, 2.2, 2.6	43.0
4	2	0.5, 0.6, 1.4, 2.6, 3.2, 7.4	34.8
5	3	0.5, 0.7, 0.9, 1.2, 1.4, 1.6	45.6
6	7	1.5, 2.2, 2.3, 2.4, 2.7, 2.9, 4.3	43.2
7	3	0.6, 0.7, 0.8, 1.0, 1.4, 2.5, 6.1	28.8
8	2	0.6, 0.8, 1.3, 2.4, 2.6	19.2
9	1	2.2, 2.8, 3.8, 5.4	11.0
10	3	2.0, 3.5, 4.3, 8.0	38.8
11	4	0.9, 1.7, 1.8, 2.4, 2.6	22.0

Table 27. Rainfall intensities occurring during the 11 periods of the second field season.

values it is reasonable to assume that periods 1, 2, 4, 5 and 6 may have generated litter flow due to dry soil conditions, although its occurrence in period 2 in plot 12 is difficult to explain as the API was 17 mm. In the remaining periods it is thought that saturated litter flow must have occurred.

The results presented so far have indicated that litter flow occurred at the selected location mainly because of saturated conditions in the peat soil. Taking into account this indication, we can now explain why more litter flow was observed in some time periods with small total rainfall and wet conditions than in time periods with a larger total rainfall and dry soil soil conditions. Antecedent soil moisture conditions and total rainfall of each period were not, of course, the only factors that must have affected the observed litter flows. The number of days included in each time period, as well as the number and duration of rain events must also have affected the amount of litter flow. In time period 6, for example, the rainfall was relatively high (43.2 mm) but the amount of litter flow was very small. The small amount of rain that fell in five of the seven days of this period and the total lack of rain on one day (Fig. 13), can explain the response of the plots during this time period.

4.3.3. Observed Flows in the Rectangular Plots

The results presented in the two previous sections demonstrated the occurrence of litter flow in the triangular plots constructed in various selected locations. In this section additional information is presented about litter flows in the rectangular plots and new information is given about the occurrence and amount of flows through the deeper soil segments. The daily amounts of rainfall and the flows from the various soil segments (in mm) in the four plots, for each time period, are shown in Fig. 14. Dotted and solid lines, as well as solid lines connected together have the same meaning as in Sections 4.3.1. and 4.3.2. The flows observed from September 28 - October 4 are not reliable due to disturbance to the plots by people shooting in the area at that time.

Figure 14 shows that the largest flows emerged from the upper soil segments in all of the plots and that most of these flows occurred during the last days of September and during October 1982. In addition to this figure, Table 28 is presented here, which shows more details of rainfall and observed flows. API was computed, as in the triangular plots, from the daily arithmetic mean of raingauges 1 and 3.

During the period of operation, flows were observed in plots 1, 2 and 3 in seventeen time periods, and in plot 4 in ten periods. Of the total rainfall of all the time periods seepages from the various soil segments amounted to 41%, 29%, 11% and 54% for plots 1, 2, 3 and 4, respectively. A reasonable question that arises at this stage is which of the four plots would have generated the largest seepage if they had been measured at all soil horizons, as in plot 1. Unfortunately, this question cannot be answered. However, if we assume that the observed difference in seepages from the A horizon between the four plots was the

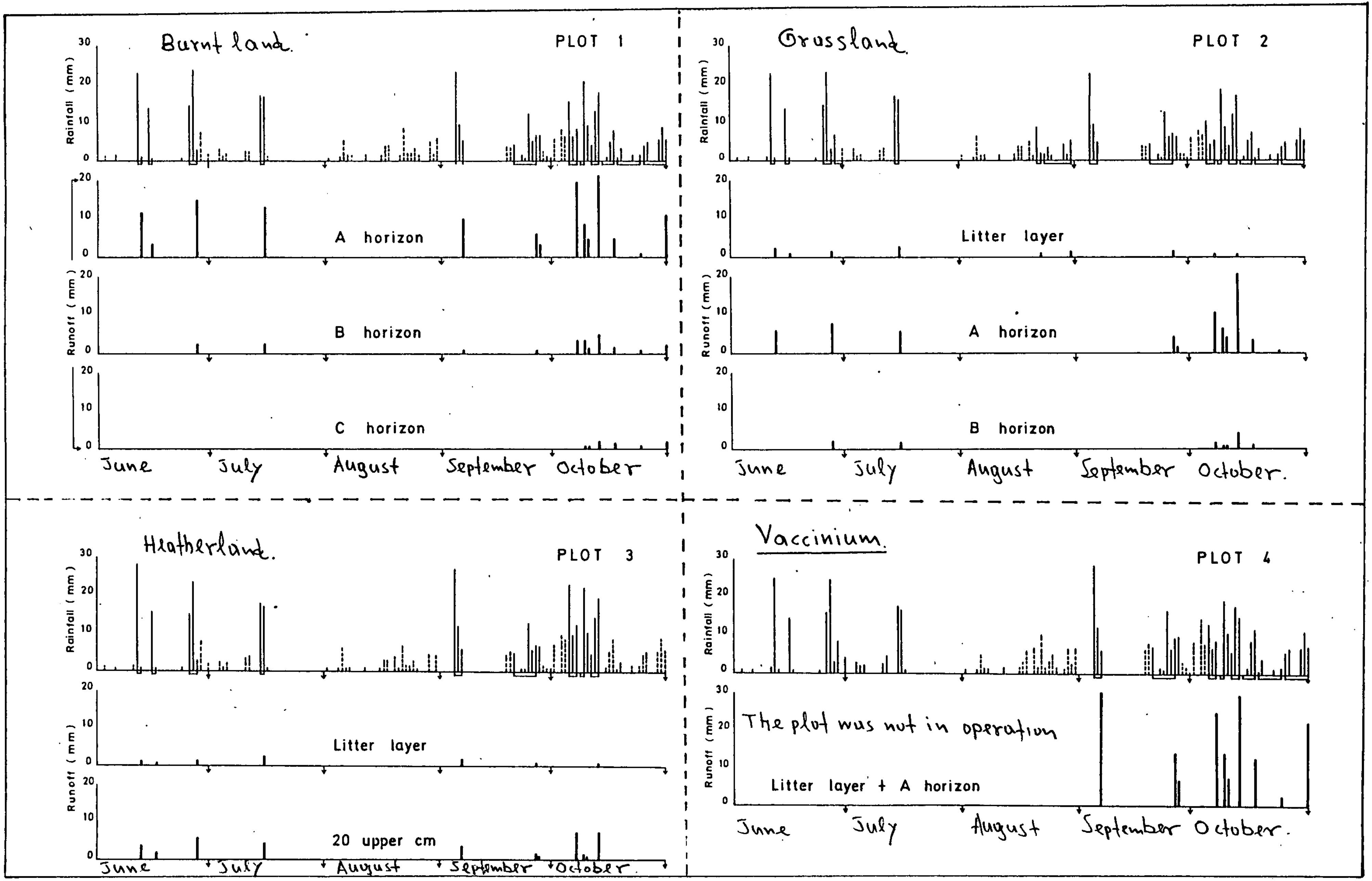


Figure 14. Observed flows in the rectangular plots.

Period no.	DATE	API (mm)	PLOT 1 Rain-fall (mm)	PLOT 1 Observed runoff (mm) A*	B*	C*	PLOT 2 Rain-fall (mm)	PLOT 2 Observed runoff (mm) L*	A	B	PLOT 3 Rain-fall (mm)	PLOT 3 Observed runoff L	20 cm	PLOT 4 Rain-fall (mm)	PLOT 4 Observed runoff L + A
1	11-12.6.82	2	25.7	11.5	-	-	24.8	2.1	5.7	-	30.1	1.4	3.2	The plot was not in operation.	
2	15-16.6.82	17	14.2	3.2	-	-	13.7	1	-	-	16.2	0.6	-		
3	25-27.6.82	4	41.6	15	2.5	-	40.9	1.4	8	2	42	1.2	6		
4	28-30.6.82	34	11.3	-	-	-	11	0.4	-	-	10.3	-	-		
5	14-15.7.82	6	34.1	13	2.6	-	33.7	2.1	5.8	1.1	35.2	2.5	4.2		
6	21-22.8.82	11	11.3	-	-	-	11.7	0.6	-	-	8.3	-	-	11.8	-
7	23-30.8.82	17	19.7	-	-	-	19.3	1.2	-	-	16.6	-	-	24.9	-
8	4-6.9.82	7	38.4	10	0.6	-	37.5	Disturbance in the plot			44.4	1.3	3.5	45.6	30.3
9	20-26.9.82	12	33.3	6.8	0.4	-	33.5	1.8	4.3	-	32.4	0.6	2	43.2	13.8
10	27.9.82	28	7.3	3.4	-	-	7.3	-	1.9	-	7.4	-	1	9.2	6.2
11	5-7.10.82	29	31.9	19.7	3.4	-	20.7	0.2	10.5	1.8	45.6	-	7.5	28.8	24.4
12	8-9.10.82	40	21.1	8.5	2.9	0.5	19.1	-	6.3	1.9	22.5	-	1.7	19.2	13.8
13	10.10.82	56	10	4.7	1.1	0.4	9.6	-	4.3	0.8	10.7	-	1	11	7.3
14	11-13.10.82	56	38.8	21.5	5	2	40.1	0.23	20.8	4.4	40.1	0.15	8.4	38.3	29.5
15	14-17.10.82	58	15	4.8	1.6	1.7	14.1	-	3.7	1.1	16.1	-	-	22	12.7
16	18-24.10.82	40	7.3	0.8	0.3	0.2	7.4	-	0.6	0.08	6.3	-	-	8.9	2.1
17	25-31.10.82	13	34.3	10.9	2.1	1.4	29.3	-	7	0.5	30.1	-	-	38.5	22.3
TOTAL			395.3	133.8	22.5	6.2	336.2	11.0	78.9	13.7	414.3	7.8	38.5	301.4	
				(A+B+C) mm		%		(L+A+B) mm		%		(L+20) mm	%		(L+20) mm / %
				162.5		41		103.6		31		46.3	11		162.4 / 54

Table 28. Observed flows from the four rectangular plots during the second field season. *A,B,C soil horizons. L litter layer.

same for the deeper (B, C) soil horizons, then the order of plots generating the largest seepages would have been the same as indicated with the measured flows.

As the Table shows, seepage occurred under relatively dry, and wet soil moisture conditions. Visual appraisal of the data indicates that the flows were more frequent, and larger, under wet soil conditions. Hence the response of the plots to rainfall would be better examined if the flows were divided and separated by shorter time intervals. For convenience a month was regarded as being a suitably short time interval, so the response of the plots to monthly rainfall is shown in Table 29. Before analysing this Table it should be clarified that the rain which fell during the last three days of September and the first few days of October has been subtracted from the monthly amounts. This subtraction was made, as explained earlier, because of the disturbance of the plots during this period. In addition to this subtraction, the rain that fell from 4th-6th September has also been subtracted for the same reason.

The Table shows that the seepages collected during the period the plots were in operation varied. The response of the plots to monthly rainfall was as follows.

During June the seepages for plots 1, 2 and 3 were 35%. 23% and 13% of the monthly rainfall, respectively. The corresponding percentages for July, despite the fact that the rainfall was almost half that of the previous month, were 33%, 19% and 14%. This small difference between the two months can be attributed to the fact that seepages in June were the average for four time periods - with

MONTH	PLOT 1			PLOT 2			PLOT 3			PLOT 4		
	Rainfall (mm) gauges $\frac{1+2}{2}$	Seepage (mm)	%	Rainfall (mm) gauge 2	Seepage (mm)	%	Rainfall (mm) gauges $\frac{1+5}{2}$	Seepage (mm)	%	Rainfall (mm) gauge 3	Seepage (mm)	%
JUNE	93	32.2	35	90	20.6	23	99	12.4	13	The plot was not in operation		
JULY	48	15.6	33	48	9	19	48	6.7	14			
AUGUST	58	0	0	60	1.8	3	47	0	0	52	0	0
SEPTEMBER	88	21.2	24	49.5	8	16	95	8.4	9	112	50.3	45
OCTOBER	158	94	59	140	64.2	46	171	18.8	11	167	112.1	67
TOTAL	445	163	37	387.5	103.6	27	460	46.3	10	331	162.4	49

Table 29. Observed monthly flows in the rectangular plots.

different rainfall, while in July the seepages came from only one time period (Table 28). August was the only month during which seepages were not observed in plots 1, 3 and 4, while in plot 2 a small amount of seepage (3%) was observed in two time periods. This seepage occurred under relatively dry antecedent soil moisture conditions and a small amount of rainfall. September was the first month during which plot 4 responded to rainfall, and 45% of the monthly rainfall seeped from the guttered soil segments of this plot. Also, all the other plots generated seepage during this month. For plots 1, 2 and 3 this amounted to 24%, 16% and 9% of the montly rainfall, respectively.

Taking into account the rainfall the catchment received during September, and the three previous months, it becomes apparent that the seepages in September were relatively small. This can be attributed to the fact that July and August were relatively dry months and so the storage capacity of the soil must have increased in September. On the other hand, September itself was a dry month; in the first seventeen days rain occurred only on three days (Fig. 14).

October was the wettest month of the period in which the plots were operated. The observed seepages from plots 1, 2, 3 and 4 were 59%, 46%, 11% and 67% of the monthly rainfall, respectively. It becomes apparent from these percentages that the seepages from plots 1, 2 and 4 increased considerably in comparison with that of the previous months. In plot 3, however, the seepage increased by only 2% in comparison with September and decreased by 2% and 3% in comparison with June and July, respectively. Fuller details concerning the difference in response to rainfall of this plot, compared with the others, will be given later.

The analysis of these data indicated that on a monthly basis the seepages from plots 1, 2, 3 and 4 ranged from 0 to 59%, 3 to 46%, 0 to 14% and 0 to 67% of the monthly rainfall, respectively. The largest amounts of seepage observed in each month of operation occurred in plot 4, and the smallest in plot 3.

The monthly response of the plots to rainfall represented better the real relationship between an amount of rainfall and an amount of seepage water than the previous averages given in Table 28. But, as the aim of flow measurement from the plots in time periods was the separation of flows from specific rain events, analysis of rainfall and observed flows at each time period was also undertaken. The results of this analysis are presented in Table 30. This shows that seepages varied from one plot to another, as noticed earlier, and from one time period to another. Vegetative cover, soil type and the gradient of the plot may have been the source of the variation between plots. The number of days in each time period, amount, duration and intensity of rainfall and antecedent soil moisture conditions may have been the source of the variation over time. This is because the factors referred to here are the main ones that affect the volume and time distribution of seepages (runoff).

The seepages in plots 1 and 2 ranged from 19% to 73% and 5% to 63% of the rainfall of the time periods, respectively. The corresponding percentages for plots 3 and 4

Time Period No.	Date	API (mm)	PLOT 1 Rainfall (mm)	PLOT 1 Seepage (mm)	PLOT 1 Seepage %	PLOT 2 Rainfall (mm)	PLOT 2 Seepage (mm)	PLOT 2 Seepage %	PLOT 3 Rainfall (mm)	PLOT 3 Seepage (mm)	PLOT 3 Seepage %	PLOT 4 Rainfall (mm)	PLOT 4 Seepage (mm)	PLOT 4 Seepage %
1	11-12/6/82	2	25.7	11.5	45	24.8	7.8	31	30.1	4.6	5	This plot was not in operation		
2	15-16/6/82	17	14.2	3.2	23	13.7	1	7	16.2	.6	4			
3	25-27/6/82	4	41.6	17.5	42	40.9	11.4	28	42	7.2	17			
4	28-30/6/82	34	11.3	-	-	11	.4	4	10.3	-	-			
5	10-15/7/82	6	34.1	15.6	46	33.7	9	27	35.2	6.7	19			
6	21-22/8/82	11	11.3	-	-	11.7	.6	5	8.3	-	-	11.8	-	-
7	23-30/8/82	17	19.7	-	-	19.3	1.2	6	16.6	-	-	24.9	-	-
8	4-6/9/82	7	38.4	10.6	28	37.5°	-	-	44.4	4.8	11	45.6	30.3	66
9	20-26/9/82	12	33.3	7.2	22	33.5	6.1	18	32.4	2.6	8	43.2	13.8	32
10	27/9/82	28	7.3	3.4	47	7.3	1.9	26	7.4	1	14	9.2	6.2	67
11	5-7/10/82	29	31.9	23.1	72	20.7	12.5	60	45.6	7.5	16	28.8	24.4	85
12	8-9/10/82	40	21.1	12.3	58	19.1	7.8	41	22.5	1.7	8	19.2	13.8	72
13	10/10/82	56	10	6.2	62	9.6	5.5	57	10.7	1	9	11	7.3	66
14	11-13/10/82	56	38.8	28.5	73	40.1	25.4	63	40.1	8.6	21	38.3	29.5	77
15	14-17/10/82	58	15	8.1	54	14.1	4.8	34	16.1	-	-	22	12.7	58
16	18-24/10/82	40	7.3	1.3	19	7.4	.7	9	6.3	-	-	8.9	2.1	24
17	25-31/10/82	13	34.3	14.4	42	29.3	7.5	26	30.1	-	-	38.5	22.3	58

Table 30. Total observed flows from each plot during the 17 Time Periods.

ranged from 4% to 21% and 24% to 85%, respectively. The largest seepages occurred in plots 1, 2 and 3 during time period 14 (11-13/10/82), while in plot 4 it was during period 11 (5-7/10/82). In period 14 the seepage from plot 4 was 77% and in period 11 the seepages from plots 1, 2 and 3 were 72%, 60% and 16%, respectively. So the difference in the amount of seepage water from the same plot in the two time periods was very small. However, it was difficult to explain why all the plots did not yield the largest amount of seepage in the same time period. In the results presented here, there are periods during which larger amounts of flows have seeped from periods with a smaller rainfall and others with the same amount of rainfall and different amounts of seepage. In periods 1 and 9, for example, plots 1, 2 and 3 generated in the first period larger seepages with a smaller amount of rainfall than in the second period. However, the same plots during periods 5 and 10 yielded almost the same amount of seepage with different amounts of rainfall. Hence the influence of the factors referred to above is evident. Examining the large percentage of rainfall that seeped from all of the plots during time periods 13, 14 and 15, when the API was high, it is apparent that the antecedent soil moisture conditions must have affected the observed flows very much. To what extent each of the other factors has affected the observed flows was not examined. This is because the purpose of these plots was only to collect and measure any flows occurring under fixed plot conditions and over a given time.

The results presented do indicate that significant amounts of water seeped from three of the four plots. The seepages might have been higher than those observed, if they had been collected from single rain events or shorter time periods. From plot 3, the maximum amount of seepage was less than the minimum observed in plot 4. The stony condition of the soil in this plot may provide an explanation for the small amount of seepage observed. The seepages from plot 4 were larger than those from plots 1 and 2 despite the fact that they were collected from deeper soil segments. In terms of the amount of seepage, plot 1 lies in second and plot 2 in third place.

The results presented so far have shown the flows emerging from the plots expressed as a percentage of the total rainfall of all time periods, of the monthly rainfall, and of the rainfall of each time period. It is also important to examine the flows that emerged from the litter layer and the deeper soil segments in the four plots. This information is presented in Table 31. The numerator of each cell refers to the amount of rainfall emerging from each soil segment and the denominator refers to the percentage of the total rainfall for the time period.

Litter flow, as explained earlier, was collected only from plots 2 and 3. During the period of operation litter flow occurred during ten time periods in plot 2, and seven time periods in plot 3. The amount observed was relatively small and it ranged from 1-8% and 0.5-7% in plots 2 and 3, respectively. Litter flow was more frequent and occurred in larger quantities in both plots under dry rather than wet soil conditions. The reasons for the occurrence of

Time period no.	DATE	A.P.I (mm)	PLOT 1 Rainfall (mm)	PLOT 1 Observed seepage A	PLOT 1 Observed seepage B	PLOT 1 Observed seepage C	PLOT 2 Rainfall (mm)	PLOT 2 Observed seepage L	PLOT 2 Observed seepage A	PLOT 2 Observed seepage B	PLOT 3 Rainfall (mm)	PLOT 3 Observed seepage L	PLOT 3 Observed seepage 20 upper cm	PLOT 4 Rainfall (mm)	PLOT 4 Observed seepage L + A
1	11-12.6.82	2	25.7	11.5 / 45	-	-	24.8	2.1 / 8	5.7 / 23	-	30.1	1.4 / 5	3.2 / 11		
2	15-16.6.82	17	14.2	3.2 / 23	-	-	13.7	1 / 7	-	-	16.2	0.6 / 4	-		
3	25-27.6.82	4	41.6	15 / 36	2.5 / 6	-	40.9	1.4 / 3	8 / 20	2 / 5	42	1.2 / 3	6 / 14		
4	28-30.6.82	34	11.3	-	-	-	11	0.4 / 4	-	-	10.3	-	-		
5	14-15.7.82	6	34.1	13 / 38	2.6 / 8	-	33.7	2.1 / 6	5.8 / 17	1.1 / 3	35.2	2.5 / 7	4.2 / 12		
6	21-22.8.82	11	11.3	-	-	-	11.7	0.6 / 5	-	-	8.3	-	-	11.8	-
7	23-30.8.82	17	19.7	-	-	-	19.3	1.2 / 6	-	-	16.6	-	-	24.9	-
8	4- 6.9.82	7	38.4	10 / 26	0.6 / 2	-	37.5	*			44.4	1.3 / 3	3.5 / 8	45.6	30.3 / 66
9	20-26.9.82	12	33.3	6.8 / 20	0.4 / 1	-	33.5	1.8 / 5	4.3 / 13	-	32.4	0.6 / 2	2 / 6	43.2	13.8 / 32
10	27.9.82	28	7.3	3.4 / 47	-	-	7.3	-	1.9 / 26	-	7.4	-	1 / 14	9.2	6.2 / 67
11	5-7.10.82	29	31.9	19.7 / 62	3.4 / 11	-	20.7	0.2 / 1	10.5 / 51	1.8 / 9	45.6	-	7.5 / 16	28.8	24.4 / 85
12	8-9.10.82	40	21.1	8.5 / 40	2.9 / 13	0.5 / 2	19.1	-	6.3 / 33	1.9 / 10	22.5	-	1.7 / 8	19.2	13.8 / 72
13	10.10.82	56	10	4.7 / 47	1.1 / 11	0.4 / 4	9.6	-	4.3 / 45	0.8 / 18	10.7	-	1 / 9	11	7.3 / 66
14	11-13.10.82	56	38.8	21.5 / 55	5 / 13	2 / 5	40.1	0.23 / 1	20.8 / 52	4.4 / 11	40.1	0.15 / 5	8.4 / 21	38.3	29.5 / 77
15	14-17.10.82	58	15	4.8 / 32	1.6 / 11	1.7 / 11	14.1	-	3.7 / 26	1.1 / 8	16.1	-	-	22	127 / 58
16	18-24.10.82	40	7.3	0.8 / 11	0.3 / 4	0.2 / 3	7.4	-	0.6 / 8	0.08 / 1	6.3	-	-	8.9	2.1 / 24
17	25-31.10.82	13	34.3	10.9 / 32	2.1 / 6	1.4 / 4	29.3	-	7 / 24	0.5 / 2	30.1	-	-	38.5	22.3 / 58
	TOTAL		395.3	133.8 / 34	22.5 / 6	6.2 / 2	336.2	11.0 / 3	78.9 / 23	13.7 / 4	414.3	7.8 / 2	38.5 / 9	301.4	162.4 / 54

Table 31. Amounts and percentages of flows emerging from each soil segment in the four rectangular plots.

litter flow in both soil types of the catchment have been explained earlier (Sections 4.3.1. and 4.3.2). These amounts of litter flow must have occurred due to very dry, or saturated soil conditions. However, which type of soil condition or whether both have occurred in each time period, would be difficult to identify. This is because in time periods with a small API litter flow may have occurred due to very dry soil conditions at the beginning of the rainfall, but later the soil may have become saturated and so more litter flow may have occurred. In time periods 2, 4, 6 and 7 (Table 31) when the API and the amount of rainfall was small, it is reasonable to assume that litter flow occurred because the soil was very dry. In contrast, in time periods 1, 3, 5, 8 and 9 when the API was small and the rainfall relatively high both types of litter flow may have occurred. As for time period 11, it is reasonable to assume that litter flow occurred when the soil became saturated, as API was high and the rainfall high and continuous. Finally, in time period 14 litter flow was observed during a cloudburst that lasted only ten minutes and had an intensity of 25 mm/hr. The author was present in the catchment area during this event. As the duration of this event was very short and the intensity high, litter flow may have occurred due to rainfall intensity being larger than the infiltration capacity of the soil. More details about this event will be presented later in the soil hydrographs section.

An examination of the observed amounts of litter flow in the triangular and the rectangular plots during the first and second field seasons (Tables 24 and 31) reveals that larger amounts of flow were observed during the first field season in a number of time periods - as, for example, time periods 4, 6 and 7 of the first field season. An explanation of this difference could be, first, the higher and more continuous rainfall in time periods 6 and 7, and second, the high intensity and duration in time period 4. Time period 4 of the first year and time period 3 of the second year both had the same rainfall (41 mm) and APIs of 12 mm and 4 mm, respectively. However, the observed amount of litter flow ranged from 10-39% in the various triangular plots, and it was only 3% in both rectangular plots 2 and 3. The intensity and duration of this ranfall, as Fig. 15 shows, were different for the two time periods. Most of the rainfall in the 1981 event fell in eight hours with a mean intensity of 3.4 mm/hr, while the rainfall in the 1982 event fell in twenty-two hours with a mean intensity of 1.3 mm/hr.

The A horizon was the soil segment through which the largest amount of flow was observed in all the plots. The observed flows from this horizon in plot 4 were analysed earlier, when the total amount of flow that seeped from each plot was presented (Table 30).

From the A horizon of plots 1, 2 and 3 seepages were observed during 14, 12 and 10 time periods, respectively. Between plots 1 and 2 there may have been a difference of only one time period, but plot 2 was disturbed during period 8. The seepages in these plots (1, 2 and 3) during the whole period of operation ranged from 11-62% for plot 1, 8-52%

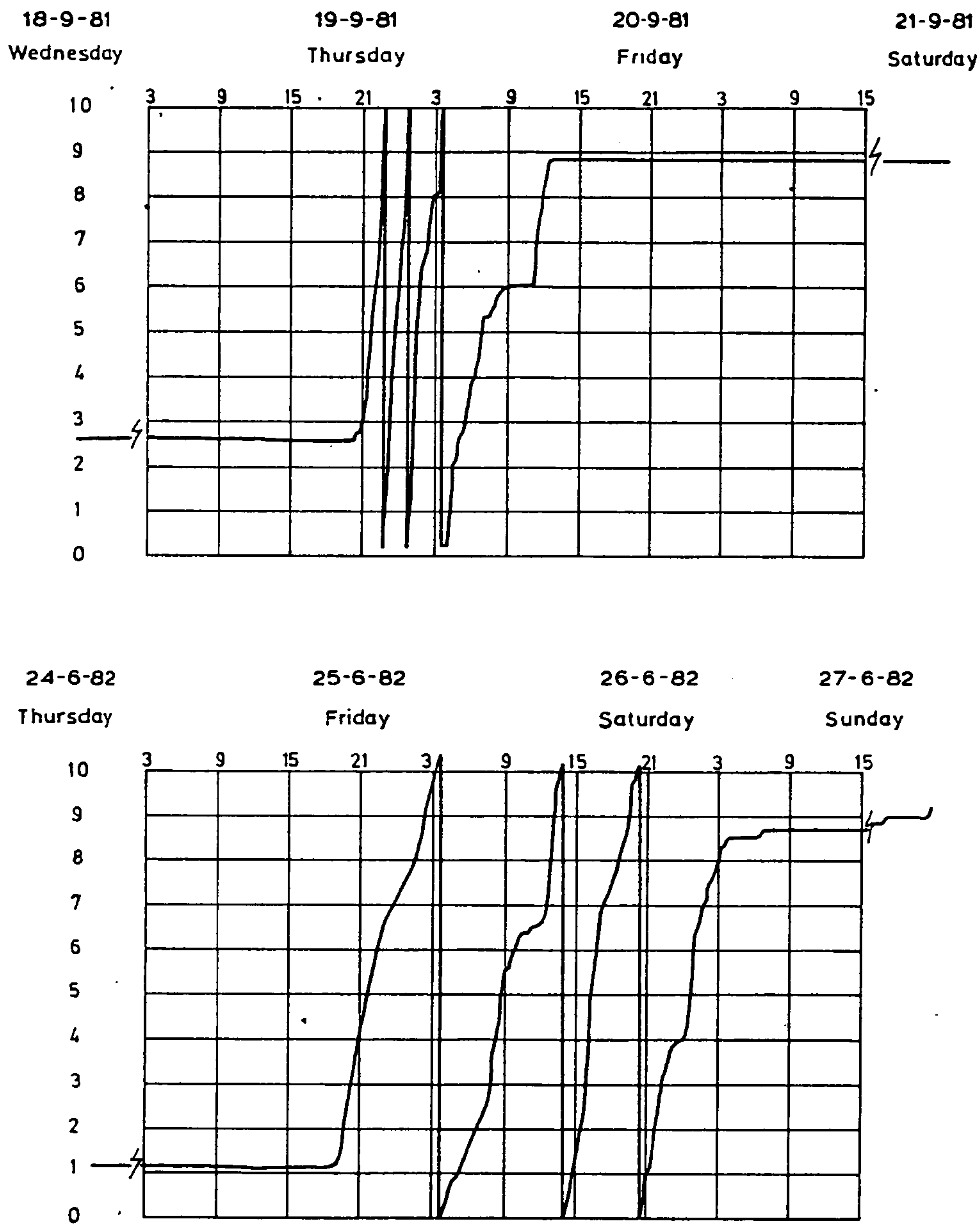


Figure 15. Two rain events of almost the same total rainfall that generated different amounts of litter flow.

for plot 2, and 6-21% for plot 3 of the rainfall for each time period. The largest seepage observed in plot 1 occurred in time period 11 while in plots 2 and 3 the largest occurred in time period 14.

The flows during time periods 1, 3, 5, 8, 9 and 17 occurred under relatively high rainfall and dry antecedent soil moisture conditions. During the other periods, with the exception of period 2, the flows occurred under relatively high or low rainfall and wet antecedent soil moisture conditions. The rainfall of this first group of periods ranged approximately from 25 to 42 mm and the API from 2 to 13 mm. In the second group the rainfall ranged approximately from 7 to 40 mm and the API from 28 to 58 mm. Time period 2 is an exception as flows were observed when the rainfall was 14.2 mm and the API 17 mm. In the first group of time periods, the flows ranged from 20-45% for plot 1, 13-23% for plot 2, and 6-14% for plot 3. The corresponding figures for the second group are 11-62%, 8-52% and 9-21% of the rainfall. This shows that under lower rainfall and wetter antecedent soil moisture conditions larger amounts of seepage were observed in all plots. Taking into account the fact that large percentages of small rainfall amounts emerged from this horizon, it is reasonable to assume that the observed amounts might have been larger if they had been collected from one separate rain event.

Flows emerged not only from the A horizon but also through the B horizon of plots 1 and 2. During the period of operation in plots 1 and 2, flows were observed over twelve and ten time periods, respectively. The flows emerging from the B horizon were smaller than those of the A horizon and ranged from 1-13% of the rainfall in plot 1 and 1-11% in plot 2. The average flows of plots 1 and 2 were 6% for the twelve time periods and 4% for the ten time periods. For time periods 3, 5, 8, 9 and 17 the flows emerged under high rainfall and low API conditions. The rainfall in these periods ranged from 26 to 42 mm and the API from 4 to 13 mm. The flows were small during these periods and in plot 1 they ranged from 1-8% of the rainfall in in plot 2 from 2-5%. In the rest of time periods the flows emerged under relatively low or high rainfall and high API conditions. The rainfall during this second group of periods ranged from 7 to 40 mm and the API from 28 to 58 mm. The flows ranged from 1-13% for plot 1 and 1-11% for plot 2. The largest seepage (13%) in plot 1 was observed during periods 12 and 14 and the corresponding seepage figures for these periods in plot 2 were 10% and 11%.

The maximum flows emerging from both A and B horizons were observed in the same period only in plot 2 (time period 14). The two largest seepages from the B horizon in plot 1 did not occur in the same time period as the two largest seepages from the A horizon. An explanation may be that there was some contribution from rainfall from the previous time period to the seepage flow of the B horizon.

Flow from the C horizon, as mentioned earlier, was collected only in plot 1. From this horizon a small volume of water (70 cm^3) was collected in the first week after the plot had been covered with a waterproof material. After that no flows emerged until the beginning of October.

The first seepage was in fact observed in time period 12 (8-9/10/82) and amounted to 2% of the rainfall. After this and until the end of October, generally small seepages were observed ranging from 2-4% of the rainfall. The average seepage of the six periods was 2%. The largest was observed in period 15 when the other two horizons of this plot did not yield their largest seepages. It is possible that the flows emerging were not only the product of the rainfall of that time period but also of the slow drainage through the C horizon by the rainfall of the previous time periods.

4.3.4. Soil Hydrographs from the Rectangular Plots

The importance of a soil hydrograph is that it gives information about the velocity with which the infiltrated rainfall moves through the soil, and about the flow rates. Furthermore, the soil hydrograph is, first, a component of the hillside where it is produced and, second, a component of the catchment hydrographs. For these reasons, as it was not possible to undertake detailed work on flow rates from the plots because suitable equipment was unavailable, during late September and the first fortnight of October 1982 flow rates were measured from four rain events using measuring cylinders and a stopwatch. Three of these rain events are part of time periods 11 and 14 (Table 28), the volumes of which were presented in the previous section. The fourth rain event is discussed in this section, in addition to the previous one (Table 28, no.10), because additional details will be given here concerning the rate and velocity of flow.

At this stage, it should be mentioned that flow rates were measured only in plot 1, and the reason for this was explained in section 3.3.3. Flows were measured until the rate had almost ceased and the duration of measurement differed between the four rain events. In plot 1, in addition to the flow rates, the time from the beginning of the rainfall to the beginning of flow (T_q), and the time from the beginning of flow to the peak flow rate (T_p) were measured. These parameters were measured in order to give some indication of the flow velocity through the soil. As they were measured in plot 1 only, it was necessary to make a subjective decision that these parameters would be the same for the rest of the plots.

The results obtained from the four rain events are shown in Table 32. The first rain event was a cloudburst that lasted 70 minutes and ceased abruptly. The mean intensity was 6.7 mm/hr and the soil was wet from previous rainfall (API = 28 mm). The portion of this rainfall that emerged from the plots has been presented in the previous section (Table 28, time period 10). In addition it should be stated that T_q and T_p were 18 and 57 minutes, respectively. The rate of flow continued to increase for five minutes after the rainfall had ceased and the peak rate was 89 cm^3/minute. Flow measurements continued for three hours after the rain had ceased, and during this period no water emerged from the soil horizons other than the A horizon. If we make the assumption that the hydrograph peaked when flow from the upper part of the plot reached the gutter, then we can have an indication of the mean flow velocity through this horizon from the inclined length of the plot (1.7 m) and the T_p (57 minutes). This velocity was computed to be 0.5 mm/sec. (1.8 m/hour, or 43 m/day). Taking into account the short time (18 minutes) the flow needed to emerge from the soil and the velocity computed above, it becomes apparent that the rainfall moved through the soil rapidly.

On 7/10/82, the intensity and duration of rainfall were different from the first rain event. In fact, the rainfall lasted for 8 hours and during this period it stopped twice for a total of half an hour. The intensity ranged from 0.5 to 3.8 mm/hr and with an API of 36 mm the soil was wetter than for the previous rain event.

Flow emerged not only from the A horizon in all the plots but also from the B horizon in plots 1 and 2. The flow emerging from the A horizon was larger than that from the B horizon in plots 1 and 2. In fact, 49% and 5% of the rain emerged from the A and B horizons of plot 1, and 22% and 2% from the A and B horizons of plot 2. Smaller amounts of seepage (8%) emerged from plot 3 and larger (64%) from plot 4.

The soil hydrographs generated from this rain event are illustrated in Figure 16. The T_q and T_p values for the first peak were 24 and 110 minutes, respectively, and the two peak rates were 35 and 20 cm^3/minute. When the rainfall ceased, the falling limb of the hydrograph from the A horizon decreased gradually and flows of approximately 2 cm^3/minute continued to emerge from the A horizon for 5 hours. The first seepage from the B horizon emerged 80 minutes after the beginning of the rainfall and started increasing at a low rate. This seepage from the B horizon

PLOT No.	Date	API (mm)	Rainfall (mm)	Duration	T_q	T_p	Observed seepages	(mm)	%
1	27/9/82	28	7.2	70 minutes	18 minutes	57 minutes	A	3.2	44
							B	-	
							C	-	
							L	-	
2			7.2				A	1.9	26
							B	-	
3			7.5				L	-	
							20 cm	1 .	13
4			9.2				L+A	5.7	62
1	7/10/82	36	10.8	8 hours	24 minutes	110 minutes	A	5.3	49
							B	.50	5
							C	-	
							L	-	
2			10.8				A	2.4	22
							B	.20	2
3			10				L	-	
							20 cm	.80	8
4			11.2				L+A	7.1	64
1	11/10/82	49	3.7	10 minutes	2 minutes	22 minutes	A	1.8	49
							B	-	-
							C	-	-
							L	.23	6
2			3.6				A	1.6	44
							B	-	-
3			3.9				L	.15	4
							20 cm	.54	14
4			4.5				L+A	3.2	71
1	13/10/82	54	2.3	20 minutes	3 minutes	27 minutes	A	1.54	67
							B	-	-
							C	-	-
							L	-	-
2			2.2				A	1.1	50
							B	-	-
3			2.4				L	-	-
							20 cm	0.55	23
4			2.8				L+A	2.1	75

Table 32. Hydrologic components of the four hydrographs generated in the rectangular plots.

emerged 80 minutes after the beginning of the rainfall and started increasing at a low rate. This seepage peaked at 100 minutes at a maximum rate of 3 cm^3/min. When the intensity of the rainfall decreased from 2 to 1 mm/hr, the seepage from the B horizon ceased completely. The results indicated that between T_q and T_p of the two curves there was a long time gap of 56 and 45 minutes, respectively. The reason for this delay may be related to the infiltration of rainfall into the A horizon. Some rainfall will be absorbed by the A horizon and the rest will percolate down to the B horizon, here again there will be absorption of water and lateral movement through the horizon. The mean flow velocity through the A horizon was computed to be 0.26 mm/sec. (22.5 m/day) and through the B horizon, 0.28 mm/sec. (24 m/day). Therefore, the flow velocity, as computed, is higher in the B horizon than in the A horizon. However, with regard to the short time (24 minutes) that flows seeped from the A horizon, and the large amount of seepage, this would be impossible, and so the assumption made must not have been valid. In other words, the opinion that the maximum rate of seepage occurs when rainfall from the upper part of the plot reaches the gutter was not correct, and seepages may have emerged only from the part of the plot nearby the gutters.

High intensity and short duration were the characteristics of the third rain event when seepages were measured on 11/10/82. In fact, it was a cloudburst that lasted only 10 minutes with an intensity of 25 mm/hr. The T_q was 2 minutes and the T_p was 24 minutes. The rate of seepage rose

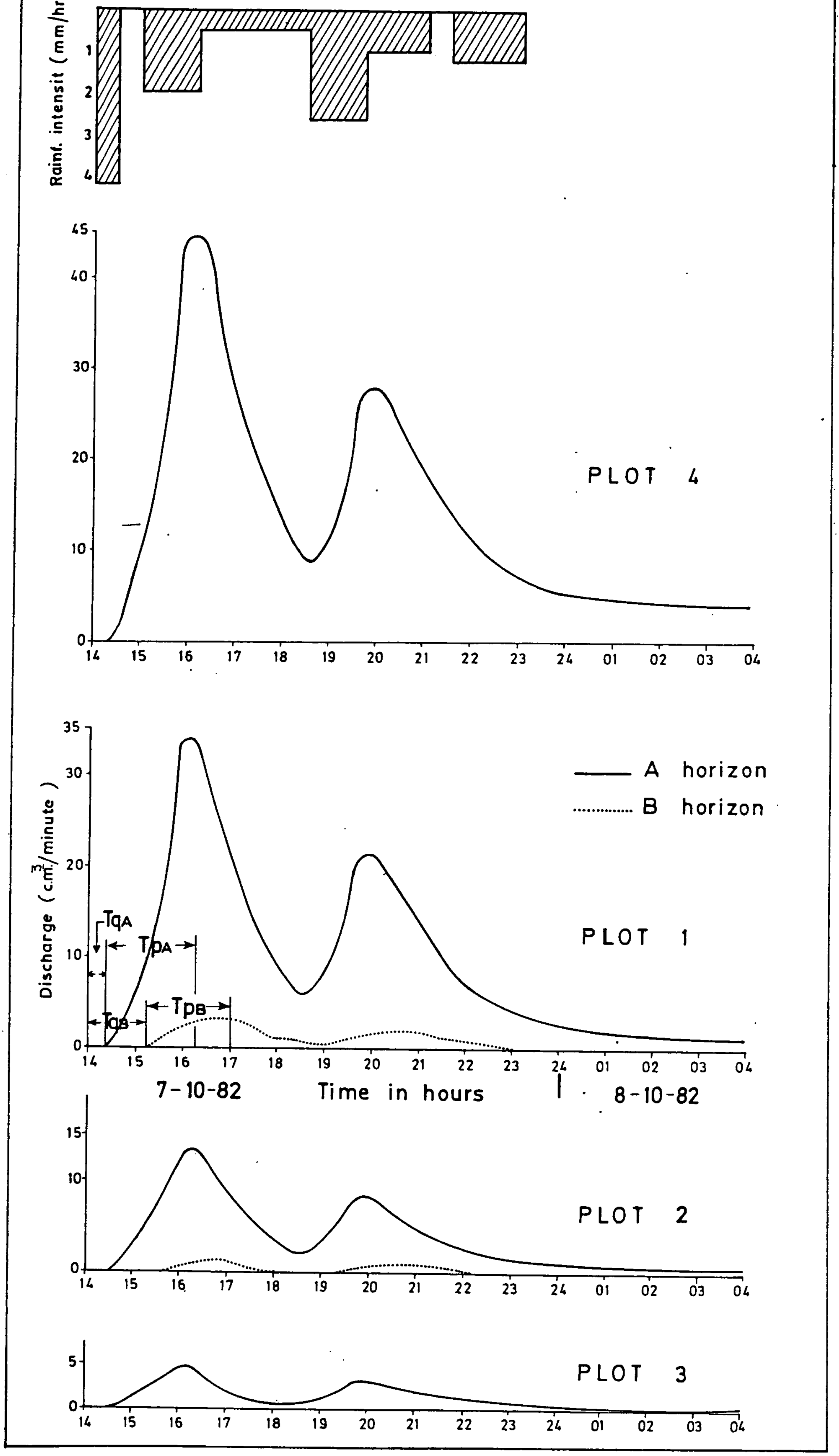


Figure 16. Soil hydrographs generated on 7.10.82.

for 14 minutes after the rain had ceased and the peak rate was 50 cm^3/minutes. Measurement of seepage continued for 100 minutes after the rainfall had ceased.

The hydrographs generated by this event are illustrated in Figure 17. Flows emerged from the A horizon of all the plots and litter flow from plots 2 and 3. No flows emerged from the B horizon in plots 1 and 2. The percentage of rainfall that emerged from the A horizon in plot 1 was the same as in the previous rain event, 45%. However, the percentage of A horizon flow from plot 2 (44%) was double the amount of flow from the previous event. This large difference was difficult to explain. The amount of water that emerged from plots 3 and 4 was 14% and 71% of the total rainfall, respectively. The flows emerging from the litter layer of plots 2 and 3 were 6% and 4%, respectively. The litter flow may have occurred because the rainfall intensity was higher than the infiltration capacity of the soil. This is because, first, the amount of rainfall was not large enough to saturate the soil and, second, with wetter soil moisture conditions, litter flow was not observed on any of the rest of the days of this month. This being so, the litter flow curves (Fig. 17) must have had a different shape with mainly short falling limb. It was unfortunate that the start and end times for these flows were not known. They are drawn as in Figure 17 only for convenience (proportional to the throughflow rates from the A horizon). The mean flow velocity of this rain event was computed to be 1.2 mm/sec. (103 m/day).

The final rain event was again a cloudburst that

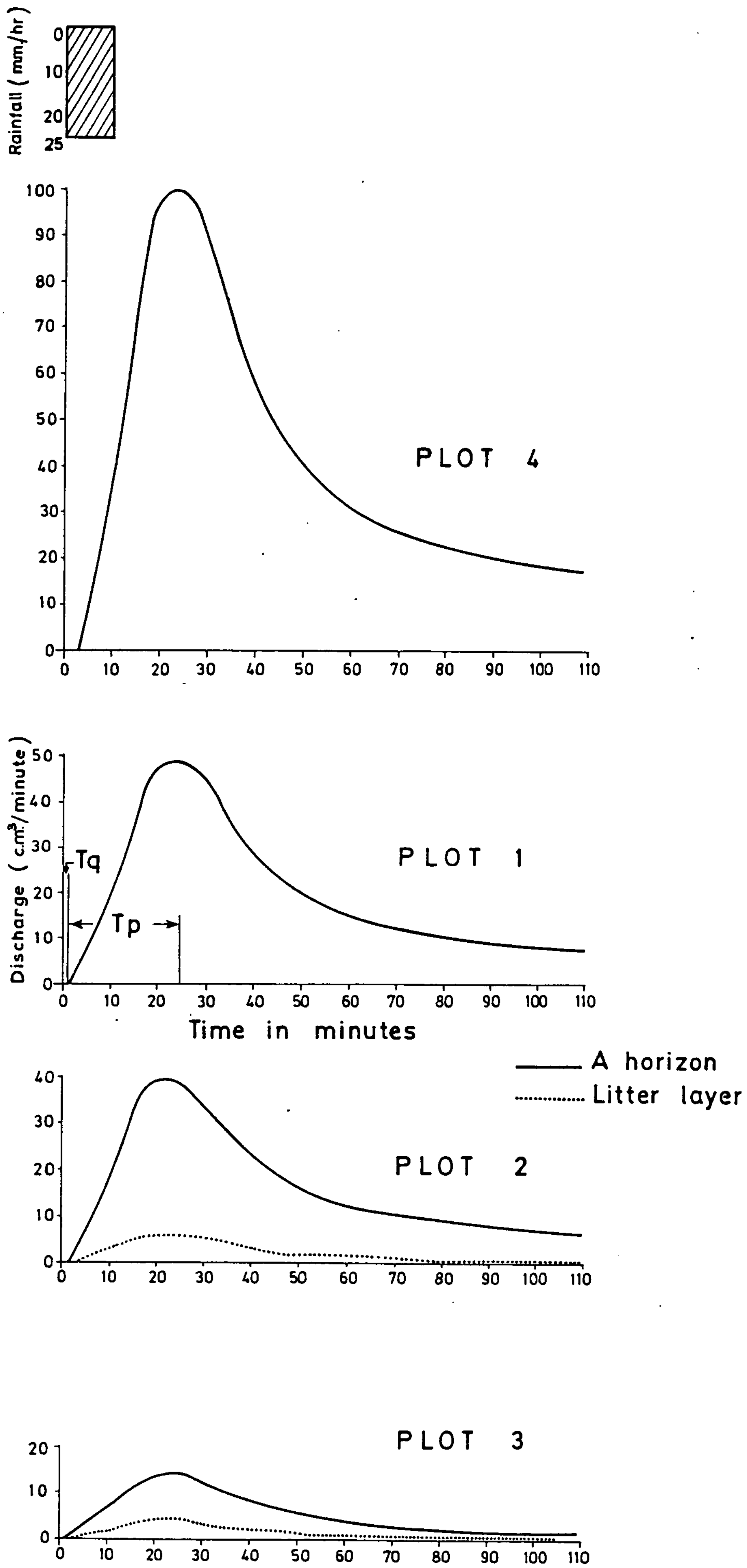


Figure 17. Soil hydrographs generated on 11.10.82.

started with very wet soil conditions (API = 54 mm) and lasted for 20 minutes. The mean intensity was 7.2 mm/hr. The T_q and T_p values were 3 and 27 minutes, respectively. As long as the seepages were measured (1 hour after the rain ceased) flows emerged only from the A horizon of the plots and these flows were larger than those observed in the previous rain event. For plots 1, 2, 3 and 4, they were 67%, 50%, 23% and 75% of the total rainfall, respectively. The mean flow velocity through the A horizon was computed to be 0.6 mm/sec. (2.2 m/hour, 53 m/day).

From the results presented here some conclusions regarding the velocity of flow through the soil horizons may be made. They are: (a) the response of throughflow to rainfall is very rapid and it ceases gradually after the end of the rainfall. An indication of the velocity of flow through the A and B horizons was obtained and it is more likely to relate to the structural and biological voids in the soil mass than to the textural porosity. (More details about this will be given at a later stage of this thesis.)

(b) Seepage emerging from the A and B horizons is not synchronous, but there is a time-lag between them. There is also a time-lag between the peak rates from these horizons. An explanation for this time-lag was given earlier.

4.3.5 Discussion

The results obtained from natural rainfall indicate that lateral flow through the soil horizons was the major flow process in the catchment during the study period. It occurred in both soil types, regardless of vegetative cover, but it was largest in the peat soil area of the catchment. Also, it was found that the amount of lateral flow in the brown earth soil area of the catchment decreased from the upper to the deeper soil horizons. The velocity of lateral flow must have been high, as the plots responded rapidly to rainfall. Another flow process that was observed, and may have been as important as lateral flow, was litter flow. This was observed during relatively large storms in all the plots regardless of vegetative cover and soil type, and it was mainly saturated litter flow. However, on rare occasions, it may have occurred due to rainfall intensities being higher than the infiltration capacity of the soil, or due to very dry soil conditions in the summer.

The lateral flow data presented here were obtained, as has been explained, from experimental plots installed on the slopes of the study catchment. The possibility of a plot installed in the middle of the slope to receive drainage from areas smaller or larger upslope of it, in case the flows were saturated or unsaturated, respectively (Atkinson, 1980) was precluded. This was because the plots were surrounded by waterproof boundaries and they had good connections with the sides of the plots.

Another point that may raise questions, is the assumption made that the parameters T_q and T_p measured in plot 1 were the same for plots 2, 3 and 4. Whether these parameters were the same or different in other plots, and to what extent, is something that unfortunately cannot be answered.

If there was a difference, it is reasonable to assume that it must have been smaller for plots 2 and 3 and higher for plot 4 compared with plot 1. This is because plots 2 and 3, except for having different vegetation from plot 1, were constructed in the same soil type and had approximately the same gradient as plot 1. In contrast, plot 4 was constructed in a different soil type and its gradient was smaller than that of plot 1. Any possible difference in these parameters could not have completely changed the shape of the hydrographs generated and so in the worst case there would be an indication of the discharges from plots 2, 3 and 4.

The fact that the minimum dry spell used to separate time periods was only 5 hours may be criticised as not being long enough for the flow to stop completely from the soil horizons. This duration was chosen because it was observed that the drainage, mainly from the upper soil horizon, was rapid. In fact, a flow would need to achieve a mean velocity of only 0.095 mm/sec. to cover the inclined length of the plot (1.7 m) in five hours. As is evident from the previous section, the mean computed velocity of flow was much higher than 0.095 mm/sec., and so five hours is regarded as sufficient time for the water to flow through the soil for a distance of 1.7 m and to stop draining. However, it was observed in plot 4 that from the beginning of October a very small, but continuous seepage occurred. But this amount of flow was not regarded as enough to affect seriously the amount of flow generated from a specific amount of rainfall.

Piezometers were not used in the area of the plots, which would have detected saturation of the soil horizons, or could have been used to compute the hydraulic conductivity. This could also be open to question. Also, the lack of textural analysis of the soil may be criticized. This kind of analysis, despite the fact that it was recognized as important for a better understanding of the various observed processes in the catchment, could not be done. This was because the fieldwork was undertaken by one person and all efforts were directed at identifying the flow processes occurring in the catchment.

After mentioning these various ways in which the results may be criticized and the reasons why the work could not be done differently, it is worth comparing them with those obtained by other investigators working on the same subject in Great Britain and elsewhere. Such a comparison may help to answer the question why the observed processes occurred, as a number of components that could have helped answer this were not measured.

General observations recorded in the literature regarding the water movement over the ground surface and through the soil, and especially regarding the amount and nature of flow as well as the horizons through which it moved and the contribution of it to storm runoff, ranged from agreement to disagreement. Table 33 shows the main field experiments about flow processes that have been carried out in various environments. The agreement and disagreement in the observed flows is apparent and a consideration of the results obtained in the present catchment with those

Type of Rainfall and Soil Conditions	Arnett (1974)	Weyman (1970, 1973)	Knapp (1974)	Hursh and Hoover (1941)	Hewlett (1961) Hewlett and Hibbert (1963)	Thukamuta (1961)	Whipkey (1965, 1969)	Ragan (1968)	Betson (1969)	Dunne and Black (1970 a, b)	Beasley (1976)	Pilgrim (1978)	Bonnell et al (1978)	Mosley (1979)	Baloutsos (1985)
	N A M E O F I N V E S T I G A T O R														
Natural Rainfall	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Artificial Rainfall	No	No	No	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	No	No	Yes
Surface Cover	Pasture grasses and bracken	Bracken and grass	---	Forest	Bare	Forest	Forest	Forest	Grassed pasture	Pasture	Forest	Grass	Tropical forest	Forest	Heather, bracken and grass
Soil Type	Free draining brown earth	Brown earth	Hill peat and Iron podzol	Forest soil	Sandy loam	Granite and Tertiary	Sandy loam	Sandy soil	Clay loam	Sandy loam	Sandy loam	Silty and clay loam	Yellow brown clay	Podzolized Yellow Brown	Brown earth and peat soil
Depth of Soil the Flows Measured	0.30m	0.75m	---	0.30m	0.46m	---	1.50 to 1.82m	0.76m	0.30m	1.52 to 2.74m		0.76m	1.00m	0.55m	0.10 to 0.90m
	T Y P E S O F F L O W O B S E R V E D														
Hortonian Overland Flow	Yes	No	No	Yes but no details about the type of surface flow.	No	Yes but no details about the type of surface flow.	No	No	No	No	No	Yes	No	No	Yes
Saturated Overland Flow	Unknown	No	Yes		No		No	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Saturated Lateral Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Unsaturated Lateral Flow	Was not examined	Yes	---	Was not examined	Yes	Unknown	Yes	No	Was not examined		Yes	Was not examined		Yes	Was not examined

Table 33. Flow processes observed in field experiments throughout the world.

obtained in Great Britain and elsewhere seems reasonable. Arnett's (1974) results, for example, who worked in an environment similar to the present study, are in general agreement with those obtained in the Lammermuir Hills. They indicated lateral movement of water through the soil, mainly through the A horizon. The lateral movement was attributed to anisotropic soil (Childs, et al., 1957), as the horizontal permeability was found to be larger than the vertical. The permeability was higher in the top soil and mainly in the summer when the soil was desiccated and cracked. There was also a wide range of permeability among the fifteen sites involved. Another factor that contributed to the lateral movement in Arnett's plot 2 was the existence of dead and living bracken rhizomes. In the present study, no measurements of horizontal and vertical permeability were made, but there were reasons to infer that horizontal permeability, mainly in the A horizon, must have been higher than the vertical. The first reason was the longer time the infiltrated water needed to seep from the B horizon of plot 1, as explained in section 4.3.4.
The second reason was the concentration of roots, mainly in the A horizon. These provided favourable conditions for the existence of voids and so for easy lateral movement of water through them. Another similarity in the results obtained from the two areas was the large variability in seepage from the plots. Finally, 'litter flow' and 'overland flow' were observed in each area. However, the reason for occurrence was different. Arnett concluded that it occurred because rainfall intensities were higher than

the infiltration capacity of the soil, whereas in the present study it occurred because the soil was saturated.

Weyman's (1970, 1973) work on flow processes in brown earth soil covered with bracken is also of interest to this study. Despite the fact that part of the Lammermuir Hills and Weyman's experimental area had the same soil type, the observed processes were different. As Table 33 shows, he observed lateral flows as well, but the water moved through the deeper soil horizons (B, B/C). No lateral flow was observed through the A horizon and no Hortonian or saturated overland flow occurred. The observed flows were both saturated and unsaturated and moved through the soil matrix. No mention was made about the possibility of flow moving through biological or structural voids despite the favourable conditions for such water movement. The response of Weyman's plots to rainfall was very slow (velocity < 0.1 mm/sec.) and it was claimed that they could not have contributed to storm runoff. Hence, these findings differ from those obtained in the study area as no flows were observed in the upper soil horizons and no saturated or Hortonian overland flow was observed. Contrary to the findings in the brown earth soil part of the experimental areas, the same processes were observed in the peat soil area. Weyman (1973) observed lateral water movement, mainly through pipes, and saturated overland flow in peat soil. These same processes were observed in the peat soil area of the catchment in the present study as well. However, in plot 4 there was no indication of pipe flow, but this did not preclude its existence. The author was present in the catchment during a number of rainstorms and observed this type of flow in the banks of artificial drainage pits. The above-mentioned processes were also observed by Knapp (1974) in a peat hillside.

From the comparison of the processes observed in the study area and in other parts of Great Britain, it becomes apparent that they may or may not differ under relatively similar conditions of vegetative cover and soil type. Both Arnett (1974) and Weyman (1970, 1973) worked in soils similar to those in the study area (brown earth) and the vegetative cover was not completely different. But, the processes observed, and the horizons through which they moved were not the same in the three experimental areas. On the other hand, when the peat soil processes are compared, they are found to be the same.

The processes identified in the study area have been observed in different environments in other countries, as Table 33 shows. A number of the investigators in the Table (Hush and Hoover, 1941; Tsukamoto, 1961; Whipkey, 1965, 1969; Beasley, 1976; Pilgrim, 1978; Bonnel et al., 1978; Mosley, 1979) observed lateral flows, and the velocity of flow was high enough to contribute to storm runoff. On the other hand, other investigators (Hewlett, 1961; Hewlett and Hibbert, 1963; Ragan, 1968; Betson, 1969; Dunne and Black, 1970a, b) observed lateral flows where the velocity was not enough to allow them to contribute to storm runoff, and where saturated overland flow instead of lateral flow contributed to storm runoff. In some cases Hortonian, saturated and lateral flow were observed together in the same plot (Pilgrim, 1978). This was detected using radioactive traces. The same processes may have been detected elsewhere had this method been employed.

Consideration of the flow processes observed in Great Britain and in other countries indicates that a large number of factors must affect their occurrence. Generally, surficially uniform plots may not generate the same processes because the conditions of the deeper soil horizons may not be uniform. Hence, the observed processes in the present thesis may be, at least to some extent, specific to the catchment studied.

4.4 RESULTS OBTAINED FROM ARTIFICIAL RAINFALL

4.4.1 Calculated Infiltration Rates

Hydrology literature reveals that a number of studies have attempted to compare infiltration rates with soil types, vegetative cover and soil moisture conditions of the catchment. However, the purpose of the infiltration measurements in the present study was, as mentioned earlier, regardless of the above-mentioned factors, to explain any occurrence of litter flows by comparing infiltration rates with the intensity of rainfall in the catchment.

Before presenting the infiltration rates, it must be pointed out that, as was explained in Part III, in the nine selected locations, two runs of infiltration measurements were taken during the second field season. This was because it was decided that the measurements should be taken under the same weather conditions. So, it was thought

Location No.	Soil Type	Vegetative cover	API mm		Infiltration rates. Arithmetic mean and standard deviation (mm/hr)				API mm	Infiltration rates. Arithmetic mean and standard deviation (mm/hr)		
					Mean of initial rates	Mean of final rates	Mean			Mean of initial rates	Mean of final rates	Mean
1	Brown Earth	Grassland	15	RUN 1	49.8±0.4	42.7±5.8	46.3±5.1	RUN 2	12	49.3±0.5	45.3±2.8	45.0±3.6
7	Brown Earth	Grassland	11	RUN 1	50.0±0.0	18.9±6.4	18.9±4.0	RUN 2	1	48.7±1.7	13.0±6.0	18.5±3.3
2	Brown Earth	Heatherland	4	RUN 1	35.7±7.5	11.9±3.8	11.7±3.1	RUN 2	17	49.6±0.7	10.9±1.0	18.0±2.7
4	Brown Earth	Heatherland	8	RUN 1	49.2±1.1	16.1±5.2	19.1±5.8	RUN 2	3	38.2±4.7	12.1±4.4	14.3±2.4
3	Brown Earth	Burntland	7	RUN 1	36.7±12.1	17.3±7.9	18.3±7.8	RUN 2	6	35.7±7.5	17.3±3.0	17.8±2.9
6	Brown Earth	Burntland	6	RUN 1	50.0±0.0	9.6±5.7	15.7±5.6	RUN 2	1	44.0±5.0	11.4±6.4	14.5±5.0
5	Brown Earth	Bracken	14	RUN 1	46.3±7.4	36.2±15.9	37.1±16.2	RUN 2	6	49.6±0.7	44.6±5.2	44.4±5.2
8	Brown Earth	Bracken	10	RUN 1	50.0±10.0	30.1±5.7	36.4±4.8	RUN 2	13	50.0±0.0	30.2±7.3	38.3±3.8
9	Peat	Grassland	2	RUN 1	45.2±5.5	14.2±7.2	23.8±8.6	RUN 2	1	43.3±2.3	5.1±4.2	17.1±7.4

Table 34. Mean infiltration rates of the two runs computed in the nine locations.

reasonable to present the rates of the two runs separately. They are shown in Table 34. For each location the mean value, as well as the means of the initial and final rates were computed. Means of initial and final rates were calculated in order to know the infiltration rates of the soil when it was dry, and wet. However, it was recognized that the mean values were more important as they would show the infiltration rates of the catchment during the type of rain events that produced flooding problems in the lowlands of a wide area in East Lothian. This is because 100 mm of artificial rain was applied in the catchment in two hours which compares with the 100-150 mm of natural rain that had produced flooding problems in the past.

A visual appraisal of the three means between the two runs reveals that the values do not differ very much within the same location. The maximum difference between initial, final and mean rates in the two runs occurs in location 2 (14 mm/hr), in location 5 (8 mm/hr), and in location 2 again (6 mm/hr) respectively. The difference in most other locations between the two runs was ±2 to 3 mm/hr or less. The values for location 9 were not taken into account in this appraisal because the eight measurements in the first run were taken over a period of one hour each, while in the second run they lasted two hours. Also the computed API does not differ very much between the two runs in most of the locations. The maximum difference was observed in locations 2, 7 and 5 where it was 13, 10 and 8 mm respectively. In the other locations it ranged from 1 to 5 mm. The small difference that was seen between mean infiltration rates and API, in the two runs of the same location, was taken into account when considering the possibility of presenting the data obtained from both runs together. Such a presentation would help the analysis and the explanation of the data. The fact that the maximum differences between mean infiltration rates were observed not only in locations having maximum difference in API, encouraged this form of presentation. In location 2, for example, the maximum differences between infiltration rates and API were the same. But this was not observed in location 7 which had a difference in API of 10 mm between the two runs. This suggests that API may not have been the factor responsible for the observed difference in mean infiltration rates. Also taken into account was the fact that the antecedent precipitation factor is only an index of the soil moisture conditions. It was by this reasoning that it was decided to present the data together.

The new recalculated means for each location are presented in Table 35. The means for location 9 were recalculated from the 10 measurements made in the two runs. From the last two measurements which had durations of two hours, the rates were observed only up to the first hour so as to have the same duration as the first eight measurements.

Initial mean rates ranged from 36.2 ± 9.4 mm/hr (location 3 - burnt-over land) to the maximum of 50 mm/hr (location 8 - bracken). All the sites in location 3 showed initial infiltration rates lower than the maximum obtainable (50 mm/hr), while all the sites at location 8 showed the

Location No.	Soil type	Vegatative cover	Infiltration rates Arithmetic mean and standard deviation (mm/hr)		
			Initial rates	Final rates	Mean
1	Brown Earth	Grassland	49.6±0.5	44.1±4.4	44.3±3.6
7			49.4±0.3	13.5±4.4	18.7±3.4
2		Heatherland	42.7±7.1	11.4±2.6	14.8±4.3
4			43.7±6.6	14.1±4.9	16.7±4.9
3		Burntland	36.2±9.4	17.3±5.5	18.1±5.5
6			47.0±4.6	10.5±5.7	15.1±4.9
5		Bracken	48.0±5.1	40.4±11.8	40.8±11.8
8			50.0±0.0	30.1±5.6	37.4±4.1
9	Peat	Grassland	44.8±4.9	15.3±7.8	23.9±7.8

Table 35. Mean infiltration rates of both runs in the nine selected locations

maximum infiltration rate. In the rest of the locations in the brown soil and peat soil, some infiltration sites showed the maximum infiltration rate during the first five minutes and some lower (Appendix 1, Table 45). The lower initial infiltration rate (19.6 mm/hr) was observed in location 3. Generally, an inter-location variability of the initial rates was observed. The tendency was for lower than maximum obtainable initial rates to occur in burnt-over land, heather and grassland. In burnt-over land and in heather, eleven out of sixteen infiltration sites showed an infiltration rate that was lower than the maximum obtainable and for the grassland the proportion was fourteen out of twenty-six (including location 9). However, bracken locations showed higher initial rates, with only two out of sixteen sites having less than maximum values.

As far as final infiltration rates are concerned, they ranged from 10.5 ± 5.7 mm/hr (location 6 - burnt-over land) to 44.4 ± 4.4 mm/hr (location 1 - grassland). Location 9 showed a final rate of 15.3 ± 7.8 mm/hr, but as mentioned earlier, this rate was calculated from 10 hourly measurements and it would have been lower had the measurement period been two hours. In some infiltration sites the final rate was very low. In two sites at location 6, for example, it was 1 and 2 mm/hr (Appendix 1, Table 46). However, in other sites the rate remained constant for two hours and the final rate equalled the initial maximum rate (50 mm/hr) as, for example, two sites in location 5. The same inter-location variability in the initial rates was observed also in the final rates. In most of the locations individual rates ranged from 10 to 15 mm/hr. However, locations

1, 5 and 8 showed very distinctive higher final rates than the other locations. Specifically, they showed 44.1 ± 4.4 mm/hr, 40.4 ± 11.8 mm/hr, and 30.1 ± 5.6 mm/hr respectively. Location 1 was grassland and the other two were bracken-covered.

Referring again to the mean rates in Table 35, it can be seen that they ranged from 14.8 ± 4.3 mm/hr (location 2) to 44.3 ± 3.6 mm/hr (location 1). They were higher than the final rates and the difference ranged from 0.2 mm/hr (location 1) to 8.6 mm/hr (location 9). The large difference in the peat soil location was attributed to two reasons. The first is the fact that the decrease of infiltration rate with time was smoother in the peat soil than the brown soil. The second is that the mean rate was calculated from measurements lasting for one and not two hours as in the other locations.

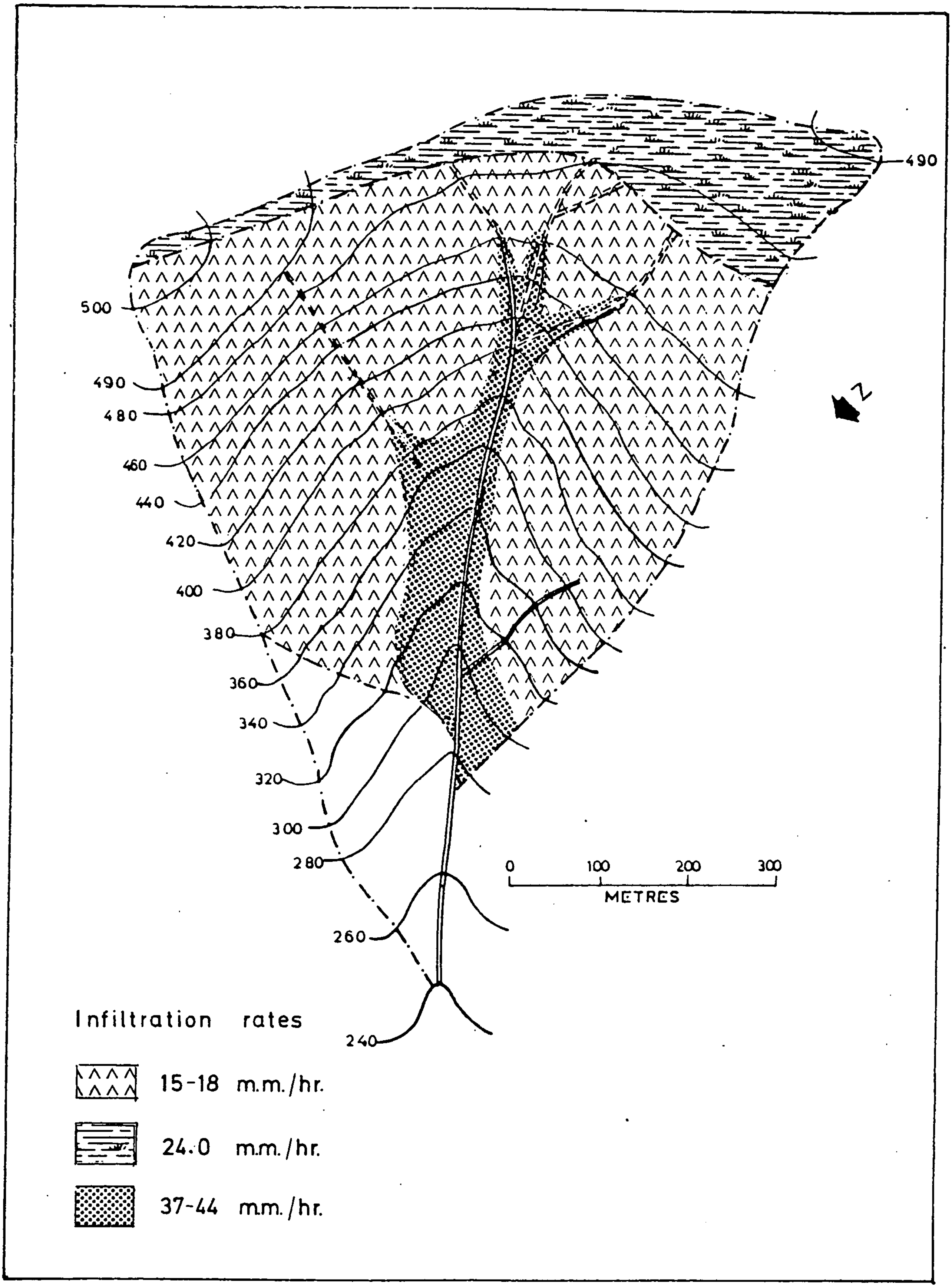
In locations 1, 5 and 8 the final rates showed high mean rates compared to the other locations. Examining the mean rates in pairs of locations having the same vegetative cover and soil type, it can be seen that the four locations (2, 3, 4 and 6) in heatherland and burnt-over land had mean infiltration rates from approximately 15 to 18 mm/hr. Location 7 showed a mean rate of 19 mm/hr, while the remaining locations (1, 5 and 8) had mean rates between 37 and 44 mm/hr. So, locations having the same vegetative cover and soil type had different mean values. The only common characteristic that the three locations (1, 5 and 8) had, was that they were all a short distance from the stream channel. None was situated further than 15 metres from the stream. So, a possible explanation for the higher mean rates could be a difference in the soil, as for example, in its depth and structure. These differences, as mentioned earlier, may have been due to the accumulation of soil from the upper parts sloping to the lower parts along the stream channel. As a result of this movement, the soil along the edge of the stream channel was deeper and well-vegetated and so infiltration rates would be expected to be higher.

Location 9 also showed high mean infiltration rates (23.9 ± 7.8 mm/hr) in comparison with the other five locations placed on the slopes of the catchment. However, this rate might have been lower if measurements had lasted for two hours instead of one. This view is corroborated by the fact that in the opened pit of the peat soil it was observed that the wetting front moved and did not reach the B horizon during the one hour period of measurement. In the two other measurements in this location, which this time lasted for two hours, the wetting front reached the B horizon in approximately 100 minutes. After this time, the infiltration rate decreased quickly and its final rate reached 2 mm/hr and 8.2 mm/hr, respectively. The fact that these rates in the peat soil were calculated when the soil was dry (API 2 and 1) is worthy of note. This is because the infiltration rates might have been much lower if the soil had been wet. This view is supported by visual observations during rain events when the author was present in the catchment and saw widespread patches of water lying on the ground surface of the peat soil.

The mean infiltration rates calculated for the catchment were grouped into three categories and are presented in Map 10. The first category includes locations having mean infiltration rates from 15 to 18 mm/hr. The third includes locations having mean rates from 37 to 44 mm/hr. This is composed of those locations along the edge of the stream channel. To identify the soil boundaries of this category, the whole area along the stream channel was examined carefully and the boundaries were placed where soil accumulation was clear. It was discovered that the same soil conditions occurred higher up the slope than locations 1, 5 and 8 and so the boundaries were expanded as shown. The second category occupied the peat soil of the catchment.

4.4.2 Rainfall Intensities and Comparison with the Infiltration Rates

In sections 4.3.1 and 4.3.2 it was suggested that the observed amounts of litter flow could not have occurred due to rainfall intensities being higher than the infiltration rates of the soil, except on rare occasions. However this suggestion was made from a specific number of rain events and conditions may have been different if rainfall intensities over a longer period had been analysed. For this reason all the rainfall intensities occurring in the study area during the two field seasons were computed and presented in Table 36. The minimum computed duration of rain events was half an hour, as shorter durations were difficult to identify on the charts.



Map 10. Computed infiltration rates in the various segments of the study area.

Intensity of rainfall (mm/hr)	Duration of rainfall (hours)																		
mm	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
0.3-0.4	1		2	3	1	3	1	3	2	1	1			3	2				
0.5-0.6			1	2	1	1	4	1		3			1			1		1	
0.7-0,8	1	3	5	4	1		1	3	1			1			1			1	
0.9-1.0	10	4	2	1			2				1								
1.1-1.2	4	5	1	1	2	1			1	1	1					1			1
1.3-1.4	4	4	2		3	1	1	3				1	1					1	
1.5-1.6	1	3	3		1	2		2			1				1				
1.7-1.8	2	1	1	2		3			2		2	1							
1.9-2.0	3	2	3	2	2		2	3	1	1									
2.1-2.2	4	1	2	3	2	1	1	1											
2.3-2.4	3	2	2	2	1	1		1											
2.5-2.6				1	1	1													
2.7-2.8	6		2			1													
2.9-3.0	7	1	2	1		1													
3.3	3		1			1													
3.7	2																		
3.9-4.0	2	1	1		2	1													
4.1-4.2	1		2				1												
4.3-4.4	1																		
4.5-4.6	2		1	1															
4.7-4.8	1			1															
5.2-5.3	1		1																
5.4-5.7		1	1																
6.0	1		1																
6.7-6.9	2		1																
7.2-7.3	3																		
7.4-7.8	1		2																
8-8.5	1		1																
8.9-9.0	2																		
11.0	1																		
14	1																		

Table 36. Rainfall recorded in the study area - May-October - (1981-82 mm) cross-classified according to duration and intensity of fall. Numbers in cells are the total numbers of events in each class

The intensities ranged from 0.3 to 14 mm/hr but it was possible that higher intensities of shorter duration did occur in the catchment during the two field seasons. For example, on 11th October 1982, when the author was present in the catchment, it rained for 10 minutes with an intensity of 25 mm/hr and this intensity could not be detected from the charts. From the Table it is apparent that in only a few rain events was the intensity higher than 4 mm/hr. Most rain events had intensities between 1 and 3 mm/hr and their durations ranged from 0.5 to 4.0 hours. Comparison of these intensities with the computed infiltration rates indicates that only on rare occasions could litter flow possibly occur due to rainfall intensity being higher than the infiltration capacity, or possibly from very short duration rainfalls with high intensities.

In addition to the rainfall intensities for the two field seasons, the two-day rainfall intensities with a return period of once in five years have been calculated and are depicted in Table 37. The intensities are calculated from the two-day [illegible] rainfall [illegible] once in 5 years [illegible] and the ratio of 60 minute M_5/2 day M_5 rainfall. The first factor for the study area was found to be 75 mm of rain and the second factor 21.[illegible] (Institute of Hydrology, Flood Studies Reports, NERC, 1975). The intensities are calculated from 1 minute up to 48 hours. It is clear from the figures presented that rainfall of high intensity is of short duration. Specifically, rainfall lasting for 1, 2 and 5 minutes has intensities of 96, 78 and 56.4 mm/hr, respectively, and

Duration of rain	Amounts of Rainfall (mm)	Intensity (mm/hr)
1 minute	1.6	96.0
2 minutes	2.6	78.0
5 minutes	4.7	56.4
10 minutes	6.9	41.4
15 minutes	8.4	33.6
30 minutes	11.6	23.0
60 minutes	16	16.0
2 hours	21	10.5
4 hours	28.5	7.1
6 hours	34	5.6
12 hours	45	3.7
24 hours	60	2.5
48 hours	79.5	1.6

Table 37. Two-day rainfall intensities with a return period of once in five years for the study catchment.

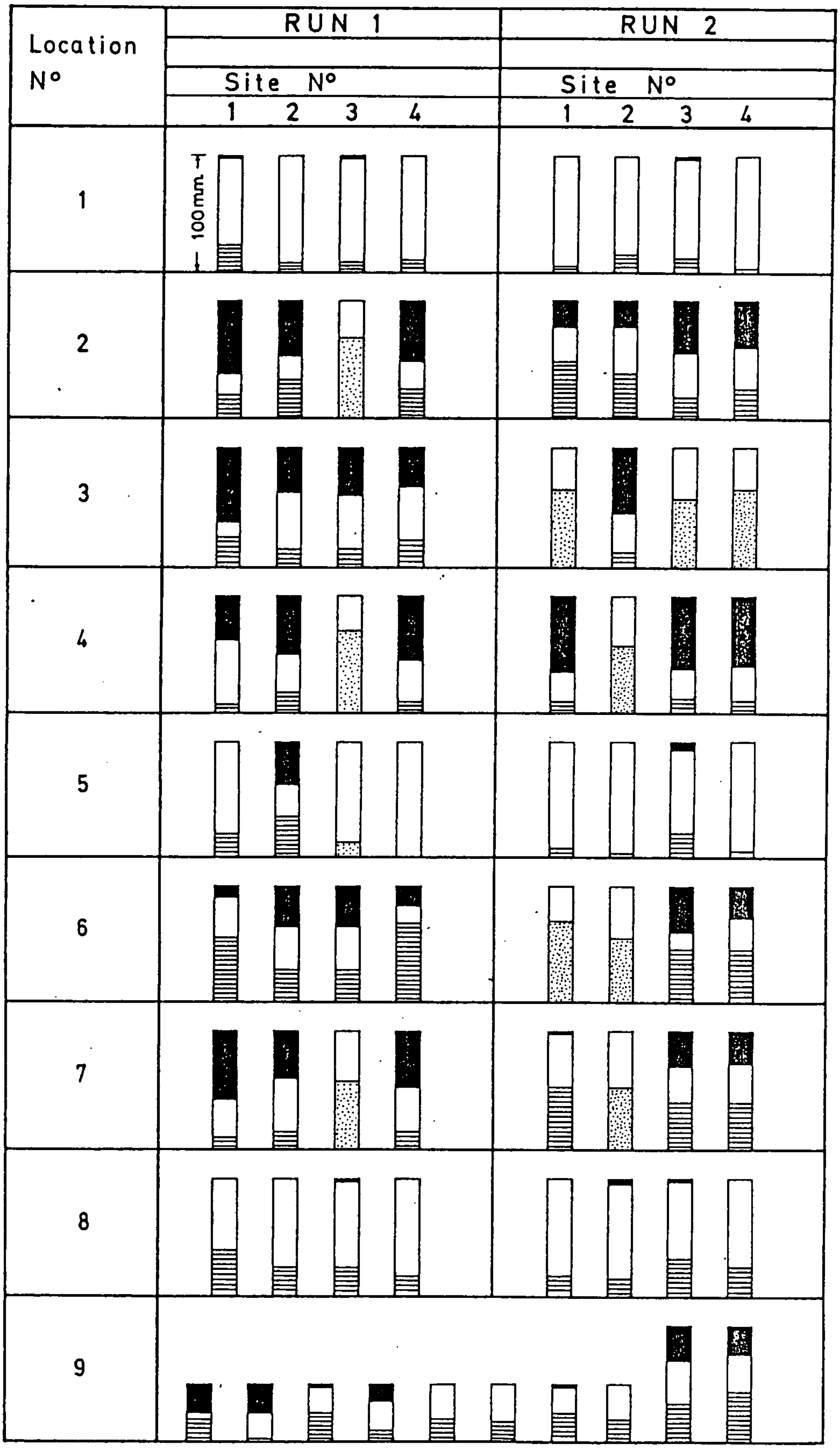
rainfall with a duration from 10 minutes to 2 hours has intensities ranging from 41.4 to 10.5 mm/hr. After the 2 hour duration the intensity drops further to 1.6 mm/hr for rainfall lasting 48 hours.

Comparing Table 37 with Table 35, the following points become clear. The intensity of short duration rain events exceeds not only mean and final infiltration rates, but the initial rate as well. Specifically, rain intensities lasting up to 5 minutes exceed all initial rates measured and intensities of rain lasting up to 30 minutes exceed most final and mean rates. Intensities of rain lasting for one hour are equal to or less or higher than, the final and mean rates. Finally, intensities of rain lasting more than two hours are lower even than final infiltration rates. Hence, it can be concluded from these comparisons that there are occasions when litter flow could occur in the catchment as a result of rainfall intensities being higher than infiltration rates. In accordance with the computed infiltration rates, litter flow can occur in both soil types and in every type of vegetative cover of the catchment (by the above method).

The question that arises after this conclusion is how important is such occurrence of litter flow. Before answering this question, two points were considered. The first was the return period of the rain having these calculated intensities and the second was its short duration. This is because the return period was long and the duration, mainly of those rain events having high intensities, was very short. So, the amount of water falling in, for example, 1, 2, 5 or 10 minutes was very small despite the high intensity. Also, this amount would become smaller after the subtraction of an amount to allow for interception in cases where the vegetation cover was dry. Furthermore, it is doubtful if any amount of litter flow generated from short duration and high intensity rain would reach the stream channel. This is due to the variability that was found in infiltration rates, even in small areas of the catchment. Taking these facts into account, the occurrence of litter flow due to rain events having the above characteristics seemed not to be important for the study area.

4.4.3 Observed Litter Flows and Throughflows in the Infiltration Locations

As was explained in section 3.2.2.2.4, the portion of water applied to each infiltration site that flowed through the litter layer and the A horizon was collected and measured using a simple guttering system. Hence the collected amounts can give information on the lateral movement of water in more locations than those examined in the various plots with natural rainfall. The results from this work are presented in Figure 18. The height of each column represents 100 mm of artificial rainfall that was applied to the site over two hours and the separation of it into the various components is shown in the same Figure. This shows that the smallest amount of lateral flow occurred at locations 1, 5 and 8. This was to be expected because these locations had shown the highest infiltration rates. The amount of lateral flow occurring at the other locations was dependent on the computed infiltration rate in each location. Efforts



a Litter flow
b Flow through the A horizon
c No separation into a and b
d Infiltrated artificial rainfall

Figure 18. Diagram showing the separation of the amount of artificial rainfall in each site in various components.

to determine litter flow and throughflow from each infiltration site separately failed because in 10 infiltration sites out of the total of 74 (Figure 18) it proved impossible to fix up a gutter system for litter flow collection. So, in these sites, it was not possible to say whether or not litter flow occurred. The lateral flows occurring in these sites were collected from one gutter fixed at the base of the A horizon. Therefore it was thought convenient to present litter flows and throughflows from all sites together. These data are shown in Table 38.

This shows the amount of litter flow and flow through the A horizon, like Figure 18, but in mm of artificial rainfall. These amounts, as was expected from the values of the infiltration rates presented in section 4.5.1 have indicated a large variability from one location to another and from one site to another in the same location. Variability was also observed between the amount of litter flow and throughflow in the same site.

In addition to the data presented, the hydrographs generated at each infiltration site were also drawn. Figure 19 illustrates the hydrographs of both runs in location 1. They are presented separately for each run for convenience of reading the curves. Otherwise, they would have been drawn together as in the case of infiltration rates (section 4.5.1). This Figure shows that at the various sites the first flows emerged within 5 to 20 minutes from the start of water application and the rate rose gradually for approximately 50 to 60 minutes until it reached a maximum value. This maximum value in the eight sites at

No. of location	RUN 1				RUN 2			
	Litterflow (L) and throughflow (TH) in mm				Litterflow (L) and throughflow (TH) in mm			
	No. of Site				No. of Site			
	1	2	3	4	1	2	3	4
	L+TH (mm)	L+TH	L+TH	L+TH	L+TH	L+TH	L+TH	L+TH
1	24.7	7.2	8.8	11.2	4.6	16.9	16.0	3.8
2	83.0	80.3	68.9	75.6	72.4	60.3	62.7	62.1
3	86.9	54.3	56.6	56.5	68.9	66.6	56.3	65.3
4	45.2	64.9	72.3	65.3	74.2	64.6	75.0	72.7
5	19.4	73.2	11.4	0	7.3	4.3	26.8	7.2
6	67.1	61.4	61.9	85.3	70.5	58.2	82.6	73.6
7	67.2	55.2	58.1	63.4	55.3	58.1	70.4	67.9
8	40.0	24.7	27.6	17.1	18.0	17.8	34.1	24.9

No. of location	RUN 1								RUN 2	
	1	2	3	4	5	6	7	8	1	2
	L+TH	L+TH	L+TH	L+TH	L+TH	L+TH	L+TH	L+TH	L+TH	L+TH
9	45.3	27.0	27.5	25.1	19.2	17.4	27.6	20.7	63.3	69.3

Table 38. Litterflow and throughflow emerging from each infiltration site

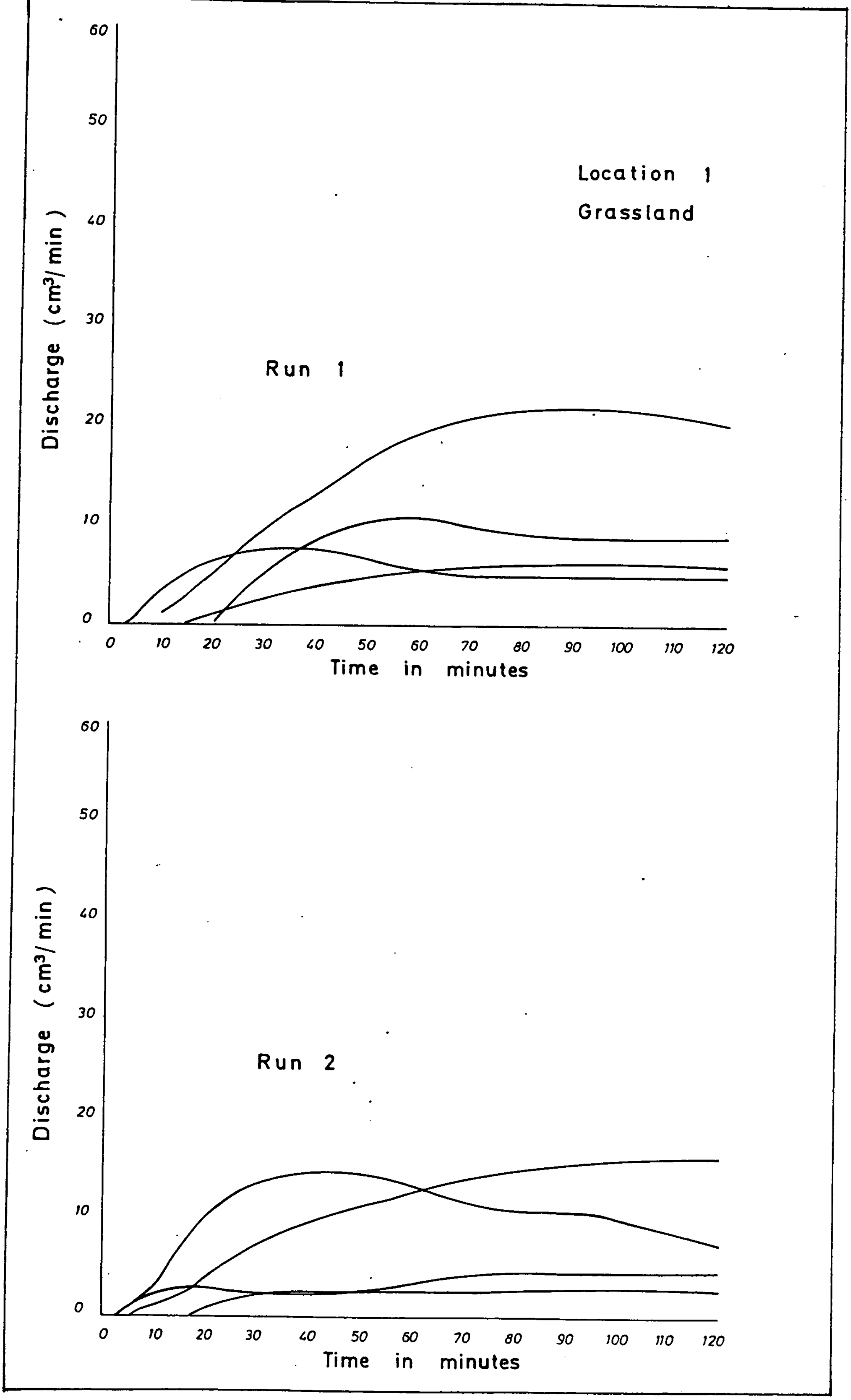


Figure 19. Hydrographs generated from artificial rainfall in each site in location 1.

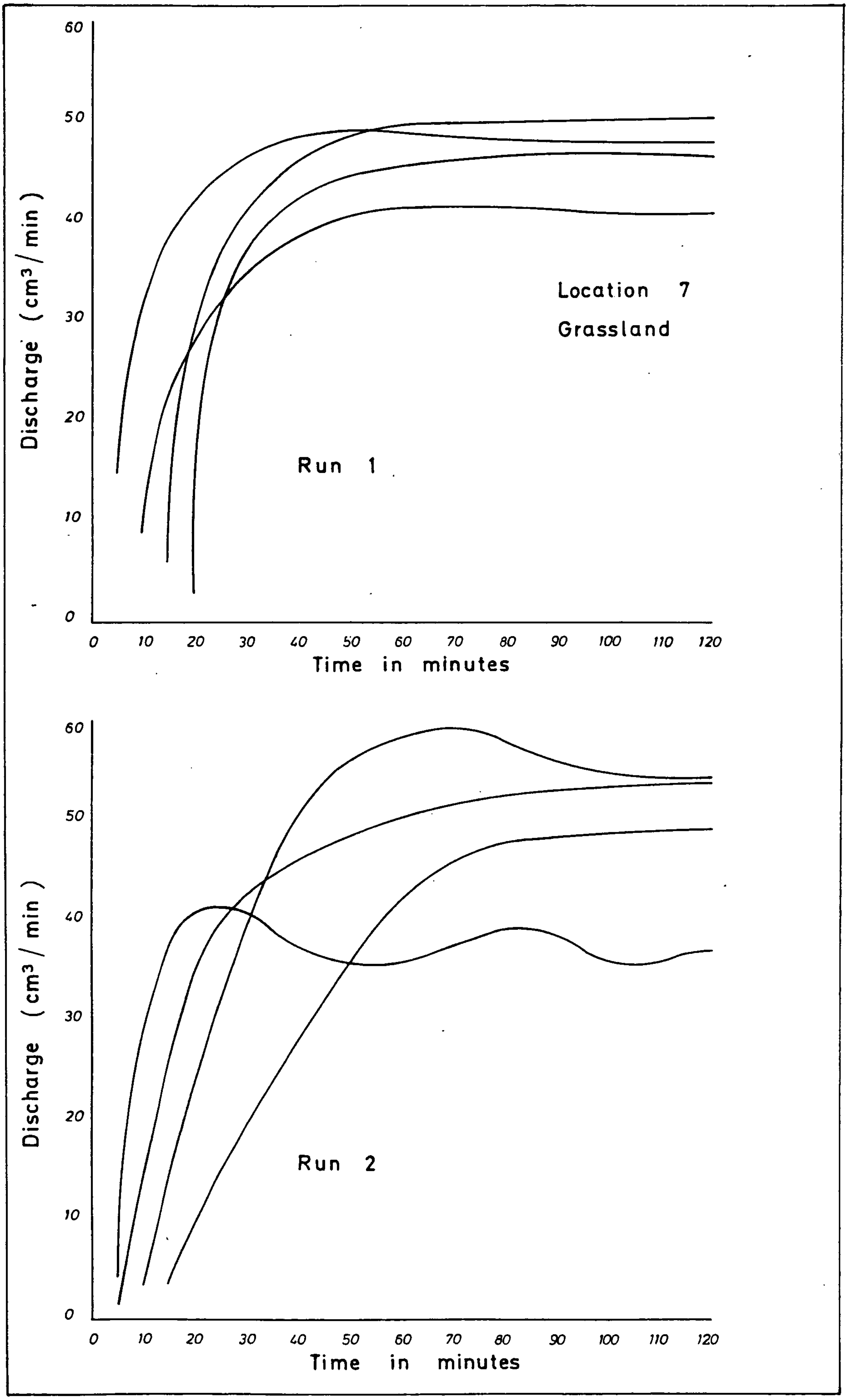


Figure 20. Hydrographs generated from artificial rainfall in each site in location 7.

location 1 ranged from 6-22 cm^3/minute and remained practically constant until the end of the second hour in most of the sites. During the planning of the experiments it was thought that locations having the same soil type and vegetative cover might respond similarly to rainfall. However, as was indicated with the computed infiltration rates in the previous section, locations with the same soil type and vegetative cover responded differently. Consequently the amount of flows that emerged were different as Figure 19 shows. As the data for location 7 show (Fig. 20) the hydrographs are also different. The first flows emerged from the various sites of this location, as in location 1, within 5 to 20 minutes of the start of water application. However, the rate of increase was higher and reached the maximum value in approximately one hour. This value ranged from approximately 35 to 52 cm^3/minute at the eight sites and remained practically constant until the end of the operation at most sites. Similar graphs have been drawn for each of the other seven locations and they are shown in Appendix 2 .

Having to deal with nine locations, each having eight sites (except location 9), it was felt convenient and reasonable to compute the median curve for each location and to present them together. They are illustrated in Figure 21. This shows a distinct separation of locations into two main groups with different responses to artificial rainfall. In three locations (1, 5 and 8) the first flows emerged within 5-25 minutes of the start of water application. The rate of increase was small in the first hour and

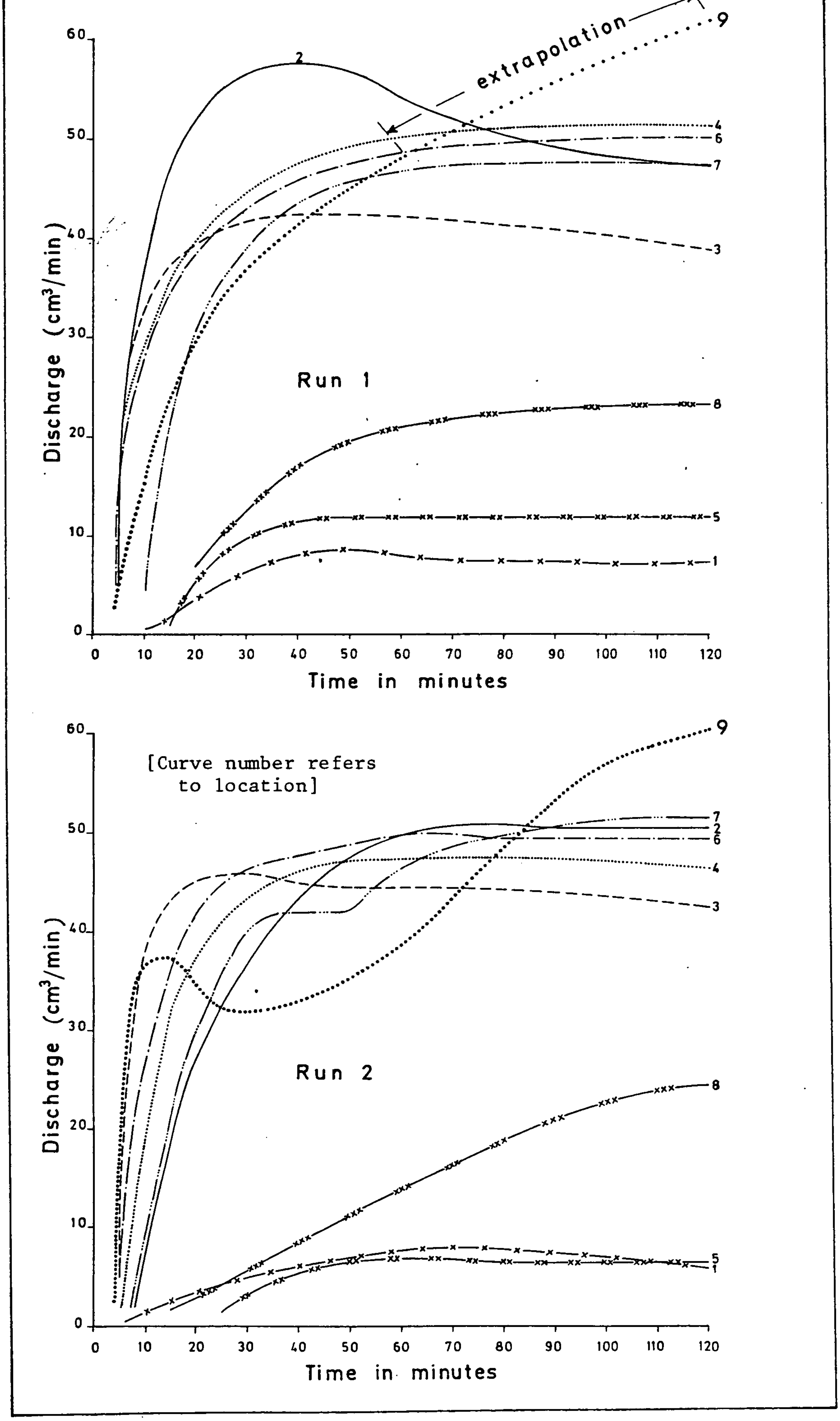


Figure 21. Median throughflow curves of the nine locations.

became practically constant at the beginning of the second hour. In two of the three locations in this group the maximum rate ranged from 5-10 cm^3/minute, while in the third it ranged from 20-25 cm^3/minute. If we take into account that the rate of application of artificial rainfall was 65 cm^3/minute, then, during the second hour the seepage from locations 1 and 5 ranged from 8-15% and from location 8 from 31-38% of the application rate.

Locations 2, 3, 4, 6, 7 and 9 make up the second group. The median curve of location 9 in Figure 21, A, is calculated only for the first hour and so the response of the eight sites during the second hour is unknown. Despite this, some information about this response is given in Figure 21, B, because the two measurements of run 2 lasted for two hours. These two sites, as becomes apparent from Figure 21, responded differently during the second hour from the sites at the other locations. If the measurements in the eight sites at location 9 had lasted two hours it is possible that they would have had the shape of the extrapolated curve No. 9 (Figure 21, A). Hence, location 9 could constitute a subgroup of this second group with a high rate of seepage during the second hour as the main characteristic. This rate, at the end of the second hour, was almost equal to the rate of application. In all locations in the second group (including location 9) the first flows emerged within 5 to 10 minutes of the start of water application. However, the rate of increase, in comparison with the first group, was higher and became constant ∿ at the beginning of the second hour. This rate was 50 and 45 cm^3/minute. Hence, 69%

and 77% of the applied artificial rainfall flowed through the litter layer and the A horizon during the second hour.

From these results it becomes apparent that the whole area of the catchment can be divided into three sections in terms of its response to artificial rainfall. The three sections have also been identified from the infiltration rates presented previously (Map 10). The first section embraces the area around the stream channel. Most of the applied water in this section, regardless of vegetative cover, moved deeper than the A horizon. However, whether it flowed vertically or laterally in the deeper soil horizons, or if it was absorbed by the soil, cannot be answered. The second section covers the slopes of the catchment occupied by brown earth soil. In this section, regardless of vegetative cover, most of the applied water flowed through the litter layer and the A horizon of the soil, mainly during the second hour of application. Finally, section three covers the peat soil area of the catchment. The location chosen in this section indicated that a large amount of the applied water was absorbed at the beginning by the peat soil, and later, when it possibly became saturated, the rate of seepage increased rapidly and at the end of the second hour it was almost equal to the rate of application.

The results presented here are in general agreement with those obtained from natural rainfall occurring in the brown earth and peat soil sections of the catchment. For the section of the catchment along the stream channel, there were, unfortunately, no data obtained from natural rainfall. But there is no reason to argue that if a plot had been operated in this section under natural rainfall, the results would have been different from those obtained from artificial rainfall. The presented data of this section and of the previous one tend to support that the area falls into three sections, each with quite distinctive response characteristics.

4.4.4 Application of Artificial Rainfall in the Runoff Plots

In addition to the work discussed in the previous section, artificial rainfall experiments were also undertaken using the runoff plots to supplement the data collected from them as a result of natural rain events. But before presenting any detailed analysis of the results, two things must be kept in mind. Firstly, flows were not collected in all the plots from the same soil horizons. The reasons for this inconvenience were explained earlier (see section 3.3.3). Secondly, in plot 3 the duration of the artificial rainfall was 2, and not 3 hours, as in the other plots. The reason for this shorter duration was also explained earlier (see section 3.3.4). These constraints, to some extent, necessitate separate analysis and explanation of the results obtained.

The flows from the plots and the soil hydrographs generated are shown in Table 39 and Figure 22, respectively. These show that flows emerged from all soil horizons in plot 1 and continued for 40 minutes after the application of artificial rainfall had ceased. The total outflow reached 73% (11 cm) of the amount applied and was not

Plot No.	API (mm)	Storm duration (min.)	Storm intensity (mm/hr)	Rain depth (cm)	Flow depth (cm)	Flow as percent of rain depth	Depth (cm) and percent of total flow by soil depth							
							Litter layer		A horizon		B horizon		C horizon	
							cm	%	cm	%	cm	%	cm	%
1	19	180	50	15	11	73	No gutter		7	64	3.3	30	0.7	6
2	14	180	50	15	8.4	56	1.6	19	5.8	69	1	12	No gutter	
3	7	120	50	10	2.2	22	0.5	23	1.7	77 *	No gutter		No gutter	
4	6	180	50	15	6.1	41	Litterflow and flow through the A horizon were not measured separately							

* Upper 20 cms

Table 39. Flows emerging from the rectangular plots from artificial rainfall

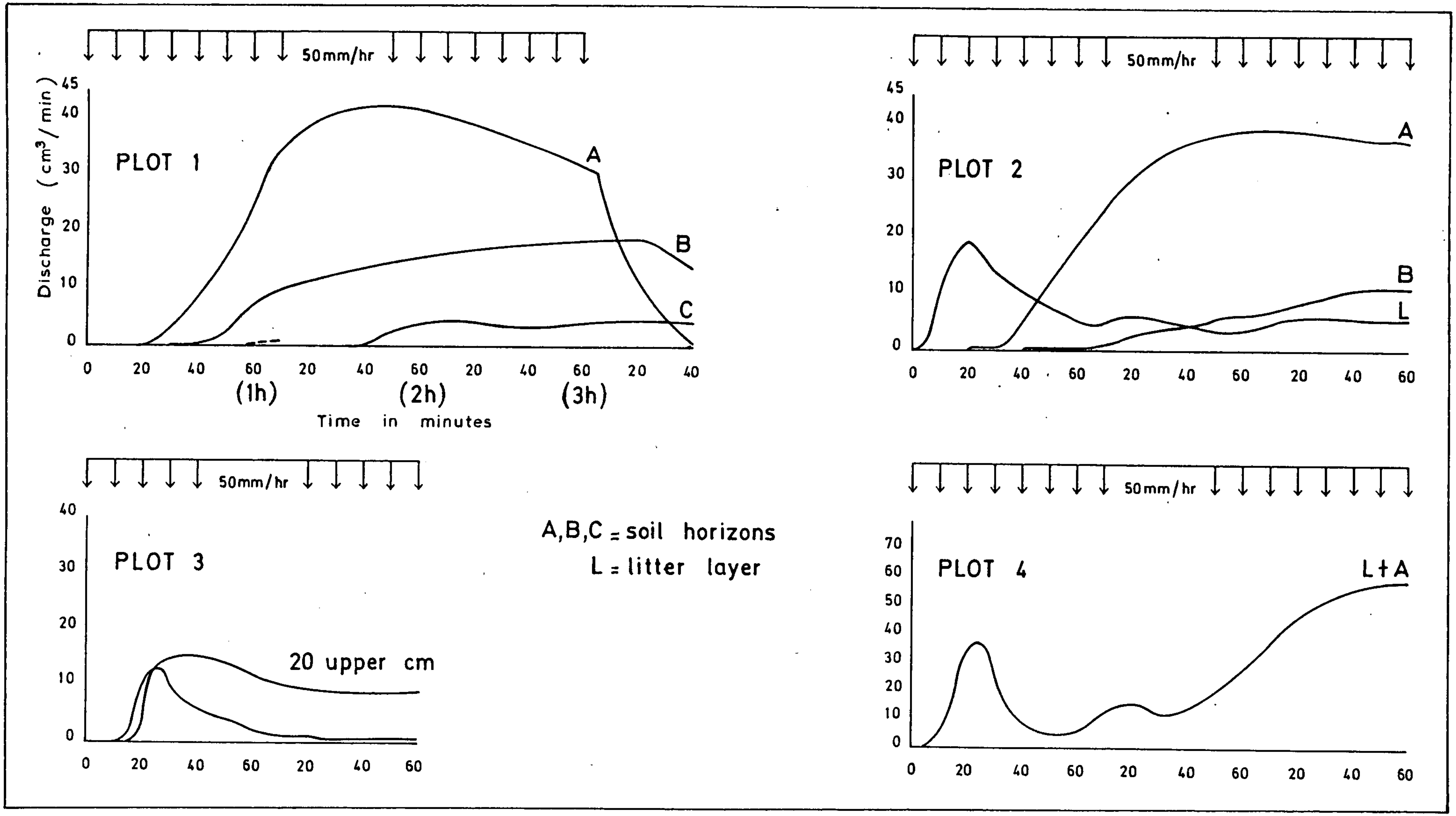


Figure 22. Generated hydrographs in the rectangular plots from artificial rainfall.

distributed uniformly in the three horizons. Of the total outflow, 64% seeped from the A horizon, 30% from the B horizon, and 6% from the C horizon. In addition to the variation observed in the amount of flow seeping from each horizon, the Tq of the three horizons varied. For the A and B horizons this parameter had a value of 20 and 25 minutes respectively. For the C horizon it is not clear whether the value for Tq was 50 or 95 minutes, as some water emerged between 50 and 70 minutes (Figure 22), then it stopped for 25 minutes and then started again. The water emerging between 50 and 70 minutes is difficult to explain. It may have been a true flow from the C horizon, or it may have been a leakage from the A and/or B horizon. The rate of flow from the A horizon increased faster than that of the B and C horizons and in approximately 80 minutes it reached its maximum rate of 40-42 cm^3/min. This rate remained almost constant for 20 minutes and then started decreasing slowly. Contrary to the rate for the A horizon, the rates for the B and C horizons increased slowly. They reached maximum values of 18 and 4 cm^3/min., respectively, at the end of the third hour when the application of water ceased. Forty minutes after cessation of the water the final rates of A, B and C horizons were almost zero, 14 and 4 cm^3/min., respectively.

Plot 2 yielded large amounts of flow as well. From the total applied water, 56% (8.4 cm) seeped from the litter layer and the two upper horizons. This amount was 5% less than that emerging from plot 1 during a similar period. However, its distribution between the three soil zones was different, with 19 and 12% emerging from the litter layer and the B horizon respectively. Adding the flows of plot 2 that were collected from the litter layer and the A horizon, we see that the flows in the second plot are larger by 15%. For plot 2 the Tq of the flows from the A and B horizons were 15 and 40 minutes, while the Tq for the litter flow was less than 5 minutes as 12 cm^3 of water collected in the first five minutes. The rate of litter flow increased rapidly and peaked after 20 minutes (peak rate 19 cm^3/min.). After this time the rate decreased gradually and after 40 minutes it was 5 cm^3/min. This rate of litter flow remained practically constant until the flow measurements stopped.

Plot 3, in contrast to the previous plots, yielded small flows. Of the total water applied only 22% (2.2 cm) emerged from the litter layer and upper 20 cm of the soil. Of this amount 23% was litter flow and the rest throughflow. The small amount of seepage may have been the result of the stony conditions of the soil in this plot (see 3.3.3). Both litter flow and throughflow had the same Tq value (15 minutes) and they both continued to rise for the next 10-15 minutes until they reached their maximum rates of 13 and 15 cm^3/min. respectively. After this the rates of both decreased gradually and in one hour became 1 and 9 cm^3/min. respectively. These rates remained constant until measurement stopped.

Finally, in plot 4, 41% of the water applied seeped from the A horizon, possibly with the addition of seepage from the litter layer. The Tq was nearly 5 minutes and the rate reached a value of 38 cm^3/min. within half an hour. It then decreased gradually to 5 cm^3/min. and then rose again until it reached a value of 60 cm^3/min. at the end of the third hour. The downward movement of the wetting front in this plot was distinctive. It was observed that the infiltrated water, covering two zones 10-15 cm wide each side of the infiltrometer, reached the B horizon approximately two hours from the beginning of water application. After that time the seepage rate increased rapidly and reached the above-mentioned value of 60 cm^3/min. This high rate of seepage from the A horizon (or possibly A horizon + litter layer) at the end of the third hour was a distinctive characteristic of this plot not observed in the others. However, despite this high rate, the total flow from this plot in the three hours was smaller than that which emerged from plots 1 and 2, and not larger, as it was in the results obtained from natural rainfall. An explanation for this difference seemed to be the absorption of a large amount of water by the soil due to drier conditions and greater depth than the other plots.

The results presented above are in general agreement with those obtained from natural rainfall. They show that large quantities of applied water flowed from the various soil horizons. The quantities ranged in the three plots from 41% to 73% of the applied water. Plot 3 responded differently, as only 22% of the applied water flowed from the guttered soil segment. In plot 4, constructed in the peat soil, the rate of seepage was very high during the last few minutes of application. The rate almost reached the rate of water application. Such a high rate of seepage was observed in plot 1 during the third hour, but in that case the water was flowing from all three horizons together. The amount of seepage in the various soil horizons was different, but in all the plots most of it emerged from the A horizon or the upper parts of the soil (e.g. plot 3). From the B horizon of plots 1 and 2, the flow was less than that from the A horizon. A smaller amount of water emerged from the C horizon, as data from plot 1 have indicated.

The results presented so far were obtained from the plots under relatively dry soil conditions. Artificial rainfall under wet soil conditions was applied only in plot 2. The amount of flow from each horizon of plot 2 under such conditions is presented in Table 40. In the same table the flows that were collected from this plot under dry soil conditions are also presented for comparison. Also, the hydrographs generated from this plot under dry and wet soil conditons are illustrated in Figure 23. Table 40 shows that of the water applied in this plot under wet conditions, 70% emerged from the soil above the B horizon. So, the flow under wet conditions was 14% higher than that under dry conditions. Of this flow, 66% came from the A horizon, 11% from the litter layer and 23% from the B horizon. In the second case (wet soil conditions), the distribution of flows in the three soil segments was also different. In fact the flow from the litter layer was 8% lower, from the A horizon 3% lower and from the B horizon 11% higher than in the first case. Between the two appli-

API (mm)	Storm duration (mm)	Storm intensity (mm/hr)	Rain depth (cm)	Flow depth (cm)	Flow as percent of rain depth	Depth (cm) and percent of total flow by soil depth					
						Litter layer		A horizon		B horizon	
						cm	%	cm	%	cm	%
14	180	50	15	8.4	56	1.6	19	5.8	69	1	12
36	180	50	15	10.4	70	1.1	11	6.9	66	2.4	23

Table 40: Observed flows in plot 2 from artificial rainfall under dry and wet soil conditions

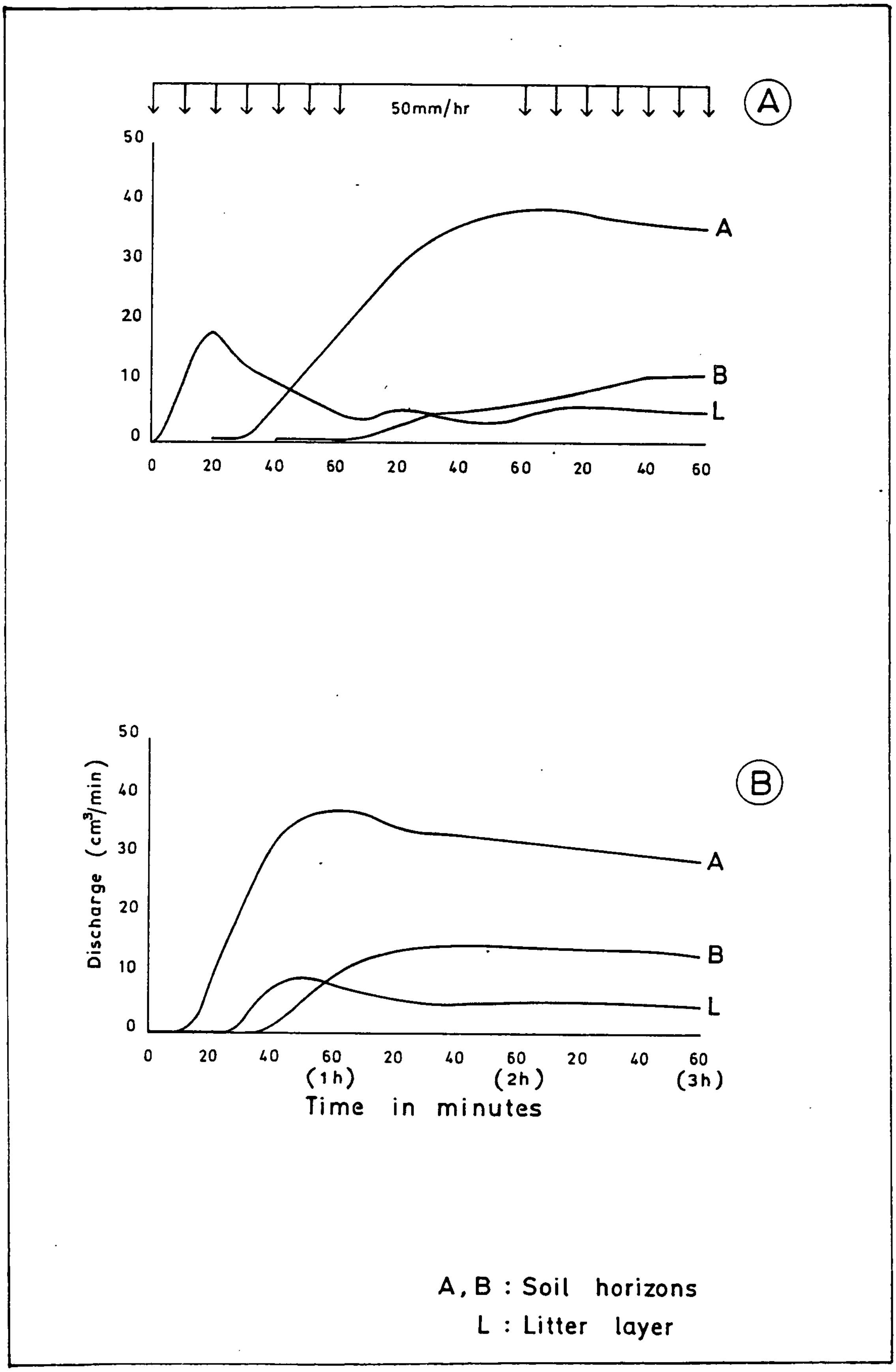


Figure 23. Generated hydrographs in plot 2 from artificial rainfall under dry (A) and wet (B) soil conditions.

cations, all factors remained the same except for antecedent soil conditions. The API was, in the first case, 14 mm and in the second 36 mm. In addition to the observed differences in flows under wet and dry soil conditions, the value of Tq was also different. In the first case the order of appearance of seepages was litter flow, then A horizon flow and finally, B horizon flow. A large difference was observed in the Tq value of litter flow as it was 5 minutes in the first case and 30 minutes in the second case. The Tq of flows from the A and B horizons in the second case was 20 and 5 minutes shorter, respectively.

4.4.5 Discussion

The application of artificial rainfall in selected locations of the catchment indicates that even the final infiltration rates of the soils were higher than the usual intensities of the rainfall in the study area. Furthermore, lateral movement of water through the litter layer and the other soil horizons was observed and the amount of it decreased from upper to lower soil segments. Finally, the infiltration sites responded rapidly to artificial rainfall and this response was attributed to water moving through biological and structural voids rather than the soil matrix.

The lateral flows, as is known, were collected by a gutter system which was dug into the soil. This technique for correcting the infiltration rates may be criticised because the soil was distorted to some degree. In such a criticism the following must be considered:

a) Lateral flow of water away from the infiltration site through the soil may be a source of considerable error (Marshall et al., 1950; Parr et al., 1960; Hills, 1970). So, if a worker is interested in vertical infiltration, it is vital to consider the effect of lateral flow (Hills, 1971). In this study, as was explained earlier, it was decided that vertical infiltration would be measured and consequently the amount of water that may have flowed laterally had to be estimated.

b) There was a lack of objective criteria for the various techniques used by previous workers to prevent lateral movement of the infiltrated water or to estimate the amount of water that moved laterally and so they were not better than those used in the present study. Some workers, for example, used a buffer zone around the infiltrometer (Burgy et al., 1956, 1957; Schiff, 1953; Marshall et al., 1950). Others applied a graphical correction procedure (Hills, 1971) or corrected the infiltration rates by applying a relationship obtained from simulated soil (Tricker, 1978). These techniques, as they had claimed, were not more accurate than techniques used previously, but they were simple to operate in specific conditions. So, as the present guttering system was found to be convenient in the rugged terrain of the catchment,. it was used for the correction of infiltration rates.

Another point that may be open to question is the number of measurements that were included in each run. Statistically, they may be criticised as not being enough to compute the arithmetic mean of the infiltration rate in each location. This disadvantage, despite the fact that it was recognized during the design of the experiments, could not be overcome because more than four measurements could not be made daily by one person.

The infiltration rates determined may also be criticised because of existence of a soil zone between the infiltration site and the guttering system that did not directly receive artificial rainfall. Some water must have been absorbed by this zone and so the computed infiltration rates may be a little higher than the "real" value. This disadvantage of the guttering system was recognized from the start and was accepted because lateral flows due to topographic and surface conditions could not be estimated any other way. On the other hand, the area of this zone was small (14% of the infiltration site) and so the results cannot have been affected to a large extent.

The infiltration rates for the sites that were tested during the two runs under different antecedent soil moisture conditions, may also be questioned. However, as was explained in the relevant section (4.5.1), the larger difference in infiltration rates did not coincide with the larger difference in antecedent soil moisture conditions (API). So, other factors may have affected the computed rates more than the API. On the other hand, antecedent soil moisture conditions play a part in the early stages of an infiltration application (Tisdall, 1951), while the measurements in the present study had a duration of two hours. So, the effect of antecedent soil moisture conditions may not have played an important role in the mean infiltration values.

Despite the above criticisms it is nevertheless interesting to note that the work in the Hopes Catchment is in broad agreement with studies undertaken by other workers elsewhere using rainfall simulators. But, as literature reveals, there has been a large amount of work carried out on infiltration with various types of rainfall simulator infiltrometer. Details about this work is given by Parr et al., 1950; Hills, 1968; Tricker, 1975 and Boontawee, 1977. So, in this thesis only a sample of the results obtained from other investigators will be considered.

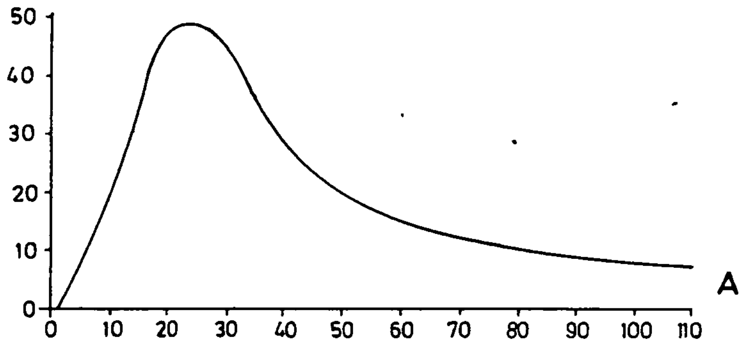
Selby (1970) measured infiltration rates in yellow brown pumice soils in Australia. The area was covered with ungrazed long grass, short pasture and parts of it were bare of vegetation. He found a large variation in the infiltration rates from one trial plot to another. Selby stressed that the most important conclusion to be drawn was that infiltration rates were extremely variable, even when trial plots were very closely spaced. In fact, infiltration rates ranged from 2 to 35 mm/hr in the ungrazed grass areas, from 1 to 10 mm/hr in the short pasture and from 2 to 40 mm/hr in the bare areas. These are individual values and the means must have been lower. Comparing these values with those obtained in the study area (15 to 44 mm/hr, Table 35) it is apparent that the observed difference is a reasonable one, taking into account the environments in which the experiments were carried out. Also, the infiltration rates obtained by Adams et al. (1957) in the USA (Iowa) show reasonable differences when compared with the present study, and considering the different environments in which the measurements were made. Adams et al. worked in silt loam soil and the crop systems were corn-oats-meadow rotation and continuous corn. In the first system the infiltration rate was 18 mm/hr and in the second, 9 mm/hr. Large variations were observed in the mean infiltration rates obtained by Blake et al. (1968) in Australia (Northland). The rates obtained from six sites of one soil type were 41, 33, 24, 36, 74 and 45 mm/hr.

The infiltration rates presented here, as mentioned earlier, are only a sample of the large amount of work done on this hydrologic component. They have indicated that variability of the infiltration rates was observed in plots with the same soil type and vegetative cover. Also, in areas having the same soil type but different vegetative cover variability sometimes occurred and sometimes did not. So, the differences in mean infiltration rates which were observed in some locations of the study area having the same soil type and vegetative cover appears to be the rule and not the exception.

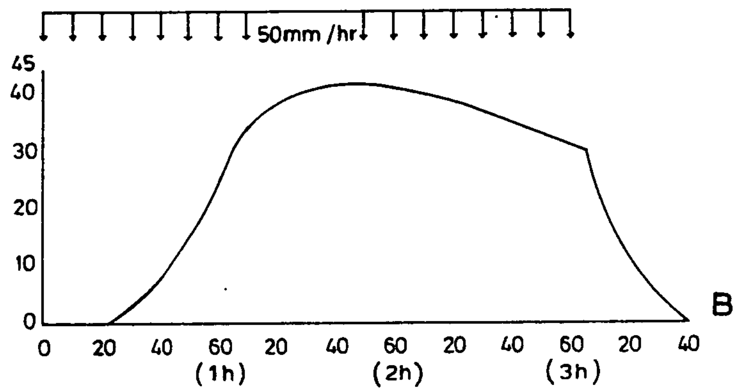
Any comparison with results obtained with cylinder infiltrometers was not regarded as worthwhile for the following reasons: firstly, a great difference was found in the infiltration rates obtained with cylinders and the rainfall simulator infiltrometer in the same locations of the catchment (Table 18). Secondly, a number of investigators (Musgrave et al., 1964; Langford, 1970) pointed out that cylinder infiltrometers are known to give higher values than the rainfall simulator infiltrometer.

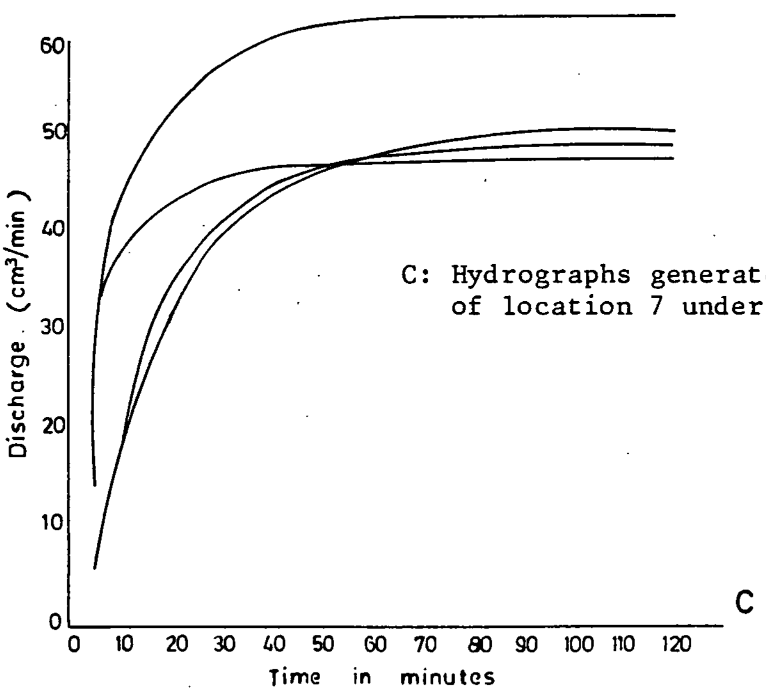
Another point that should be emphasized is the difference in the shape of the hydrographs observed under natural and artificial rainfall conditions. Figure 24 illustrates a number of hydrographs that were generated in the brown earth area of the catchment under both types of rainfall. Hydrographs A and B were generated in plot 1 from natural and artificial rainfall respectively and the flows came from the A horizon. Hydrograph C was generated from four sites in location 7 from artificial rainfall.

It is apparent from this figure that the rising limb is the same, i.e. steep, in all the hydrographs, while the peak and the falling limb differ in shape between hydrographs. In fact, in the hydrographs generated from artificial rainfall the peak forms an almost horizontal crest and the falling limb is steeper than that of natural rainfall. An explanation for this difference can be found if we take into account that the area exposed to artificial rainfall was very small and the intensity of the rainfall was high. So, the soil must have become saturated some time after the beginning of application and after this, the seepage would remain constant. In other words, the sites responded like a completely impermeable area and the hydrograph took the shape of a "parking lot" hydrograph. When the application of artificial rainfall ceased, the sites must have drained very quickly which is seen in the steep falling limb. However, the discharge in the hydrograph for natural rainfall has not become constant, either because the whole area of the plot did not contribute to it, or



A,B: Hydrographs generated from the A horizon of plot 1 under natural (A) and artificial (B) rainfall.





C: Hydrographs generated from the A horizon of location 7 under artificial rainfall.

Figure 24. Hydrographs generated from natural and artificial rainfall.

because the duration of the rainfall was not long enough for a constant discharge. Furthermore, when the rain ceased the drainage was slower due to the larger area of the plot.

From the consideration of the points mentioned in this section it becomes apparent that the results obtained from artificial rainfall agree generally with those obtained with natural rainfall in the study catchment and any differences observed with the results obtained by other investigators elsewhere may be due to climatic and topographic conditions of the areas they worked.

4.5 FLOW VELOCITY THROUGH THE A SOIL HORIZON

4.5.1 Results and Discussion

The reasons why the velocity of flow through the A horizon of the soil had to be measured were explained in section 3.3. The values obtained are presented in Table 41. This also includes information concerning the land treatment, average gradient and the number of measurements made in each location. No API of the soil was computed for the measurements taken at the first four locations, because it was saturated as a result of application of high intensity (140 mm/hr) artificial rainfall for one and a half hours.

Litter flow was observed for only a short downslope distance in front of the rainulator and was then absorbed by the soil without reaching the gutter. Only in site 1 at location 3 was such flow observed to reach the gutter. This took 68 seconds (Table 41) and the mean velocity was computed at 1.47 cm/sec. The existence of bare patches in

Location no.	Site no.	Date	Land treatment	Average gradient	Elapsed time	Mean flow velocity of site (cm/sec)	Mean flow velocity of location (cm/sec)	Mean flow velocity of all sites (cm/sec)	REMARKS
1	1	1. 9.82	Young heather (burnt in May 1980)	24°	6'38"	0.25			Natural exposed soil face. No litter flow observed.
	2				6'07"	0.27			
	3				3'53"	0.43	0.32 ± 0.09		
2	1	3. 9.82	Grassland	34°	3'57"	0.43			Artificial soil face. No litter flow observed.
	2				6'50"	0.24			
	3				4'26"	0.37			
	4				4'29"	0.33			
	5				6'44"	0.25	0.32 ± 0.08		
.3	1	13. 9.82	Heatherland	29°	4'32"	0.36			Artificial soil face. *Litter flow observed only in site 1.
	1*				1'08"	1.47*			
	2				4'00"	0.42			
	3				4'52"	0.34			
	4				5'27"	0.30	0.35 ± 0.05		
4	1	20. 9.82	Grassland	31°	3'56"	0.42			Artificial soil face. No litter flow observed.
	2				4'06"	0.41			
	3				3'42"	0.45	0.43 ± 0.03		
5	1	7.10.82	Grassland	32°	4'40"	0.36			Artificial soil face. No litter flow observed. The soil was wet from natural rainfall. A.P.I. = 46.00 mm.
	2				7'44"	0.22			
	3				4'47"	0.35			
	4				5'52"	0.28			
	5				5'17"	0.31	0.30 ± 0.05	0.34 ± 0.07	

Table 41. Values of flow velocity through the A horizon in the five selected locations.

the wetted strip may explain why litter flow occurred at this one site. In each site the green dye used in this experiment showed that flow came first from one or more isolated small parts of the exposed soil face and was followed rapidly by a zone that spread horizontally and upward across the soil face at a rapid rate. No colourless water, indicating translatory flow, was observed.

It was recognized from the beginning that the number of measurements made in each location was very small for making comparisons of the velocity of flow between locations with different land treatment and gradient. However, for qualitative information the arithmetic mean of the values was calculated for each location. This would allow the crude analysis investigation of the variability of the throughflow velocities not only from one location to another but also between sites at the same location. In addition the arithmetic mean for all twenty measurements in all locations was calculated regardless of variations in land treatment and gradient. This value was calculated in 0.34 ± 0.07 cm/sec. The values for throughflow velocities obtained from location 5 where the soil was wetted from natural rainfall, seemed as far as the limited number of measurements allows, to have similar variability to those values for locations wetted with artificial rainfall. The API for location 5 was 46 mm. The values of the individual measurements ranged from 0.22 cm/sec (location 5, site 2) to 0.45 cm/sec (location 4, site 3).

A number of questions can be raised concerning these values. The first is whether or not they can provide useful information about the movement of water through the organic layer. Since the number of measurements was very small and no volumes of outflow were measured, they clearly cannot provide quantitative information. On the other hand, there is no doubt that the measurements do permit a qualitative discussion of the movement of water through the A horizon regarding fast movement of it, variability of the velocity from one location to another and from one site to another in the same location and existence or not of translatory flow.

A second point is whether the velocities were values of saturated hydraulic conductivity through the organic layer or values of the velocity of flow through macropores existing in this layer. Lack of information about values of saturated hydraulic conductivities of the organic layer or about the existence of any macropores in the catchment makes this a difficult question to answer. The reason why saturated hydraulic conductivity was not measured is explained in section 4.4. However, values of saturated hydraulic conductivities, specifically for the organic layer measured by other investigators can be considered and compared with the measured values of throughflow velocity in the study area. Also studies concerning the existence of macropores in various environments can be examined and compared with the physical characteristics of the catchment to assess the possibility of the existence of macropores in the soil horizons.

A summary of measured velocities of saturated hydraulic conductivities of various soils was presented by Dunne (1980)

Soil Type	Saturated hydraulic conductivity (cm/hr)	Source
Upper 7.5 cm of a sandy loam (A_0 horizon)	118 (highest of a series of measurement)	Laboratory measurement, Dunne (1969a)
Sandy loam topsoil	34.2-37.2	Field measurements, Dunne (1969a)
Sandy loam	30.5	Field measurements, Hewlett and Hibbert (1963)
Sandy loam (56-90 cm depth)	28.6	Field measurement, Whipkey (1965)
Sandy loam (7.5-60 cm depth)	Mean 24.3 Range 17.2-46.0	Laboratory measurements, Dunne (1969a)
Silt loams and loams	Medium 8.4-10.4 Range 0.15-16.5	Field measurements, Rawitz et al (1970)
Verved sandy silt subsoil	Mean 8.9 Range 1.3-18.5	Laboratory measurements, Dunne (1969a)
Verved sandy silt subsoil	Mean 4.8	Field measurements, Dunne (1969a)
Clay loam topsoil	2.5-7.5	Field measurements, Betson et al (1968)
Loam subsoil (90-120 cm depth)	1.7	Field measurement, Whipkey (1965)
Clay loam subsoil	0.75	Field measurements, Betson et al (1968)
Clay loam subsoil (120-150 cm depth)	0.2	Field measurement, Whipkey (1965)

Table 42. Saturated hydraulic conductivity of soils in which subsurface storm flow has been measured (after Dunne et al., 1980).

(Table 42). Those values obtained from the upper soil horizon were much lower than the measured values for the study catchment. For example, the higher values from the upper 7.5 cm measured in the laboratory were 118 cm/hr (Table 42) and in the field for the same soil ranged from 34.2 to 37.3 cm/hr. In the study catchment these values ranged from 792 to 1620 cm/hr. Despite the fact that the soils were different, the difference is so large that it is impossible to suppose that they were values of saturated hydraulic conductivity through the organic layer. Hence the existence of macropores and movement of the water through them must be the reason for the high measured velocities. This assumption is supported by the conclusions of a number of investigators (Gaiser, 1952; Aubertin, 1971; Ehlers, 1975; Mosley, 1979 and 1982) about the existence of macropores in various environments. Despite the fact that most of these studies were carried out in forested land, a number of reasons supports their relevance to the study area, particularly in the organic layer. These reasons are:

a) The fact that seepage occurred first from a number of small areas in the soil profile rather than from its whole area.

b) The fact that there is a concentration of the roots and the activity of insects, worms and other soil fauna in the thin organic horizon. These provide favourable conditions for the development of macropores because the diameter of the pores does not need to be large enough for the water to move through them, due to the force of gravity. A pore with a diameter of 1.5 mm is large enough for water to flow under gravity (German and Beven, 1981). The evident existence of rabbit burrows is not included in this case because they are mainly between the A and B horizons.

The high measured values of the velocities compared with the values of saturated hydraulic conductivities should not be a surprise, because as Aubertin (1971) stressed "there seems to be a close correlation between the presence of old root channels and overall conductivity". In his studies, for example, the overall conductivity was made up of two parts. The first was the hydraulic conductivity through the soil matrix itself and the second was the inner mass flow through the root channels, cracks and macroorganism pathways. Of particular importance is the fact that he found the hydraulic conductivity of the soil matrix to be several hundred times less than the inner mass flow. A number of previous investigators, however, have given only qualitative information about the existence of macropores and the movement of water through them. Velocities of flow through macropores were measured by Mosley (1979), and his results may permit a comparison with the measured values in the study catchment, despite the fact that the environments were different. Mosley worked in podzol yellow-brown earth soils with a well-developed upper humus mantle and the seepage water was intercepted at the base of the B horizon. The measured velocities in the eight sites were 0.38, 0.81, 0.17, 1.11, 1.20, 0.54, 1.40 and 2.10 cm/sec respectively. The large variability of the values is due to measurement errors and variations in the distance between the applied water and the interceptor. Further information was given by the same author (Mosley, 1982) when he made measurements at 51 sites keeping a constant distance of 1 m between the applied water and the interceptor. Mean, minimum and maximum velocities of flow in each site were calculated. Taking all sites, the overall mean velocity was 0.30 cm/sec, and the mean maximum velocity was 0.42 cm/sec. The variability of the velocity among the sites was the main characteristic and a sample size of over 1000 would have been required to show a significant difference in velocity of even 10%. Consequently the variability observed in the twenty measurements in the study catchment is a phenomenon which should be expected, and the measured values are in general agreement with Mosley's results.

Despite the fact that no detailed survey has been carried out concerning the possible existence of macropores in the catchment, the high velocities of throughflow and the existing conditions in the A horizon tend to support their existence. If this assumption is true, then it means that an increasing amount of the falling rain moves downslope through the macropores when the soil becomes saturated. As the infiltration measurements showed, approximately 20-30 mm of continuous rain is required for the A horizon in the flanks of the catchment, when it is dry, to become saturated. Hence after that amount of rainfall a portion of any further rain can be expected to move downslope through macropores. However, the volume and velocity of this flow cannot be quantified because of the small number of measurements made and the large variability in velocity from one site to another. If, for example, the assumption is made that the arithmetic mean (0.34 cm/sec) of the twenty measurements is correct, and that a remote part of the catchment is 300 m from the stream channel, then a volume of water moving through macropores soils would need approximately 25 hours to reach the stream channel.

The process of water movement through the A and other horizons clearly requires much more investigation. Nevertheless the reported observations demonstrated that the high throughflow velocities can be explained only by the existence of macropores in the study catchment.

4.6 RESPONSE OF THE CATCHMENT TO RAINFALL

4.6.1 Hydrograph analysis

The various plots of the catchment that were tested under natural and artificial rainfall responded to it very fast and a significant amount of the applied rainfall seeped from the litter layer and the deeper soil horizons. However, the plots represented only a small percentage of the catchment and a reasonable question that arises is whether the rest of the catchment would respond in the same manner as the plots. As Barnes (1939, 1940), Hewlett et al.(1967), Dunne et al. (1978), have shown, an answer to this question can often be obtained by analysing the hydrographs generated at the outlet of the catchment. Such an analysis is presented in this section.

Two key concepts underlie hydrograph analysis for the purpose for which it will be used in this thesis. One is the idea that a hydrograph can be divided into storm runoff and base flow. Storm runoff as used in this thesis can be defined as the hillslope runoff that reaches the stream channel during or within a day or so of rainfall, causing an increase in the discharge rate of the channel (Dunne et al., 1978). The other is the idea of hydrologic response of a catchment. The hydrologic response as defined by Hewlett (1969) is the rapidity with which rainfall or snowmelt becomes stream flow. Hewlett also suggested that hydrologic response can be expressed as follows:

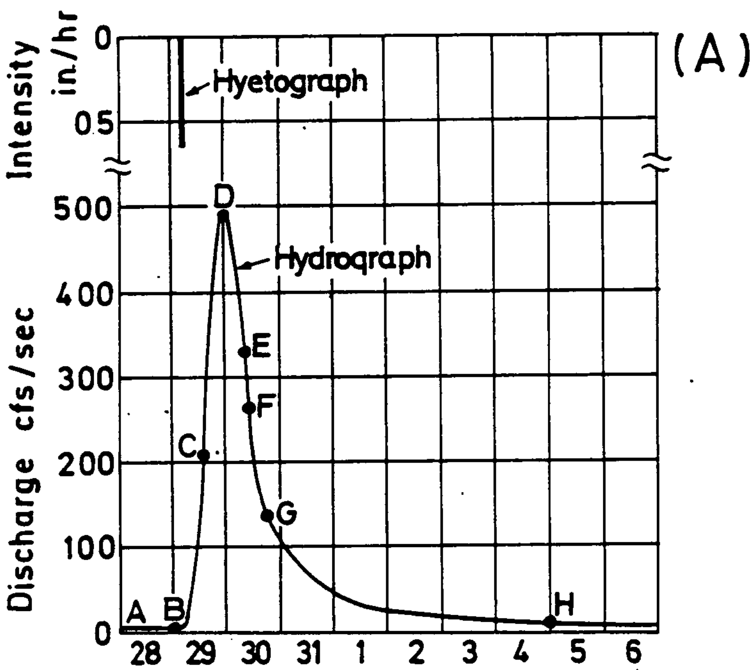
$$\text{Hydrologic response} = \frac{\text{Storm Runoff}}{\text{Precipitation}} \times 100$$

The above expression can be seen to show the percentage of rainfall that contributes to storm runoff.

In the present study, where there is no previous information about the response of the catchment to rainfall, it is necessary to make reference to some of the techniques used by other investigators in order to select a technique of hydrograph separation suitable for this catchment. Barnes (1939, 1940) suggested a method of hydrograph separation based on an analysis of the recession curve. In this method it is assumed that the recession curve for a given catchment may be represented by an equation which does not change in form from different storms, but only varies in the value of the recession constant, Kr, of $Qt = QoKr^{t}$, in which t is the time between the occurrence of discharge Qt and Qo. Barnes found from actual hydrographs that if this equation is plotted on semi-log paper, the lower part of the recession curve is nearly a straight line and this may be the time at which overland flow and throughflow stops. This is not valid for the upper part of the recession curve because it contains overland flow and throughflow and they have different log characteristics. Figure 25 illustrates this method of hydrograph separation and point H being the time at which storm runoff stops. The groundwater flow is calculated by extending the recession line back to an appropriate point (J) under the inflection point (E) of the recession hydrograph and then drawing a further straight line to the initial point of rise (B). Thus the groundwater flow is defined by ABJH and can be subtracted from the total flow of the hydrograph. If the same procedure is followed for the rest of the hydrograph, then the amount of overland flow and throughflow can be determined.

Contrary to Barnes, who separated the storm hydrograph into three components, most other investigators have divided the hydrograph into only two components: storm runoff and base flow. These methods are described with details in standard hydrology text books; some are illustrated with a brief explanation in Figure 26.

Another approach to hydrograph separation worthy of note was proposed by Hewlett and Hibbert (1967). In this method "quick flow" instead of storm runoff is separated from "delayed flow" instead of base flow by a line of constant slope of 0.05 cubic feet per second per square mile per hour. This line is projected from the start of the rising limb to the point at which it intersects the falling limb of the hydrograph. The method has been widely used since its introduction (Harr, 1977; Mosley, 1979).



August - September 1951

A typical hydrograph with corresponding hyetograph
(Panther Creek at El Paso, Illinois (after Chow, 1964)).

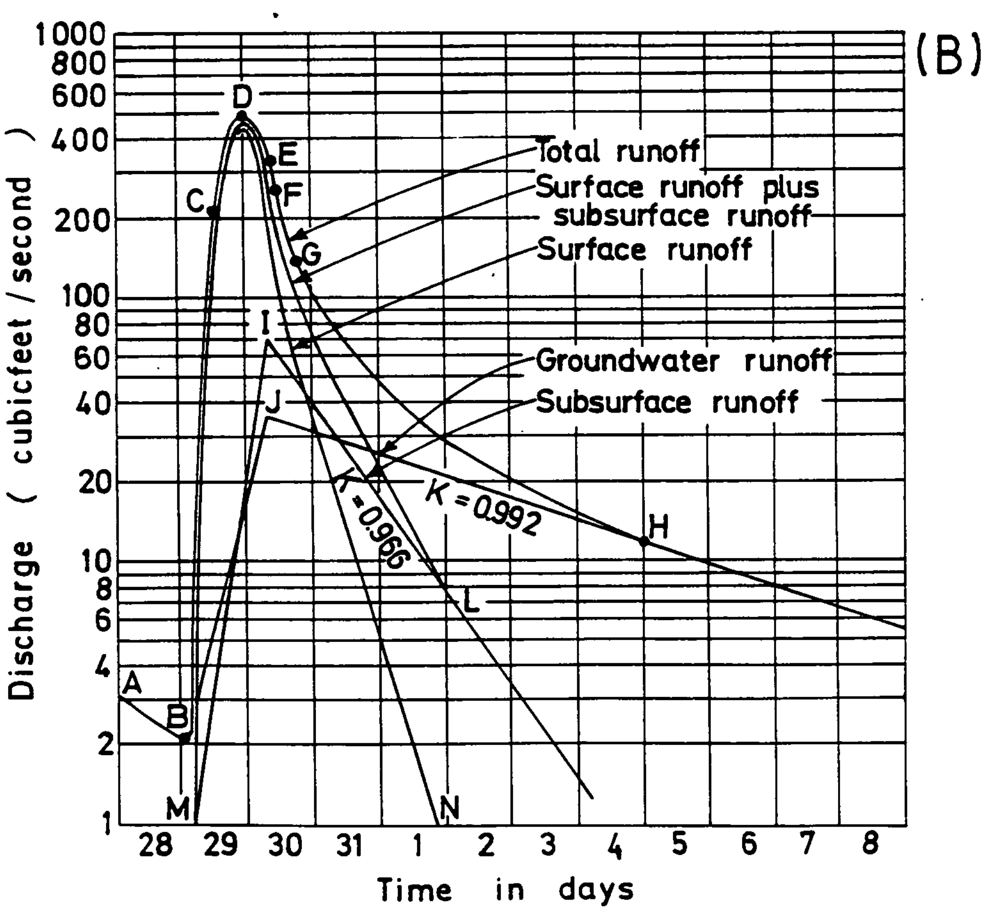
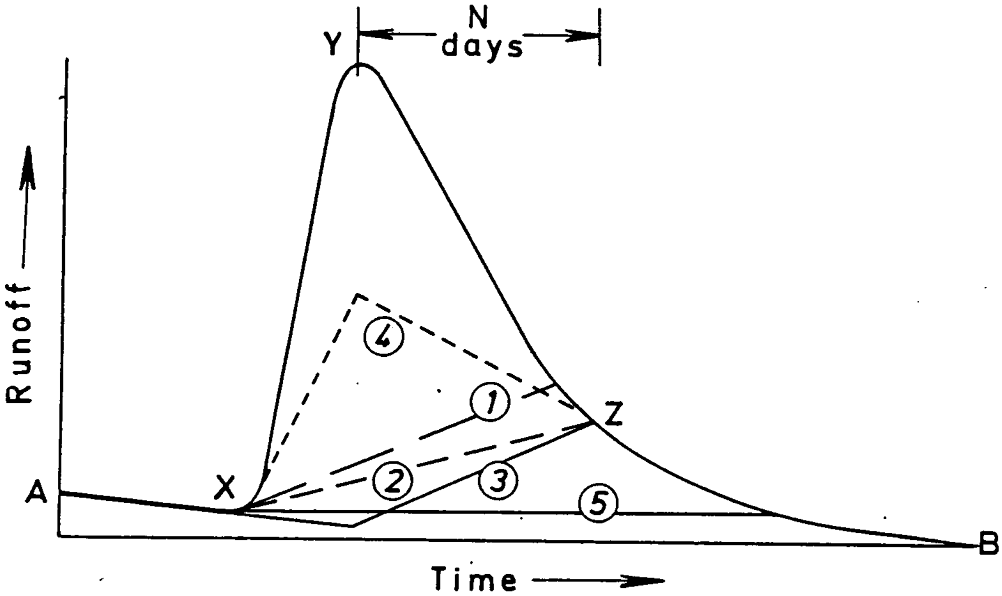


Figure 25. Hydrograph analysis (A) by Barnes' method (after Chow, 1964).



Line 1: This connects the beginning of the rising limb with the point of greatest curvature near the lower end of the recession curve

Line 2: The time interval (N) may be determined from hydrograph inspection or from a simple empirical equation: $N = A^{0.2}$, where N is expressed in days and A is the catchment drainage area in square miles.

Line 3: The pre-storm base flow recession curve (Ax) is projected towards a point beneath the peak flow and then connected by another straight line to the arbitrarily chosen point of greatest curvature.

Line 4: The average base flow recession curve, determined from a number of recession limbs, is extended backwards to a point beneath the peak flow and then joined by a straight line to the beginning of the rising limb.

Line 5: A horizontal line is drawn from point X to its intersection with the recession limb.

Figure 26. Various methods of hydrograph separation (after Ward, 1975)

A problem with all the methods of hydrograph separation is that they are arbitrary because, on the one hand, the flow components cannot be separated in reality, and, on the other, the speed of arrival of the water to the stream channel is a more important factor in determining the shape of the hydrograph than the various pathways followed by the water in reaching the channel. Therefore the various methods of hydrograph separation are open to criticism. So a number of questionable assumptions have been made in Barnes' method, the main one being that the peak of the groundwater flow and interflow are both below the inflection point of the recession hydrograph. As Kulandaiswamy et al. (1969) stressed, neither Barnes nor subsequent workers have clearly defined the locations of the peaks of interflow or groundwater flow components. The same investigator also emphasised that Barnes' method is likely to yield storm runoff values that may be considerably lower than those obtained using other methods. Nash et al. (1969), referring to the separation of the recession hydrograph into two or three components, stressed that it is perhaps arguable whether there are in fact any distinct components or whether there is a continuum of different pathways by which runoff reaches the stream and called for a rejection of <u>a priori</u> division of hydrographs into [illegible] components. Additionally, Freeze (1972) on the same subject emphasised that hydrograph separation is little more than a convenient fiction. Linsley et al. (1982) concluded that "since there is no ready basis for distinguishing between direct and groundwater flow in a stream at any instant, and since definitions of these two components are relatively arbitrary, the method of separation is equally arbitrary". Furthermore, Hewlett and Hibbert (1967) used the method of hydrograph separation referred to above because, as they stressed, the main trouble with elaborate hydrograph separation techniques is that an arbitrary classification of the total flow is usually added to another arbitrary classification of the source flow. Dunne et al. (1978) stressed that all the techniques of hydrograph separation are arbitrary and have little or nothing to do with the processes occurring in the catchment and those by which storm runoff is generated. However, the same investigator suggested that if one method is employed consistently, then useable results are obtained.

It was with this idea in mind that a method of hydrograph separation for the study catchment had to be chosen. As Barnes' method was regarded to be the most sophisticated it was the first to be considered. This method, as already mentioned, was criticised as not being applicable and was time-consuming. Because of this, it was rejected.

Of the other methods, Hewlett's was found to be a simple and quick way of separating storm flow from base flow. In addition this method has been used by other investigators in uplands catchments (Harr, 1977; Mosley, 1979). For these reasons it was adopted for this study. Figure 27 illustrates the separation by this method of a hydrograph generated on 6th October 1982 from 23.00 mm of rainfall. A line with a constant slope of 0.0055 l/sec/ha/h was drawn from the beginning of the rising limb up to the point it intercepted

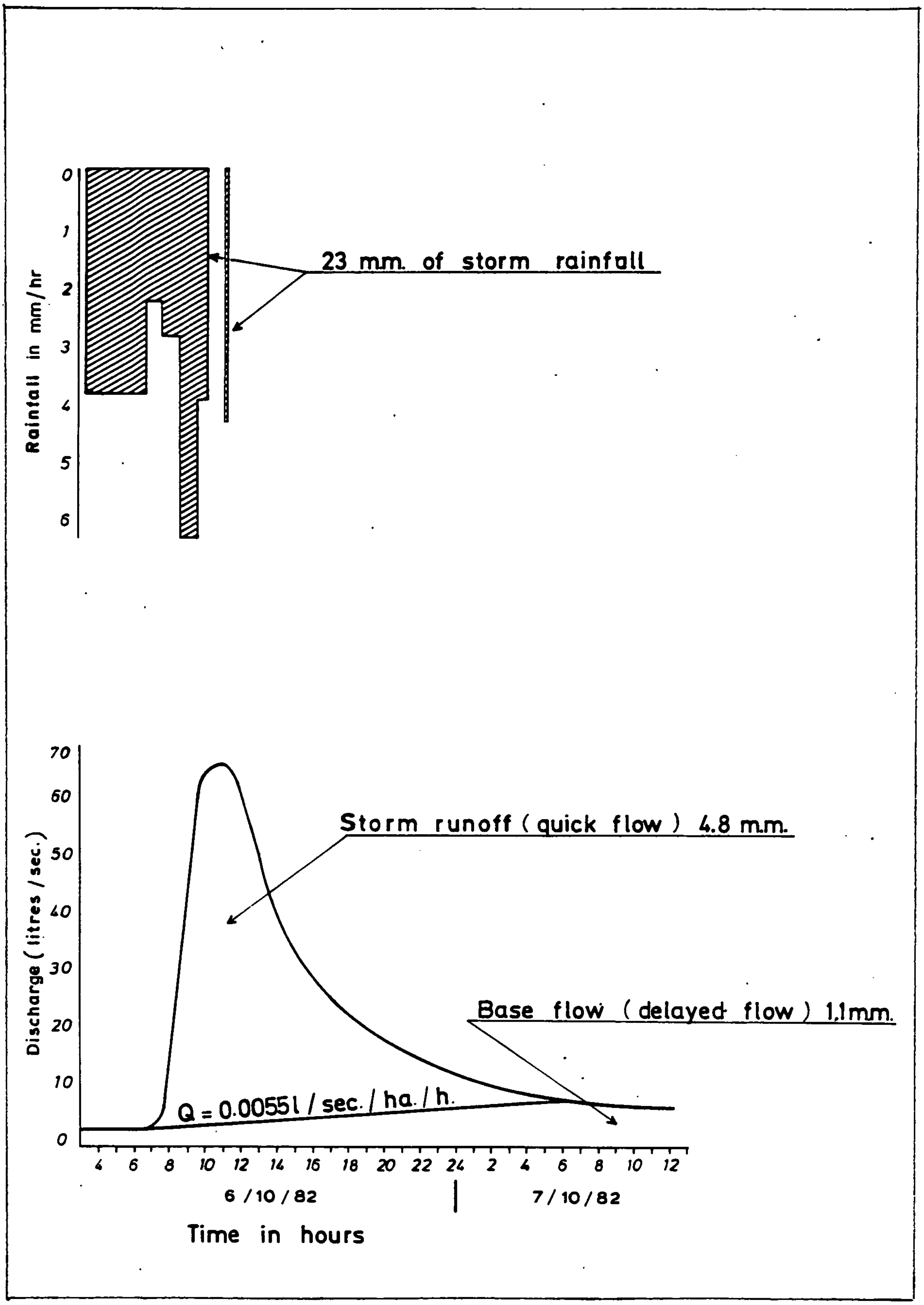


Figure 27. Hydrograph analysis by Hewlett's method.

the recession limb. So, the total runoff (2,168 m^3 or 5.9 mm) was separated into 4.8 mm of storm runoff and 1.1 mm of base flow. Of the total amount of storm rainfall (23 mm) 21% was converted to storm runoff and 5% to base flow. These two hydrologic components seem to be reasonable, taking into account the fact that the separated hydrograph was generated from 23 mm of storm rainfall. All the other hydrographs had the same recession limb, although they differed to some extent in the gradient of the rising limb.

4.6.2 Minimum Contributing Area to Storm Runoff

It was described in the previous section how storm runoff (quick flow) was computed by analysing the hydrographs generated in the outlet of the catchment into two components. From the computed amounts of storm runoff and the amount of rainfall of each event the hydrologic response of the catchment could be estimated. However, the hydrologic response as defined earlier, has nothing to do with the areas of the catchment where the rain falls and produces the storm runoff.

The importance of identifying and assessing these areas contributing to storm runoff has been stressed by a number of investigators (i.e. Ergman, 1974; Dunne et al., 1975), and an attempt to give a quantitative analysis of storm runoff and rainfall was made by Dickinson and Whiteley (1970), using the term "minimum contributing area to storm runoff". Dickinson and Whiteley's concept was decided to be applied for the study of the hydrologic response of the present catchment. They defined this term as that area of the catchment which returning 100% of the effective precipitation as storm runoff, would generate the observed storm runoff for a catchment. By the term effective precipitation is meant the average precipitation for a catchment minus an amount for intercepted and evaporated precipitation (Chorley, 1980).

Dickinson and Whiteley evaluated the minimum contributing area as:

$$R = \frac{CV}{P}$$

where R = Minimum contributing area in percentage of catchment area (M^2)

V = volume of storm runoff (M^3)

P = depth of effective precipitation (M)

C = dimensionless coefficient determining the units of R.

The use of this approach to the minimum contributing area to storm runoff in the study catchment was considered worthwhile for the following reason: the established plots in the catchment area and the measurements that were made by applying artificial rainfall in the various selected locations (see Part III) had yielded a lot of information concerning the response of these segments to natural and artificial rainfall. The equation that was used for computing the minimum contributing area as a percentage of the total area of the catchment for all the flood events occurring during the two field seasons had the form:

$$E\ min.(\%)^{*} = \frac{\left[\frac{\text{storm runoff } (M^3)}{\text{catchment area } (M^2)}\right]}{\text{Effective rainfall } (M)} \times 100.$$

C was computed as $\frac{100}{\text{catchment area (m}^2\text{)}} = \frac{100}{365{,}000} =$ 0.000274. It follows that $R = \frac{0.000274 \times \text{(storm runoff)}}{\text{effective rainfall}} = \frac{0.000274 \times V}{P}$, as used by Dickinson and Whiteley (1970).

The term effective rainfall in place of effective precipitation is used in this study because between May and October, when the work was carried out, rain was the only form of precipitation. The effective storm rainfall was considered to be equal to the gross storm rainfall because some of the catchment was bare (burnt patches) or sparsely vegetated. Therefore, losses due to interception and evapotranspiration during storms were regarded as negligible. Total runoff was taken to indicate storm runoff and base flow only up to the time at which storm runoff ends.

Five distinctive hydrographs generated during the first field season and three during the second were analysed in this way. The results are presented in Table 43. The arithmetic mean of the daily rainfall, from gauges 1 and 3, which were situated at the bottom and the top of the catchment respectively, were used for the computation of the API. This is because, as mentioned earlier, the antecedent precipitation factor is only an index to soil moisture conditions of the catchment. The third hydrograph in 1982 was that generated on 6th October 1982. After that date, and despite the fact that a large amount of rain fell up to the end of that month, and the rate of runoff increased, it was impossible to distinguish separate hydrographs from a

A/A	Date	API (mm)	Effective rainfall (m)	Storm Runoff (m^3)	Minimum Contributing area (% catchment)	Time to start of runoff (h)	Duration of rain (hours)	Remarks
1	22/7/81	10	0.0416	470	3.1	9.5	28	Rainfall intensity from 1.2 to 1.9 mm/hr
2	19/9/81	13	0.0364	181	1.4	5.0	14*	Rainfall intensity from 0.2 to 6.0 mm/hr
3	25/9/81	37	0.0494	4,238	23.5	3.0	19.5	Rainfall intensity from 0.6 to 11.0 mm/hr
4	1/10/81	32	0.0844	15,512	50.3	7.0	36.0	Rainfall intensity from 1.7 to 5.2 mm/hr
5	8/10/81	39	0.0260	547	5.8	6.0	30.0***	Rainfall intensity from 1.0 to 2.5 mm/hr
6	25/6/82	4	0.0393	712	5.0	21.5	32.5**	Rainfall intensity from 0.2 to 2.3 mm/hr
7	15/7/82	6	0.0333	165	1.4	22.5	26.0	Rainfall intensity from 0.4 to 2.9 mm/hr
8	6/10/82	21	0.0231	1,767	21.0	3.5	6.5	Rainfall intensity from 2.2 to 6.3 mm/hr

* Two breaks of the rainfall 40 min. and 2.0 hours respectively

** Two breaks as well, 1.0 and 2.0 hours respectively

*** Five breaks from 0.5 to 5.0 hours

Table 43. Characteristics of flood events during the two field seasons

specific amount of rainfall. The reasons for this difficulty are mentioned in section 4.2.

Table 43 reveals that the minimum contributing area values ranged between 1.4 and 50.3% of the catchment and had an arithmetic mean of 14.0 and a median of 4.5. This range of 49 units is very large and shows the dynamic state of minimum contributing areas. The rain event which occurred on 1st October 1981 contributed very much to the large difference between the minimum and maximum values. However, even without this rain event, that had, as mentioned in section 4.2, a 10-year return period, the dynamic state of minimum contributing areas is still obvious. The fact that the percentage of minimum contributing areas is approximately the same for three pairs of rain events with different hydrologic parameters is of interest. Specifically for rain events 2 and 7, 3 and 8 and 5 and 6, the percentage is approximately 1.4, 22 and 5.4% respectively. This clearly reveals how the total amount of rainfall of each event, its intensity and duration, changes in intensity, breaks in rainfall and variations in its spatial distribution, as well as antecedent soil moisture conditions of the catchment affect the volume of storm runoff and consequently the minimum contributing areas. The amount of rainfall, for example, for rain events 2 and 7 (Table 43) was 36 and 33 mm respectively. Furthermore, they had API values of 13 and 6 mm and rain durations of 14 and 26 hours, respectively. Also, the intensity of the rain ranged from 0.2 to 6.0 mm and 0.4 to 2.9 mm/hr. Yet they still had similar contributing area values. The same differences are found when comparisons are made in the two other pairs of rain events.

The results obtained by other investigators around the world concerning the range of values for minimum contributing areas are of interest when compared with the values computed in this study. These are summarised in Table 44. It should be mentioned that entries 1 to 7 of Table 44 were reprinted from Dickinson and Whiteley's work and entries 8 to 11 were added from the author's referred work. A consideration of these results suggests that the wide range (1.4 to 50.3%) of minimum contributing area computed for the catchment is not an exception. On the contrary, it is in general agreement with the results obtained by most of the investigators mentioned in Table 44.

Examination of surface conditions between the study area and the ones in Table 44 in order to find any similarities was not considered reasonable. This was because, as was stressed in the general introduction (see 1.1), two areas with the same vegetative cover may respond to a rain event in entirely different ways. In Table 44, for example, both Ragan and Mosley carried out field work in forested areas. The minimum contributing area ranged from 1.2 to 2% in the first case and in the second from 4.3 to 99% of the catchment. The same thing has been observed with the work carried out by Riddle and Dickinson on agricultural land.

Another point that has to be emphasised is the meaningfulness of the minimum contributing area. As far as this point is concerned, the partial or variable source area concept and the dynamic watershed concept mean that the

A/A	Author	Catchment area (km²)	Catchment characteristics	Contributing area characteristics
1	Betson (1964)	0.015	Pasture cover + 2% swamp	Mean value: 4.6%
2	Betson (1964)	0.020	Area denuded of vegetation	Mean value: 85.8%
3	TVA (1965)	0.019	Heavily grazed pasture	Range: 5 to 20%
4	Zorodchkov (1965)	1,000 to 5,000	Springmelt conditions	Range: 20 to 60%
5	Ragan (1968)	0.460	Forested	Range: 1.2 to 3%
6	Riddle (1969)	24	Agricultural intermittent stream	Median value: 2.2% Range: 0.2 to 40%
7	Riddle (1969)	28	Agricultural perennial stream	Median value: 2.7% Range: 0.5 to 8%
8	Dickinson (1970)	18	Agricultural	Mean value: 10% Range: 0.99 to 50%
9	Weyman (1974)	0.10	Pasture cover	Range: 0.7 to 2%
10	Harr (1977)	10.23 (ha)	Forested	Mean value: 38% Range: 23 to 51%
11	Mosley (1979)	0.308 (ha)	Forested	Range: 4.3 to 99%

Table 44. Contributing area values noted in the literature.

area contributing to storm runoff shrinks and expands during the course of the storm and does not remain fixed as in the minimum contributing area concept. Weyman (1974), in considering this concept, suggested that the area contributing to storm runoff, calculated by Dickinson and Whiteley's method, may be underestimated for two reasons. Firstly, because the contributing area expands during the storm and rainfall is absorbed into the expansion, the actual runoff area is larger than that computed by the method referred to previously. Secondly, if processes other than overland flow (throughflow or pipe flow) generate the storm hydrograph, then the contributing area may not yield 100% of available rainfall to the stream and the [illegible] contributing area is again underestimated.

The question that now arises, therefore, is how meaningful are the computed values of minimum contributing area for the study catchment. In particular, are there segments in the catchment that generated the storm runoff and which varied during the two field seasons between 1.4 and 50.3% of the catchment area? This question is considered in the next section.

4.6.3 Storm Runoff Generation

A comparison of the results concerning minimum contributing areas to storm runoff with those obtained from the various plots operated under natural and artificial rainfall, reveals that the slopes of the catchment responded to rainfall more frequently than the catchment as a whole (as observed at the stream gauge station at the catchment outlet). For example, litter flow was observed in the triangular plots during ten time periods in the first field season. This figure includes the rain event on 22nd July 1981, during which flows may have occurred not only from the litter layer, but also from the upper part of the A horizon of the soil. The number of responses might have been higher had the plots been checked more frequently. This is because in each time period more than one rain event was usually included. During this first field season, however, only five distinctive hydrographs were generated at the catchment outlet. A similar situation occurred in the second field season; from the rectangular plots flows were observed during 17 time periods, while only three distinctive hydrographs were generated at the catchment outlet. This means that the response of the slopes and of the catchment as a whole to rainfall was not direct.

Another point that has to be stressed is the portion of the rainfall that was observed as litter flow or throughflow in the various plots and that which was converted to storm runoff in the outlet of the catchment. In fact, on the occasions when both the plots and the catchment responded to rainfall, the amount of litter flow and throughflow from the plots was larger than the amount of storm runoff in the catchment. In the 26th June 1982 and 15th July 1982 rain events, for example, from 39.0 and 33.0 mm of weighted rainfall respectively, only 5% and 1.4% were converted to storm runoff in the outlet. However, during these events the flows generated from the rectangular plots 1, 2 and 3 were 42, 28 and 17% of the rain in the first event and 46, 27 and 19% in the second event (Table 30). Another distinctive example regarding the response of the plots and of the catchment to rainfall is the rain event on 6th October 1982. The storm runoff of the catchment was then 21% of the rainfall and for plots 1, 2, 3 and 4 the flows were 72, 60, 16 and 85%, respectively. The same response of the plots and of the catchment was observed many times during the first field season. On the 19th September 1981, for example, from 36.0 mm of weighted rainfall only 1.4% was converted to storm runoff, while the amount of litter flow in the triangular plots ranged from 2.5 to 39% of the rainfall (Table 24).

From the above comparison, two points are clear: firstly, the inconsistency of the response of the slopes and of the catchment to rainfall; and secondly, the differences in the amount of rainfall converted to litter flow and throughflow on the slopes and the amount of storm runoff at the catchment outlet (when both plots and catchment responded). The fact that an amount of the total rainfall in a specific event is never converted to litter flow or throughflow, is of interest because it implies that there are no areas in the catchment that return 100% of the rainfall. The calculated values of contributing area must not have corresponded to areas returning 100% of the rainfall, but to larger ones returning a smaller amount of the received rainfall and being located both near and far from the stream channel. Thus, during a rain event, storm runoff is generated by processes occurring not only along the stream channel, but also in the brown earth and peat soil areas of the catchment. These processes consist of saturated flows through biological voids of the A horizon and saturated litter flow. It is doubtful whether flows through the lower soil horizons contribute to storm runoff.

The fact that in the study area the peat soil surrounds the brown earth soil, also needs consideration. This is because the largest flows are generated in this soil section and they have to move through the brown earth to reach the stream channel. Hence, saturated throughflow and litter flow in the brown earth soil must increase significantly during a rain event. These flows must be affected to a large degree when they reach the flood plain, as a large portion of the rainfall is absorbed by this section of the catchment, due to its greater depth in comparison with the depth of the soil of the slopes. Thus, there must be a reduction in the amount of flow in the flood plain, and when this becomes saturated the rainfall is converted to storm runoff as throughflow or litter flow (via the soil of the flood plain). These speculations about storm runoff generation in the catchment are based on the results obtained from the plots, from hydrograph analysis, and from visual observations of runoff processes made during a number of rain events in the catchment. It is worth mentioning some of these rain events as they have shown some interesting flow processes.

The first visual observations were of the rain event of 1st October 1981. The rain started at 8.00 a.m. on 1st October and continued for 36 hours. The author was present in the catchment on 2nd October 1981 from 8.00 a.m. to 11.00 a.m. During this event, as mentioned in section 3.2.1.2, an accident befell the author and unfortunately, as a result, only one photograph was taken of the flood plain section of the catchment. However, the rain gauges were read and so the author, while walking around the catchment, was able to observe saturated litter flow, pipe flow and throughflow on a large scale. In fact, it was during this rain event that the flow processes contributing to storm runoff in the catchment were fully observed. The peat soil area of the catchment was almost totally covered with litter flow. Also pipe flow was seeping from the sides of artificial drainage ditches. In the locations of this area that were covered with heather, litter flow was also occurring, its presence being obvious from the noise of the water on the ground as the author was walking. Also, on the slopes of the catchment, widespread litter flow was observed and the sheep tracks looked like small rivulets from the top of the catchment to the stream channel. In addition to the litter flow, throughflow was observed in every natural and artificial cutting in the slopes of the catchment. The flood plain along the edge of the stream channel was completely covered by litter flow. Plate 6 shows a location in the flood plain; the occurrence of widespread litter flow is clear. The large amount of litter flow in the flood plain during this event must have been the result of litter flow and throughflow from the slopes. In addition to this source, the water table of the flood plain must have risen to the ground surface and so direct rainfall on it increased the amount of litter flow.

These flow processes were observed again in October 1982. On 6th October 1982, it started raining at 4.00 a.m.

Plate 6: Saturated litter flow on the flood plain of the study catchment on 2nd October 1981.

and stopped at 10.30 a.m. on the same day. The weighted catchment rainfall for 6.30 hours was 23 mm. This time, however, the processes were not as widespread. Plate 7 (A,B) was taken at 10.00 a.m. and shows saturated litter flow in the peat soil area. Green pyranine was mixed with the water to make it more visible. A large part of this area was covered with litter flow. Pipe flow was observed in many ditches, as in October 1981. Litter flow was observed also in slopes I and II of the catchment. Plate 8 (A,B) shows saturated litter flow in a sheep scar lying in the middle of slope II. Without this feature this flow process would not have been distinctive, as the location was heavily vegetated. Apart from litter flow, throughflow was observed in both slopes of the catchment, moving through the A horizon. Plate 9 shows two pieces of zinc guttering inserted into the soil and a large amount of water seeping out. During this rain event, no litter flow was observed from the top of the catchment down to the stream channel, neither was it observed in the flood plain.

Similar observations were also made during a number of smaller events, for example on 26th June and 16th July 1982. In neither of these events was litter flow observed in the flood plain, while in the peat and brown earth soil areas the flows were similar for both events but localized and not widespread. Litter flow was, however, observed on the flood plain for the second time on 18th October 1982. This occurred not after a single large rain event, but after a large amount of rain falling over the period between the 5th and 18th of October. The flow was only a small trickle

(A)

(B)

Plate 7: Saturated litter flow in the peat soil area of the study catchment on 6th October 1982.
(A) On a flat site.
(B) On a sloping site.

(A)

(B)

Plate 8: Litter flow at a sheep scar of a well-vegetated site of slope II of the study catchment.
(A) General view showing location of scar.
(B) Close-up view showing litter flow.

Plate 9: Flow through the A horizon demonstrated by inserting zinc guttering into the soil (6th October 1982).

in the middle of the flood plain, but it was clear that the water table had risen to the surface.

Considering the way that locations near to the stream channel and those far away from it responded to rainfall, queries arise about the existence or not of variable or partial source areas in the study catchment. This is because during the course of the study no locations remained completely inactive, as the results from the plots and from observations made during natural events have shown. Thus, storm runoff seems to originate during a relatively large rain event from all the area of the catchment, or at least from the larger part of it, and not only from areas around the stream channel (variable source areas) or from other fixed areas in the catchment (partial source areas). The portion of rain that falls at the top of the catchment and becomes storm runoff must be smaller than that from areas near to the stream channel. Generally, the portion of the total rainfall during an event that becomes storm runoff must increase from the top to the bottom of the catchment and must originate from the new rainfall and not from that of a previous rain event. This is because the computed flow velocity under saturated soil conditions is high enough for water to reach the stream channel.

The flood plain of the catchment seems to play a very important role in the amount of rainfall that is converted to storm runoff, especially during relatively small rain events. This is because in contrast to the slopes, it has a very deep soil and thus a large amount of water must be absorbed by it before it becomes saturated. Due to this difference in soil depth, the slopes respond even to a relatively small rain event while the catchment as a whole responds after a relatively large rain event, or after a small one when the soil is saturated. Hence, the flood plain plays a role in storm runoff generation during relatively small rain events and at the beginning of large rain events, quite the opposite of that suggested by Hewlett and Hibbert (1967).

Conclusively, the results obtained from natural and artificial rainfall during the two field seasons are in agreement with those obtained by Mosley (1979) and Bonnel et al. (1978) in that storm runoff is generated from the whole area of the catchment and not only from variable or partial areas as proposed by Hewlett and Hibbert (1967) and Betson (1964) respectively.

PART V CONCLUSIONS

As was stated in the Introduction, the purpose of the work reported in this thesis was to study hillslope flow processes in an upland catchment in South-east Scotland, and also to explain qualitatively how the rain falling on it was converted to storm runoff. The previous Parts of the thesis have described the various experiments that were carried out in order to achieve these objectives, and the results obtained have shown that the following conclusions can be drawn.

1. The area of the study catchment is divided into three sections, each with quite distinctive infiltration characteristics. The first is the brown earth soil part, occupying the slopes of the catchment. Mean infiltration rates from 15-18 mm/hr were computed for this section. The second is the peat soil area part, occupying the upper slopes of the catchment. For this section the mean infiltration rate was computed to be 24.0 mm/hr. However, it must be taken into account that this latter value derived from a small number of measurements that lasted for one hour and were taken under very dry antecedent soil moisture conditions, so lower mean infiltration rates should be expected under wet soil conditions and from measurements of longer duration. Finally, the third section occupies the area along the stream channel with mean infiltration rates ranging from 37-44 mm/hr.

2. In the brown earth soil section of the study catchment the main flow process is lateral flow through the soil

horizons. The high velocities of flow obtained suggest that a large portion of the infiltrated water moves through structural and biological voids (macropores) rather than through the soil matrix. The quantity of the infiltrated water that flows laterally decreases from the upper (A) to the deeper (B,C) soil horizons. The reasons for this decrease seem to be, firstly, the restricted biological activity in the B and C horizons and, secondly, the sharp change from one soil horizon to another. This is because such a sharp change favours lateral water movement just above the plane of change from one soil horizon to another (Whipkey, 1965; Weyman, 1973; Whipkey and Kirkby, 1980).

The lateral flow must be saturated in the macropores and in the soil matrix as well, or saturated in the macropores and unsaturated in the soil matrix. Flow through macropores contributes to storm runoff, due to its high velocity, while flow through the soil matrix must feed and sustain the falling limb of the hydrograph when the rain ceases.

3. Another flow process that occurs in the brown earth soil section of the catchment, is saturated litter flow. This is very important because rain is added directly onto the saturated litter flow and so significant amounts of flow contribute to storm runoff. This type of flow seems to occur due to low hydraulic conductivity of the deeper soil horizons (B,C) and due to the small depth of the A horizon. Under these conditions the A horizon becomes easily saturated and so water flows through it and over the ground surface. The results and the observations of

flow processes during natural rain events have shown that this type of flow occurs not only in areas adjacent to the stream channel, but on the slopes of the catchment as well. It is widespread during relatively large rain events but localized on the slopes during relatively small rain events.

4. Horton "litter flow" does not usually occur in the study area, as the comparison of the computed infiltration rates of the soil with the rainfall intensities have shown. Even the final infiltration rates far exceed the usual rainfall intensities occurring in the study catchment. However, there might be rain events or short showers with high intensities exceeding the infiltration rates of the soil, and so producing Horton "litter flow". Such an event, with an intensity of 25 mm/hr for 10 minutes, occurred on 11th October 1982 and quite clearly generated such flow. However, considering the scarcity of these events, as well as the locations of the catchment with infiltration rates lower than the rainfall intensities, Horton "litter flow" is not a significant flow process in the study area.

5. Litter flow occurs in the catchment during the summer under dry soil conditions. This type of flow, as the results have shown, is irrelevant to infiltration rates of the soil and to rainfall intensities and may occur due to hydrophobic properties of the soil. It occurs mainly in bare and burnt patches of the ground and is not a significant flow process.

6. The flow processes that occur in the peat soil area of the catchment are:

(a) Slow vertical flow of the infiltrated water until it reaches the impermeable B horizon.

(b) Slow lateral flow through the A horizon and mainly in sloping ground.

(c) Fast pipe flow through the A horizon.

(d) Saturated litter flow.

All these processes occur together only when the peat soil is dry at the beginning of a rain event. Otherwise the rain falling on the surface of it can take different paths depending on antecedent soil moisture conditions. Specifically, when the peat soil is saturated, pipe flow and saturated litter flow are the main processes that occur and contribute to storm runoff. Saturated litter flow is very important because the B horizon is impermeable and so much of the rain flows over the ground surface. Furthermore, new rain is added directly to it and hence the quantity of litter flow contributing to storm runoff increases. This flow process, as the experiments and observations of natural rain events have shown, occurs in bare locations as well as in those covered with grass and heather.

The second flow process that contributes to storm runoff in the peat soil area, is pipe flow. The fact that it was observed only in the banks of the artificial drainage ditches and not in the runoff plot does not reduce its significance. Details about time of start and percentage of rain that is converted to pipe flow cannot, unfortunately, be given and need specific investigation.

7. Storm runoff is generated in the study catchment from the whole, or at least from the largest part of the catchment and not only from variable or partial source areas. This conclusion is drawn from the following observations:

(a) During the course of the study no locations of the catchment either near or far from the stream channel remained inactive during the application of natural and artificial rainfall to them. Furthermore, observations of natural rain events revealed widespread areas contributing to storm runoff.

(b) The computed velocity of flow through the A horizon was high enough to enable water from the remote parts of the catchment to reach the stream channel in sufficient time to contribute to storm runoff.

(c) The amount of storm runoff that was recorded in the outlet of the catchment during rain events was high and in some events at least 50% of the catchment area would give this amount of runoff by returning 100% of the rainfall. But no locations returned 100% of the rain, and so the areas contributing to storm runoff must have been higher (larger) than computed.

(d) Despite the fact that larger amounts of runoff were measured and observed in the peat soil area of the catchment than in the brown earth soil area, the recorded amounts of flows in the outlet of the catchment could not have originated only from the peat soil because most of the water had to flow through the brown earth soil before reaching the stream channel.

Consequently, the way storm runoff is generated in the present study catchment does not agree with the concept of variable source areas proposed by Hewlett and Hibbert (1967), or partial source areas proposed by Betson (1964). It does, however, agree with models proposed by Mosley (1979) and Bonnel et al. (1978). The flood plain in the study area during relatively small rain events and also at the beginning of large ones and under dry moisture conditions in both cases, not only fails to contribute to storm runoff, but also absorbs most of the flows generated in the peat and brown earth soil areas of the catchment as they flow towards the main channel. Only when it becomes saturated, do flows emerge from it and flows from the rest of the catchment reach the stream channel.

8. The study of flow processes in upland catchments with steep and windswept slopes by only one person is a very difficult task. Instruments and equipment are carried with difficulty and after installation, damage by animals, even after protection, is not unusual.

The difficulties are not helped by the fact that many of the methods generally recommended for catchment studies are not applicable, or are difficult to use in upland areas. Rainfall catch, for example, varies significantly from one site to another, even with small differences in altitude, aspect and gradient of the sites, when the storm is accompanied by wind. So, assessment of the mean area rainfall needs particular attention. Also, runoff measurement is not an easy task in upland catchments and in the study area such measurements would be very difficult without the existence of the ready-made stream gauging site. Furthermore, the cylinder infiltrometer is not suitable equipment for assessing the infiltration rates of the soil and comparing them with the rainfall intensities. This is because the soil is disturbed to a large degree when the equipment is inserted into it. Specific measures that are taken to avoid the disturbance of the soil do not seem to work. Hence, the entry of water into the soil is easy and the infiltration rates are overestimated. On the other hand, the rainfall simulator infiltrometer, after some modifications in order to become suitable to topographic and climatic conditions of the upland areas, gives infiltration rates closer to the actual ones.

Additionally, information about the occurring flow processes in upland areas during the winter cannot be easily obtained. This is because instruments and equipment may be damaged by frost. Finally access to, and staying in upland catchments for detailed work is not easy.

But despite these problems, information from small upland catchments is very useful. This is becuase, as Freeze (1974) emphasized "the larger rivers are fed by the smaller tributaries and it is this network of small tributary streams that drains by far the larger percentages of the land surface". It is felt that the data presented here, although not wholly conclusive, nevertheless represent an advance in the understanding of flow generation processes in the Scottish uplands.

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APPENDICES

Appendix 1: Initial, final and mean infiltration rate of each infiltration site of the nine locations

Location No.	RUN 1 Site No. 1	RUN 1 Site No. 2	RUN 1 Site No. 3	RUN 1 Site No. 4	RUN 2 Site No. 1	RUN 2 Site No. 2	RUN 2 Site No. 3	RUN 2 Site No. 4
	Initial infiltration rate (mm/hr)				Initial infiltration rate (mm/hr)			
1	50.00	50.00	49.20	50.00	50.00	49.30	49.20	48.80
2	30.70	34.70	35.40	42.20	50.00	50.00	48.60	50.00
3	19.60	37.00	46.30	44.00	29.60	34.90	47.00	31.20
4	50.00	47.60	49.20	50.00	32.90	36.60	39.50	44.00
5	50.00	35.20	50.00	50.00	50.00	50.00	48.60	50.00
6	50.00	50.00	50.00	50.00	37.80	50.00	43.60	44.80
7	50.00	50.00	50.00	50.00	46.40	50.00	50.00	48.60
8	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00

Location No.	RUN 1 Site 1	RUN 1 Site 2	RUN 1 Site 3	RUN 1 Site 4	RUN 1 Site 5	RUN 1 Site 6	RUN 1 Site 7	RUN 1 Site 8	RUN 2 Site 1	RUN 2 Site 2
9	37.10	44.30	48.60	36.80	50.00	45.20	49.30	50.00	41.70	45.00

Table 45. Initial infiltration rate of each site of the nine locations.

Location No.		Run 1: Site No. 1	Run 1: Site No. 2	Run 1: Site No. 3	Run 1: Site No. 4		Run 2: Site No. 1	Run 2: Site No. 2	Run 2: Site No. 3	Run 2: Site No. 4
		Final infiltration rate (mm/hr)					Final infiltration rate (mm/hr)			
1	RUN 1	34.30	46.20	46.70	43.80	RUN 2	46.70	41.70	44.90	48.10
2		6.70	12.50	15.80	12.70		9.80	11.50	10.40	12.00
3		5.50	22.10	20.00	21.70		14.80	15.10	21.10	18.20
4		23.80	14.50	12.40	13.70		12.10	18.40	9.50	8.60
5		37.90	13.50	43.50	50.00		45.40	50.00	37.40	45.50
6		12.20	12.80	12.40	1.00		15.40	17.30	2.00	9.80
7		13.40	10.80	13.90	18.10		21.60	12.60	9.50	8.40
8		22.20	31.20	31.10	35.80		36.00	37.10	23.90	23.80

Location No.		1	2	3	4	5	6	7	8		1	2
9	RUN 1	1.10	17.30	13.20	21.00	12.10	25.10	16.60	13.10	RUN 2	2.00	8.20

Table 46. Final infiltration rate of each site of the nine locations.

Location No.	RUN 1 Site No. 1	RUN 1 Site No. 2	RUN 1 Site No. 3	RUN 1 Site No. 4	RUN 2 Site No. 1	RUN 2 Site No. 2	RUN 2 Site No. 3	RUN 2 Site No. 4
	Mean infiltration rate (mm/hr)				Mean infiltration rate (mm/hr)			
1	37.70	46.50	45.70	44.50	47.80	41.70	42.10	48.30
2	8.70	10.00	15.70	12.40	14.00	20.00	18.80	19.10
3	6.60	23.00	21.80	21.90	15.10	16.80	22.00	17.50
4	27.50	17.70	13.90	17.50	13.10	17.80	12.60	13.80
5	40.40	13.50	44.50	50.00	46.50	48.00	36.70	46.50
6	16.50	19.50	19.20	7.50	14.90	21.00	8.90	13.40
7	16.60	22.50	21.10	18.50	22.40	19.90	14.90	16.70
8	30.10	37.80	36.30	41.60	41.10	41.30	33.10	37.60

Location No.	RUN 1 Site 1	RUN 1 Site 2	RUN 1 Site 3	RUN 1 Site 4	RUN 1 Site 5	RUN 1 Site 6	RUN 1 Site 7	RUN 1 Site 8	RUN 2 Site 1	RUN 2 Site 2
9	4.90	22.90	22.60	24.90	31.00	32.00	22.50	29.40	18.70	15.50

Table 47. Mean infiltration rate of each site of the nine locations

Appendix 2: Hydrographs generated from artificial rainfall in each infiltration site of the locations 2, 3, 4, 5, 6, 8 and 9

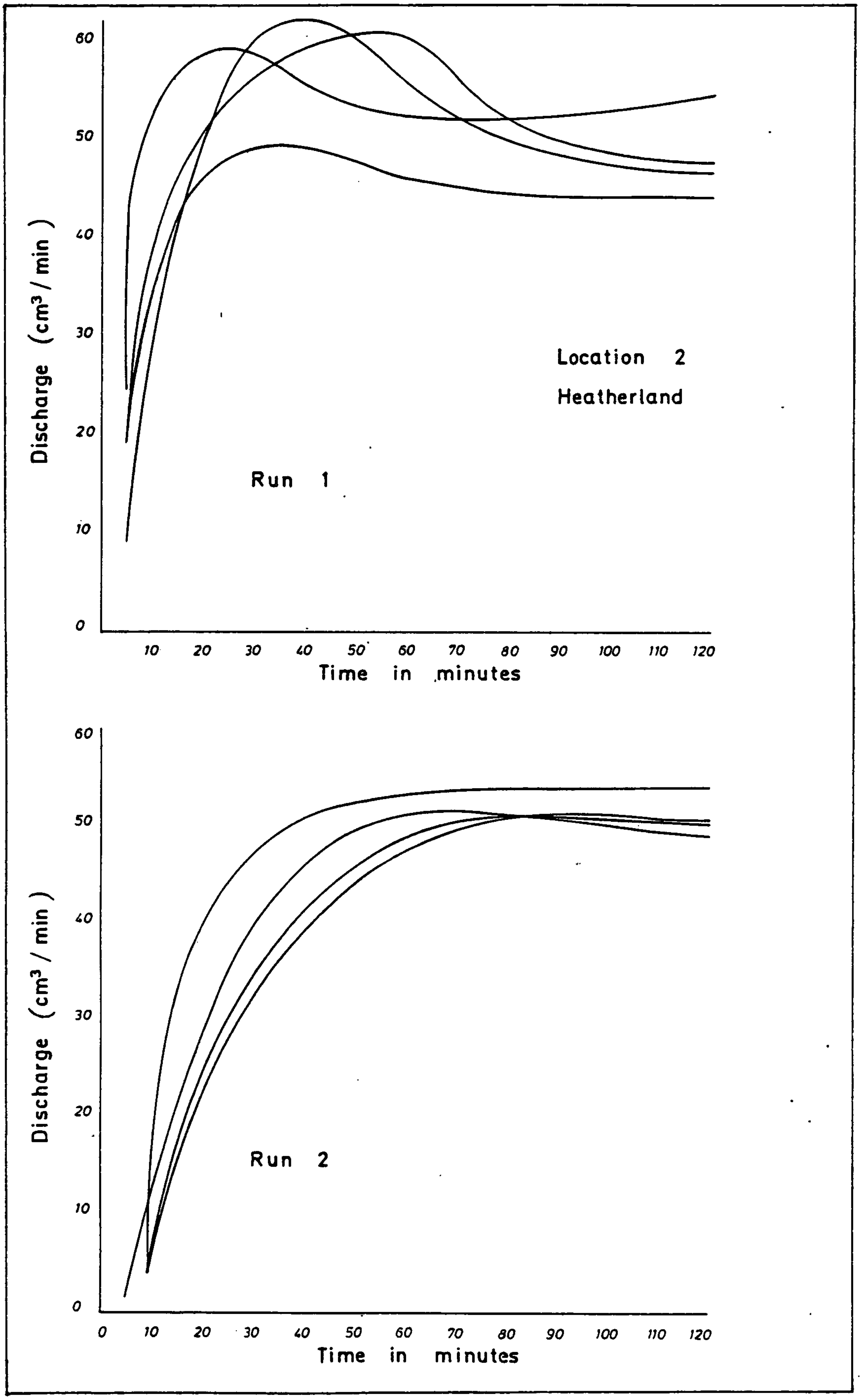

Figure 28. Hydrographs generated from artificial rainfall in each site of location 2.

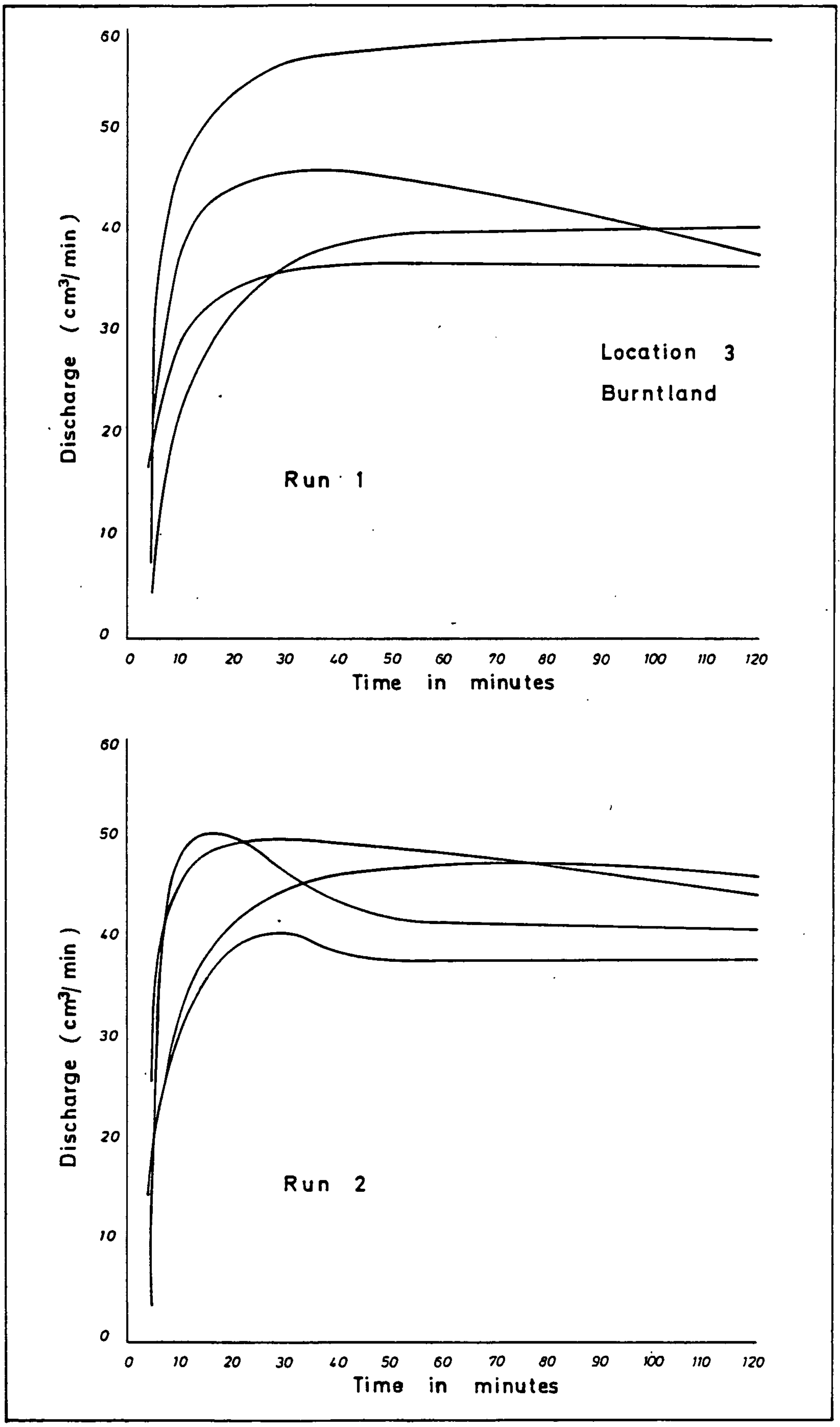

Figure 29. Hydrographs generated from artificial rainfall in each site of location 3.

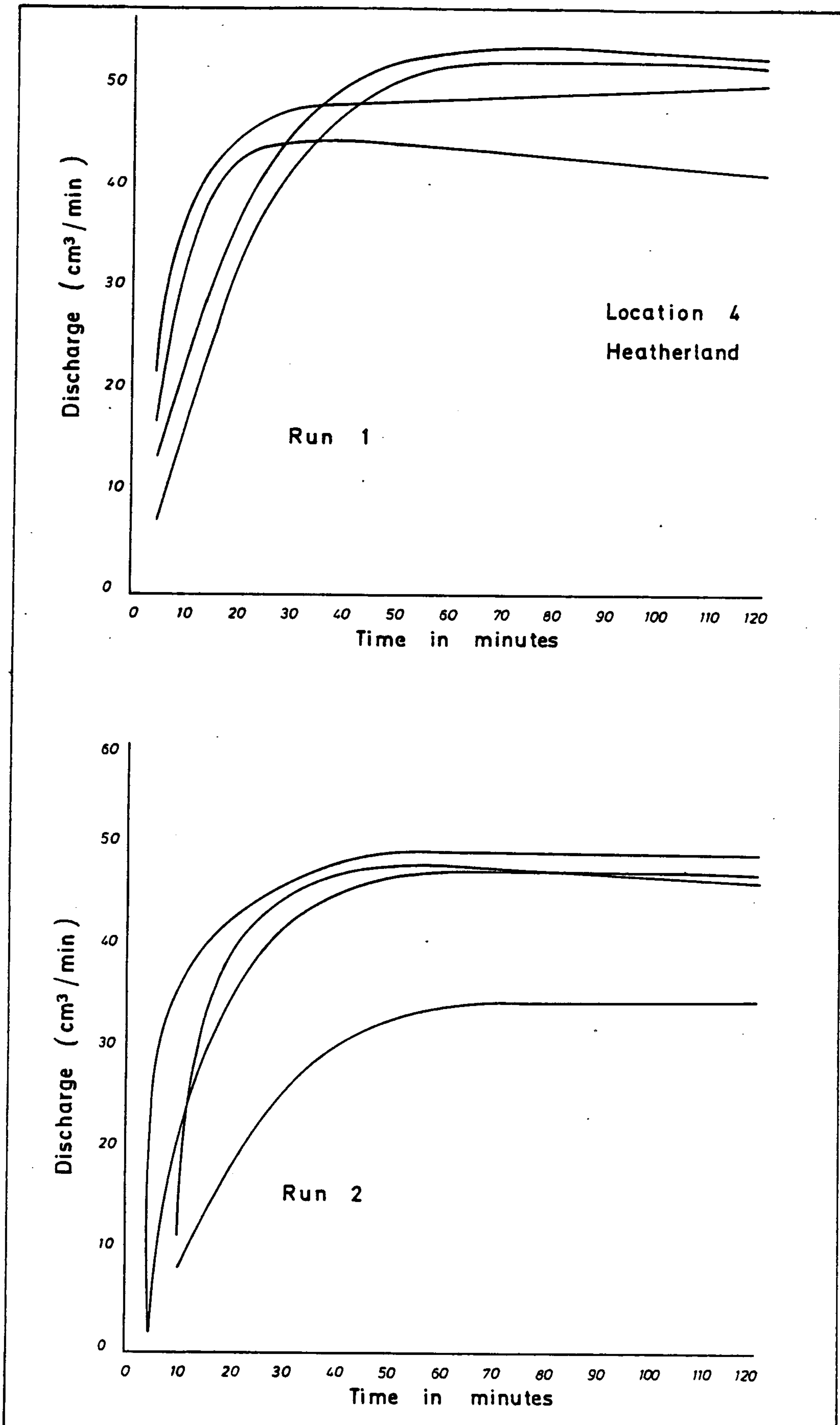

Figure 30. Hydrographs generated from artificial rainfall in each site of location 4.

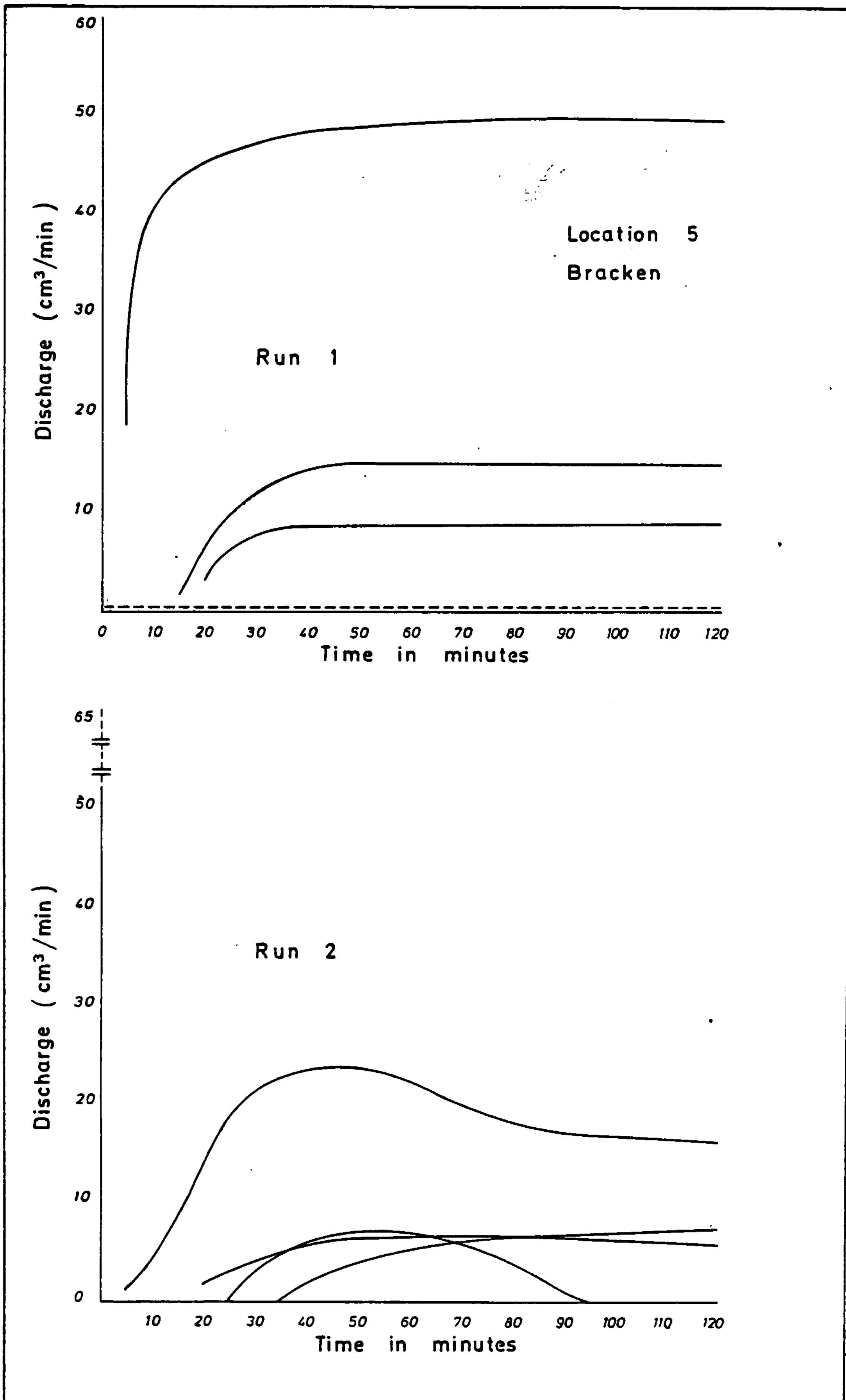

Figure 31. Hydrographs generated from artificial rainfall in each site of location 5.

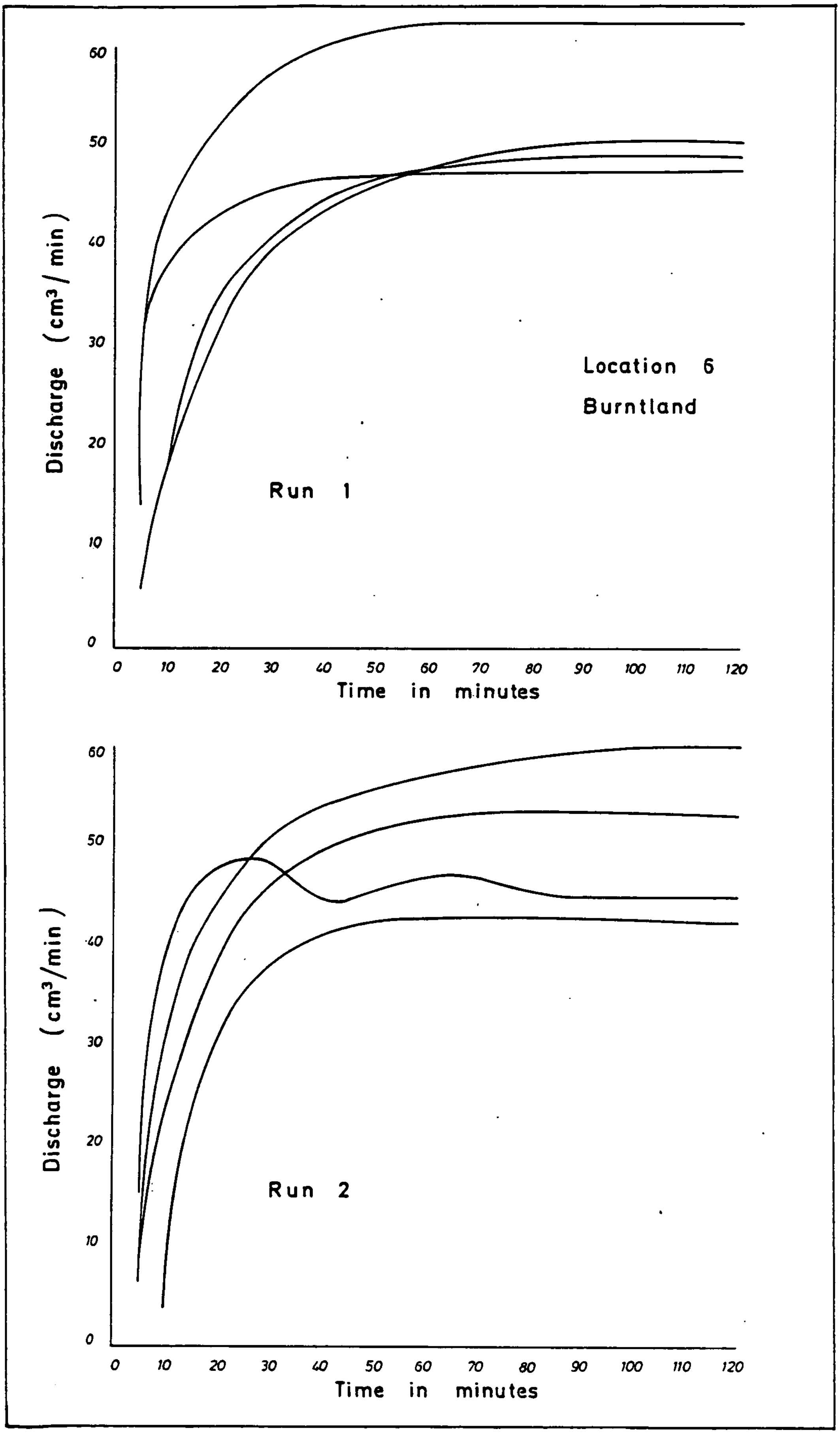

Figure 32. Hydrographs generated from artificial rainfall in each site of location 6.

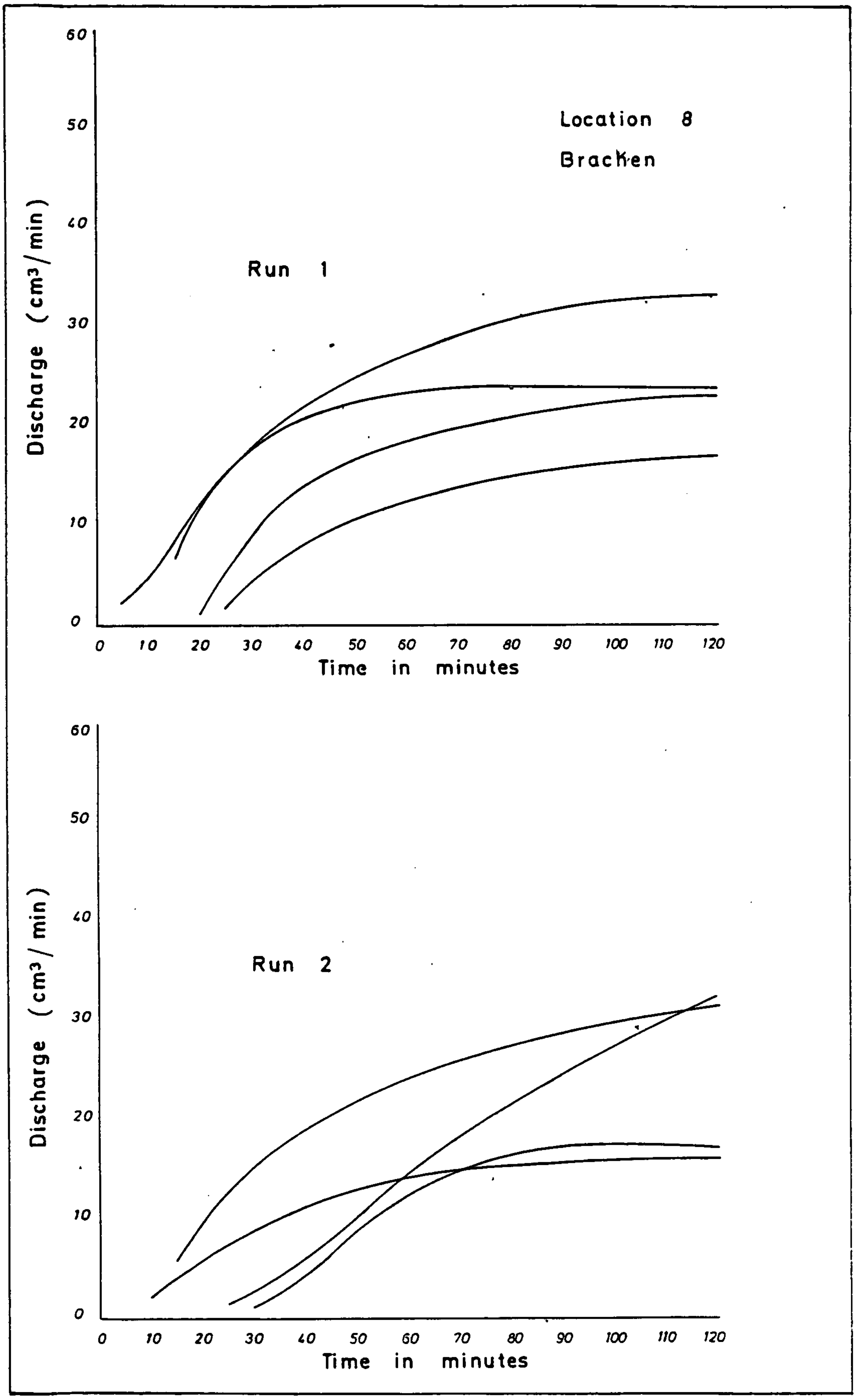

Figure 33. Hydrographs generated from artificial rainfall in each site of location 8.

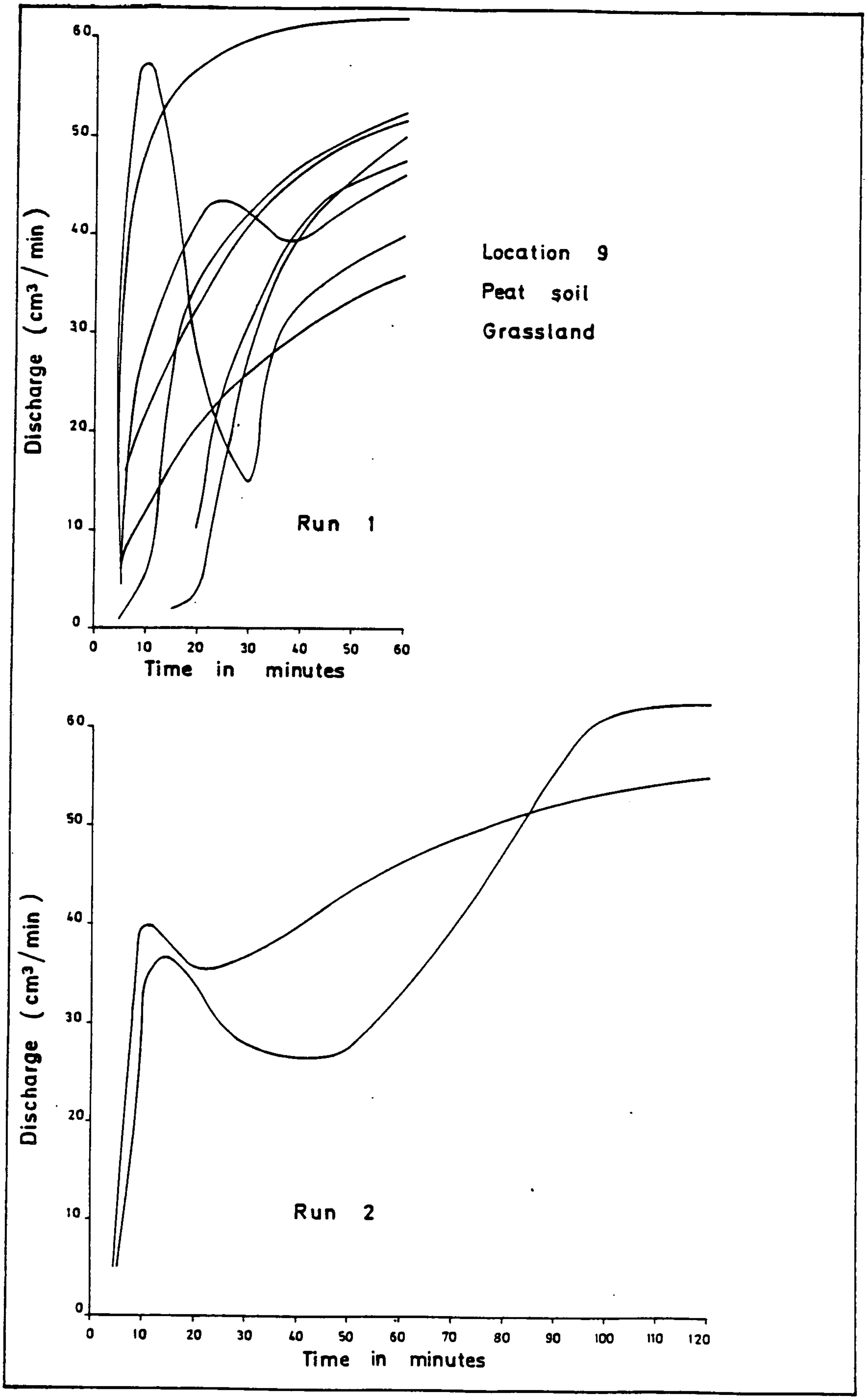

Figure 34. Hydrographs generated from artificial rainfall in each site of location 9.