DEVELOPMENT AND EVALUATION OF A PERMEABLE LABORATORY CATCHMENT TO INVESTIGATE RELATIONSHIPS OF ANTECEDENT MOISTURE, RAINFALL INTENSITY INFILTRATION AND RUNOFF

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ISMAEL OBWOYA UMA

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ABSTRACT

DEVELOPMENT AND EVALUATION OF A PERMEABLE LABORATORY CATCHMENT TO INVESTIGATE RELATIONSHIPS OF ANTECEDENT MOISTURE, RAINFALL INTENSITY, INFILTRATION AND RUNOFF

By

Ismael Obwoya Uma

A permeable laboratory catchment was developed to investigate the interrelationships among measurable hydrologic parameters which affect the rainfall-runoff process, such as antecedent moisture content, infiltration, evaporation, rainfall and runoff.

A laboratory catchment 7 ft. by 34.25 in. was constructed. The actual watershed area for runoff was 2900 square inches. A porous flow medium was formed by placing four inches of well drained clay loam soil on the watershed. The soil was uniformly compacted on the watershed. The soil surface was stabilized with a thin coating of a catalyzed mixture of fine silica sand, epoxy resin and hardener. Two heating cables were buried in the soil to heat the watershed for a known length of time and thus vary its antecedent soil moisture content prior to simulated rainfall application.

Ismael Obwoya Uma

Studies were conducted by using several rainfall intensities. The watershed soil was kept under different initial soil moisture content before rainfall of a particular intensity was applied. Surface runoff and infiltration rates were measured for these rainfall intensities. A runoff prediction model which related watershed yield to soil moisture parameters was developed from the water balance equation. Runoff volumes from the watershed were predicted by using the model. The experimental runoff volumes were then used to verify the values obtained from the prediction model. The two sets of results showed satisfactory agreement.

Tests were also conducted to examine the effects of antecedent soil moisture content and rainfall intensity on peak runoff and steady state percolation rates, and time of concentration. For this watershed, definite relations were found to exist between rainfall intensity and peak runoff rate, steady state percolation rate and time of concentration.

This study pointed a clear need for more permeable laboratory catchments to study hydrologic systems.

APPROVED G. E. Merva 11/8/73
Major Professor EHK

APPROVED B A Stout
Department Chairman

DATE 11/8/73

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Ismael Obwoya Uma

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LIST OF SYMBOLS

A: watershed area; soil parameter

a: cross-sectional area of sample

C: conversion constant

D: soil moisture diffusivity

E: total evaporation

e: napierian base

F: total infiltration

f: infiltration rate

f_o: maximum infiltration rate at time zero

f_c: minimum infiltration rate

H: soil water pressure

ΔH: hydraulic head difference across sample

i: rainfall intensity

∂j: constant

k: hydraulic conductivity; constant

k_o: saturated hydraulic conductivity

k_s: surface runoff coefficient

ℓ: distance from crest of watershed to outlet

ℓ_1: length of core sample

ℓ_o: slope length

m: slope in unit hydrograph

n: Manning's coefficient; soil constant in Brutsaert's table

P: total precipitationl inflow

Q: runoff volume up to peak flow rate

q: instantaneous runoff rate

q_1: volume of outflow from sample

q_m: peak runoff rate

q_o: runoff rate at a given time

S: watershed slope; watershed storage

ΔS: change in watershed slope; change in watershed storage

S_n: normalized soil moisture content

t: time; mean annual temperature

t_o: time when rainfall starts

t_1: time when runoff starts

t_2: total rainfall time

t_3: total experiment time

t_c: time of concentration

t_ℓ: lag time

Δt: time increment

X: total runoff

x: vertical coordinate; constant for unit graph

y: constant for unit graph

δ: water depth on watershed

Γ: gamma function

ϕ, X, β, ω - - - : soil moisture content functions

Ψ: constant in Brutsaert's table

σ: excess rainfall rate

τ: positive constant

θ: volumetric actual moisture content

θ_i: volumetric initial moisture content

θ_o: volumetric saturated moisture content

CHAPTER I

INTRODUCTION

The agricultural engineer in soil and water engineering bears the responsibility to design hydrologic structures and channels that will handle natural flows of water safely. These flows may be from rainfall or a combination of rainfall and melting snow. The runoff constitutes the hydraulic load which the structures and channels must withstand. For the design, he needs quantitative estimates of runoff rates, volumes and temporal distribution of runoff rates and volumes, (Schwab *et al.*, 1966).

However, accurate prediction of runoff rates and volumes is a difficult job. Methods of runoff estimation which have been developed to date neglect some factors and make simplifying assumptions concerning the influence of others. Chow (1962), reviewed sixty six formulas developed to predict peak runoff rates. However, he noticed that each of the formulas was applicable only for a specified set of conditions. Its application without considering the conditions for which it was developed may give erroneous results. Merva *et al.*(1969), attributed this to a lack of analytic definitions for the pertinent parameters related to the runoff process.

Amorocho and Hart,(1964), pointed out that the study of the hydrologic cycle and its components has undergone a rapid transitional change. Modern hydrology has only existed for about the last forty years. Before then, most of the engineering decisions involving quantitative values dependent on hydrologic parameters were based on the estimation and personal judgement of the designers. To characterize hydrology as a science was also somewhat presumptous (Amorocho and Hart, (1964)).

However, since then, significant advances have been made in the quantitative analysis of hydrologic information. Merriam-Webster editorial staff, (1961) defined hydrology as a science dealing with the properties, distribution and circulation of water on the surface of the land, in the soil horizons and in the atmosphere, particularly with respect to evaporation and precipitation. Hydrology therefore can be said to deal with scientific examination and appraisal of the whole continuum of the water cycle. Different phases through which water in nature circulates and becomes transformed can be represented by the hydrologic cycle. The cycle is represented by a group of arcs which cover the entire earth system: the atmosphere, hydrosphere and lithosphere.

The hydrologic cycle goes through numerous complicated processes of evaporation, precipitation, interception, transpiration, infiltration, percolation, storage and runoff. The cycle can also be represented by the following hydrologic equation, (Chow, (1964), p. 1-4).

$$P - X = \Delta S \qquad (1)$$

where: P = inflow during a given period (in.^{3} per unit area)

X = outflow during the given period (in.^{3} per unit area)

ΔS = change in storage (in.^{3} per unit area).

Finally, the cycle can also be illustrated diagramatically in various ways, (Butler, (1957), p. 253).

The major rainfall characteristics required for hydrologic analyses are intensity, duration, amount and distribution. They affect both the rate and volume of runoff. Rainfall of high intensity is usually of short duration, and covers only small areas. Long duration storms, lasting several hours, are usually of low intensities and cover large areas. There is also a relationship between storm intensity and frequency of occurrence. The higher the rainfall intensity, the less frequent the occurrence, and vice versa. Raindrop sizes, and hence their kinetic energy, also increase with rainfall intensity. There also appears to be a relationship between latitude and rainfall intensity and frequency. The lower latitudes experience both higher frequencies and intensities.

Rainfall patterns also have indirect effects on the rate and volume of runoff. The pattern and seasonal distribution of rainfall, which is characteristic of a particular locality, may influence the antecedent soil moisture content prior to rainfall. This has an important effect on the amount and rate of infiltration, and thus runoff. Average annual rainfall also governs the amount,type and density of vegetation. These are further factors which affect the nature of runoff considerably.

Rainfall intensity values for design purposes are selected for particular recurrence intervals, and from these values one may estimate the desired rate and volume of runoff. The choice of a particular interval depends on the importance of the structure, its cost, the cost of repair or replacement, and the damage to other properties and finally the possible loss of life which may result from its failure.

Peak runoff occurs when water from all parts of the watershed reaches the outlet point simultaneously. This particular instant of time is known as the "time of concentration". While for the design of irrigation dams, flood storage reservoirs and other water detention and storage structures it is necessary to know runoff volumes to be expected, for the design of channels or other waterways, bridges or flow protection structures, peak runoff rates are important.

Most previous rainfall and runoff data have been collected from either large areas, above twenty five square miles, or from small areas of only a few acres. Most of these areas are generally equipped with only a few recording rain gages. This causes a deficiency in detailed rainfall data necessary for proper hydrologic analysis. This is particularly true of predominantly agricultural watersheds, (Myers, (1960)).

In recent years, numerous laboratory watersheds have been constructed for hydrologic studies. They possess obvious advantages for such studies, since experimental conditions can be controlled very carefully in the laboratory, and measurements taken accurately.

Two types of laboratory watersheds are in normal use. The first type is the "Model Watershed" in which an attempt is made to replicate the physical characteristics and parameters of natural hydrologic systems at a known scale. Similarity criteria can then be applied to the prediction or prototype behaviour of the model. The second type is the "Laboratory Prototype Watershed" where the objective may be to study in detail specific hydraulic properties to develop generalized laws of fluid motion applicable to natural watersheds. It may also be to provide data for the test of theories and methods for the analysis of input-output relationships. Such a model may then be called a "Prediction Analysis Prototype", (Amorocho and Hart, (1965)).

When prediction analysis prototypes are used, no attempt is made to simulate the detailed behaviour of a particular watershed. But, the laboratory watershed should have similar non-linearities as exist in natural watersheds, because its purpose is to furnish information relating input to output which apply to non-linear systems in general. Hydrologic systems generally are non-linear because their response to any particular inflow can not be predicted by simple superposition of elemental responses, (Amorocho and Hart, (1965)).

The main purpose of this study is with a Prediction Analysis Prototype. The potential and practicality of mathematical modeling for watershed management under various hydrologic conditions will be investigated. Through this study also, suitable parameters will be determined which can be applicable to the operational watershed model.

CHAPTER II

REVIEW OF LITERATURE

The study of modern hydrology has undergone through rapid transitional changes in the last forty years. Amorocho and Hart (1964), compared it to the evolution of hydraulics and fluid mechanics through the second half of the nineteenth century and the early twentieth century. They concluded that the starting point of modern hydrology occurred as recently as the second quarter of this century.

2.1. Watershed

1. Runoff rate

The "Unit Graph" method of hydrologic analysis was developed by Sherman, (1932). He defined the unit graph as the hydrograph of runoff from a given area, due to a one-inch runoff-depth applied in one day or in any other convenient unit of time. After the unit graph has been derived for a particular watershed, the unit graph for other similar watersheds can be determined, irrespective of size.

Horner and Flynt (1934), developed equations describing the rising and recession limbs of the hydrograph. The rising limb of the hydrograph was described by the equation:

$$q = q_m \left(\frac{t}{t_\ell}\right)^j \tag{2}$$

The recession limb was described by the equation:

$$q = \frac{q_m}{K^{t-t_e}} \tag{3}$$

where: q = runoff rate on rising or recession limb of hydrograph (in/hr).

q_m = runoff rate at peak flow (in/hr).

t = time from beginning of rainfall (hours).

t_ℓ = lag time (hours).

j and k = arbitrary constants found by trial and error.

Horton (1936), developed an equation describing runoff rate for shallow, fully turbulent flow in a thin sheet using the Manning formula:

$$q = \frac{1.486}{n} \delta^{\frac{5}{3}} Z \sqrt{S} \tag{4}$$

where: q = runoff rate ($ft.^3$/sec).

δ = average depth (ft.)

S = slope (%).

n = coefficient of roughness.

Z = length of stream margin.

Horton (1938), developed a formula for estimating runoff from rainfall with uniform intensity:

$$q = \sigma \tan h^2 (3/2\, \sigma\, k_s t) \tag{5}$$

where: q = runoff rate (in/hr).

σ = excess rainfall rate (in/hr).

k_s = surface roughness coefficient.

t = time from beginning of rainfall (hours).

Horner and Jens (1941), showed that overland flow is mostly turbulent and the profile is parabolic, as described by the equation:

$$q = k\delta^2 \tag{6}$$

where: q = rate of flow (in/hr).

k = constant with dimensions of $\frac{1}{1/\text{hr.in}}$

δ = depth of flow on watershed (in.)

Edson (1951), developed a formula which relates runoff to the watershed characteristics and time of runoff. The proposed model was:

$$q = \frac{CA_y(yt_1)^x \, e^{-yt_1}}{\Gamma(x+1)} \tag{7}$$

where: q = runoff rate (ft^3/sec).

C = conversion constant.

A = drainage area (sq. miles).

t_1 = time from beginning of runoff (days)

x and y = constants for unit hydrograph.

$\Gamma(x+1)$ = gamma function of $(x+1)$.

Taylor and Schwarz (1952), also investigated the relationship of unit-hydrograph lag and peak flow and watershed characteristics. They found that the most significant watershed characteristics were drainage area, length of long watercourse, length to center of watershed area, and equivalent mainstream slope. They investigated twenty watersheds and empirically related unit-hydrograph lag and peak flow values to watershed characteristics, and to the duration of the rainfall excess.

Holtan and Overton (1963), developed a method of hydrograph analysis to derive parameters for computing hydrographs tailored to specific watersheds and specific rainstorms. To the time of peak flow, the volume of runoff is:

$$Q = \frac{t_2}{2} q_m \tag{8}$$

where: Q = volume of runoff to time of peak flow (in.^{3})

t_2 = total rainfall time (hours).

q_m = peak runoff rate (in.^{3}/hr).

The rate at any time during recession is:

$$q = q_o e^{-t/m} \tag{9}$$

where: q = runoff rate one time increment, Δt, later (in./hr).

t = rainfall time (hours).

q_o = runoff rate at a given time (in.hr)

m = slope of hydrograph.

Betson (1964), studied watershed runoff and noticed that runoff usually starts from a small, but relatively consistent part of the watershed. He further noticed that runoff was frequently not linear with respect to causative factors.

Linsley (1967), discussed relationship between rainfall and runoff, and introduced a runoff equation which incorporates temperature as one of the parameters:

$$X = 0.934S^{0.155}, \quad P^2/t \tag{10}$$

where: X = total annual runoff (in.)

S = watershed slope (%)

P = total annual precipitation (in.)

t = mean annual temperature (^{o}F)

Overland flow is a major component of any runoff event where the cultural practices significantly affect the watershed runoff hydrograph. A model based on kinematic flow theory was proposed by Foster, Huggins and Meyer (1968) that satisfactorily predicted overland flow on very rough, short erodible slopes. At equilibrium, discharge for any position on the watershed was:

$$q = \sigma\ell \tag{11}$$

The average discharge at the midpoint of the watershed was:

$$q = \frac{\sigma\ell_o}{2} \tag{12}$$

The average velocity of flow on the watershed was:

$$\bar{v} = \frac{\sigma\ell_o}{2\delta} \tag{13}$$

where: q = discharge per unit width (ft.^{3}/hr)

ℓ = distance from upstream of watershed (ft.)

σ = rainfall excess rate (in./hr)

ℓ_o = slope length (ft.)

$\bar{v}$ = average velocity (ft./sec)

δ = average depth of water on watershed (in.)

A hydraulic watershed system consists mainly of the stochastic processes of precipitation, runoff, evapotranspiration and watershed storage. They are all related by the water balance equation. Kareliotis and Chow (1972), developed a method of analysis of "Residual Hydrologic Stochastic Processes". They defined residual hydrologic stochastic processes as the components which remained after the trend and periodicity were removed from a hydrologic process.

2. Infiltration rate

The flow of liquids through unsaturated porous media follows the laws of hydrodynamics. The flow of fluid is due to gravity and the pressure gradient force acting in the liquid. Richards (1931), combined Darey's law with the equation of continuity to develop a model describing vertical flow of water in a partly saturated porous medium.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \quad k \; \frac{\partial H}{\partial x} \qquad - \frac{\partial k}{\partial x} \tag{14}$$

where: t = time (hours)

x = vertical coordinate positive downward (feet)

θ = volumetric soil moisture content (in.^{3}/in.^{3})

k = hydraulic conductivity in appropriate units.

H = soil water pressure (feet).

Horizontal infiltration was described by the same equation, but without the term $\frac{\partial k}{\partial x}$ which represents the effect of gravity. The boundary conditions governing equation (14) are:

$$\begin{aligned} &\theta = \theta_i; \quad H = H_i; \quad x > 0; \quad t = 0 \\ &\theta = \theta_o; \quad H = 0; \quad x = 0; \quad t \geq 0 \end{aligned} \tag{15}$$

The subscripts i and o refer to the initial and saturated soil conditions, respectively. Childs and Collis-George (1950), introduced the concept of soil moisture diffusivity which is of fundamental importance in unsaturated flow where the soil moisture content is continually changing.

$$D = k \frac{\partial H}{\partial \theta} \tag{16}$$

where: D = soil moisture diffusivity (in.^{2}/hr).

k = soil hydraulic conductivity (in./hr)

H = soil water pressure (in.)

θ = volumetric soil moisture content (in.^{3}/in.^{3})

By using (16), one can transform (14) into:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \; D\frac{\partial \theta}{\partial x} - \frac{\partial k}{\partial x} \tag{17}$$

subject to boundary conditions (15).

The role infiltration plays in the hydrologic cycle appears to have first been recognized by Horton (1933). He noticed that infiltration pertained to the passage of water through the soil surface, and that the maximum rate of water entry into the soil depended on several factors. He postulated a maximum infiltration rate which occurred at the beginning of a rain, and a minimum infiltration capacity which occurred several hours later. He also concluded that the minimum infiltration capacity approached the steady percolation rate of the soil profile.

He proposed the following infiltration capacity equation:

$$f = f_c + (f_o - f_c)e^{-\tau t} \qquad (18)$$

where: f = infiltration capacity (in./hr)

f_c = minimum infiltration capacity (in./hr)

f_o = maximum infiltration capacity at time zero (in./hr)

t = time (hours)

e = Napierian base

τ = positive constant depending on soils and vegetation (1/hr)

Surface runoff can only occur after the demands of infiltration capacity, evapotranspiration rate, and detention and storage have been fulfilled. At this time, the soil surface will have been saturated.

Brutsaert (1968a,b) derived the following infiltration equation:

$$f = \frac{k_o A(\theta_o - \theta_i)^{1/2} t^{-1/2}}{2n} + \psi k_o \qquad (19)$$

where: f = infiltration rate (in./hr).

k_o = saturated conductivity (in./hr)

A = constant

n = constant for particular soil type

θ_o = saturated soil moisture content (in.^{3}/in.^{3})

t = time (hours)

ψ = constant from Brutsaert's table.

Brutsaert's infiltration capacity equation appears to hold great promise for future hydrologic studies, since it is directly linked to the soil moisture properties and duration of precipitation.

3. Time of Concentration

Hydrologic structures are usually designed using peak rates of runoff. The time for runoff to peak is known as the time of concentration. It occurs when all parts of the watershed are contributing simultaneously to the flow past an outlet point. A number of formulas for computing time of concentration have been developed.

Kirpich (1940), proposed the following formula:

$$t_c = \frac{0.00013\ell^{0.77}}{S^{0.385}} \qquad (20)$$

where: t_c = time of concentration (hours)

ℓ = distance from crest of watershed to outlet (miles)

S = slope of watershed (%)

Kerby (1959), proposed the following formula to estimate time of concentration for use in the national formula:

$$t_c^{2.14} = \frac{2}{3}\frac{\ell k_s}{\sqrt{S}} \tag{21}$$

where: t_c = time of concentration (hours)

ℓ = length of flow from crest to outlet (feet)

S = watershed slope (%).

k_s = surface roughness coefficient.

Once the time of concentration is calculated the next step is to determine the required design rainfall intensity. The selected rainfall intensity is that which occurs for a duration equal to the time of concentration, and for a recurrence interval appropriate for the particular structure.

CHAPTER III

OBJECTIVES AND THEORY

3.1. Definition of the Problem

The primary objective of this investigation was to develop a model for predicting runoff from a watershed when the soil and rainfall parameters are known. The water balance equation was utilized in the development of the model. A homogeneous soil was used to form a porous flow medium on the watershed.

The specific objectives of the thesis were:

1. To develop and test a runoff model demonstrating the interrelationship between soil moisture content and the runoff behavior of a permeable laboratory watershed.
2. To investigate the validity of Brutsaert's infiltration equation using the permeable laboratory watershed.
3. To use the laboratory watershed to examine the interrelationship among measureable hydrologic parameters such as time of concentration, peak runoff rate and steady state percolation rate, as affected by rainfall intensity.

3.2. Development of Theory

1. Infiltration rate model

Brutsaert (1968a,b), developed the following relationship for a soil at different soil moisture content:

$$S_n = \frac{(\theta - \theta_i)}{(\theta_o - \theta_i)} \tag{22}$$

where: S_n = normalized soil moisture content

θ = actual soil moisture content (in.^{3}/in.^{3})

θ_i = initial soil moisture content (in.^{3}/in.^{3})

θ_o = saturated soil moisture content (in.^{3}/in.^{3})

Brutsaert (1968a), also developed an equation describing the relationship between soil moisture content and soil moisture suction:

$$S_n = \frac{A}{(A + (-H)^n)} \tag{23}$$

where: n = constant for a given porous material.

H = soil moisture suction (feet)

A = soil parameter (feet).

S_n = normalized soil moisture content.

Through inspection of a number of wetting characteristics for different soils, Brutsaert concluded that n was very close to unity. Equation (23) then became:

$$Sn = \frac{A}{(A-H)} \tag{24}$$

Phillip (1956), obtained a series solution of equation (17) which describes vertical infiltration into a soil column:

$$x = \phi t^{1/2} + xt + \beta t^{3/2} + \omega t^2 + - - - - - \\ + f_m(\theta) t^{m/2} - - - - - - - - - - \quad (25)$$

where: x = length of vertical infiltration into soil column (in.)

t = time (hours)

ϕ, x, β, ω -- = functions of soil moisture content

Phillip (1956), noticed that the series in equation (25) converge very rapidly, and that the first two terms were adequate to describe vertical infiltration. Hence,

$$x = \phi t^{1/2} + xt \quad (26)$$

Brutsaert (1968b), proposed an equation describing cumulative infiltration into a soil profile:

$$F = (\theta_o - \theta_i) \int_0^1 x dS_n \quad (27)$$

From (26),

$$F = (\theta_o - \theta_i) \quad t^{1/2} \int_0^1 \phi dS_n + t \int_0^1 x dS_n \quad (28)$$

The infiltration rate can be obtained by differentiation, viz.,

$$F = \frac{dF}{dt} \quad (29)$$

where: F = cumulative infiltration (in.)

f = infiltration rate (in./hr)

t = time (hours).

Brutsaert (1968b), derived the following expression to describe vertical infiltration into a soil column:

$$f = {\frac{k_oA(\theta_o - \theta_i)}{2n}}^{1/2} t^{-1/2} + (\theta_o - \theta_i) \int_0^1 X dS_n \quad (30)$$

To facilitate the use of equation (30), Brutsaert (1968b), tabulated values for

$$\frac{(\theta_o - \theta_i)}{k_o} \int_0^1 X dS_n$$

for different values of the parameter n normally encountered for most soils, using as a parameter,

$$\psi = \frac{(\theta_o - \theta_i)}{k_o} \int_0^1 X dS_n \quad (31)$$

where ψ = constants in Brutsaert's table. The infiltration rate equation (30), then becomes:

$$f = {\frac{k_oA(\theta_o - \theta_i)}{2n}}^{1/2} t^{-1/2} + \psi k_o \quad (32)$$

2. Runoff model

The hydrologic response of a watershed may be represented by the following water balance equation:

$$X = P - F - E \quad (33)$$

where: X = total runoff (in.)

P = total precipitation

F = total infiltration (in.)

E = total evaporation (in.)

Differentiating equation (33) with respect to t leaves one with the expression:

$$\frac{dX}{dt} = \frac{dP}{dt} - \frac{dF}{dt} - \frac{dE}{dt} \qquad (34)$$

or $$\bar{x} = i - f - e \qquad (35)$$

where: $\bar{x}$ = runoff rate (in./hr) = $\frac{dX}{dt}$

i = rainfall rate (in./hr) = $\frac{dP}{dt}$

f = infiltration rate (in./hr) = $\frac{dF}{dt}$

e = evaporation rate (in./hr) = $\frac{dE}{dt}$

If we substitute equation (32) into (35) for f, we obtain:

$$\frac{dX}{dt} = i - \frac{k_o A(\theta_o - \theta_i)}{2n}^{1/2} t^{-1/2} + \psi k_o - e \qquad (36)$$

The following notations will be used during the analysis:

t_o = time when rainfall starts, in hours, assumed to be zero for a given event.

t_1 = time when runoff starts (hours).

t_2 = total precipitation time (hours).

t_3 = total experiment time (hours).

Integration of equation (36) yields:

$$\int \frac{dX}{dt} = \int_0^{t_2} i dt - \int_0^{t_2} \frac{k_o A(\theta_o - \theta_i)}{2n}^{1/2} t^{-1/2} + \psi k_o - \int_0^{t_3} e dt \qquad (37)$$

$$\text{or } X = it\Big|_{o}^{t_2} - 2\left(\frac{k_oA(\theta_o-\theta_i)}{2n}\right)^{1/2} t^{1/2} + \psi k_o t\Big|_{t_o}^{t_2} - et\Big|_{o}^{t_3} \qquad (38)$$

$$X = it_2 - \left(\frac{2k_oA(\theta_o-\theta_i)}{n}\right)^{1/2} t_2^{1/2} - k_o\psi t_2 - et_3 \qquad (39)$$

For Morley clay loam soil, by interpretation in Brutsaert's (1968b) table n = 2.

Equation (39) then becomes:

$$X = it_2 - \left(k_oA(\theta_o-\theta_i)\right)^{1/2} t_2^{1/2} - k_o\psi t_2 - et_3 \qquad (40).$$

CHAPTER IV

EXPERIMENTAL SET-UP

In recent years, there was a growing trend towards building laboratory catchments for hydrologic studies. Most of the catchments used were impervious surfaces for runoff. Rainfall was simulated using hypodermic needles which produced sprays with uniform drop sizes and intensities.

At the present time, there is a clear need to incorporate a permeable medium or a laboratory watershed for studying hydrologic systems. The catchment being used for this investigation has incorporated a porous medium on the watershed. Through review of literature, this laboratory catchment seems to be the first to incorporate a porous medium which enabled runoff, infiltration and steady state percolation to be determined under simulated rainfall.

4.1. Watershed Layout

The base of the watershed was constructed of lumber plywood fir 4 ft. by 8 ft. by 3/8 in. nominal size. The size of the base was 7 ft. by 34.25 in. It was supported 3 feet above ground level by a frame constructed of lumber fir 2 in. by 4 in. nominal size. The size of the frame was 7 ft. by

3ft. by 7 ft. The watershed had a uniform slope of one percent. Its actual area was 7 ft. by 34.25 in. Fig. 1(a) illustrates the complete arrangement of the watershed.

Water was conveyed to a pressure regulator through a hose connected to a water tap. The hose passed through an air trap which helped to absorb the vibration in the hose due to water passing through it. This eliminated the extreme deflections of the pressure gage needle and an exact water pressure value could be maintained on the gage.

A ceiling was constructed about four feet above the watershed surface. Water from the pressure regulator was conveyed to the ceiling through tygon tubing 0.5 inch inside diameter. The tygon tubing ran in five parallel rows across the ceiling. The rows were spaced six inches apart. Rainfall was simulated by using pieces of microtubes two inches long and 0.036 inch inside diameter. They were spaced at ten inches interval along each row of the tygon. Each row contained six pieces of microtubes. The microtubes were inserted into the 0.5 inch tygon tubing by making suitably sized holes and held in place by friction (Kenworthy, (1972)).

The rows at the boundary of the watershed began an inch from the boundary so that all the rain fell within the watershed area. The watershed was enclosed by an aluminum sheet twelve inches high to prevent water from splashing out of the watershed area when rain was falling. The watershed

Fig. 1(a). The laboratory watershed model.

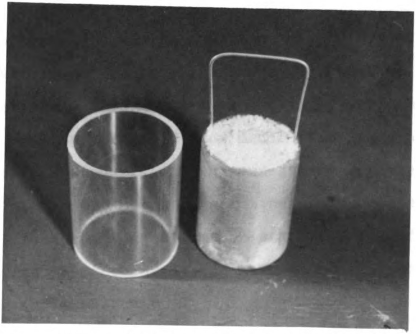

Fig. 1(b). Apparatus for determination of soil moisture content on the watershed.

surface was painted to make it waterproof. The rest of the frame was painted white to improve appearance, see Fig. 1(a). Numerous small holes were drilled all over the watershed base to allow water passing through the soil to fall onto a plane surface supporting the watershed.

The watershed was raised one-half inch above the plane surface to give enough clearance for the percolator to run to a measuring point situated in the middle of the watershed outlet, see Fig. 1(a). The surface runoff from the watershed was collected in an eavestrough at the watershed outlet, and conveyed to a measuring point at the left extremity of the watershed outlet, Fig. 1(a).

4.2. Soil Investigation

1. Preliminary

The objective was to construct a porous flow system to make the watershed completely permeable so that water could infiltrate freely through it. Lehr (1936), developed a technique for forming permeable flow media from granular materials. The method consisted of bonding sand grains together with epoxy resin, but the pores between the grains would still remain open. The epoxy sand mixture was workable and could be cast in forms. After curing, it maintained the shape of the form in which it was cast.

Approximately twenty tests were conducted in which different mixing ratios of sand and the cementing epoxy resins were tried. The intention was to find a mixing ratio which would produce a permeable medium with an infiltration rate of about 1.5 inches per hour. The sand used in the tests was a commercial sand blasting material classified as Fine Silica. The epoxy resin used was a general purpose polyester boat resin, BOAT-ARMOR Super Iso-Resin, manufactured by Valspar Marine of the Valspar Corporation. It had the accompanying hardener manufactured by Sarafan Corporation. The hardener contained methyl-ethyl-keton.

The silica sand used in the test had a gradation of 30-40 mesh. Its infiltration rate was 56.4 inches per hour. Various mixtures of the sand and resin were tested for permeability by casting the sand-epoxy resin-hardener mixture inside plastic drain tubes of general diameter 5.5 inches. The mixture had good workability, but the permeabilities were too high for all the mixing ratios tested. It was then felt that it would be extremely difficult to find a mixing ratio of sand and the catalyzed epoxy resin which would produce a permeable medium with an infiltration rate of about 1.5 inches per hour. It was then decided to look for soil with finer materials than Fine Silica sand, and lower permeability.

2. Final design

The soil finally used on the watershed model was Morley clay loam collected from a well drained field on one of the University farms. The soil had an infiltration rate of about 1.2 inches per hour. It was suitable for the watershed. It was sieved by passing through various sieve sizes. Particles with the following gradations were used on the watershed:

Percent retained (by weight)	Sieve opening (in.)	U.S. Standard Sieve Size (Meshes/in.)
7	0.0550	12
30	0.0232	28
40	0.0165	35
20	0.0116	48
3 (Passing)		

The soil was thoroughly mixed before putting on the watershed.

The bulk density of the soil was 1.38 grams per cubic centimeter. The soil was uniformly compacted to a depth of four inches on the watershed. The surface was uniformly coated with fine silica sand-epoxy-hardener mixture to a depth of 1/8 inch and compacted. This helped to stabilize the soil surface and prevent erosion. The infiltration rate of the surface coating was 8.1 inches per hour, while that of the underlying soil was 1.2 inches per hour. The coating may also be considered to act as a mulch over the soil surface.

4.3. Watershed Soil Moisture Content

Four pairs of concentric plastic pipes of internal diameters 2 inches and 1.75 inches, respectively, were cut to a length of 2.5 inches each. A hooking mechanism was fixed to the inner pipe 1/2 inch from the top so that it could be conveniently lifted out of the soil for weighing at suitable intervals. The lower end of each of the inner pipes was closed by wire gauze of very fine pores. The gauze was fixed to the end of each of the pipes by a mixture of epoxy resin and hardener. The inner surface of the gauze was covered with material of finer pores than the gauze to prevent from coming out of the pipes. Fig. 1(b) shows the two concentric plastic pipes.

The inner pipes were filled with soil of the same gradation as that on the watershed, and was packed to similar density as the watershed soil. The top 1/8 inch of the soil surface in each pipe was covered with a mixture of fine silica sand, epoxy resin and hardener mixed in the same ratio as the surface coating used on the watershed to give them equal infiltration rate. Fig. 1(b) shows the plastic pipe full of clay loam soil, and the top of the soil coated with a mixture of fine silica sand and catalyzed resin mixture.

The pipes were arranged concentrically before insertion into the soil as shown in Fig. 2(a). Fig. 2(b) shows one of the concentric pipes in position in the soil on the

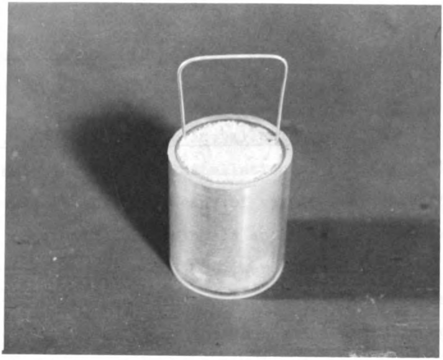

Fig. 2(a). Concentric pipes for measuring soil moisture content before insertion into the soil.

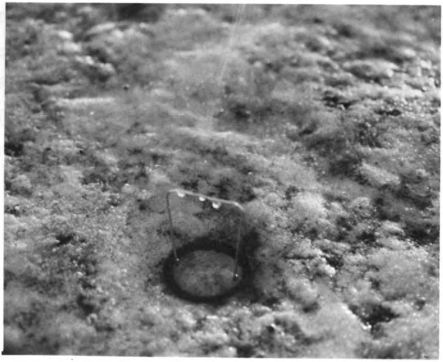

Fig. 2(b). Concentric pipes in position in the soil on the watershed.

watershed. The top of the pipes were levelled with the watershed surface.

4.4. Heating Cable Installation

The objective for installation of heating cables in the soil was to afford a means of varying the antecedent soil moisture content before rainfall application. Two Wrap-On Electric Heat Tapes, model T80, were buried into the soil at depths of 1.0 inch and 3.0 inches from the soil surface respectively. The spacing of the heat tapes was 3 inches, and the length of run was 80 inches as shown in Fig. 3. Each tape was 80 feet long and required 400 watts. They were manufactured by Wrap-On Co., Inc., Chicago, Illinois.

The heat tapes were expected to dry the soil completely in 55 hours, starting from complete saturation.

Figure 4 is a side view of section A-A through the soil column (see Fig. 3). It shows the positions of the top and bottom heat cables in the soil profile.

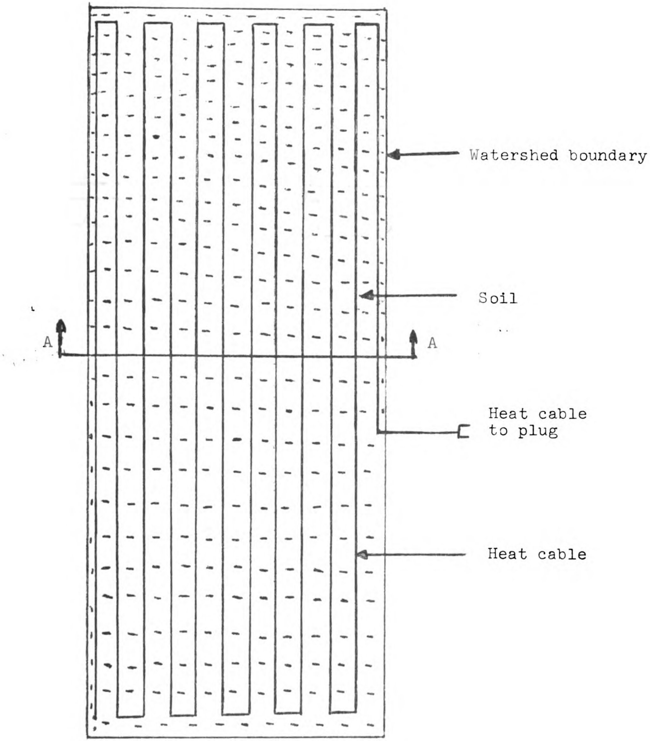

Fig. 3. Cross-section through the soil showing layout of heating cables. Plan view.

Scale: 1" = 11.4"

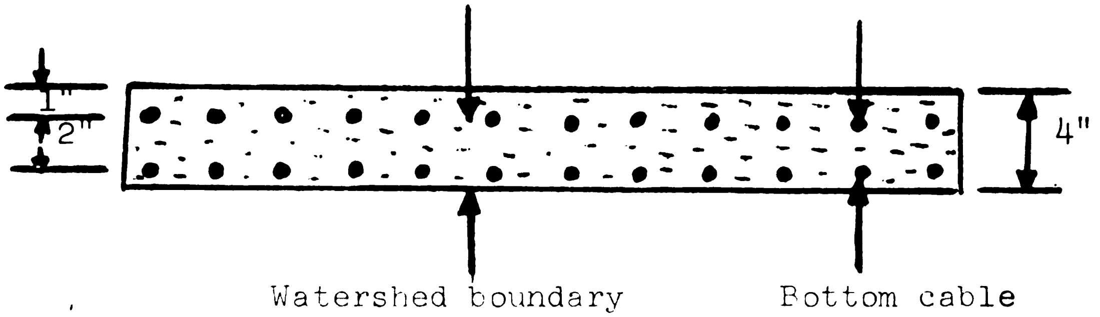

Fig. 4. Side view of section A-A through soil profile showing positions of heating cables.

Scale: 8" ≡ 1"

CHAPTER V

EXPERIMENTAL PROCEDURE AND RESULTS

5.1. Drying Cycles and Rainfall Application

Theoretical developments and data records of the rainfall-runoff process have provided good information and increased understanding of the hydrologic system. Most hydrologists recognize the importance of antecedent soil moisture conditions, and feel that they have direct effects on the resulting runoff from precipitation.

This experiment was designed with a provision to enable antecedent soil moisture conditions to be varied by heating the soil for a known length of time. The drying period was in increments of six hours. All drying started from saturated soil condition.

The experiment was conducted with different rainfall rates, and for different soil drying periods. However, only three different rainfall rates were selected for analysis. The rainfall rates used were 2.68, 3.68 and 4.88 inches per hour. Figure 5(a) illustrates the procedure of regulating the water pressure to produce the desired rainfall rate. Figure 5(b) illustrates the condition of the watershed during rainfall. The hooking mechanisms projecting above the soil

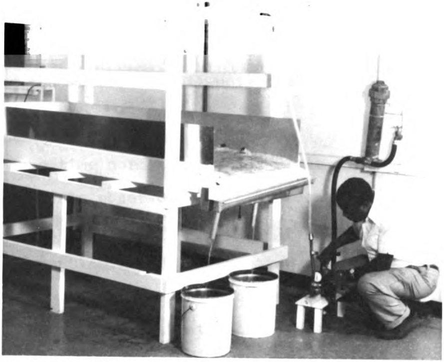

Fig. 5(a). Regulation of the water pressure to produce the desired rainfall rate.

Fig. 5(b). Condition of watershed during rainfall. Hooking mechanisms projecting above soil surface indicate positions of the plastic pipes for measuring soil moisture content.

surface indicate the positions of the plastic pipes for measuring the watershed soil moisture content.

5.2. Measurements

Some time normally elapses after rain begins falling before runoff is observed. This is because precipitation has to first satisfy the demands of evaporation, infiltration, interception, surface detention and storage and channel detention. When all these demands are satisfied, the soil surface will be saturated and runoff begins.

1. Calibration of rainfall intensity

A calibration of the rainfall intensity was conducted before soil was introduced on the watershed. The watershed surface was painted to make it waterproof. It was smoothened with a hand sander to remove grease from the surface and to allow runoff water to flow in a continuous uniform fashion. Rainfall of various intensities were applied to the watershed surface, and continued to fall for 15 minutes before runoff was measured. This time interval allowed peak flow to be achieved. Since there was no infiltration, these peak runoff values were equal to the rainfall intensities being applied. The values of the applied water pressure at the regulator and the corresponding rainfall intensities are shown in Table 10 in the appendix. Figure 6 shows the calibration curve for rainfall intensity.

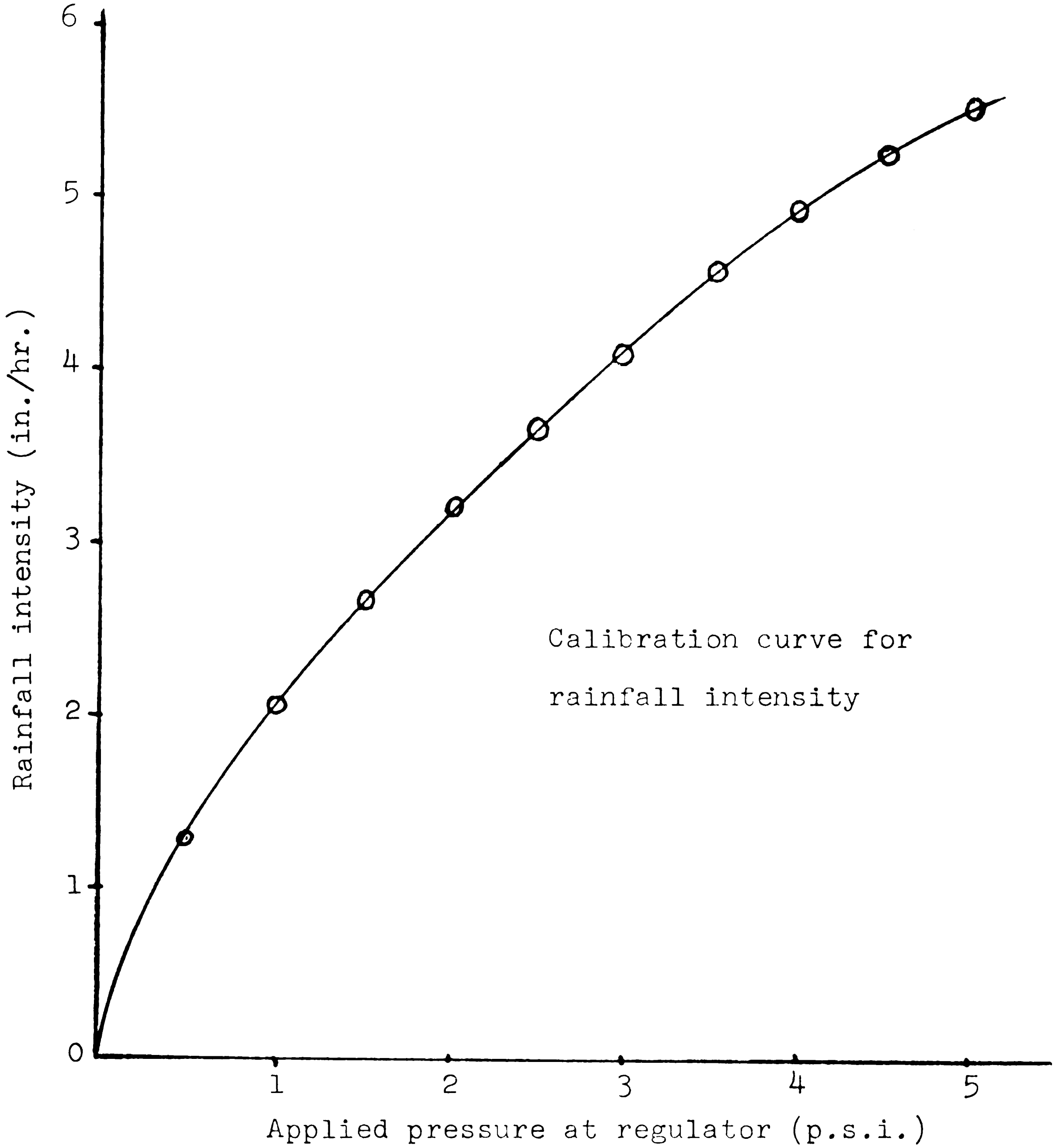

Fig. 6. Rainfall intensity vs. Applied pressure at regulator.

2. Runoff and steady state percolation rates

Surface runoff and steady state percolation rates were measured after soil was introduced on the watershed. Surface runoff and steady state percolation volumes were measured using calibrated beakers for suitable consecutive time intervals. For each drying period and particular rainfall intensity, surface runoff was measured from the beginning of runoff until several consecutive measurements over an equal interval of time showed constant values. This indicated peak flow rate and would occur at the time of concentration when every part of the watershed was contributing to the flow at the outlet simultaneously.

Peak runoff and steady state percolation rates for various rainfall intensities are shown in Table 1. Figure 7 shows peak runoff rate against rainfall intensity. Figure 8 shows steady state percolation rate against rainfall intensity. The surface runoff rates for rainfall intensity of 2.68 inches per hour following a 6-hour soil drying period are shown in Table 2. The runoff rate values obtained when rainfall intensity of 2.68 inches per hour was applied following 24 and 48-hour soil drying periods are shown in Tables 11 and 12 in the appendix. The runoff hydrographs for this rainfall intensity are shown in Figures 9, 10 and 11.

The surface runoff rates obtained when rainfall intensity of 3.68 inches per hour was applied following 6-hour

Table 1. Values of rainfall intensity and peak runoff and steady state percolation rates. Soil was saturated prior to rainfall.

Rainfall intensity (in./hr.)	Peak runoff rate (in./hr.)	Steady state percolation rate (in./hr.)
5.52	4.35	1.19
5.28	3.98	1.11
4.92	3.87	1.03
4.57	3.56	0.93
4.10	3.17	0.87
3.68	2.78	0.77
3.31	2.52	0.73
2.68	1.84	0.70
1.79	1.16	0.65
1.26	0.92	0.64
1.24	0.90	0.63
1.18	0.87	0.62
1.08	0.80	0.63

⊗ Denotes rainfall cutoff point

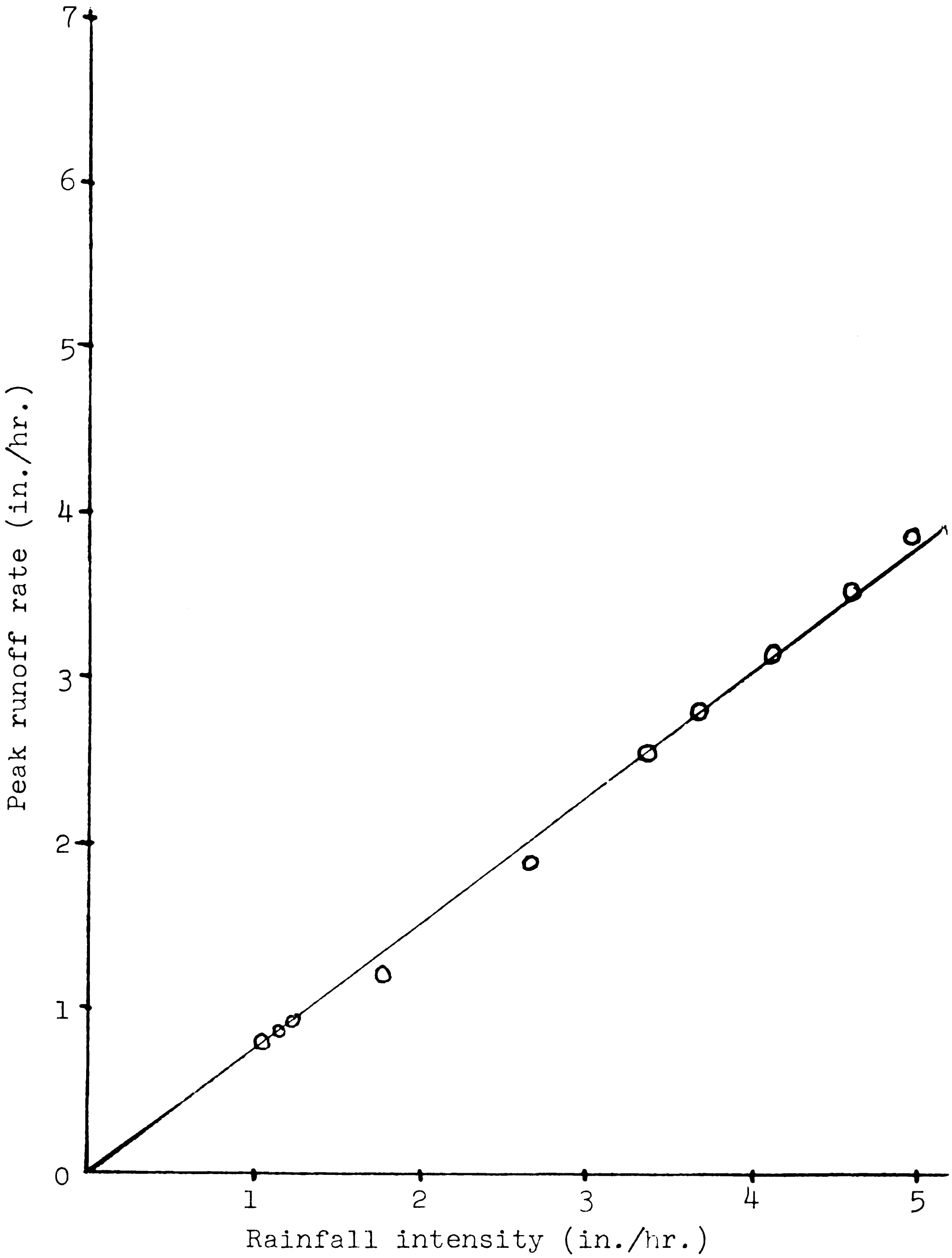

Fig. 7. Peak runoff rate vs. Rainfall intensity.

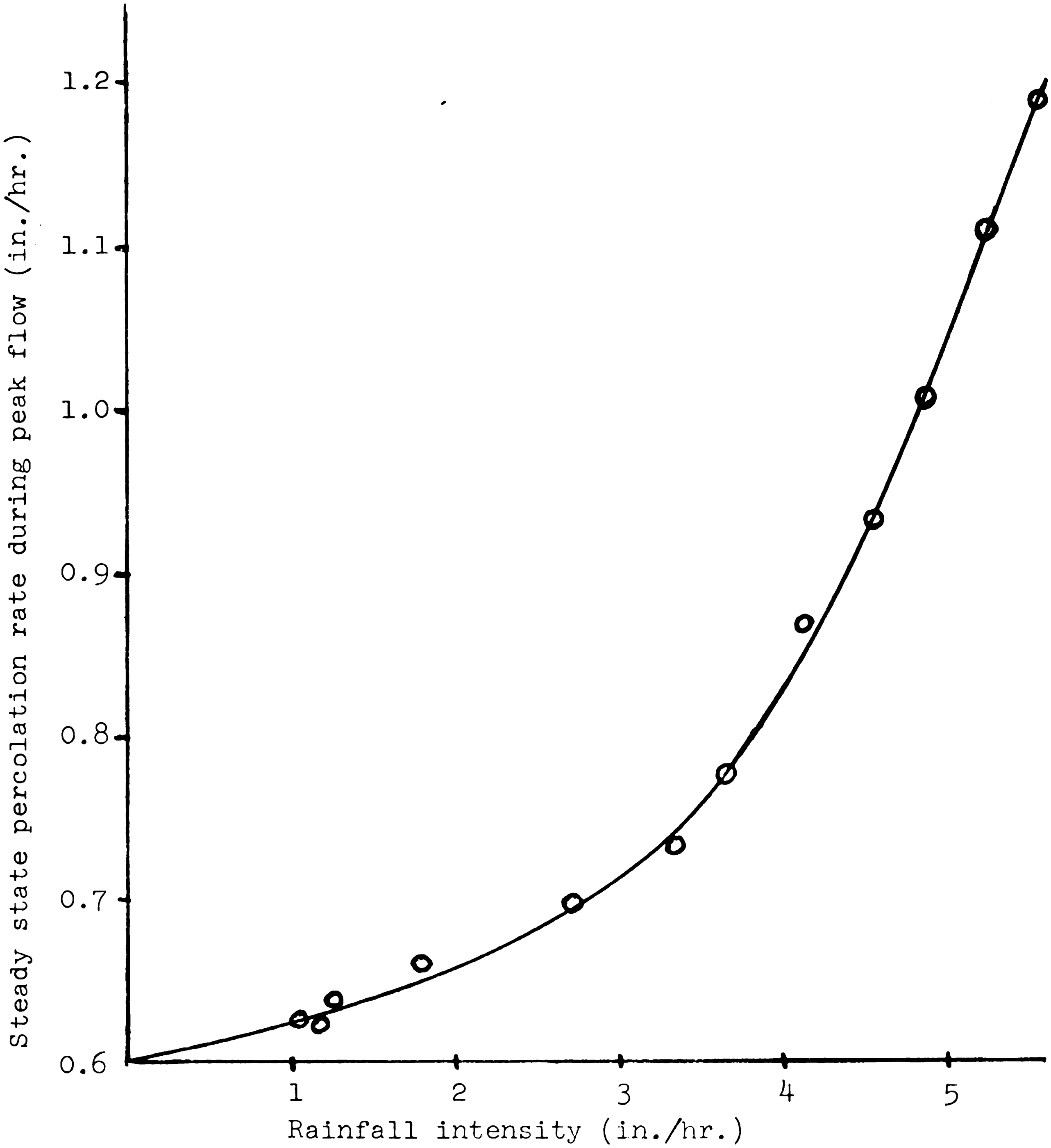

Fig. 8. Steady state percolation rate during peak flow vs. Rainfall intensity.

Table 2. Runoff, measured and predicted infiltration rates following 6-hour soil drying.

Rainfall intensity (in./hr.)	Runoff rate (in./hr.)	Infiltration rate (in./hr.)		Cumulative time (hr.)
		Measured	Predicted	
2.68	0.000	2.68	3.20	0.039
	0.640	2.04	1.86	0.092
	0.930	1.75	1.72	0.109
Rainfall	1.050	1.63	1.65	0.119
intensity	1.080	1.60	1.62	0.125
uniform	1.080	1.60	1.57	0.134
	1.190	1.49	1.52	0.144
	1.170	1.51	1.49	0.150
	1.260	1.42	1.45	0.158
	1.200	1.48	1.43	0.164
	1.250	1.43	1.42	0.167
	1.260	1.42	1.39	0.175
	1.210	1.47	1.38	0.178
	1.260	1.42	1.36	0.183
	1.210	1.47	1.35	0.186
⊗	1.210	1.47	1.34	0.189
	1.043	-	-	0.194
	0.378	-	-	0.199
	0.126	-	-	0.203
	0.040	-	-	0.219
	0.014	-	-	0.236
	0.006	-	-	0.270

⊗ Denotes rainfall cutoff point

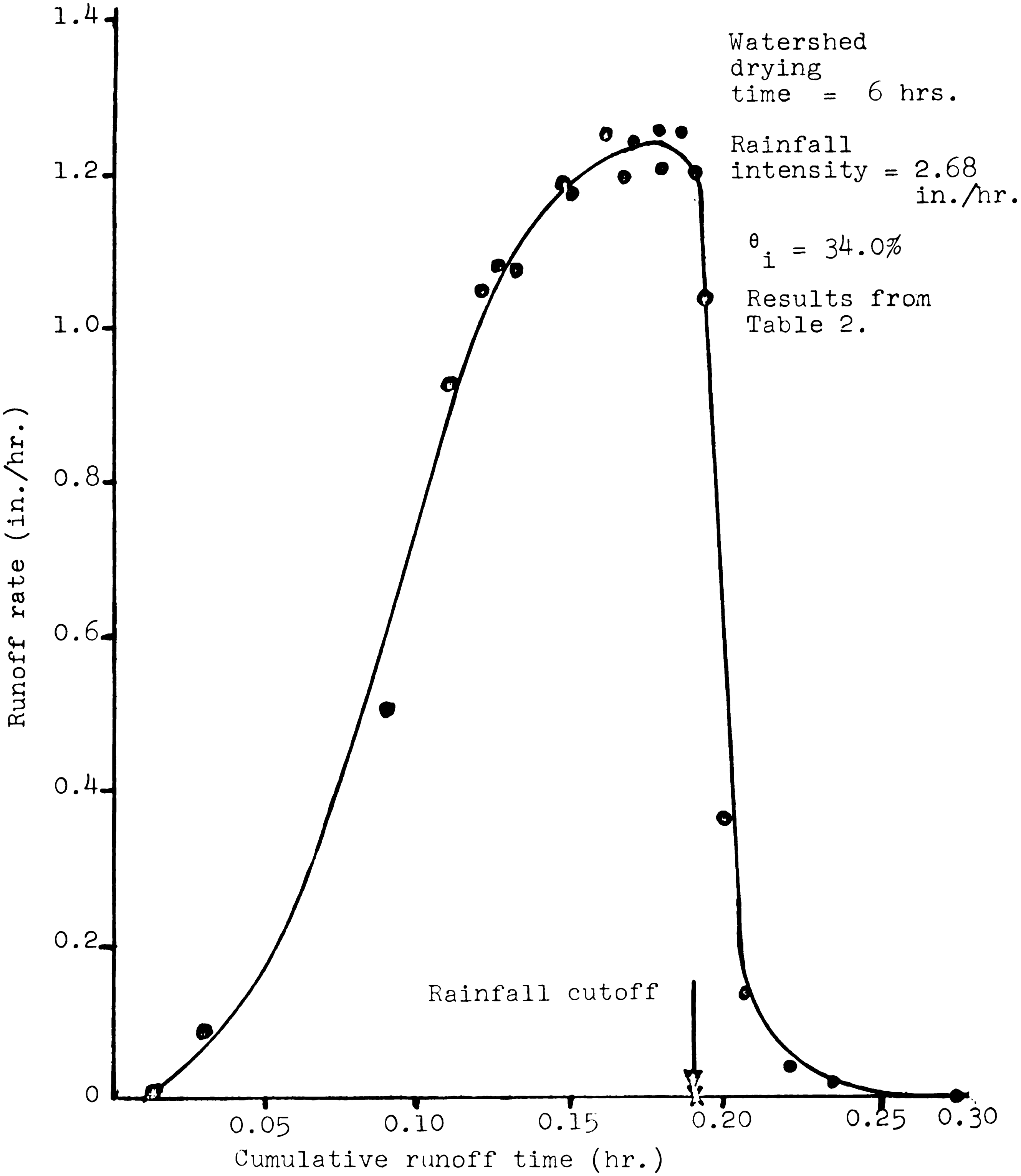

Fig. 9. Runoff rate vs. Cumulative runoff time.

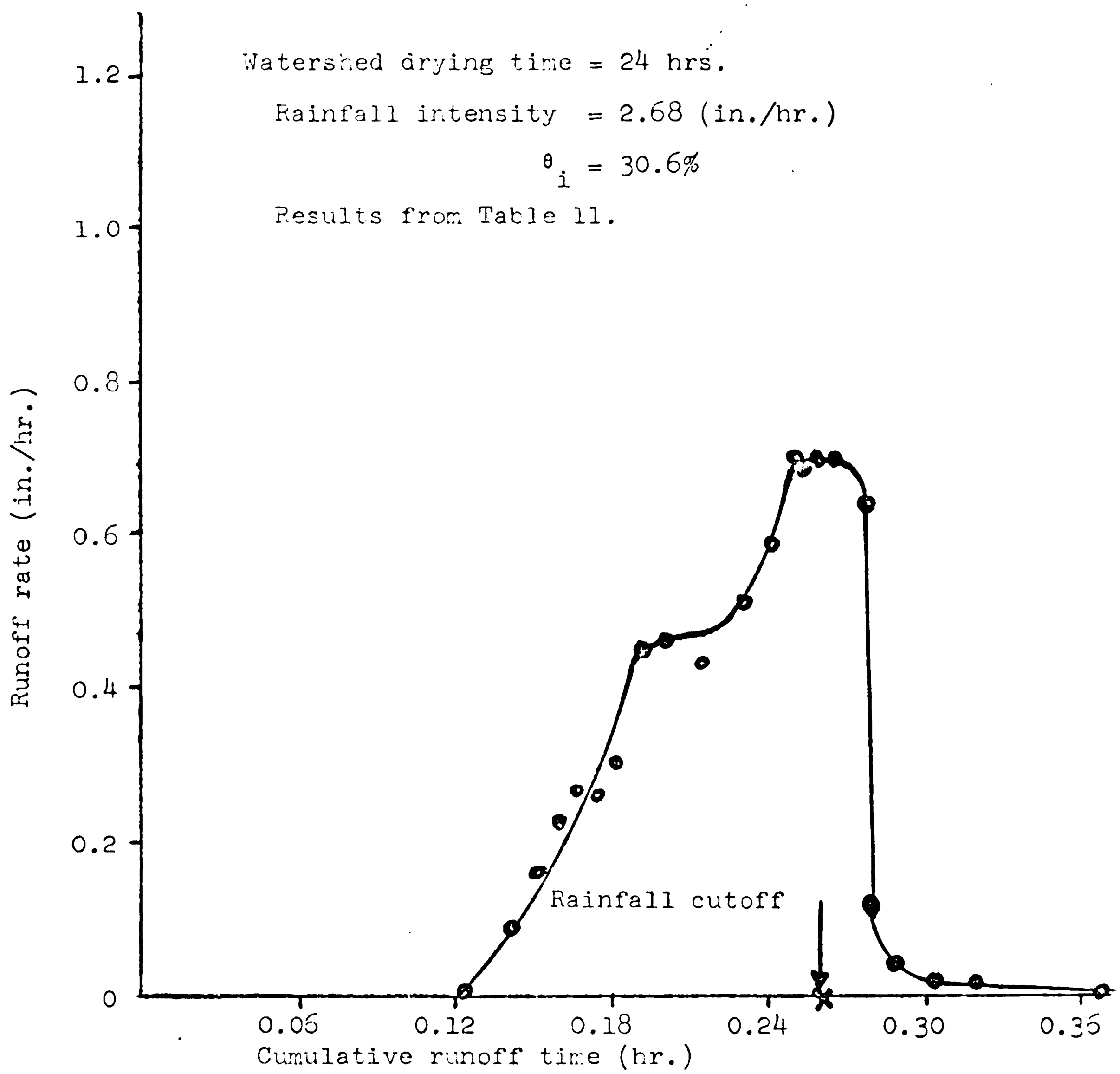

Fig. 10. Runoff rate vs. Cumulative runoff time.

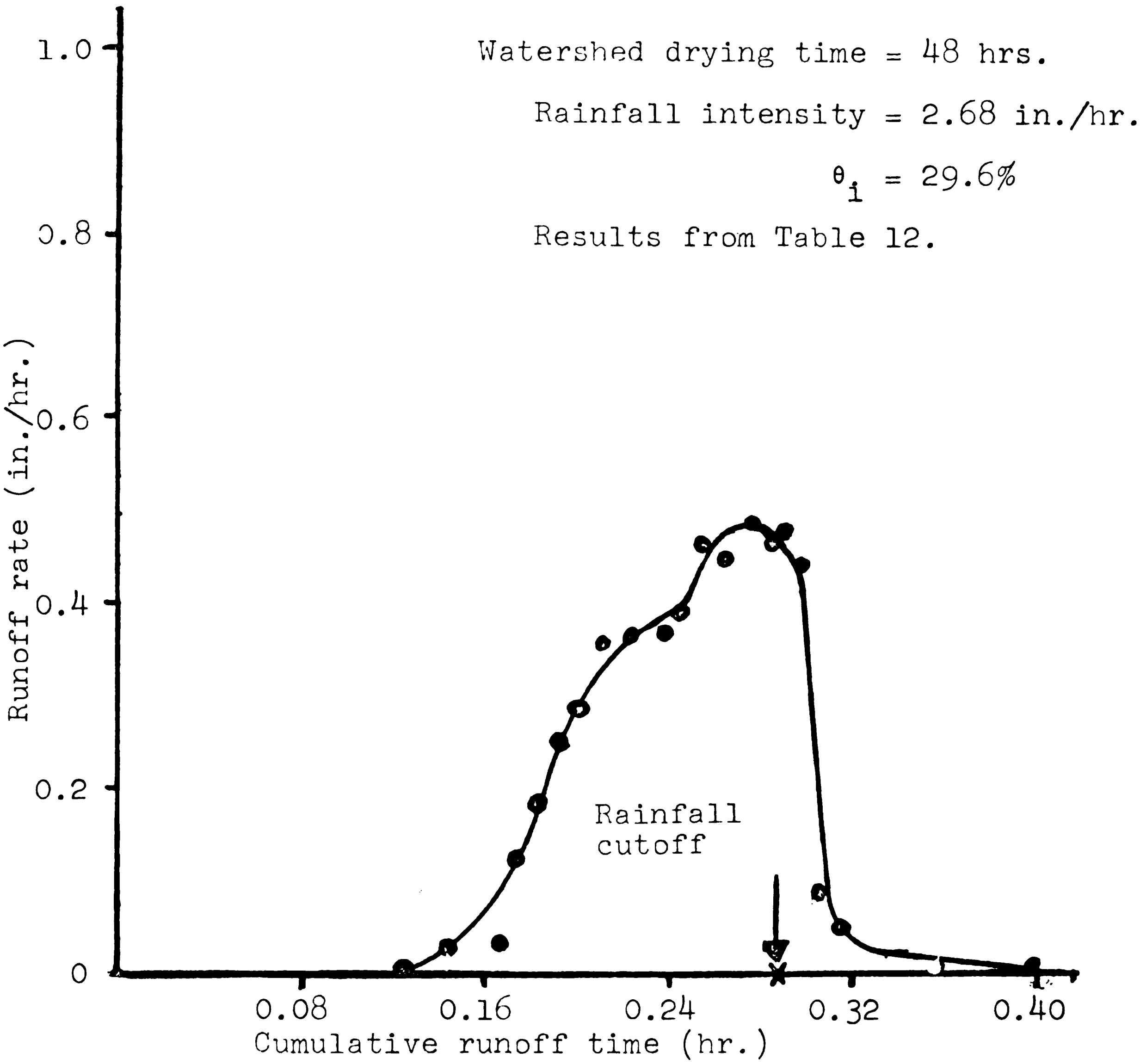

Fig. 11. Runoff rate vs. Cumulative runoff time.

watershed soil drying are contained in Table 3. The runoff rate values obtained when the same rainfall intensity was applied following 24 and 48-hour soil drying periods are contained in Tables 13 and 14 in the appendix. The runoff hydrographs for this rainfall intensity are shown in Figures 12, 13 and 14.

Similar runoff rates obtained after applying rainfall intensity of 4.88 inches per hour following 6 hours of watershed soil drying are shown in Table 4. The runoff rates obtained from the same rainfall intensity following 24 and 48 hours of soil drying are shown in Tables 15 and 16 in the appendix. The runoff hydrographs for this rainfall intensity are shown in Figures 15, 16 and 17.

The experimental infiltration rate was obtained by subtracting the runoff rate from rainfall intensity. The predicted infiltration rate was calculated by using equation (32). The results obtained for the rainfall intensities and drying periods investigated are shown in Tables 2, 3 and 4, and also in Tables 11, 12, 13, 14, 15 and 16 in the appendix. The curves of infiltration rate against time for the experimental and predicted values are illustrated by Figures 18, 19, 20, 21, 22, 23, 24, 25 and 26.

Table 3. Runoff, measured and predicted infiltration rates following 6-hour soil drying.

Rainfall intensity (in./hr.)	Runoff rate (in./hr.)	Infiltration rate (in./hr.)		Cumulative time (hr.)
		Measured	Predicted	
3.68	0.000	3.68	4.27	0.016
	1.220	2.46	2.18	0.065
	1.380	2.30	2.06	0.074
Rainfall intensity uniform	1.540	2.14	1.97	0.082
	1.590	2.09	1.90	0.088
	1.680	2.00	1.85	0.093
	1.740	1.94	1.80	0.099
	1.790	1.89	1.76	0.104
	1.940	1.74	1.72	0.109
	1.940	1.74	1.68	0.115
	1.960	1.72	1.64	0.121
	1.990	1.69	1.61	0.126
	2.070	1.61	1.56	0.132
	2.040	1.64	1.55	0.138
	2.070	1.61	1.52	0.143
	2.100	1.58	1.51	0.145
	2.120	1.56	1.48	0.151
	2.150	1.53	1.47	0.154
	2.160	1.52	1.46	0.157
⊗	2.140	1.51	1.45	0.160
	1.880	-	-	0.164
	0.840	-	-	0.168
	0.520	-	-	0.172
	0.260	-	-	0.181
	0.04	-	-	0.198
	0.01	-	-	0.247

⊗ Denotes rainfall cutoff point

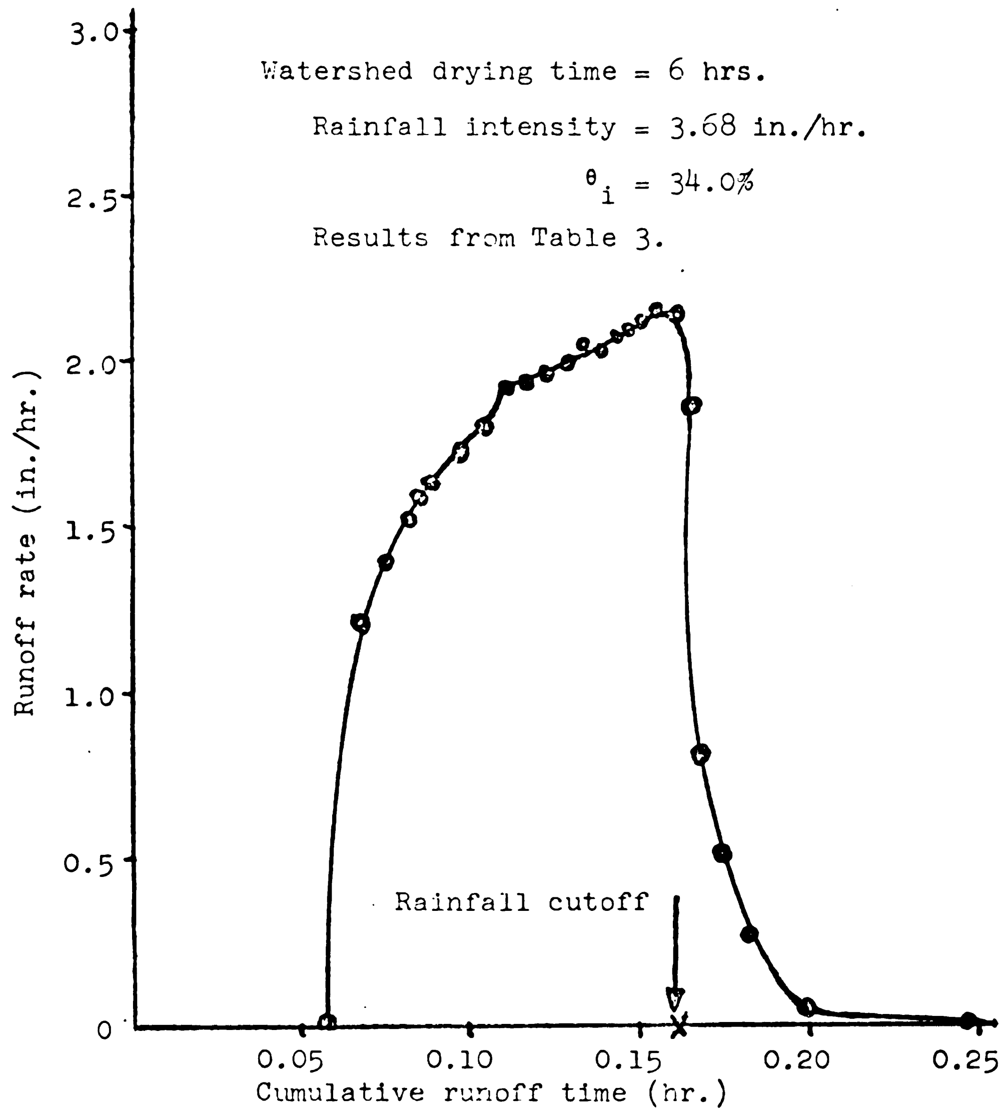

Fig. 12. Runoff rate vs. Cumulative runoff time.

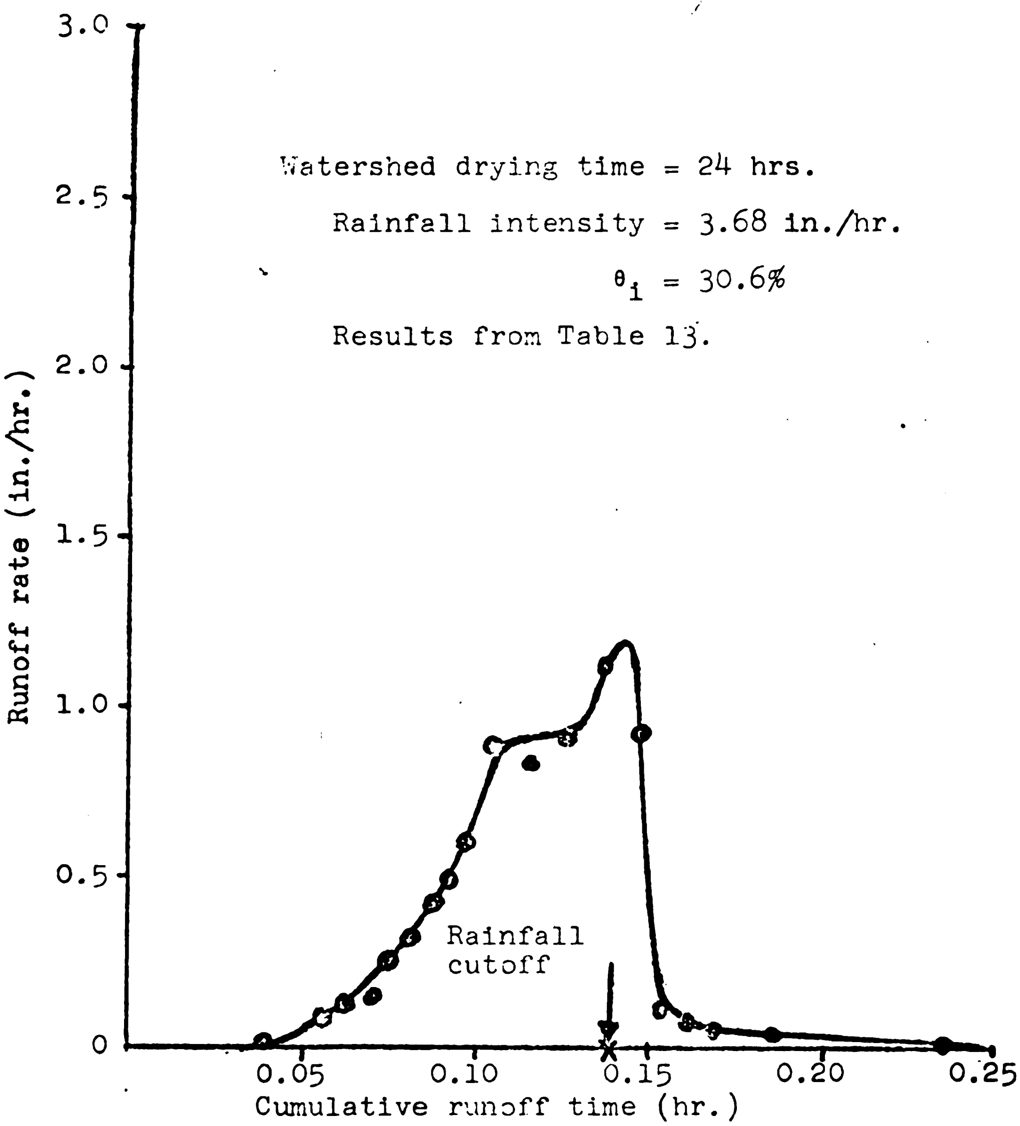

Fig. 13. Runoff rate vs. Cumulative runoff time.

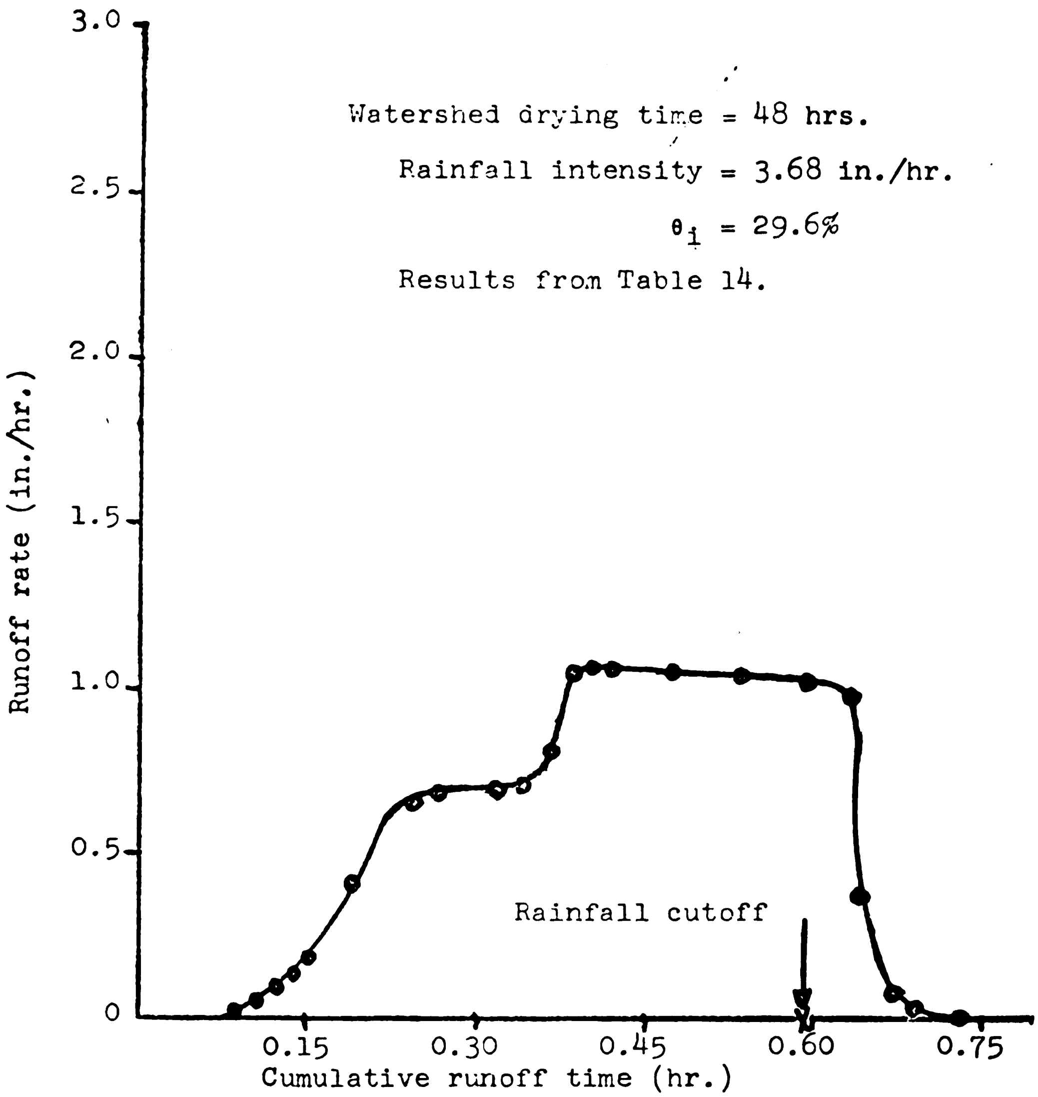

Fig. 14. Runoff rate vs. Cumulative runoff time.

Table 4. Runoff, measured and predicted infiltration rates following 6-hour soil drying.

Rainfall intensity (in./hr.)	Runoff rate (in./hr.)	Infiltration rate (in./hr.)		Cumulative time (hr.)
		Measured	Predicted	
4.88	0.000	4.88	8.35	0.014
	2.370	2.51	2.34	0.056
	2.530	2.35	2.18	0.065
Rainfall	2.630	2.25	2.09	0.072
intensity	2.680	2.20	2.01	0.078
uniform	2.730	2.15	1.96	0.084
	2.830	2.05	1.89	0.089
	2.900	1.98	1.84	0.095
	2.960	1.92	1.79	0.100
	3.020	1.86	1.74	0.106
	3.050	1.83	1.71	0.111
	3.180	1.70	1.67	0.117
	3.200	1.68	1.64	0.122
	3.210	1.67	1.64	0.128
	3.210	1.67	1.60	0.133
	3.240	1.66	1.57	0.136
	3.200	1.68	1.55	0.139
	3.260	1.60	1.54	0.144
	3.280	1.60	1.52	0.147
®	3.320	1.56	1.49	0.150
	1.080	-	-	0.154
	0.232	-	-	0.158
	0.101	-	-	0.167
	0.058	-	-	0.183
	0.035	-	-	0.200
	0.010	-	-	0.234

® Denotes rainfall cutoff point

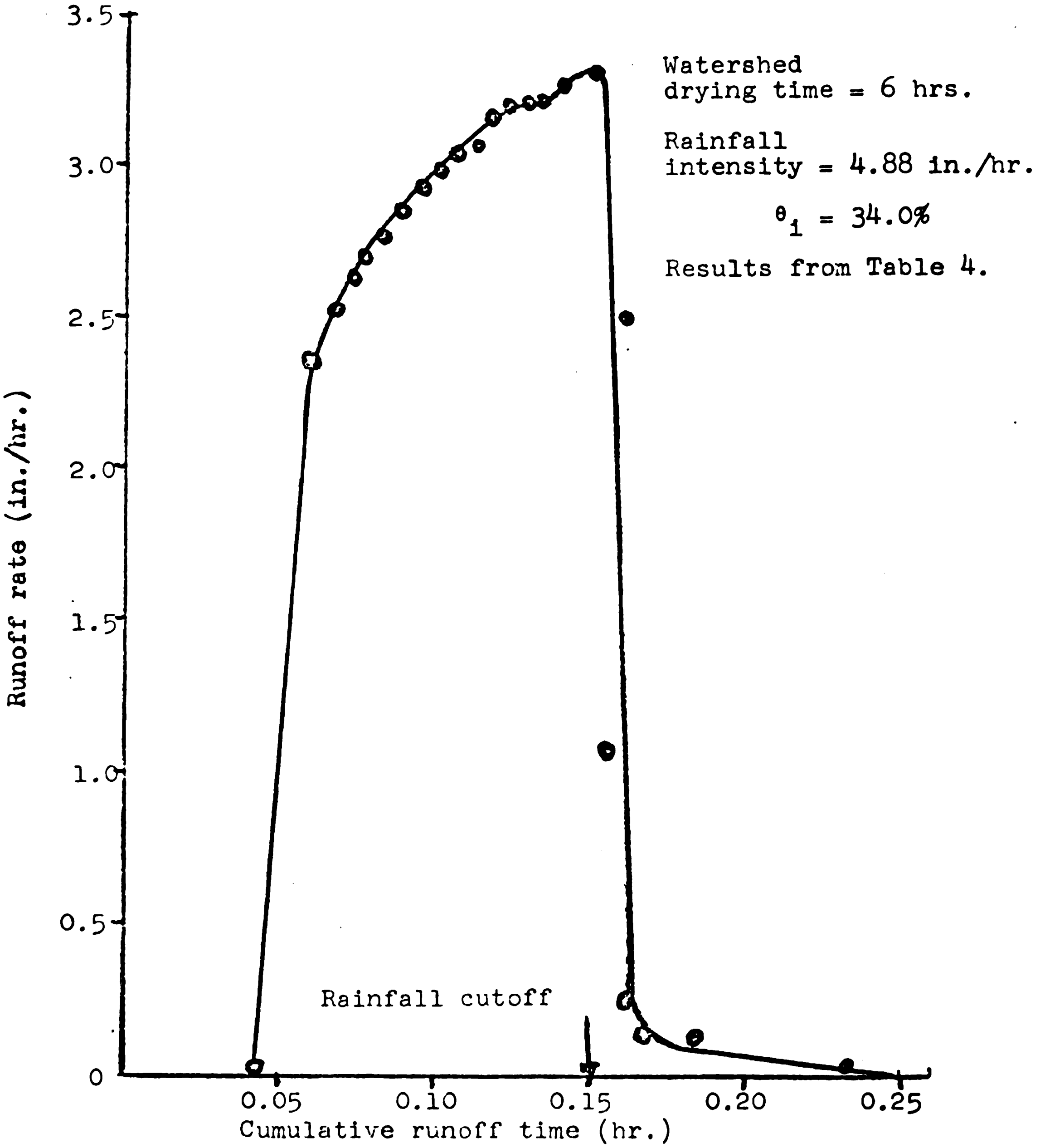

Fig. 15. Runoff rate vs. Cumulative runoff time.

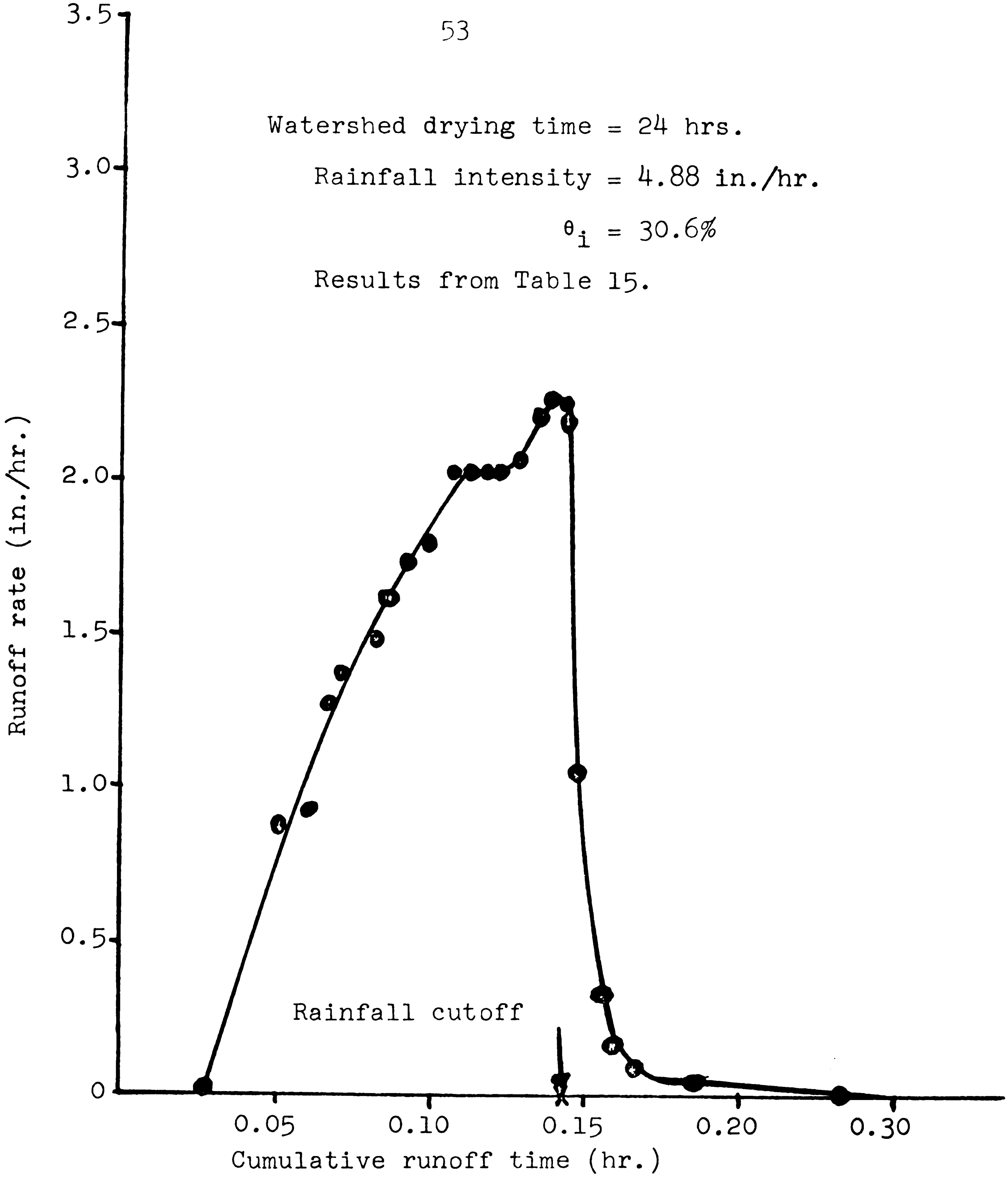

Fig. 16. Runoff rate vs. Cumulative runoff.

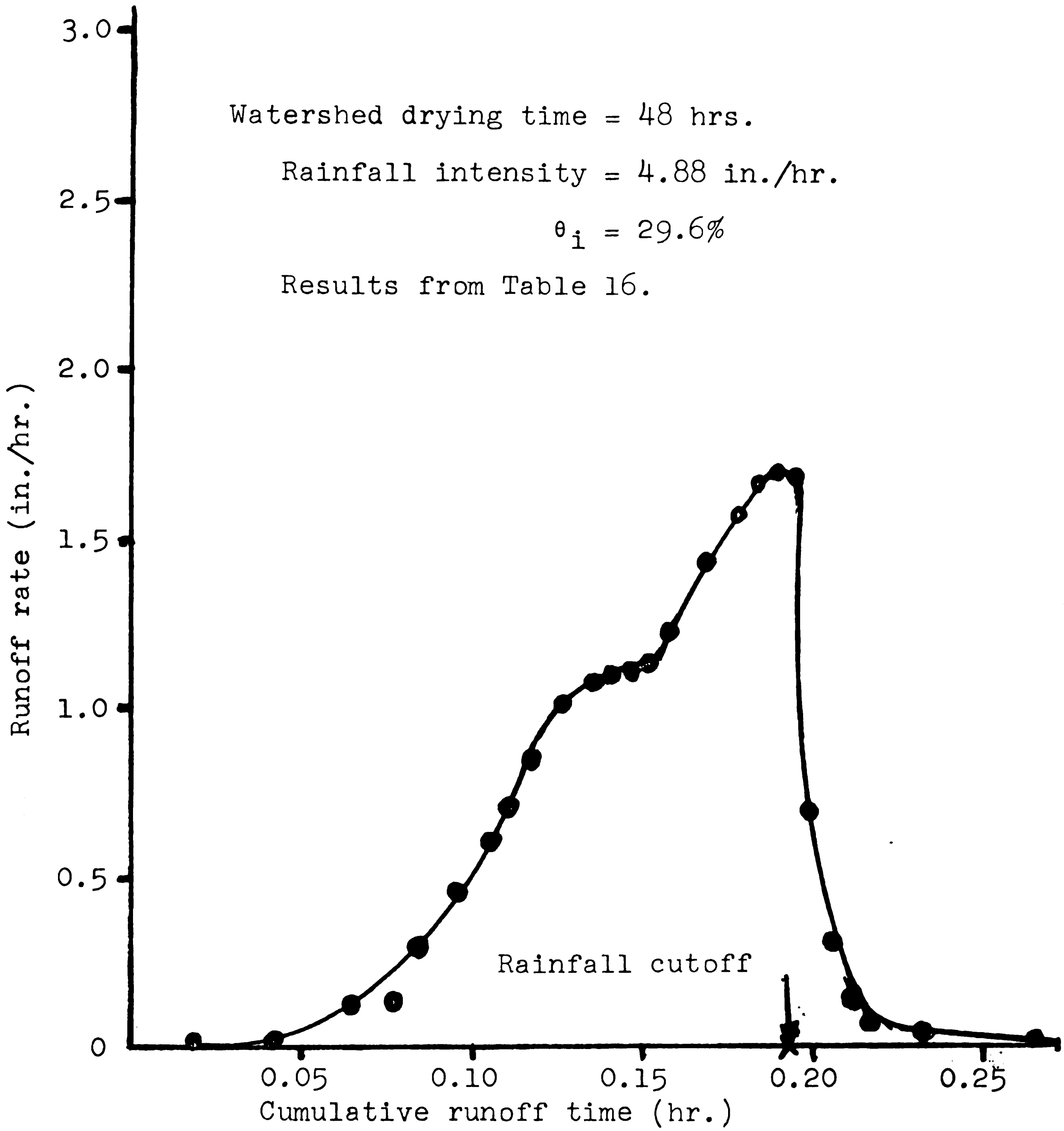

Fig. 17. Runoff rate vs. Cumulative runoff time.

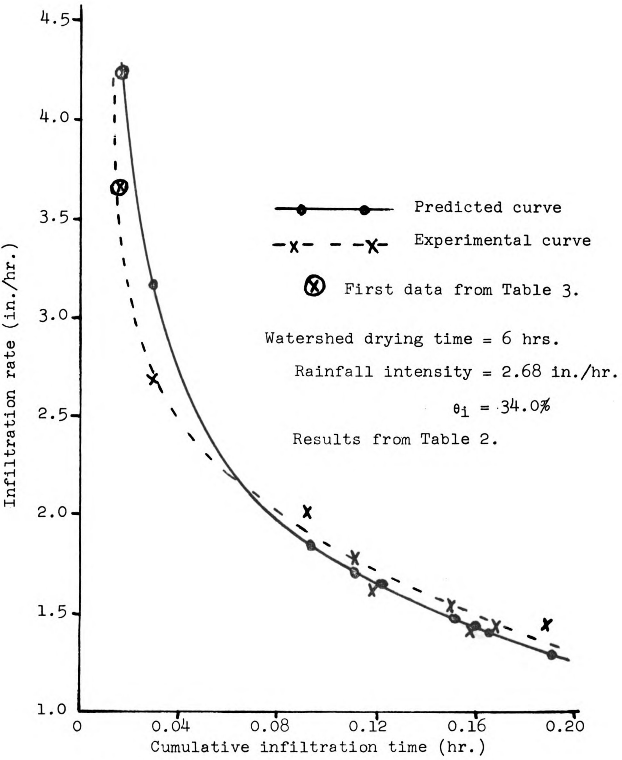

Fig. 18. Infiltration rate vs. Cumulative infiltration time.

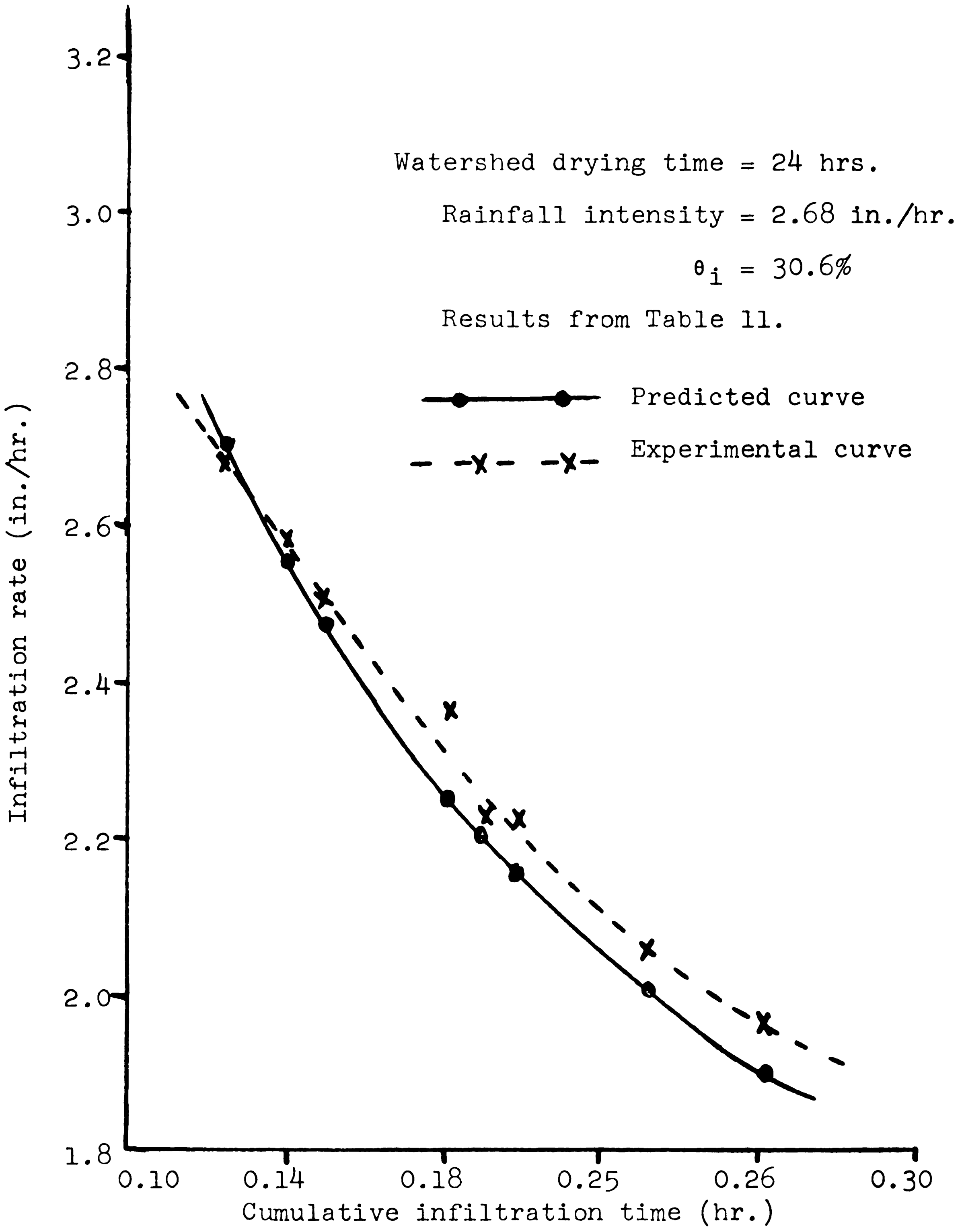

Fig. 19. Infiltration rate vs. Cumulative infiltration time.

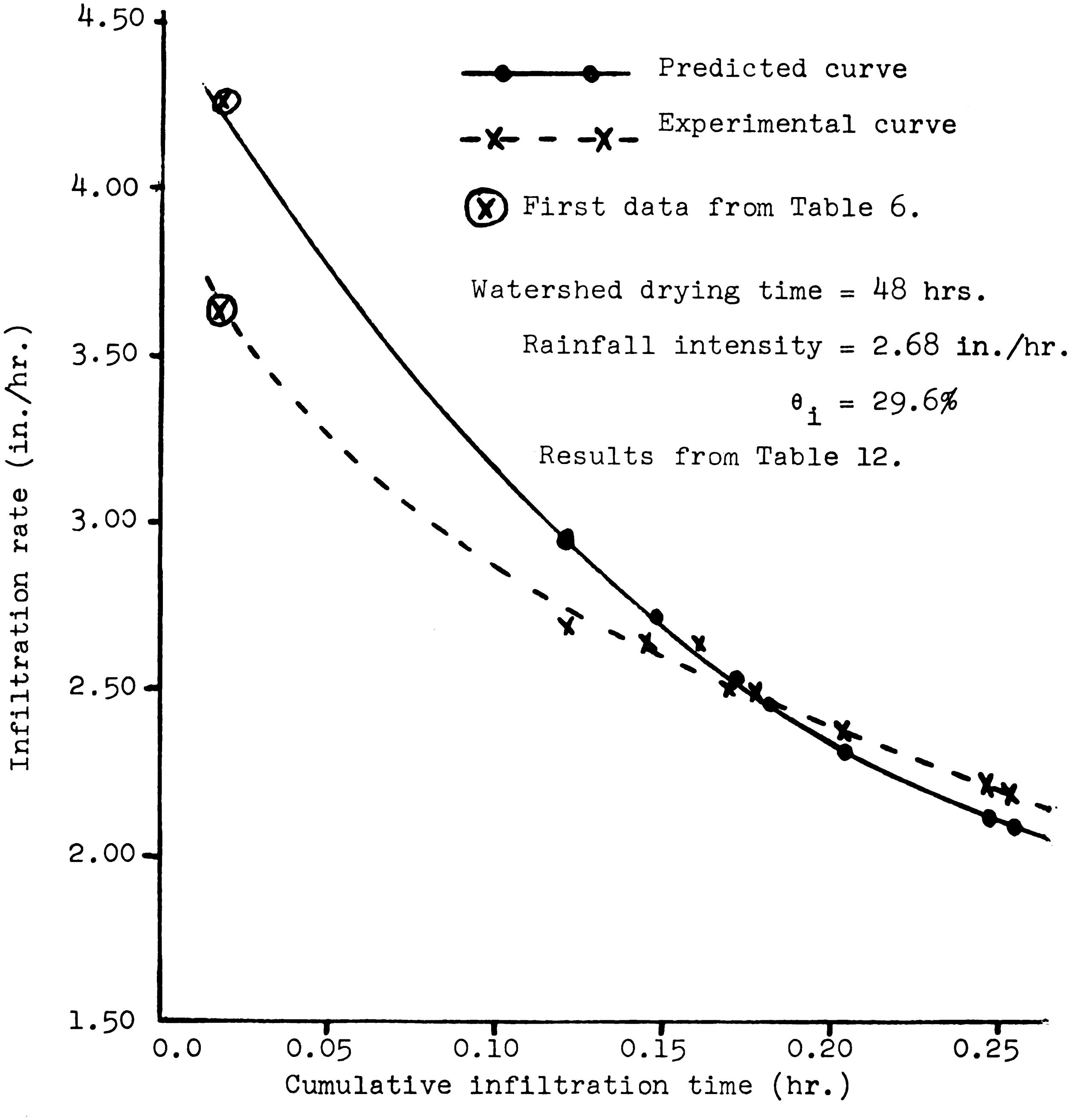

Fig. 20. Infiltration rate vs. Cumulative infiltration time.

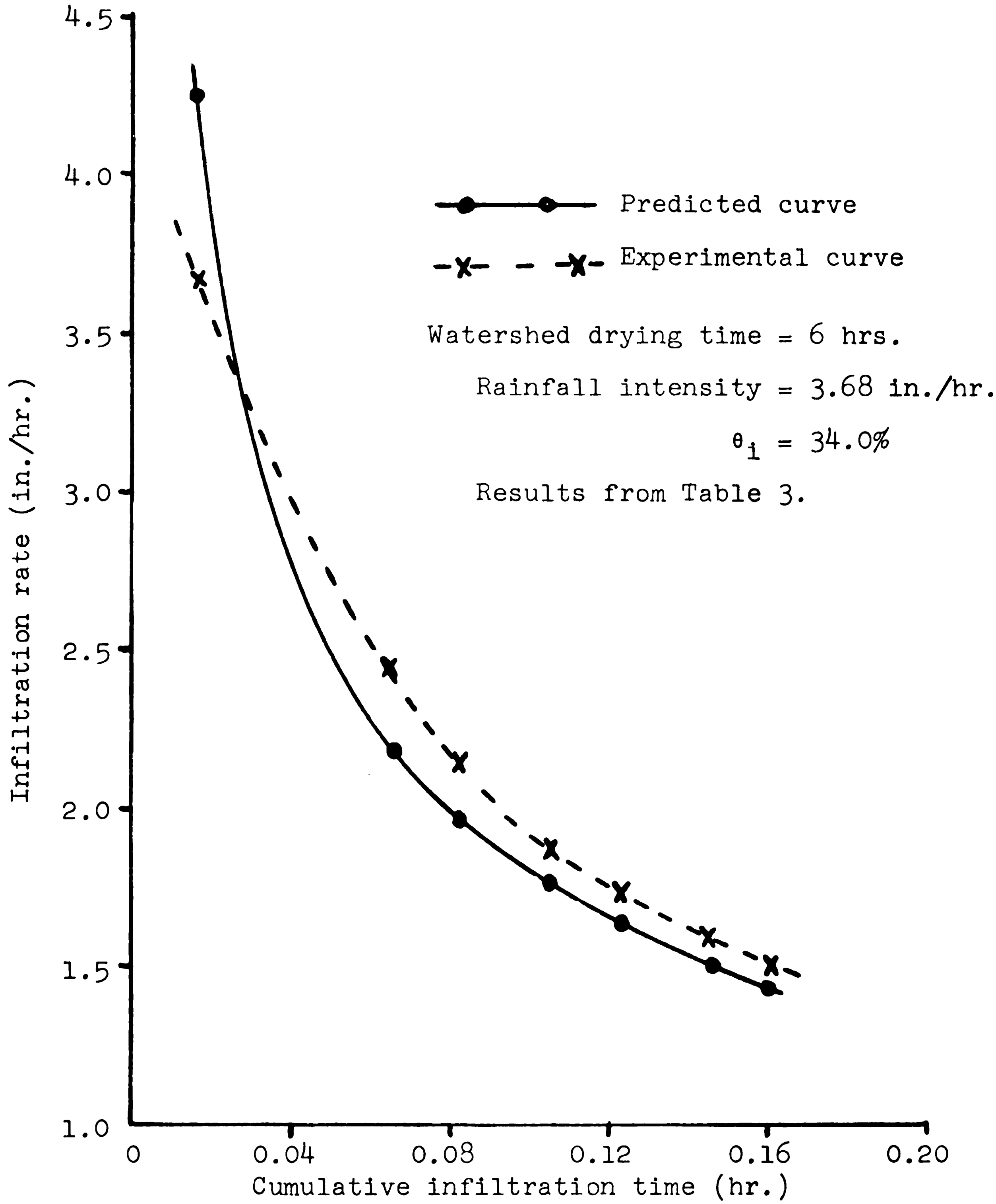

Fig. 21. Infiltration rate vs. Cumulative infiltration time.

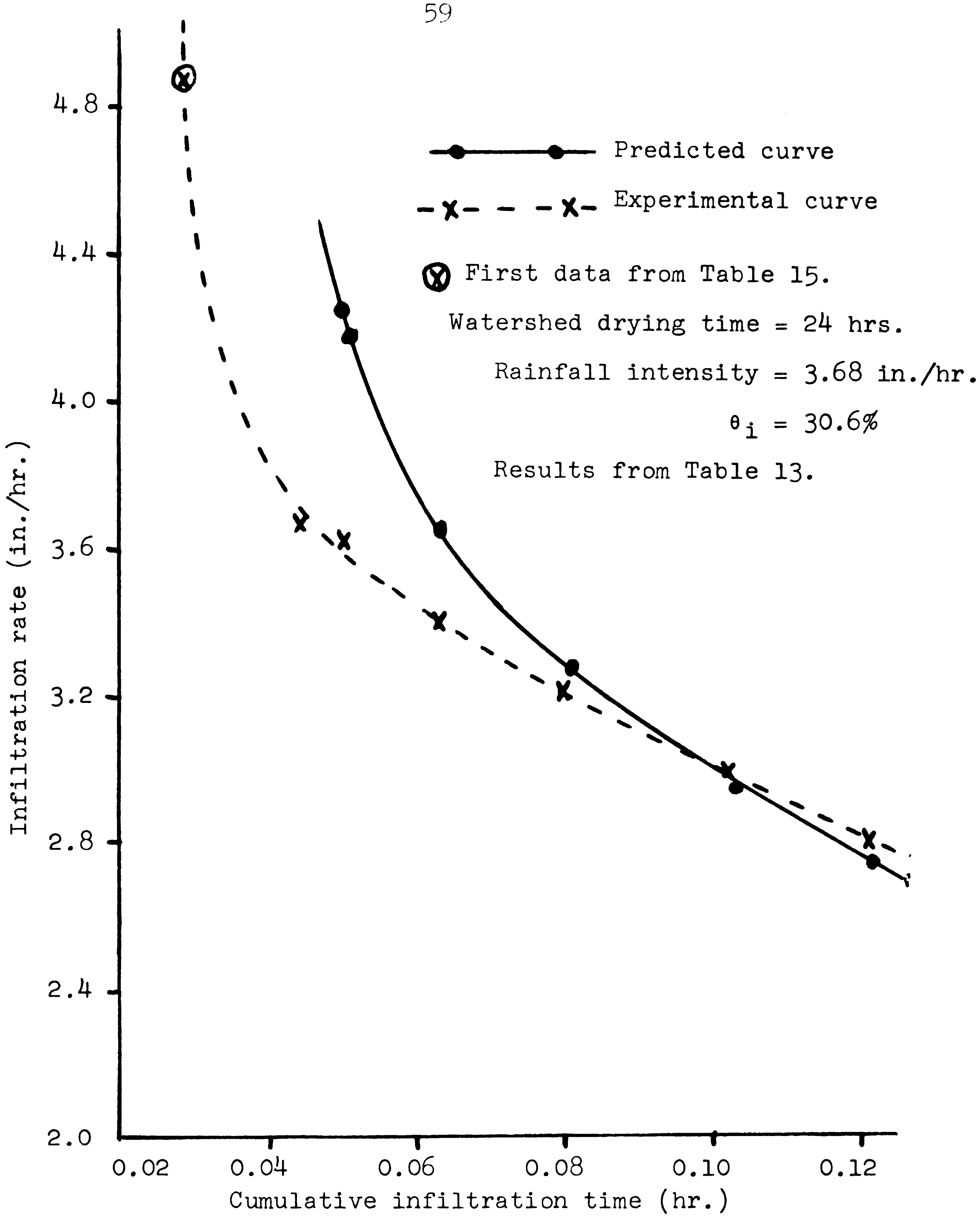

Fig. 22. Infiltration rate vs. Cumulative infiltration time.

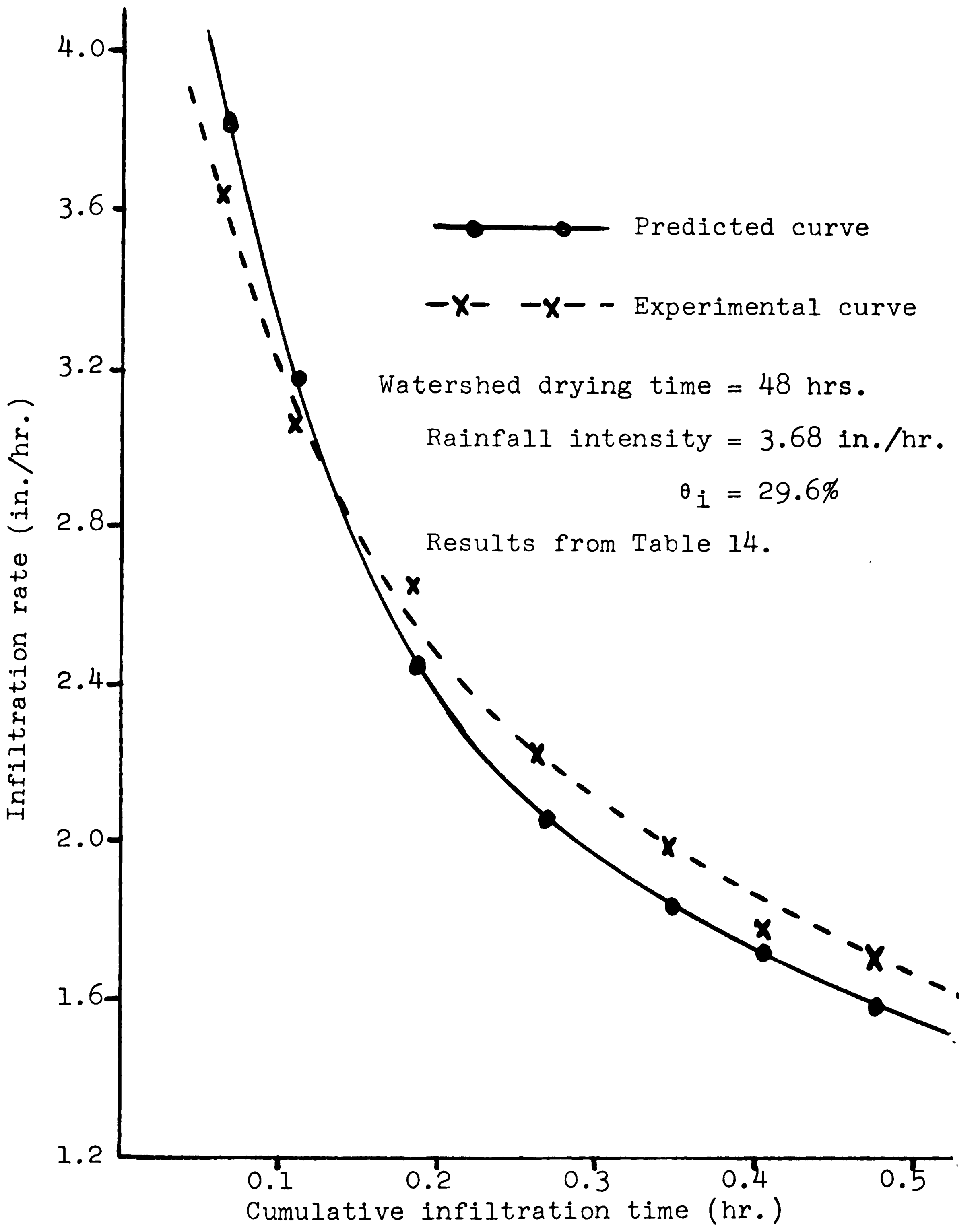

Fig. 23. Infiltration rate vs. Cumulative infiltration time.

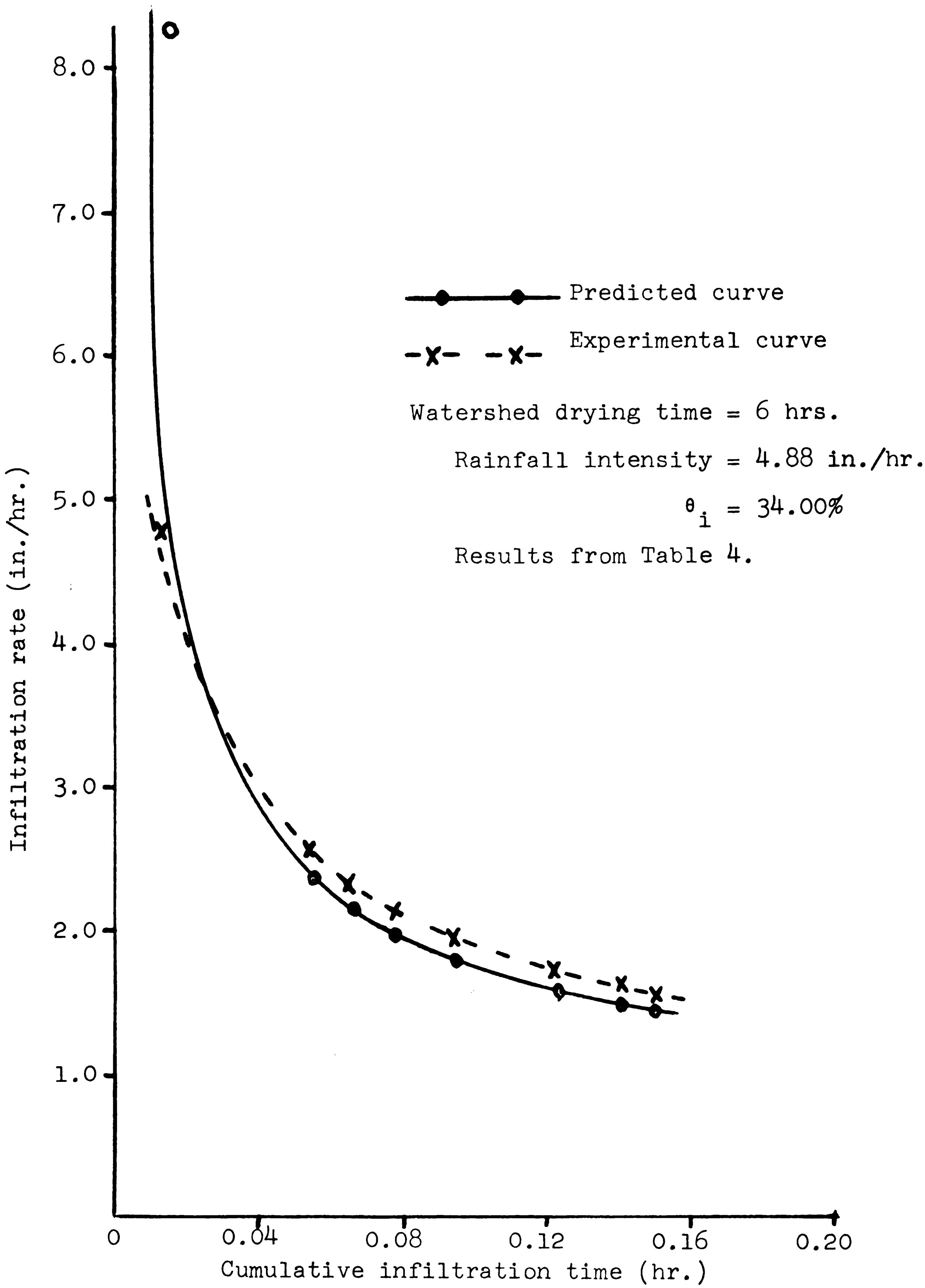

Fig. 24. Infiltration rate vs. Cumulative infiltration time.

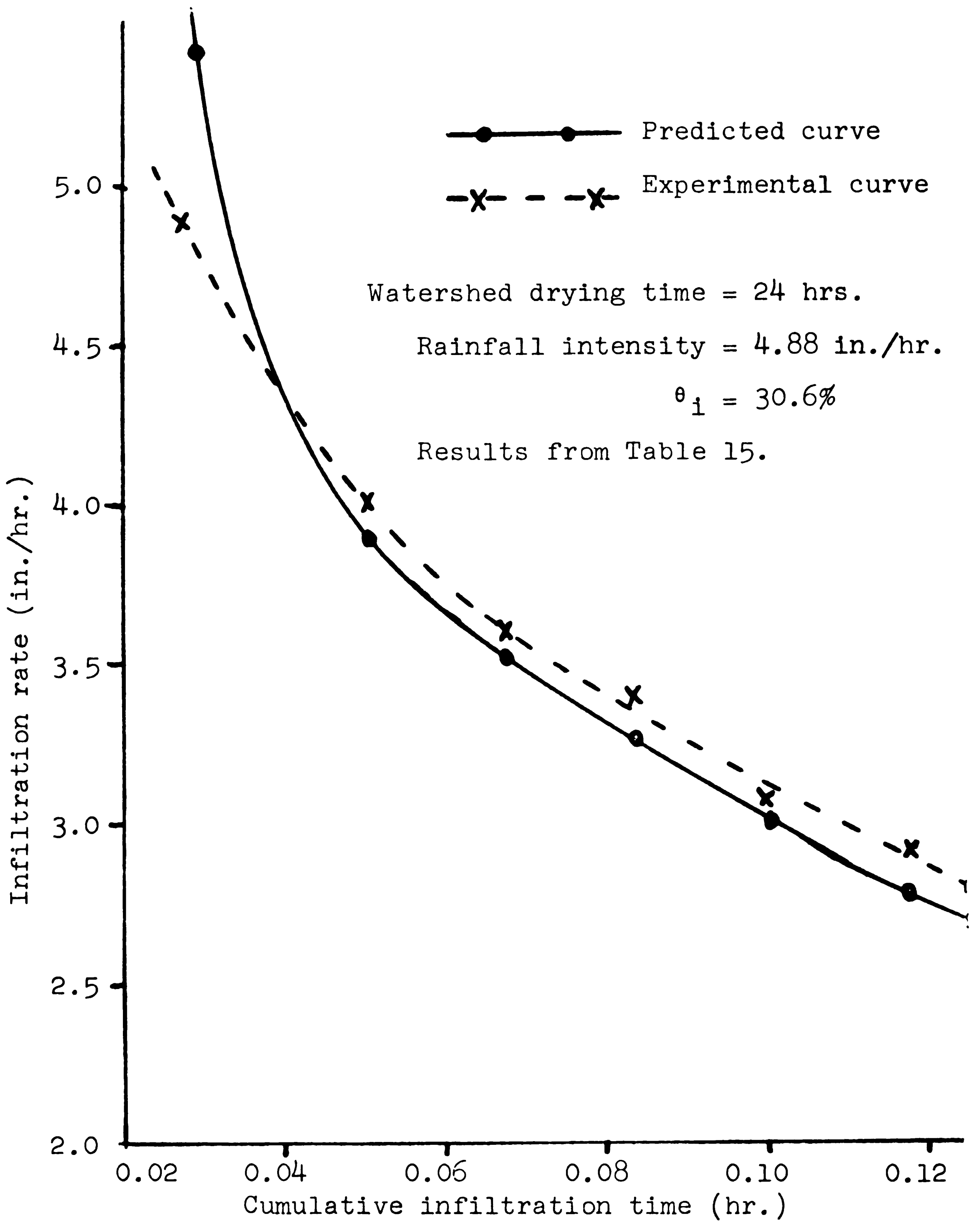

Fig. 25. Infiltration rate vs. Cumulative infiltration time.

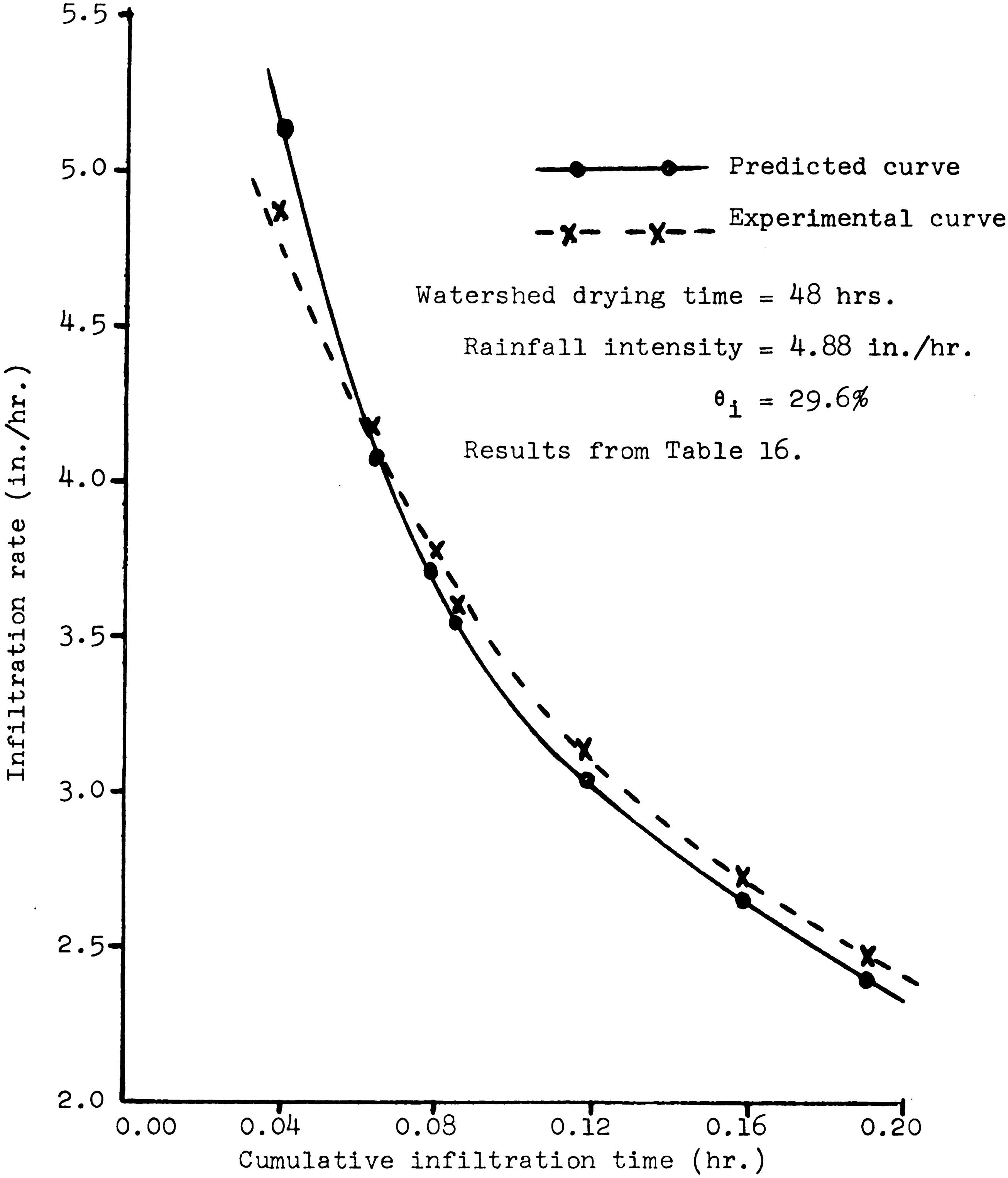

Fig. 26. Infiltration rate vs. Cumulative infiltration time.

The values for time of concentration obtained for different rainfall intensities for saturated soil are shown in Table 5. Figure 27 shows the curve of rainfall intensity against time of concentration.

Table 5. Values of rainfall intensity and time of concentration. Soil was saturated prior to rainfall.

Rainfall intensity (in./hr.)	Time of Concentration (sec.)	Time of Concentration (hr.)
5.52	80	0.022
5.28	88	0.024
4.92	100	0.028
4.57	115	0.032
4.10	132	0.037
3.68	150	0.042
3.31	162	0.045
2.68	186	0.052
1.79	230	0.064
1.26	310	0.086
1.24	350	0.097
1.18	400	0.111
1.08	480	0.133

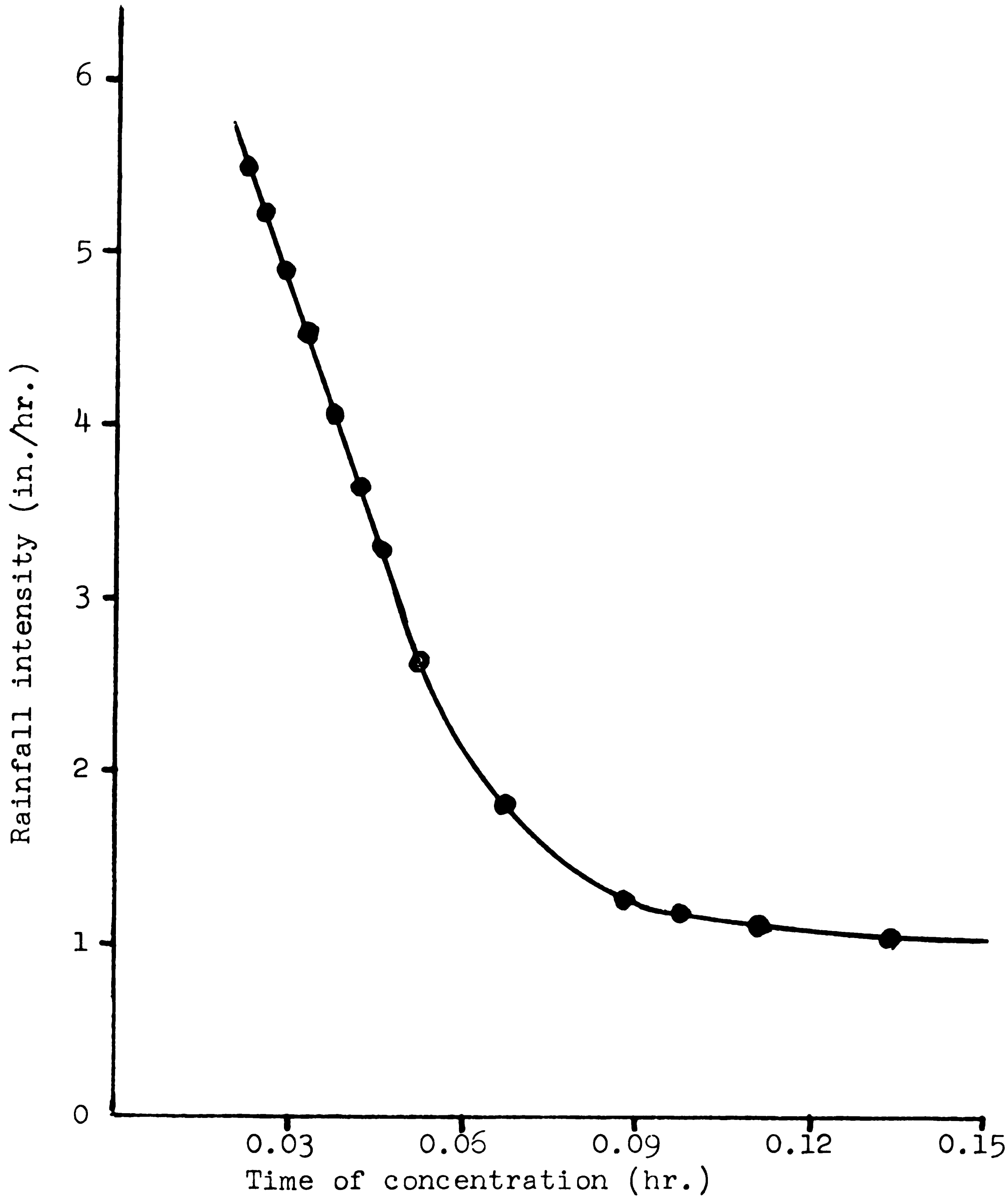

Fig. 27. Rainfall intensity vs. Time of concentration measured to the highest peak of the hydrograph.

3. Watershed soil moisture content

The watershed soil moisture content was determined using the concentric plastic pipes illustrated in Figures 1(b), 2(a) and 2(b). Figure 2(b) shows the plastic pipes in position in the soil on the watershed. The watershed soil heating periods selected for analysis were 6, 24 and 48 hours. After each heating period, the cables were unplugged and the cylinders containing the soil samples removed from the watershed and weighed prior to rainfall application. The initial weights when the cylinders were filled with oven-dried soil were known. The difference between the two weights gave the amount of moisture present in the watershed prior to rainfall application. They were expressed as percentages on volumetric basis. The results obtained are shown in Table 6.

The watershed soil moisture content was also determined after each rainfall application by weighing the cylinders thirty minutes after each rainfall application. The thirty minutes were necessary so that measurements for runoff volumes could be completed. The difference between the weights of the cylinders thirty minutes after rainfall and when filled with oven-dried soil indicated the amount of moisture present in the watershed following rainfall. They were also expressed as percentages on volumetric basis. Figure 5(b) shows the soil moisture measuring devices placed

Table 6. Watershed soil moisture content immediately before and 30 minutes following rainfall.

Watershed drying time from saturation (hr.)	Watershed soil moisture content prior to rainfall % (θ_i)	Watershed soil moisture content 30 minutes following rainfall %	Rainfall duration (min.)	Rainfall intensity (in./hr.)
0	35.70	35.70	16.00	2.68
6	34.00	36.20	16.60	2.68
12	34.00	35.20	16.00	2.68
18	33.10	34.80	15.91	2.68
24	30.60	34.60	14.25	2.68
30	31.40	33.75	16.40	2.68
36	30.80	32.80	14.00	2.68
42	30.10	31.90	17.50	2.68
48	29.60	31.30	17.50	2.68
75	25.60	30.60	18.20	3.68
120	19.08	29.70	24.3	3.68
150	15.20	29.80	28.2	3.68
200	8.60	29.50	30.00	3.68
250	2.04	29.60	36.00	3.68
265	0.00	29.7	40.20	3.68

in position in the soil in the watershed. Table 6 shows the watershed soil moisture content for two rainfall intensities following different watershed drying periods. Figure 28 shows curves of watershed soil moisture content against drying time. Figure 29 illustrates the relationship between the soil moisture content thirty minutes following rainfall and the antecedent soil moisture content prior to rainfall application. The curve was plotted using results in Table 6.

5.3. Determination of Normalized Soil Moisture Content, A and Saturated Conductivity

Ten soil core samples each 3 in. by 3 in. nominal size were prepared using the same soil as that on the watershed. The packing density was also similar to the soil on the watershed. The samples were saturated by standing in a tray of water for 48 hours, and weighed immediately to determine the saturated weights. Five of the samples were put on a pressure plate apparatus where they were subjected to suction pressures of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 atmosphere. The remaining five samples were placed on a pressure plate apparatus where they were subjected to suction pressures of 1, 2, 3, 4, 5, 6 and 7 atmospheres. The volumes of outflow from the samples were noted when equilibrium was reached for a particular pressure.

After equilibrium, each sample was weighed and put back on the pressure plate. More water was then added to the

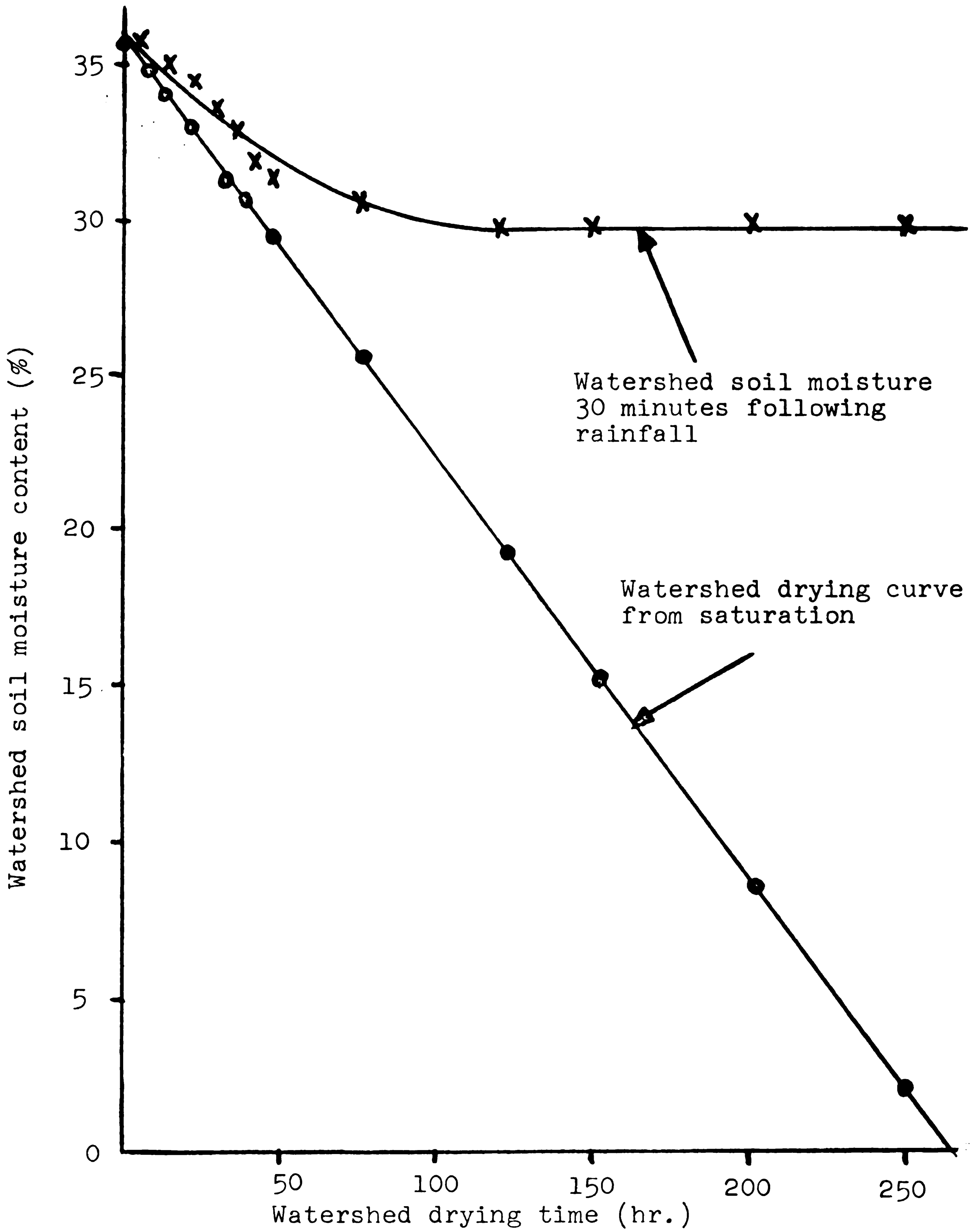

Fig. 28. Watershed soil moisture content vs. Watershed drying time.

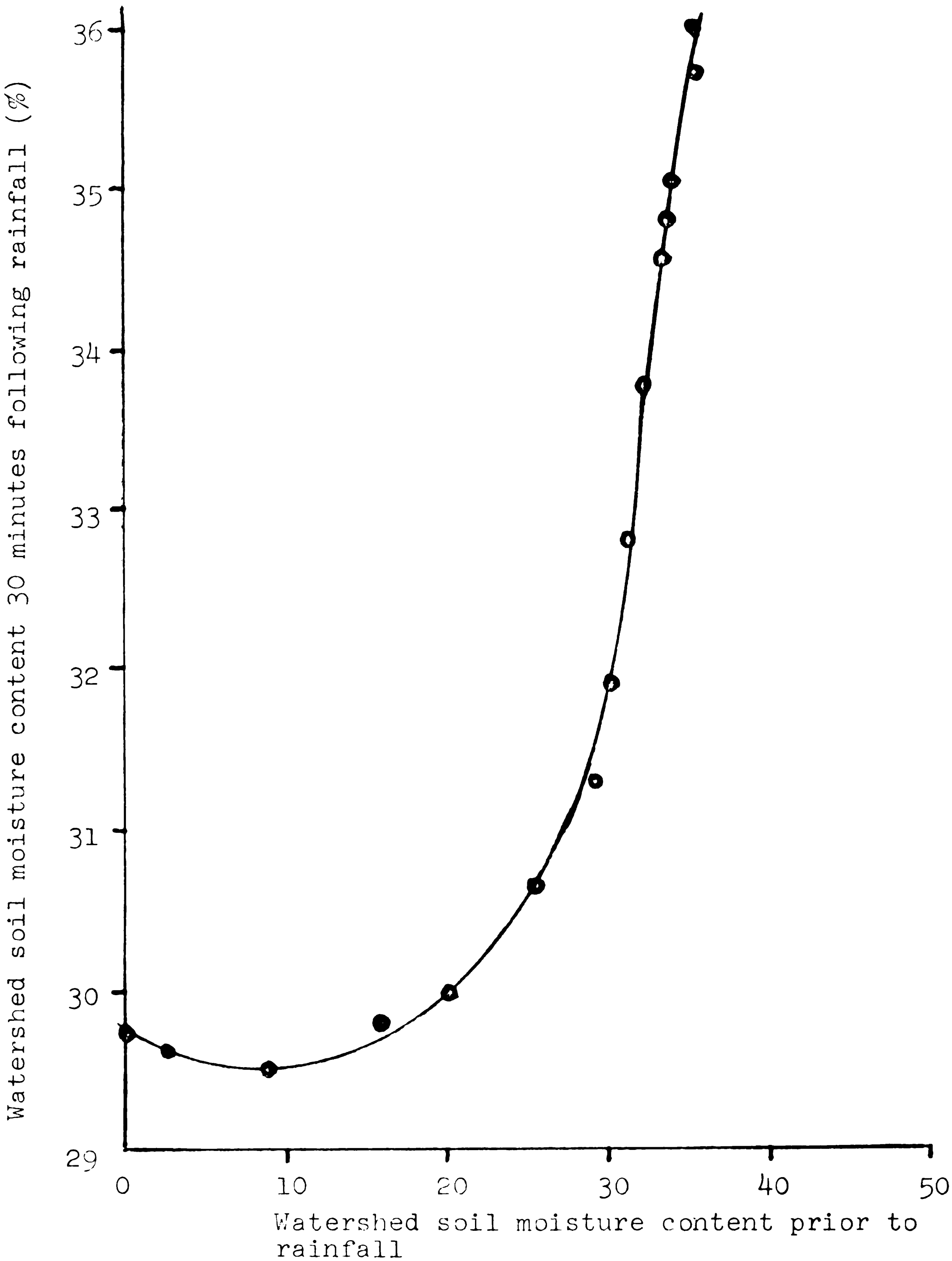

Fig. 29. Watershed soil moisture content 30 minutes following rainfall vs. Watershed soil moisture content prior to rainfall.

plates to soak the samples for thirty minutes before the next higher suction pressure was applied. The same procedure was repeated for all the pressure ranges selected for investigation. Table 7 shows the soil moisture content values for the suction pressures applied. Figure 30 illustrates the soil moisture characteristic curve obtained from this test.

The normalized soil moisture content, (S_n) was calculated by using equation (22). θ_i was taken to be equal to 13.76%. This was the equilibrium soil moisture content at seven atmospheres suction. Various trial values of A were used to calculate the values of (A-H). A log-log plot was made for S_n against (A-H). The curve with the value of A which gave the best fit with a straight line drawn at -45^o in the range $0.6 < S_n < 1.0$ was taken as the correct curve. The range $0.6 < S_n < 1.0$ represented the higher soil moisture content range. Figure 31 shows that A=15 feet corresponds to a curve which gave the best fit with a -45^o straight line in the range $0.6 < S_n < 1.0$. Table 7 shows the values of S_n and (A-H) for A=15.

The saturated soil hydraulic conductivity was determined in the laboratory by using the constant-head method. Eight soil core samples were prepared and saturated by standing in a tray of water for forty eight hours. Two hydraulic conductivity measuring apparatus were used so that two core samples could be tested simultaneously. A

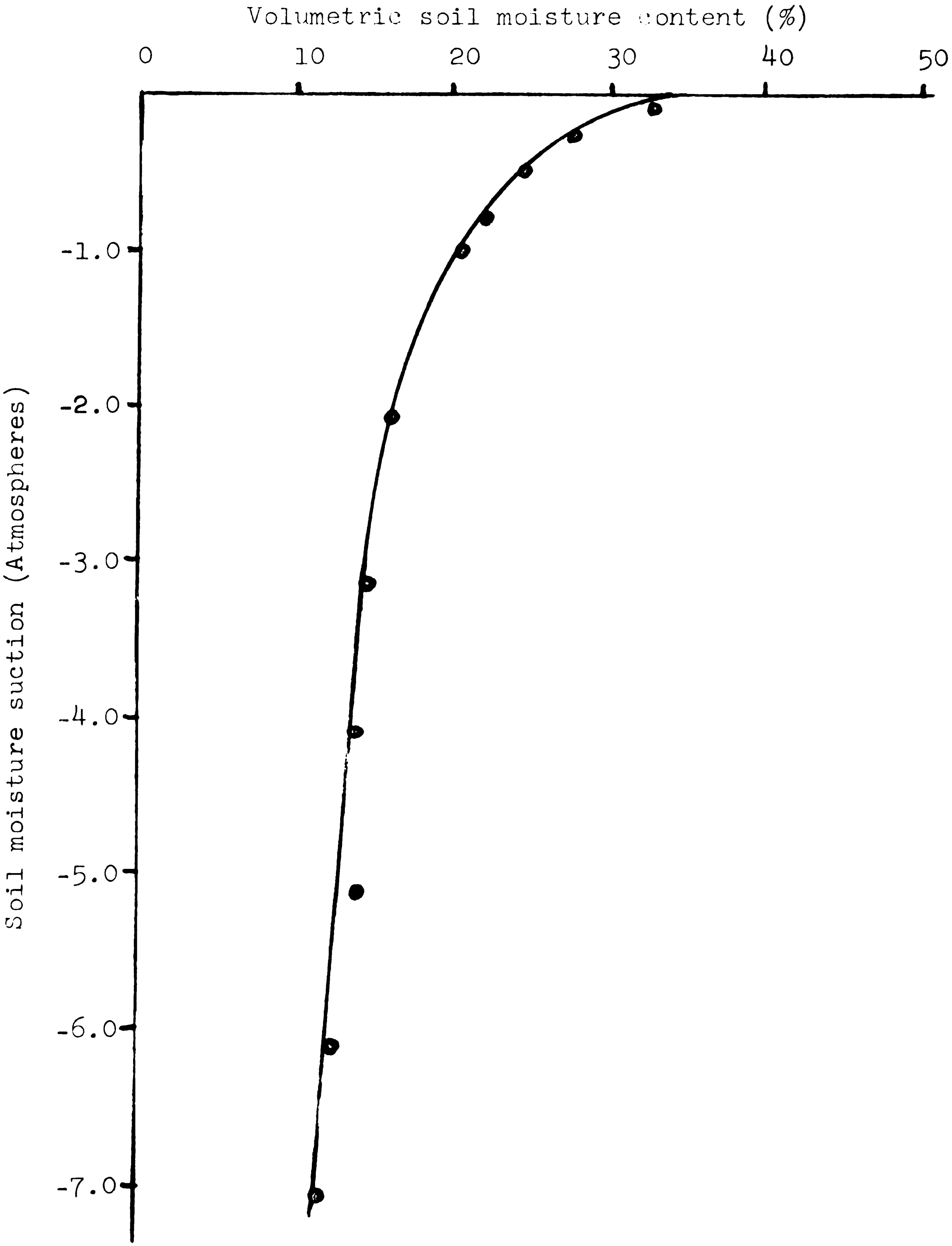

Fig. 30. Soil moisture content vs. Soil moisture suction.

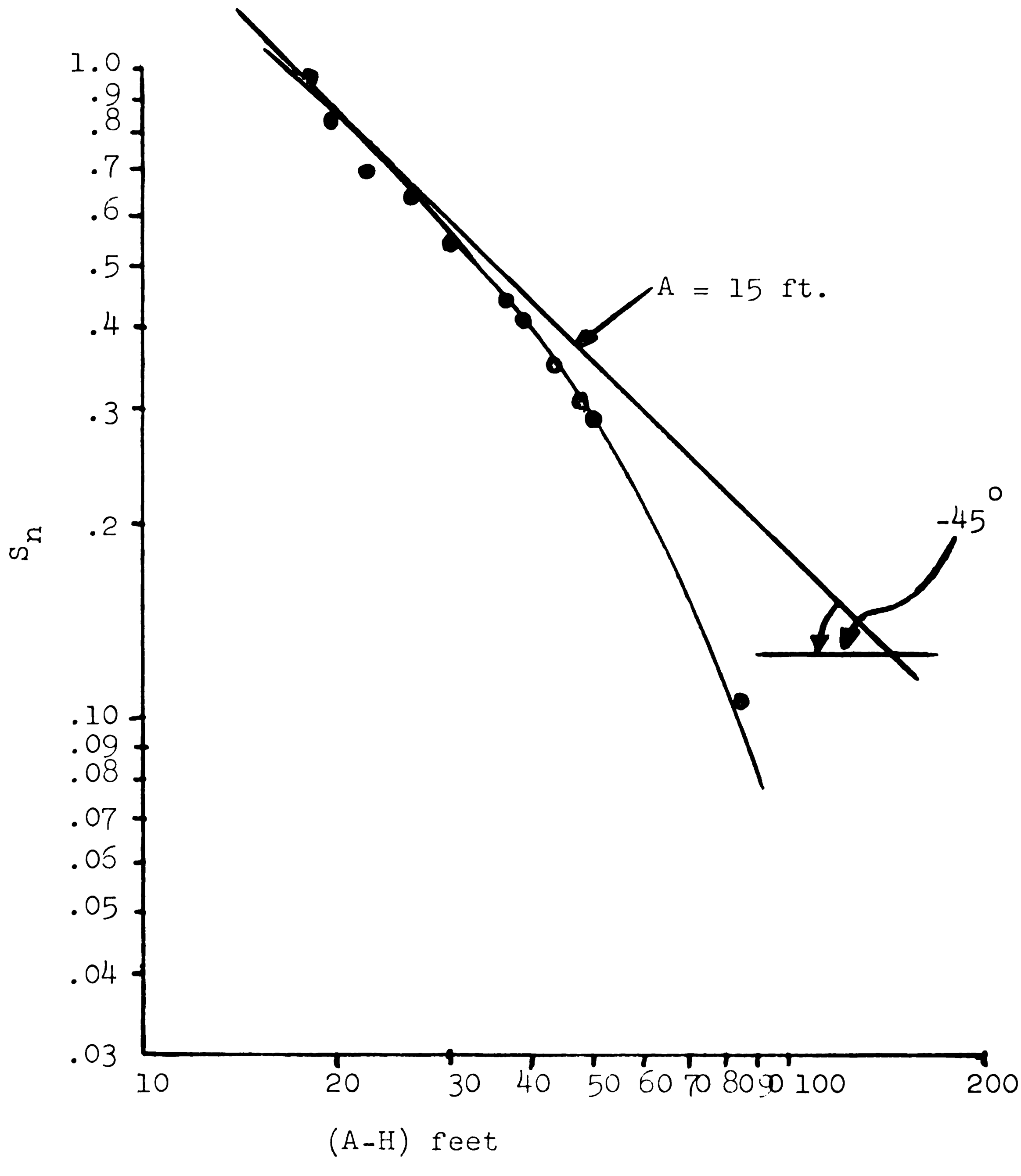

Fig. 31. S_n vs. (A-H).

Table 7. Soil water suction and normalized soil water content from soil core samples.

Soil water suction (negative) (atmospheres)	(ft.) H	A (ft.)	(A-H) (ft.)	Equilibrium soil moisture content following suction (percent)	Normalized soil moisture content (S_n)
0.0	0.0	15.0	15.0	35.70	1.00
0.1	3.4		18.4	32.26	0.85
0.2	6.8		21.8	28.08	0.70
0.3	10.2		25.2	28.06	0.65
0.4	13.6		28.6	25.44	0.54
0.5	17.0		32.0	25.02	0.51
0.6	20.4		35.4	23.75	0.45
0.7	23.8		38.8	22.00	0.42
0.8	27.2		42.2	21.70	0.36
0.9	30.6		45.6	20.60	0.31
1.0	34.0		49.0	20.40	0.30
1.5	51.0		66.0	17.48	0.17
2.0	68.0		83.0	16.17	0.11
3.0	102.0		117.0	15.90	Negligible
4.0	136.0		151.0	15.75	
5.0	170.0		185.0	15.25	
6.0	204.0		219.0	14.26	
7.0	238.0		253.0	13.76	

siphon connected to a water tap was used to maintain a constant head of water on the samples. No water was allowed to drain from the top of the samples.

Initially, for each sample, water was allowed to drain through the soil until the water level on top of the sample became stabilized. The volume of water which percolated through the sample in a known time was then measured. Tests for each sample were continued for two days. The saturated hydraulic conductivity was calculated by using the following formula:

$$k_o = \frac{q_1}{at} \quad \frac{\ell_1}{\Delta H} \tag{41}$$

where: k_o = saturated hydraulic conductivity (in./hr)

q_1 = volume of outflow from sample (in.^{3})

a = cross-sectional area of sample (in.^{2})

t = time (hr.)

ℓ_1 = length of core sample (in.)

ΔH = hydraulic head difference across sample (in.)

The values of the saturated hydraulic conductivity are shown in Table 8.

Runoff from the watershed was predicted by using equation (40) for the rainfall intensities of 2.68, 3.68 and 4.88 inches per hour. The watershed drying periods were 6, 24 and 48 hours before each of the rainfall intensities was applied. Table 9 shows the experimental and predicted runoff values for the above rainfall intensities and watershed drying periods. The experimental runoff values were obtained by planimetering the runoff hydrographs.

Table 8. Values of saturated hydraulic conductivity.

Soil core No.	k_o Values (in./hr.)	
	1st day	2nd day
461	0.387	0.361
462	0.256	0.238
463	0.406	0.375
464	0.387	0.357
465	0.382	0.366
466	0.372	0.359
467	0.373	0.359
468	0.367	0.361
Average	0.366	0.347

Overall average value of k_o = 0.356 in./hr.

Table 9. Measured and predicted values of runoff from watershed. Runoff predicted using equation (40).

$\theta_o = 35.7\%$

Rainfall intensity (in./hr.)	Watershed drying period (hr.)	t_2 (hr.)	t_3 (hr.)	Average watershed moisture content prior to rainfall % (θ_i)	Runoff Measured (in.)	Runoff Predicted (in.)
2.68	6	0.189	0.270	35.0	0.123	0.197
	24	0.261	0.368	33.4	0.065	0.042
	48	0.288	0.396	29.6	0.063	-0.332
3.68	6	0.160	0.247	35.0	0.187	0.299
	24	0.140	0.235	33.4	0.064	0.040
	48	0.595	0.734	29.6	0.420	0.575
4.88	6	0.150	0.234	35.0	0.306	0.439
	24	0.144	0.232	33.4	0.188	0.216
	48	0.194	0.265	29.6	0.106	0.048

The measured runoff values were obtained by planimetering the runoff hydrographs.

CHAPTER VI

DISCUSSION OF RESULTS

6.1. Runoff Hydrograph

Tables 2, 3 and 4 show values of the experimental runoff rates obtained from the watershed when rainfall intensities of 2.68, 3.68 and 4.88 inches per hour were applied following watershed drying periods of 6, 24 and 48 hours. Further results are contained in Tables 11 to 16 in the appendix. Figures 9 to 17 show the runoff hydrographs derived from these values. They clearly indicate that for a given rainfall intensity, higher runoff rates were obtained when the soil was initially wet than when it was dry.

This was because sustained runoff could only occur when the soil surface was saturated. Soils with higher antecedent moisture contents became saturated at the surface sooner than those with lower antecedent moisture contents. This then resulted in more rapid and hence higher watershed runoff.

Figures 9 to 17 show that runoff rates reached a momentary peak and then continued to a higher second peak. This was attributed to the following reasons.

(a) Before rainfall application, the soil capillaries were filled with air. As rain began falling, the percolating water dissolved the air from the capillaries. The first momentary runoff peak was assumed to occur when air from the larger capillaries escaped through the surface and the percolation rate through the soil reached a steady state. The second runoff peak was assumed to occur when most of the capillaries had their contained air dissolved in the percolating water. The percolation rate then reached a steady value and the soil approached saturation.

(b) A second explanation was assumed to be related to the dryness of the soil. As rain began falling, the percolating water caused suction to develop within the soil capillaries. This increased the infiltration rate and reduced the runoff rate. However, as most of the capillaries became filled with water, there was a decrease in both suction and infiltration, hence runoff increased. The first momentary runoff rate peak in the hydrograph was assumed to occur in this phase. The second runoff rate peak was thought to occur when there was no suction in the soil capillaries.

Table 9 shows the experimental and predicted runoff volumes for the rainfall intensities and watershed drying periods investigated. The experimental and predicted runoff volumes show good agreement. A small runoff was obtained from the watershed when a rainfall intensity of 2.68 inches per hour was applied after 48 hours soil drying. The predicted runoff, however, was negative, indicating that there was no runoff expected. That was because the prediction model assumed a uniform antecedent soil moisture content prior to rainfall. However, in practice, the watershed soil moisture content was probably not uniform throughout the profile after 48 hours of drying. But, as rain began falling, runoff would start as soon as the soil surface became saturated, irrespective of the soil moisture regime in the profile.

6.2. Infiltration Rate

Infiltration rates for the watershed were determined experimentally by substracting runoff rates from the corresponding rainfall intensities. They were also predicted by using Brutsaert's (1968b) infiltration equation, viz. equation (32) in this text. Tables 2, 3 and 4 show both the experimental and predicted infiltration rates for the conditions investigated. Further results are contained in Tables 11 to 16 in the appendix. Figures 18 to 26 show curves of infiltration rates versus time for both experimental and predicted values. There is good agreement between the experimental and predicted infiltration rates. This demonstrated the validity of Brutsaert's infiltration rate model.

The results also indicated definite relationship between infiltration rate and antecedent soil moisture content. Higher rates of runoff occurred when the soil was wet than when it was dry. This implied there was less infiltration for wet soils than for dry soils. This may be due to the fact that wet soils may have swollen colloids due to chemical reactions, or they may have reduced porosity due to raindrop impacts. All these tend to promote high and rapid runoff from a given precipitation.

Since runoff occurs whenever the soil surface is saturated, a wetter soil is likely to produce a more rapid runoff than a drier soil under similar conditions. Figures 18 to 26 also show that, initially, the predicted infiltration rates were higher than the experimental values. However, as rain continued to fall, the experimental infiltration rates began to exceed the predicted values, but the two sets of values remained close to each other. This was attributed to the fact that the prediction model contained parameters that implied a high initial infiltration rate that diminished to a lower constant rate with time during continued rainfall.

In practice, however, interception, surface detention and storage and evaporation all decrease surface runoff,

resulting in higher infiltration rate values. For the permeable laboratory watershed utilized in this investigation, the soil surface was stabilized with a coating of a mixture of silica sand, epoxy resin and hardener so that there was no soil puddling, compacting or clogging of the pores. This might have promoted higher infiltration rates as indicated by Figures 18 to 26.

6.3. Time of Concentration

Table 5 gives values of the time of concentration of the watershed for various rainfall intensities when the soil was saturated. Figure 27 shows the relationship between rainfall intensity and time of concentration. It appears that time of concentration for the watershed increases logarithmically with decreasing rainfall intensity. Below a rainfall intensity of about 1.0 inches per hour, time of concentration would be difficult to achieve, since all the rainfall would go into infiltration without producing any runoff.

6.4. Peak Runoff and Steady State Percolation Rates

Table 1 shows values of the peak runoff and steady state percolation rates for various rainfall intensities. Figure 7 shows graphically the linear relationship between rainfall intensity and peak runoff rate for this catchment. Figure 8 shows a parabolic relationship between rainfall intensity and steady state percolation rate. It illustrates that steady state percolation increased with increasing rainfall intensity. This was assumed to occur because higher rainfall intensities induced higher infiltration rates resulting in higher percolation rates. However, this could only occur when the soil surface was sufficiently stabilized so that soil puddling, compaction and crusting did not occur due to high rainfall impacts. These phenomenon normally reduce the infiltration rate through the soil.

Higher rainfall intensities also meant more ground surface was covered with water, and infiltration occurred over a larger area, resulting in higher percolation rates. The depth of water over a soil surface has also been known to increase the rate and amount of infiltration due to increased hydraulic head which promotes rapid entry of water into the soil.

6.5. Watershed Soil Moisture Content

Table 6 gives values of the soil moisture content corresponding to different watershed drying times immediately prior to and 30 minutes following rainfall application. The soil moisture content indicated a linear variation with watershed drying time, as shown in Figure 28. This was because the heating cables buried in the soil supplied energy at a constant rate so that the evaporation rate from the soil was also uniform. The soil on the watershed was also only 4 inches thick and homogeneous and isotropic. Heat conduction through the soil was therefore taken to be uniform.

On natural watersheds, however, soil moisture usually decreases logarithmically with time during periods of no precipitation. The rate of decrease depends on the available solar energy, amount and type of watershed vegetation, the type of soil and the general prevailing climatic conditions. A watershed drying time is also related to the antecedent soil moisture content prior to rainfall. Figure 28 illustrates relationship between soil moisture content 30 minutes following rainfall application and watershed drying time starting from saturated soil condition.

The figure shows that the moisture content of a wet soil approached the saturation value more easily than that of a dry soil, if rainfall was applied for similar length of time. As the soil dried up, it became increasingly difficult for the final soil moisture content to approach the saturation value after rainfall. The saturation moisture content could be attained if rainfall was continued for several hours. Figure 29 shows that soil moisture content following rainfall increased parabolically with increasing antecedent soil moisture content prior to rainfall.

CHAPTER VII

CONCLUSIONS

The results of this investigation yielded the following conclusions:

1. A permeable laboratory catchment can be used to study the response of a watershed with varying antecedent soil moisture contents subjected to different intensities of precipitation.
2. The experimental and predicted watershed yield showed good agreement.
3. The model can be a useful laboratory tool for teaching hydrologic concepts. It contains parameters that are physically meaningful and easily measurable. It can augment the understanding of the hydrologic response of non-linear systems in general.
4. There is a definite relationship between antecedent soil moisture content and runoff from a given precipitation rate. Higher antecedent soil moisture contents produce more rapid and larger runoff than lower ones, for a given precipitation.

5. The investigation showed the validity of Brutsaert's infiltration capacity model.
6. For this catchment, higher rainfall intensities induce higher infiltration rates, resulting in higher steady state percolation rates.
7. For this catchment, peak surface runoff is linearly proportional to rainfall intensity.
8. For this catchment, time of concentration increases logarithmically with decreasing rainfall intensity.

CHAPTER VIII

SUGGESTIONS FOR FURTHER INVESTIGATIONS

The main interest in hydrology is to predict both the amount and rate of runoff from a given precipitation. Such prediction is essential for safe design of hydraulic structures. This investigation suggested the need for additional studies in the following areas:

1. To construct permeable laboratory catchments to study the non-linear behavior of hydrologic parameters.
2. The present study was based on a homogeneous soil. Further work is needed to test the model on layered soils.
3. The concept of uniform antecedent soil moisture content prior to rainfall can be extended to layered soils by dividing soil mass into layers of uniform initial soil moisture content. Alternatively, the average antecedent soil moisture content in the soil profile may be taken.
4. A series of field tests should be conducted to test the runoff model under non-uniform rainfall intensities. The results can be compared with measured values.

5. Improvements should be made in the methods of determining parameters A and antecedent soil moisture content, θ_i.

APPENDIX

Table 10. Applied water pressure at the pressure regulator, and corresponding rainfall intensity for calibration of rainfall intensity curve.

Applied pressure at regulator (psi)	Rainfall intensity (in./hr.)
0.5	1.26
1.0	2.09
1.5	2.68
2.0	3.24
2.5	3.68
3.0	4.09
3.5	4.57
4.0	4.88
4.5	5.27
5.0	5.52

Table 11. Runoff, measured and predicted infiltration rates following 24-hour soil drying.

Rainfall intensity (in./hr.)	Runoff rate (in./hr.)	Infiltration rate (in./hr.)		Cumulative time (hr.)
		Measured	Predicted	
2.68	0.000	2.68	2.71	0.124
	0.090	2.59	2.56	0.140
Rainfall	0.170	2.51	2.48	0.149
intensity	0.230	2.45	2.42	0.157
uniform	0.270	2.41	2.36	0.165
	0.260	2.42	2.31	0.174
	0.310	2.37	2.26	0.182
	0.460	2.22	2.21	0.190
	0.470	2.21	2.16	0.199
	0.460	2.22	2.13	0.207
	0.430	2.25	2.09	0.215
	0.500	2.06	2.02	0.232
	0.590	2.09	1.98	0.240
	0.700	1.98	1.95	0.249
	0.680	2.00	1.94	0.253
	0.700	1.98	1.92	0.257
⊗	0.710	1.97	1.90	0.261
	0.644	-	-	0.271
	0.126	-	-	0.278
	0.041	-	-	0.285
	0.020	-	-	0.302
	0.015	-	-	0.318
	0.007	-	-	0.368

⊗ Denotes rainfall cutoff point

Table 12. Runoff, measured and predicted infiltration rates following 48-hour soil drying.

Rainfall intensity (in./hr.)	Runoff rate (in./hr.)	Infiltration rate (in./hr.) Measured	Infiltration rate (in./hr.) Predicted	Cumulative time (hr.)
2.68	0.000	2.68	2.98	0.121
	0.020	2.66	2.73	0.146
	0.030	2.65	2.59	0.163
Rainfall	0.130	2.55	2.53	0.171
intensity	0.190	2.49	2.46	0.179
uniform	0.260	2.42	2.40	0.188
	0.290	2.39	2.36	0.196
	0.310	2.37	2.31	0.204
	0.360	2.32	2.26	0.212
	0.370	2.31	2.23	0.221
	0.380	2.30	2.19	0.229
	0.380	2.30	2.15	0.238
	0.390	2.29	2.12	0.246
	0.470	2.21	2.09	0.254
	0.450	2.23	2.05	0.263
	0.480	2.20	2.02	0.271
	0.490	2.19	2.01	0.275
	0.480	2.20	2.00	0.279
	0.460	2.22	1.98	0.284
⊗	0.490	2.19	1.97	0.288
	0.430	-	-	0.296
	0.330	-	-	0.300
	0.091	-	-	0.304
	0.045	-	-	0.312
	0.025	-	-	0.329
	0.009	-	-	0.396

⊗ Denotes rainfall cutoff point

Table 13. Runoff, measured and predicted infiltration rates following 24-hour soil drying.

Rainfall intensity (in./hr.)	Runoff rate (in./hr.)	Infiltration rate (in./hr.)		Cumulative time (hr.)
		Measured	Predicted	
3.68	0.000	3.68	4.27	0.048
	0.040	3.64	4.19	0.050
	0.080	3.60	3.89	0.058
Rainfall	0.140	3.40	3.68	0.065
intensity	0.130	3.55	3.54	0.071
uniform	0.280	3.40	3.39	0.077
	0.630	3.25	3.30	0.082
	0.440	3.24	3.18	0.088
	0.480	3.20	3.10	0.093
	0.600	3.08	3.00	0.098
	0.910	2.97	2.93	0.104
	0.860	2.82	2.88	0.109
	0.830	2.85	2.80	0.115
	0.900	2.78	2.74	0.121
	0.900	2.71	2.67	0.127
	0.970	2.71	2.66	0.129
	1.000	2.68	2.63	0.132
	1.140	2.54	2.50	0.135
⊗	1.000	2.64	2.56	0.140
	0.940	-	-	0.147
	0.112	-	-	0.152
	0.076	-	-	0.160
	0.051	-	-	0.168
	0.028	-	-	0.185
	0.007	-	-	0.235

⊗ Denotes rainfall cutoff point

Table 14. Runoff, measured and predicted infiltration rates following 48-hour soil drying.

Rainfall intensity (in./hr.)	Runoff rate (in./hr.)	Infiltration rate (in./hr.) Measured	Infiltration rate (in./hr.) Predicted	Cumulative time (hr.)
3.68	0.000	3.68	3.84	0.065
	0.620	3.06	3.18	0.106
	0.740	2.94	3.15	0.108
Rainfall	0.860	2.82	2.91	0.128
intensity	1.080	2.60	2.70	0.145
uniform	1.070	2.61	2.64	0.156
	1.030	2.65	2.45	0.183
	1.350	2.33	2.14	0.244
	1.440	2.24	2.07	0.264
	1.610	2.07	1.90	0.316
	1.640	2.04	1.88	0.322
	1.628	2.00	1.84	0.342
	1.730	1.95	1.78	0.362
	1.770	1.81	1.74	0.381
	1.900	1.78	1.71	0.400
	1.900	1.78	1.67	0.420
	1.970	1.71	1.57	0.478
	1.940	1.74	1.49	0.535
⊗	2.380	1.50	1.42	0.595
	1.000	-	-	0.635
	0.384	-	-	0.643
	0.126	-	-	0.650
	0.063	-	-	0.667
	0.038	-	-	0.683
	0.013	-	-	0.734

⊗ Denotes rainfall cutoff point

Table 15. Runoff, measured and predicted infiltration rates following 24-hour soil drying.

Rainfall intensity (in./hr.)	Runoff rate (in./hr.)	Infiltration rate (in./hr.) Measured	Infiltration rate (in./hr.) Predicted	Cumulative time (hr.)
4.88	0.000	4.88	5.44	0.029
	0.900	3.98	3.89	0.050
	0.940	3.94	3.89	0.058
Rainfall	1.300	3.58	3.56	0.067
intensity	1.360	3.52	3.51	0.072
uniform	1.500	3.38	3.38	0.078
	1.480	3.40	3.28	0.083
	1.620	3.26	3.17	0.089
	1.740	3.14	3.08	0.095
	1.800	3.08	3.00	0.100
	2.010	2.87	2.91	0.106
	2.030	2.85	2.88	0.111
	2.040	2.84	2.78	0.117
	2.080	2.84	2.73	0.122
	2.060	2.82	2.66	0.128
	2.230	2.65	2.62	0.133
	2.260	2.62	2.56	0.139
	2.220	2.66	2.55	0.141
⊗	2.280	2.60	2.52	0.144
	1.070	-	-	0.149
	0.330	-	-	0.153
	0.150	-	-	0.157
	0.090	-	-	0.165
	0.050	-	-	0.182
	0.020	-	-	0.232

⊗ Denotes rainfall cutoff point

Table 16. Runoff, measured and predicted infiltration rates following 48-hour soil drying.

Rainfall intensity (in./hr.)	Runoff rate (in./hr.)	Infiltration rate (in./hr.) Measured	Infiltration rate (in./hr.) Predicted	Cumulative time (hr.)
4.88	0.000	4.88	5.15	0.039
	0.700	4.18	4.08	0.064
	1.130	3.75	3.74	0.077
Rainfall	1.280	3.60	3.57	0.085
intensity	1.380	3.50	3.42	0.093
uniform	1.540	3.34	3.25	0.103
	1.620	3.26	3.16	0.109
	1.740	3.14	3.05	0.118
	1.810	3.07	2.97	0.125
	1.820	2.96	2.89	0.132
	2.100	2.78	2.81	0.140
	2.100	2.78	2.73	0.148
	2.140	2.74	2.66	0.157
	2.140	2.74	2.66	0.165
	2.260	2.62	2.54	0.174
	2.310	2.57	2.48	0.182
	2.400	2.48	2.43	0.190
⊗	2.420	2.46	2.40	0.194
	0.710	-	-	0.198
	0.304	-	-	0.203
	0.127	-	-	0.207
	0.086	-	-	0.215
	0.058	-	-	0.232
	0.025	-	-	0.265

⊗ Denotes rainfall cutoff point

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