Hydrological Sciences Journal

ISSN: 0303-6936 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/thsj19

THE INFLUENCE OF SLOPE AND RAIN INTENSITY ON RUNOFF AND INFILTRATION / L'influence de l'inclinaison de terrain et de l'intensité de pluie sur l'écoulement et l'infiltration

S. H. NASSIF & E. M. WILSON

To cite this article: S. H. NASSIF & E. M. WILSON (1975) THE INFLUENCE OF SLOPE AND RAIN INTENSITY ON RUNOFF AND INFILTRATION / L'influence de l'inclinaison de terrain et de l'intensité de pluie sur l'écoulement et l'infiltration, Hydrological Sciences Journal, 20:4, 539-553, DOI: 10.1080/02626667509491586

To link to this article: https://doi.org/10.1080/02626667509491586

Published online: 25 Dec 2009.

THE INFLUENCE OF SLOPE AND RAIN INTENSITY ON RUNOFF AND INFILTRATION

S.H. NASSIF
SLETCO, Beirut, Lebanon

and

E.M. WILSON
Department of Civil Engineering, University of Salford, Salford M5 4WT, Lancashire, UK

Revised MS. received 31 July 1975

Abstract. The design and construction of a special-purpose laboratory catchment and rainfall simulator is described. The equipment consists of a soil catchment area that can be inclined at various angles. Additional instrumentation then measures the flow of water across the surface of, and through, the soil bed. Precipitation is provided by a unit that simulates rainfall at particular rates with uniform distribution.

The equipment was used to examine infiltration, runoff and other hydrological properties of a number of soils under different rainfall intensities and with different catchment slopes. Correlations were obtained for these variables.

L'influence de l'inclinaison de terrain et de l'intensité de pluie sur l'écoulement et l'infiltration

Résumé. Une description du dessin et construction d'un bassin versant et du simulateur de pluie est présentée. L'installation est composée d'un sol de captage qui peut prendre de diverses inclinaisons. Les débits d'écoulement d'eau en surface et à travers le sol, sont mesurés par une instrumentation additionelle. La pluie est générée par une unité qui simule des précipitations à une intensité et distribution constante particulière.

Cet appareil a été utilisé pour étudier les phénomènes d'infiltration, de ruissellement ainsi que d'autres propriétés hydrologiques de plusieurs sols par des intensités de précipitation différentes et aux versants de captage différents. Corrélations entre ces variables sont obtenues.

INTRODUCTION

A rainfall simulator and laboratory catchment were constructed to study the behaviour of rainfall flowing over and through a soil surface. The equipment was similar to previously reported laboratory models, though on a somewhat larger scale. The equipment was used to collect data about runoff and infiltration from several different types of soil, at various slopes and under widely differing rainfall intensities.

THE EQUIPMENT

The rain simulator

Simulated rainfall should have the following characteristics:

(1) the drop-size distribution should be that or near to that of natural rain;
(2) rain should be uniformly distributed at the required intensities of application;
(3) raindrops should attain the terminal velocities of natural rain.

Many types of simulator have been proposed which to a greater or lesser extent meet these criteria (Hall, 1970; Mutchler and Hermsmeier, 1965). After reviewing the literature the Child's swirl-nozzle type of distributor was adopted. The nozzle components which are shown in Fig. 1 were made from rigid polyvinyl chloride sheet and tube.

An array of 130 nozzles, spaced 0.5 m apart and in rows 0.5 m apart, was erected 4.5 m above the soil catchment. The spacing and height were chosen after elaborate tests of uniformity of application (Nassif, 1974). Uniformity coefficients, using Christiansen's formula (Christiansen, 1941), in the range 0.907-0.920 were obtained for pressure heads between 1.83 and 6.55 m of water and for durations between 2 and 8 min.

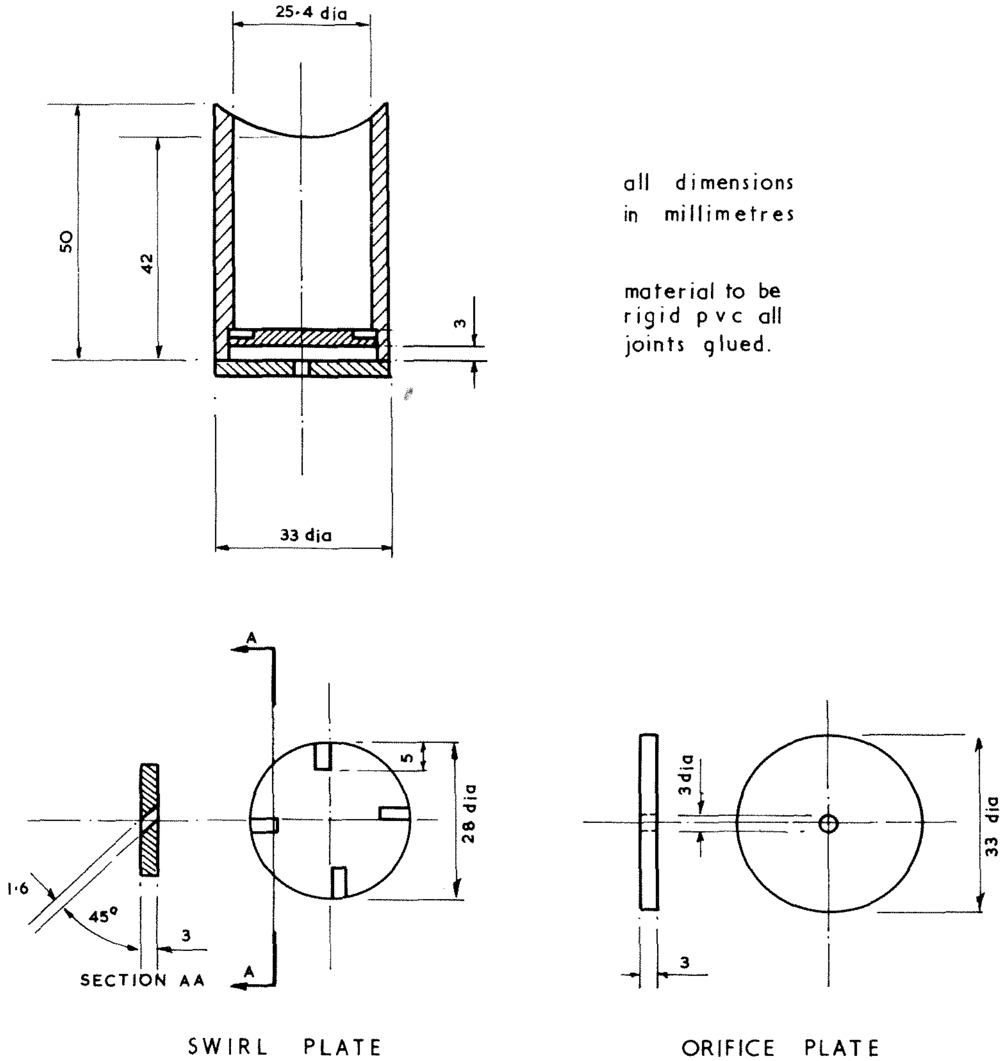

Fig. 1 – Nozzle assembly and details.

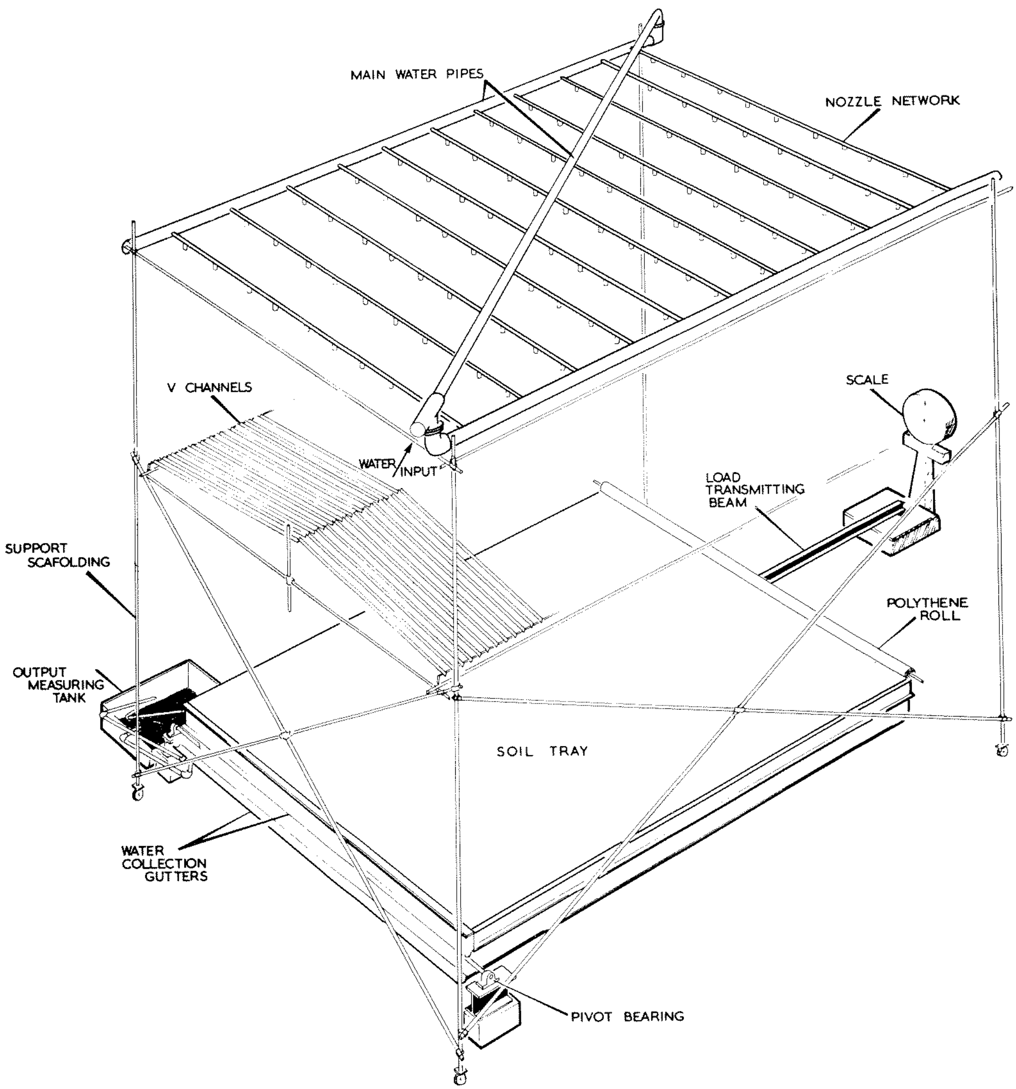

Fig. 2 – Diagram of apparatus.

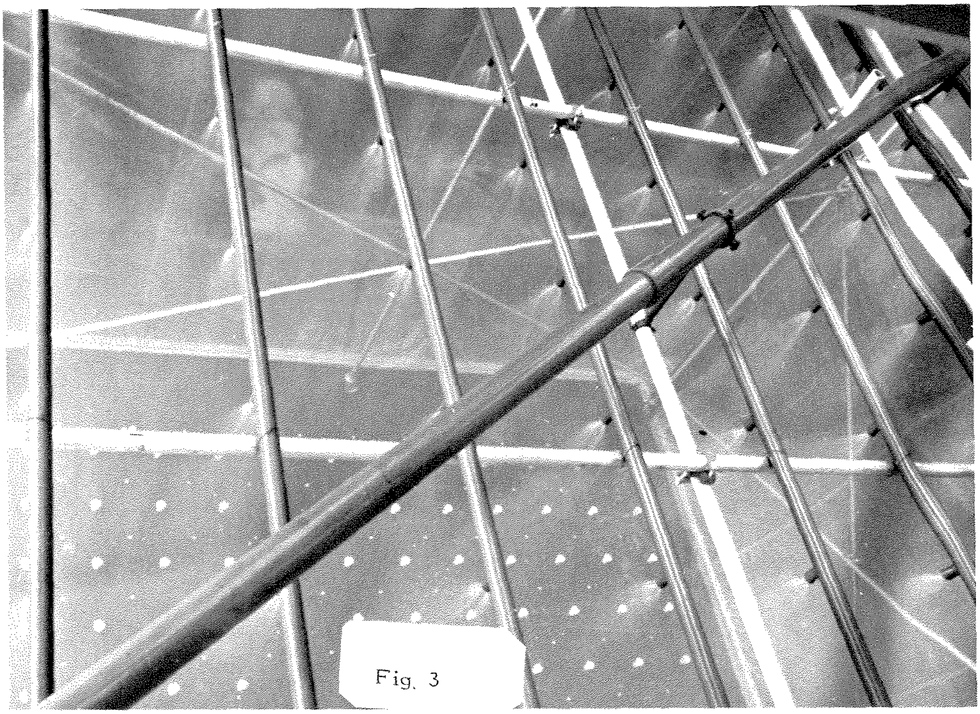

Fig. 3 – Rainfall simulator in action

The pressure variation caused a change in drop-size distribution and provided too small a working range of rainfall intensities, so a method of intercepting varying amounts of a standard rainfall was devised. Light aluminium V-channels were fixed in a regular pattern between the nozzles and catchment. Each channel was 2.5 m long and 30 mm wide, set in a notch at one end and supported on a wire cable at the other end which was over the centre of the catchment. The V-channels, therefore, sloped slightly down from the centre to each side. Notches were cut in hardwood side rails so that regular channel patterns intercepting a quarter, a half and three-quarters of the standard rainfall could be set up. Since the standard rainfall was always used, at constant nozzle pressure, drop-size distribution was always the same. Distribution tests showed no more than 1 per cent variation in uniformity coefficients from those of the standard at any of the resulting three lesser rainfalls on the catchment. The nozzle network and interception channel arrangement are shown diagrammatically in Fig. 2. Figure 3 shows the nozzles discharging 'standard' rain of 31.2 mm/h. This rather high intensity was used so that trends and differences from the test programme, could be detected easily and quickly.

The catchment area

The experimental catchment was contained in a rigid framework of steel beams with a porous bottom of fine nylon mesh, supported on galvanized steel mesh in panels, in turn supported on beams. Plastic coated metal sheets were attached to the underside of the beams to convey infiltrating water to a discharge point. The overall dimensions of the soil tray thus formed were 6.15 by 4.10 m with a soil surface area of 23.5 m^2, a soil depth of 0.22 m and a volume of 5.2 m³. The rain nozzle network extended beyond the soil tray on all sides to ensure uniformity over the catchment. The loaded wet weight of tray and soil amounted to 11 tonnes.

One end of the tray was supported on two low-friction concentric bearings, the other on a single knife-edge strut loading a pivoted beam, whose free end rested on a weighing machine platen. Struts of various lengths were made to set the tray at various predetermined slopes. The tray was raised and lowered to allow strut fitting by the laboratory overhead crane.

The levered weighing arrangement permitted measurement of tray weight in units of 34 N. This represented a change in soil weight of 0.04 per cent. The catchment tray is shown empty and loaded in Figs. 4 and 5.

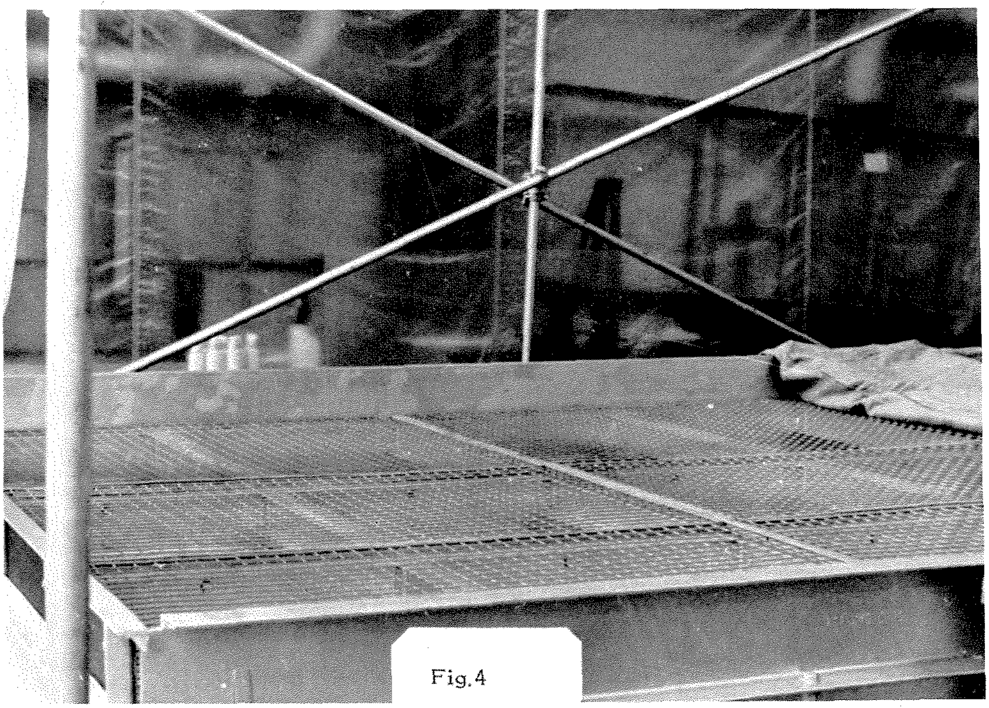

Fig. 4 – Catchment tray.

Discharge collection

The lower end of the soil tray was panelled with wire mesh so that any water moving through the soil parallel to the surface slope (interflow) could be collected separately from surface runoff and water which had infiltrated through the surface and the thickness of the soil layer. Gutters picked up the runoff and infiltration flows separately and these were continuously metered over small V-notches by automatic water surface followers controlling a two-channel pen recorder. Interflow appeared in such small quantities that it was simply collected in graduated glass cylinders. The discharge collection and recording arrangements are shown in Fig. 6. The equipment worked well and consistently, producing virtually identical results successively under the same conditions.

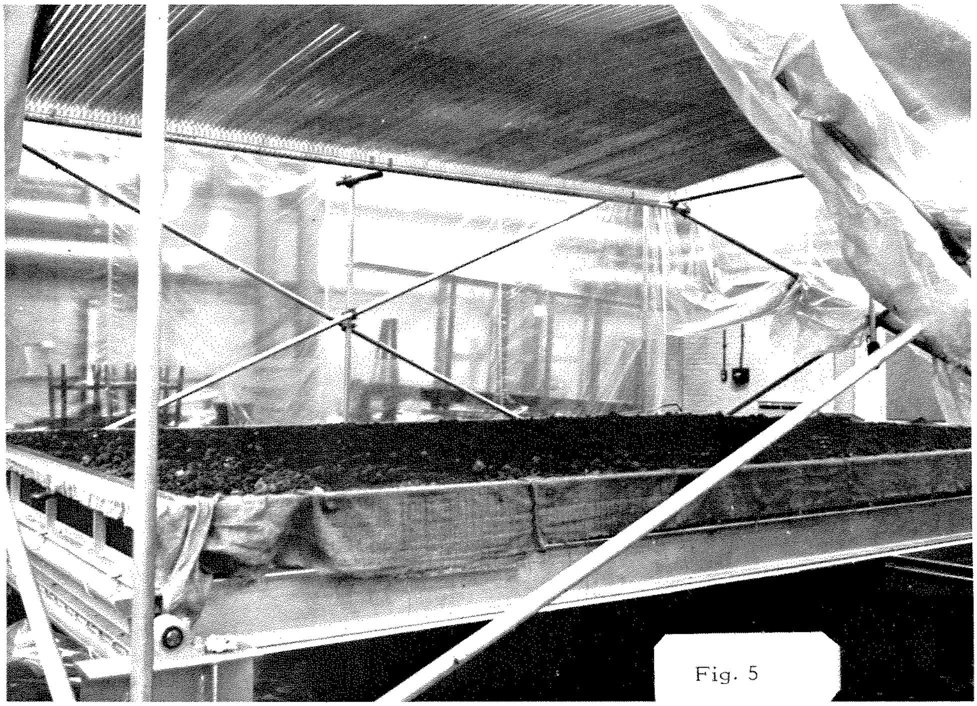

Fig. 5 – View of loaded tray showing rain-interceptor channels.

THE EXPERIMENTS

Each test consisted of applying rain of particular intensity, to a particular soil with the catchment at a particular slope. Four rain intensities were used, i = 78, 156, 234, and 312 mm/h, and five slopes, s = 0, 8, 16, 24 and 32 per cent. Three different soils were used; two of them each with two different surfaces, i.e. bare soil and established grass turf, so that five different surfaces were used. Soil properties are listed in the appendix. In all more than 100 tests were performed.

Soil moisture content was determined at the beginning and the end of the test, initially by drying samples but latterly by weight determination only, since correlation between total soil weight and moisture content was linear and consistent. Since runoff and percolation from an initially dry model differ from those for initially wet conditions, the testing sequence was arranged when necessary to ensure initial conditions were the same.

Simulated rainfall was applied at a constant rate and continued until a near-steady state of both runoff and infiltration was reached. This usually occurred within 15 min, after which time the rain was stopped. Occasionally stability was not reached in this time but any rates of change still evident were very small. Runoff and infiltration measurements were continued until they became negligible. Most measurements were made automatically but the time to the beginning of overland flow was obtained visually.

Recorded water surface levels in V-notch tanks were converted to hydrographs. A water budget was made for each test, comparing total runoff, infiltration and interflow volumes

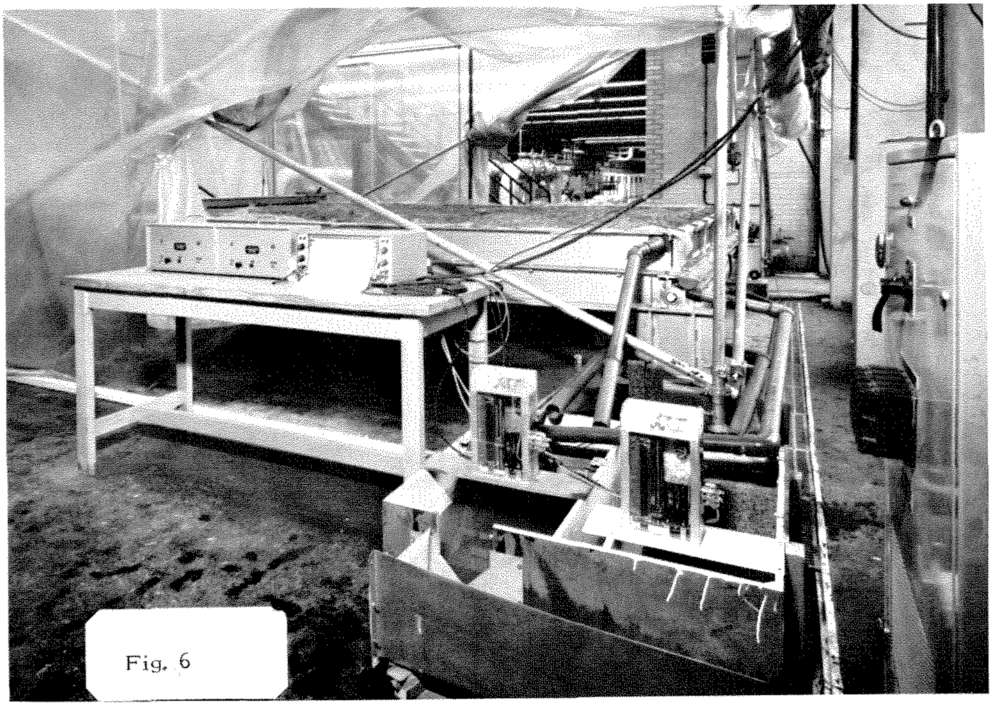

Fig. 6 – Discharge and recording arrangements.

with the quantity of rain applied plus the difference in storage weight. This check never disclosed a discrepancy greater than 1 per cent of the total water applied. There was, of course, a time lag in the system of the order of 1 or 2 min and for this reason it is the 'steady-state' results which have significance.

ANALYSIS OF TEST RESULTS

Effect of rainfall intensity on runoff

Runoff hydrographs for various rain intensities and for each of the five surfaces are shown in Fig. 7. These are for a 16 per cent slope and are typical of all slopes in demonstrating the near linearity of the runoff-intensity relationship. A point of interest is the reduction in runoff (caused by the increase in infiltration) on the grassed standard soil compared with the bare version.

Effect of rainfall intensity on infiltration

Infiltration capacities under various rain intensities (also at 16 per cent slope) are shown for the five surfaces in Fig. 8. (The data points are observed and the continuous lines are plots of Horton's equation, given later.) For soils of low permeability such as the peat and clayey sand, there is little effect, but for the standard agricultural soil there is a strong correlation between the steady-state infiltration and rain intensity. This is much more marked on grassed soil.

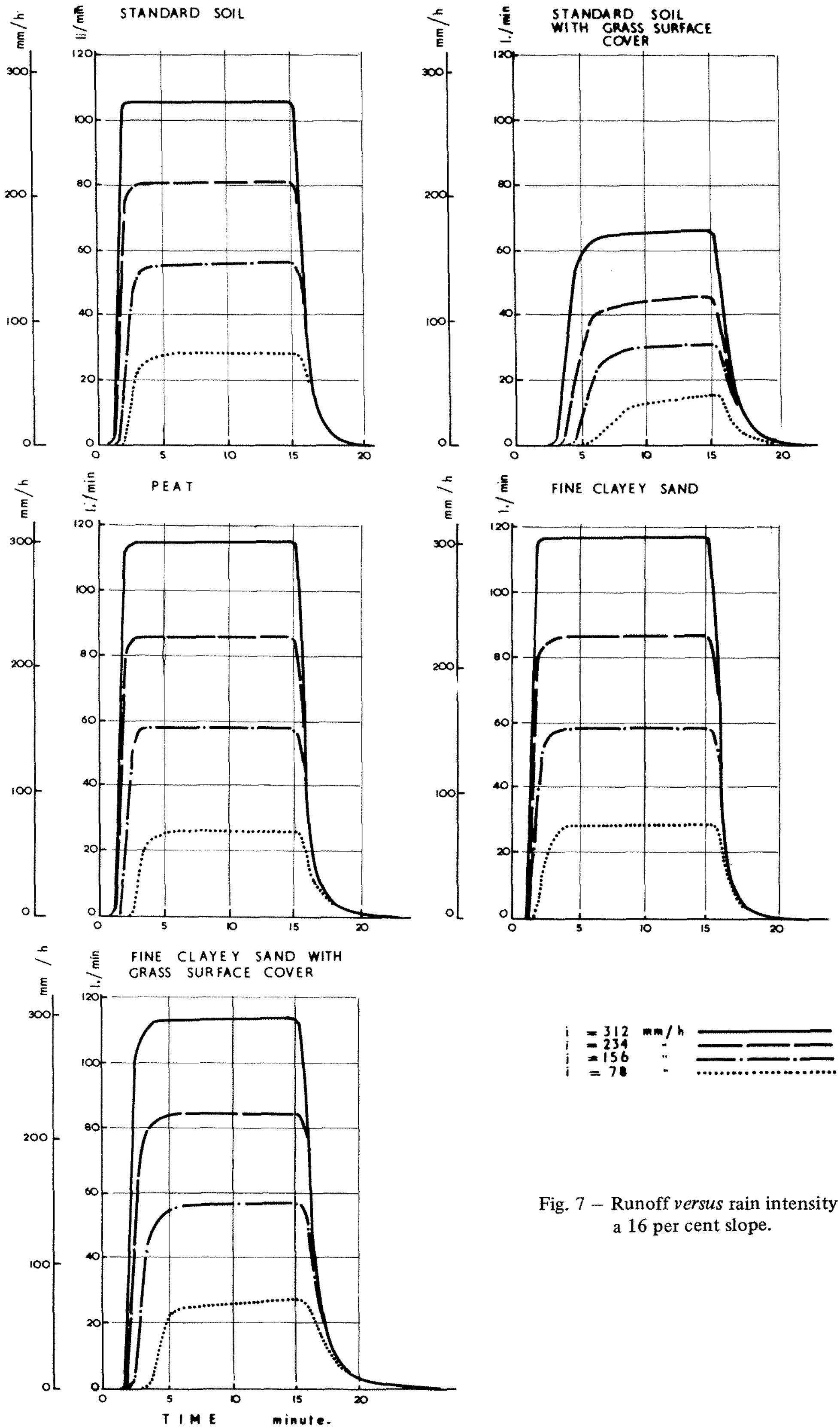

Fig. 7 – Runoff *versus* rain intensity for a 16 per cent slope.

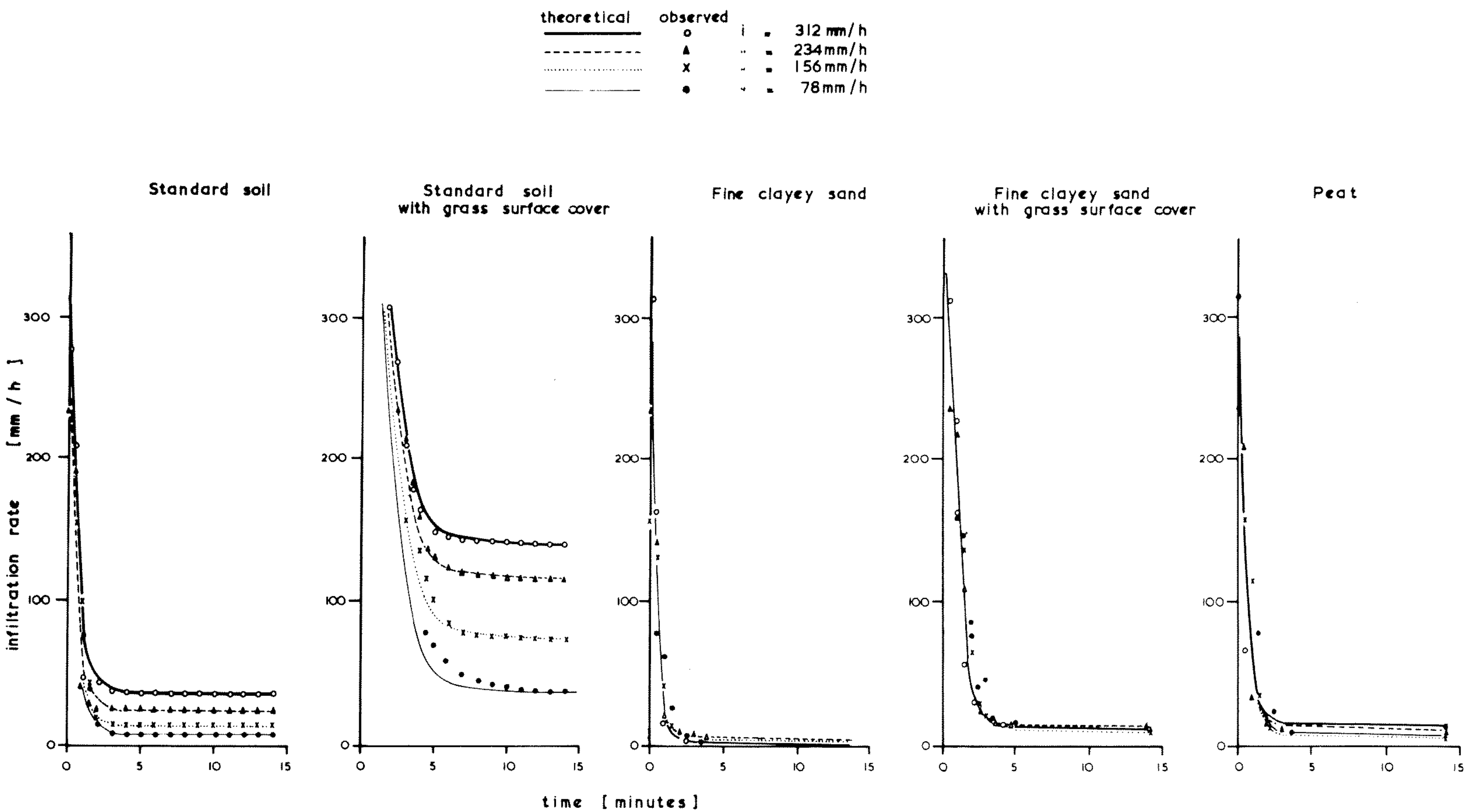

Fig. 8 – Infiltration capacity *versus* rain intensity for a 16 per cent slope.

148

Effect of catchment slope on runoff

Figure 9 shows the correlation between runoff and slope for the five surfaces. Slope has little effect on the relatively impermeable soils but a marked effect on the standard soil up to about 16 per cent in the bare condition and 24 per cent in the grassed condition. There appears to be some 'critical slope' beyond which the peak runoff is relatively unaffected. An increase of slope beyond the critical value only affects the time to reach the peak but does not appreciably increase the peak itself.

Effect of catchment slope on infiltration capacity

Figure 10 shows this correlation for the five surfaces at a rain intensity of 234 mm/h. The graphs demonstrate what might have been expected from Fig. 9; for permeable soils the greater the slope the lower the infiltration capacity with evidence of a limiting value beyond which this no longer holds; for impermeable soils little or no effect.

The most significant thing about Figs. 9 and 10 is the rapid rise in runoff (and decrease in infiltration capacity) as the slope is increased from 0 to 8 per cent followed by a much slower or no rise in runoff (and decrease in infiltration capacity) until the critical slope is reached.

Effect of initial moisture content of soil

Some experiments were carried out with differing initial soil conditions classified as dry, damp, medium wet, wet and very wet. Typical results are shown in Fig. 11 for different soils, rain conditions and slopes. The various effects of increasing initial wetness confirm what is already well-known that runoff starts earlier and is obtained earlier. These effects are more pronounced as soil permeability increases. However, only in the case of the grassed agricultural soil was there much evidence that the effect persisted beyond 30 min at the rain intensities used in the experiments.

THE INFILTRATION PROCESS

The sequence of events which occurs under high-intensity rainfall is as follows. To begin with, water infiltrates into the soil very rapidly and is totally absorbed. As all the soil particles in the surface layers become wetted, the rate of infiltration declines and a thin layer of water forms on the surface and accumulates in small depressions. Once these depressions are full, water overflows generally on the surface and overland flow commences.

In laboratory catchments the rate of surface infiltration is greater than the rate of percolation past any particular horizon at all times up to a state of complete saturation. However, water enters into storage in the soil comparatively slowly and so near-equilibrium is reached comparatively quickly in both infiltration and runoff.

Since at the start of rain, water is being completely absorbed by the soil it is assumed that the infiltration rate has an initial high value of f_0. Due to a combination of increasing storage, particle surface absorption, colloidal particle swelling etc., the rate declines with time and an equation which describes this decay, first produced by Horton, is:

$$f = f_c + \mu^{-Kt} \tag{1}$$

where

f = infiltration rate [mm/h],
f_c = infiltration capacity at large t [mm/h],
μ = $f_0 - f_c$,
f_0 = initial infiltration capacity at $t = 0$ [mm/h],
K = constant positive exponent for a given soil and surface [min^{-1}],
t = time from start of rain [min].

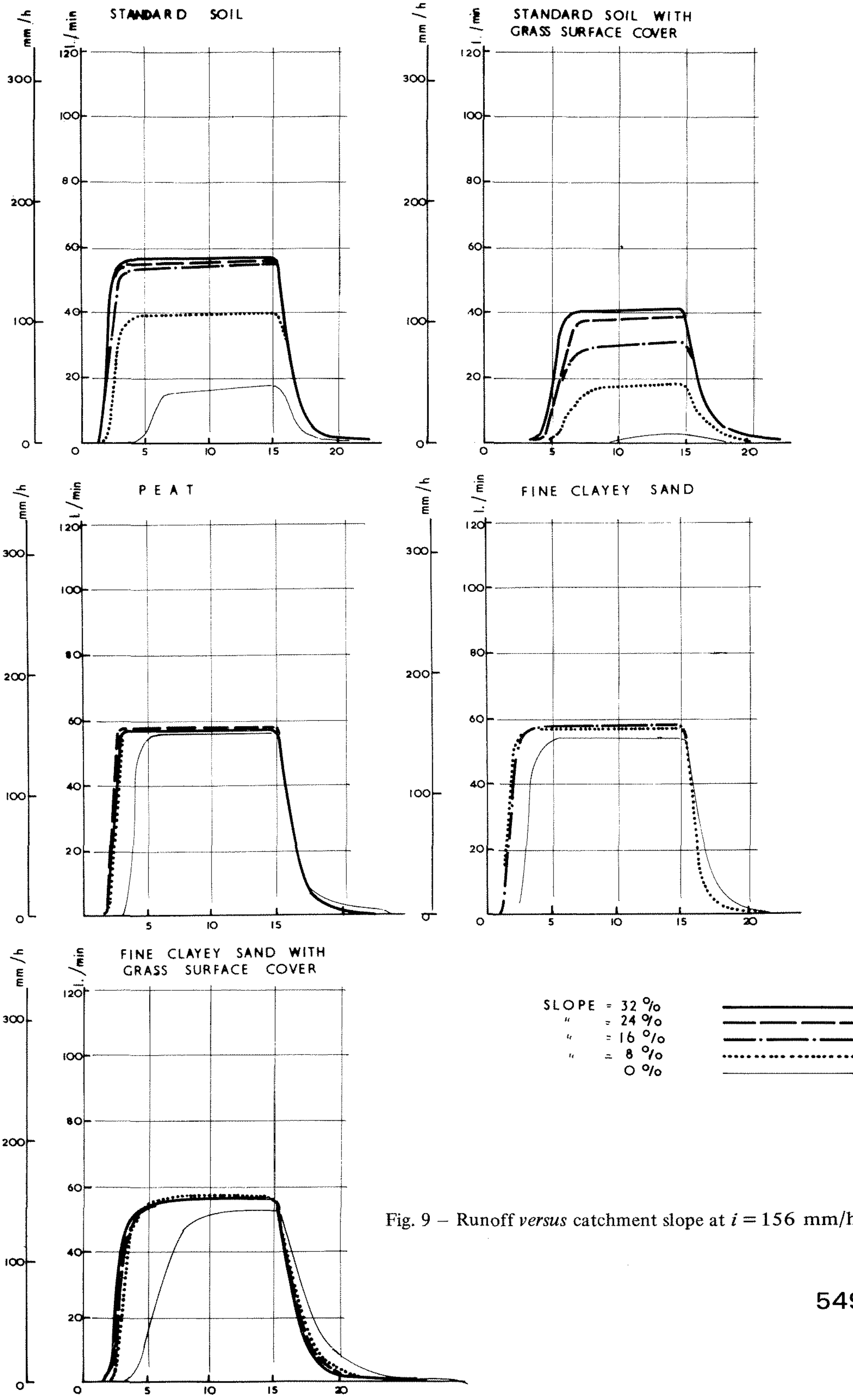

Fig. 9 – Runoff *versus* catchment slope at $i = 156$ mm/h.

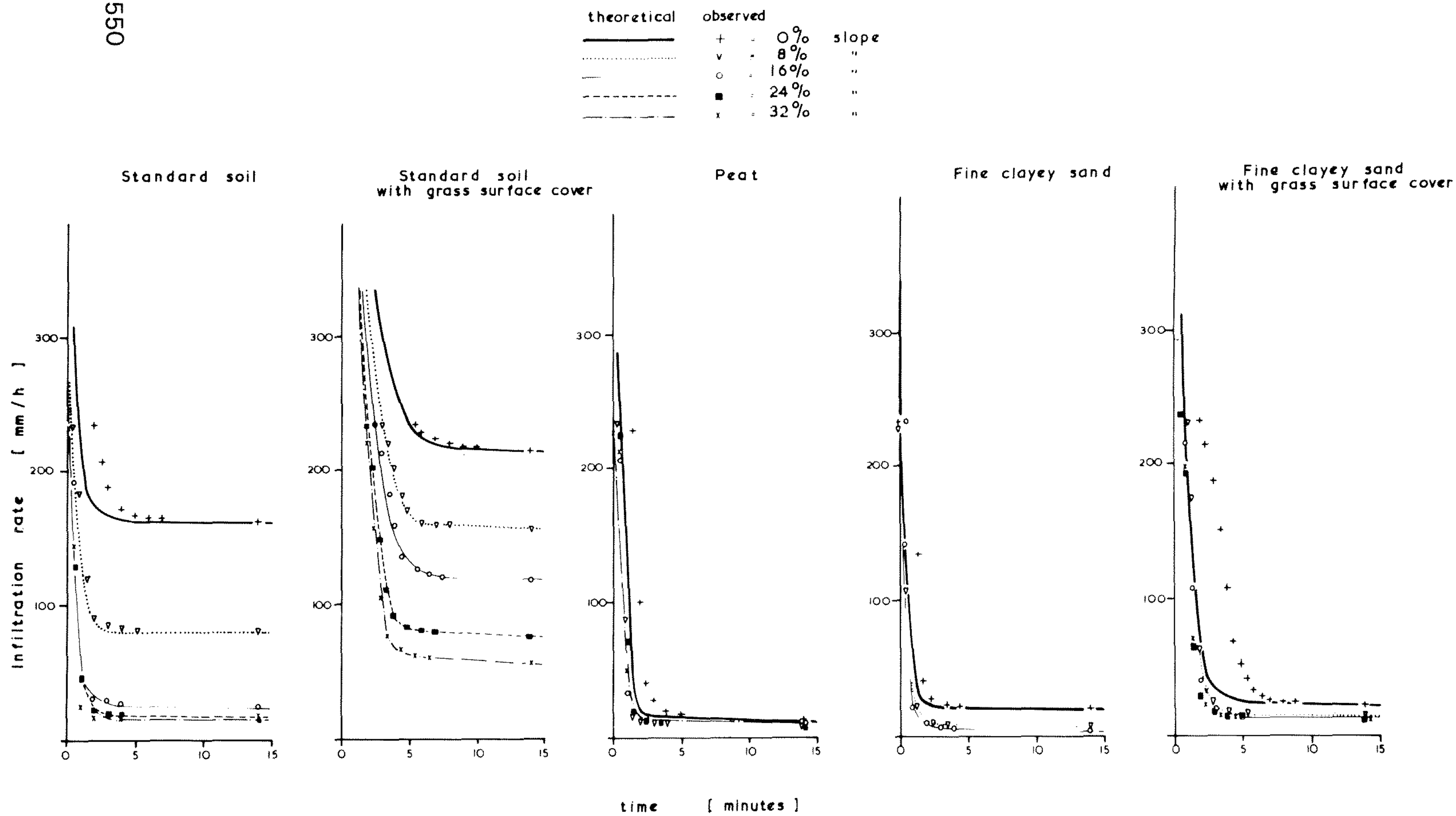

Fig. 10 – Infiltration capacity *versus* catchment slope at $i = 234$ mm/h.

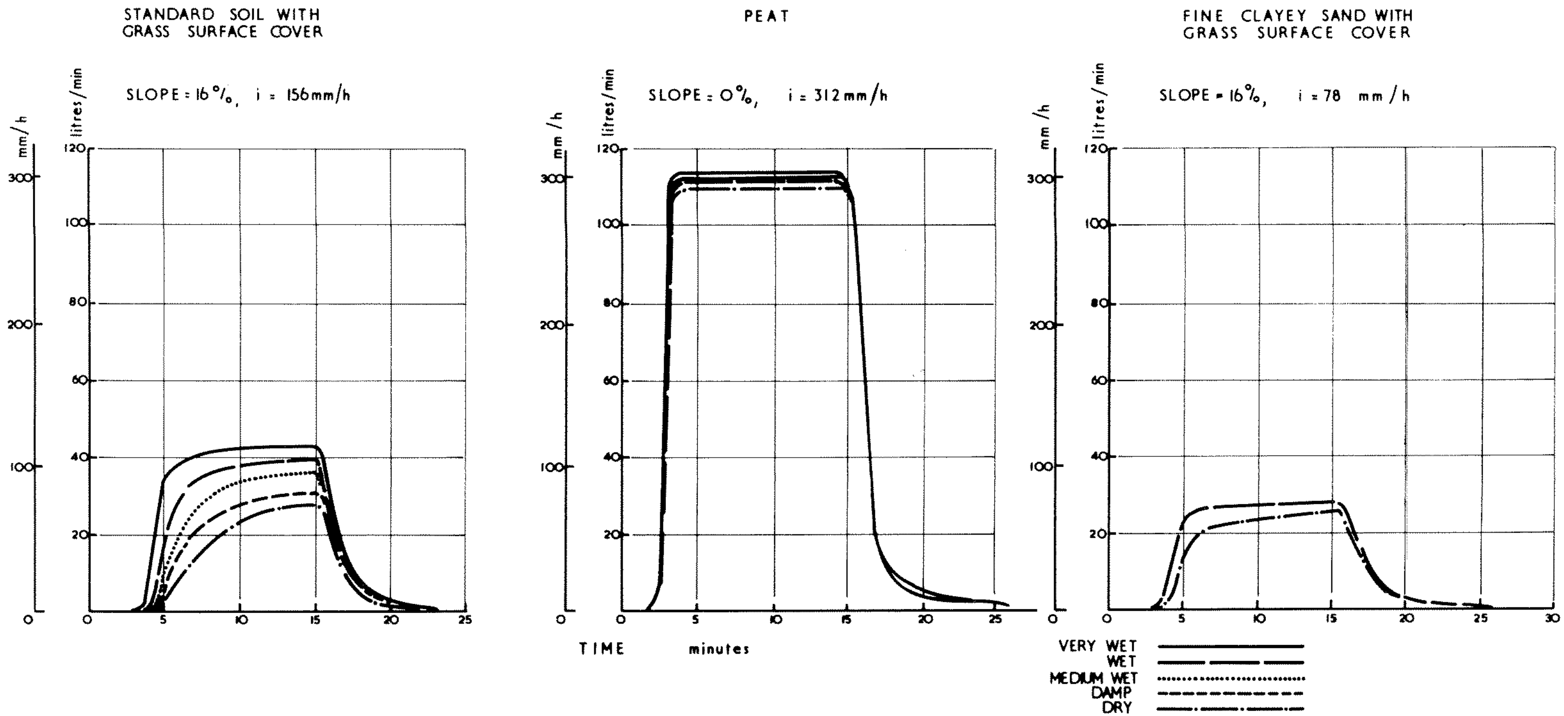

Fig. 11 – Variation of runoff with initial soil conditions.

The method of least squares was used to obtain the lines of best fit for the Horton equation to the data of the tests. The lines are plotted on Figs. 8 and 10. The values of f_0 and K were found to be almost constant for each soil, while f_c varied widely in individual experiments. Typical values and ranges are listed in Table 1.

K is a function of surface texture: if vegetation is present K is small, while a smoother surface texture such as bare soil will yield values about twice as large.

f_0 and f_c are functions of both soil type and cover. For example, permeable soils such as sands and gravels have high values of f_0 and f_c while clayey soils have low f_0 and f_c. Both values increase for both soils if they are turfed.

TABLE 1

Soil type	f_0 [mm/h]	K [min^{-1}]	f_c [mm/h]
Standard, bare	280	1.62	6-220
Standard, turfed	900	0.76	20-290
Peat	325	1.80	2-20
Fine clayey sand, bare	210	2.01	2-25
Fine clayey sand, turfed	670	1.36	10-30

f_c is a function of slope up to some limiting value (varying between 8 and 24 per cent) after which there is little variation.

f_c is a function of rain intensity. If i is large, f_c is large and if i is small f_c is small. This parameter varies in importance with soil permeability. It had a very marked influence on the standard soil of the tests, but was less significant on the less permeable soils.

f_c is a function of initial moisture content. The dryer the soil initially, the larger is f_c, but the variation may be quite small.

It is clear that in these tests soils did not have a particular equilibrium value of f_c but rather a wide range of values, (varying by up to a factor of 10 or more) and at any particular time a soil's infiltration rate was dependent on a number of inherent properties and a number of applied parameters, the latter including those being permanent (e.g. slope), semipermanent (e.g. cover) and temporary (e.g. rain intensity).

REFERENCES

Christiansen, J.E. (1941) The uniformity of application of water by sprinkler systems. *Agric. Engng* **22**, 89-92.

Hall, M.J. (1970) A critique of methods of simulating rainfall. *Wat. Resour. Res.* 6, no. 4, 1104-1114.

Horton, R.E. (1939) Analysis of runoff-plot experiments with varying infiltration-capacity. *Trans. Amer. Geophys. Un.*, part IV, 693-711.

Mutchler, C.K. and Hermsmeier, L.F. (1965) A review of rainfall simulators. *Trans. Amer. Soc. Agric. Engrs* 8, 67-68.

Nassif, S.H. (1974) Hydrological studies of a laboratory catchment area under rainfall simulation. Ph. D. thesis, University of Salford, Lancashire, UK.

Appendix

Soil properties

Soil test	Standard soil	Peat	Fine clayey sand
Location	Bramhall, Cheshire	Astley, Lancashire	Chelford, Cheshire
Specific gravity	2.62	1.40	2.64
Density [kg/m3]	1 640	910	1 860
Porosity [%]	49.56	90.15	39.02
Void ratio	0.98	9.15	0.64
Average moisture content [%] = $\frac{\text{weight of water}}{\text{weight of solids}} \times 100$	23.80	580.5	15.26
Average dry density [kg/m3]	1 330	140	1 610
Permeability [m/day]	0.13-0.54	2.3×10^{-3} to 8.2×10^{-3}	1.4×10^{-2} to 7.4×10^{-2}
Plasticity index	12.1	–	–
P.H.	–	4.8	–
Sieve analysis, [% finer than sieve 200]	49.5	–	14.7
Fineness modulus [%]	4.75	–	1.90
Sedimentation [%]			
Medium silt	22.2	–	7.3
Fine silt	13.7	–	4.4
Clay	11.1	–	2.8
Organics	2.5	–	0.2