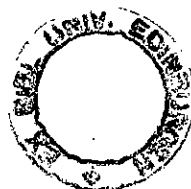


RAINFALL SIMULATION AS A TECHNIQUE
FOR MEASURING INFILTRATION

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In partial fulfilment of the requirements
for the degree of
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DECLARATION

I certify that this thesis is my own work and has not been submitted for any degree other than that of Master of Philosophy in the University of Edinburgh.

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SUMMARY

This thesis is concerned with the problem of measuring The infiltration capacity of watershed soils in a country such as Thailand. The literature relating to the measurement of infiltration by instrumental methods is reviewed, and the conclusion reached that a small portable rainfall simulator might be the best instrument for this purpose.

The design, construction and calibration of such a rainfall simulator is described, and the results obtained from its use in a variety of test conditions are presented and discussed. the conclusion is that the instrument as designed and constructed proved a satisfactory means of determining infiltration capacity under the range of conditions in which it was tested and that with slight modifications it could be of considerable use in Thailand

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CONTENTS

	Page
Declaration.	i
Summary.	ii
Acknowledgements.	iii
List of Figures.	vii
List of Tables.	ix
List of Plates.	x
List of Appendices.	xi
<u>CHAPTER I.</u> Introduction.	
I.1 The importance of infiltration.	1
I.2 Factors affecting infiltration capacity.	2
I.2.1 Nature of soil surface.	2
I.2.2 Nature of the underlying soil mass.	4
I.2.3 Characteristics of the fluid.	7
I.2.4 Time variation.	8
I.2.5 Land use.	9
<u>CHAPTER II.</u> Methods of infiltration measurement.	
II.1 General Methodologies.	11
II.2 Direct measurement.	11
II.2.1 Flooding-type infiltrometers.	11
II.2.2 Rainfall-simulator infiltrometers.	19
II.3 Discussion.	30
<u>CHAPTER III.</u> Design, construction and calibration of a rainfall-simulator infiltrometer.	
III.1 Essential parts of the instrument.	33
III.1.1 Reservoir and control unit.	33
III.1.2 The rainulator.	34
III.1.3 Supporting tripod and wind screen.	34

	Page	
III.1.4	Base and splash shield.	35
III.1.5	Runoff-water and sediment measuring system.	35
III.2	Proposed modifications to McQueen's apparatus.	35
III.3	Design and construction of rainulator.	36
III.3.1	Preliminary investigations.	37
III.3.1.1	Drop-size experiment.	38
III.3.1.2	Seven-hole rainulator experiments.	40
III.3.2	The full-scale rainulator and its auxiliary parts.	43
III.4	Testing and calibration of the full size instrument.	48
III.4.1	Drop-size test.	48
III.4.2	Representativeness of plot area catch.	49
III.4.3	Consistency in water delivery rate over time.	51
III.4.4	Relationships between hydraulic head and rainfall intensity.	51
III.4.5	Calculation of kinetic energy.	52
<u>CHAPTER IV.</u>	Experience gained using the simulator to make infiltration measurements under laboratory and field conditions.	
IV.1	Introduction.	54
IV.2	Measurements made in the laboratory.	55

	Page	
IV.2.1	The effect of bulk density on infiltration capacity.	55
IV.2.2	The effect of soil moisture content on infiltration capacity.	57
IV.2.3	The effect of rainfall intensity on infiltration capacity.	59
IV.3	Measurements made in the field.	60
IV.3.1	Experience gained using the simulator on the Department's nursery area.	60
IV.3.2	The effect of burning on the infiltration capacity of a Sourhope on Winton soil association.	61
IV.3.3	Seasonal differences in the infiltration characteristics of a shallow upland soil.	63
IV.3.4	Effect of surface cover removal on infiltration capacity.	65
IV.3.5	Experiment made on the alluvial fan.	66
IV.3.6	Investigation of lateral water. movement.	68
IV.4	Discussion.	70
<u>CHAPTER V.</u>	Conclusion.	72
	References.	77

LIST OF FIGURES

	Page
Figure 1. Form of infiltration relationship with time.	8.1
Figure 2. Diagram of McQueen's apparatus (1963).	33.1
Figure 3. Relationship between diameter of water drop and the spot it produces on treated filter paper Whatman No. 1.	37.1
Figure 4. The drop forming system.	38.1
Figure 5. Diagram of the seven-hole rainulator operation.	40.1
Figure 6. Diagram of the rainfall-simulator infiltrometer.	44.1
Figure 7. Diagram of the instrument in dynamic equilibrium.	45.1
Figure 8. The relationship between hydraulic head and delivery rate over a 60 minute period. Temperature 22.5°C. Tap water. Measurements taken at 10 minute intervals.	51.1
Figure 9. Relationship between hydraulic head and rainfall intensity using tap water at temperature 22.5°C.	51.2
Figure 10. Effect of bulk density on infiltration capacity of a soil.	56.1
Figure 11. Effect of moisture content on infiltration capacity of a soil	58.1
Figure 12. Relationships between rainfall intensity and infiltration capacity for a soil with a constant bulk density.	59.1
Figure 13. Graph showing infiltration capacity for a soil when dry and at field capacity.	60.1

	Page
Figure 14. Infiltration capacity of burned and unburned grassland on the Sourhope over Winton Soil association.	61.1
Figure 15. Infiltration capacity of the Brown Earth Soil on the Pentland Hills above Boghall Farm.	63.1
Figure 16. Infiltration capacity of a gleyed soil of the Colzium association.	65.1
Figure 17. Infiltration capacity of an alluvial soil in relation to rainfall application rate at Boghall Farm in Summer 1976.	67.1
Figure 18. Autumn infiltration capacity of an alluvial soil at Boghall Farm, 1976.	69.1
Figure 19. Results from an investigation of lateral water movement in the use of the infiltrometer.	69.2
Figure 20. Diagram showing an estimation of the amount of the lateral water movement from the base unit.	71.1

LIST OF TABLES

	Page
Table 1. Land use in order of associated infiltration. (After Musgrave and Holton, 1964)	9
Table 2. Velocities of falling water-drops of different sizes after various heights of fall (after Laws, 1941).	23.1
Table 3. Comparisons between infiltrometers (after McQueen, 1963).	28.1
Table 4. Drop size produced by several combinations of hole size, wire size and width of countersinking.	39
Table 5. The relationship between the hydraulic head and the rate of dripping.	41
Table 6. Rainfall intensity test for the small device.	43
Table 7. Result of drop-size measurements of the rainfall simulator.	49
Table 8. Scale reading on reservoir in relation to depth of rainfall caught on the plot area for 10 minutes.	50
Table 9. Comparison of kinetic energy to McQueen's instrument.	
Table 10. Infiltrometer data sheet.	55.1
Table 11. The relationship between bulk density of a soil and the average infiltration capacity.	56

LIST OF PLATES

		Page
Plate 1.	Drop size measurement by the filter paper method.	38.2
Plate 2 (A & B).	Base units and installation.	47.1
Plate 3 (A & B).	The instrument in field use.	48.1

LIST OF APPENDICES

	Page
Appendix 1. Infiltrometer, list of materials, details.	88
Appendix 2. Rates of delivery over an extended period of time at 22.5°C in relation to water caught at the plot position in 10 minute intervals.	91
Appendix 3. Scatter diagram of the bulk density experiment.	93
Appendix 4. Results of the experiment to determine the effect of moisture content on infiltration capacity.	100
Appendix 5. Scatter diagram of rainfall intensity in relation to infiltration capacity.	103
Appendix 6. Results obtained on the Department of Forestry & Natural Resources' nursery area.	109
Appendix 7. Results of experiment to determine the effect of burning on the infiltration capacity of a Sourhope soil on Winton soil association.	114
Appendix 8. Results of experiment to determine the effect of seasonal differences in the infiltration characteristics of a shallow upland soil.	120
Appendix 9. Results of experiment to determine the effect of surface cover removal on infiltration capacity.	127
Appendix 10. Results of experiment made on the alluvial fan.	133
Appendix 11. Results of experiment to investigate lateral water movement.	139

CHAPTER I

INTRODUCTION

I.1 The Importance of Infiltration

The infiltration capacity of a soil is generally believed to be one of its most important hydrological characteristics. As has been pointed out by Kittredge (1948), Colman (1953), and many others, it is this capacity which determines the proportion of any given rain event that becomes immediate surface runoff and which can therefore cause erosion and contribute directly to the generation of flood peaks. Consequently in areas where erosion and flooding are serious problems as they are in my own country of Thailand, the introduction of land management systems that can increase infiltration rates is a matter of considerable importance.

Infiltration was first defined by Horton (1933) as the process involved where water soaks into, or is absorbed by, the soil. This definition serves to distinguish it from the term "percolation" which is referred to as the free downward flow by gravity of water in the zone of aeration. Both terms may be used in the same sense, but to avoid equivocation the latter should be reserved for the movement of water below the surface layer of the soil. The maximum rate at which a specified soil when in a given condition can absorb rainfall is defined as "infiltration capacity". When the rate of supply of water to the soil is less than this maximum rate, the rate at which water enters the soil, then, is termed "infiltration rate". As long as infiltration is proceeding at a rate higher than the rate of supply at the soil surface during a storm, all of the rainfall will infiltrate into the soil so there will be no surface runoff. Only when the supply rate exceeds the maximum rate, will surface detention or runoff occur.

I.2 Factors Affecting Infiltration Capacity

Infiltration takes place in a complex environment at the terrestrial surface. The infiltration capacities of most soils are therefore characterized by high variability. Many experiments have been undertaken over the years to determine the factors that have most effect on this variability, and in general terms these are now well known. Excellent reviews of the factors affecting infiltration have been published by Free, Browning, and Musgrave (1940), Sherman and Musgrave (1942), Kittredge (1948), Colman (1953), Parr and Bertrand (1960), Johnson (1963), Musgrave and Holton (1964), and the summary that follows is based mainly on these reports.

I.2.1 Nature of Soil Surface

One of the major factors affecting the infiltration rate is the nature of the soil surface. This is controlled by many interacting factors such as vegetation cover, compaction, swelling and shrinkage of the soil due to moisture changes, surface sealing, and frost.

The vegetation cover is perhaps the most important of these influences. It helps to retard surface flow, protects the soil from being beaten by raindrops, and increases the permeability of the soil surface by creating passages along root channels (Ward, 1975). Evidence from many experiments has shown that soils under the cover of vegetation always have higher infiltration capacities than those for the same soils without such cover. This evidence also suggests that density of vegetation cover is more important

than vegetation type (Kittredge, 1948, Bruce and Clark, 1966).

Compaction of the soil surface is well known for greatly and rapidly reducing infiltration capacity. This may result from raindrop impact, the tramping effect of man and animal, and compression from agricultural and other machinery particularly on soils with fine texture such as silts and clays (Ellison, 1945).

Since most soils contain colloids they are prone to shrinkage when dry and swelling when wet. This shrinkage and swelling can have a considerable effect on the porosity of the soil surface. Shrinking can result in cracking which means that dry clays, for example, can have very high initial infiltration capacities. Swelling on the other hand reduces pore spaces and can be the major cause of the extremely low infiltration capacities that characterise clay soils when wet.

In the absence of an adequate surface cover, raindrop impact can break down soil crumbs into particles of different sizes. Subsequently a slaking action is created, particularly in fine textured soils, and these particles may be washed into the surface layer of the soil, clogging pores and greatly reducing the infiltration capacity (Lowdermilk, 1930). In addition, some soils which have experienced prolonged dry conditions may suffer a surface sealing from dust, and this, too, can reduce infiltration capacity (Colman, 1953).

Soil wettability is another factor that affects the infiltration capacity of the soil surface. Some soils with abundant organic matter and dried materials may resist wetting, and water is often found ponded on the surface for some considerable time. As a result the infiltration capacity is considerably

reduced (Jamison, 1945). This effect is offset to some degree, however, by the fact that ponded water on the soil surface creates hydraulic pressure which induces higher infiltration than might otherwise occur (Buower, 1963, Dixon, 1975).

Freezing of the soil moisture at the surface, due to the effects of frost also reduces infiltration capacity; but unless the soil is frozen to considerable depths, this reduction occurs only at the beginning of the rain event because surface frost generally melts quickly under the influence of rain (Wisler and Brater, 1959).

I.2.2 Nature of the Underlying Soil Mass

The second major factor affecting infiltration capacity is the nature of the underlying soil mass. As with soil surface conditions, this, too, is determined by a wide range of complex and interacting factors, the most important being porosity, soil moisture content, nature of the soil profile, organic matter, and biotic effects.

Porosity is one of the most important factors which determines the rate at which the water may move into the soil. Of particular importance is the number of large pores of above capillary size existing throughout the soil mass through which water is able to move under the force of gravity. This seems to be more important than total porosity of the soil. Total porosity of the soil, however, may well serve to indicate the potential capacity for retaining water, but not necessarily the rate at which water may move into the soil. For instance, soils

rich in clay have high porosities, but because most of the pores are very small they also have very low permeabilities. Sands, on the other hand, have lower porosities, but contain more large pores which permit a rapid flow of water through them.

Pore distribution is also of considerable significance. Most soils are generally composed of particles of different sizes ranging from coarse sand, to fine sand, to silt, and to clay. These particles may exist in the soil mass as single grains or primary particles such as pure sands, or they may flocculate into tiny crumbs or secondary particles. The pore spaces in the soil mass which are the result of the arrangement of these particles will therefore be different in size depending upon size and shape of the particles (Baver, 1956, Russell, 1961). Soils which are composed of large single grains will have pores of greater diameter than soils made up of fine particles only, thus the infiltration of water into the larger pore soils is greater than the small ones, all other things being equal.

As the result of flocculation, however, a clay soil may possess large aggregates which may behave very much like single grains of similar size. These aggregates may form sufficient large pore spaces to permit a high rate of infiltration. Whether such a soil can maintain a high rate of infiltration depends upon the degree of the aggregate stability and the permanency of the pore size. Aggregates often disintegrate when wetted, thereby rapidly reducing the non-capillary porosity (Musgrave and Holton, 1964). Thus it is obvious that both structure and porosity of soils are dynamic characteristics.

In natural conditions the existence of a uniform moisture content throughout a soil profile is impossible. The relation

of infiltration capacity to the moisture content of the soil has been discussed by Horton (1933), Neal (1937), Wilm (1941), and many others. There is general agreement that infiltration capacity of a soil varies inversely with the moisture content. Dry soils generally have high infiltration capacities because (a) most of their ^{their} large pores are filled with air, not water, and (b) because the movement of water into them is often speeded up by capillary forces which pull water downwards from the surface (Colman, 1953). As rainfall continues, however, the moisture content increases, the pore spaces in the soil mass are gradually filled with water and the space available for subsequent water flow is reduced. Consequently the rate of water intake by the soil decreases, and ultimately the soil becomes saturated and the minimum infiltration capacity is reached. In soils such as silts and clays colloidal swelling may also reduce pore spaces and lead to an even more rapid decrease in infiltration capacity.

The nature of the soil profile is also a factor affecting infiltration capacity. Water cannot continue to enter the soil more rapidly than it can be transmitted downwards through the least permeable layer in the profile. Repeated cultivation of land, for example, can result in pan formation of the soil. The initial infiltration of such soil depends upon the ability of the upper soil layers to take in water, but once it becomes saturated, the transmission rate through the subsoil then regulates the infiltration capacity of the whole profile. In contrast, if the uppermost soil layer is the least permeable, then the infiltration capacity of the soil is limited by the movement of water into this layer from the surface (Musgrave and Holton, 1964).

Organic and biotic effects have considerable influence on the infiltration characteristics of the soil mass. Organic matter helps to bind, lighten, and expand soil aggregates which in turn helps to create large pore spaces (Brady, 1974); whilst biotic activities such as the presence of earthworms and other burrowing creatures also provide non-capillary porosity in the soil mass (Ward, 1975). Both influences tend to increase the infiltration capacity of the soil.

Other factors influencing infiltration capacity in the underlying soil mass are entrapped air and temperature. Unless air which is already present in the soil mass can escape freely when water infiltrates into the soil resistant forces will be created and the rate of infiltration will be retarded as reported by Christiansen (1944), Vachud et al. (1974), and Dixon (1975). Infiltration capacity is also influenced by soil temperature which changes water viscosity. Higher temperature increases the infiltration capacity as shown by Musgrave (1955).

I.2.3 Characteristics of the Fluid

Infiltration capacity is also affected by the fluid itself. Turbidity resulting from clays and colloids can decrease infiltration rate due to clogging of the pore spaces. Contamination of the fluid by salts is often found, particularly in alkali soils, which may affect the viscosity of the fluid and form complexes with the soil colloids which, therefore, affect the swelling rate when wet. The temperature of the infiltrating water is also significant, for it affects its viscosity and can

either increase or decrease the infiltration rate (Musgrave and Holton, 1964).

I.2.4 Time Variation

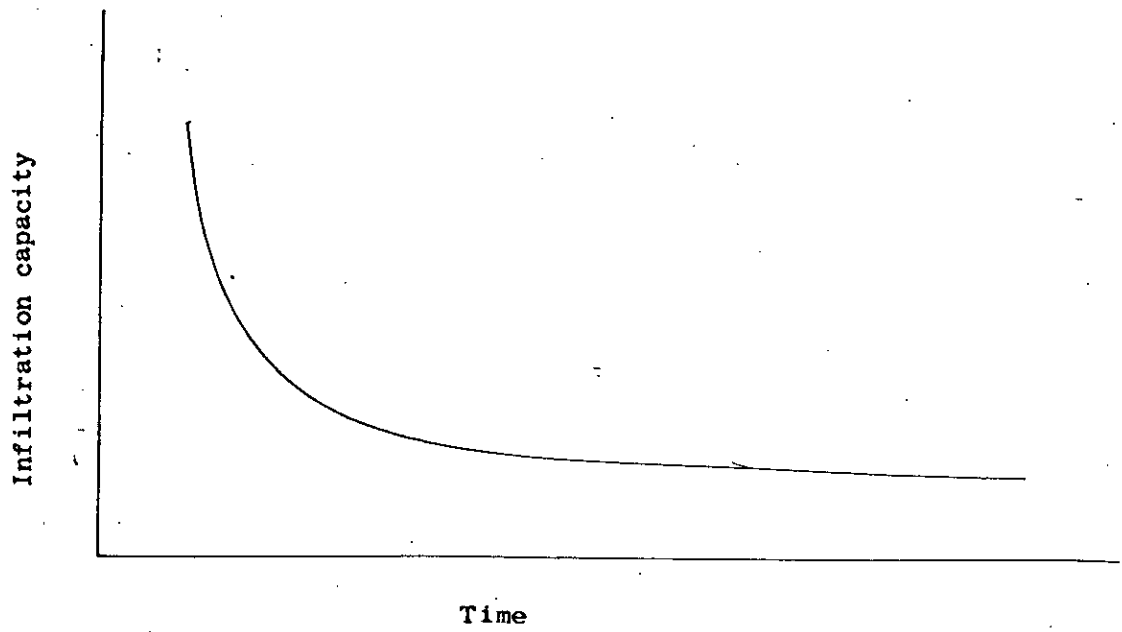
It is apparent from the preceding account that many of the factors affecting infiltration vary with time, and that the infiltration capacity of a soil is a dynamic rather than a static property. Such variability falls into several quite distinct time scales.

In the short term it is quite normal for infiltration capacity to be high at the beginning of a period of rain, and to fall rapidly to a much lower, relatively stable rate, as shown in Fig. 1.

The initial rates can be very high, often exceeding 100 mm/hr. (Bruce and Clark, 1966). But such rates occur for only a short period of time, and in most soils the flatter part of the curve is reached in an hour or so. The rates experienced in this part of the curve, however, are much lower ranging from c.3.75 mm/hr. in sandy soils down to c.1.25 mm/hr. in clays (Musgrave, 1955). This variation is mostly influenced by rapid changes in nature of the soil both surface and sub-surface conditions with time.

Many of the factors affecting infiltration also exhibit longer term variations and trends. For example, seasonal changes occur in many localities due to changes in vegetation, temperature, and soil moisture conditions. Wisler and Brater (1959) found that the average summer infiltration capacities of soils in the Range River basin in Michigan were 3 to 4 times higher than they were in

Figure 1. Form of infiltration relationship with time.



winter. Longer term trends can also be expected to occur in response to systematic changes in soil or vegetation characteristics over long periods of time.

I.2.5 Land Use

It is apparent from the preceding discussion that infiltration capacity is mainly controlled by soil conditions and vegetation cover both of which can be greatly affected by man's activities. Soil conditions, for example, may be affected by cultivation, fertilizing, and drainage practices which may, in turn, change the natural structural aggregates of the soil profile. The general relationships between land use and infiltration capacity are fairly well established. We know, for instance, that lands where grazing is conducted nearly always have low infiltration capacities. We also know from work by Sherman and Musgrave (1942) that good grazing management can give average infiltration rates 7 to 8 times as much as those on poorly managed pastures. Similar results were found by Shali (1967), and Peason, et al. (1975). We further know from data published by Musgrave and Holton (1964) that bare soil generally has the lowest, and good woodland the highest, infiltration capacity as shown in Table I.

Table I Land Uses in Order of Associated Infiltration.

(After Musgrave and Holton, 1964)

- | | |
|--------------------------------|-------------------|
| 1. Fallow | 8. Pasture, fair |
| 2. Row crops, poor rotation | 9. Woods, poor |
| 3. Row crops, good rotation | 10. Pasture, good |
| 4. Pasture, poor | 11. Woods, fair |
| 5. Legumes after row crops | 12. Meadows |
| 6. Small grains, poor rotation | 13. Woods, good |
| 7. Small grains, good rotation | |

In many cases, however, those attempting to manage land use to achieve specified hydrological objectives need to have more specific information than this. They need to know the rates at which water will actually infiltrate into the ground under different land uses in any given locality. This information can generally be obtained only by interpreting infiltration measurements in the area concerned.

Unfortunately, such measurement is far from easy, and despite much research and experimentation in the United States and elsewhere, no general agreement has yet been reached as to the best instrument for this purpose. It is difficult, therefore, for workers in developing countries such as Thailand to know how best to set about collecting infiltration data.

The purpose of this thesis is, therefore, to review from the literature those instruments which have been used to measure infiltration and then to describe the construction and evaluation of a prototype rainfall simulator which appears to be an appropriate instrument for use in conditions similar to those found in Thailand.

CHAPTER IIMETHODS OF INFILTRATION MEASUREMENTII.1 General Methodologies

There are two major methodologies in the determination of infiltration. One is the direct measurement by instruments - the infiltrometer method, the other is the indirect approach by which infiltration capacity is evaluated from rainfall and run-off data, the so-called hydrograph analysis method.

The indirect method can only produce generalised infiltration data for entire catchment areas. These may be suitable for engineering purposes (Horton, 1940) but as Parr and Bertrand (1960) pointed out such data are of very little value for land management purposes. For this reason the method is not considered further in this thesis.

II.2 Direct Measurement

The direct or infiltrometer method can be divided into two categories according to the manner of the application of water. These are generally described as the flooding, and the rainfall simulator approaches.

II.2.1 Flooding-Type Infiltrometers

The main principle of this method is that infiltration capacity can be determined by ponding water in an open-ended container resting on, or driven into, the soil and measuring the

rate at which water is lost from it.

According to Hills (1968), this technique was probably first used by Muntz (1908) to study infiltration between irrigation canals, but few details are available to indicate the exact nature of the equipment he used. The first papers to contain such details are those published by Bürger in 1927, and 1929. In these he reports results obtained using an open-ended steel cylinder with an area of 100 cm^2 . This was driven into the soil, filled with water to a depth of 10 cm., and allowed to stand until all the water had soaked into the ground.

In forest land with a good humus cover, this process occurred in just over one minute. In arable fields it took as long as 3 hours and 38 minutes. Bürger considered that his method gave acceptable results, although he did suggest that they might have been more accurate if he had used a long cylinder.

Simple open ended cylinders were also used by Katchinsky in 1930. These consisted of graduated glass tubes, 3 cm. in diameter, with open ends which were inserted into the ground through a borehole 6 cm. deep. Known amounts of water were periodically added and infiltration data were averaged. Similar experiments were reported on by Auten (1933) and Stewart (1933), and by Auten again in 1934, although this time he used square rather than round enclosures. Of these works, however, only Katchinsky recognised that the results obtained using simple instruments like these might be affected by lateral seepages, and in 1936 he published a second paper in which he reported on experience gained using a cylinder surrounded by a "buffer zone". This comprised an inner cylinder separated from the soil body by a surrounding channel which was also filled with water but from

which seepage was not measured. He concluded that lateral seepage was important and that his earlier results overestimated the true infiltration capacities of the soils concerned.

The problem of lateral seepage was also recognised by Musgrave (1935). He attempted to overcome it by jacking 15 cm. diameter metal cylinders into the soil until they reached the B-horizon. The lower end of ^{each} cylinder was sharpened to make it easier for driving into the soil, and to avoid too much soil disturbance. Musgrave also introduced the method of maintaining a constant hydraulic head in the cylinder by using a dispensing graduated burette located above it. The purpose of this practice was not clearly explained but it was well understood that the method was to equalize the driving force at all times. The burette served as a water feeder tube from which infiltration capacity was determined. The instrument also incorporated a screen to prevent dust falling on the ponded water and possibly affecting the soil surface beneath. Musgrave considered the results of this work to be highly satisfactory, and this method was widely used in the United States during the late 1930's (Musgrave and Free, 1936, Free et al, 1940).

Other researchers, however, were less certain about this kind of instrument.

Kohnke (1938), in the first paper to consider the flooding infiltrometer as a useful standardised instrument for determining infiltration capacity believed that any such instrument should meet three requirements. These are that it should provide downward penetration of water into the soil; it should not impede the lateral flow of water because this is part of the natural infiltration process; and it should not create air pressure greater

than that occurring naturally. He developed a flooding infiltrometer which was different from that of Musgrave's by utilizing a block unit composed of 16 compartments, each of which was 20 cms. long, 10 cm. wide, and 7.5 cm. deep. When set in position, the compartments were driven 3 - 5 cm. into the soil. The four centre compartments were used to measure infiltration, while the other twelve served as a buffer area. Each compartment was supplied with water in a manner devised by Musgrave, and ^aperforated disc was also provided to exclude dust. This arrangement was probably the first instrument in which the buffer zone was introduced to minimize air confinement in the soil, and to provide an appropriate lateral flow of water under the plot. Kohnke did not, however, produce conclusive evidence that the use of a buffer zone gave significantly better results than instruments not using this technique. He could only suggest that the use of such a zone appeared to give lower and less variable results.

A simpler, and more convenient type of buffered infiltrometer was devised by Nelson and Muckenhirm (1941). This was the double ring infiltrometer consisting of two concentric rings of galvanised iron - the inner one having a diameter of 20 cm. and a height of 12.5 cm., the outer one a diameter of 40 cm. and a height of 7.5 cm. Both rings were pushed 2.5 cm. to 5 cm. into the ground, and a hydraulic head of c. 6 mm. was maintained in both rings by Musgrave's method. They found that virtually no lateral flow from the central ring occurred with this treatment, and that it disturbed the soil much less than the use of either Kohnke's or Musgrave's type of instrument.

Further information on the effect of ring size and buffer

area on the results obtained by using flooding infiltrometers was produced by Marshall and Stirk (1950). After experimenting with several sizes of single and double ring infiltrometers, they came to the conclusion that: (a) increasing the size of the buffer area decreased lateral flow below the ring, (b) increasing the ring diameter decreased the rate of infiltration, which meant that the lateral movement of water through the plot boundary was probably small in relation to the large amount of water applied.

The 1950's saw a move towards work intended to rationalise and control the sources of error involved in using ring infiltrometers. Schiff (1953) in a study using ^{an} infiltrometer to determine artificial ground water recharge rates found that the rate of intake was affected not only by changes in hydraulic head within the instrument, but also by the length of the wetted soil column beneath it - a factor not considered by earlier workers.

Aronovici (1955) also studied the effects of hydraulic head on infiltration rate. He found that changes of infiltration with time using ring infiltrometers could be attributed prominently to the changing characteristics of the head of water in the soil column beneath them. He also found that increasing the size of the infiltrometer rings decreased the rate at which water entered the soil, a similar result to that obtained earlier by Marshall and Stirk (1950).

Another important problem that received attention was that concerning the number of measurements needed to characterize the infiltration capacity of an area. Burgy and Luthin (1956, 1957) conducted tests with both single and double ring infiltrometers. They found that an average of six came within 30% of the true mean when no restricting layers were present in the soil. They also

found no significant differences between the results obtained by the two different types of instrument used. In the discussion of this paper, however, Schiff, as quoted by Parr and Bertrand (1960), pointed out that these results occurred because the soils were too permeable for lateral seepage to be an important consideration. He would not expect single and double ring infiltrometers to produce identical results in less permeable situations. Slater (1957) also studied this problem using sets of 15 single ring infiltrometers 11.25 cm. in diameter, and found that 48 replications on each test were needed to ensure an accuracy of $\pm 10\%$ of the mean at the 95% probability level.

Work aimed at achieving a better understanding of how ring infiltrometers work continued during the 1960's. Olson and Swartzendruber (1960), for example, used a laboratory sand model to determine the ring sizes for accurate infiltration measurement by double ring infiltrometers. They found that a buffer width of at least 30 cm. was required before the infiltration rate through the inner ring could be regarded as a reasonable accurate measure of the true infiltration capacity. At lesser ring widths, measured infiltration greatly exceeded the true rate. In a second paper, (Swartzendruber and Olson, 1961 (a)) they concluded that a double ring system with ring diameter of 100 and 120 cm. was large enough to overcome the problems of site variability in most situations. They realized, however, that it was not always practicable to use a system as large as this, and in a third paper (Swartzendruber and Olson, 1961 (b)) they suggested that for most purposes an instrument with inner and outer ring diameter of 20 and 30 cm. respectively would prove satisfactory. The importance of cylinder size was also stressed by Johnson (1963).

The problem of soil disturbance as the infiltrometer was pushed into the soil also received attention at this time. Indeed, Erie (1962) went so far as to suggest that "the thickness of cylinder material probably has more effect on the validity of measurements than the diameter". After testing various designs he suggested that "an 20 cm. (8 in.) cylinder made from 12-gauge metal equipped with a ring on top represents a very suitable piece of equipment". The need to use thin-walled cylinders was also emphasised by Davis and Fry (1963).

Following the publication of a series of paper on the theory of infiltration by Philip (1957, 1958), Bouwer (1963) used a buffered infiltrometer to explain, theoretically, the effect of hydraulic head in the rings on water movements under the infiltrometers. Details of equipment used were not stated, but the work was centred on the depth of cylinder penetration, the diameter of cylinder, and the level of water being maintained in it. The conclusions were that: differences in water levels between the inner and the outer rings caused an error in measuring infiltration, and that this error could be reduced by increasing the depth of cylinder penetration into the soil. Shull (1964) also studied the effect of cylinder penetration, and found that 30 cm. diameter cylinders at depths of 6, 12, 18 and 24 cm. gave significantly different results at the 1% probability level. He recommended that the depth of insertion should be carefully controlled and standardised.

Although most of the work undertaken in the 1950's and 1960's had been concerned with double ring infiltrometers. Hills (1968, 1970) did not consider that it had demonstrated conclusively that this form of flooding infiltrometer had any great advantages over

the earlier single ring type, particularly for use in areas that were not flat. He pointed out that most of this work had been carried out to provide answers to irrigation problems and that the workers concerned had not been faced with problems that occur when one tries to install a large ring infiltrometer on sloping terrain. In his view these could lead to greater errors than those occurring from the absence of a buffer zone. After extensive field and laboratory tests he concluded that a thin-walled, single ring, infiltrometer 10 cm. in diameter, carefully pushed 5 cm. into the ground was a perfectly adequate means of measuring differences in the infiltration capacities of the various soils occurring in his research watershed.

Hills' conclusions about the usefulness of single ring infiltrometers are supported by Williams et al. (1969), who found that when single and double ring infiltrometers were used at the same place at the same time they gave very similar results.

The most recent publications concerning flooding infiltrometers such as Vachaud, Gaudet, and Kuraz (1974); and Dixon (1975) have been largely concerned with the effects of entrapped air on measured infiltration rates. Both have shown that results are likely to seriously underestimate the true infiltration capacity if air cannot escape freely from the soil as infiltration proceeds: a fact already known from work by Powers (1934).

II.2.2 Rainfall-Simulator Infiltrometers

As the name suggests, this approach attempts to determine infiltration capacity by applying water to the area under investigation in the form of "artificial rainfall". Water is applied to the ground at a rate exceeding that at which it can be absorbed, and the infiltration capacity is taken to be the difference between the rate at application and the rate of runoff. The "artificial rain" is generally produced either by pressure sprays, or by gravity devices producing controlled rates of dripping.

The earliest rainfall-simulators were very simple. According to Wisler and Brater (1959) one of the first simulators was that devised by Horton before the First World War. It consisted of a simple sprinkling system with a number of radial horizontal pipes rotating on a vertical axis 1.8 metres above the ground. Horizontal spray jets attached to the pipes in order to spray water into the test plot below. It is not known, however, whether he ever published the results of this work. Another early device was that used by Lowdermilk (1930). This comprised two horizontal 2.5 cm. pipes fitted with special Skinner overhead sprinkling nozzles (No.2). These nozzles were spaced at 60 cm. intervals on each pipe and were so placed as to stagger the jets 30 cm. apart. The device sprayed water upward under pressure on plots ranging from 10 to 1,000 sq.ft. Rainfall intensity was averaged from nine small rain gauges located on the test plot; but other characteristics of this artificial rain, such as drop size and distribution, were not studied. Duley and Hays (1932) reported on infiltration experiments in which the water was applied

by men with watering cans. This method was also used by Duley and Ackerman (1934). Other early equipment was described by Nichols and Sextor (1932), Neal (1937), and Craddock and Pearse (1938).

These early instruments had many deficiencies. The "artificial rain" they generated bore little resemblance to natural rain either in drop size or velocity. They were often cumbersome and inconvenient to use - Craddock and Pearse's equipment, for example, required $1\frac{1}{2}$ -ton truck to transport it, and two men half a day to set it up - and they were unreliable. Nevertheless they did suggest that a better measure of infiltration capacity might be obtained using this approach than by the flooding infiltrometer techniques.

Accordingly the U.S. Department of Agriculture sponsored a series of research programmes aimed at solving these problems. This research resulted in the production of a series of simulators in the late 1930's and early 1940's based primarily on the use of spray nozzles, and known as Type A, B, C, D, E, F, and FA respectively. These nozzles were often described by their trade name: such as "Skinner Catfish nozzle", the "Grinnell 1.5 nozzle", and the "80100 veejet".

Type A to C were not considered particularly satisfactory and little is known about them. Type D, E, and F, however, were considered a major improvement in earlier devices and were used in many subsequent infiltration studies.

The D-type apparatus consisted of four stationary 1.5 "Mulsifyre" nozzles mounted on an overhead frame which allowed water to be applied to a plot 1.8 m. wide by 7.2 m. long, and to an 0.45 m. strip adjacent to the sides and upper end of the plot.

The water was sprayed ^{downwards} ~~upwards~~ and fell directly onto the plot.

It was used by Beutner, Gaebe, and Horton (1940) to evaluate the effects surface soil conditions and their management on erosion and infiltration. They considered that it produced a satisfactory distribution of water, and that the drop size was comparable to actual rainfall.

The type-E apparatus was developed by Brost and Woodburn in 1938, 1939, (Parr and Bertrand, 1960) and Brost and Woodburn again, (1942). It used upward pointing "Smiling Cat" nozzles, to spray water onto a 1/100 acre plot, and specialised in studying the effects of small drop-size rain.

The type-F apparatus was based on a nozzle (the "Type-F nozzle") designed to produce a high energy spray of low intensity. The nozzle produced large drops, 3.2 to 5.0 mm. diameter, with a low impact velocity and a kinetic energy less than 65% of that of natural rain. The water was sprayed upwards and allowed to fall in an arch-like pattern from a height of about 2.1 m. onto the test plot, which was generally 1.8 x 3.6 m. with a surrounding 0.9 m. buffer zone (Diebold, 1941, Mutchler and Hermsmeier, 1965).

The type-FA apparatus was the same as the type-F except that it used fewer nozzles with a lower pressure and employed a plot size only 30 x 75 cm. with a buffer zone of 45 cm. (Diebold, 1941). A further version of this apparatus was the Rocky Mountain infiltrometer which used a plot of 60 x 120 cm. (Wilm, 1941).

Wilm (1941) considered that most of these newer infiltrometers gave satisfactory estimates of "relative" infiltration, but in the tests he carried out he found that his results were too variable for any assessment to be made of the accuracy with which they measured true infiltration capacity. Horton (1940), however, was less ^{sure} ~~sure~~ of their value. He felt that none of these

instruments generated sufficiently "fine" rainfall for them to give realistic results. He also felt that the effect of plot size on infiltration had been inefficiently investigated. His own view was that lateral seepage could seriously affect the results from installation using small plots, in just the same way as it affected the results of flooding infiltrometer experiments.

Horton's comments about the nature of the "rainfall" produced by their simulators had in fact been anticipated by the U.S. Soil Conservation Service's research programme, for in addition to investigating simulator design it had also involved a study of natural rainfall characteristics and their relation to infiltration. The outcome of this work was a series of important papers by J.O. Laws. In his first paper (Laws, 1940) he reported on a detailed comparison of five different rain applicators. He found that drop size ranged from c. 1 mm. to c. 5 mm. in diameter. He also found that as the drop size increased the infiltration rate decreased by as much as 70%, and that erosion losses increased by as much as 1200%. He was able to show these graphically in terms of energy of rain per unit of area - the E/A index of rain erosivity. This index depended solely upon the drop size and velocity of the spray and increased with increasing drop size or increasing drop velocity. The experiment led Laws to conclude that the drop size of rainfall had an important effect on erosion and runoff, and that artificial rain apparatus must actually simulate rainfall so far as drop size was concerned. Laws also suggested that to adequately describe rain so far as erosion and infiltration were concerned it was necessary in addition to know the size and velocity of its drop.

In his second publication Laws (1941) described techniques for using a still camera to take photographs of falling water drops

produced from glass tubes of small diameter. The drops of known sizes were allowed to fall in still air from different heights ranging from 0.5 to 20 metres. He also measured the drop sizes. This enabled him to produce the information summarized below in Table 2.

In addition, Laws also made observations of natural raindrop-velocities and found that there was a tendency for the velocities of natural raindrops falling from great heights to be lower than the velocities of similar sized waterdrops falling from only 20 metres indoors. He suggested that this might be due to the turbulence of the atmosphere through which the raindrops passed.

It is apparent from Table 2 that small water drops need only a short distance of fall to reach their terminal velocity. A drop of 1.25 mm. diameter, for example, takes only 5 metres to reach its terminal velocity of 4.85 m/sec. Large drops, on the other hand, require greater distance - over 10.5 metres in the case of drops of 6.1 mm. diameter (not shown in Table - p.720).

A third paper (Laws and Parsons, 1943) was concerned with characteristics of natural rainfall. It described the range and distribution of drop sizes associated with rainfalls of different intensities, and showed that medium drop size increased by a factor of 3 over the range of intensities studied.

As the result of Laws' work it became apparent that of the instruments described earlier only Types F and FA produced artificial rain that bore much resemblance to natural rain. In a thorough test of both instruments Wilm (1943) estimated that the errors resulting from differences between the rain they generated and natural rain would account for only 6% of the total errors involved in using them to determine infiltration capacity. Errors due to

Table 2 Velocities of falling water-drops of different sizes
after various heights of fall (after Laws, 1941)

(Velocity in metres per second; height of fall, H, in metres;
diameter, D, in millimetres)

D	H											
	0.5	0.75	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	8.0	20
1.25	2.65	3.15	3.52	3.97	4.21	4.43	4.56	4.80	4.85	4.85	4.85	4.85
1.50	2.76	3.26	3.64	4.18	4.50	4.82	4.99	5.25	5.39	5.47	5.51	5.51
1.75	2.84	3.34	3.74	4.34	4.73	5.10	5.31	5.64	5.80	5.92	6.08	6.08
2.00	2.89	3.40	3.83	4.47	4.92	5.29	5.55	5.91	6.15	6.30	6.53	6.58
2.25	2.93	3.45	3.91	4.57	5.07	5.44	5.74	6.14	6.42	6.63	6.90	7.02
2.50	2.96	3.50	3.98	4.65	5.19	5.57	5.89	6.34	6.67	6.92	7.22	7.41
2.75	2.98	3.54	4.04	4.72	5.28	5.69	6.02	6.52	6.89	7.16	7.50	7.76
3.00	3.00	3.58	4.09	4.79	5.37	5.80	6.14	6.68	7.08	7.37	7.75	8.06
3.25	3.02	3.61	4.12	4.85	5.45	5.89	6.25	6.82	7.25	7.56	7.96	8.31
3.50	3.03	3.64	4.15	4.90	5.52	5.98	6.35	6.95	7.40	7.73	8.15	8.52
3.75	3.04	3.66	4.18	4.95	5.58	6.06	6.44	7.07	7.53	7.88	8.31	8.71
4.00	3.05	3.67	4.21	4.98	5.63	6.12	6.52	7.17	7.65	8.00	8.46	8.86
4.50	3.07	3.70	4.24	5.05	5.72	6.24	6.66	7.36	7.85	8.21	8.70	9.10
5.00	3.09	3.72	4.27	5.11	5.79	6.33	6.77	7.50	8.00	8.36	8.86	9.25
5.50	3.10	3.74	4.29	5.16	5.85	6.40	6.86	7.61	8.11	8.47	8.97	9.30
6.00	3.10	3.75	4.31	5.20	5.90	6.46	6.94	7.69	8.20	8.55	9.01	9.30

site variability, lateral seepage and other factors were far more important. He concluded that further improvement of the rainfall generating aspects of these instruments was unnecessary. Further evidence to support the use of the type F and FA infiltrometers was provided by Duley and Domingo (1943) who found that the buffer zones recommended for use with these sprayings was wide enough to prevent lateral seepage from being a significant source of error.

These findings led to the widespread adoption and use of the F and FA type infiltrometers, and the results of many studies involving its use were published during subsequent years (e.g. Woodward 1943, Izzard and Augustine 1943, Rowe 1948, Packer 1951, Dortignac 1951, Turner and Dortignac 1954, Dortignac and Love 1960, 1961).

Not all workers in the field, however, were convinced that the spray-rig was the final answer to the rainfall-simulator problem. The apparatus was quite complicated, it required power to generate the pressures needed to force water through the nozzles, and there was some doubt about the rainfall pattern it produced. Ellison and Pomerance (1944) suggested the generation of water drops by gravity as an alternative. They devised an infiltrometer based on the use of a drip tower and drip screen. A tank with holes drilled on 10 cm. centres supplied the water to the drip tower. A screen of 2.5 cm. mesh chicken wire was placed directly below the tank and cheesecloth was spread loosely over the wire so that it would be pressed into the openings. A short piece of yarn was hung from each pocket to form water drops of uniform diameters. Different yarn sizes were used to obtain various uniform drop sizes - ranging from 3.5 to 5.1 mm. in diameter. Drop velocity was controlled by varying the height of the apparatus, and intensity by

varying the head of water in the supply tank. The drip screen was oscillated to distribute drops evenly over the plot.

Ellison and Pomerance's apparatus was cumbersome, but the results it produced were encouraging and led others to experiment further with this approach.

Woodburn, 1948, Bisal, 1950, Osborn, 1953, Goodman, 1952, and Barnes and Costel, 1957, all devised instruments based on the "hanging yarn" principle. For the most part, these too, were large in size. That produced by Barnes and Costel, for example, involved using a tower c. 5 metres in height, and while it could be transported on a $\frac{1}{2}$ ton truck, it was clearly not a great improvement over the type-F spray-rig in terms of its portability. It also required a large volume of water to operate it for any length of time.

A much smaller instrument was designed by Adams, Kirkham, and Nielsen (1957). It consisted of a small supply tank resting on a wind shield 1 metre above the soil surface. Drops were produced by glass capillary tubes protruding through the base of this tank. Rainfall intensity was controlled by the depth of water in the tank, which in turn was controlled by a pressure head regulator. The drops were allowed to fall onto a circular plot of 14.38 cm. in diameter, and were protected from wind effects by the wind shield extending from the ground to the base of the supply tank. The instrument could be carried by one man, and required only 5-10 litres of water per measurement. According to the authors it produced rain whose kinetic energy was similar to that of natural rain. Its disadvantages ^{W/C/V} that it produced drops of large (5.56 mm. diameter) uniform size, and that it took no account of lateral seepage.

A number of important papers relevant to rainfall simulator design were published in the late 1950's and early 1960's. First of all Wischmeier and Smith (1958) showed conclusively that one of the most important factors controlling the disposition of rainfall was its kinetic energy. This paper led Meyer and McCune (1958) to reappraise the performance of the type-F infiltrometer which was then widely used for infiltration studies. They found that the "rain" produced by this instrument has only c. 60% of the kinetic energy of natural rain for any given intensity. They therefore developed a new rainfall simulator based on an 80100 veejet spray system which they called a "Rainulator". This produced "rain" whose kinetic energy was c. 76% of natural rain at an intensity of 62.5 mm/hr. It also produced drops whose size distribution and velocity were similar to those of natural rainfall, and could be controlled to vary the rainfall characteristics during the course of an experimental run. Like many of its predecessors, however, this spray-rig was complicated and expensive to build and operate. It was also suitable for use only in large uniform areas, for it required a plot size of c. 25 by 3 metres. Its usefulness as a field instrument, was therefore rather limited. Meyer and McCune's success in generating more realistic rain than that achieved before led to renewed experimentation with spray-rig design. Most of this effort was aimed at devising a small, simple, portable version of Meyer and McCune's apparatus. One such instrument was that described by Bertrand and Parr (1961). It consisted of a single nozzle spraying water downwards from a height of 2.70 metres onto a plot 1.143 sq. metre. Rainfall intensity was controlled by changing the nozzle. The instrument could be assembled quickly by two men, was light in weight, and did

not use large volumes of water comparing with Meyer and McCune's instrument. Other portable spray-rigs were described by Rogers, Barnett, and Cobb (1964), Swanson (1965), Hudson (1965), and Bubenzer and Meyer (1965).

None of these instruments, however, reproduced rainfall as accurately as Meyer and McCune's apparatus, and for the most part they were no real improvement on the older type-F infiltrometer. In addition to stimulating work on spray-rig design, Wischmeier and Smith's findings (Wischmeier and Smith, 1958) also stimulated work on gravity-operated rainfall simulators. The most important outcome of this work was the development of a hand portable rainfall simulator by I.S. McQueen in 1963. McQueen's instrument was devised for research work in the dry wildlands of the Western U.S.A. The following specific requirements were set up to guide instrument design:

1. The accuracy and constancy of measurements should be equal to or better than other infiltrometer systems currently in use.
2. It should be portable. It is to be transported in field vehicles such as pickup trucks, carryalls, or sedan delivery trucks. It should be portable by hand to inaccessible sites if necessary.
3. Water requirements should be as small as possible, consistent with accuracy requirements.
4. It should not disturb the surface structure of the soil during installation or operation.
5. It should provide a means for preventing lateral movement of water past the plot boundary, or, for measurement of and correction for such lateral movement.
6. It should provide for collection and measurement of water and sediments splashed out of the plot separately from water and

sediments accumulating on the plot. Water should be allowed to accumulate on the plot only to the depth necessary to cause runoff under natural storm conditions.

7. Energy of simulated rain should correspond to the average energy level of natural storms.
8. Rainfall intensity should be controllable over a wide range and should be stable at any intensity chosen for a given test.
9. Installation and operation of the instrument should be rapid and convenient. Data obtained should require little or no computation.
10. The instrument should operate satisfactorily under adverse conditions, such as high winds.

McQueen considered that only an infiltrometer designed along the principles suggested by Adams, Kirkham and Nielsen (1957) had any hope of meeting these requirements. His own version consisted of a supply tank resting on a tripod at a height of 1.5 metres above the ground. Drops were formed by drilling capillary-size holes through the bottom of this tank, and were allowed to drop onto a circular plot 14.38 cm. in diameter. The boundary of this plot was a thin walled metal cylinder c. 15 cm. high. To avoid disturbance this was not inserted into the soil, but was surrounded instead by a bentonite seal. The instrument generated rain at rates varying from 25 mm. to 400 mm. per hour, at a constant drop size of 5.61 mm. diameter. Tests showed that the instrument compared very favourably in performance with its possible rivals in terms of kinetic energy generated, man-power requirements, portability and cost (see Table 3). McQueen accepted that the small plot area would cause errors due to lateral seepage, but

Table 3. Comparisons between infiltrometers (after McQueen, 1963)

Reference	McQueen's	U.S.Forest Service "Rocky Mountain" (Dortignac,1951)	Soil Cons. Service (Osborn,1950)	Agricultural Research Service (Barnes & Costil,1957)
Method of rain-drop production	Drops form on plastic surface around metal pins	Typ-F nozzle	Drops form on pieces of yarn attached to muslin screen	Drops form on pieces of yarn 5 cm. in length attached to muslin screen
Drop size (diam.in mm.)	5.6	Produce wide range of drop sizes	5	5
Normal application rate (mm/hr)	100	100	150	75
Range of rates (mm/hr)	25 - 375	50-90. Extr-emes of range result in un-even distri-bution	50 - 250	50-75 rates depends on nozzle size used
Drop-fall distance (metres)	1.5	Variable	4.3	2.6
Energy of rain (J/cm ² /cm of rain)	0.137.Slightly less energy per unit of rainfall than natural rain of the same intensity	0.153	0.453 Exceeds thun-der storm of 180 mm/hr. intensity in detaching capacity	0.154

Table 3 (continued)

Reference	McQueen's	U.S.Forest Service "Rocky Mountain" (Dortignac,1951)	Soil Cons. Service (Osborn,1950)	Agricultural Research Service (Barnes & Costil, 1957)
Equivalent natural storm (mm/hr)	47.5	52.5	130.0	52.5
Area of plot (sq.cm.)	193.3	1857.6	1393.2	3715.2
Water Require- ments (Litre per hour)	5 - 10	3,000	1.000	250 - 300
Manpower require- ments per unit	1	2 or 3	2	2
Sampling frequency measurements per unit per day	4 - 5	1 - 2	3 - 4	3 - 4
Man hours per measurement	1½ - 2	6 - 16	4 - 8	4 - 8

felt that this was not a major problem.

Another method of forming drops was devised by Chow and Harbaugh (1965). This consisted of a number of polyethylene tubes 0.575 mm. in diameter placed at 2.5 cm. centres in the bottom of a plexiglass tank 60 cm. square by 30 cm. deep. It could produce drops 3.2 mm. in diameter which is a more realistic size than those produced by other methods. This technique was used by Blackburn, Meeuwig and Skau (1974) in a mobile infiltrometer designed for use on rangeland. This instrument, though mobile, was much larger than McQueen's, and involved using a 120 cm. square tank held 2.10 metres above the ground. The unit was built onto a two-wheel trailer which also carried the water supply tanks. The simulated raindrops reached about 70% of terminal velocity.

A small version of this instrument was described by Munn and Huntington (1976), and was found to give good results when used in rugged mountain country in California. The raindrop-producing unit was supported on a light weight frame 2.5 metres high which also held a 20-litres water tank. The plot size was 61 cm. square. It was reported that the equipment could be operated by one man, and that used thus an average of 4 plots a day could be sampled. But clearly the instrument's portability is somewhat reduced by the need to carry water sufficient to fill a 20-litres tank held 2.5 metres above the ground several times a day.

II.3 Discussion

It is apparent from the preceding review that although most of the infiltrometers described are adequate for certain purposes, they all have important disadvantages.

The advantages and disadvantages of flooding infiltrometers have been summarized by Hills (1970). Points in favour of this method are its compactness, portability, ease of installation, simplicity of design, low cost of construction, and the water usage. Its limitations are:

1. Soil disturbance during installation.
2. Water seepage down the cylinder-soil interface.
3. Lateral flow of water through plot boundary.
4. Air entrapped within and beneath the cylinder.
5. Effect of hydraulic head.
6. Lack of rain-beat characteristics.

Most of these limitations have been recognised for a long time. For example, Katchinsky (1936) recognised the lateral flow problem, and Kohnke (1938) was greatly concerned with the effects of air entrapment on water movement below the cylinder. The development of the double-ring infiltrometer by Nelson and Muckenhirn (1941) and the various experiments carried out by Marshall and Stirk (1950) and others to determine the effects of ring size on measured infiltration rate were all intended to reduce the errors resulting from these difficulties. It is doubtful, however, whether any of these problems, have been, or can ever be, completely solved.

Another problem with the flooding infiltrometer is its unsuitability for use on sloping surfaces. The instrument was

devised originally to provide infiltration data for the better management of soils in irrigated areas, which are generally flat. It is difficult to install a flooding infiltrometer on a slope without causing a bit of soil disturbance.

Also the use of this method in such areas means that the upper and lower parts of the plot area are flooded to different depths, which almost certainly leads to increased errors. This problem is particularly restricting in the case of double ring infiltrometers, which many people believe to be the best instrument of the flooding type.

Soil disturbance and lateral seepage are also problems that affect infiltration measurements made using rainfall simulation techniques. But those who advocate this approach agree that it reproduces natural conditions far more accurately than the flooding infiltrometer. They consider that infiltration is greatly affected by the nature of the rainfall itself, and that measurements involving ponding of water on the soil surface are found to be inaccurate. It is apparent from the preceding discussion, however, that the rain produced by these instruments often differs markedly from natural rainfall in terms of drop size, drop distribution, terminal velocity, and kinetic energy.

Many rainfall simulators also suffer from the disadvantages of large size, large water usage, high cost, and complex design.

Hills (1968) considered that rainfall simulators had no obvious advantages over flooding infiltrometers, and advocated use of the latter because of their greater simplicity, lower cost, and ease of transport over rough ground. For many situations this advice is probably very sound. But there are situations where a portable rainfall simulator such as that described by McQueen (1963)

might be a better choice. Examples of such situations are sloping sites, with soils which are particularly susceptible to disturbance, sites where erosion by raindrop impact might be expected to affect infiltration rates, and sites where raindrop deformation occurs as, for instance, below a forest canopy. Many sites of this nature occur in Thailand. For this reason it was decided to build and test a rainfall simulator modelled closely on the design recommended by McQueen.

Chapter III

DESIGN, CONSTRUCTION AND CALIBRATION OF A RAINFALL-SIMULATOR INFILTROMETER

The purpose of this chapter is to describe the work involved in designing, constructing and calibrating a rainfall simulator similar to that developed by I.S. McQueen (1963). It is logical, therefore, to start by describing McQueen's instrument in some detail.

III.1 Essential Parts of the Instrument

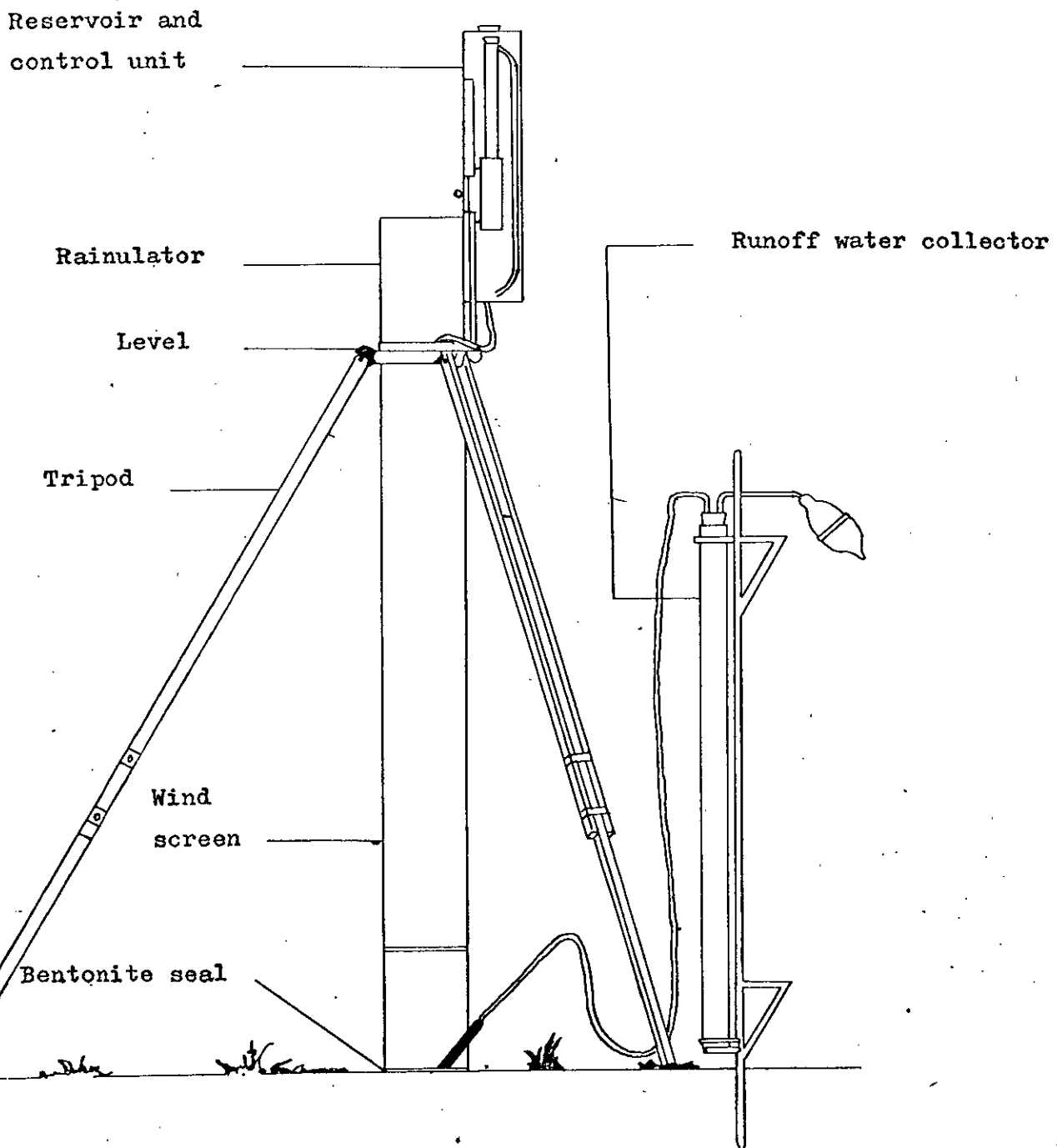
As Fig.2 indicates McQueen's rainfall simulator consists essentially of five parts:-

(1) A reservoir and control unit; (2) a rainulator; (3) a supporting tripod and wind screen; (4) a base unit containing a splash shield; and (5) a system for measuring runoff water and sediment.

III.1.1 Reservoir and Control Unit

This major part performs three functions; (1) it supplies water to the rainfall simulator or rainulator; (2) it indicates the quantity of water supplied; and (3) it controls the hydraulic head and consequently the rate of application of the rainulator. In essence the unit is a calibrated Mariotte bottle with an added bubbler tube to extend the controlled level below the reservoir to provide for greater sensitivity. The unit is calibrated to measure the depth of water applied to the plot in both inches and

Figure 2. Diagram of McQueen's apparatus (1963).



centimetres, the calibration being computed from the ratio of the square of the plot diameter to the square of the reservoir diameter.

III.1.2 The Raimulator

The function of this unit is to generate raindrops in a uniform, controlled manner. It consists of a transparent tank with a plastic base through which are drilled capillary-size holes on 1.25 cm. centres. The bottom of each hole is countersunk to form a drop control surface, and to prevent water dripping through it too quickly each hole is partially blocked by a wire pin of slightly smaller diameter. McQueen found that several combinations of hole and wire size could give satisfactory results; but recommended that holes should be drilled with an American gauge drill No. 57 and blocked with wire gauge No. 19.

III.1.3 Supporting Tripod and Wind Screen

The instrument is supported over the infiltration plot by adjustable tripod legs similar to those used to support surveying instruments. The wind screen is a length of 15 cm. O.D. plastic tube about 1.3 metres long hung in an aluminium ring supported by the tripod legs. A bulls-eye-type level is mounted on the support ring to show when the wind screen is vertical. A steel rod of 1.25 cm. diameter extends up from the support ring to hold the reservoir and control assembly. The raimulator is fitted into the top of the wind screen, and the instrument set up so that the raimulator base is 1.5 metres above the ground.

III.1.4 Base and Splash Shield

This consists of an open ended metal cylinder about 15 cm. high, and of the same diameter as the wind shield. This is designed to be sealed to the soil surface with a sealing material such as bentonite clay.

III.1.5 Runoff-water and Sediment Measuring System

Excess water and suspended sediments are withdrawn from the plot into a calibrated cylinder by a simple suction device. In order to provide for accurate measurement of sediment volumes, the cylinder bottom is an accurately machined cone shape. This cylinder is calibrated to measure the depth of water and sediment removed from the plot in the same manner as the water reservoir.

III.2 Proposed Modifications to McQueen's Apparatus

It is apparent from the data presented earlier in Table 3 that McQueen's rainfall simulator compares very favourably with other portable rainfall simulators in most respects. One major fault with the instrument, however, is the fact that the data it produces relate to a very small unbuffered plot area. This undoubtedly leads to errors due to lateral seepage past the plot boundary. McQueen recognised this, and suggested that this could be accounted for quite adequately by using a correction factor proposed by

Marshall and Stirk (1950).

The literature relating to flooding infiltrometers indicates that this is a questionable assumption, and that better results would be obtained using a buffered plot. Work by Olson and Swartzendruber (1960) indicates that a buffer zone half the width of the plot diameter is sufficient to reduce lateral seepage to a negligible amount. Accordingly it was decided from the onset to modify McQueen's design by enlarging the rainulator and the windshield so that simulated rain would fall on both the plot and a 7.5 cm. band surrounding it.

A second modification was also decided on at an early stage. This was to reduce the height of the rainulator above the ground from 1.5 to 1.0 metres. One reason for this is that most Thais are not tall, and that it would be difficult for them to use an instrument which involved filling a water reservoir almost 2 metres above the ground. The other reason is that the canopy in many of Thailand's forests is very low and it would be difficult to install apparatus as tall as that suggested by McQueen.

III.3 Design and Construction of Rainulator

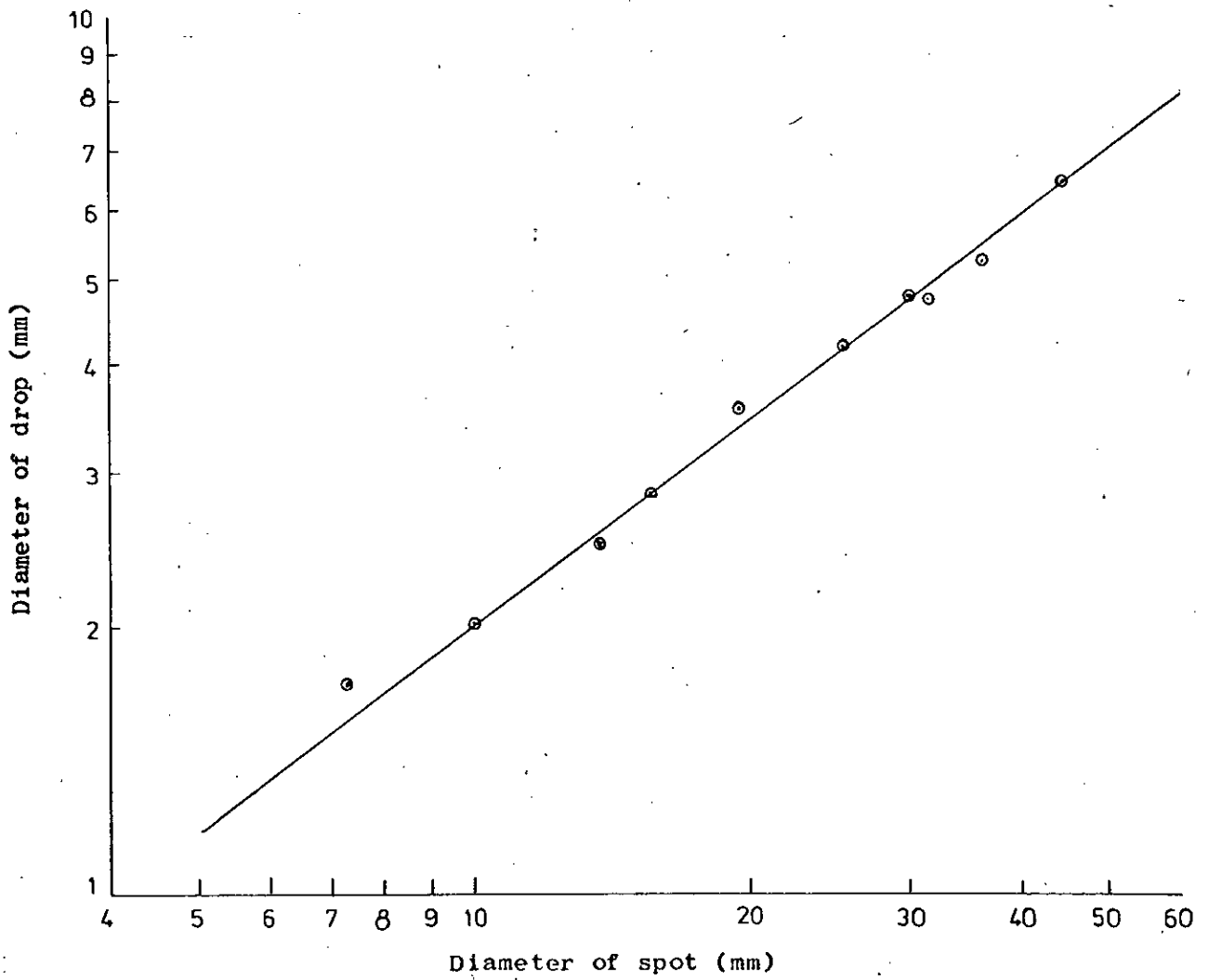
It is apparent from McQueen's paper that the rainulator is the most difficult part of his instrument to design and build. It seems logical, therefore, to report first on the design and construction of this part of the infiltrometer.

III.3.1 Preliminary Investigations

The design of any rainfall simulator cannot proceed far without devising a method for measuring the size of the drops it produces. Techniques which have been widely employed for this purpose are the flour method, and the filter paper method. It is now generally recognised (Best 1950, Mason 1957) that the second method is better and more convenient. The method involves dropping water onto filter paper soaked in a solution of Bromo-Cresol Green dissolved in absolute alcohol, and then dried at room temperature. A number of Whatman No.1 filter papers were prepared in this way, the ratio of Bromo-powder to liquid alcohol used being one teaspoonful per 250 ml., and were placed in a sealed plastic box to keep the humidity constant.

A calibration graph was produced by allowing drops of known volume to drip on to some of these treated filter papers and measuring the size of the spots they produced. Drop volume was measured by sucking water into a precision made fine glass capillary tube, and measuring the length of the water column. This water was assumed to form a spherical drop when forced out of the tube onto the filter paper. The graph of drop diameter versus spot diameter produced in this way is shown in Fig.3. All calibration graphs of this type are liable to some error. However, the data in Fig.3 compare very favourably with those available in the University's Department of Meteorology (Dr. K. Weston, personal communication), and are not believed to be seriously at fault.

Figure 3. Relationship between diameter of water drop and the spot it produces on treated filter paper Whatman No.1.



III.3.1.1 Drop-size Experiment

As was mentioned earlier in section III.1.2 McQueen recommended that the holes in the rainulator should be drilled with an American gauge drill No.57 and blocked with wire of gauge No.19. It is clear from his paper, however, that in some cases other combinations of drill and wire size might give better results. To clarify this point drop size tests were carried out.

In the first test a hole was drilled into the centre of a perspex disc c. 5 cm. in diameter and 1.25 cm. in thickness using a No.60 drill. This was then reamed successfully with drills Nos. 59, 58 and 57 as recommended by McQueen. The bottom of the hole was countersunk to form a drop control surface. The disc was then inserted into the bottom of an open ended perspex tube, and sealed to it with Bostik-Blu-Tak to prevent water leakage. A No.19 gauge stainless steel hook was inserted into the hole such that its lower end extended c. 6 mm. below the bottom surface (Fig.4A).

This drop forming unit was then clamped to a stand and filled with tap water (Fig. 4B). Drops were allowed to fall from it without being measured until it appeared that the pin and drop control surface were completely wetted. After that drops were allowed to fall onto treated filter papers placed about 5 cm. below the dropper. The papers were dried, and the spot diameter determined by averaging measurements taken across two axes at right angles to each other (Plate 1). Thirty-one drops were measured in the first experiment and the mean diameter was found to be 5.57 mm. which was very close to the drop size produced by McQueen.

Similar experiments were carried out using several other combinations of hole size, wire size and width of countersinking. The results are shown in Table 4.

Figure 4. The drop forming system.
(not to scale)

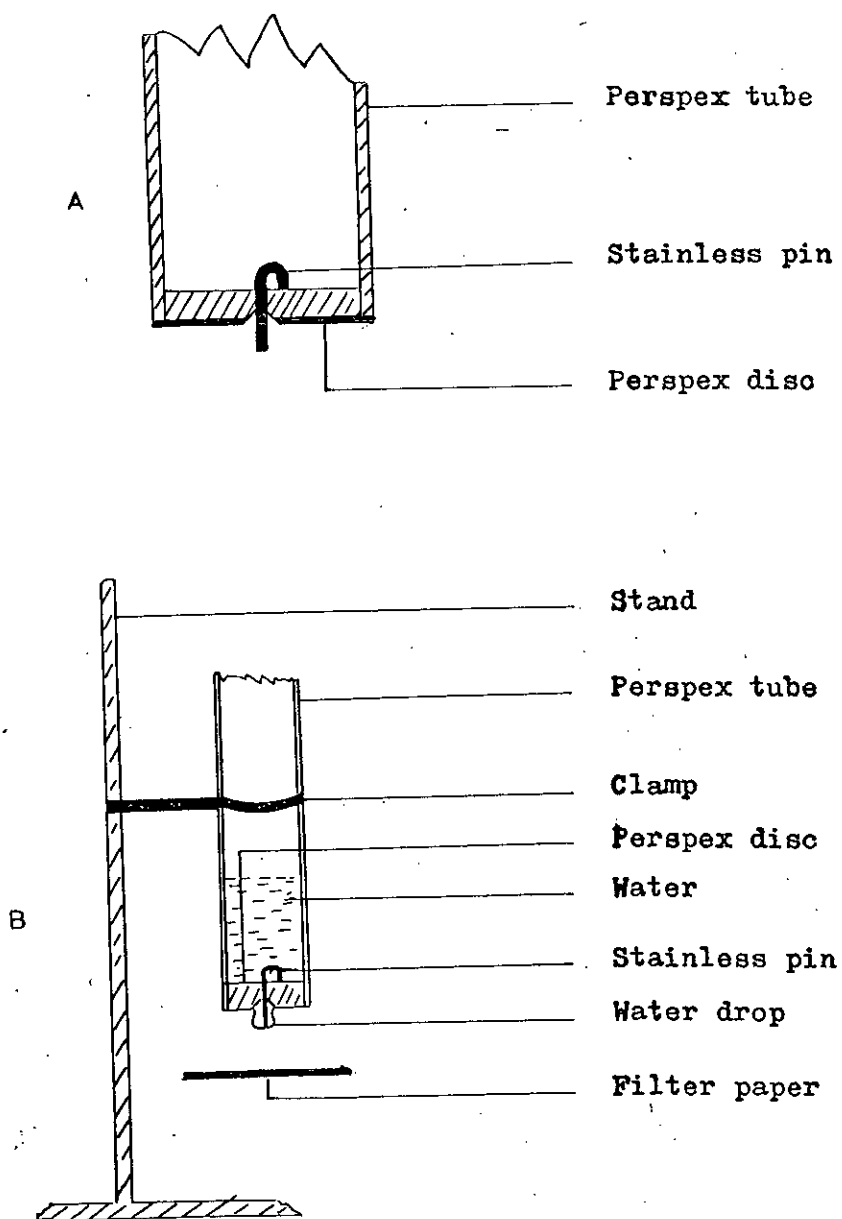


Plate 1. Drop size measurement by the filter paper method.

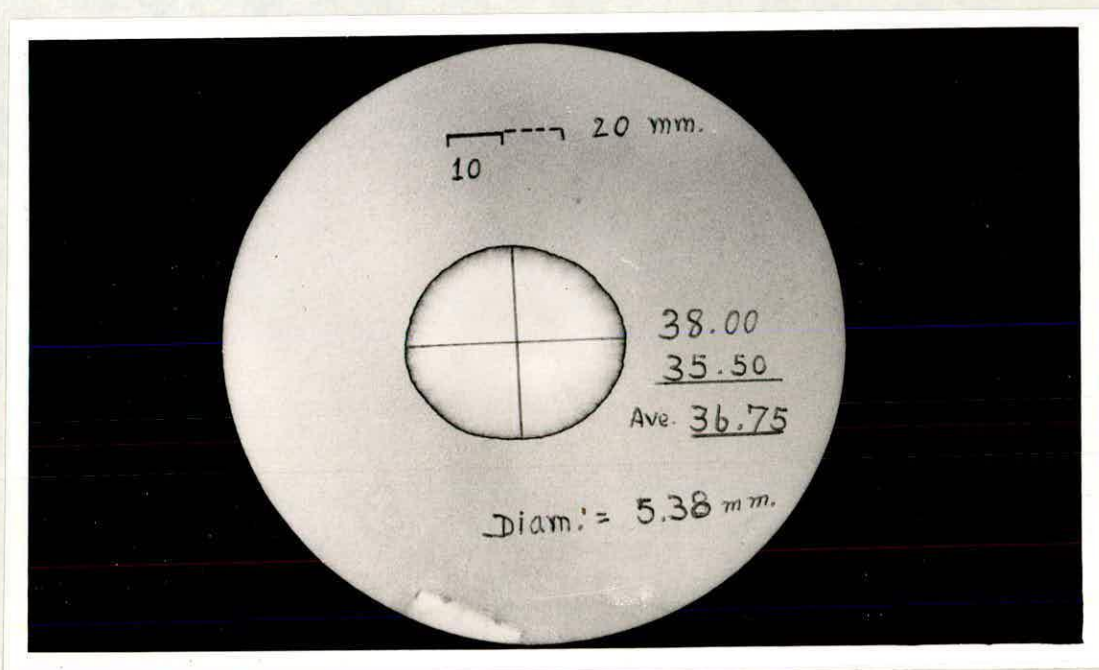


Table 4. Drop sizes produced by several combinations of hole size, wire size and width of countersinking.

Drill No.	Diameter of countersinking (mm)	Gauge Wire No.	No. of drops caught	Average Diameter (mm)
57	1.6	19	20	4.40
57	3.2	19	20	5.20
57	4.8	19	20	5.28
57	6.4	19	20	5.57
55	6.4	18	24	5.65 ⁺
55	1.6	18	39	5.55
55	3.2	18	39	5.72
55	4.8	18	41	5.75
55	6.4	18	37	5.73

⁺ Hand drill

Table 4 indicates that the diameter of the countersunk hole on the lower surface has an important effect on drop size, and that drops only 4.4 mm. in diameter could be produced using a gauge 57 hole, gauge 19 wire and a countersinking of 1.6 mm. The smallest drops that could be produced using a 55 gauge hole and gauge 18 wire, on the other hand, had a diameter of 5.55 mm.

On the evidence of these experiments the use of a 57 gauge hole and a 19 gauge wire as recommended by McQueen seemed justified. Unfortunately, however, despite extensive enquiries in Edinburgh and elsewhere, it proved impossible to obtain gauge No.19 wire in sufficient quantity at the time it was required. As a result this method of forming drops had to be abandoned in favour of the less satisfactory combination of a 55 gauge hole and 18 gauge wire.

III.3.1.2 Seven-hole Rainulator Experiments

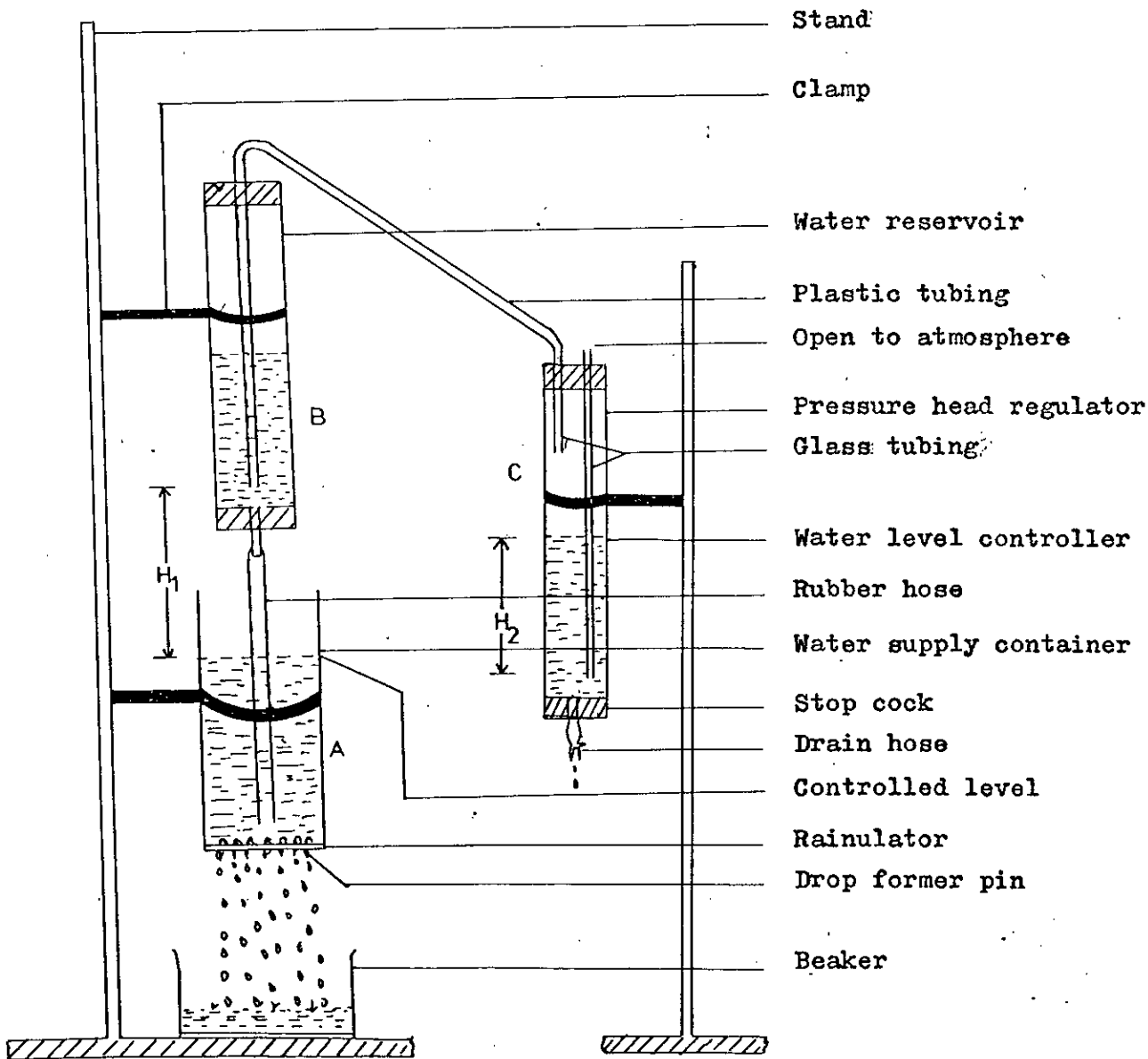
The next stage in the development of the instrument was the construction of a small multi-hole rainulator. This was done firstly to check that the techniques used were precise enough to ensure that each hole produced drops of the same size; secondly to ensure that the rate of dripping from each hole was the same at any given hydraulic head; and thirdly to determine the relationship between hydraulic head and rate of rain production.

A seven-hole rainulator with the holes drilled at 12.5 mm. centres as recommended by McQueen was considered adequate for this purpose. A new perspex disc was prepared, drilled and sealed into the bottom of a perspex cylinder as described in section III.3.1.1 (drop-size experiment). It was then attached to a stand and linked to a water supply tank and a pressure head regulating device as illustrated in Fig.5.

The first test was undertaken with countersunk holes 1.6 mm. in diameter, as this had been found to produce the smallest drops in the earlier experiment with a single hole device. The results were very unsatisfactory. It was found that the amount of countersinking was too small to prevent drops of water flowing laterally across the bottom surface of the disc and coalescing with each other. Doubling the width of the countersunk hole effected some improvement, but the problem persisted until this width had been increased to 6.4 mm.

It was also found that the shape and length of the piece of pin extending below the disc also had an effect on drop characteristics. Drop size was found to vary according to the roughness and length of the pin end: the longer and rougher the end, the

Figure 5. Diagram of the seven-hole rainulator operation.
(not to scale)



larger the drop. Only when the lower end of each pin was carefully filed and smoothed to a point of the same length did each hole produce similar sized drops. The optimum length was found to be between 4 and 6 mm. Pins shorter or longer than this resulted in larger drops. When characteristics had been standardised in this way it was found that each hole produced drops averaging c. 5.55 mm. in diameter, which is very similar to those produced by the same combination of hole and wire size in the one-hole experiment.

Once the drop-size problem had been resolved, dripping rate tests were carried out. The water level in the rainulator was set and maintained at various levels by means of the pressure head regulating system shown in Fig.5. When required water level had been established the instrument was allowed to drip for 1-2 minutes to wet the drop control surfaces. The time taken for each hole to produce five drops was then measured. The tests were carried out using both tap and distilled water. The results obtained are summarized in Table 5.

Table 5. The relationship between the hydraulic head and the rate of dripping.

Height (cm)	Tap Water		Distilled Water		Remarks
	Rate of dripping sec/drop	Standard deviation	Rate of dripping sec/drop	Standard deviation	
2.5	36.4	10.3	22.6	4.54	Seven-hole rainulator, drill No.55, 6.4 mm. counter-sinking, and No.18 gauge wire. Drops drip very evenly for distilled water, but rather uneven for tap water due to small bubbles on the pin surface.
5.0	13.6	2.96	12.2	3.18	
7.5	10.8	2.10	9.1	2.06	
10.0	8.4	1.61	6.6	1.22	
12.5	7.0	1.40	5.6	1.37	
15.0	5.4	1.32	4.7	0.99	

In Table 5, they show firstly, as one might expect, that the rate of dripping increases as the hydraulic head becomes greater. With tap water, for example, the holes averaged only one drip per 36.9 seconds with a head of 2.5 cm., compared to one drip per 5.4 seconds at 15.0 cm. Secondly, they show that there is some variation between the rates at which different holes drip. This is quite large at low hydraulic heads, but diminishes greatly once the head exceeds 5 cm. This variation is due partly to differences in hole characteristics, for at the early stages in particular it was not easy to drill holes exactly to the intended dimensions. It is also due partly to the formation of air bubbles around the pins. The experiment was conducted in a warm laboratory, and as it proceeded an increasing number of small air bubbles was found around the pins and holes. This had most effect at low hydraulic heads because these measurements took the longest time. Measurements made using distilled water were not affected by this problem which accounts for the faster rate of dripping particularly at low hydraulic heads. The results of this test suggested that variability between holes, and the bubble problem would not cause difficulties provided the hydraulic head exceeded c. 5 cm.

The final phase of this preliminary work was, therefore, to determine the relationship between hydraulic head, hole density and rainfall intensity. This was done by measuring the volume of water dripping through the 20.4 cm² rainulator at different water levels over a period of about 30 minutes. The tests were made using both tap water and distilled water. The results are given in Table 6.

Table 6. Rainfall intensity test for the small device

Height (cm)	Tap Water	Distilled Water
	Intensity (mm/hr)	Intensity (mm/hr)
2.50	36.4	58.4
<u>5.0</u>	92.4	99.0
<u>7.50</u>	120.8	144.4
10.00	155.6	198.2
12.50	184.0	252.0
15.00	224.4	305.6

They show that 7 holes per 20.4 cm². (c. 1 hole per 3 cm².) results in rainfall intensities for tap water ranging from 36.4 mm/hr. at a 2.5 cm. head to over 220 mm/hr. at 15 cm. Somewhat higher rates were obtained using distilled water. The intensities produced by hydraulic heads of from 5 to 7.5 cm. at this hole spacing were considered quite satisfactory for rainfall intensities of this magnitude are quite common in Thailand for short periods of time.

The result of these tests indicated, therefore, that it would be well worth while building a larger rainulator to the same specifications.

III.3.2 The Full-scale Rainulator and its Auxiliary Parts

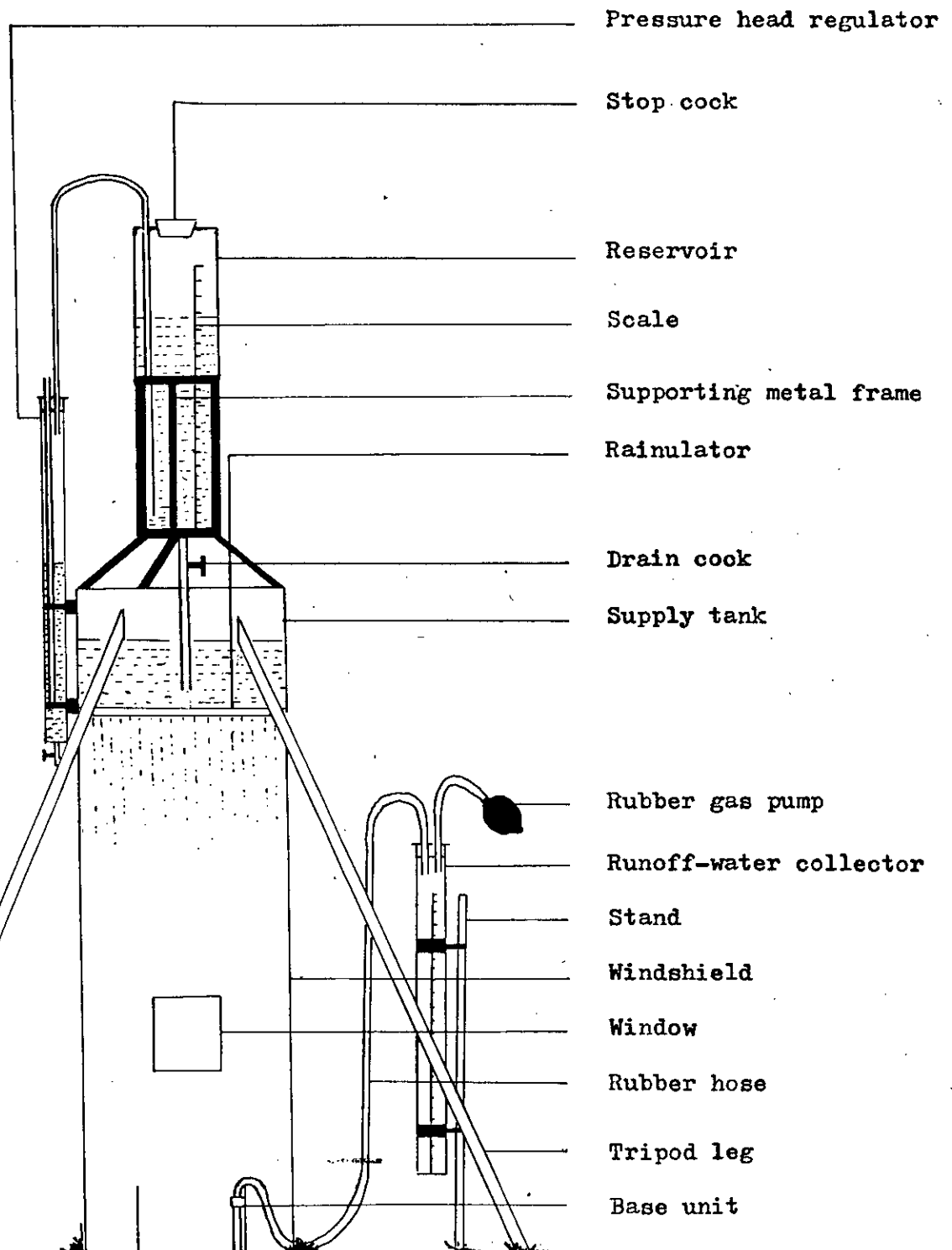
The size of the final version of the rainulator was determined by the requirements discussed earlier in Section III.2. These were that the instrument should be large enough to generate rain over a plot similar in size to that used by McQueen plus a surrounding

buffer zone equal in width to the plot radius. The resultant diameter is 31.4 cm. A perspex disc of this diameter was cut and drilled at 12.5 mm. centres, as described earlier, and stainless steel hooks were made for each of the 434 holes. This disc was then sealed into a galvanised iron cylinder 18 cm. from the top and 10 cm. from the bottom. On the outer wall of the cylinder, directly level to the disc, a metal ring was sealed in order to rest it on top of the wind shield. Against the inner wall of the cylinder, above the disc, two scale-rulers opposite each other were placed.

The work undertaken with the seven-hole rainulator indicated that a reservoir of c. 10 litres capacity would be needed to operate the full-scale version of the rainulator if frequent refilling was to be avoided. A reservoir of this capacity was made from a perspex tube 14.65 cm. in diameter and 60 cm. in length, sealed at both ends with circular perspex blocks. These blocks were drilled to take a tap attachment at the bottom, an airflow tube and sealable water inlet at the top. The reservoir was calibrated so that the depth of rain applied to the plot area could be read directly from it. The spacing of the calibration marks was computed from the ratio of the square of the diameters of the rainulator and the reservoir respectively:-

$$\begin{aligned}
 \text{Scale factor} &= \frac{(\text{Diameter of rainulator})^2}{(\text{Diameter of reservoir})^2} \\
 &= \frac{(31.4)^2}{(14.65)^2} \\
 &= 4.59
 \end{aligned}$$

Figure 6. Diagram of the rainfall-simulator infiltrrometer.
(not to scale)



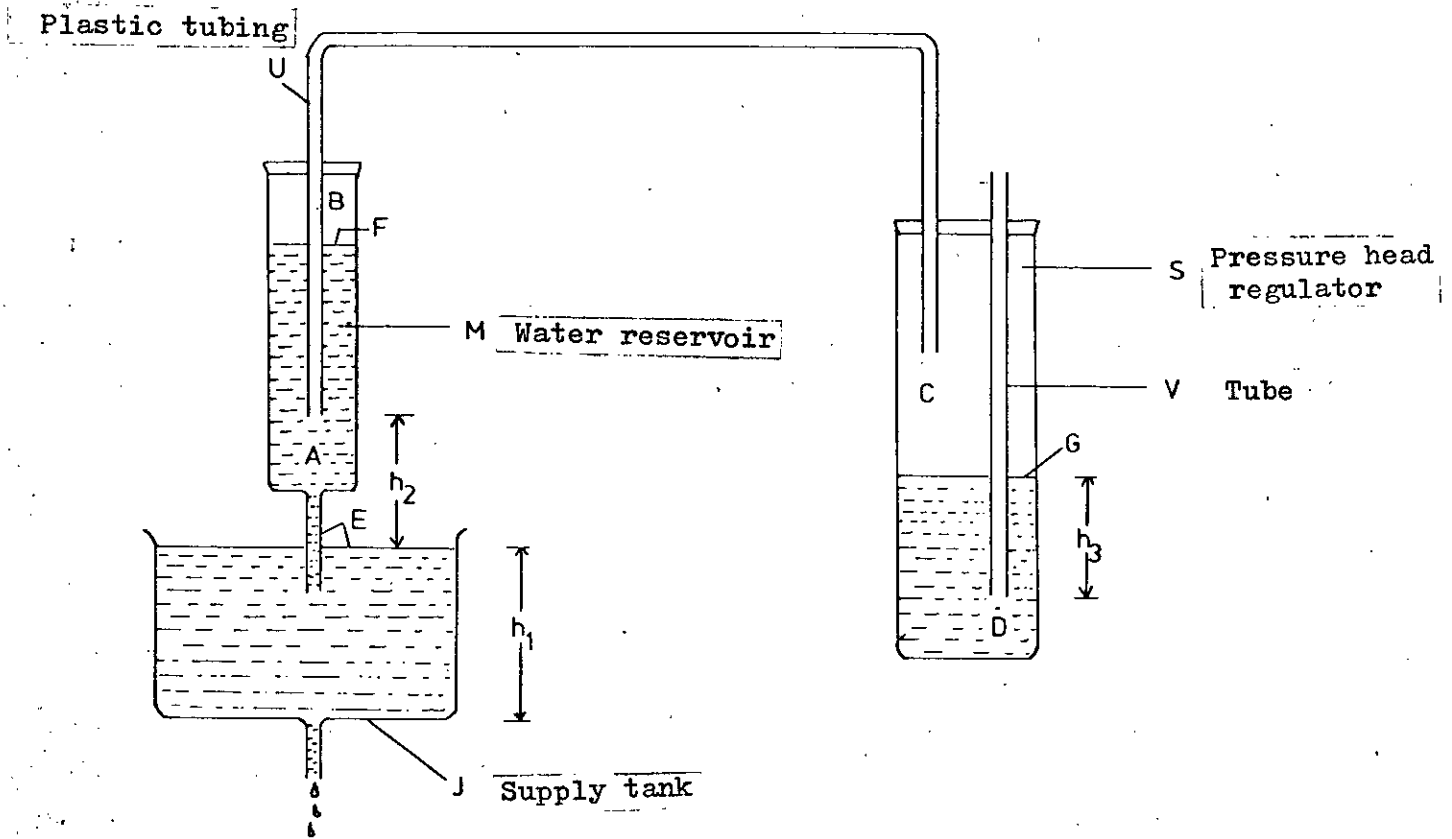
Thus a water level drop of 4.59 cm. in the reservoir indicates that 1 cm. of rain has passed through the rainulator onto the ground beneath.

The pressure head regulator was made from perspex tubing 50 cm. long and 4.5cm in diameter. Both ends were sealed with perspex discs. The upper disc was drilled to take inlet and outlet tubes and a rubber bung which could be removed to allow the cylinder to be filled with water. The lower disc was drilled to take a tap attachment so that it could be drained easily if required.

The reservoir and regulator unit were attached to the rainulator and linked to each other by plastic tubing as indicated in Fig.6. The manner in which this part of the simulator works is shown in more detail in Fig.7. This figure shows at dynamic equilibrium a pressure head regulator (S), water reservoir (M), connecting plastic tubing (U) and supply tank (J). From the supply tank water drops are falling at a steady rate under an equilibrium head h_1 shown. A vertical tube (V) in the pressure head regulator is open to the atmosphere at its upper end.

In order to maintain the head h_1 , water must be supplied from the reservoir (M) into the supply tank (J). As water leaves the reservoir, a partial vacuum is created in an air space B at the top of the reservoir. This vacuum causes water, which originally stood in the left (vertical) arm of the plastic tubing (U) to the level F, to be sucked down to point A where the air which follows the falling water is sucked into the reservoir (M) and rises as bubbles (not shown) up to the air space B to relieve the vacuum. As air flows from plastic tubing (U) down to A and bubbles up to the air space B, a partial vacuum is created in the plastic tubing (U); and hence, a partial vacuum is also created in an air space C

Figure 7. Diagram of the instrument in dynamic equilibrium.



in the pressure head regulator. The vacuum in C causes water, which originally stood in tube (V) to the level G in the pressure head regulator S, to be pulled down to point D at the base of tube (V), causing air to be sucked into the water of the pressure head regulator and to rise as air bubbles (not shown) up to air pressure C (the air then flowing to A and bubbling up to B, permitting water to leave the water reservoir (M) to maintain the head h_1).

At dynamic equilibrium the water in the pressure head regulator stands to height h_3 above the point D. To determine how h_2 and h_3 and hence h_1 are related, one proceeds as follows:

At equilibrium the pressure P_E at points E of the level of the water in the supply tank is, if P_A is the pressure at point A, d the density of the water, and g the acceleration of gravity, given by

$$P_E = dgh_2 + P_A$$

At point D the pressure P_D is, if P_C is the pressure at C, given by

$$P_D = dgh_3 + P_C$$

But P_E and P_D are both atmospheric pressure so that $P_E = P_D$; that is

$$dgh_2 + P_A = dgh_3 + P_C$$

Furthermore, since dynamic pressure losses of air as it moves through the plastic tubing (U) are negligible, so that $P_A = P_C$.

Therefore

$$\begin{aligned} \text{or} \quad dgh_2 &= dgh_3 \\ h_2 &= h_3 \end{aligned}$$

The last equation, although showing how h_2 is related to h_3 , does not show how h_1 is related to h_2 and h_3 . It will be observed from figure 7, however, that if h_3 is decreased (by releasing water from the drain cock at the bottom of the head pressure regulator in Fig.6), h_1 will rise; for otherwise, h_2 would not stay equal to h_3 as demanded by the physical situation. Thus, decreasing h_3 decreases h_2 and hence increases h_1 - and vice versa. In view of the equation, $h_2 = h_3$, it is also clear that the head h_1 may be controlled by raising or lowering the water reservoir and pressure head regulator together as a unit (Adams et al, 1957).

This part of the apparatus was then completed by attaching three adjustable tripod legs to the rainulator so that it could be supported at the required height above the ground, and adding a windshield made from lightweight plastic pipe 1 metre long and 32 cm. in diameter. The windshield was provided with 2 removable windows 15 x 20 cm. in size on the opposite side 40 cm. from the bottom to allow access to the plot, and facilitate observation of the plot area while the apparatus was in use.

Base units 16.59 cm. in diameter were made from galvanised iron sheet for delimiting the plot area, this size being chosen to give a plot area identical in size to that used by McQueen. Three units were made; one for use on flat ground; the others cut at 10° and 20° slopes respectively for use on sloping ground. Each unit was fitted with removable crossbars so that it could be positioned exactly in the centre of the windshield, and with a metal ring to hold the hose from the runoff collector unit firmly in place (Plate 2 A, B).

This collector unit was made from a perspex tube 4.5 cm. in

Plate 2. Base units and installation.



A



B

diameter and 60 cm. in length sealed at the bottom end and graduated so that the water collected in it could be measured directly as runoff depth over the plot area. The top of the unit was blocked with a rubber bung containing 2 holes through which were passed tubes connected respectively to the base unit and to a rubber gas pump. The unit was attached to a metal stand so that it could be supported vertically for use in the field as shown in Fig.6 and Plate 3(A, B).

For convenience, full specification of the instrument and its parts are given in Appendix I.

III.4 Testing and Calibration of the Full Size Instrument

Once the various parts of the rainfall simulator had been constructed they were assembled in the laboratory so that the instrument's performance could be tested under controlled conditions.

III.4.1 Drop-size Test

In view of the variability in the performance of individual rainulator holes during earlier experiments (section III.1.1) the instrument was subjected to detailed drop size testing. In the first instance 33 drops were measured at random by the filter paper method. As Table 7 indicates the results were very satisfactory.

Plate 3. The instrument in field use.

The instrument installed on a sloping site.

The instrument on a flat site.



A



B

Table 7. Result of drop-size measurements of the rainfall simulator.

Diameter of drop (mm)	Diameter of drop (mm)	Diameter of drop (mm)
5.90	5.70	5.54
5.58	5.90	5.59
5.38	5.58	5.55
5.40	5.56	5.54
5.55	5.58	5.58
5.55	5.55	5.57
5.57	5.56	5.58
5.58	5.54	5.56
5.58	5.58	5.58
5.52	5.55	5.57
5.55	5.58	5.53

None of the drops measured was larger than 5.90 mm. nor smaller than 5.38 mm. in diameter. The mean value of 5.58 mm. is almost the same as that recorded in earlier tests involving the 7-hole experiment rainulator. In a second test 385 drops were caught at random in a testtube. The volume of water caught divided by the number of drops producing it again showed an average drop diameter of 5.58 mm.

III.4.2 Representativeness of Plot Area Catch

As described in section III.3.2 the reservoir was calibrated to give a direct reading of the depth of water reaching the ground beneath the rainulator. Much of this water falls on the buffer zone, and clearly changes in reservoir level will give an accurate

measure of the water landing on the plot area only if water falls at the same rate from all parts of the rainulator base. To test this a flask of exactly the same diameter as the base units was made. This was placed in the centre of the rainulator, and the depth of water caught by it in a series of 10 minute tests at different hydraulic heads was measured and related to reservoir scale readings.

Table 8. Scale reading on reservoir in relation to depth of rainfall caught on the plot area for 10 minutes.

Hydraulic Head (cm)	Change in Reservoir level (mm)	Depth in flask (mm)
	7.0	7.9
2	7.1	8.2
	7.0	8.0
	9.5	11.0
3	9.5	10.9
	9.5	11.0
—	12.0	13.4
4	12.0	14.2
	12.0	13.4
	12.7	15.1
5	14.5	16.4
	15.2	16.8
	17.2	19.0
6	17.2	19.0
	17.0	19.1

As Table 8 shows the results of the depths measured in the flask was very similar to those deduced from reading the reservoir scale. The consistent underestimation by the reservoir readings

was almost certainly due in part to the difficulty of reading the scale to an accuracy greater than ± 0.1 mm.

III.4.3 Consistency in Water Delivery Rate Over Time

The rainulator was also tested to ensure that it gave a reasonably constant delivery rate over an extended period of time. This was done by measuring the amount of water falling on the plot area over a series of 10 minute intervals at different hydraulic heads. Again, as Fig. 8 shows, the results were very satisfactory, at all rates, the instrument's performance at the end of the tests being the same as that at the beginning.

III.4.4 Relationships Between Hydraulic Head and Rainfall Intensity

The use of a rainulator requires information relating the hydraulic head to the intensity of the rainfall it produces. This information was obtained by measuring the water falling to the plot area at different levels in the supply tank. The resultant calibration curve is shown in Fig. 9. This indicates that the instrument is capable of producing rainfall intensities ranging from c. 35 mm/hr to c. 145 mm/hr.



Figure 8. The relationship between hydraulic head and delivery rate over a 60 minute period. Temperature 22.5°C. Tap water. Measurements taken at 10 minute intervals.

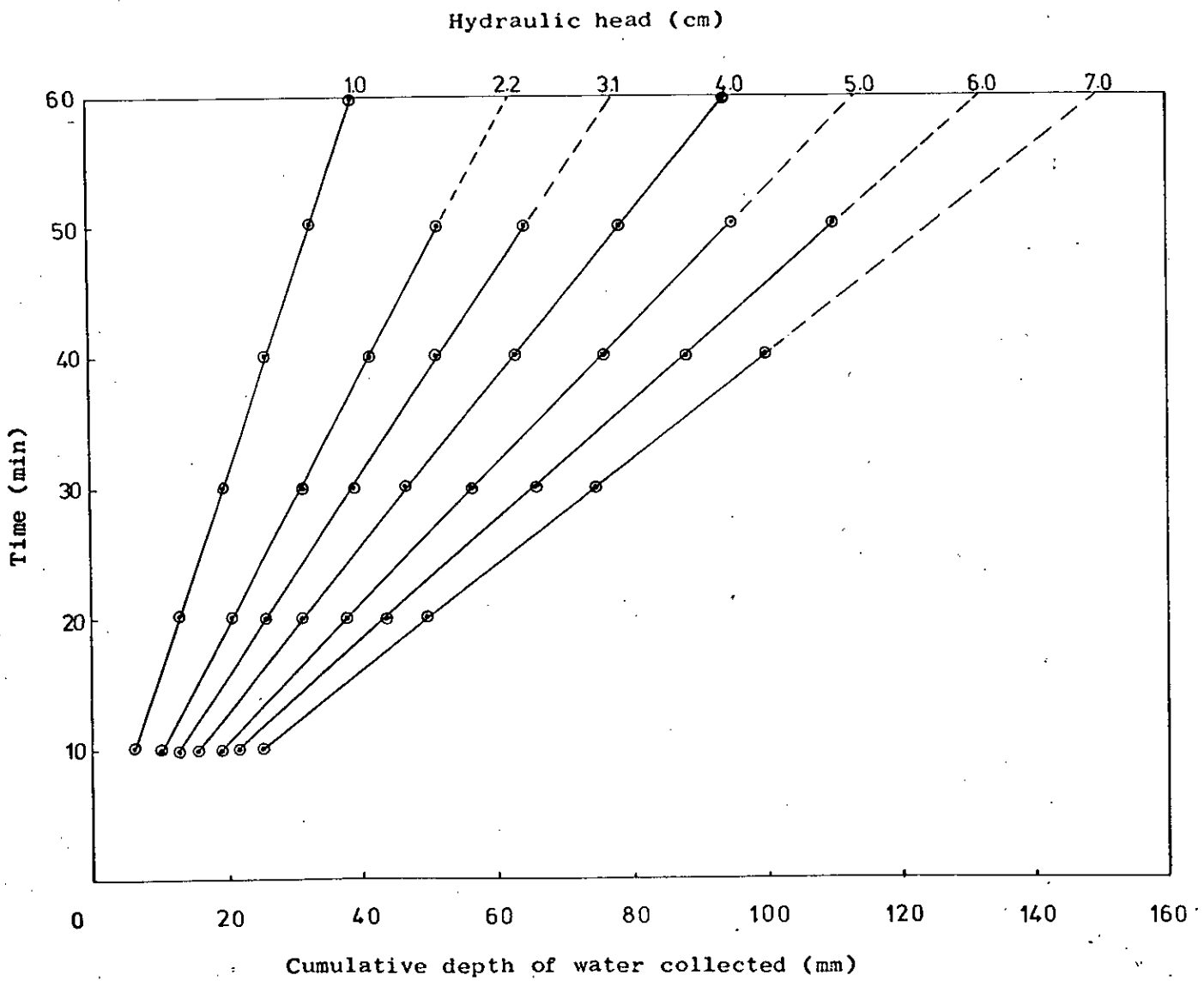
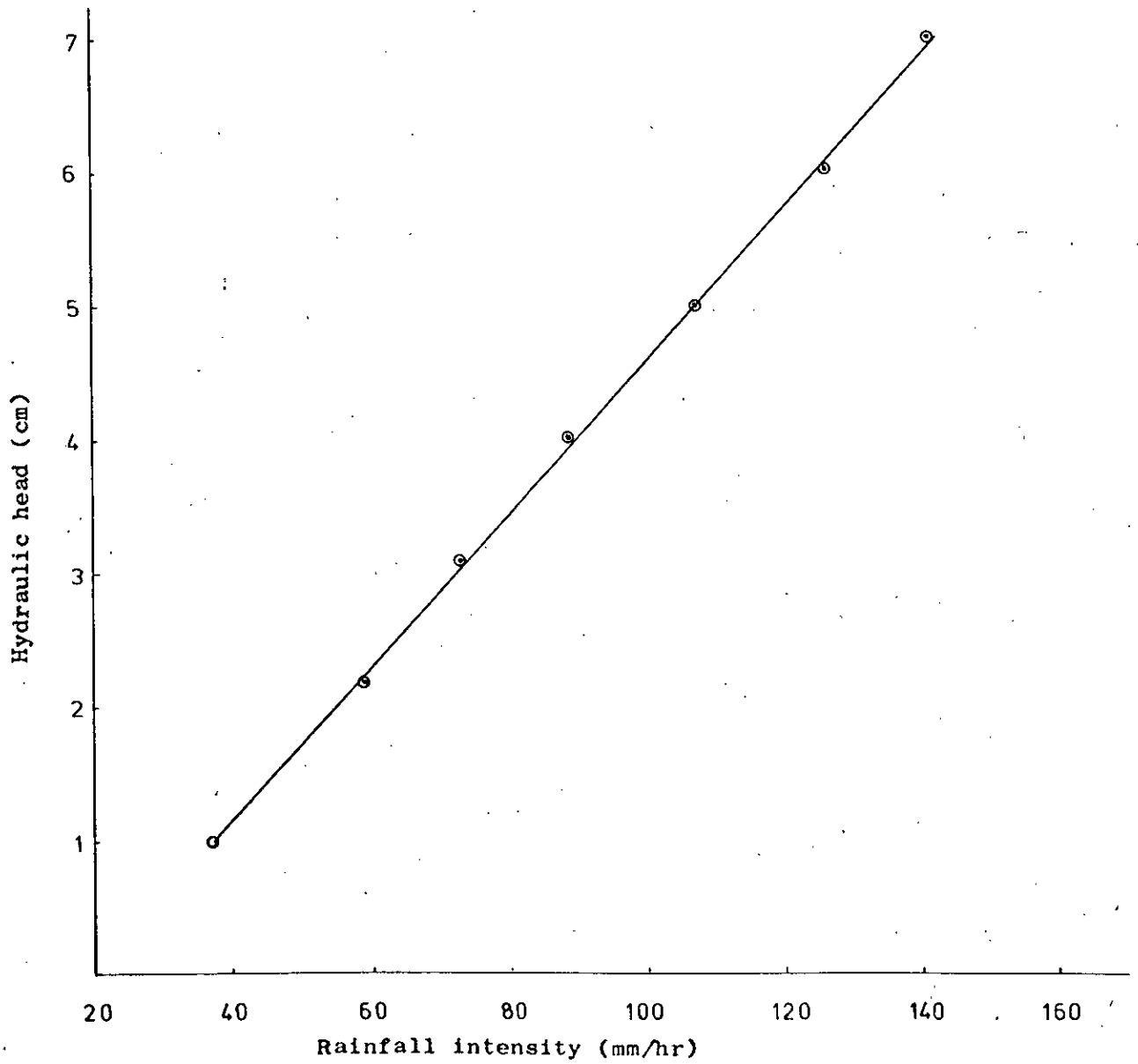


Figure 9. Relationship between hydraulic head and rainfall intensity using tap water at temperature 22.5°C .



III.4.5 Calculation of Kinetic Energy

As was described earlier (Chapter II), the kinetic energy produced by a rainfall simulator is an important aspect of its performance. This can be calculated from the formula

$$KE = \frac{1}{2} MV^2$$

Where KE is kinetic energy in joules,

M is mass in kilogrammes,

V is velocity in metre/second.

Data published by Gunn and Kinzer (1949) show that the mass of a drop of 5.58 mm. in diameter is 92,000 micrograms - 9.2×10^{-5} kg., and that the terminal velocity of a drop of this size falling from a height of 1 metre is 4.30 metres/sec. (Laws, 1941). Thus

$$\begin{aligned} KE &= \frac{1}{2} \times 9.2 \times 10^{-5} \times 4.3^2 \\ &= 8.5 \times 10^{-4} \text{ joules/drop.} \end{aligned}$$

As Table 9 indicates the energy generated by the simulator is less than that produced both by McQueen's instrument and by natural rain of the same drop size. However, this difference is probably only of real significance when using the instrument to study erosion by raindrop impact, and this topic is not of major concern in the present study.

Table 9. Comparison of kinetic energy to McQueen's instrument.

Simulator type	Plot area (cm ²)	Drop diam. (mm)	Height of fall (m)	Drop velocity (m/sec)	KE/drop (J)	KE/unit area - depth (J/ha/cm)	Equivalent natural rainfall (mm/hr)
McQueen	167	5.61	1.50	5.2	12×10^{-4}	14×10^5	1.5
Edinburgh	216	5.58	1.00	4.3	8.5×10^{-4}	9.4×10^5	0.51

Chapter IVEXPERIENCE GAINED USING THE SIMULATOR TO MAKE INFILTRATION
MEASUREMENTS UNDER LABORATORY AND FIELD CONDITIONSIV.1 Introduction

The purpose of this chapter is to report on work undertaken with the instrument in a variety of laboratory and field situations. Before proceeding with this report, however, it is important to understand the procedures used to make the measurements concerned.

The first step in each study was to choose a plot and install the appropriate base unit around it - the unit used being determined by the angle of slope. The cylinder was placed on the ground and pressed gently into it by hand to position it firmly. Any vegetation around the outside of the unit was pulled away so that cylinder was in direct contact with the soil. The soil around the unit was then cut gently with a very thin knife to a depth of about 1 cm. and the unit pushed gently into the soil to about this depth. Care was taken to keep the upper surface level. The outside cylinder wall was then sealed to the soil with model clay to prevent leakage.

Crossbars were then fitted to the base unit and metal rods inserted into the ground at the four outer ends to locate the precise position for the windshield. The crossbars were removed and the windshield placed in position and levelled. The water supply tank and rainulator were then inserted into the top of the windshield and made firm by appropriate positioning of the tripod * legs. * The reservoir, control, and water removal units were placed in level position and connected together as illustrated earlier in Fig.6, and the reservoir and regulator filled with water. *

To start an infiltration measurement, water was poured into the

rainulator unit to a level higher than that required to give the desired application rate. When the water in this unit dropped to a level required to produce the required intensity the reservoir control unit was opened and adjusted to maintain that level. Measurement then proceeded by pumping excess water from the plot as it accumulated and recording the quantity water applied to, and removed from, the plot at 5 minute intervals. Special record sheets were prepared for this purpose (Table 10).

When a test was completed, the flow from the reservoir was stopped, and the instrument emptied, taken apart and moved to the next site.

Once some experience had been obtained, the instrument could be assembled and set up in about 15 minutes by one person if the area was flat, or in about 25 minutes if it was sloping.

IV.2 Measurements made in the Laboratory

Partly because of unfavourable weather conditions and partly to gain experience of using the instrument under the easiest circumstances, the first studies were carried out in the laboratory. Three such studies were undertaken.

IV.2.1 The Effect of Bulk Density on Infiltration Capacity

The first experiment was to investigate the effect of soil compaction on its infiltration capacity. Soil from the same source was sieved with a 2 mm. mesh sieve and left to dry for 2 days. It was then packed into 35 cm. square wooden boxes

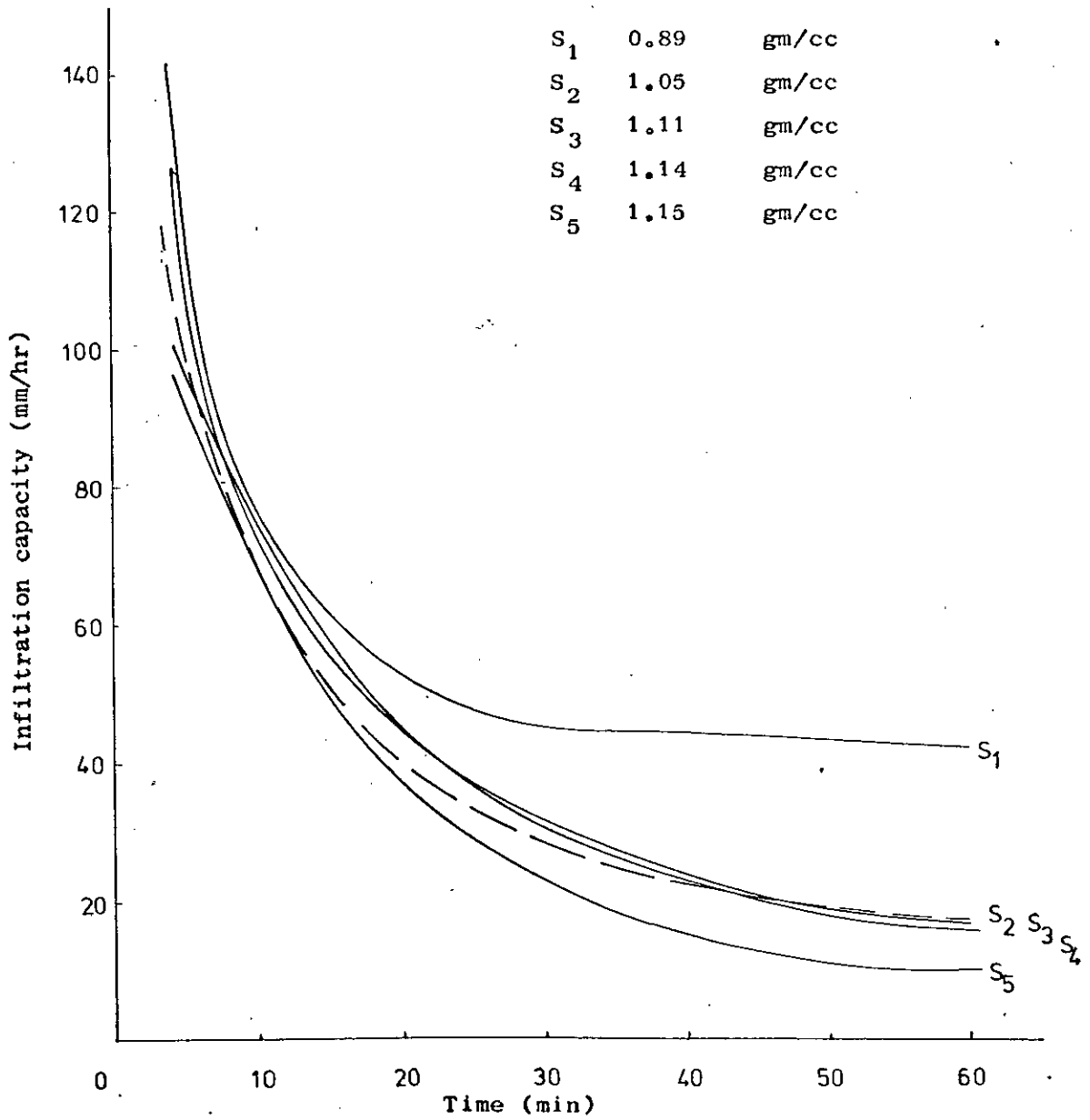
containing holes at the bottom to allow free drainage of water passing through the soil. The soil depth in each box was standardised at 6 cm. but each sample was subjected to varying degree of compaction such that the bulk densities ranged from c. 0.9 to c. 1.2 gm/cc. Each box was then placed under the rainulator, the base unit was installed as described above, and subjected to one hour's rain at an intensity of c. 95 mm/hr.

Five samples of soil were studied in this way. The results are summarised in Fig.10 and Table 11 and detailed in full in Appendix 3.

Table 11. The relationship between bulk density of a soil and the average infiltration capacity.

No.	Bulk density gm/cc.	Average infiltration capacity for 1 hr. (mm/hr.)
1	0.894	54.83
2	1.05	37.60
3	1.11	39.87
4	1.14	36.98
5	1.15	30.18

Figure 10. Effect of bulk density on infiltration capacity of a soil.



They show that in all cases the initial infiltration capacity was very high - well over 100 mm/hr. - but that it decreases rapidly as the experiment continued, all 5 curves following the classical pattern illustrated at the beginning of this thesis (Fig.1). There is considerable variation, however, in the level to which the infiltration capacity had fallen by the end of the experiment, which, is clearly related to bulk density. The least compacted soil (bulk density 0.89 gm/cc.) was still absorbing water at over 40 mm/hr. after 60 minutes, whereas in the most compacted sample (1.15 gm/cc.) the rate was only 12 mm/hr. The average infiltration capacity over the entire experiment ranged from 55 mm/hr. for the least compacted to 30 mm/hr. for the most compacted soil. The results indicate that only small differences in bulk density can greatly affect infiltration capacity.

This particular experiment did not reveal any problems with the simulator. It did, however, indicate that it was not easy to make all the relevant observations at exactly 5 minute intervals as planned. Some of the scatter in the graphs in Appendix 3 is undoubtedly due to observational error resulting from this cause, which is why smoothing the data to produce Fig.10 was considered acceptable.

IV.2.2 The effect of soil moisture content on infiltration capacity

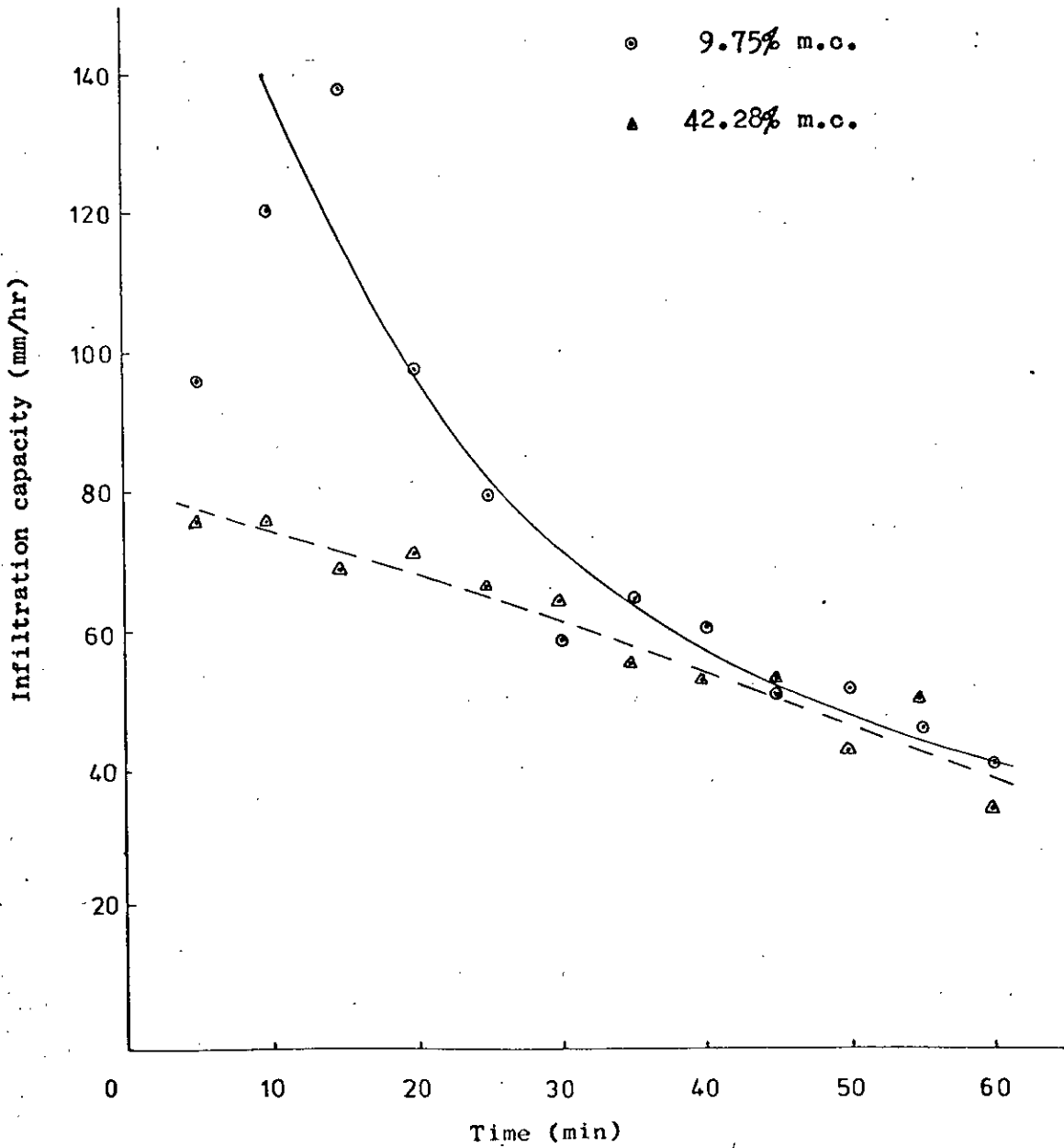
As was described in Chapter I, the initial moisture content of a soil is one of the factors that can affect its infiltration capacity. To investigate this the boxes were filled with an equal weight of air dried soil from the same source as that used in the bulk

density experiment above. Each was then wetted to a different level by means of a water spray and left for 20 minutes. It was then placed under the rainulator, and just before rain was applied a sample of soil was taken from which its moisture content was determined later by gravimetric methods. Rainfall was applied to each sample at an average rate of 116 mm/hr. for 60 minutes, and the excess water removed and measured at 5 minute intervals.

The results are summarised in Fig.11 and detailed in full in Appendix 4. They indicate, as expected, that the infiltration capacity of soil when wet differs quite considerably from that when it is dry. This difference is particularly noticeable at the beginning of the experiment. The initial infiltration capacity of the dry soil (9.75% moisture content) was considerably in excess of 120 mm/hr., whereas that of wet soil (42.28% moisture content) was just under 80 mm/hr. As the rain continued, however, these differences diminished, and at the end of the hour the capacities were very similar, being about 40 and 35 mm/hr. respectively. These terminal rates are very similar to that for the uncompactd soil from the same source in the previous experiment (section IV.2.1).

No instrumental difficulties were encountered during this experiment, and the results contained no inconsistencies or deviations that could be explained only in terms of errors due to leakage from the plot cylinder, or some similar cause.

Figure 11. Effect of moisture content on infiltration capacity of a soil.



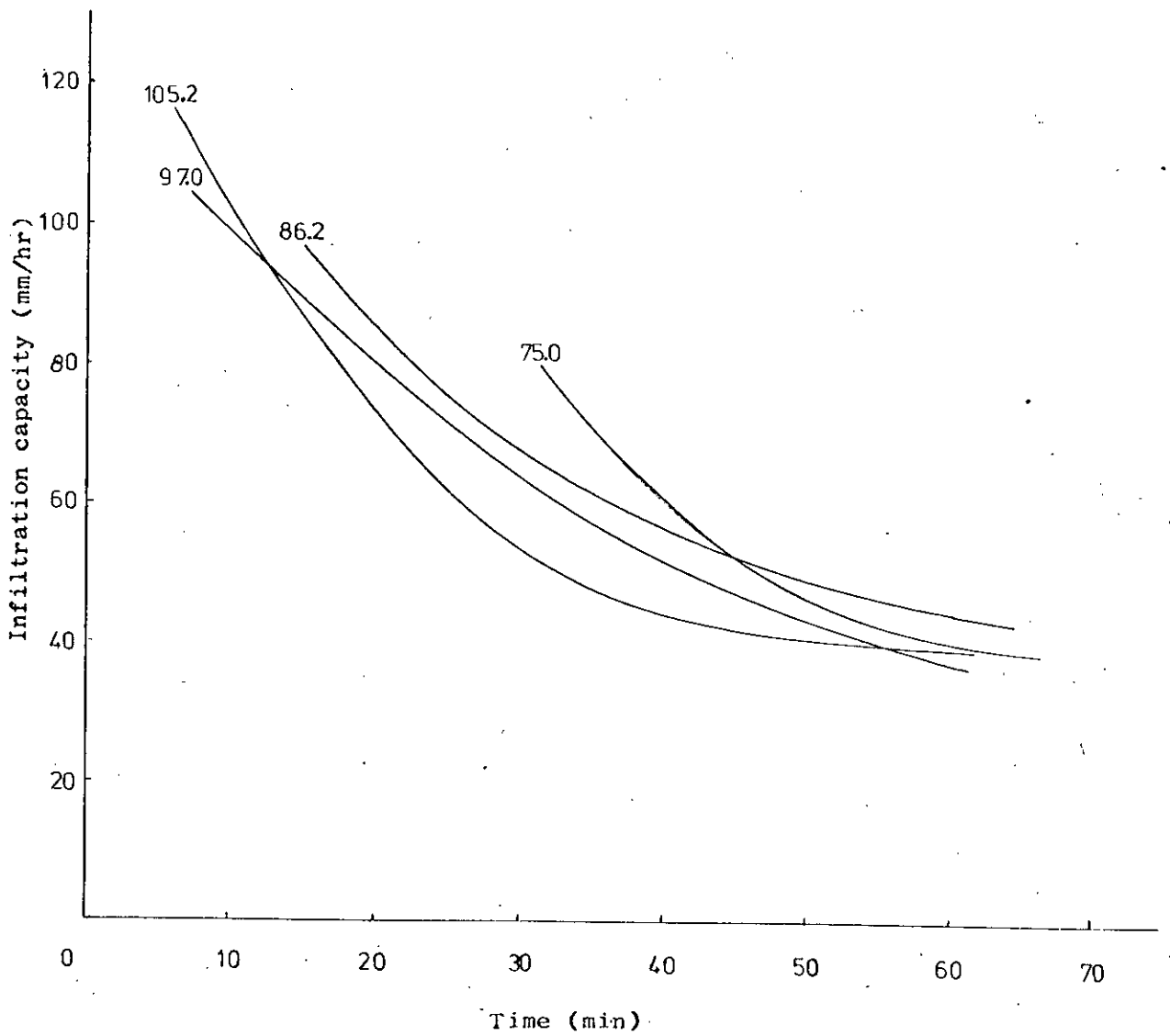
IV.2.3 The effect of rainfall intensity on infiltration capacity

Another factor which can affect the infiltration capacities of dry, unprotected soils in particular, is rainfall intensity. This is because the higher the intensity of the rain the more quickly it is able to puddle the surface of the soil, thus reducing its infiltration capacity. To see whether the infiltration capacity of the soil used in the 2 earlier experiments was susceptible to this effect, samples of the same bulk density and moisture content were placed into wooden boxes as described above (section IV.2.1), and subjected to one hour of rain. A different rainfall intensity was used for each sample, the range being from 75 mm. to 105 mm. per hour.

The results are summarised in Fig.12 and detailed in full in Appendix 5. They are more difficult to interpret than those obtained in the previous experiments, but they do suggest that the infiltration capacity of this particular soil becomes lower as rainfall intensity increases. This difference, however, appears to diminish as the period of rain becomes longer, and at the end of 60 minutes the rates are very similar. It is interesting to note that the terminal rate of c. 40 mm/hr. is again the same as that obtained previously using uncompacted soil.

No further discoveries were made about the apparatus and its operation during this experiment. The similarity of the results to those of earlier experiments did however increase confidence that the simulator could be used meaningfully for this kind of laboratory work.

Figure 12. Relationships between rainfall intensity and infiltration capacity for a soil with a constant bulk density.



IV.3 Measurements made in the field

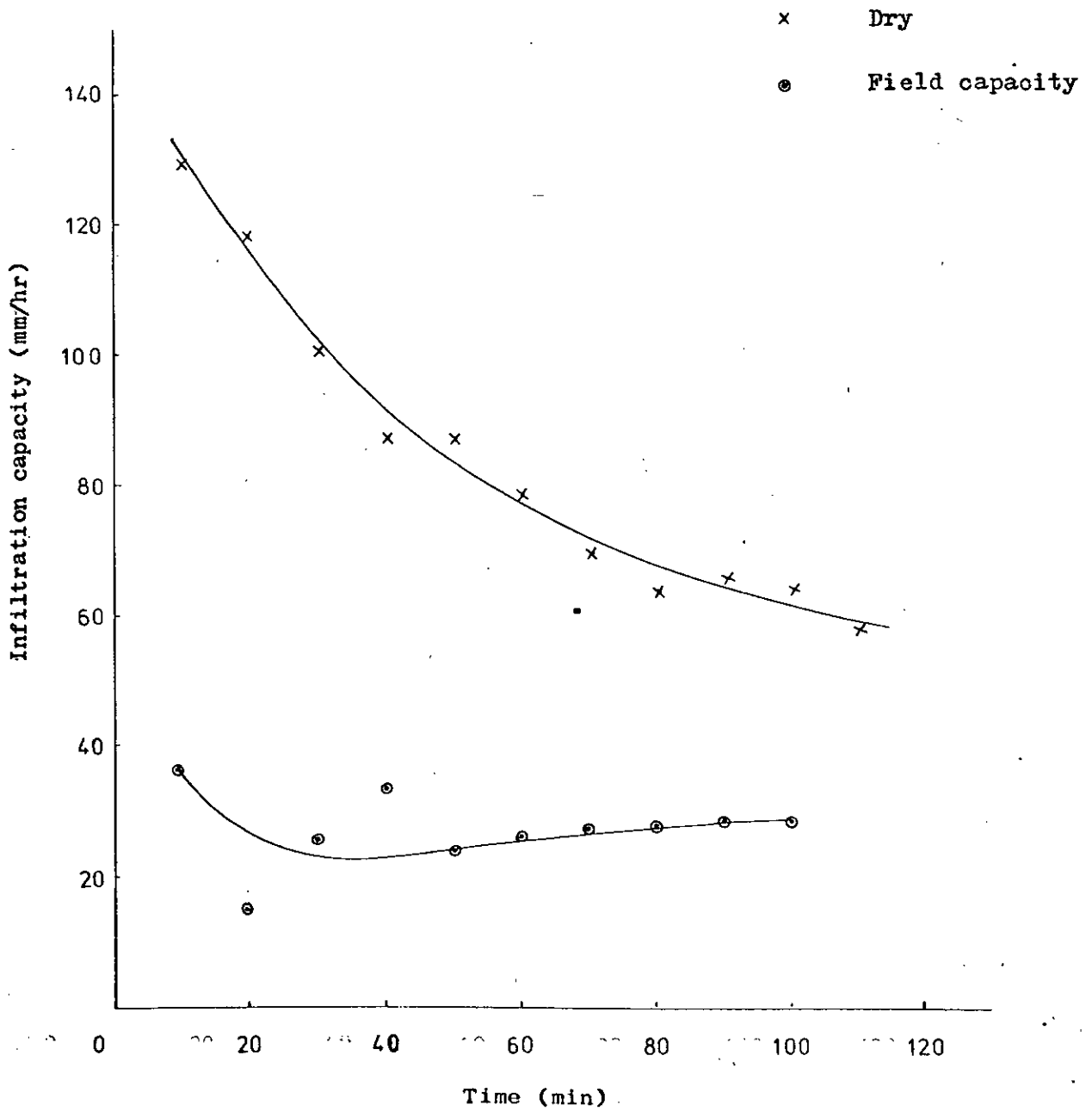
IV.3.1 Experience gained using the simulator on the Departments nursery area

In order to gain experience of using the simulator in field conditions the first outdoor tests were conducted on a small nursery plot next to the Department of Forestry and Natural Resources.

The experiment was set up as described at the beginning of this chapter over a relatively dry soil which had been graded and prepared for use as a seed bed. Rain was then applied to the area for 110 minutes at an average intensity of 122.5 mm/hr., the water accumulating in the plot area being sucked out and measured at 5 minute intervals as before. After 115 minutes the instrument was turned off and taken away. The plot cylinder, however, was left in place. Twenty-four hours later the rainulator was again set up over the same plot, care being taken not to disturb the cylinder. Rain was then applied at the same rate of c. 120 mm/hr. for 100 minutes, and the excess water collected and measured.

The results are summarised in Fig.13, and given in full in Appendix 6. As one might expect the infiltration capacity of the soil when dry is considerably higher than when wet. During the first run, for example, the capacity diminished from c. 129 mm/hr. at the start to c. 55 mm/hr. at the end. The second run, which is essentially a continuation of the first, in that the soil had not had time to dry much in the intervening 24 hours, shows much less change, falling from only c. 45 mm/hr. at the start to c. 30 mm/hr. at the end. An interesting feature of this curve is the gradual increase in the infiltration capacity during the last hour.

Figure 13. Graph showing infiltration capacity for a soil when dry and at field capacity.



It is possible that it is due to some inherent soil characteristic. But it is also possible that it is due to lateral seepage from the plot area. This might be caused by water from the plot area penetrating to the subsoil at a faster rate than that from the surrounding buffer zone. However, no evidence of this was found when the soil was dug up for investigation.

IV.3.2 The effect of burning on the infiltration capacity of a sourhope on Winton soil association

Burning is a practice believed to cause a significant reduction in infiltration capacity. It both removes the protection effects of the vegetation cover, and hakes and seals the soil surface. An opportunity to investigate the effect of burning arose when disease necessitated the use of this method to destroy an area of grassland, mainly Agrostis stolonifera, on the Edinburgh University experimental farm at Boghall.

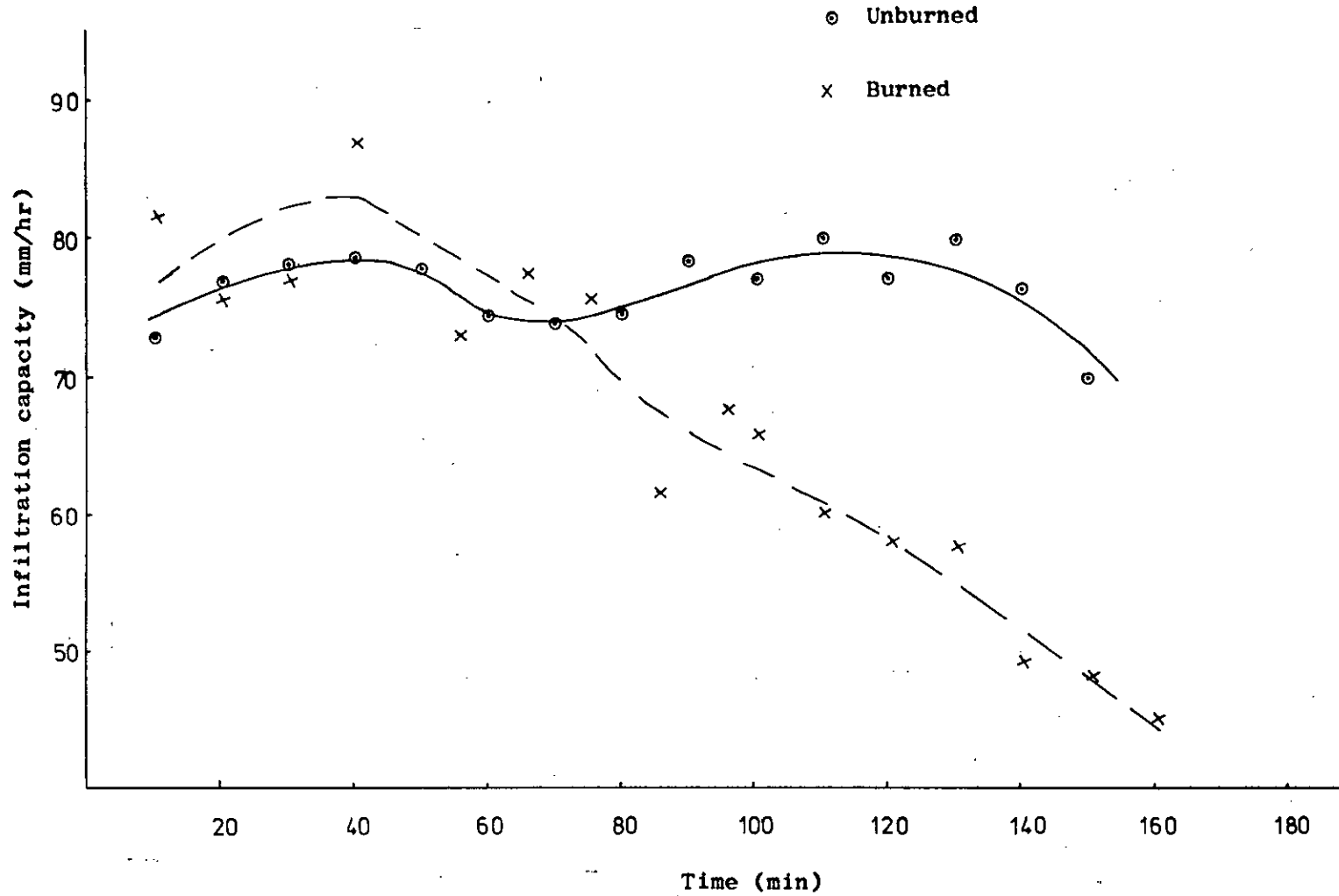
Two plots were studied, one inside the burnt area, the other outside it, in an ungrazed pasture. Both were located in a flat field on the intergrade soil of soliflucted andistic drift over Winton subsoil horizons, (The Soils of The Bush Estates, Midlothian; Edinburgh Centre of Rural Economy, 1969) at an altitude of c. 200 metres above sea level, and both were studied on the same day after an extended period of dry weather.

Each plot was prepared and measured as described at the beginning of this chapter. Water was applied to each plot at a rate of c. 95 mm/hr. for $2\frac{1}{2}$ hours.

The results are summarised in Fig.14 and listed in full in Appendix 7. It is apparent from Fig.14 that the capacity curves

Figure 14. Infiltration capacity of burned and unburned grassland on the

Sourhope Soil association.
Winton



obtained were more complex than those resulting from earlier experiments. For instance, during the first 30 minutes at each site the infiltration capacity increases; this behaviour contrasting markedly with the initial rapid decrease noted in earlier measurements. Again the subsequent decrease after this first half hour is irregular and produces a convex rather than a concave curve as in the work represented earlier in this chapter. Part of this behaviour can be explained by the very dry nature of the soil at the beginning of each measurement. The initial rise, for example, probably reflects the fact that the soils are dry enough to repel the first water applied to them. The rise in each curve after about an hour, however, is more difficult to explain. It is possible that this increase might be due to the effect of raindrop impact having a progressive loosening of ^{effect on} the soil surface after an hour or so, leading to a temporary increase in infiltration capacity. But it is also possible that the main cause is lateral seepage, but no evidence of this could be found when the soil was dug up afterwards. But while the measured infiltration capacities may not be wholly accurate, it is clear that the burnt plot has a substantially lower infiltration capacity than the unburnt one during the second half of the measurement period. In retrospect it is a pity that water was not applied to each plot for a longer period to see whether the curves would assume a more normal shape once the soil had been thoroughly wetted. It is apparent from this experiment that even on the burnt plot very heavy rain would (over 40 mm/hr.) be needed to cause surface runoff.

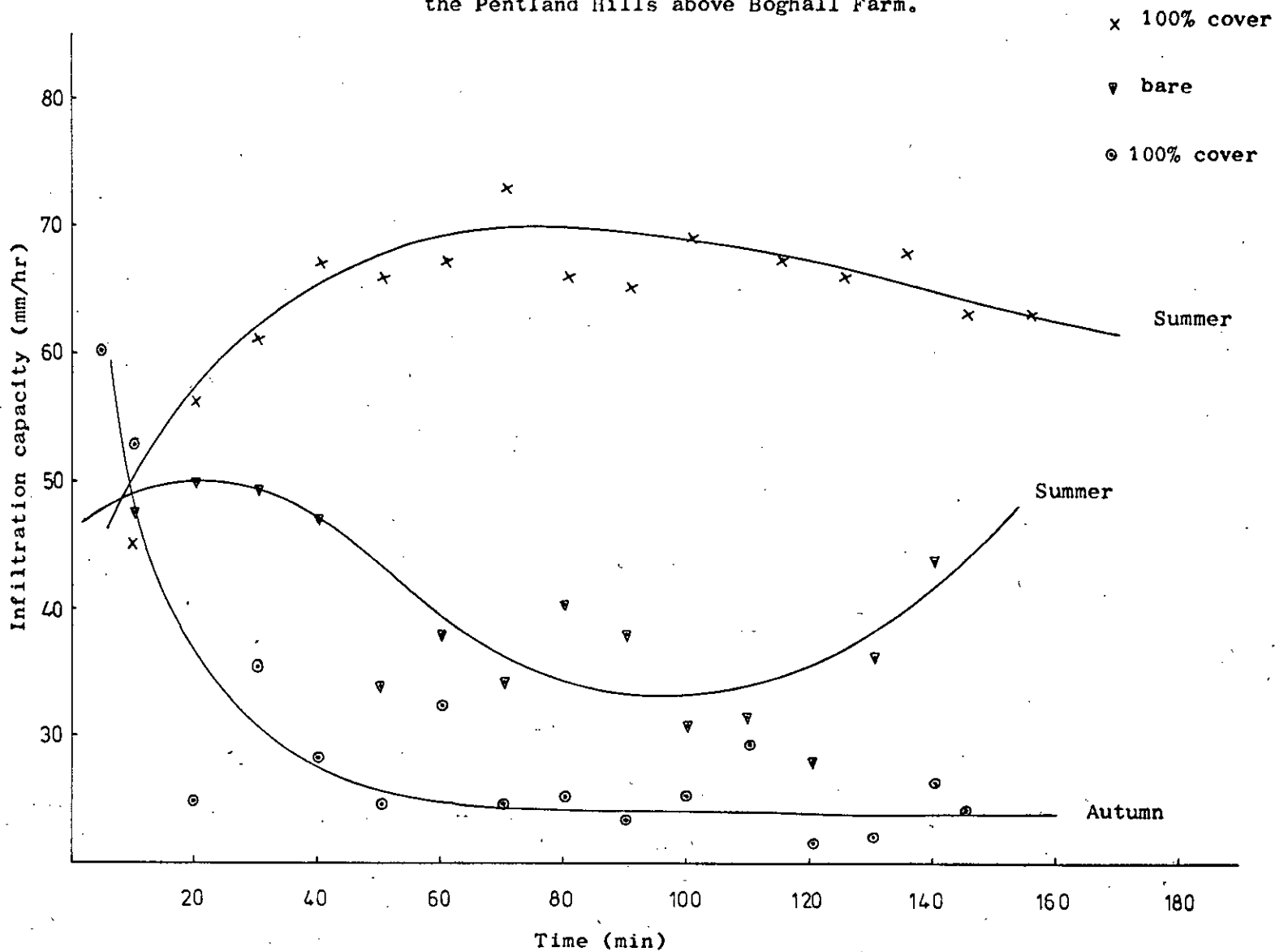
IV.3.3 Seasonal differences in the infiltration characteristics of a shallow upland soil

The summer of 1976 was exceptionally hot and dry. Conditions were ideal therefore to study the effect of drought on the infiltration characteristics of the then acid brown earth soils of the Pentland Hills on the outskirts of Edinburgh. The site chosen was located at an altitude of c. 300 metres above sea level on the south east side of the Pentland Hills above Boghall Farm.

Two plots were measured under drought conditions on September 6th, 1976, one covered with close grazed grass of Agrostis tinnis, Festuca ovina and Rhitiadelphus loreus, the other was bare soil in the vicinity of a rabbit warren. A third plot, also grass covered, was measured 3 months later after several weeks of heavy autumn rain. All 3 plots had surface sloping at c. 20°, and organic matter content c. 19.2%.

The results obtained by applying rain to each plot for 1½ hours at an average intensity of 95 mm/hr. are summarised in Fig.15 and given in detail in Appendix 8. The most startling feature of these results is the remarkable contrast between the late summer and late autumn infiltration curves for the grass cover plots. The autumn data show the sharp decrease and flat recession of the classical infiltration curve. The summer data, on the other hand, show a rapid increase in infiltration capacity during the first 1-1½ hours, followed by a gradual recession thereafter. The explanation for the initial rapid increase is that the organic matter at the soil surface was so dry that it repelled much of the first rain falling on it. Only when it had been wetted for some time was water able to penetrate through to the

Figure 15. Infiltration capacity of the Brown Earth Soil on
the Pentland Hills above Boghall Farm.



freely draining soil beneath. The curves failure to fall rapidly as the experiment proceeded was due largely to lateral seepage. It was found that once water had penetrated about 4 cm. into the soil it flowed laterally out of both the plot area and the buffer zone. Even after $2\frac{1}{2}$ hours of rainfall application the soil below 5 cm. under the root zone was completely dry. One can only assume that although heavy rain falling on such a soil might infiltrate through the surface, it would then flow rapidly downslope as "interflow" and would reach a stream channel almost as rapidly as if it had become surface runoff.

The curve for the bare soil plot exhibits the S shape curve characteristic of a dry soil with a high organic matter (Allison, 1947). This results from a gradual increase in soil permeability as the organic matter is slowly rewetted by the rain infiltrating into it.

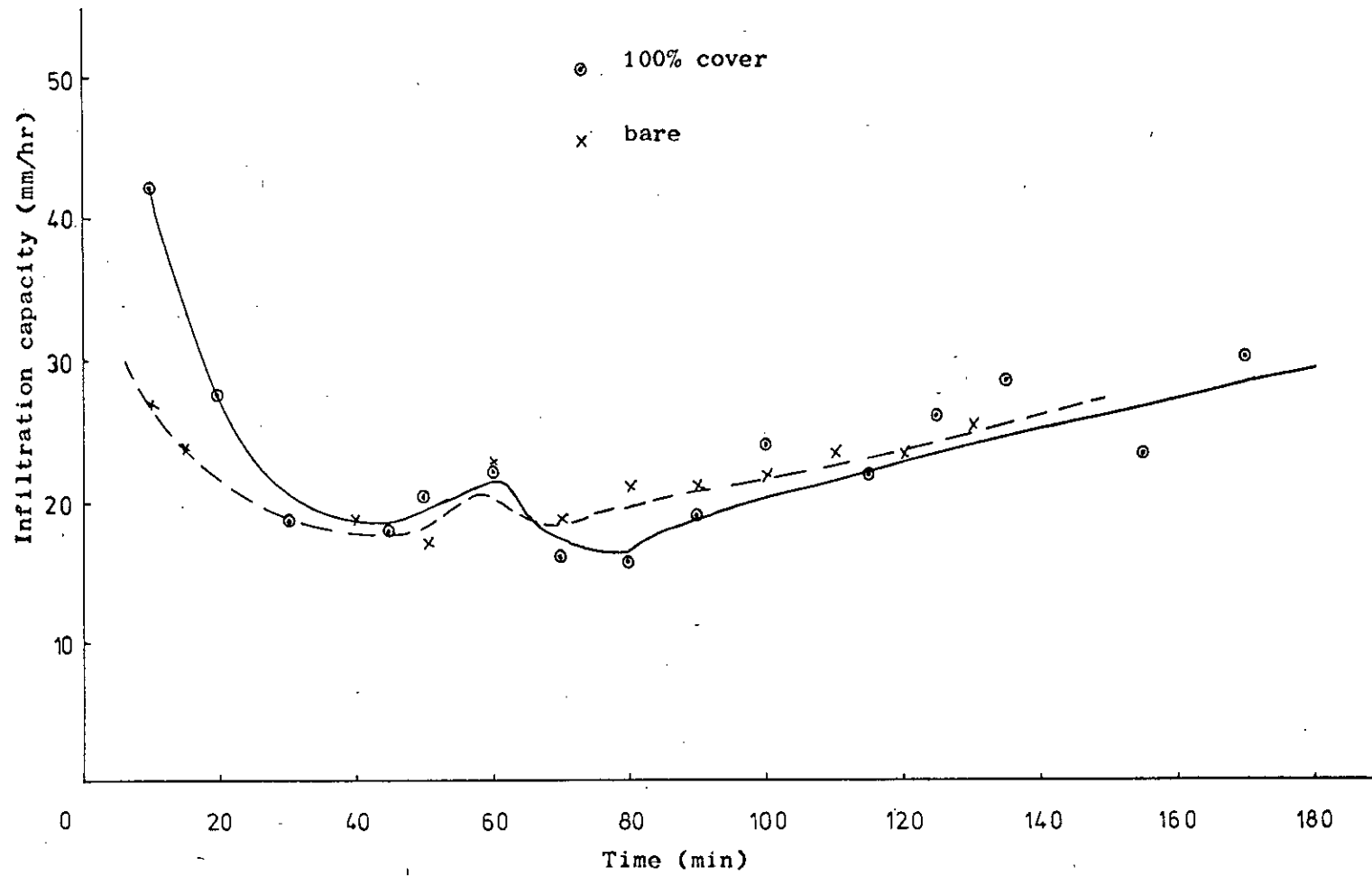
Contrary to expectation, no real difficulty was encountered in erecting and using the simulator on a steep slope. The only problems that arose were due to buffetting by the wind, and to dust. The latter problem was easily solved by covering the rainulator with cheesecloth during the course of a measurement run.

IV.3.4 Effect of surface cover removal on infiltration capacity

Surface cover is one of the factors that affect the infiltration capacity of a soil. To investigate this and to evaluate the efficiency of the instrument, two experiments (on September 3rd, 1976) were conducted on the gleyed soil of the colzium association above Boghall Farm at an altitude of c. 300 metres above sea level. The area was flat and the sites were about 10 metres apart with a vegetation mainly of Mardus stricta and Anthoxanthum odoratum. The surface cover of one plot was left untouched while the other had the vegetation entirely removed from the plot and surface area leaving the soil bare. The instrument was installed as before and each sample area received applied rain at a rate of c. 80 mm/hr. for a 2 hour period. The results obtained are summarised in Fig.16, and given in detail in Appendix 9.

During the first hour, the infiltration capacity of the plot with undisturbed cover was slightly greater than that of bare plot but for the second hour it was almost the same. The explanation of this may be that the surface cover prevents raindrop impact by interception and subsequently slowly release the water to the soil, giving a higher initial infiltration capacity. In addition a proportion of the water applied is absorbed such that it cannot readily be collected by pumping it out. The difference of c. 20 mm/hr. in the capacities of the plots may also be partly due to surface sealing by raindrop impact on the bare plot resulting in a lower infiltration. However both plots exhibit the classical decrease of infiltration capacity with time. Both plots show an increase in infiltration capacity after 45 minutes and subsequently reach almost the same level by the 60th minute during the next 10

Figure 16. Infiltration capacity of a gleyed soil of the Colzium association.



minute period then decrease again. This trend is difficult to interpret but they may be caused by lateral seepage due to the greater hydraulic head of the plot cylinder compared to the buffer zone, as described before. On the other hand, it may be coincidental due to fluctuation in rainfall rate and the manner of withdrawal of water from the plot.

A marked feature of the results is the gradual increase in infiltration capacity with time during the second hour. This, perhaps, could be due to the escape of air initially trapped under the wetted area which would increase the resistance to water movement (Christiansen, 1944). Alternatively, the more likely explanation is lateral seepage of water through the root zone, as when the soil was excavated after the experiment, there was a wide wetted area in this zone to a depth of 3.5 - 4 cm. It is clear that in this situation the effect of removal of vegetation cover is of short duration.

IV.3.5 Experiment made on the Alluvial fan

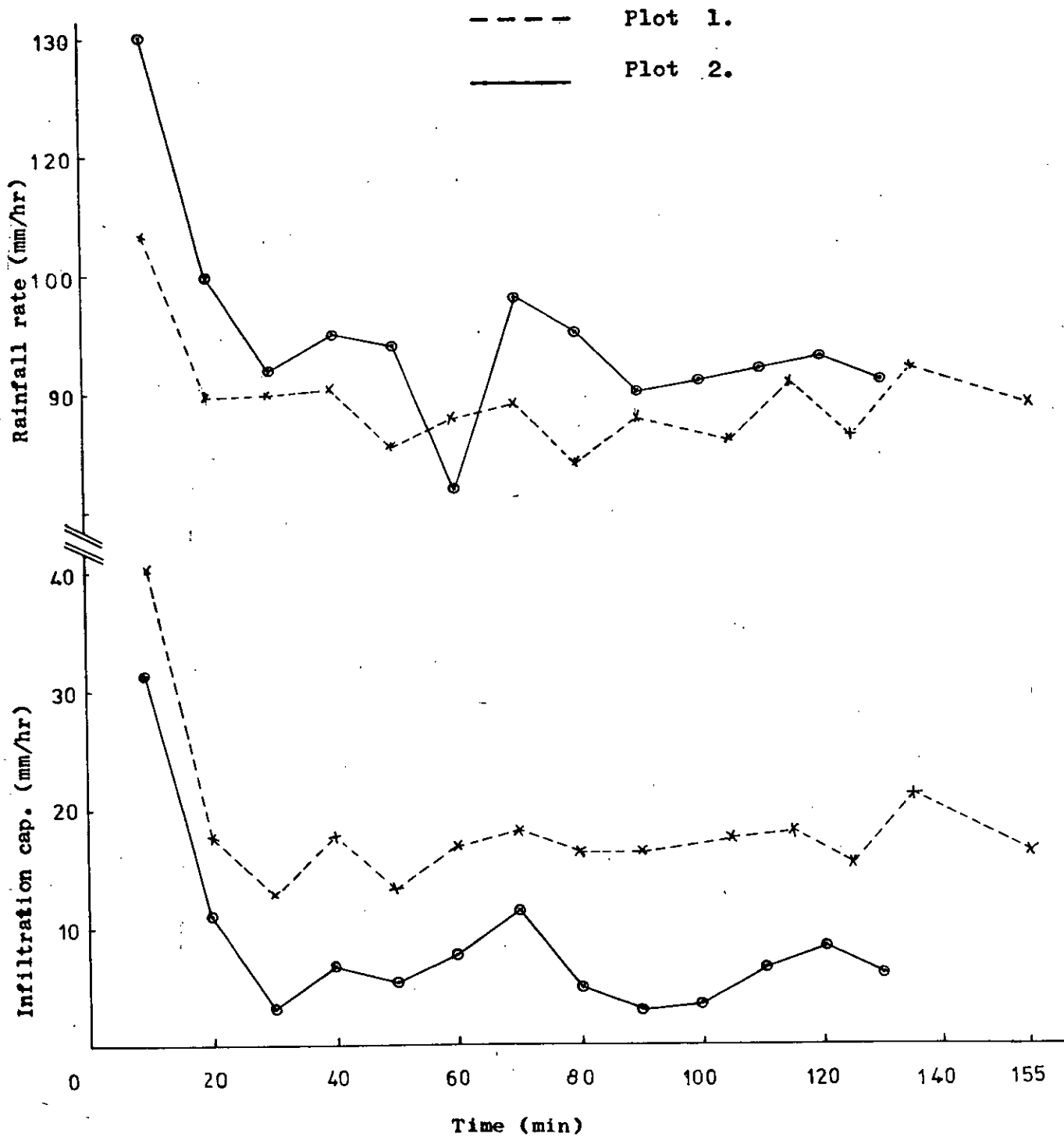
In view of the possibility of lateral flow seriously influencing the measured infiltration capacity, an experiment has been conducted on an area of fine textured soil on a flat alluvial fan. The soil selected was observed to be of uniform structure and the site allowed for easy installation of the instrument. Two plots were chosen in a sheep-grazed field at an altitude of c. 200 metres above sea level (on September 7th, 1976). The vegetation was improved grass pasture of Lolium perenne and Poa trivialis which provided about 25% cover on one plot which the other was bare. Both plots had an intensity of about 100 mm. rain per hour applied over 2 hours

with measurements taken every 5 minutes. The results are summarised in Fig.17 and given in detail in Appendix 10.

The infiltration capacity of both plots was found to be very similar and with parallel fluctuations. Characteristically the infiltration shows a rapid decrease in the first $\frac{1}{2}$ hour and then a gradual increase for short periods of 10 to 20 minutes. The initial decrease was because the soil was dry and hard and it took some time to wet before allowing easy penetration of the soil. The bare soil plot had a slightly higher infiltration capacity than the plot with approximately 25% of surface cover. One reason may be that as raindrops repeatedly strike the bare soil surface at the same points they tend to penetrate into the surface so that water could infiltrate from these shallow holes both downwards and laterally and so increase infiltration. Another reason might be variation within the soil itself.

The gradual increase of the curves after half an hour was noted again, as in the previous reported experiments. To explain this part of the curves the rainfall application rates were drawn for comparison as shown in Fig.17. It is apparent that the slight increase between the 30th and the 40th minute periods might really be due to lateral flow, but it is also possible that this effect could be due to considerable fluctuation in rainfall application during an adjustment of the instrument. The infiltration capacity may be controlled alternately by the subsoil layer characteristics. After each run was over, the soil under the plot and the buffer area was dug up to a depth of 15 cm. where the wetting front could be observed to be at apparently the same level under both. It is very difficult, however, to decide exactly whether there is lateral movement of water across the plot boundary in the earlier part of

Figure 17. Infiltration capacity of an alluvial soil in relation to rainfall application rate at Boghall Farm in Summer 1976.



the run, but if it does occur, it is negligible and lasts for only a short period. The amount involved and the duration could be assessed if a very precise set of values is required.

IV.3.6 Investigation of lateral water movement

The question remained as to whether the lateral flow of water across the plot boundary is the principle problem in using the instrument. An opportunity arose during the autumn of 1976 to study this problem on 3 plots on the same alluvial site described in section 3.5. As these experiments were designed to test the lateral flow only, rainfall intensity was not considered, the base unit installation and time interval of water withdrawal being changed for the last two plots.

In the first plot (November 17th, 1976) rain was applied at an average intensity of 77 mm/hr. for 135 minutes; the base unit and installation being as for previous experiments while water was removed at 5 minute intervals. To test the effect of hydraulic head and the method of sealing the base unit with model clay, in the second plot (November 19th, 1976) the base was pushed into the soil to a depth of c. 1 cm. and the soil gently firmed both within and outside the wall. Excess water was pumped out at 2.5 minutes although still recorded at 5 minute intervals. This method was repeated in the third plot (November 19th, 1976) but particular attention was paid to infiltration capacity in that as soon as infiltration capacity increased and subsequently decreased the instrument was removed and the wetting front examined by digging up the soil.

The results are summarised in Figs. 18, 19 and are given in full in Appendix II. The first plot showed a rapid decrease in infiltration capacity, dropping to zero in 30 minutes followed by an increase before becoming more or less steady. This parallels the results obtained in summer (Fig.17) but the slower reaction may be due to the higher soil moisture content at this time. The pattern of infiltration followed the classic curve with minor fluctuations. In plot 2 infiltration capacity decreased from more than 50 mm/hr. in the first 5 minutes to only 9 mm/hr. in 10 minutes later which was about the minimum rate. This may have been influenced by changes in the rainfall application rates but the infiltration then levels off, showing that the water in both plot and buffer zone reaches the bottom of the cylinder at nearly the same time. Subsequent fluctuations probably are due to windy conditions and subsoil variation. Upon digging up both plots the wetting front was very difficult to distinguish due to the general moistness of the soil.

The last plot (November 19th, 1976) had rainfall applied at an average rate of 101 mm/hr. for 45 minutes. As shown in Fig.19 there is a rapid decrease in the first 10 minutes which by comparison to the rainfall intensity is not a very sharp decrease as an infiltration characteristic. A constant rate at a slightly higher level was then established from 10-35 minutes followed by a further increase at 40 minutes but the rate then fell again. Clearly infiltration capacity is unaffected by rainfall rate, the changes having to be explained in terms of the soil characteristics. The soil was examined to a depth of 5 cm., no differences in colour or consistency being detected upon rubbing, between the plot and buffer zone although both appeared moister than the soil outside the

Figure 18. Autumn infiltration capacity of an alluvial soil at Boghall Farm, 1976.

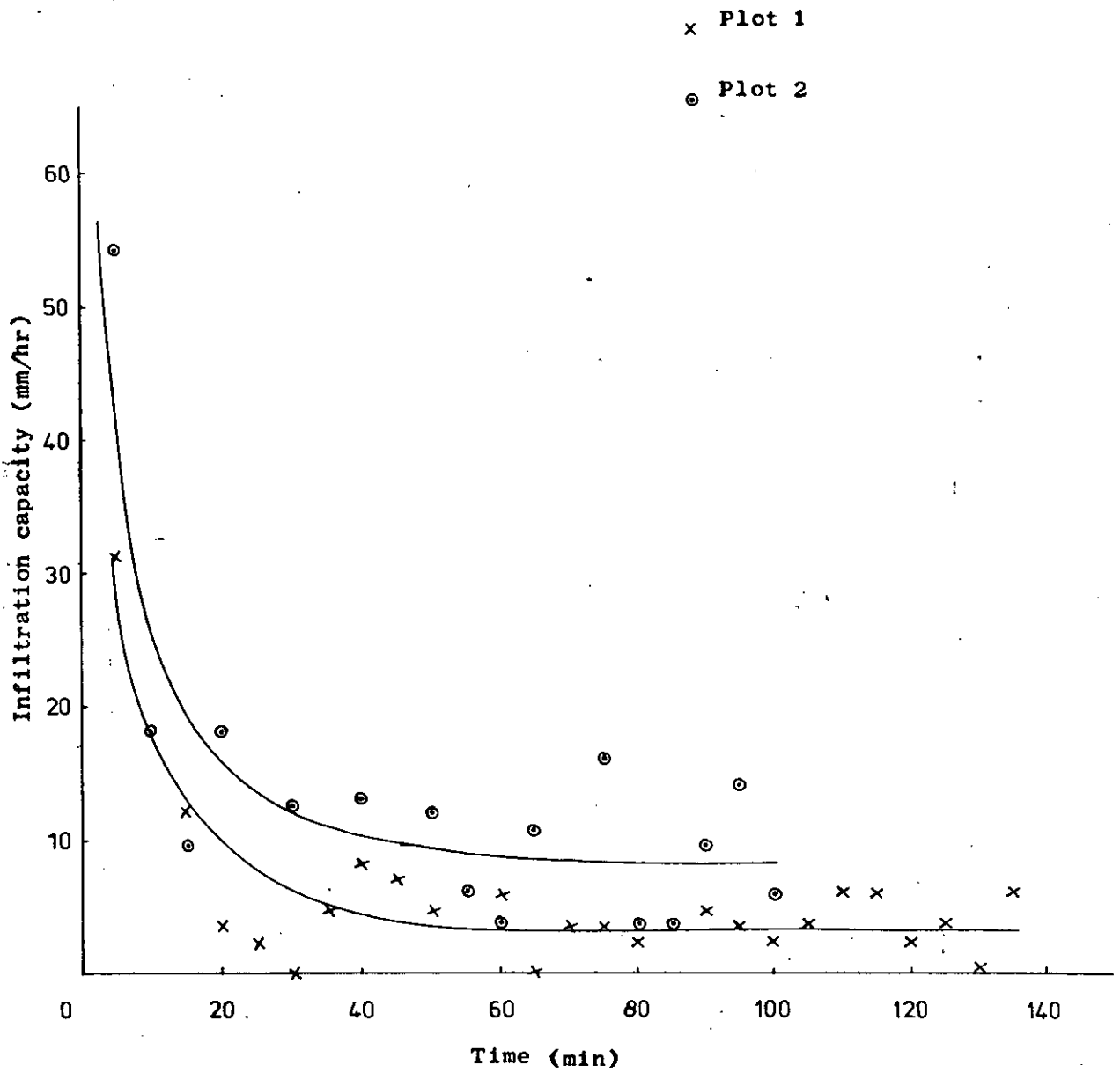
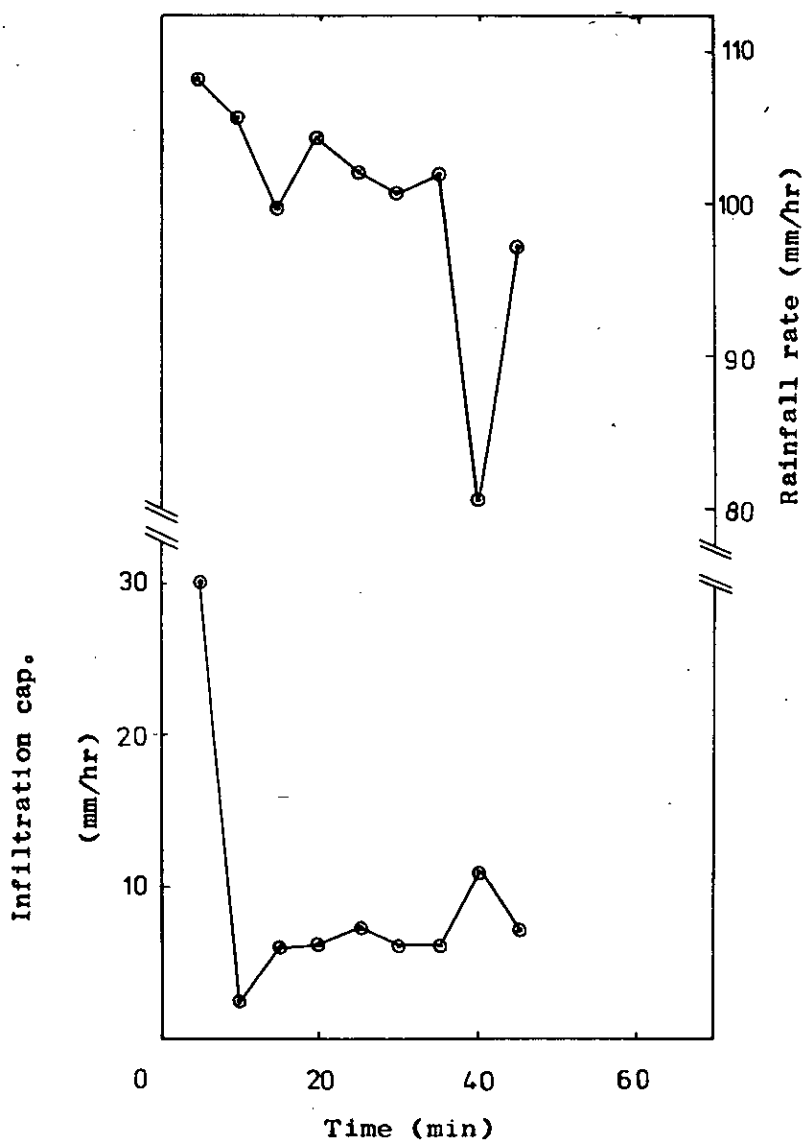


Figure 19. Results from an investigation of lateral water movement in the use of the infiltrometer.



instrument. It was, however, very difficult to ascertain that there was definitely no lateral flow but the adoption of the 2.5 minute interval in water removal and the lack of a model clay seal made the instrument more sensitive to lateral flow than in earlier experiments.

IV.4 Discussion

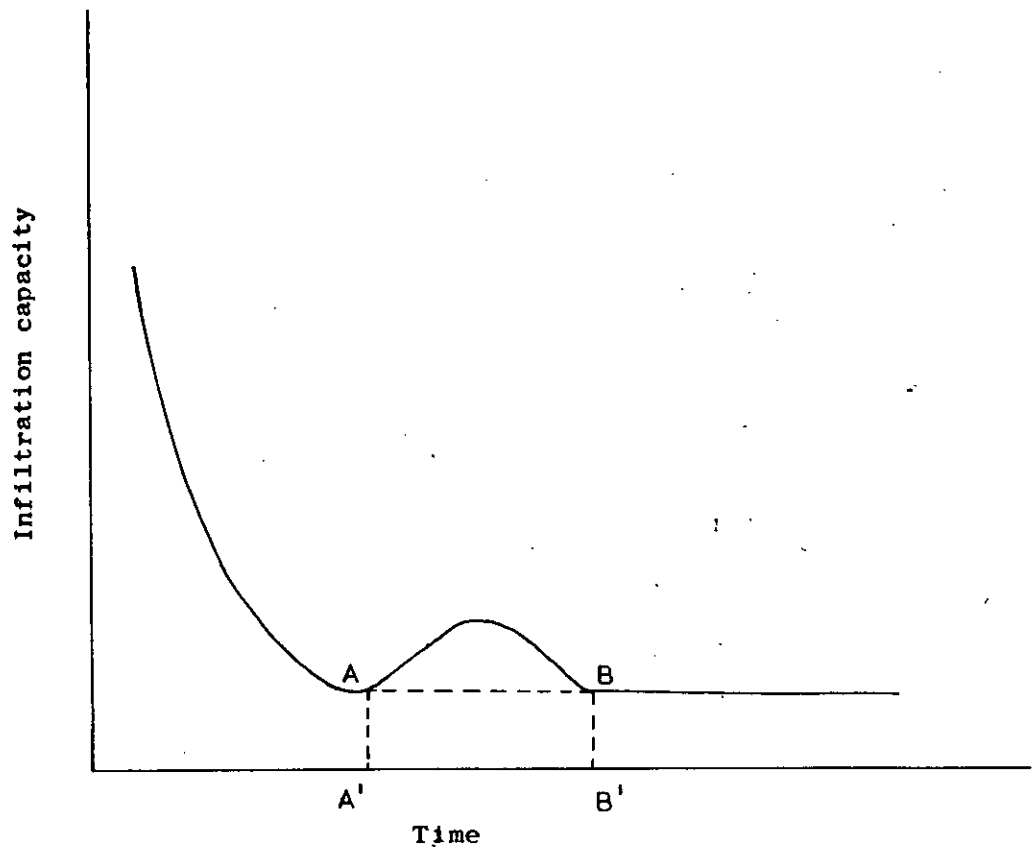
The aim of the experiments in different field conditions was to evaluate the use of the instrument rather than to fully characterise the soils tested. For the latter purpose greater precision and replication would be required. It is however worth discussing the effect of the unusually dry summer of 1976 on the infiltration capacity of some of the soils. For example on the high organic Brown Earth (see Fig. 15) the bare soil plot showed an initial decrease and later increase in infiltration capacity. This was due to the resistance of wetting of the dry organic matter and not to the functioning of the instrument. This was demonstrated by digging a hole and pouring water into it which took a considerable time to drain. Jamison (1945) reported that the surface layer which was richer in organic matter became much less wettable than the subsoil and that this acted as a water-impermeable resistant roof over the subsoil layers and prevented the wetting of the deeper soil layers. It is also reasonable to expect variation in the infiltration capacity through different soil layers as even in late autumn the subsoil remained dry despite heavy rain.

An interesting feature of the infiltration curves is the frequency of a gradual increase during the first hour of most experiments.

For example this is particularly true for section IV.3.4 (Fig. 16) between the 50th and 70th minutes. This anomaly might be due to lateral seepage. Differences in hydraulic head may result in water from the plot reaching the base of the cylinder before that from the buffer zone, or the effect of the model clay seal may prevent water in the bufferzone from flowing down the outside surface of the cylinder, as it does inside the plot. The amount of this lateral flow may be assessed as shown in Fig. 20 from the infiltration curve at points A and B if the expected minimum rate (as shown by the dotted line) is drawn from A to B. If however, points A and B do not occur during this period of the run the assessment will be very difficult to make and the above suggestion may not be used without field experience and soil investigations. It proved difficult to establish this feature even though the wetting front was examined in each plot as no observable differences between plot and buffer zone were found.

Vibration from wind makes it difficult to read the scales on both the reservoir and water supply tanks and was a source of error on several occasions. Dust entering the supply tank may clog the rainulator holes while weather conditions may cause fluctuation in the flow rates as shown in Fig. 17 which is very different from laboratory tests (Fig. 8). Further variation in infiltration capacity may be due to the method of withdrawal of excess water from the test plot, as some is left in the rubber tubing and there may be some variation in the pumping intervals. Despite these sources of error it is possible to obtain results which are comparable between experiments and are similar to already published infiltration curves.

Figure 20. Diagram showing an estimation of the amount of lateral water movement from the base unit.



Chapter VCONCLUSION

Attempts have been made for years to accurately measure the rates of intake of water into soils, or infiltration. There are many well known factors affecting infiltration which cause serious problems in the field soil measurements. Different kinds of instrument have been constructed and developed beginning from a very simple method of pouring water into a tube and timing its disappearance into the soil to the most complicated system of rainfall simulation, but very few have shown satisfactory results.

When natural rainfall characteristics became more widely known in the 1940's, the subsequent development of instruments was largely based on the duplication of those rainfall characteristics which had been found to have major effects on the soil surface. Although numerous instruments have been developed for this purpose no single method has yet attained universal acceptance. The best known rainfall simulation infiltrometers for watershed research are those based on the type-F nozzle (P. 21, 23) and for agricultural work those developed by Meyer and McClune (1958) and Bertrand and Parr (1961). However, these instruments are very big and expensive and were not suited for work in forest watersheds which often have inadequate access. A small, portable rainfall-simulator developed by I.S. McQueen (1963) has proved to be very efficient for this purpose, but this apparatus fails to prevent lateral water movement, and it is rather tall for use in forested areas.

A similar portable rainfall-simulator has been designed and developed based on McQueen's model but with modifications to meet the above stated defects and in addition to allow its use on sloping

land. The design allowed for sufficient water to simulate high intensity rainfall, such as is frequent in areas like Thailand, for a period in excess of one hour.

The preliminary tests with a pilot model were found to be very satisfactory. During these laboratory tests, some problems such as air bubbles and characteristics of water which affected the ratio of rainfall were also found. These problems, however, are not considered serious in use of the larger field instrument for which rain water, the usual source of domestic supply in Thailand, has been shown to be perfectly satisfactory.

The construction and calibration of a rainfall-simulator infiltrometer has been described. After being tested in the laboratory, it proved very satisfactory with raindrop production of 5.58 mm. diameter and height of fall of 1 metre. Lateral movement of water was found to be negligible. It is able to produce controllable rain ranging from about 35 mm/hr. to 145 mm/hr. which is considered to be a satisfactory performance for use in tropical countries.

The instrument was tested in the field both on slopes and flat topography during one summer and winter. It could not completely avoid the problem of soil disturbance, and it is not possible to install a cylinder on the ground without some degree of disturbance, however this should be minimal in areas of uniform soils such as in Thailand. Lateral movement of water across the plot boundary in field use still may occur on dry soils for a period if measurements based on McQueen's method are made, but for longer periods of over an hour the infiltration capacity of the soil may be readily assessed from the stabilised infiltration curve. The amount of water that moves laterally during the test may also be estimated. This matter

can be resolved by withdrawing excess water from the test plot over shorter periods than those used by McQueen, and by leaving the outer wall of the cylinder without sealing. These problems are unlikely to be of consequence in Thailand where most forest soils are not very dry and there are few of rock outcrops allowing the cylinder tube to be driven easily into the soils.

The air bubble problem was not found after using the instrument in the field, as the large amount of water was not easily affected very much by slight temperature change. Under Thailand conditions, therefore, it is anticipated that the instrument will be able to be used successfully. The materials used in construction should be perfectly transparent so as to avoid errors due to misreading of scales which can only be seen at an angle if the tank sides are opaque. In the construction of the "rainulator" it is very difficult to attain uniformity of hole and pin size so that the possibility of using standard capillary tubing for drop formation (Adams et al, 1957 and Chow et al, 1965) should be investigated. However a rainulator plate of perspex gives poor control of uniform drop size as the surface is readily wettable with a low surface tension allowing water to creep out from the countersinking, particularly when the surface is moist and not perfectly smooth.

Another interesting condition, which McQueen did not mention, is the evaporation of water from the test plot during the run which condenses and clings to the bottom of the rainulator and therefore results in a coalescence of drops with even a slight rise in temperature. This effect would be a serious problem for this type of drop formation if the instrument was used in tropical areas where high temperature is often present. An alternative wind

shield is needed which might provide ventilation in the lower part but which would not affect the dropping rain in an area where wind is not frequently strong such as in Thailand.

Weather conditions also influence the regulation of rain intensity by means of the hydraulic head. It was found that even if the same hydraulic head was employed different intensities were achieved on days of bright sun or cloud. This effect may be due partly to temperature differences which lead to changes in the viscosity of water as has been shown by Musgrave (1955). An alternative possibility is that the instrument is affected by changes in atmospheric pressure as well as the effect of high temperature on bright days on the vapour pressure in the water reservoir. These effects may alter the dynamic equilibrium and possibly the water level in the supply tank. Such changes in the supply tank level are difficult to read (p. 74) and adjust for when using the instrument in the field with changeable weather conditions. Such errors due to environmental effects have been described before (Mech, 1965) but do not form a serious limitation to the use of the instrument in view of the heterogeneity encountered in the soils under examination.

To take account of these possible sources of error in field operation, the imposed rainfall should be set at a higher rate than required and thereafter adjusted, in accordance with the prevailing conditions and previous experience gained in the use of the instrument. A further improvement can be obtained by making the water reservoir vertically adjustable to enable fine control of the hydraulic head and consequently the rainfall intensity (Adam, 1957).

The instrument, as designed and constructed, proved a satisfactory means of determining the infiltration capacity of the

soils on which it was tried. The further modifications proposed here, both in construction and use, would materially enhance its effectiveness for use in conditions such as those found in Thailand.

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APPENDICES

Appendix 1.Infiltrometer, List of materials, detailsRainulator:

Perspex disc diam.	31.4	cm.
Thickness	1.2	cm.
Total holes	434	
Holes over the plot	129	
Hole size	0.145	cm.
Countersinking size	0.6	cm.
Stainless wire gauge no.	18	
Wire size	0.124	cm.

Supply tank:

Galvanized sheet gauge no.	18	
I.D.	31.4	cm.
Length	28	cm.
Water capacity at normal rate (5 cm.)	4	litres
Number of scale attachments	2	

Reservoir:

Perspex tube diam.	14.65	cm.
Thickness	0.3	cm.
Length	60	cm.
Water capacity	10	litres
Height above the supply tank	5	cm.
Perspex regulator tubing diam.	0.6	cm. (I.D.)
Water refill opening diam.	6.6	cm.
Stop cock no.	62	
Drain cock diam.	1	cm.
Supporting metal frame	37	cm.

Pressure Head Regulator:

Perspex tube diam.	4.5	cm.
Thickness	0.3	cm.
Length	50	cm.
Water refilling bore hole diam.	2	cm.
Stop cock no.	19	
Drain cock diam.	0.6	cm. (O.D.)
Inlet and outlet perspex tubings	0.6	cm. (I.D.)
Number of metal support fasteners	2	

Wind Shield:

Plastic tube diam.	32	cm.
Thickness	0.3	cm.
Height	100	cm.
Stabilize metal supporter length	50	cm.

Base units:

Galvanised metal sheet gauge no.	18	
Diameter	16.6	cm.
Height	20	cm.
Area	216.32	cm ² .

Tripod legs:

Length	150	cm.
Adjustable metal tips (pointed)	20	cm.
Screws	0.6	cm. (O.D.)

Runoff water collector:

Perspex tube diam.	4.5	cm.
Length	60	cm.
Rubber hose	0.6	cm. (I.D.)
Inlet and outlet perspex tubing	0.6	cm. (I.D.)
Stop cock no.	43	
Number of rubber gas pump	1	

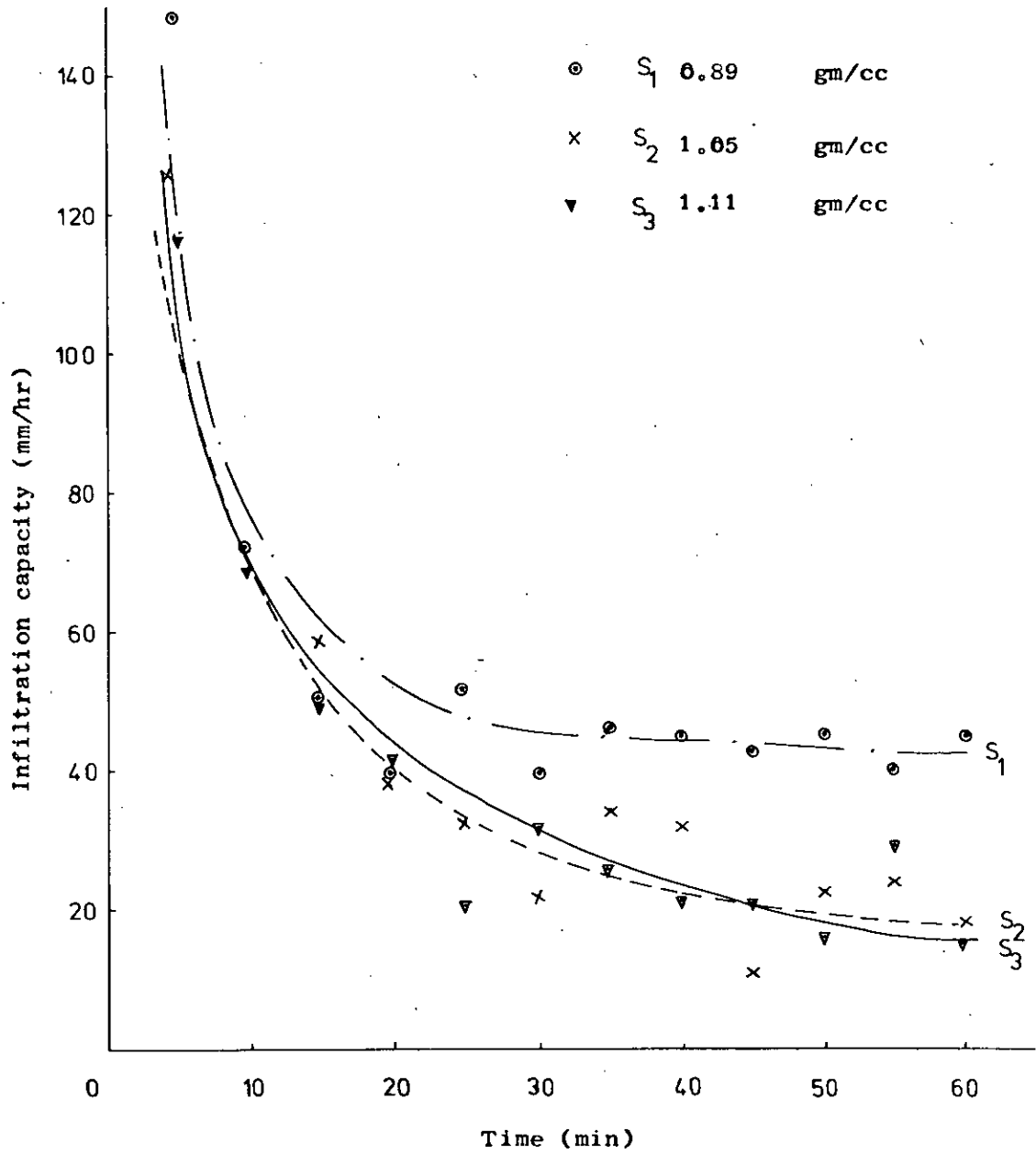
Appendix 2.

Rates of delivery over an extended period of time at temperature 22.5°C. in relation to water caught at the plot position in 10 minute intervals.

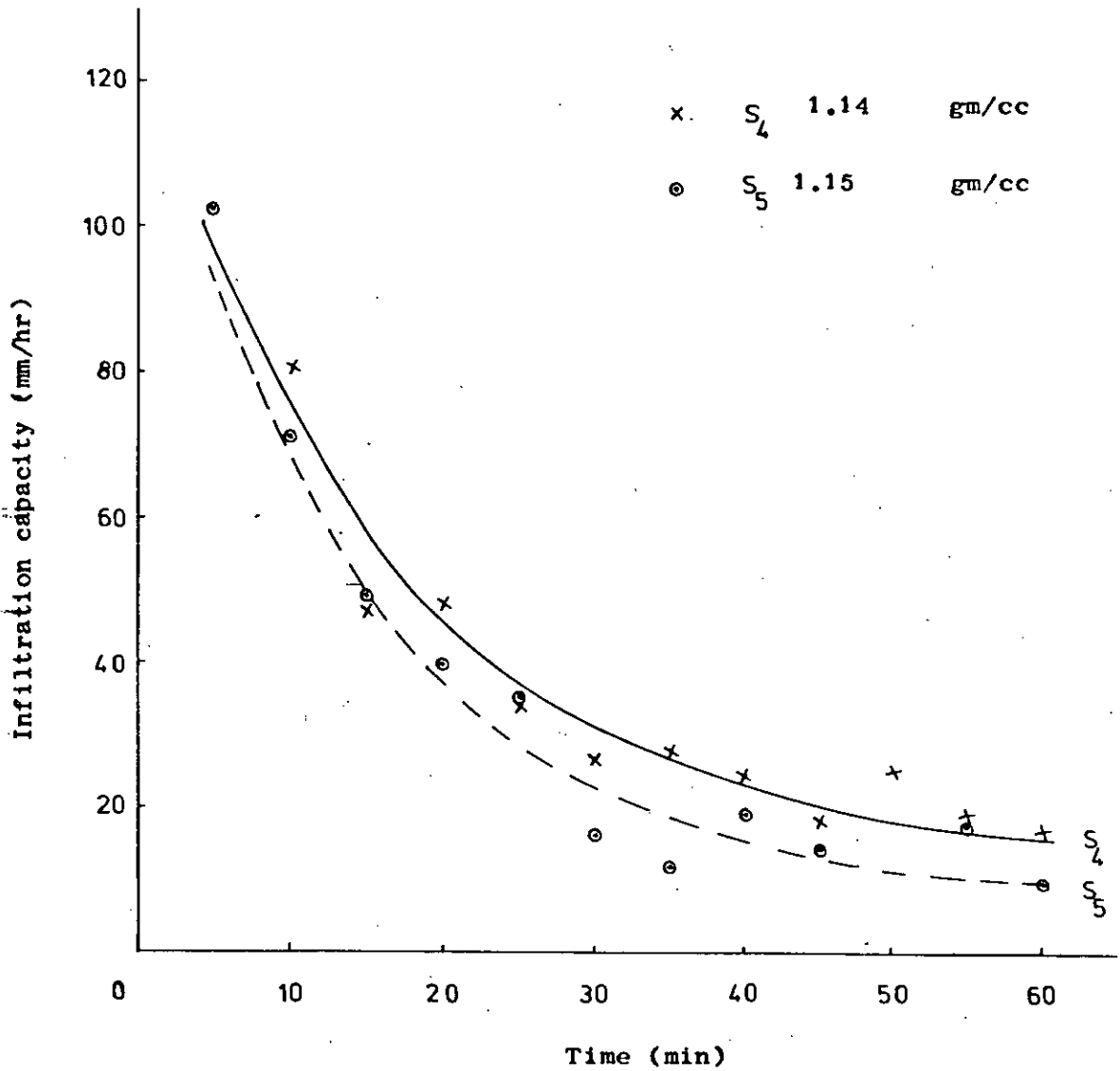
Hydraulic head (cm.)	Changes on Res. (cm.)	Vol.cm ³ .	Depth cm.	Acc. cm.	Average drop dripping sec/drop
1.0	0.65	142	0.66	.66	60 - 75
	0.60	140	0.65	1.31	
	0.60	142	0.65	1.96	
	0.61	142	0.65	2.61	
	0.64	144	0.66	3.26	
	0.63	142	0.65	3.91	
2.2	1.00	220	1.03	1.03	30 - 45
	0.97	224	1.04	2.07	
	0.96	224	1.04	3.11	
	1.00	223	1.04	4.15	
	0.98	222	1.03	5.18	
	1.00	-	-	-	
3.1	1.20	280	1.29	1.29	25 - 30
	1.25	285	1.32	2.61	
	1.25	285	1.32	3.93	
	1.15	260	1.20	5.13	
	1.25	285	1.32	6.45	
	1.20	-	-	-	
4.0	1.45	338	1.56	1.56	18 - 25
	1.50	340	1.57	3.13	
	1.48	340	1.57	4.70	
	1.50	335	1.55	6.25	
	1.50	340	1.57	7.82	
	1.46	344	1.59	9.41	
5.0	1.80	410	1.89	1.89	15 - 20
	1.80	410	1.89	3.78	
	1.80	414	1.91	5.69	
	1.80	415	1.92	7.61	
	1.82	4.0	1.90	9.51	
	1.85	-	-	-	

Hydraulic head (cm.)	Changes on Res. (cm.)	Vol. cm ³ .	Depth cm.	Acc. cm.	Average drop dripping sec/drop
6.0	2.08	475	2.19	2.19	10 - 15
	2.10	477	2.21	4.40	
	2.12	478	2.21	6.61	
	2.10	472	2.18	8.79	
	2.10	477	2.21	11.00	
7.0	2.30	540	2.50	2.50	8 - 12
	2.35	535	2.47	4.97	
	2.41	545	2.52	7.49	
	2.35	540	2.50	9.99	
	-	-	-	-	

Appendix 3. Scatter diagram of the bulk density experiment.



Appendix 3. Scatter diagram of the bulk density experiment.



Infiltrometer Data Sheet

Date: 29 . 5 . 76

Location:

Slope Angle:

Land Use:

Soil Condition: Bulk density experiment

Surface Cover:

Experimental data for S₁

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
12.25	6.30	0.30		-	-				Soil particles are very loose, when water is pumped out from the plot there are some soil particles being sucked out, this may cause the reading of runoff water in error
12.30	5.30	0.50		-	1.20	1.20	1.20	144	
12.35	5.20	1.12	0.12	0.12	0.72	1.92	0.60	72	
12.40	5.20	1.87	0.45	0.33	0.75	2.67	0.42	50.4	
12.45	5.20	2.61	0.86	0.41	0.74	3.41	0.33	35.6	
12.50	5.20	3.44	1.26	0.40	0.83	4.24	0.43	51.6	
12.55	5.20	4.14	1.63	0.37	0.70	4.94	0.37	44.4	
13.00	5.20	4.94	2.04	0.41	0.80	5.74	0.39	46.8	
13.05	5.20	5.70	2.42	0.38	0.76	6.50	0.38	45.6	
13.10	5.20	6.45	2.81	0.39	0.75	7.25	0.36	43.2	
13.15	5.20	7.22	3.20	0.39	0.77	8.02	0.38	45.6	
13.20	5.20	7.95	3.59	0.39	0.73	8.75	0.34	40.8	
13.25	5.20	8.72	3.98	0.39	0.77	9.52	0.38	45.6	
13.30	5.20	9.51	4.37	0.39	0.79	10.31	0.40	48.0	
Total			4.37	4.37					

Rainfall intensity

95.2 mm/hr.

Infiltrometer Data Sheet

Date:..... 29 . 5 . 76

Location:.....

Slope Angle:.....

Land Use:.....

Soil Condition:..... Bulk density experiment

Surface Cover:.....

Experimental data for S₂

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
14.58	5.50	0.80			-	-			
15.00	5.30	0.98		-	0.38	0.38			Soil depth
15.05	5.20	1.85		-	0.97	1.35	0.97	116.4	6.5 cm.
15.10	5.20	2.55	0.13	0.13	0.70	2.05	0.57	68.4	
15.15	5.20	3.30	0.47	0.34	0.75	2.50	0.41	45.2	Soil sample
15.20	5.20	4.08	0.91	0.44	0.78	3.58	0.34	40.8	taken from
15.25	5.20	4.83	1.49	0.58	0.75	4.33	0.17	20.4	the same place
15.30	5.20	5.61	2.01	0.52	0.78	5.11	0.26	31.2	and sieved
15.35	5.20	6.40	2.59	0.58	0.79	5.90	0.21	25.2	with 2 mm.
15.40	5.20	7.15	3.17	0.58	0.75	6.65	0.17	20.4	mesh sieve
15.45	5.20	7.90	3.75	0.58	0.75	7.40	0.17	20.4	
15.50	5.20	8.69	4.41	0.66	0.79	8.19	0.13	15.6	
15.55	5.20	9.49	4.97	0.56	0.80	8.99	0.24	28.8	
16.00	5.20	10.22	5.58	0.61	0.73	9.72	0.12	14.4	
	Total		5.58	5.58					

Rainfall intensity

93.4 mm/hr.

Infiltrometer Data Sheet

Date:.....29..5..76.....

Location:.....

Slope Angle:.....

Land Use:.....

Soil Condition:.....Bulk density experiment.....

Surface Cover:.....

.....Experimental data for S₃.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
16.45	5.80	0.05		-	-				Soil taken from the same area as S ₁ and S ₂
16.50	5.20	0.50		-	1.05	1.05	1.05	126.0	
16.55	5.20	1.26	0.15	0.15	0.76	1.81	0.51	61.2	
17.00	5.20	2.05	0.45	0.30	0.79	2.60	0.49	58.8	
17.05	5.20	2.80	0.87	0.42	0.75	3.35	0.33	39.6	
17.10	5.20	3.60	1.40	0.53	0.80	4.15	0.27	32.4	
17.15	5.20	4.37	1.99	0.59	0.77	4.92	0.18	21.6	
17.20	5.20	5.15	2.54	0.55	0.78	5.70	0.23	27.6	
17.25	5.20	5.90	3.11	0.57	0.75	6.45	0.18	21.6	
17.30	5.20	6.65	3.68	0.57	0.75	7.20	0.18	21.6	
17.35	5.20	7.45	4.29	0.61	0.80	8.00	0.19	21.8	
17.40	5.20	8.20	4.84	0.55	0.75	8.75	0.20	24.0	
17.45	5.20	8.94	5.43	0.59	0.74	9.49	0.15	18.0	
17.50	5.20	9.73	6.02	0.59	0.79	10.28	0.20	24.0	
	Total		6.02	6.02	cm.				

Rainfall intensity 94.9 mm/hr.

Infiltrometer Data Sheet

Date:.....30 . 5 76.....

Location:.....

Slope Angle:.....^o

Land Use:.....

Soil Condition:.....Bulk density experiment....

Surface Cover:.....

Experimental data for ^S4
.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
12.05	5.95	0.00		-	-	-	-		
12.10	5.10	0.00	0.03	0.03	0.85	0.85	0.82	98.4	
12.15	5.20	0.97	0.23	0.20	0.87	1.72	0.67	80.4	
12.20	5.20	1.71	0.58	0.35	0.74	2.46	0.39	46.8	
12.25	5.20	2.55	1.02	0.44	0.84	3.30	0.40	48.0	
12.30	5.20	3.35	1.54	0.52	0.80	4.10	0.28	33.6	
12.35	5.20	4.14	2.11	0.57	0.79	4.89	0.22	26.4	
12.40	5.20	4.95	2.66	0.55	0.81	5.70	0.26	31.2	
12.45	5.20	5.72	3.23	0.57	0.77	6.47	0.20	24.0	
12.50	5.20	6.52	3.88	0.65	0.80	7.27	0.15	18.0	
12.55	5.20	7.27	4.42	0.54	0.75	8.02	0.21	25.2	
13.00	5.20	8.05	5.04	0.62	0.78	8.80	0.16	19.2	
13.05	5.20	8.80	5.65	0.61	0.75	9.55	0.14	16.8	
13.10	5.20	9.58	6.26	0.61	0.78	10.33	0.17	20.4	
	Total		6.26	6.26	cm.				

Rainfall Intensity 95.5 mm/hr.

Infiltrometer Data Sheet

Date:..... 30 . 5 . 76

Location:.....

Slope Angle:.....

Land Use:.....

Soil Condition:..... Bulk density experiment

Surface Cover:.....

Experimental data for ^S5

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
14.15	6.00	0.10		-	-	-	-		
14.20	5.30	0.27	0.02	0.02	0.87	0.87	0.85	102.0	
14.25	5.20	0.92	0.24	0.22	0.75	1.62	0.53	63.6	
14.30	5.20	1.66	0.57	0.33	0.74	2.36	0.41	49.2	
14.35	5.20	2.45	1.03	0.46	0.79	3.15	0.33	39.6	
14.40	5.20	3.30	1.67	0.64	0.85	4.00	0.21	25.2	
14.45	5.20	4.00	2.24	0.57	0.70	4.70	0.13	15.6	
14.50	5.20	4.80	2.94	0.70	0.80	5.50	0.10	12.0	
14.55	5.20	5.60	3.58	0.64	0.80	6.30	0.16	19.2	
15.00	5.20	6.40	4.26	0.68	0.80	7.10	0.12	14.4	
15.05	5.20	7.10	4.94	0.68	0.70	7.80	0.02	2.4	
15.10	5.20	7.92	5.61	0.67	0.82	8.62	0.15	18.0	
15.15	5.20	8.71	6.32	0.71	0.79	9.41	0.08	9.6	
15.20	5.20	9.51	7.00	0.68	0.80	10.21	0.12	14.4	
	Total		7.00	cm.					

Rainfall intensity 94.1 mm/hr.

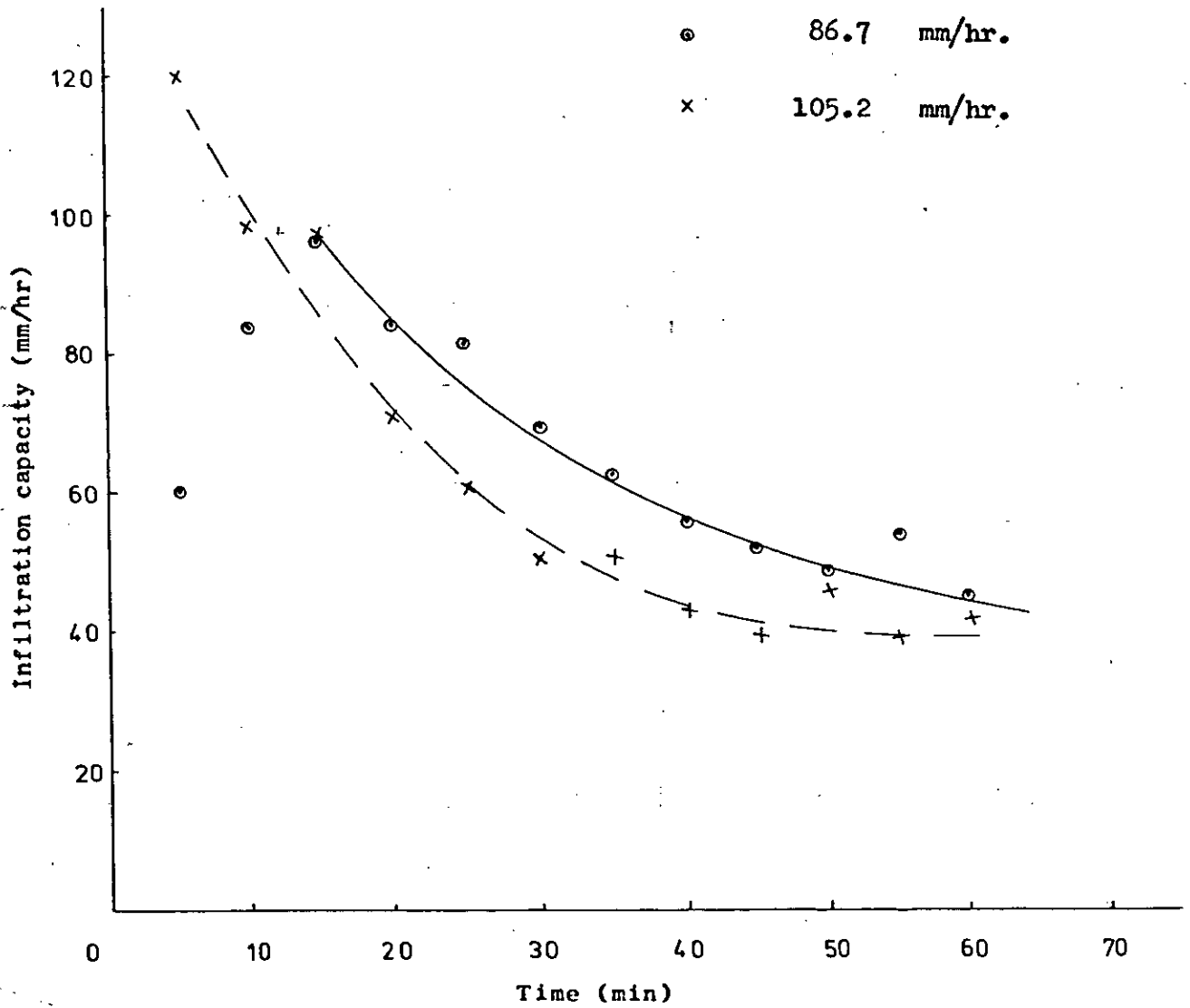
Appendix 4.

Results of the experiment to determine the effect
of moisture content on infiltration capacity.

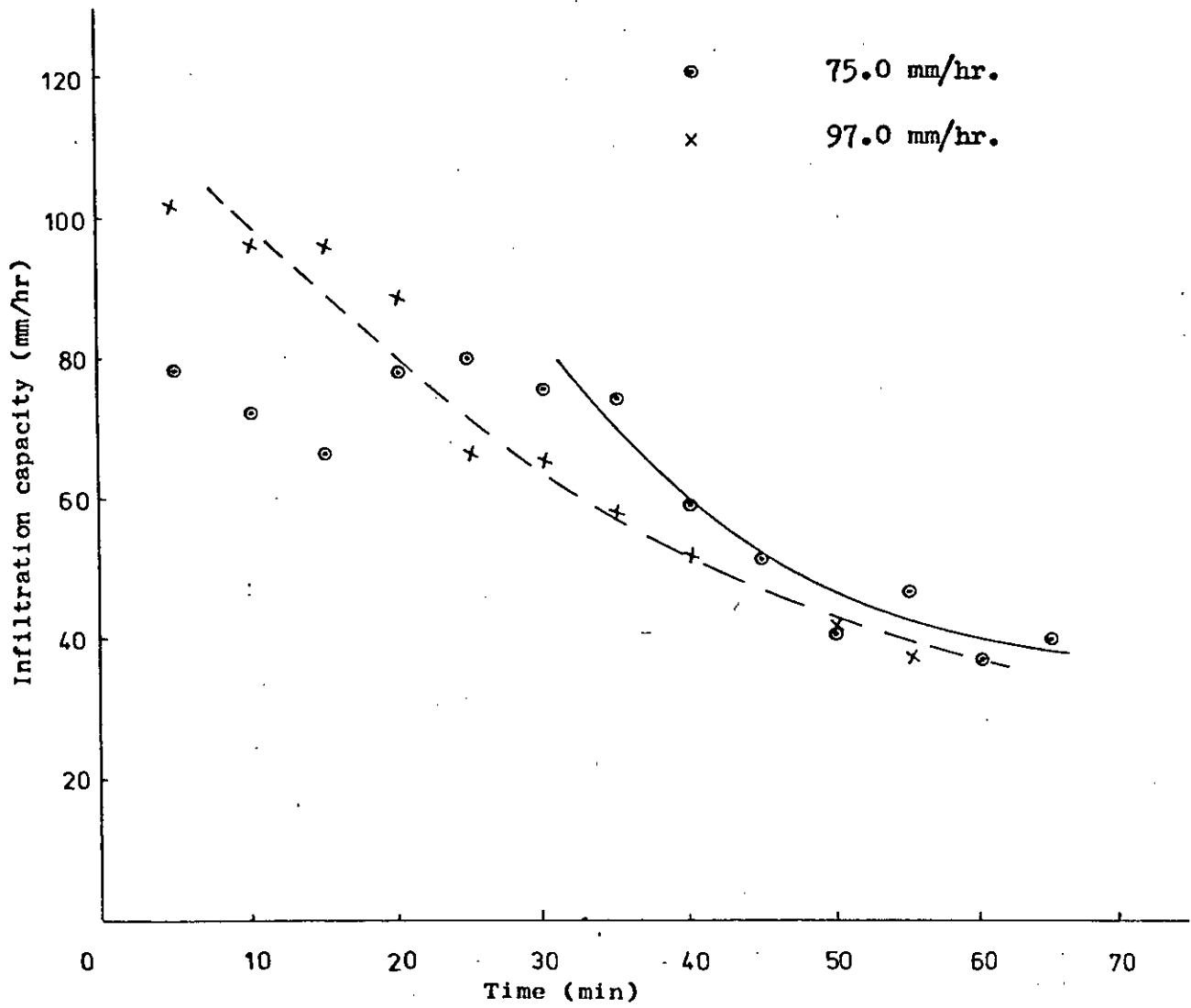
Appendix 4.

Results of the experiment to determine the effect
of moisture content on infiltration capacity.

Appendix 5. Scatter diagram of rainfall intensity in
relation to infiltration capacity.



Appendix 5. Scatter diagram of rainfall intensity in relation to infiltration capacity.



Infiltrometer Data Sheet

Date:.....22.7.76.....

Location:.....

Slope Angle:.....

Land Use:.....

Soil Condition:.....

Surface Cover:.....

.....Rainfall intensity data.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acco.	cm.	mm/hr	
			Acco.	△					
10.20	5.50	0.00							
10.25	5.25	0.25	-	-	0.50	0.50	0.50	60.0	
10.30	4.80	0.50	-	-	0.70	1.20	0.70	84.0	
10.35	4.80	1.30	-	-	0.80	2.00	0.80	96.0	
10.40	4.80	2.00	-	-	0.70	2.70	0.70	84.0	
10.45	4.80	2.73	0.05	0.05	0.73	3.43	0.68	81.6	
10.50	4.80	3.50	0.24	0.19	0.77	4.20	0.58	69.6	
10.55	4.80	4.25	0.47	0.23	0.75	4.95	0.52	62.4	
11.00	4.80	5.00	0.75	0.28	0.75	5.70	0.47	56.4	
11.05	4.80	5.73	1.04	0.29	0.73	6.43	0.44	52.8	
11.10	4.80	6.45	1.35	0.31	0.72	7.15	0.41	49.2	
11.15	4.80	7.25	1.70	0.35	0.80	7.95	0.45	54.0	
11.20	4.80	7.97	2.04	0.34	0.72	8.67	0.38	45.6	
			Rain intensity		86.7	mm/hr.			

Appendix 6.

Results obtained on the Department of Forestry
& Natural Resources' nursery area.

Infiltrometer Data Sheet

Date: 16.8.76

Location: Old nursery

Slope Angle: Flat

Land Use:

Soil Condition: Rained 3 days previous

Surface Cover: Bare soil

Experimental data for dry soil

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
17.10	6.50	+0.35							Rainfall intensity c. 122.5 mm/hr. It takes approx. 2 min. to refill the water reservoir. Bulk density of the soil is 1.084 gm/cc. Moisture content of the soil is 20.03%
17.15	6.00	0.30			1.15	1.15	1.15		
17.20	6.00	1.30			1.00	2.15	1.00	129.0	
17.25	6.00	2.35			1.05	3.20	1.05		
17.30	6.00	3.30	0.03	0.03	0.95	4.15	0.92	118.2	
17.35	6.00	4.40	0.20	0.17	1.10	5.25	0.93		
17.40	6.00	5.40	0.45	0.25	1.00	6.25	0.75	100.8	
17.45	6.00	6.45	0.77	0.32	1.05	7.30	0.73		
17.50	6.00	7.55	1.15	0.38	1.10	8.40	0.72	87.0	
17.55	6.00	8.65	1.44	0.29	1.10	9.50	0.81		
18.00	6.00	9.65	1.79	0.35	1.00	10.50	0.65	87.6	
18.05	6.00	10.70	2.18	0.38	1.05	11.55	0.66		
18.10	6.00	11.70	2.53	0.35	1.00	12.55	0.65	78.6	
18.15	6.00	1.80 ⁺	3.00	0.47	1.65	13.60	0.58		
18.20	6.00	2.80	3.43	0.43	1.00	14.60	0.57	69.0	

+ Refill

Infiltrometer Data Sheet

Date:.....16.8.76.....

Location:.....Old nursery.....

Slope Angle: Flat.....

Land Use:.....

Soil Condition:.....Rained 3 days previous.....

Surface Cover:.....Bare soil.....

.....Experimental data for dry soil.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
18.25	6.00	3.80	0.45 ⁺	0.45	1.00	15.60	0.55		
18.30	6.00	4.80	0.94	0.49	1.00	16.60	0.57	63.6	
18.35	6.00	5.80	1.40	0.46	1.00	17.60	0.54		
18.40	6.00	6.80	1.85	0.45	1.00	18.60	0.55	65.4	
18.45	6.00	7.75	2.25	0.40	0.95	19.55	0.55		
18.50	6.00	8.75	2.73	0.48	1.00	20.55	0.52	64.2	
18.55	6.00	9.65			6.90	21.45			
19.00	6.00	10.65	0.92		1.00	22.45	0.98	58.8	

+ Refill

Infiltrometer Data Sheet

Date:.....17.8.76.....

Location:.....Old Nursery.....

Slope Angle: Flat..°

Land Use:.....

Soil Condition:.....

Surface Cover:.....Bare soil.....

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
16.35	6.40	+0.05 ⁺							
16.40	6.00	0.60	0.70	0.70	1.05	1.05	0.35		Rainfall
16.45	6.00	1.63	1.48	0.78	1.03	2.08	0.25	36.0	intensity
16.50	6.00	2.68	2.36	0.88	1.05	3.13	0.17		124.1 mm/hr.
16.55	6.00	3.73	3.33	0.97	1.05	4.18	0.08	15.0	
17.00	6.00	4.78	+0.65	0.65	1.05	5.23	0.40		B.D. and M.C.
17.05	6.00	5.88	1.73	1.08	1.10	6.33	0.02	25.2	of the soil
17.10	6.00	6.93	2.59	0.86	1.05	7.38	0.19		were not
17.15	6.00	7.98	3.27	0.68	1.05	8.43	0.37	33.6	investigated
17.20	6.00	8.98	+0.82	0.82	1.00	9.43	0.18		because the
17.25	6.00	9.98	1.61	0.79	1.00	10.43	0.21	23.4	cylinder was
17.30	6.00	10.98	2.48	0.87	1.00	11.43	0.13		left at the
17.35	6.00	1.05	3.24	0.76	1.05	12.48	0.29	25.2	same place
17.40	6.00	2.10	+0.83	0.83	1.05	13.53	0.22		over night
17.45	6.00	3.15	1.65	0.82	1.05	14.58	0.23	27.0	

+ Refill

Infiltrometer Data Sheet

Date:.....17.8.76.....

Location:.....Old Nursery.....

Slope Angle: Flat

Land Use:.....

Soil Condition:.....

Surface Cover:.....Bare soil.....

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
17.50	6.00	4.20	2.49	0.84	1.05	15.63	0.21		
17.55	6.00	5.20	3.12	0.63	1.00	16.63	0.27	27.6	
18.00	6.00	6.23	3.89	0.77	1.03	17.66	0.26		
18.05	6.00	7.25	+ 0.80	0.80	1.02	18.68	0.22	28.8	
18.10	6.00	8.25	1.54	0.74	1.00	19.68	0.26		
18.15	6.00	9.25	2.32	0.78	1.00	20.68	0.22	28.8	

+ Refill

Appendix 7.

Results of experiment to determine the effect of
burning on the infiltration capacity of a
Sourhope soil on Winton soil association.

Infiltrometer Data Sheet

Date:.....2.9.76.....

Location:.....Boghall Farm.....Plot No.1.....

Slope Angle:.....Flat^o.....

Land Use:.....Grass land.....

Soil Condition:.....Dry.....

Surface Cover:.....Unburnt.....

.....Experimental data of unburnt grassland.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
10.45	6.60	00							Scale reading and water applied in cm. Moisture content of surface soil (0-4 cm.) 23.43 % and subsoil layer (12 ⁺ cm.) 24.87 % Bulk density 1.3, 1.42 gm/cc. Organic matter % Average rainfall 91 mm/hr.
10.50	5.90	0.10	0.16	0.16	0.80	0.80	0.64		
10.55	5.60	0.55	0.34	.18	0.75	1.55	0.57	72.6	
11.00	5.60	1.30	0.48	0.14	0.75	2.30	0.61		
11.05	5.60	2.10	0.61	0.13	0.80	3.10	0.67	76.8	
11.10	5.60	2.90	0.74	0.13	0.80	3.90	0.67		
11.15	5.60	3.65	0.86	0.12	0.75	4.65	0.63	78.0	
11.20	5.60	4.45	1.01	0.15	0.80	5.45	0.65		
11.25	5.60	5.20	1.10	0.09	0.75	6.2	0.66	78.6	
11.30	5.60	5.91	1.18	0.08	0.71	6.91	0.63		
11.35	5.60	6.65	1.25	0.07	0.74	7.65	0.67	78.0	
11.40	5.60	7.45	1.42	0.17	0.80	8.45	0.63		
11.45	5.60	8.20	1.56	0.14	0.75	9.20	0.61	74.4	
11.50	5.60	8.95	1.68	0.12	0.75	9.95	0.63		
11.55	5.60	9.65	1.78	0.10	0.70	10.65	.60	73.8	

Infiltrometer Data Sheet

Date:.....2.9.76.....

Location:.....Boghall Farm.....Plot No:1.

Slope Angle: Flat.

Land Use:.....Grass land.....

Soil Condition:.....Dry.....

Surface Cover:.....Unburnt.....

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
12.00	5.60	10.42	1.89	0.11	0.77	11.42	0.66		Water infiltrated into the soil more than 15 cm.
12.05	5.60	11.15	2.04	0.15	0.73	12.15	0.58	74.4	
12.10	5.25	-	2.10	0.06	0.72	13.22	0.66		
12.15	5.60	2.40	2.21	0.11	0.75	13.97	0.64	78.0	
12.20	5.60	3.15	2.34	0.13	0.75	14.72	0.62		
12.25	5.60	3.91	2.44	0.10	0.76	15.48	0.66	76.8	
12.30	5.60	4.65	2.54	0.10	0.74	16.22	0.64		
12.35	5.60	-	2.60	0.06	0.75	16.97	0.69	79.8	
12.40	5.60	6.15	3.69	0.09	0.75	17.72	0.66		
12.45	5.60	6.85	2.77	0.08	0.70	18.42	0.62	76.8	
12.50	5.60	7.60	2.85	0.08	0.75	19.17	0.67		
13.00	5.60	9.05	3.04	0.10	0.70	26.62	0.60		
13.05	5.60	9.80	3.12	0.08	0.75	21.37	0.67	76.2	
13.10	5.60								
13.15	5.60	11.25	3.41	0.29	1.45	22.82	1.16	69.6	

Infiltrometer Data Sheet

Date:.....2.9.76.....

Location:.....Bog Hall.....Plot No.2.....

Slope Angle: Flat..°

Land Use:.....Burned area.....

Soil Condition:.....Dry at surface soil.....

Surface Cover:.....Nearly bare soil.....

.....Some litter scatters on the surface.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
13.55	6.70	0.00							Scale reading and
14.00	6.00	0.30	0.17	0.17	1.00	1.00	0.83		water applied in cm.
14.05	6.00	1.12	0.46	0.29	0.82	1.82	0.53	81.6	Moisture content of
14.10	6.00	2.00	0.70	0.24	0.88	2.70	0.64		surface soil
14.15	6.00	2.85	0.93	0.23	0.85	3.55	0.62	75.6	(0-4 cm.)
14.20	6.00	3.70	1.14	0.21	0.85	4.40	0.64		18.07 %
14.25	5.90	4.45	1.35	0.21	0.85	5.25	0.64	76.8	and subsoil layer
14.30	5.90	-	1.55	0.20	0.90	6.15	0.70		(12 ⁺ cm.)
14.35	5.90	6.30	1.75	0.20	0.95	7.1	0.75	87.0	18.85 %
14.40	5.90	7.18	1.95	0.20	0.88	7.98	0.68	81.6	Bulk density
14.45	5.90								1.22, 1.15 gm/cc.
14.50	5.90	8.85	2.40	0.45	1.67	9.65	1.22	73.2	Organic matter
14.55	5.90	9.75			0.90	10.55			%
15.00	5.90	10.55	2.81	0.41	0.80	11.35	1.29	77.4	Average rainfall
15.05	5.90	11.45	3.06	0.25	0.90	12.25	0.65		101 mm/hr.

Infiltrometer Data Sheet

Date:.....2.9.76.....

Location:....Boghall.....Plot No: 2

Slope Angle: Flat.

Land Use:....Burned Area.....

Soil Condition:....Dry at surface soil.....

Surface Cover:....Nearly bare soil.....

.....Some litter scatters on the surface.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
15.10	5.90	0.85	3.30	0.24	0.85	13.10	0.61	75.6	Raindrop may vary in size due to water vapour coating at ^{the} bottom of the rainulator.
15.15	5.90	1.65	3.57	0.27	0.80	13.90	0.53		
15.20	5.90	2.45	3.87	0.30	0.80	14.7	0.50	61.8	
15.25	5.90	3.30	4.16	0.29	0.85	15.55	0.56		
15.30	5.90	4.15	4.44	0.28	0.85	16.40	0.57	67.8	
15.35	5.90	5.00	4.74	0.30	0.85	17.25	0.55	66.0	
15.40	5.90	5.84	5.03	0.29	0.84	18.09	0.55		
15.45	5.90	6.61	5.35	0.32	0.72	18.86	0.45	60.0	
15.50	5.90	7.47	5.71	0.36	0.86	19.72	0.50		
15.55	5.90	8.30	6.07	0.36	0.83	20.55	0.47	58.2	
16.00	5.90	9.14	6.39	0.32	0.84	21.39	0.52		
16.05	5.90	9.95	6.76	0.37	0.81	22.20	0.44	57.6	
16.10	5.90	10.80	7.23	0.47	0.85	22.05	0.38		
16.15	5.90	8.81	7.60	0.37	0.81	23.86	0.44	49.2	
16.20	5.90	9.64	0.42	0.42	0.83	24.65	0.41		

Appendix 8.

Results of experiment to determine the effect of seasonal differences in the infiltration characteristics of a shallow upland soil.

Infiltrometer Data Sheet

Date:.....6.9.76.....

Location:..Bog Hall (Hill)....Plot 1.....

Slope Angle:10-20°

Land Use:....Sheep grazing up the hill, Brown Earth.

Soil Condition:..Nearly dry.....

Surface Cover:..Covered with dry coll. sp.

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
11.00	6.60	0.00							Scale reading and water applied in cm. Moisture content of surface soil (0-4 cm.) 8.90 % and subsoil layer (10 ⁺ cm.) 11.80 % Bulk density 0.58, 1.17 gm/cc. Organic matter 18.5%, 13.5 % Average rainfall 100 mm/hr.
11.05	-	-	0.30		-				
11.10	5.85	1.01	0.97	0.67	1.76	1.76	0.79	47.4	
11.15	5.85	1.90	1.10	0.43	0.89	2.65	0.46		
11.20	5.85	2.65	1.48	0.38	0.75	3.40	0.37	49.8	
11.25	6.10	3.80	1.94	0.46	0.90	4.30	0.44		
11.30	6.10	4.61	2.37	0.43	0.81	5.11	0.38	49.2	
11.35	6.10	-	2.75	0.38					
11.40	6.10	6.22	3.20	0.45	1.61	6.72	0.78	46.8	
11.45	6.10	7.14	3.67		0.78	7.50			
11.50	6.10	7.92	0.50	0.50	0.78	8.28	0.28	33.6	
11.55	6.10	8.81	1.05	0.55	0.89	9.17	0.34		
12.00	6.10	9.60	1.55	0.50	0.79	9.96	0.29	37.8	
12.05	6.10	10.44	2.12	0.57	0.84	10.80	0.23		
12.10	6.10	11.40	2.74	0.62	0.96	11.76	0.34	34.2	

Infiltrometer Data Sheet

Date:.....6.9.76.....

Location:.....Bog Hall (Hill).....Plot 1..

Slope Angle: 10-20°

Land Use:.....Sheep grazing up the hill, Brown Earth

Soil Condition:.....Nearly dry.....

Surface Cover:.....Covered with dry coll. sp.

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
12.15	6.10	-	3.22	0.48					Reading taken in
12.20	6.10	1.65	3.72	0.50	1.65	13.41	0.67	40.2	10 min. at the
12.25	6.10	2.50	0.55	0.55	0.85	14.26	0.30		beginning of the
12.30	6.10	3.33	1.05	0.50	0.83	15.09	0.33	37.8	run, runoff water
12.35	6.10	4.10	1.62	0.57	0.77	11.86	0.20		was still collected
12.40	6.10	4.98	2.19	0.57	0.88	16.74	0.31	30.6	in 5 min. (at 11.05)
12.45	6.10	5.82	2.76	0.57	0.84	17.58	0.27		At first grasses
12.50	6.10	6.62	3.30	0.54	0.80	18.38	0.26	31.8	are very dry,
12.55	6.10	7.42	3.89	0.59	0.80	19.18	0.21		therefore, water-
13.00	6.10	8.22	0.55	0.55	0.80	19.98	0.25	27.6	drops striking the
13.05	6.10	9.00	1.07	0.52	0.78	20.76	0.26		soil become runoff.
13.10	6.10	9.82	1.55	0.48	0.82	21.58	0.34	36.0	As water-drops
13.15	6.10	10.72	2.09	0.54					penetrate the grass
13.20	6.10	11.60	2.60	0.51	1.78	23.36	0.73	43.8	cover infiltration
									then becomes more
									quickly, this period
									occurs about 10-15
									min. after the run.

Infiltrometer Data Sheet

Date:.....6.9.76.....

Location:..... B.H. up Hill Plot No.2

Slope Angle: 20°.....

Land Use:..... Sheep grazing on hill slope of Brown Earth soil

Soil Condition:..... Dry

Surface Cover:..... 100% cover, green grass

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
14.00	6.60	0.00							Scale reading and water applied in cm. Moisture content of surface soil (0-4 cm.) 11.32 % and subsoil layer (10 ⁺ cm.) 9.99 % Bulk density 0.74, 1.03 gm/cc. Organic matter 16.86%, 11.45% Average rainfall 95 mm/hr.
14.05	6.05	0.45	0.55	0.55	1.00	1.00	0.45		
14.10	6.05	1.25	1.05	0.50	0.80	1.80	0.30	45.0	
14.15	6.05	2.05	1.40	0.35	0.80	2.60	0.45		
14.20	6.05	2.90	1.76	0.36	0.85	3.45	0.49	56.4	
14.25	6.05	3.-	2.07	0.31	-				
14.30	6.05	4.50	2.34	0.27	1.60	5.05	1.02	61.2	
14.35	6.05	5.30	2.58	0.24	0.80	5.85	0.56		
14.40	6.05	6.10	2.82	0.24	0.80	6.65	0.56	67.2	
14.45	6.05	6.90	3.10	0.28	0.80	7.45	0.52		
14.50	6.05	7.70	3.32	0.22	0.80	8.25	0.58	66.0	
14.55	6.05	8.55	3.57	0.23	0.85	9.10	0.62		
15.00	6.10	9.30	.25	0.25	0.75	9.85	0.50	67.2	
15.05	6.10		0.45	0.20			-		
15.10	6.10	4.35	0.67	0.22	1.85	11.70	1.23	73.8	

Infiltrometer Data Sheet

Date:.....6,9,76.....

Location:..B.H. up Hill..... Plot No. 2...

Slope Angle: 20....°

Land Use:..... Sheep grazing on hill slope of Brown Earth soil

Soil Condition:..... Dry

Surface Cover:..... 100% cover, green grass

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
15.15	6.10	5.05	0.91	0.24	0.70	12.40	0.46		Surface soil
15.20	6.10	5.90	1.12	0.21	0.85	13.25	0.64	66.0	abundant with O.M.
15.25	6.10	-	-	-	-				c. 4 cm. deep,
15.30	6.10	7.43	1.56	0.44	1.53	14.78	1.09	65.4	underlying soil is
15.35	6.10	8.20	1.74	0.22	0.77	15.55	0.55		still dry. Water
15.40	6.10	9.00	1.94	0.20	0.80	16.35	0.60	69.0	runs down slope as
15.45	6.10	9.75	2.14	0.20	0.75	17.10	0.55	66.0	interflow c. 70 = 80
15.50	-	-	-	-					cm. from the plot.
15.55	6.10	4.00	2.50	0.36	1.48	18.58	1.12	67.3	It took some consider-
15.60	6.10	4.75	2.70	0.20	0.75	19.33	0.55	66.0	able time for the sub-
16.05	6.10		2.89	0.19					soil to take in water
16.10	6.10	6.25	3.07	0.18	1.50	20.83	1.13	67.8	when holes were dug.
16.15	6.10								Strong wind causes
16.25	6.10	7.72	3.48	0.41	1.47	22.30	1.06	63.6	difficulty in reading
16.30	6.10	9.15	3.86	0.38	1.43	23.73	1.05	63.0	

Infiltrometer Data Sheet

Date:.....24.11.76.....

Location:.....Hill site.....

Slope Angle:..20..°

Land Use:.....Unimproved grassland. (Autumn).....

Soil Condition:.....Moist.....

Surface Cover:.....100% greengrass.....

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
13.00	5.80	*0.84	1.83	0.61	0.84	12.47	0.23		Strong winds. Difficulty in reading and measuring the level. Subsoil at approx- imately 5 cm. is still dry. Water infiltrated down slope of approx- imately 50-70 cm.
13.05	5.80	1.63	2.43	0.60	0.79	13.26	0.19	25.2	
13.10	5.80	2.47	3.11	0.68	0.84	14.10	0.16		
13.15	5.80	3.27	3.68	0.57	0.80	14.90	0.23	23.4	
13.20	5.80	4.15	0.61	0.61	0.88	15.78	0.27		
13.25	5.80	4.95	1.26	0.65	0.80	16.58	0.15	25.2	
13.30	5.80		1.85	0.59					
13.35	5.80	6.65	2.47	0.62	1.70	18.28	0.49	29.4	
13.40	5.80	7.48	3.10	0.63	0.83	19.11	0.20		
13.45	5.80	8.29	0.65	0.65	0.81	19.92	0.16	21.6	
13.50	5.80	9.09	1.28	0.63	0.80	20.72	0.17		
13.55	5.80	9.93	1.92	0.64	0.84	21.56	0.20	22.2	
14.00	5.80	10.83	2.61	0.69	0.90	22.46	0.21		
14.05	5.80	*7.92	3.20	0.59	0.82	23.28	0.23	26.4	
14.10	5.80	8.77	3.85	0.65	0.85	24.13	0.20		

* Refill

Appendix 9.

Results of experiment to determine the effect of
surface cover removal on infiltration capacity.

Infiltrometer Data Sheet

Date: 3.9.76.....

Location: Boghall Burn, Boghall Farm, Colzium Ass.

Slope Angle: Flat^o

Land Use: Unimproved sheep grazing, Plot 1.

Soil Condition: Nearly dry, with mottling in subsoil.

Surface Cover: Thick grass cover (100%).....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
10.50	6.60	0.00							Scale reading and water applied in cm. Moisture content of surface soil (0 - 4 cm.) 21.7 % and subsoil layer (12") 25.29 % Bulk density 0.81, 1.10 gm/cc. Organic matter 14.6 %, 8.08 %. Average rainfall 82 mm/hr. Strong wind shakes the instrument at 11.30 hr.
10.55	6.10	0.30	0.30	0.30	0.80	0.80	0.50		
11.00	6.10	1.00	0.80	0.50	0.70	1.50	0.20	42.0	
11.05	6.05	1.69	1.32	0.52	0.75	2.25	0.23		
11.10	6.00	2.41	1.86	0.54	0.77	3.02	0.23	27.6	
11.15									
11.20	6.00	3.85	2.99	1.13	1.44	4.46	0.31	18.6	
11.25	6.00	4.50	3.55	0.56	0.66	5.12	0.10		
11.30	6.00	-	0.56	0.56	-	-			
11.35	6.10	6.00	1.04	0.48	1.40	6.52	0.36	18.4	
11.40	6.10	6.70	1.87	0.53	0.70	7.21	0.17	20.4	
11.45	-	-	-	-	-	-			
11.50	6.10	8.15	2.65	1.08	1.45	8.66	0.37	22.2	
11.55	6.10	8.80	3.20	0.55	0.65		0.10		
12.00	6.10	9.53	3.76	0.56	0.73	10.04	0.17	16.20	

*Ave. for 15 min.

Infiltrometer Data Sheet

Date:.....3:9:76.....

Location:....Boghall Burn, Boghall Farm, Colzium Ass. Slope Angle: Flat.
Plot 1.

Land Use:....Sheep grazing, unimproved grassland

Soil Condition:....Nearly dry.....

Surface Cover:....100% cover, very thick grass

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
12.05	6.10	10.20	0.55	0.55	0.67	10.71	0.12		Water infiltrated into the soil only 3 - 5 cm. from the surface. Water took considerable time in infiltrating through the root zone to the real soil mass, most of water applied moved laterally in the root zone. When a hole was dug and water was poured into it then water did not go quickly into the soil as expected.
12.10	6.10	10.86	1.06	0.51	0.66	11.37	0.15	16.2	
12.15		-	-						
12.20	6.10	2.51	2.05	0.99	1.31	12.68	0.32	19.2	
12.25	6.10	3.20	2.54	0.49	0.69	13.37	0.20		
12.30	6.10	3.90	2.99	6.45	0.70	14.07	0.25	27.0	
12.35	6.10	4.56	3.47	0.48	0.66	14.73	0.18	21.6	
12.40	6.10	-	-	-	-				
12.45	6.10	5.90	0.97	0.97	1.34	16.07	0.37	22.2	
12.50	6.10	-	-	-					
12.55	6.10	7.26	1.89	0.92	1.36	17.43	0.44	26.4	
13.00	6.10	-	-	-	-				
13.05	6.10	8.63	2.78	0.89	1.37	18.80	0.48	28.8	
13.10	6.10	-	3.59	0.81	-				
13.15	6.10	9.94	0.24	0.24	1.31	20.11	0.16	9.6	

Appendix 10.

Results of experiment made on the alluvial fan.

Infiltrometer Data Sheet

Date:.....7.9.76.....

Location:..Boghall Farm.....Plot No.1.....

Slope Angle:..2%...^oLand Use:.....Improved*land for sheep grazing
*grass.....

Soil Condition:.....Dry.....

Surface Cover:.....Bare soil with some litters.....

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
10.30	6.50	*+0.05	-						Scale reading and
10.35	5.60	0.07	0.52	0.52	1.02	1.02	0.50		water applied in
10.40	5.70	1.04	1.22	0.70	0.87	1.89	0.17	40.2	Moisture content
10.45	5.70	1.86	1.92	0.70	0.82	2.71	0.12		of surface soil
10.50	5.70	2.70	2.59	0.67	0.84	3.55	0.17	17.4	(0-4 cm.)
10.55	5.70	3.55	3.31	0.72	0.85	4.40	0.13		16.08 %
11.00	5.70	4.36	4.04	0.73	0.81	5.21	0.08	12.6	and subsoil layer
11.05	5.70	5.21	0.68	0.68	0.85	6.06	0.12		(cm.)
11.10	5.70	6.03	1.38	0.70	0.82	6.88	0.12	17.4	%
11.15	5.70	6.85	0.29	0.71	0.82	7.70	0.11		Bulk density
11.20	5.70	7.62	2.75	0.66	0.77	8.47	0.11	13.2	1.31 gm/cc.
11.25	5.70	8.50	3.40	0.65	0.88	9.35	0.23		Organic matter
11.30	5.70	9.25	4.10	0.70	0.75	10.10	0.05	16.8	6 %
11.35	5.70	10.08	^x 0.68	0.68	0.83	10.93	0.15		Average rainfall
11.40	5.70	10.90	1.35	0.67	0.82	11.75	0.15	18.0	99 mm/hr.

* Water level is 0.05 cm. above the 0.00 level.

Infiltrometer Data Sheet

Date:.....7.9.76.....

Location:..Roghall Farm.....Plot No.1..

Slope Angle:.....^o

Land Use:..Improved land for sheep grazing....

Soil Condition:.....Dry.....

Surface Cover:..Bare soil with some litters....

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
11.45	5.70	1.36	2.02	0.67	0.76	12.81	0.09		Error may be caused by difficulty in scale reading due wind shakes. Some drops flow across the rainulator surface and join with the others, this results from the evap. of water applied which condenses and clings to the bottom face of the rainulator. The instrument also suffers from dust clogging the rainulator holes which results uneven flow rates.
11.50	5.70	2.17	2.65	0.63	0.81	13.32	0.18	16.2	
11.55	5.70	2.98	3.32	0.67	0.81	14.13	0.14		
12.00	5.70	3.80	x 0.69	0.69	0.82	14.95	0.13	16.2	
12.05	5.70	4.62	1.38	0.69	0.82	15.77	0.13		
12.10	5.70	-	2.03	0.65	-	-	-	-	
12.15	5.70	6.22	2.69	0.66	1.60	17.37	0.29	17.4	
12.20	5.70	7.08	3.38	0.69	0.86	18.23	0.17		
12.25	5.70	7.90	+ 0.69	0.69	0.82	19.05	0.13	18.0	
12.30	5.70	8.68	1.35	0.66	0.78	19.83	0.12		
12.35	5.70	9.50	2.04	0.69	0.82	20.65	0.13	15.0	
12.40	5.70	10.34	2.72	0.68	0.84	21.49	0.16		
12.45	5.70	11.20	3.39	0.67	0.86	22.35	0.19	21.0	
12.50	5.70	Refill	+ 0.75	0.75	-	-	-		
12.55	5.70	7.60	1.41	0.66	-	-	-		

Infiltrometer Data Sheet

Date: 7.9.76

Location: Bog Hall Farm Plot 2

Slope Angle: 1%^o

Land Use: Improved grass land for sheep grazing

Soil Condition: Dry, Alluvial soil

Surface Cover: 25%

.....

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
14.20	6.60	0.00	-						Scale reading and water applied in cm. Moisture content of surface soil (0-4 cm.) 19.62 % and subsoil layer (12 ⁺ cm.) 21.75 % Bulk density 1.39, 1.23 gm/cc. Organic matter 6.7%, 5.7 % Average rainfall 104 mm/hr.
14.25	7.00	1.55	0.70	0.70	1.05	1.05	0.35		
14.30	6.10	1.77	1.65	0.95	1.12	2.17	0.17	31.2	
14.35	5.70	2.30	2.54	0.89	0.93	3.10	0.04		
14.40	5.60	3.10	3.10	0.76	0.90	4.00	0.14	10.8	
14.45	5.60	3.96	x 0.85	0.85	0.86	4.86	0.01		
14.50	5.60	4.80	1.65	0.80	0.84	5.70	0.04	3.0	
14.55	5.60	5.70	2.49	0.84	0.90	6.60	0.06		
15.00	5.60	6.55	3.29	0.80	0.85	7.45	0.05	6.6	
15.05	5.60	7.40	x 0.82	0.82	0.85	8.30	0.03		
15.10	5.60	8.29	1.65	0.83	0.89	9.19	0.06	5.4	
15.15	5.60	-	-	-	-	-	-	-	
15.20	5.60	9.82	3.05	1.40	1.53	10.72	0.13	7.8	
15.25	5.60	10.78	x 0.85	0.85	0.96	11.68	0.11		
15.30	5.60	11.62	1.61	0.76	0.84	12.52	0.08	11.4	

Appendix 11.

Results of experiment to investigate lateral
water movement.

Infiltrometer Data Sheet

Date: 17.11.76

Location: Bog Hall Farm Alluvial fan Plot No.1

Slope Angle: Flat

Land Use: Sheep grazing, improved grassland

Soil Condition: Moist

Surface Cover: 50%

Time	Scale Reading				Water Applied		Infiltration		Remarks
	Tank	Res.	Runoff		△	Acc.	cm.	mm/hr	
			Acc.	△					
10.45	6.00	6.00			-	-			Scale reading and water applied in cm. Moisture content of surface soil (0-4 cm.) 33.17 % and subsoil layer (20+ cm.) 33.40 % Bulk density 1.31, 1.27 gm/cc. Organic matter % Average rainfall 77 mm/hr.
10.50	5.50	0.30	0.44	0.44	0.70	0.70	0.26	31.2	
10.55	5.50	1.02	1.21	0.77	0.73	1.43			
11.00	5.50	1.70	1.79	0.58	0.68	2.11	0.10	12.0	
11.05	5.50	2.32	2.38	0.59	0.62	2.73	0.03	3.6	
11.10	5.50	2.95	3.00	0.62	0.64	3.37	0.02	2.4	
11.15	5.35	3.60	3.66	0.66	0.65	4.02	0.00	0.0	
11.20	5.30	4.15	0.62	0.61	0.65	4.67	0.04	4.8	
11.25	5.30	4.80	1.20	0.58	0.65	5.32	0.07	8.4	
11.30	5.30	5.45	1.79	0.59	0.65	5.97	0.06	7.2	
11.35	5.30	6.10	2.40	0.61	0.65	6.62	0.04	4.8	
11.40	5.30	6.70	2.95	0.55	0.60	7.22	0.05	6.0	
11.45	5.30	7.35	3.55	0.60	0.65	7.87	0.05	6.0	
11.50	5.30	7.95	4.15	0.60	0.60	8.47	0.60	0	
11.55	5.30	8.63	0.65	0.60	0.63	9.10	0.03	3.6	

