OVERLAND FLOW OVER STEEP ROUGH SURFACES

By

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PREFACE

The interest in hydraulically-based solutions to hydrologic problems has increased considerably in the past decade. Overland flow, the initial phase of the runoff process, presents a logical starting point for an analysis of the runoff process based on physical laws.

Overland flow is a very complex phenomenon and this thesis deals with only a small, albeit important, part of the subject. The purpose of the study was to investigate the momentum and continuity equations for overland flow and to test their applicability to the conditions of steep rough surfaces.

The tests reported in this thesis were conducted on a three-foot channel ninety-six feet long using three surface roughnesses. This channel was part of the facilities of the Stillwater Hydraulic Laboratory.

The author is indebted to Mr. W. O. Ree for making these facilities available and for his suggestions for the analysis of the data. The author wishes also to acknowledge Mr. F. R. Crow for his guidance in the preparation of this thesis. The suggestions of Mr. A. K. Turner of the University of Melbourne were very helpful and are gratefully acknowledged.

The assistance of many others made this thesis possible. In particular the author is indebted to Dr. J. E. Garton, Professor J. Porterfield, Mr. L. O. Roth, and Mr. Albert Mink for their valuable suggestions.

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CHAPTER I

INTRODUCTION

Statement of the Problem

When a rain of sufficient intensity and duration occurs water begins to build up on the land surface and then moves down slope toward a channel. This movement of the surface detention is called overland flow. It has a very important influence on the overall surface runoff process.

In the past decade the interest in overland flow has considerably increased. One reason for this interest is the desire of hydrologists to have available a method for predicting runoff based on the established laws of hydraulics. At present runoff predictions are made by relying on empirical relations. These relations differ for each watershed depending upon the influence of the pertinent variables. If instead, the relation between the variables could be established from known physical laws, predictions of surface runoff and other desired quantities could be made for any watershed.

Erosion is a second phenomenon influenced considerably by overland flow. A reliable hydraulic description of the water surface profile would be of aid in studies of the erosion process. Likewise drainage and irrigation problems are influenced by most of the same variables which influence overland flow.

The study of overland flow is complicated by its hydraulically bizarre characteristics. It is unsteady and spatially varied since it is supplied by rain and depleted by infiltration, neither of which is necessarily constant with respect to time or location. The depths may be subcritical or supercritical or may change from one to the other. Flow may be laminar or turbulent or a mixture of the two. Under certain conditions, not yet well defined, the flow may become unstable giving rise to the formation of roll-waves. The action of the raindrop impact on the sheet of water further complicates the overland flow problem.

This variety of possibilities suggests that overland flow may best be studied in a laboratory where the conditions may be reasonably well controlled. It further made certain assumptions necessary in the theoretical analysis as are noted in the following chapter.

Pertinent Quantities

The quantities pertinent to overland flow may be grouped generally into three categories: surface characteristics, fluid properties, and rain characteristics. Under natural conditions these variables cover a great range, and their importance depends on the particular circumstances. In the tests reported in this thesis the variables were controlled at values which are shown in Table I. A listing of the pertinent variables is made below and their importance to this study is briefly noted.

Surface Characteristics

1. Roughness
2. Slope
3. Length of flow
4. Infiltration capacity

Surface roughness and slope were of salient importance in these tests. The interaction between gravity accelerating the flow and bed drag retarding the flow were thought to be determining factors. Length of flow and infiltration were invarient in the tests.

Fluid Properties

1. Viscosity
2. Density
3. Surface tension

The fluid density and viscosity are related to the action of gravity and drag and were therefore of great importance in these tests. The importance of surface tension depends upon the depth of flow. Where the flow is shallow it contributes to the surface drag.

Rain Characteristics

1. Intensity
2. Drop size and velocity

Rain intensity is important since it is the source of supply. The effect of the drop size and velocity is to initiate or intensify turbulent flow, and its magnitude is indicated by the kinetic energy of the spray.

TABLE I

VALUES FOR THE PERTINENT VARIABLES IN THE EXPERIMENTS

Surface Characteristics		
Slope	5%	
Infiltration	0	
Roughness (Ave. gravel dia)		
Surface I	0.109 in.	
Surface II	0.160 in.	
Surface III	0.219 in.	
Fluid Properties		
Properties for pure water		
Rain Characteristics	Nozzle 1	Nozzle 2
Intensity	5.9 iph	7.7 iph
Mean drop size	0.5 mm	0.8 mm
Vel. of mean drop	18.1 fps	19.0 fps

Objectives

Three objectives were set for this thesis. These were:

1. To derive an expression from basic hydraulic laws describing the surface profile for overland flow over steep rough surfaces.

2. To obtain experimental evidence with which to test the derived expression.

3. To compare the theoretically predicted results to those observed and thereby determine its suitability for the conditions of the tests.

CHAPTER II

REVIEW OF LITERATURE

The literature relevant to the study of overland flow is concerned with four topics in general. These topics are: side channel spillway and gutter flow analyses, studies of shallow uniform flows, studies of rain characteristics and simulation, and of course overland flow studies.

The Overland Flow Formula

Flow in a side channel spillway and overland flow are similar in one respect; both are spatially varied. Thus the formulas which describe these flows are somewhat similar in that they are both based on the concept of conservation of linear momentum.

Hinds (1926) was apparently the first to develop an expression for spatially varied flow in a side channel spillway using the conservation of mementum concept. In this analysis the effect of the impact of the entering water and the effect of friction were neglected. The depth profile in the spillway could be predicted by Hinds' formula if a control section could be located from which to start the calculations. His work was verified by experiments.

Favre (1933) used the concept of conservation of momentum in his analysis of flow in a side channel spillway. Terms were included to account for the effect of the lateral inflow and for friction. Favre's equation, like Hinds', required a stepwise solution starting from a position of known depth. His work also was experimentally verified.

Beij (1934) analyzed flow in a roof gutter using the conservation of momentum concept. He assumed that the inflow was normal to the direction of flow and thus contributed no momentum. Experiments were run to verify his analysis.

Horton (1938) derived a formula for overland flow from the assumption that flow rate is proportional to some power of the depth. He assumed further that the flow was 75% turbulent thus setting 2 as the exponent of depth. This relation in conjunction with the storage equation allowed a direct solution for runoff rate in terms of rain intensity, time, and a constant. The constant depended in part upon the surface roughness which Horton accounted for by the Manning coefficient.

Camp (1940) derived an expression for flow in a spillway which was similar to Hinds' equation except for the inclusion of a term to account for friction. Camp developed a graphical solution for his expression and tested the solution by experiments.

Keulegan (1944) appears to be the first to have used the concept of conservation of momentum to analyze overland flow. This analysis accounted for variation in depth with respect to time and for a possible initial inflow. Terms were included for the effect of friction and the momentum of the entering flow. Keulegan compared the terms indicative of momentum and friction losses and thereby arrived at a criterion for neglecting the momentum term.

Li (1955) derived an equation for spatially varied flow in dimensionless terms. His analysis, also based on the conservation of momentum, assumed that the channel friction was balanced by the momentum component of the entering flow. Thus no term was included in the equation to account for either of these effects. A graphical method of solution was given for certain cases of channel slope and cross-section.

Appleby (1956) derived an equation for runoff due to rain from the hydrologic storage equation. He modified this equation, however, by including a term for lateral inflow in addition to the inflow and outflow at a section. The result is an equation similar to the heat flow equation. A heat conduction analog was, therefore, proposed and developed.

Chow (1959) used the conservation of momentum concept to derive an expression for spatially varied flow. A term accounting for friction was included but the momentum of the entering flow was neglected.

Liggett (1959) analyzed the 'upstream' problem of calculation of streamflow in hydrology. His model was a long channel with continuous lateral inflow but no initial inflow. Liggett's equation accounted for temporal changes as well as spatial changes and was based on the concept of momentum conservation. The mathematical method of characteristics was used in the solution. A semi-graphical method for computation of surface profiles was proposed.

Chen (1962) analyzed overland flow by the concept of conservation of momentum. His solution incorporated temporal and spatial variations. Chen accounted for the influence of the rain drops impinging on the water surface as two separate effects. The first effect was caused by the normal velocity component of the rain drops. This component created a pressure distributed uniformly over the water surface. The second effect of the rain drops was caused by the velocity component parallel to the direction of flow. Chen's solution by numerical methods was made practical by the use of a digital computer.

Critical Reynold's Number

The flow rates prevalent in overland flow are such that either laminar or turbulent flow may exist. The parameter indicative of the conditions necessary for a change from one state to the other is usually the Reynold's number. The range of values for this parameter in open channels has not been well established. Values for the critical Reynold's number have been reported, however, for various conditions.

Jefferies (1925) found laminar flow to persist below a value of N_R equal to 310. He uses the bulk Reynolds number as his criterion. This is given by:

$$N_R = q/\nu$$

where N_R is the bulk Reynolds number

q is the flow rate per unit width

ν is the kinematic viscosity

Jefferies measured the velocity of flow by observations of ink drop movements in a wooden flume 20 feet long and 4 inches wide. He compared these observed velocities to velocities predicted for laminar flow. These comparisons were used to determine the point of transition to turbulent flow. Jefferies cited critical values 300 to 330 determined by Hopf (1910) from similar tests.

Horton et al (1934) found that the critical bulk Reynolds number ranged from 548 to 773. A smooth wooden flume 4 feet long and 5.6 inches wide was used for the tests. Velocities were measured and compared to velocities predicted for laminar flow and for turbulent flow by the Manning formula using an n of 0.009. In this study the adequacy of the Reynolds number as a criterion for laminar flow in a rough open channel was questioned. Another criterion for the critical flow state was developed by reasoning that there was some critical velocity below which the energy of the flow would be insufficient to maintain a state of turbulence. Setting equal, therefore, the formulas for the velocity of a laminar flow and a turbulent flow Horton found:

$$7.214\ (n/\nu)y^{1.33}(So)^{0.5} = 1$$

where n is the Manning coefficient

ν is kinematic viscosity

y is depth

So is the channel slope

According to this criterion flow could not be turbulent if the left side of the equation were less than unity. A tacit assumption in this analysis is that the state of flow changes instantaneously.

Straub (1939) found the critical Reynold number to be 640. His tests were made using two fluids in an aluminum channel 15 feet long and 3 inches wide. Straub noted the dependence of the Chezy and Manning coefficients on the value of Reynolds number.

Owen (1954) found a value of 1000 for the critical Reynolds number. A rectangular polished brass channel 20 feet long and 1.5 feet wide was used for the tests. In a discussion of Owen's paper Iwagaki (1954) cited tests in which similar critical value limits of 500 to 1250 had been determined.

Woo and Brater (1961) found that flow ceased to be laminar at Reynolds numbers from 400 to 900. A wooden flume 29 feet 7 inches long and 6.25 inches wide was used for the tests. Two surface conditions were tested. The first was made of masonite board with the rough side up. Sand grains averaging one millimeter in diameter were glued to the masonite board for the second surface.

Woo and Brater in their discussion noted that the Darcy-Weisbach expression for friction had been verified for laminar flow in smooth channels. This relation is:

$$f = C/N_R$$

where f is the Darcy-Weisbach friction factor for open channels

C is a constant. (for smooth channels C = 6 theoretically.)

N_R is the Reynolds number

For rough surfaces Woo and Brater's tests indicated a deviation from the theoretical value of the constant. They found C to be 7.7 for the masonite surface. The sand surface showed C to vary with slope. At a five per cent slope as used in this thesis, C was about 25.

Rain Characteristics and Simulation

The properties of rain which are most important to the study of overland flow are intensity, drop size, and drop velocities. Quantitative determination of these properties has been the objective of several investigators. Likewise numerous rain simulators have been proposed, each one having advantages and shortcomings. The type-F nozzle was used frequently in early tests. This and other rain simulators are well described and discussed by Meyer (1958).

Laws (1941) measured the velocities of rain drops and water drops. He found that the drops reach a terminal velocity which is related to the distance of fall. Laws also showed photographically that the shape of the larger drops is distorted thus affecting their velocities.

Laws and Parsons (1943) found a relation between rain intensity and the mean drop size:

$$D_{50} = 2.31\ I^{0.182}$$

where I is rain intensity in inches per hour

D_{50} is the median droplet diameter in millimeters

Meyer (1958) reviewed much of the literature related to rain characteristics and simulation and listed a very helpful bibliography. He developed a rain simulator which consisted of intermittently operated nozzles which could be oscillated to affect a uniform areal distribution.

Wishmeier and Smith (1958) analyzed the data of previous investigators and developed an equation for rainfall energy as a function of intensity. A simple procedure for computing the kinetic energy of a rainstorm was also given.

Turner (1963) tested a variety of nozzles on the basis of uniformity of runoff. He selected two nozzles which gave acceptable results and had very different drop size distributions. The drop velocities were determined photographically and related to size. From these relations Turner found the kinetic energies of the two nozzles to be 69.8 and 71.7 foot tons/sec/acre inch. These values compare favorably to the value of 86.1 foot tons/sec/acre inch given by Weishmeier and Smith.

These two nozzles selected by Turner's tests were used in the rain simulator for the tests reported in this thesis. They are referred to as nozzles 1 and 2 respectively. Figure (9) shows the size distributions of the spray drops compared to natural rain and figure (10) shows the runoff patterns of the two nozzles.

Overland Flow Tests

Horton's analysis (1938) provided a base for much of the interest in a rational analysis of the overland flow phenomenon. The experiments made in the decade following Horton's analysis generally determined constants for his equation. Among the investigators who gave values for these constants were Ree (1939), Beutner et al (1940), Horner and Jens

(1942), and Izzard (1943). Analysis by the conservation of momentum concept provides a base for most of the more recent tests. As noted before, this approach to overland flow appears to have been first proposed by Keulegan (1944).

Izzard (1944) ran tests on a channel 6 feet wide with various lengths up to 72 feet. The type-F nozzle was used to simulate rain over both smooth and turfed surfaces. Average surface detention was compared to the detention predicted by the steady state solution of Keulegan's equation. The results showed good correlation.

Izzard noted a rapid increase in runoff rate at the cessation of the simulated rain. He reasoned from this that the impinging drops acted as a roughness imposed on the water surface, retarding the flow.

In a further analysis of this data, Izzard (1946) found that the rising hydrographs of overland flow could be represented by a single dimensionless hydrograph. A nomograph was proposed for determination of overland flow parameters and an example solution was given.

Parsons (1949) concluded from his experiments that the depth of overland flow could be expressed as the product of a constant and the depth for a corresponding laminar flow. The constant depended upon the surface characteristics.

A tilting flume 2 feet wide and 8 feet long was used for Parsons' tests. Rain was simulated by the type-F nozzle over two mortar surfaces. The first surface was trowled smooth and the second was pitted by water drops. Several vegetative surfaces were tested as well, and the constants for his expression were tabulated for the various conditions.

Woo (1956) made a theoretical and experimental analysis of overland flow. His analysis by the concept of conservation of momentum utilizes the Darcy-Weisbach friction factor for open channels to account for friction. In Woo's expression the friction factor was modified to account for the effect of the rain drop impact. By rearranging his equation Woo solved for the modified friction factor using short stretches of his experimental profiles. He found no consistent relation between the Reynolds number and the modified friction factor. Woo noted, however, that for rough surfaces and steep slopes with high rain intensity the relation seemed to follow a straight line.

Woo verified his theoretical analysis by conducting tests on a tilting flume 29 feet 7 inches long and 6.25 inches wide. Rain was simulated by water drops from a cheese-cloth mattress suspended 6.5 feet above the channel. Short strips of yarn were tied beneath the cheese cloth to guide the drops and provide a uniform distribution.

Yu and McKnown (1963) analyzed data collected by the Los Angeles District of the Corps of Engineers. These tests were conducted on three concrete channels 500 feet long and 3 feet wide with rain simulated at various intensities. Yu and McKnown proposed a simplified version of Keulegan's equation which was obtained by dropping all terms except those expressing the effects of gravity and friction. They reasoned that the dropped terms were negligible, for the conditions under which the data was obtained, when compared to the two terms retained.

The rapid increase in runoff rate at the cessation of rain which had been reported by Izzard was also noted by Yu and McKnown. They reasoned however that the rain drop impact caused the flow to become turbulent whereas it would normally be laminar. Therefore, at the cessation of the rain laminar flow would be re-established with a consequent increase in flow rate.

Depth and outflow hydrographs which were predicted by Yu and McKnown's simplified formula showed good correlation with the experimental results.

The simplified formula proposed in this thesis is the steady state solution given by Yu and McKnown. The tests reported in this thesis, however, were made under conditions which were somewhat different from those of previous investigations.

CHAPTER III

THEORETICAL ANALYSIS

Assumptions

The general overland flow problem under natural conditions is extremely complex. This complexity has led past investigators to certain assumptions which make a theoretical analysis tenable. The analysis presented here is also for a simpler version of the general problem. The necessary assumptions are listed below:

1. The channel is infinitely wide so that the flow is unidirectional and the depth closely approximates the hydraulic radius.
2. The rain is uniform and of constant intensity.
3. The surface is impervious and has a uniform slope.
4. Bottom drag can be expressed by the Darcy-Weisbach resistance coefficient factor for a corresponding uniform flow.
5. Sufficient time has elapsed for equilibrium conditions to be established.

The General Formula

The surface profile of overland flow is shown in Figure (1). According to the Eulerian method of analysis the flow through a small segment of the profile is investigated. Figure (2) shows such a segment with the forces acting on the two end sections. At equilibrium the

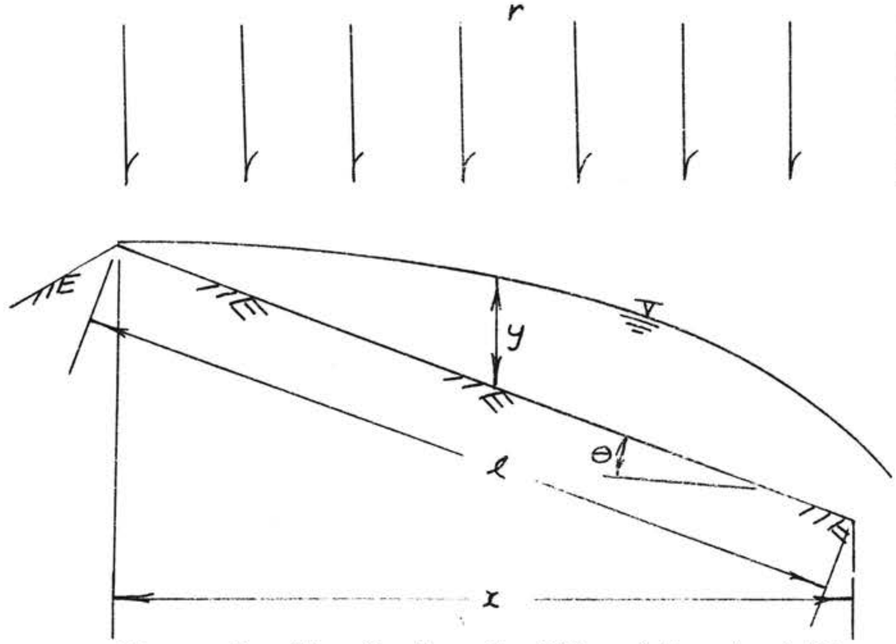

Figure 1. The Surface Profile of Overland Flow

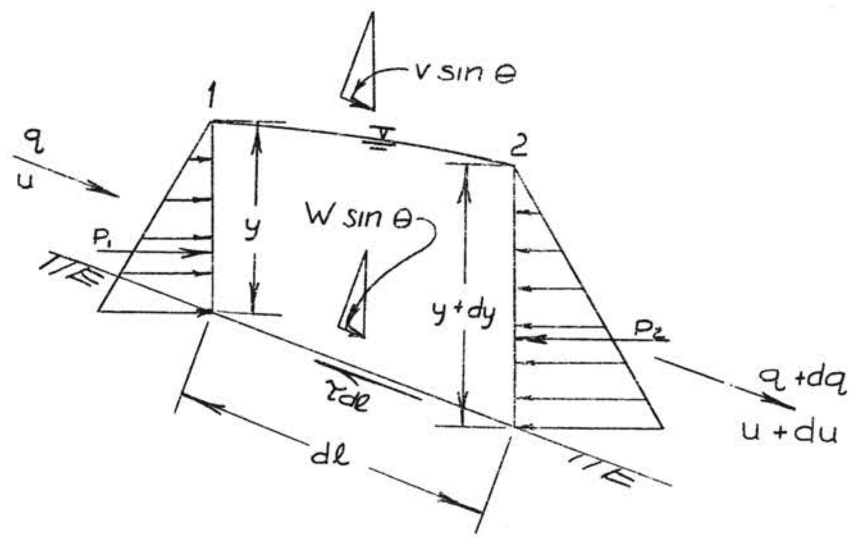

Figure 2. An Incremental Segment of the Overland Flow Profile

summation of these forces in the direction of flow must equal the change in momentum flux within the segment per unit time.

The definitions for symbols used in the derivation are listed in Appendix A.

The momentum flux entering at section 1 is,

$$M_1 = \rho qu$$

And at section 2 the momentum flux leaving is,

$$M_2 = \rho (q+dq)\ (u+du)$$

The component of velocity of the rain drops in the flow direction contributes a momentum flux to the flow,

$$M_r = \rho rv \sin \theta \, d\ell$$

Taking the downslope direction as positive, the change in momentum flux is,

$$M_2 - M_1 - M_r = \rho (q+dq)\ (u+du) - \rho qu - \rho rv \sin \theta \, d\ell$$

Simplifying and ignoring differentials of second order,

$$dM = \rho (udq + qdu) - \rho rv \sin \theta \, d\ell \quad - - - - 1$$

The forces acting on the segment are pressure, the gravity force, and bottom drag.

The surface curvature of the profile is very gradual so that the pressure distribution can be considered to be simple hydrostatic pressure.

At section 1, the pressure force is,

$$P_1 = \frac{1}{2} \rho g y^2$$

And at section 2 the pressure force is,

$$P_2 = \frac{1}{2} \rho g (y+dy)^2$$

The net pressure force is the difference between the forces at either end, and again neglecting derivatives of second order, this force becomes,

$$P_2 - P_1 = -\rho gydy \quad \text{-----------------} \; 2$$

The weight component of the segment, if second order derivatives are neglected is,

$$W = \rho g \left[\frac{y+(y+dy)}{2}\right] d\ell \sin \theta$$

For small angles (less than 10^o) sin θ approximates tan θ closely and since tan θ is the bottom slope,

$$W = \rho gy\ So d\ell \quad \text{-----------------} \; 3$$

The force offered by bottom drag is,

$$F = \tau d\ell$$

According to the method first used by Chezy, this resisting shear force is equivalent to the weight component in the flow direction for a uniform flow on an appropriate slope, sometimes called the friction slope. Thus,

$$F = \rho gy\ S_f\ d\ell \quad \text{----------------} \; 4$$

Summing these forces given by equations 2, 3, and 4 and setting them equal to the change in momentum flux given by equation 1,

$$-\rho gy\,dy + \rho gy\,So\,d\ell - \rho gy\,S_f\,d\ell = \rho(udq+qdu) - \rho rv\sin\theta\;d\ell$$

For small angles (less than 10^o) the error introduced by replacing $d\ell$ by dx is negligible so that,

$$-\rho g\,y\,dy + \rho gy\,So\,dx - \rho g\,y\,S_f\,dx = \rho(udq+qdu) - \rho rv\sin\theta\,dx$$

If q/y is substituted for u and the equation is divided through by $-\rho gydx$, then,

$$\frac{dy}{dx} - (So-Sf) = -\frac{q}{gy^2}\frac{dq}{dx} - \frac{q}{gy}\frac{d}{dx}(q/y) + \frac{rv\sin\theta}{gy}$$

Now performing the indicated differentiation,

$$\frac{d}{dx}(q/y) = -\frac{q}{y^2}\frac{dy}{dx} + \frac{1}{y}\frac{dq}{dx}\;,$$

and noting that $\frac{dq}{dx} = r$, the general formula for overland flow at equilibrium after simplifying becomes,

$$\left(1 - \frac{q^2}{gy^3}\right)\frac{dy}{dx} = (So-Sf) - \frac{2qr}{gy^2} + \frac{rv\sin\theta}{gy}\;. \text{ ---------- } 5$$

The equation of continuity at equilibrium may now be written as,

$$q = qo + \int_0^x rdx$$

and after integrating,

$$q = qo + rx \text{ -------------------- } 6$$

The Simplified Formula

The close inspection of the terms in equation 5 reveals that they are of very different orders of magnitude for the conditions of these tests. The term on the left side of the equation and the last two terms on the right side are much smaller than the two remaining terms which represent the bottom slope and the friction slope respectively. This can best be illustrated by an example using typical test conditions. The spray drops are assumed to fall vertically so that the velocity component used in the appropriate term is the component down the 5% slope. Values are shown for two distances down the channel for surface 1 with rain simulated by nozzle 1. These values are:

$x = 20$ ft	$x = 90$ ft
$y = 0.006$ ft	$y = 0.018$ ft
$r = 1.773 \times 10^{-4}$ cfs/ft^2	r = same
$q = 1.773 \times 10^{-3}$ cfs/ft	$q = 1.596 \times 10^{-2}$ cfs/ft
$v \sin \theta = 18.1 \sin 2.8^\circ = 0.9$ fps	$v \sin \theta = 18.1 \sin 2.8^\circ = 0.9$ fps
$g = 32.144$ ft/sec^2	g = same

For these values,

$$\left(1 - \frac{q^2}{gy^3}\right) \frac{\Delta y}{\Delta x} = 0.000135 \quad \text{and} \quad -0.000072,$$

$$\frac{rv \sin \theta}{gy} = 0.00091 \quad \text{and} \quad 0.000306,$$

$$\frac{2qr}{gy^2} = 0.00054 \quad \text{and} \quad 0.00054,$$

for the shorter and longer distances respectively.

Since So is about 0.05 and Sf is of the same order of magnitude it can be seen that these two terms are nearly 100 times as great as the terms in question.

Dropping these negligible terms, therefore, and expressing the friction slope by the Darcy-Weisbach formula,

$$So = \frac{f\ u^2}{8\ gy}$$

Which, after rearranging, becomes,

$$y = \frac{fu^2}{8g\ So}. \quad \text{------------------} \quad 7$$

Equation 7 is simply the expression for uniform flow in an open channel. Thus overland flow over steep rough surfaces may be treated as a quasi-uniform flow and the water surface profile can be adequately described by equation 7 in conjunction with the continuity equation and the proper resistance relationship as given in Figure 14 .

Computer Solution

As noted above, equations 6 and 7 along with Figure 14 can be used to describe the water surface profiles in the tests of this thesis. This solution must be made by a trial and error procedure and is, therefore, quite tedious. Use of a digital computer, however, provides a quick solution for these profiles.

The computer program listed in Appendix B was written in Fortran for use on the IBM 1620. The procedure of the solution is as follows:

1. For some value of x assume a depth.
2. Compute q from equation 6 and the rain intensity.
3. Compute $u = q/y$, using the assumed depth.
4. Compute $NR = q/\nu$ and find the corresponding resistance coefficient from Figure 14.

5. From equation 7 find the computed depth.
6. Compare the assumed and computed depths.
7. If the assumed and computed depths do not agree, reassume a depth and repeat steps 3 through 6 till sufficiently close agreement is found.
8. Increase the value of x and repeat steps 2 through 7 till the end of the channel is reached.

By this procedure the theoretical profiles listed in Appendix D were predicted.

CHAPTER IV

EXPERIMENTAL APPARATUS

The facilities for these tests were located at the Stillwater Outdoor Hydraulic Laboratory which is supplied with water from Lake Carl Blackwell. A channel, a rain simulator, and various measuring devices composed the basic apparatus used. Figures (3) and (4) show respectively a schematic drawing of the channel and flow system and a cross-section of the channel and test apparatus.

The Channel

The tests described in this thesis were conducted on a concrete channel 35 inches wide and 96 feet long. It was one of 8 such channels at the laboratory separated by concrete curbings and sloped uniformly at 5 per cent. Smooth aluminum strips one inch deep were attached to the concrete channel sides to reduce side effects. These sides can be seen in figure (5).

At the head of the channel was a small reservoir from which a uniform flow could be introduced through a baffle and across a flat weir plate. This plate marked the head of the channel which ended in a vertical edge.

Three surface roughnesses were created by attaching sieved pea-gravel to the concrete. Waterproof spar-varnish held the gravel in place when it had been spread on the channel to a one-layer thickness. The uniformity

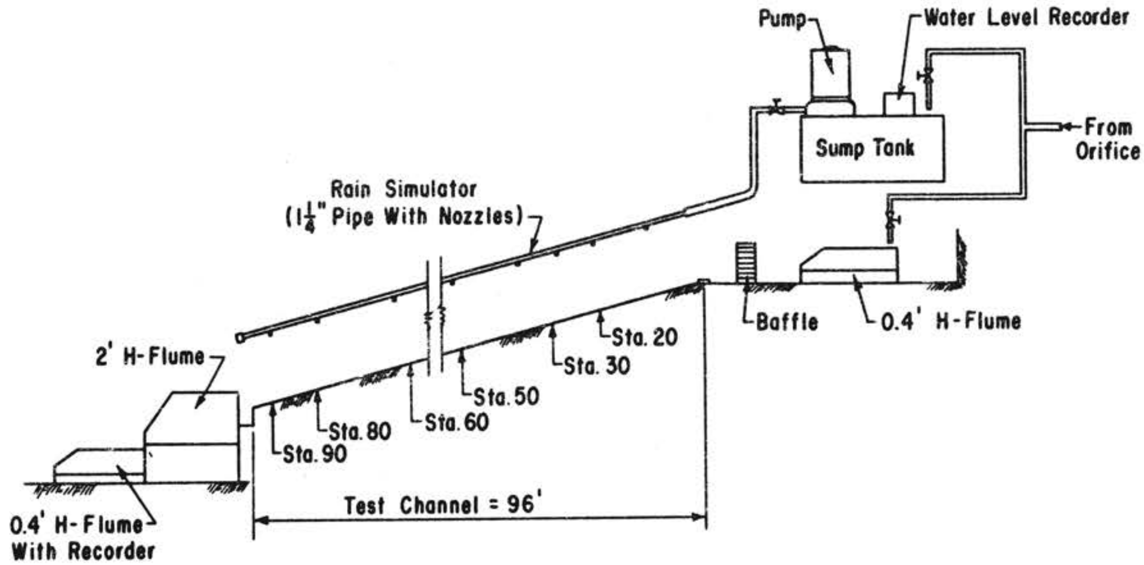

Figure 3. Schematic Diagram of the Channel and Flow System

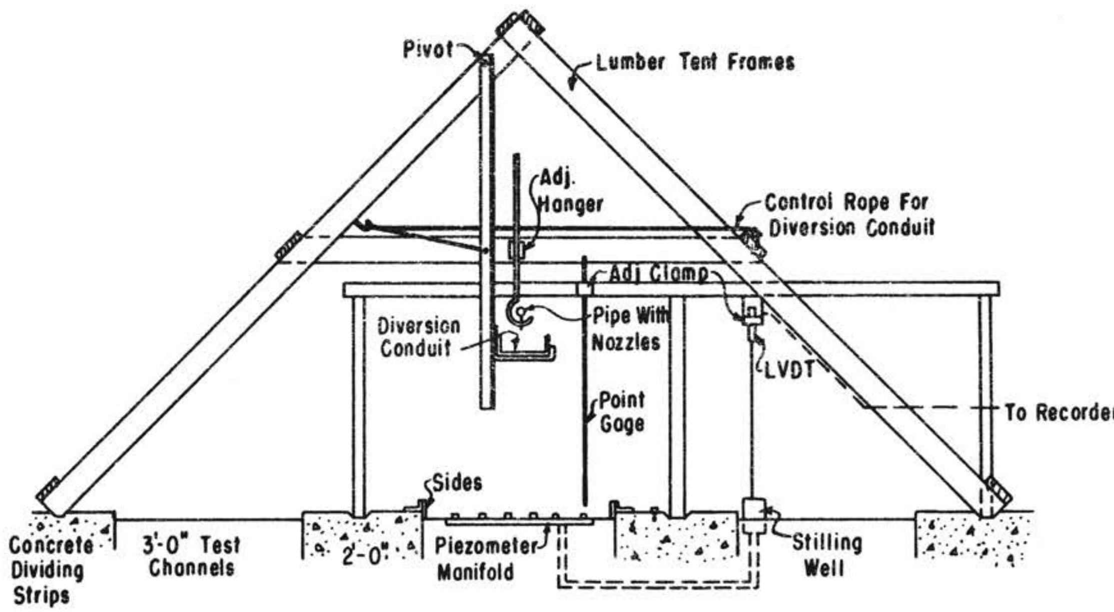

Figure 4. Cross-section of the Channel and Test Apparatus

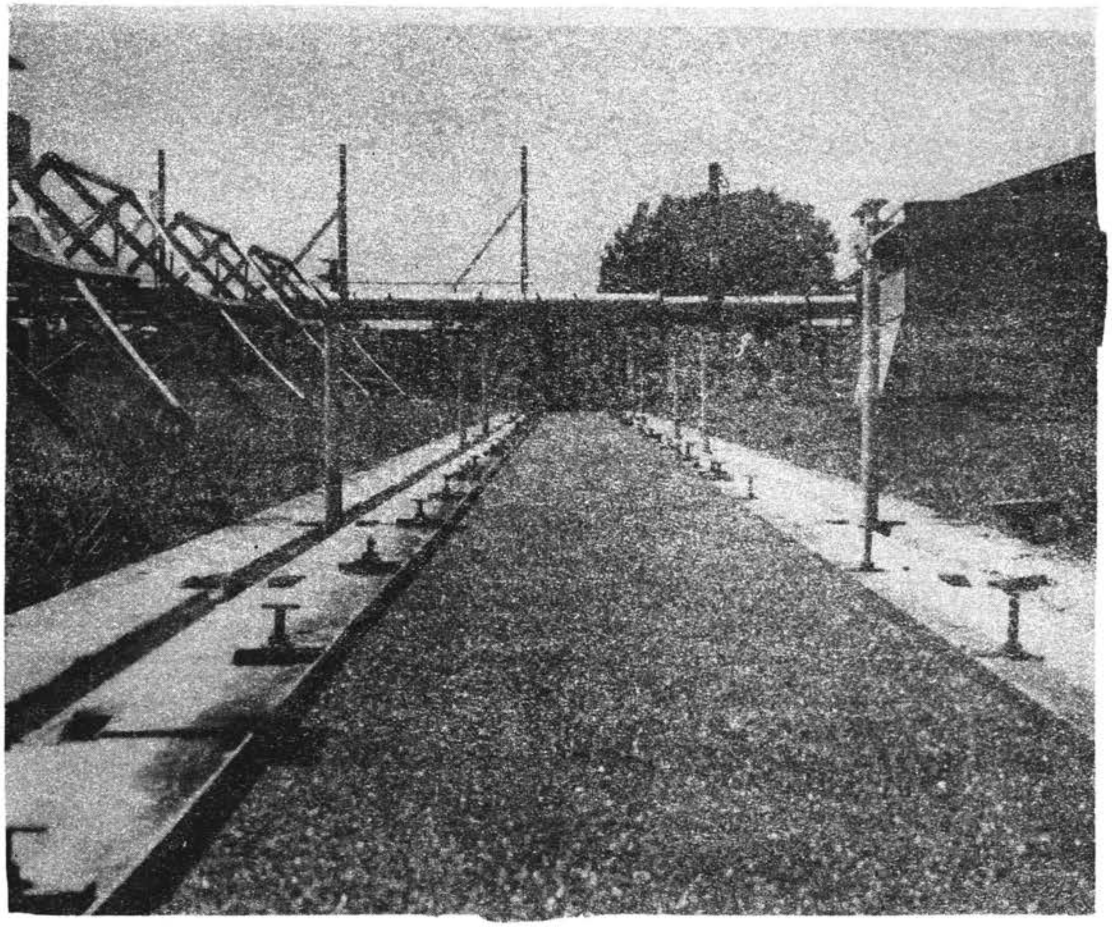

Figure 5. The Test Channel Viewed from the Lower End

of the gravel can be seen in Figure (7). The average diameter of the gravel used was 0.109, 0.160, and 0.219 inches for surfaces 1, 2, and 3 respectively. These gravel sizes were obtained by first passing the pea-gravel through 1/4 and 1/8 inch hardware cloth and finally through Tyler seives of 0.0937, 0.132, and 0.187 inch openings. Figure (6) shows the three gravel sizes compared.

Depth Measurements

Two methods of measuring depths were employed. Point gages were mounted directly over the channel and a piezometer was connected to a well located outside the channel. A float in the well actuated a linearly variable differential transformer (LVDT) which indicated depths. With this latter system it was possible to take readings of transient conditions.

Depth measurements were made with both systems at six locations along the channel length. The stations were located at 20, 30, 50, 60, 80, and 90 feet from the head of the channel and are hereafter denoted by these locations.

The two foot vernier type point gages rested in movable carriages with which it was possible to obtain readings at any location across the channel. This carriage was clamped to a 2 1/2 by 2 1/2 inch steel angle which in turn was clamped to adjustable uprights. Figure (4) shows this transverse profiler.

When making point gage readings in simulated rain tests,a skirt was used to prevent water drops on the point from influencing the readings. A conical drinking cup was inverted and placed over the tip as is shown in Figure (12).

Across the channel at each measuring station there extended a piezometer manifold connected by 3/8 inch pipe to a 3 1/2 inch diameter well outside the channel. Six intakes in the manifold were spaced at 6 inch intervals across the channel and 2 1/2 inches from either side.

Brass cylinders 3/4 inch long and 3/8 inch in diameter were used for the intakes. To admit water to the manifold 0.0625 inch diameter holes were drilled into the intakes which are shown in Figure (7). These cylinders were free to move vertically inside brass sleeves in the manifold. The close tolerence fit of the cylinders allowed them to be set at any height above the channel bed. This adjustment was necessitated by the large gravel sizes used.

A 2 1/2 inch diameter styrofoam float rested in the well and actuated the core of the LVDT's. The well and LVDT are shown in Figure (8). Each of the six Columbia model H-1000-SIRX LVDT's reported to a dual channel Sanborn 321 recorder. A switching device allowed the LVDT signals to record in sequence on a single channel of the recorder.

Flow Measurements

Water could be introduced into the channel either as simulated rain or from the reservoir at the head of the channel. Both the rain simulator and the reservoir were supplied through a common pipe. An orifice meter measured the total flow rate in this supply pipe.

The rain simulator was supplied from a sump tank by a high pressure pump. Adjustment of the inflow pipe gate valve could be made to maintain a constant water level in the sump tank. A Freiz water level recorder kept continuous records of the sump water level.

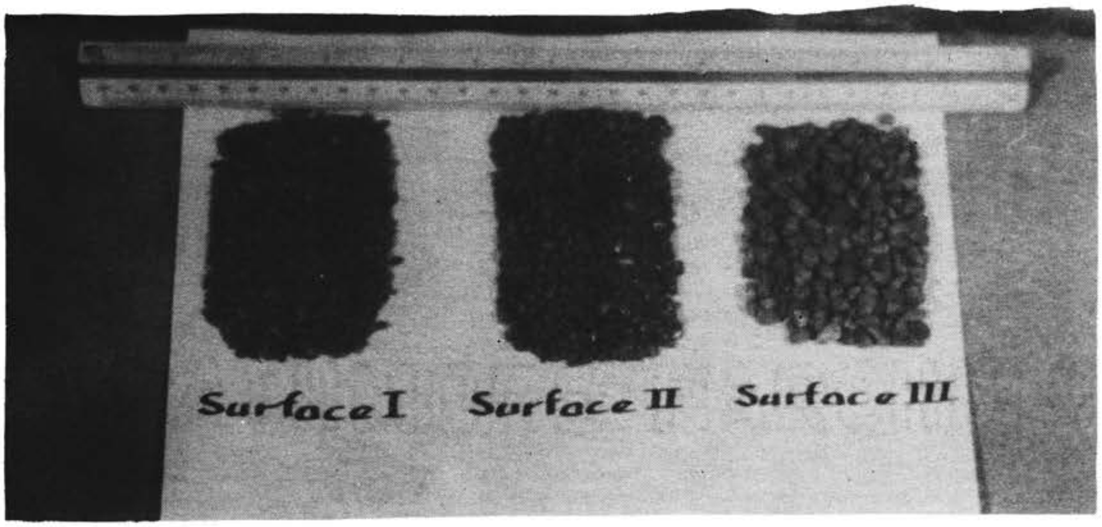

Figure 6. The Three Sizes of Pea Gravel used to Roughen the Channel

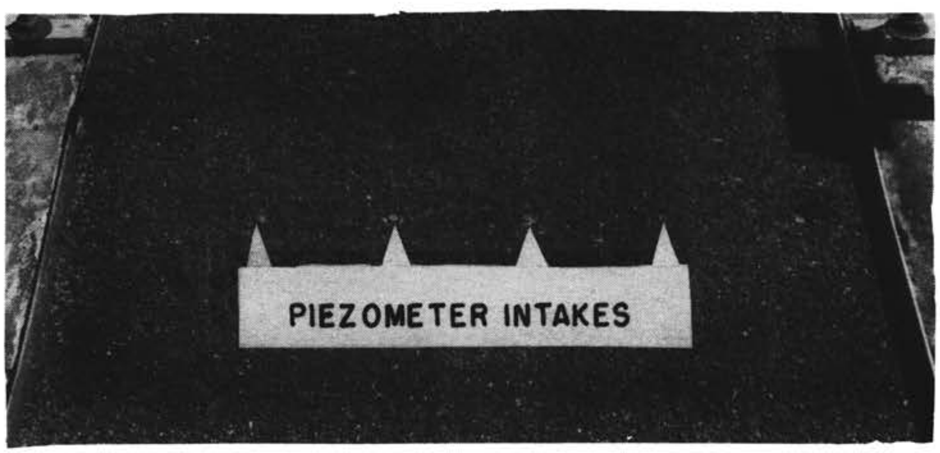

Figure 7. Close-up View of Surface 2 Showing the Piezometer Intakes

Figure 8. The Stilling Well and LVDT Depth Measuring Device

The inflow rate from the reservoir into the channel was measured by a 0.4 foot H-flume equipped with a point gage.

Outflow from the channel was measured by H-flumes and point gage. Available materials and the range of flow rates desired suggested the use of two H-flumes in tandem. Runoff from the channel flowed directly into a stilling box and through a 2-foot H-flume. This flume discharged into the stilling box of a 0.4 foot H-flume which was equipped with a Freiz water level recorder.

Spray falling outside the channel limits collected in the gutters in the center of the curbs on either side of the channel and was measured volumetrically.

Rain Simulator

The system of rain simulation consisted basically of a 1 1/4 inch pipe suspended directly over and parallel to the center of the channel as shown in Figure (4). Spray nozzles were attached to this pipe at appropriate spacings. At each end of the spray pipe and in the center Bourdon type gages were attached to measure pressure.

Five lumber A-frames supported the spray pipe in such a way that its height above the channel could be adjusted. There was a diversion conduit suspended directly under the spray nozzles as shown in Figure (4). This galvanized metal conduit was clamped to a vertical member which in turn was bolted at the apex of the A-frame. With this arrangement it was possible to adjust the conduit to the height of the nozzles and also to swing it out from under the spray pipe. Simulated rain could be started and stopped quite suddenly by positioning this diversion conduit.

Canvas covers were placed over the A-frames to reduce wind effects. Between the frames a clear plastic cover was used for this purpose while allowing enough light for making readings.

Two types of spray nozzles were used in these tests. One, nozzle 1, delivered approximately a square pattern of relatively large drops and the other, nozzle 2, produced an oval pattern of smaller drops. The drop size distributions and the runoff patterns of these nozzles are shown in Figure (9) and (10) respectively.

Nozzle 1 was operated at 10 psi and had a 52½ inch spacing along the spray pipe. It was suspended 32 inches above the channel. Nozzle 2 was suspended 24 inches above the channel. It operated at 20 psi with 7 1/2 inch spacings.

The kinetic energies of the spray from these nozzles compared favorably to that for a natural rainstorm of the same intensity as noted in Chapter II.

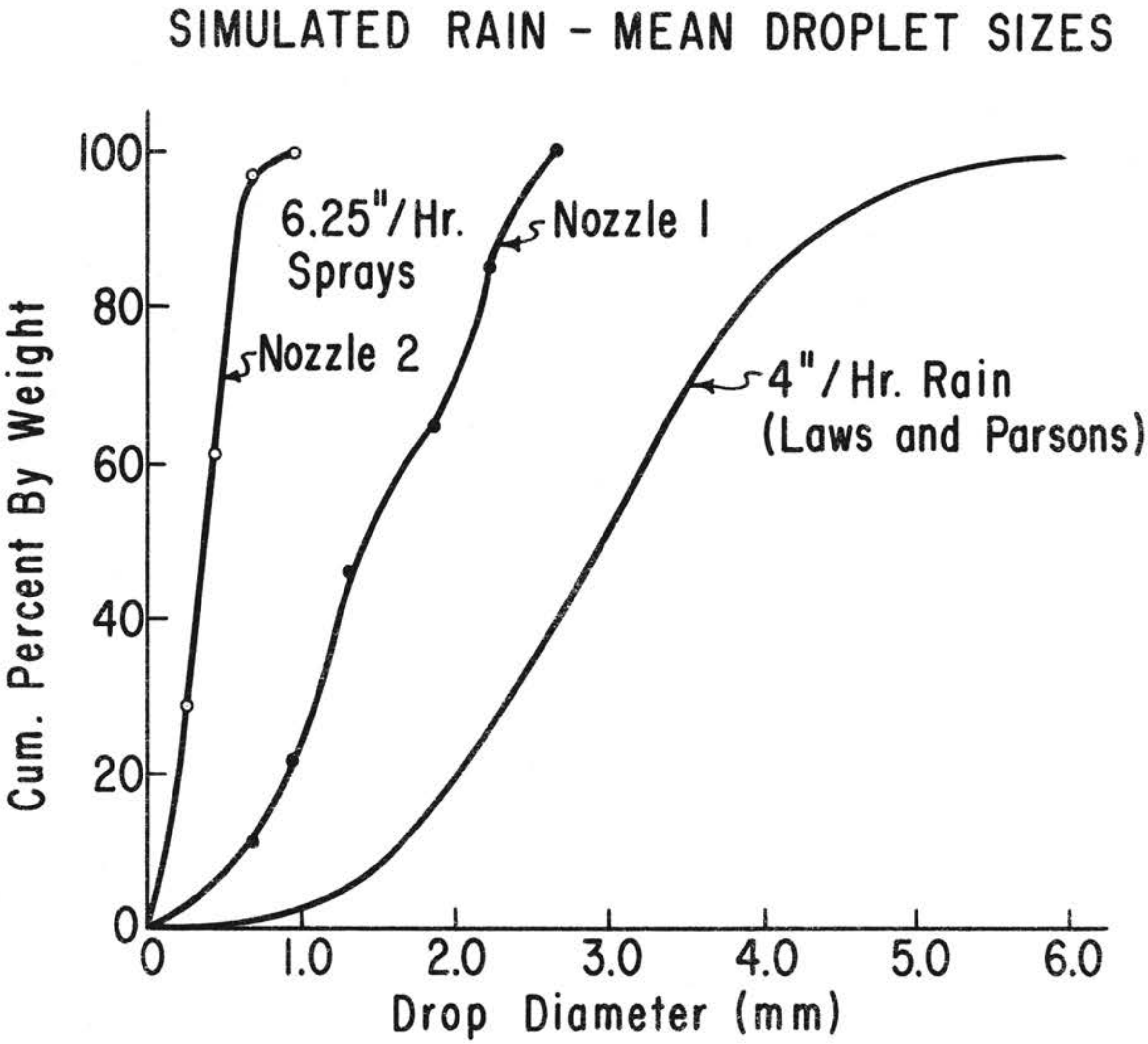

Figure 9. Drop Size Distributions for Nozzle 1 and 2 of the Rain Simulator

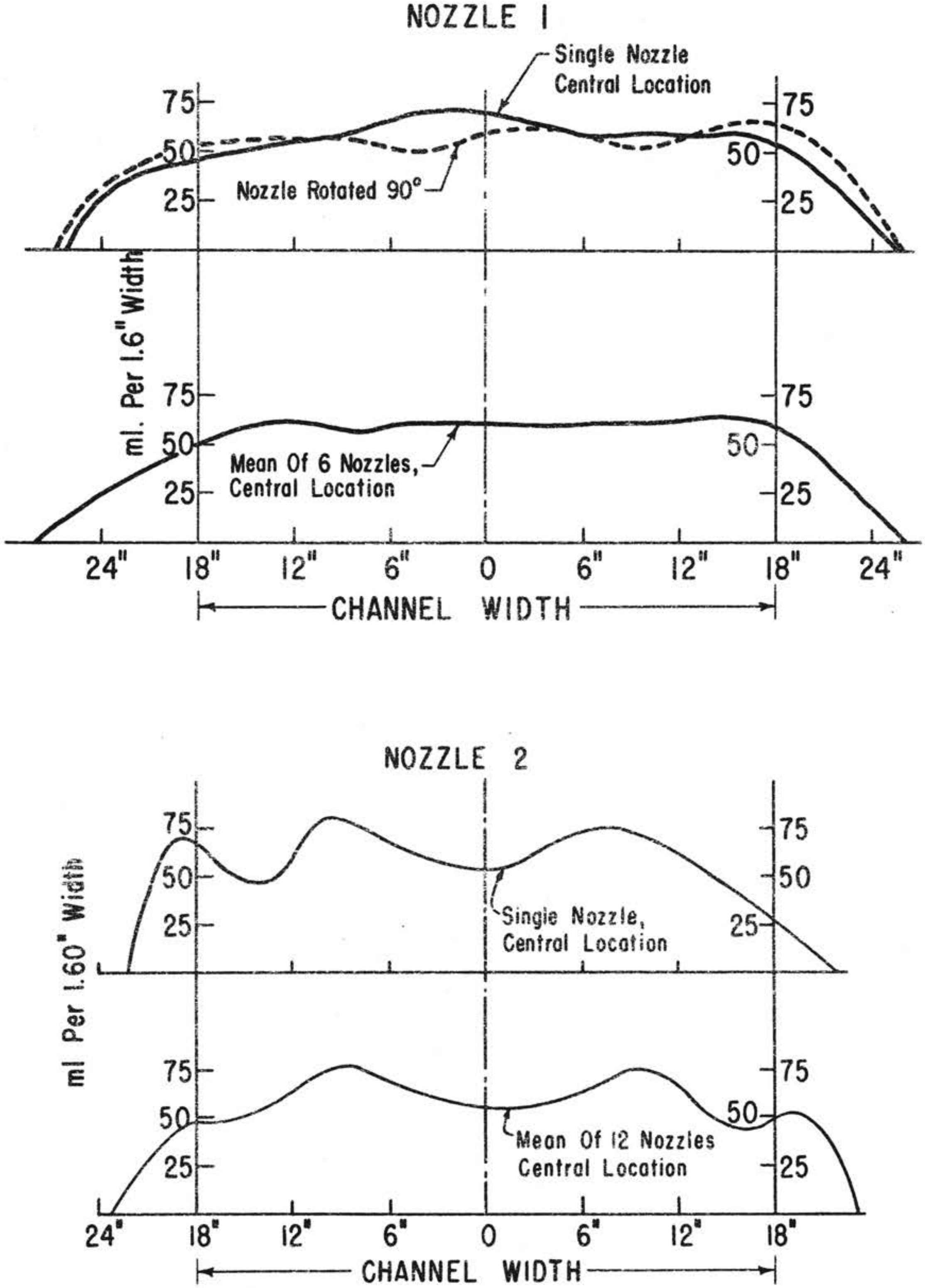

Figure 10. Runoff Patterns for Nozzles 1 and 2 of the Rain Simulator

CHAPTER V

EXPERIMENTAL PROCEDURE

Three types of tests were made on each of the three surfaces used in this study. Uniform flow tests, made at flow rates covering the range expected in the simulated rain tests, provided information describing the bed drag characteristics of the surface. The two other types of tests were made with flows created by simulated rain. In one of these simulated rain tests the spray was directed onto an established uniform flow. In the other type test spray alone created the flow.

Before the tests certain leveling and zeroing procedures were necessary. The H-flumes and the profilers were leveled and checked periodically with an engineer's level reading on a point gage. Imbedded in the concrete curb at each measuring station was a bolt which served as a datum on which the point gages were zeroed. Zeroing the LVDT's was accomplished by the following procedure. The stilling wells were first filled and a flow introduced into the channel. This flow was stopped after a short period and the channel was allowed to drain. Soon the water surface level in the stilling well was the same as the level of the piezometer intakes. At that moment, indicated by a point gage reading in the well, the LVDT's were set to their null positions.

Bottom Readings

Two sets of bottom readings were taken at each of the six measuring stations. Readings at two inch intervals were taken on the top of the gravel particles using a blunt point in the point gage. At the same two inch intervals readings were taken on the concrete bottom using a sharp point. The average reading on the gravel tops was found and the adjustable piezometer intakes set to that reading. This was easily accomplished by setting the point of the gage on the intake and adjusting the gage down to the proper reading.

Uniform Flow Tests

Preselected flow rates from the head-water reservoir were established. After the flow had become steady the various readings were taken. Flow rates were measured both by the orifice system and the inflow H-flume. In order to minimize the possible error due to fluctuations in the manometer reading of the orifice system a series of ten readings were taken in quick succession. Five readings were taken on the H-flume since the variations were smaller.

Point gage readings on the water surface were taken at nine locations across the channel. Figure (11) shows the spacings of these locations. The readings near the edge were spaced farther apart to eliminate the possibility for error due to side effects. To make these readings the tip of the point gage was lowered slowly to the water surface till water was seen to jump up on it. The tip was then retracted and once again lowered to the water surface. In this manner at least three readings, and generally more were taken.

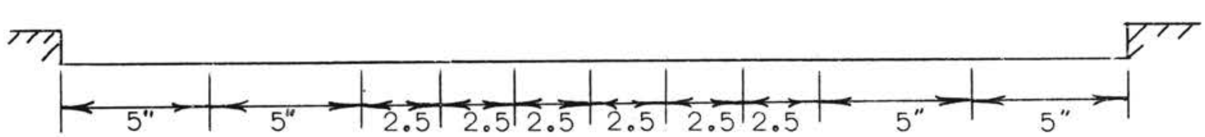

Figure 11. Transverse Locations for Point Gage Readings on the Water Surface

Simulated Rain Tests

The spray pipe was first set to the proper height and the nozzles checked to insure that they were clear. A uniform flow was then introduced into the channel for a short time to wet the surface. With the diversion conduit in place so that no spray fell on the channel, the pump was started and the pressure in the pipe brought to the proper value.

The test was begun by swinging the diversion conduit aside so that spray was directed onto the channel. After the flow became steady, point gage readings on the water surface were taken in the same manner as used in the uniform flow tests. In these simulated rain tests, a skirt was used with the point gage as shown in Figure (12).

It was necessary to maintain a constant water level in the sump tank during these tests. This was accomplished by adjustment of a gate valve. When the sump tank water level was constant, manometer readings were taken on the orifice system to determine the flow rate.

The flow rates in each of the two gutters was obtained by directing the flow into a small container for a measured length of time. The volume of the water was then determined by weighing. Ending the test was accomplished simply by replacing the diversion trough under the nozzles. After the channel had drained till the flow rate was negligible, the entire test was repeated. As nearly as possible the same conditions were maintained in both tests.

Simulated Rain on an Initial Inflow

For the most part, these tests were conducted by the same procedure as given in the previous section. In addition, however, an inflow which was about equal to the total flow from the nozzles alone was introduced from the headwater reservoir. This initial inflow was established and allowed to become steady before the spray was directed onto the channel. This allowed profiles to be obtained which simulated those of longer lengths than the actual 96 feet length of the test channel.

Both rising and falling hydrographs were taken for the tests involving spray. However, these results were not used in this thesis.

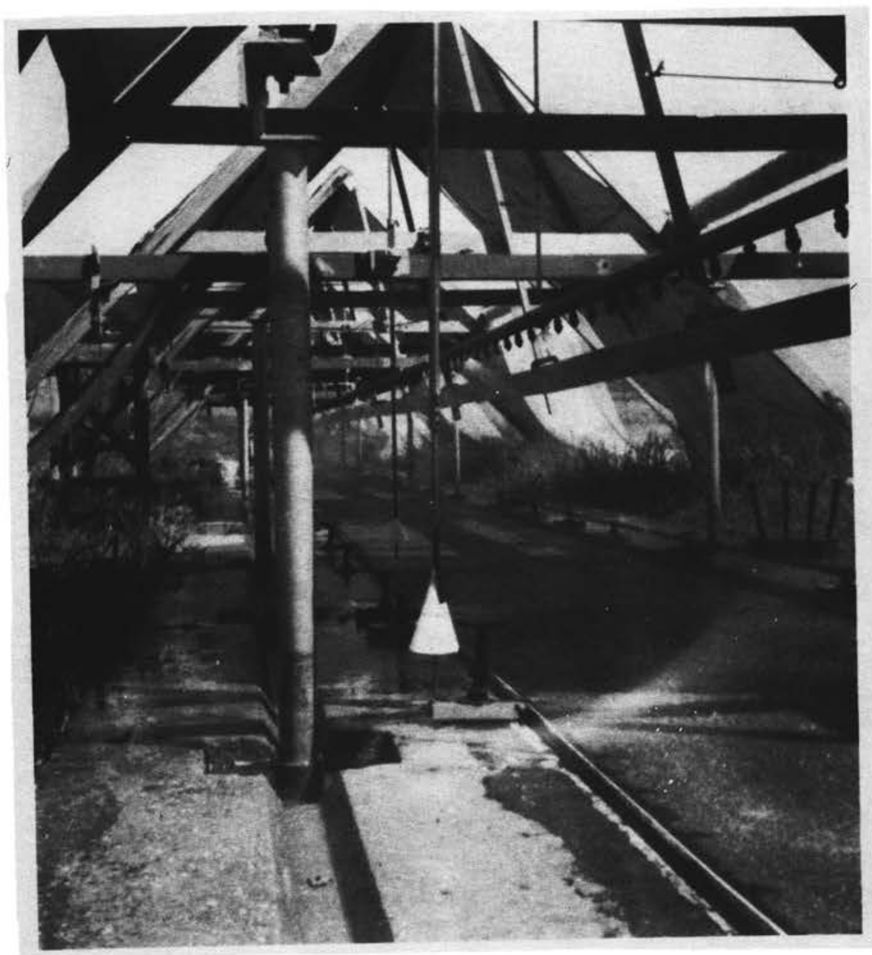

Figure 12. A View of the Apparatus During a Simulated Rain Test

CHAPTER VI

PRESENTATION AND DISCUSSION OF RESULTS

The tests reported in this thesis provided the necessary data to determine the resistance characteristics of the three surfaces and the water surface profiles resulting from simulated rain on these surfaces. The resistance characteristics, as represented by the Darcy-Weisbach resistance coefficient for open channels, were determined from uniform flow tests. This relation was then used in conjunction with equations 6 and 7 to predict water surface profiles of flow due to simulated rain. Finally these predictions were checked against results from the simulated rain tests. The readings indicated by the point gages were used instead of those indicated by the LVDT's. No consistent relation between these two could be found. It was thought that the point gage readings, although subject to shortcomings, would be more logically used since the effect of the large gravel particles on the piezometer readings was unknown.

Location of Bottom

Because the size of the pea gravel represented a considerable portion of the flow depths it was necessary to give much attention to the location of the channel bottom. Three possible methods for locating the bottom were considered: 1) Add the average gravel diameter, or some portion thereof to the elevation of the concrete bottom, 2) Average a series of point gage readings on the gravel tops across the channel, which is hereafter referred to as the measured bottom, and 3) Find a hydraulically effective bottom.

Nineteen gage readings on the gravel tops across the channel were averaged to indicate the measured bottom at each station. Gage readings are indicative of depth which, for fully developed turbulent flow, is proportional to the 0.6 power of flow rate. Therefore, if gage readings are plotted against flow rate to the exponent 0.6, the intercept on the ordinate, as in Figure 13, is the gage reading of the effective channel bottom. By this method the effective bottom gage readings were determined for each station down the channel for each of the three surfaces. The least squares method of linear regression was employed to determine the best fit line. Table II lists the correlation coefficients resulting from these regressions. In all instances excepting one, station 20 on surface 2, the correlation coefficients are above 0.9 and generally much higher. This high correlation is thought to justify the assumption that flow was fully turbulent for all flow rates tested.

Table III lists the differences in elevation between the concrete bed and the channel bottom as determined by each of the three above methods. Statistical analysis of these differences revealed that at the 99% confidence level there was no significant difference between the measured bottom and the effective bottom. The lone exception was at station 20 on surface 2. This further justified the dropping of this station from the analysis of results on surface 2. It was decided, therefore, to use the measured channel bottoms due to their greater practicality and for another reason explained later in this section.

Depth Adjustments

Depths of the uniform flows were computed from the water surface

TABLE II

CORRELATION COEFFICIENTS FOR THE LINEAR REGRESSION OF FLOW RATE TO THE 0.6 POWER VS WATER SURFACE GAGE READINGS

	Sta 0+20	Sta 0+30	Sta 0+50	Sta 0+60	Sta 0+80	Sta 0+90
Surface I	0.977	0.973	0.915	0.953	0.992	0.986
Surface II	0.743	0.976	0.977	0.940	0.985	0.904
Surface III	0.987	0.994	0.961	0.994	0.984	0.999

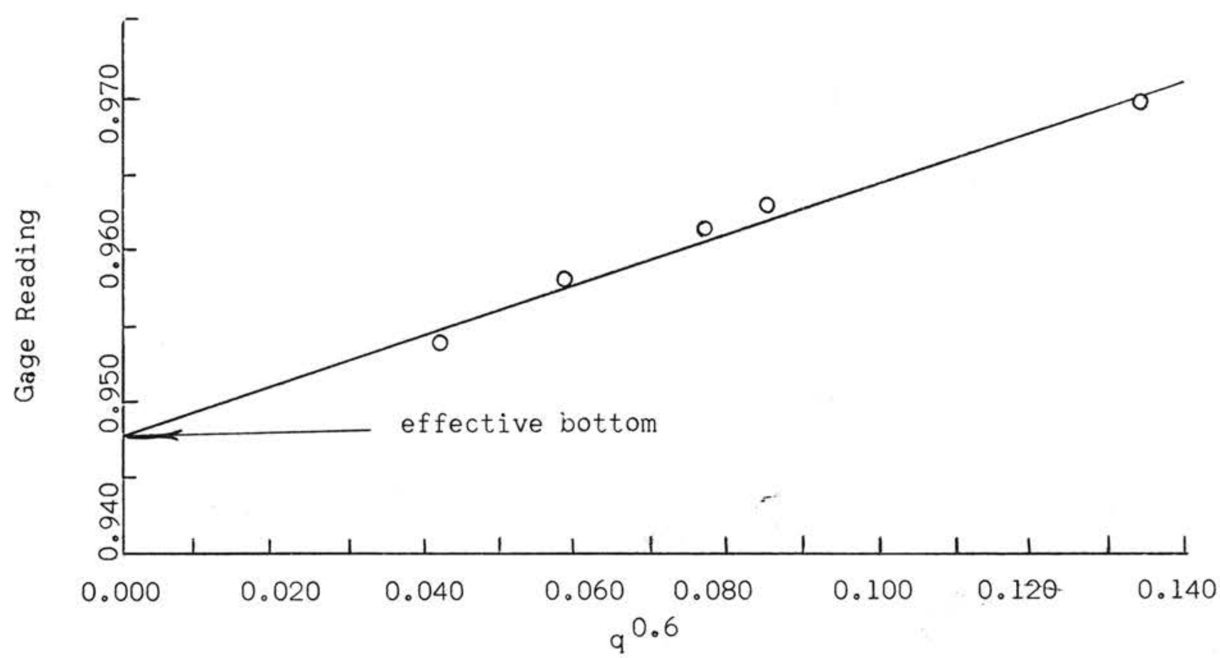

Figure 13. The Plot Used for Finding Gage Reading of Effective Bottom. Shown is Station 60 on Surface 3.

TABLE III

COMPARISON OF MEASURED BOTTOM AND EFFECTIVE BOTTOM

	Surface 1			Surface 2			Surface 3		
Sta.	Ave. Gravel Dia.	Meas. Bottom	Eff. Bottom	Ave. Gravel Dia.	Meas. Bottom	Eff. Bottom	Ave. Gravel Dia.	Meas. Bottom	Eff. Bottom
0+20	0.009	0.001	0.000	0.013	0.003	0.016	0.018	0.005	0.001
0+30	0.009	0.008	0.009	0.013	0.015	0.018	0.018	0.015	0.019
0+50	0.009	0.008	0.013	0.013	0.010	0.011	0.018	0.013	0.015
0+60	0.009	0.011	0.010	0.013	0.013	0.013	0.018	0.019	0.021
0+80	0.009	0.008	0.006	0.013	0.013	0.010	0.018	0.015	0.018
0+90	0.009	0.012	0.008	0.013	0.013	0.014	0.018	0.015	0.017
Ave.		0.0080	0.00767		0.011	0.01483		0.01367	0.01517
Ave.					0.0126*	0.0146*			
Deg. of Freedom					5	5			
		5	5		4*	4*		5	5
Student t		0.6			4.5 2.0*			1.5	

* Neglecting Station 20

gage readings and the readings of the measured bottoms. It was found that the depths indicated at the six stations varied somewhat. The average depth was, therefore, calculated and the deviations of the depth at each station from this average depth was found and listed in Table IV. The local effect of the gravel particles is thought to have caused these deviations. This possibility is substantiated to some degree by the consistency of the deviations in most instances. Averaging these deviations provided adjustment factors which were later applied to the profiles of flow due to simulated rain. These adjustment factors had the same magnitudes as the deviations but were opposite in sign. They were different for each station and each surface as might be expected.

Resistance Coefficients

The flow rates and average depths for each uniform flow run were used to compute the Darcy-Weisbach resistance coefficients and the other parameters listed in Table V.

The following relations were used:

$$f = \frac{8gSoy^3}{q^2}$$

$$n = 1.49 \; \frac{So^{0.5} \; y^{5/3}}{q}$$

$$Nr = \frac{q}{\nu}$$

A log-log plot of the resistance coefficients against Reynolds number provided the necessary relation indicative of bed drag for each surface. Figure 14, which shows these plots reveals a considerable scatter of the points. There are several possible reasons for this scatter. The sensitivity of the resistance coefficient to changes in

TABLE IV

DEVIATIONS FROM AVERAGE DEPTH IN FEET FOR UNIFORM FLOWS

Test No	Sta 0+20	Sta 0+30	Sta 0+50	Sta 0+60	Sta 0+80	Sta 0+90
Surface I						
1	0	+0.002	+0.002	-0.002	+0.001	0
2	-0.001	+0.003	+0.002	-0.003	-0.001	-0.001
3	-0.002	+0.002	+0.006	-0.002	-0.002	-0.004
4	+0.001	0	+0.002	-0.001	0	-0.003
5	-0.003	+0.002	+0.002	0	-0.001	-0.001
Average	-0.001	+0.002	+0.003	-0.002	-0.001	-0.002
Surface II						
1	-	+0.002	0	-0.002	+0.003	-0.005
2	-	+0.002	-0.001	-0.002	+0.005	-0.005
3	-	+0.002	0	-0.003	+0.004	-0.001
4	-	0	+0.001	-0.004	+0.003	-0.004
5	-	0	-0.002	-0.003	+0.002	-0.004
6	-	+0.001	-0.002	-0.001	+0.004	-0.003
7	-	+0.001	0	-0.001	+0.005	-0.004
8	-	0	0	-0.001	+0.004	-0.005
9	-	-0.001	-0.002	+0.002	+0.002	0
10	-	-0.001	-0.002	+0.002	+0.003	0
11	-	0	-0.002	-0.004	+0.004	0
12	-	-0.002	+0.001	0	+0.003	-0.001
Average		0	-0.001	-0.001	+0.004	-0.003
Surface III						
1	-0.003	+0.002	0	-0.001	+0.002	+0.001
2	-0.001	+0.001	0	-0.002	+0.001	-0.001
3	-0.001	+0.002	-0.002	-0.001	+0.002	+0.001
4	+0.002	0	-0.002	-0.004	+0.001	0
5	-0.002	0	+0.002	-0.001	-0.001	0
Average	-0.001	+0.001	0	-0.002	+0.001	0

TABLE V

SUMMARY OF RESULTS FROM UNIFORM FLOW TESTS

Test No	Depth ft	Flow Rate cfs/ft	Kinematic Viscosity ft^2/sec	Reynolds Number	Resistance Coefficient	Mannings "n"
Surface I						
1	0.026	0.04224	0.930×10^{-5}	4542	0.126	0.018
2	0.015	0.01701	0.876	1942	0.149	0.018
3	0.011	0.00896	0.876	1023	0.212	0.014
4	0.007	0.00490	0.876	559	0.182	0.018
5	0.016	0.01661	0.876	1896	0.190	0.020
Surface II						
1	0.008	0.00457	1.059	435	0.308	0.023
2	0.012	0.00886	0.930	955	0.280	0.024
3	0.014	0.01111	0.930	1195	0.284	0.024
4	0.017	0.01446	0.876	1651	0.300	0.026
5	0.017	0.01661	0.876	1896	0.231	0.022
6	0.020	0.02620	0.876	2983	0.150	0.019
7	0.024	0.03460	0.876	3949	0.148	0.019
8	0.028	0.04282	0.876	4885	0.153	0.020
9	0.018	0.01778	0.876	2030	0.236	0.023
10	0.014	0.01018	0.876	1162	0.338	0.027
11	0.010	0.00607	0.876	693	0.347	0.026
12	0.014	0.01223	0.876	1396	0.234	0.022
Surface III						
1	0.009	0.00498	0.991	502	0.376	0.025
2	0.014	0.00877	0.930	943	0.446	0.031
3	0.016	0.01410	0.930	1516	0.263	0.024
4	0.028	0.0355	0.876	4050	0.222	0.024
5	0.018	0.01640	0.991	1655	0.277	0.025

depth is thought to be most important. Another possibility is that the resistance offered by the channel actually changed during a test. This change would be due to dislodging of the gravel at places down the channel, a condition that was noted in some instances. When this happened the particles were reattached to the concrete before the next tests were made. A third possible explanation is that turbulent flow was not fully established and flow was still in the transition region. Although in some instances of low flow rate this could be possible it is thought that the results shown in Table II indicate that it was unlikely.

The lines through the points in Figure 14 were determined by linear regression. Table VI lists correlation coefficients resulting from these regressions using depths above measured and effective bottoms. As mentioned above, these correlation coefficients substantiated the use of the measured bottoms and further justified the deletion of Station 20 from the results on Surface 2. Extension of the lines in Figure 14 beyond Reynolds numbers observed in the tests is not strictly justified. It is obvious, however, that the theoretical line indicating resistance coefficients for laminar flow, $f=C/N_r$ where $C=6$, would fall far below the points in this figure. The value of $C=25$ given by Woo and Brater (1961) for their sand surface also indicates a relation well below the points in the figure. Since there appeared to be no satisfactory method by which to determine the laminar flow resistance coefficient, it was decided simply to extend the line in the figure realizing its limitations. In the theoretical profile calculations only the first increment of distance has flow rates which are indicative of possible laminar flows so that the possible error is minimal.

Profiles of Overland Flow

A summary of the flow conditions for the simulated rain tests is shown in Table VII. Subtracting the gutter flow and the initial inflow from the total flow through the orifice and dividing the result by the surface area of the channel gave the rain intensity.

The adjusted depths at each station down the channel are shown in Figures 15 through 20. The figures also show the profiles determined by the method discussed in Chapter III. These predicted profiles were computed on an IBM 1620 using the Fortran program listed in Appendix B. The input data to this program are listed in Appendix C and the resultant profiles are given at 10-foot intervals for all tests in Appendix D. Rain intensity in inches per hour and initial inflow in cfs/ft are shown on these graphs.

The close agreement of the predicted and the observed results lead to the conclusion that overland flow over steep rough surfaces may be treated as a quasi-uniform flow. Inspection of the profiles in Figures 15 through 20 shows that in several instances the theoretically predicted

TABLE VI

CORRELATION COEFFICIENTS FOR REGRESSION OF LOG f VS LOG N_R

	Using Depths Above Measured Bottom	Using Depths Above Effective Bottom
Surface I	0.7581	0.6991
Surface II	-	0.3312
Surface II*	0.8723	0.5153
Surface III	0.8426	0.8813

TABLE VII

SUMMARY OF CONDITIONS FOR RAIN-INDUCED FLOWS

Test No	Total Flow cfs	Gutter Flow cfs	Initial Inflow cfs/ft	Rain Intensity cfs/ft^2	Kinematic Viscostiy ft^2/sec
Surface I Nozzle I					
1	0.06724	0.01760	0.0	$1.773x10^{-4}$	$0.930x10^{-3}$
2	0.1269	0.01812	0.02134	1.662	0.930
3	0.06724	0.01818	0.0	1.752	0.876
4	0.1189	0.01893	0.01788	1.708	0.876
Surface I Nozzle II					
1	0.04932	0.01176	0.0	$1.341x10^{-4}$	$0.930x10^{-5}$
2	0.1012	0.00871	0.01839	1.388	0.930
3	0.04961	0.00848	0.0	1.469	0.930
4	0.09266	0.00875	0.01512	1.421	0.930
Surface II Nozzle I					
1	0.06809	-	0.0	$1.771x10^{-4}$	$0.876x10^{-5}$
2	0.06724	0.01765	0.0	1.771	0.876
3	0.1286	0.01531	0.02178	1.780	0.876
4	-	0.01765	0.02163	1.780	0.930
Surface II Nozzle II					
1	0.04903	0.00952	0.0	$1.418x10^{-4}$	$0.930x10^{-5}$
2	0.04844	0.00955	0.0	1.389	0.930
3	0.09585	0.00956	0.01677	1.335	0.930
4	0.1066	0.00959	0.02050	1.328	0.876
Surface III Nozzle I					
1	0.07036	0.01815	0.0	$1.865x10^{-4}$	$0.930x10^{-5}$
2	0.1189	0.01960	0.01751	1.722	0.930
3	0.06934	0.01518	0.0	1.934	0.911
4	0.1182	0.01701	0.01726	1.816	0.991
Surface III Nozzle II					
1	0.04633	0.00836	0.0	$1.356x10^{-4}$	$0.991x10^{-5}$
2	0.09358	0.01046	0.01606	1.296	0.991
3	0.04874	0.00986	0.0	1.388	0.991
4	0.09141	0.00984	0.01606	1.241	0.991

profile lies slightly below the observed points. This would be expected recalling that the resistance coefficients used for these predictions took no account of raindrop effect. The slight differences involved allow only a qualitative conclusion that, while rain effect on the resistance coefficient is indicated, it is of negligible consequence for these conditions.

Computer Program

The computer program listed in Appendix B is relatively simple and, therefore, was not made perfectly general. If it were desired to use this program for any conditions other than those of this thesis a few adjustments would need to be made. As noted previously, the relation for turbulent flow is used to calculate all resistance coefficients. If the relation for the laminar flow resistance coefficient were known, it would be a simple matter to add a loop in the program for this calculation when the Reynolds number fell outside certain limits. In this program the channel length and closeness of agreement between assumed and calculated depths were set at 100 and 0.0001 feet respectively. This could, of course, be changed to suit other circumstances. The constant in the equation in the program corresponding to equation 7 in Chapter III was determined using a value of 32.144ft/sec^2 for the local gravitational acceleration. For areas of very different elevation and latitude from Stillwater, Oklahoma, this value would be changed.

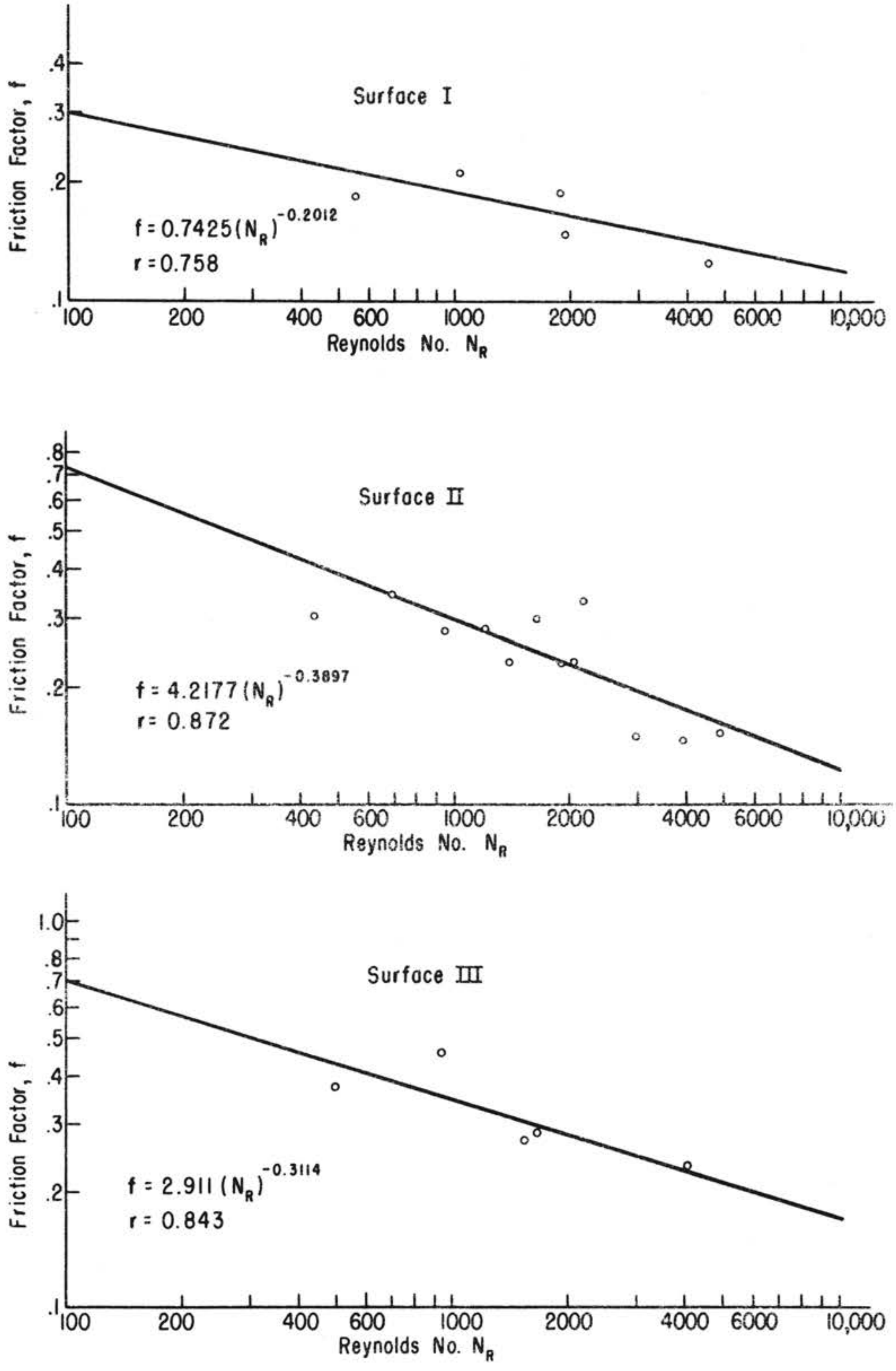

Figure 14. Resistance Coefficients for the Three Surfaces

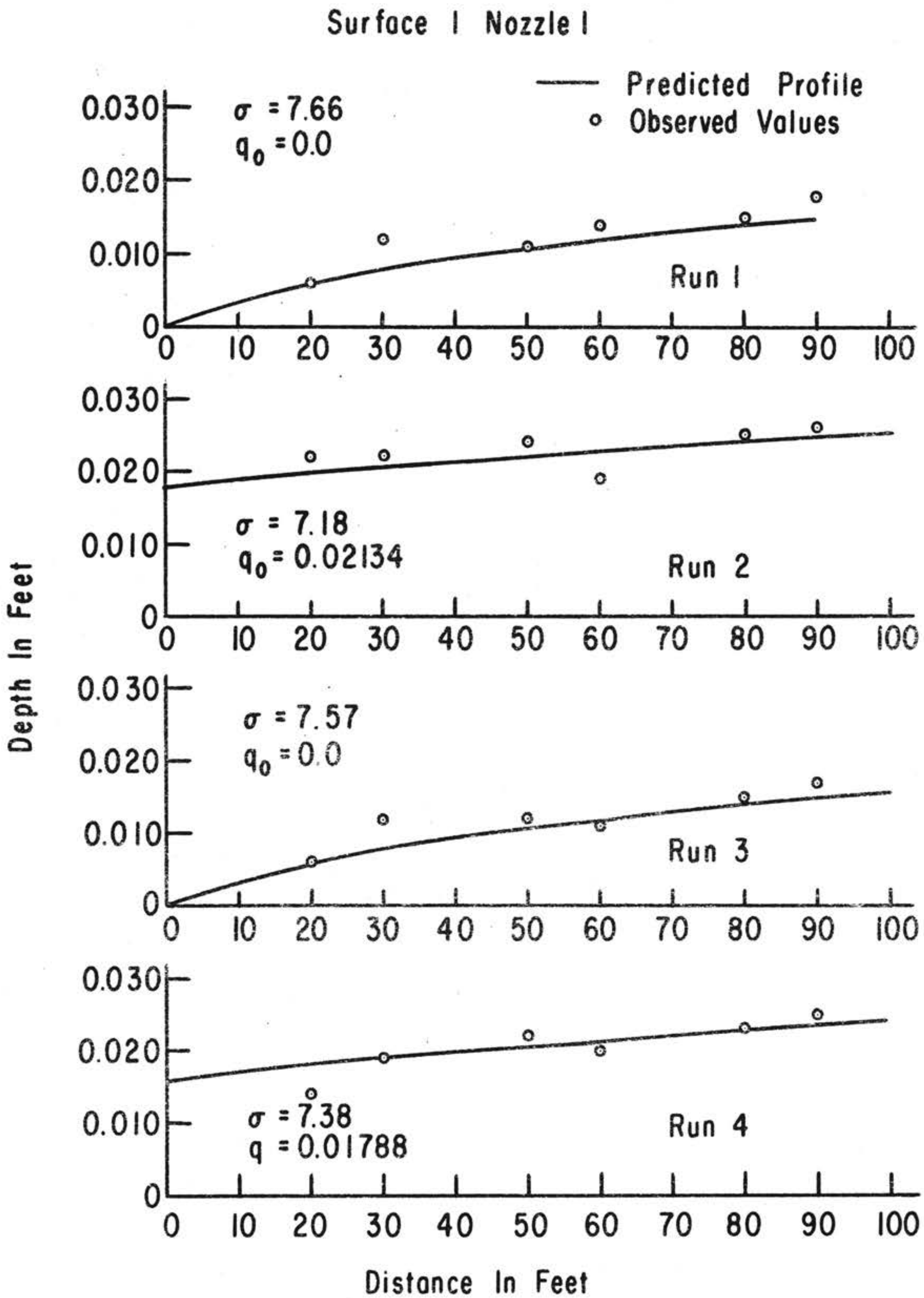

Figure 15. Overland Flow Profiles from Simulated Rain

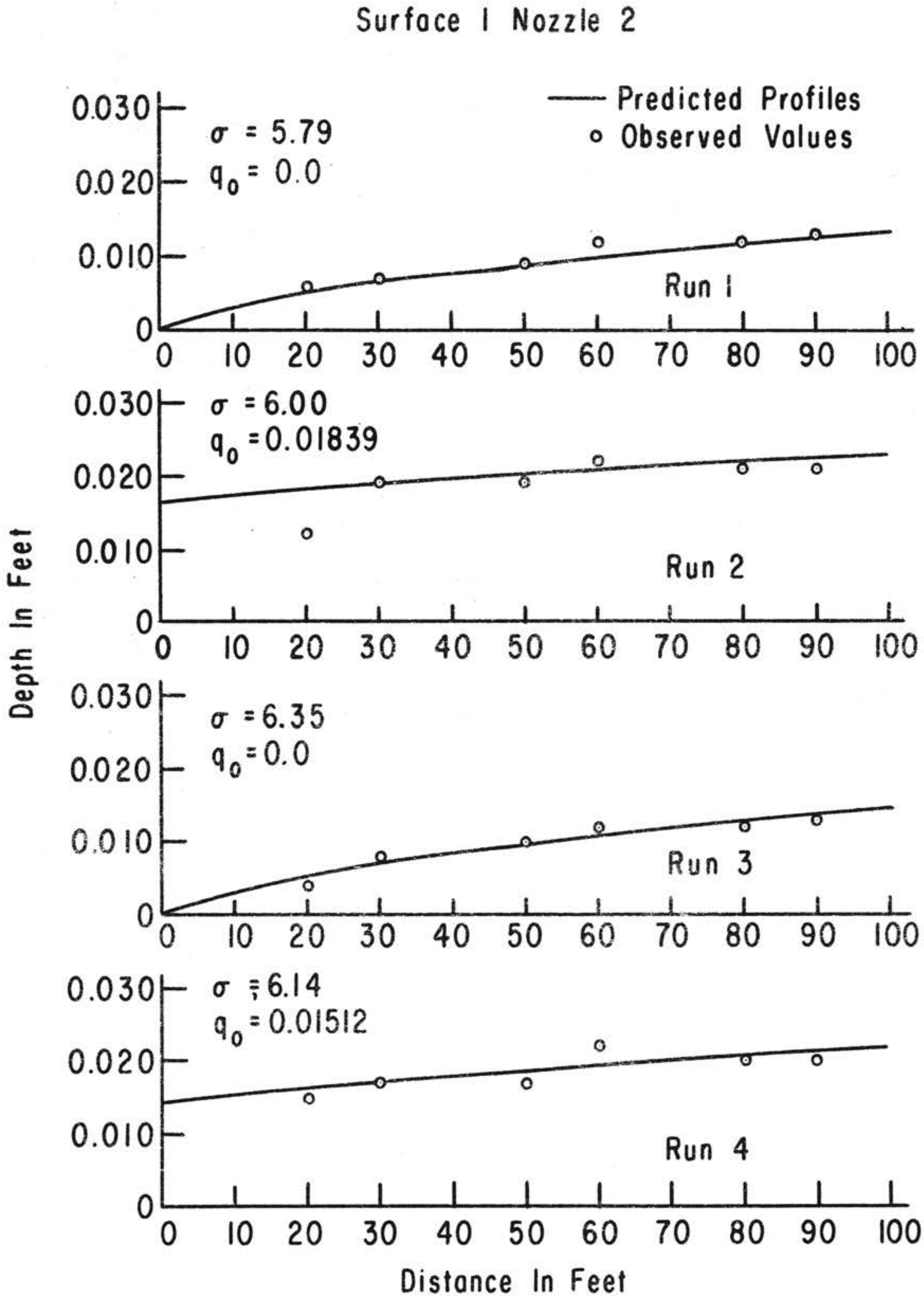

Figure 16. Overland Flow Profiles from Simulated Rain

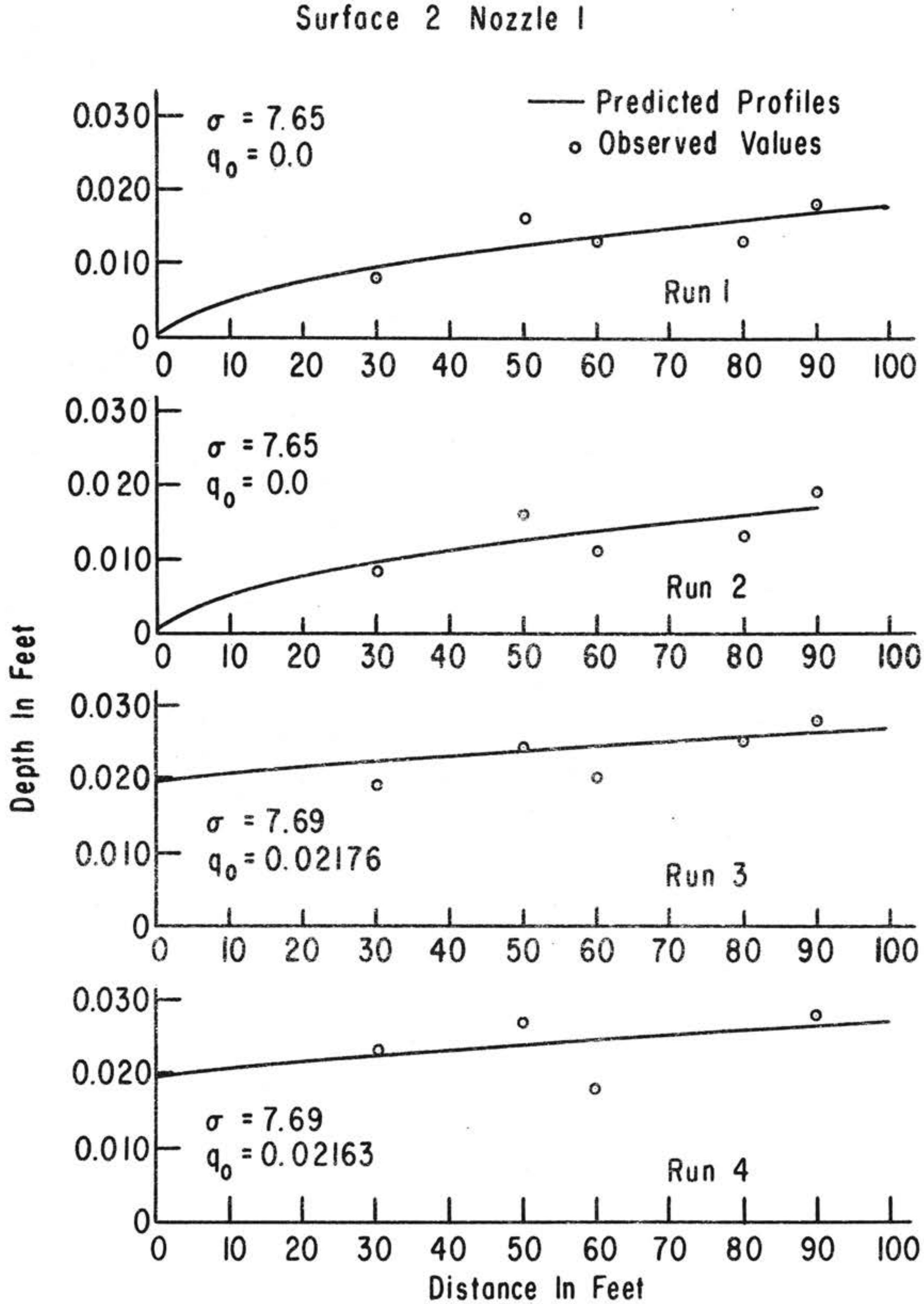

Figure 17. Overland Flow Profiles from Simulated Rain

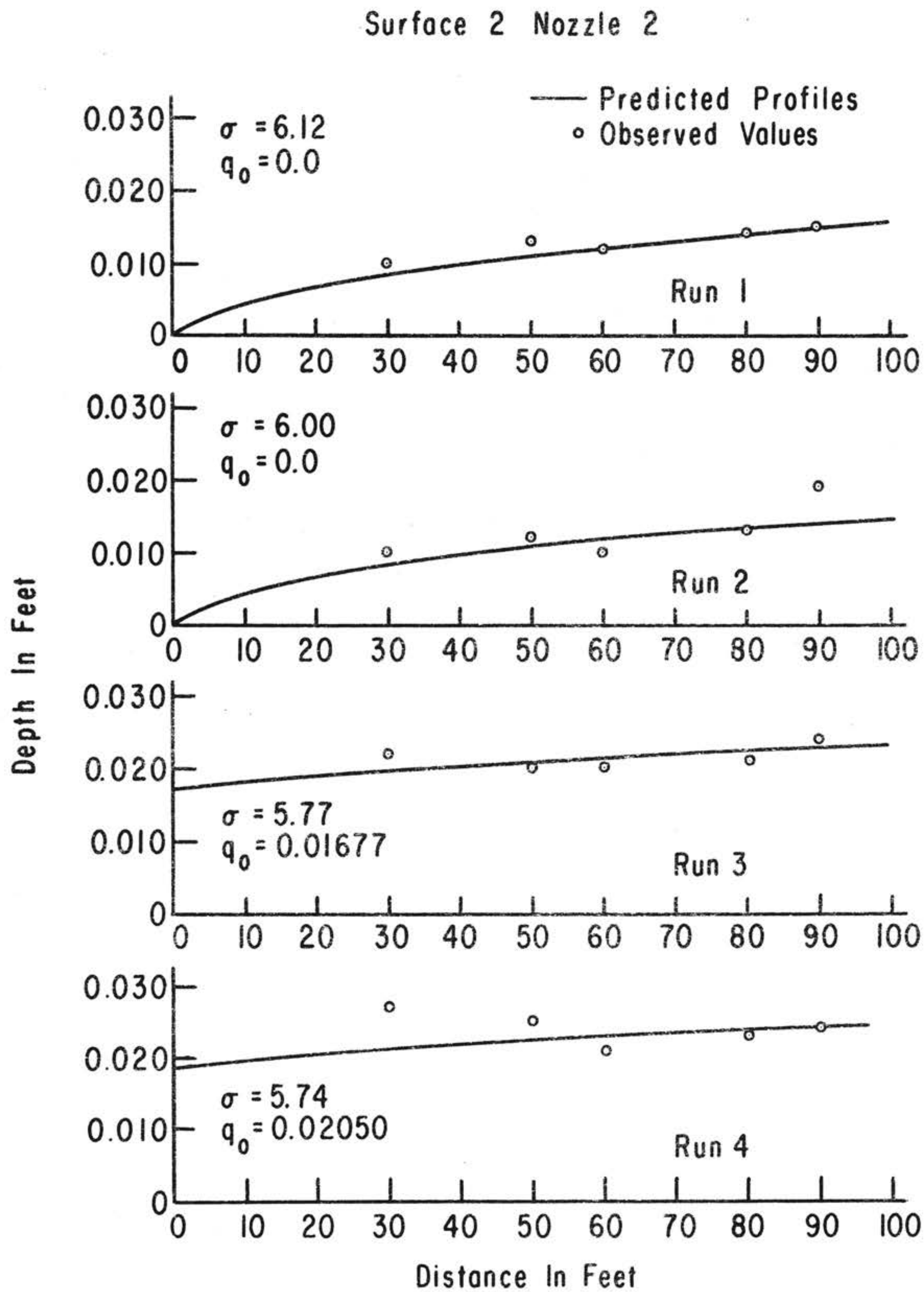

Figure 18. Overland Flow Profiles from Simulated Rain

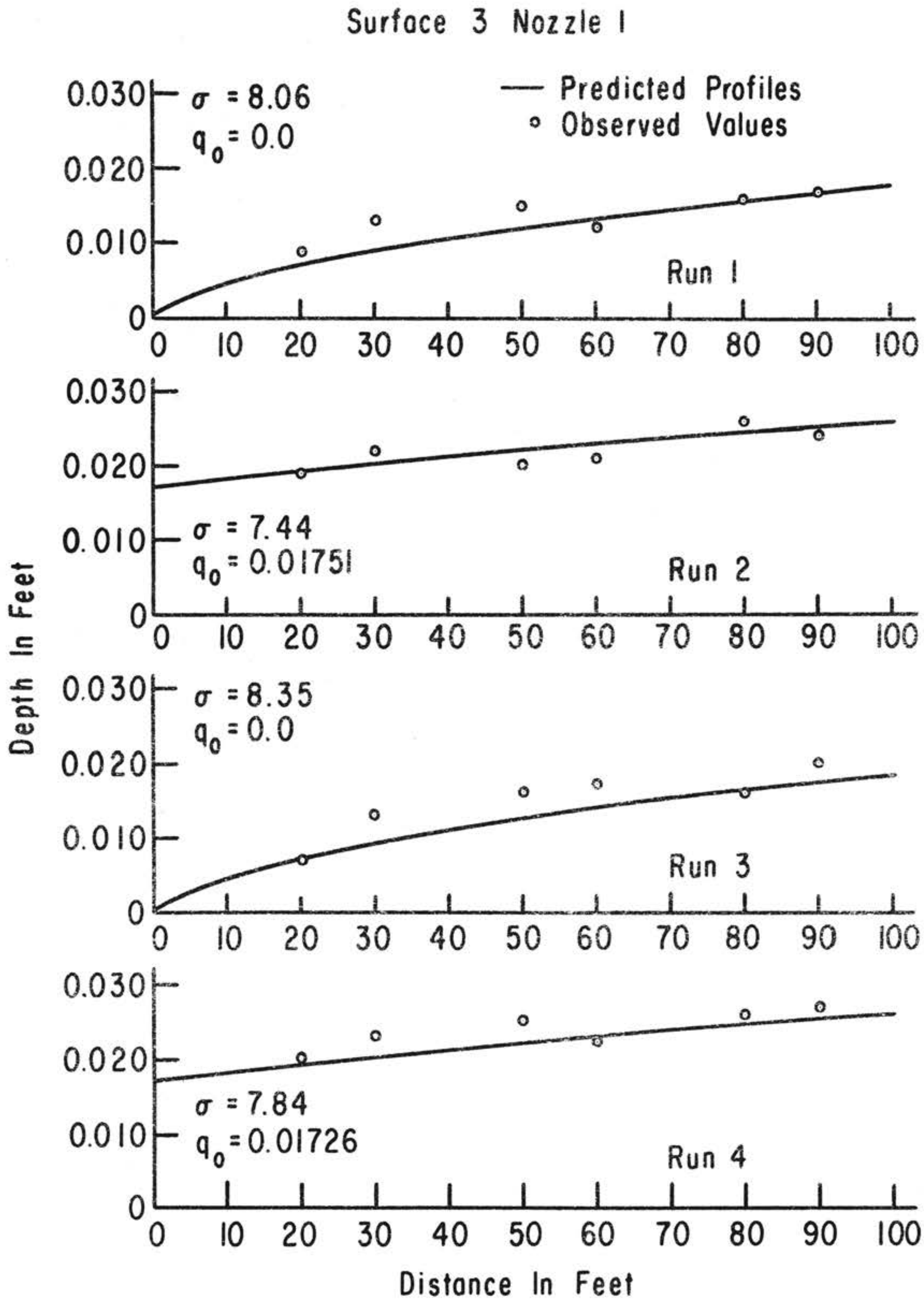

Figure 19. Overland Flow Profiles from Simulated Rain

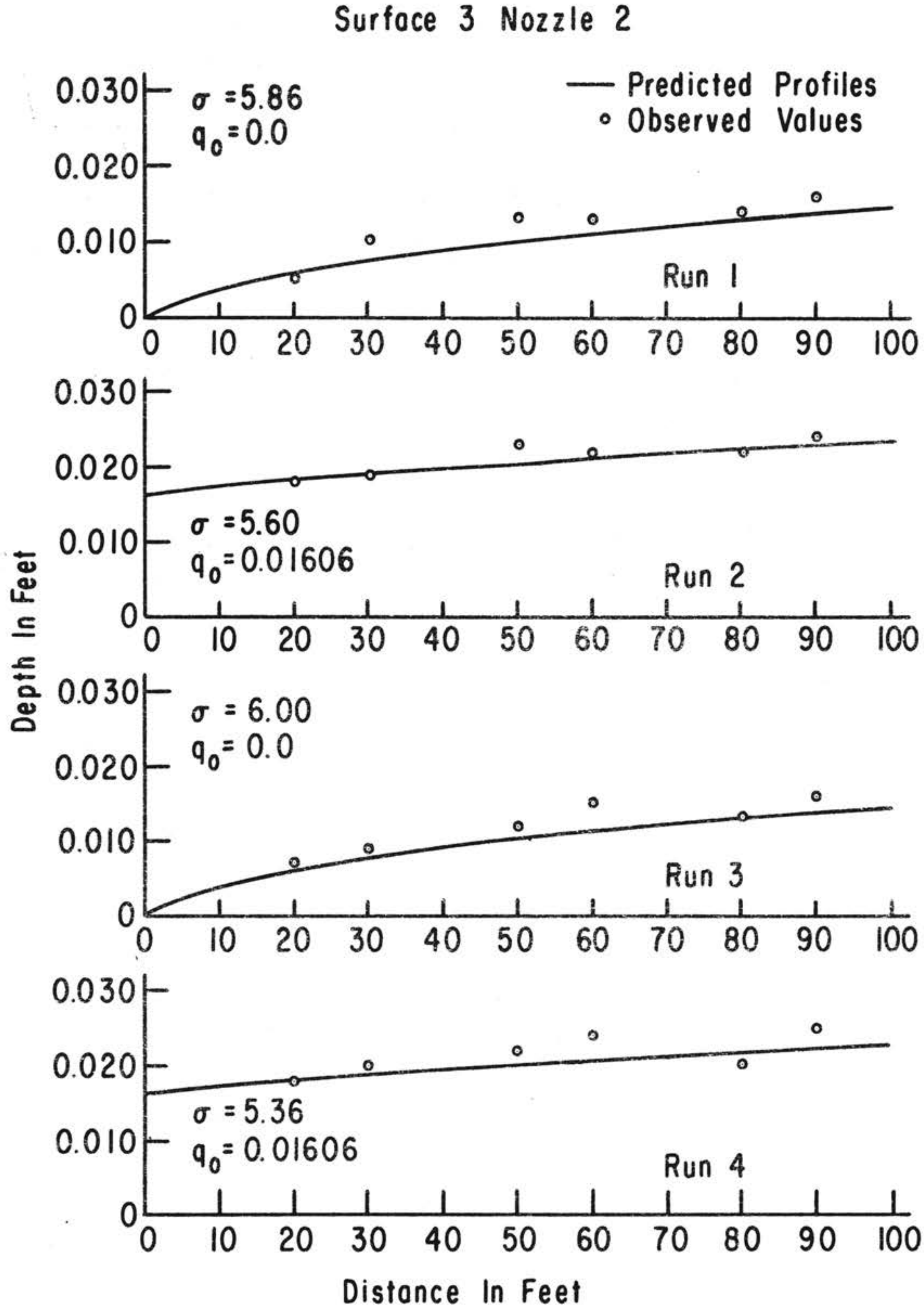

Figure 20. Overland Flow Profiles from Simulated Rain

CHAPTER VII

SUMMARY AND CONCLUSIONS

A theoretical and experimental analysis was made describing the water surface profiles of overland flow over steep rough impervious surfaces. The theoretical analysis resulted in an equation that was solved by trial and error procedures in conjunction with the continuity equation and resistance relation. Digital computer techniques were used to calculate profiles predicted by this method.

The tests were made on a three-foot channel, ninety-six feet long and uniformly sloping at five percent. Three sizes of pea gravel, (average diameters 0.109, 0.160, and 0.219 inches) were glued to the concrete bottom to create roughness. Flow depths were measured with a point gage and with a float actuated linearly variable differential transformer. Rain was simulated with two types of nozzles which produced similar intensities but differed with respect to drop size and velocity. The kinetic energies of these sprays approached that of natural rain.

Resistance characteristics of the surfaces were determined from uniform flow tests. Flows created by the rain simulator provided experimental values with which the theoretical predictions were compared. The results showed good correlation leading to the following conclusions which apply strictly only for conditions similar to those of these tests.

1. Surface drag is of over-riding importance to the overland flow profile.

2. The impact of the spray drops on the water surface had relatively little effect on the resistance coefficient.

3. Turbulence prevailed in all tests made herein.

4. Overland flow over steep rough surfaces may be treated as a quasi-uniform flow. The water surface profiles are adequately described by equation 6 and 7 in conjunction with Figure 14.

Suggestions for Further Study

Since it has been shown that surface resistance is determinant for the overland flow profile under certain conditions it is now necessary to have a greater knowledge of the contribution made to resistance by various land conditions. Tests similar to those reported in this thesis, but with different forms of roughness, would, therefore, be desirable. A lower limit of slope and roughness for the applicability of equation 7 should be investigated.

Further investigations relative to the use of the LVDT and float depth measuring system are desirable due to both the ease of operation of these instruments and the fact that transient conditions may then be studied.

The possibility of an analog solution for the overland flow problem suggests itself as a fruitful area for study. The analysis of transient as well as equilibrium conditions could possibly be made with such an analog.

Further study is desirable to determine the conditions under which flow becomes unstable causing the formation of roll waves. Of particular interest to the Agricultural Engineer would be the effect of rain drops on this instability and the role of these waves in erosion problems.

SELECTED BIBLIOGRAPHY

Appleby, F. V. "Runoff Dynamics." Civil Engineering and Public Works Review. 51: No. 601. pp. 772-774. July, 1956. No. 602. pp. 891-893. August, 1956.

Beij, K. H. "Flow in Roof Gutters." Journal of Research, National Bureau of Standards. 12: pp. 193-213. 1934.

Beutner, E. L., R. R. Gaebe, and R. E. Horton. "Sprinkled-Plat Runoff and Infiltration Experiments on Arizona Desert Soils." Transactions, American Geophysical Union. 21: pp. 550-558. 1940.

Camp, Thomas R. "Lateral Spillway Channels." Transactions, American Society of Civil Engineers. 105: pp. 606-637. 1940.

Chen, Chen-Lung. An Analysis of Overland Flow. Ph.D. Dissertation. Michigan State University Library, 1962.

Chow, Ven T. Open Channel Hydraulics. New York: McGraw-Hill Book Co., Inc., 1959. pp. 148-150.

Hinds, Julian. "Side Channel Spillways: Hydraulic Theory, Economic Factors, and Experimental Determination of Losses." Transactions, American Society of Civil Engineers. 89: pp. 881-939. 1926.

Hopf, L. "Turbulenz bei einen Flusse." Annalen der Physik. Halle and Leipzig. 32: Sec. 4. pp. 778-808. April, July, 1910. Cited by Jefferys. London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science. S-6, 49: p. 793. 1925.

Horner, W. W. and S. W. Jens. "Surface Runoff Determination from Rainfall Without Using Coefficients," Transactions, American Society of Civil Engineers. 107: pp. 1039-1117. 1942.

Horton, R. E. and H. R. Leach and R. Van Vliet. "Laminar Sheet Flow." Transactions, American Geophysical Union. 15: pt. 2. pp. 393-404. 1934.

Horton, R. E. "Hydrologic Interrelations of Water and Soils." Proceedings, Soil Science Society of America. I: pp. 401-429. 1936.

_______. "The Interpretation and Application of Runoff Plot Experiments with Reference to Soil Erosion Problems." Proceedings, Soil Science Society of America. III: pp. 340-349. 1938.

Iwagaki. "Discussion of Laminar to Turbulent Flow in Wide Open Channels." by Owen. pp. 1165-1166. Transactions, American Society of Civil Engineers. 119: pp. 1157-1175. 1954.

Izzard, C. F. and M. T. Augustine. "Preliminary Report on Analysis of Runoff Resulting from Simulated Rainfall on a Paved Plot." Transactions, American Geophysical Union. 24: pp. 500-509. 1943.

Izzard, C. F. "The Surface Profile of Overland Flow." Transactions, American Geophysical Union. 25: pp. 959-968. 1944.

______. "Hydraulics of Runoff from Developed Surfaces." Proceedings, Twenty-Sixth Annual Meeting of the Highway Research Board. 26: pp. 129-146. 1946.

Jeffreys, Harold. "The Flow of Water in an Inclined Channel of Rectangular Section." London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science. S-6, 49: pp. 793-807. 1925.

Keulegan, G. H. "Spatially Variable Discharge Over a Sloping Plane." Transactions, American Geophysical Union. pp. 956-959. 1944.

Laws, J. O. "Measurements of the Fall-Velocity of Water-Drops and Raindrops." Transactions, American Geophysical Union. 22: pp. 709-721. 1941.

Laws, J. O. and D. P. Parsons. "The Relation of Raindrop - Size to Intensity." Transactions, American Geophysical Union. 24: pp. 452-460. 1943.

Li, Wen-Hsiung. "Open Channels with Monuniform Discharge." Transactions, American Society of Civil Engineers. 120: pp. 255-280. 1955.

Liggett, J. A. Unsteady Open Channel Flow with Lateral Inflow. Department of Civil Engineering, Stanford University, Technical Report. No. 2, 73 pages. 1959.

Meyer, Donald L. "An Investigation of Methods for Simulating Rainfall on Standard Runoff Plots and a Study of the Drop Size, Velocity, and Kinetic Energy of Selected Spray Nozzles." Special Report No. 81, Eastern Soil and Water Management Research Branch. Soil and Water Conservation Research Division, ARS, USDA. May, 1958.

Meyer-Peter, Dr. E. and Dr. Henry Favre. "Analysis of Boulder Dam Spillways Made by Swiss Laboratory." Eng. News Record. pp. 520-522. October 25, 1934.

Owen, W. M. "Laminar to Turbulent Flow in a Wide Open Channel." Transactions, American Society of Civil Engineers. 119: pp. 1157-1175. 1954.

Parsons, D. A. <u>Depths of Overland Flow</u>. Soil Conservations Service Technical Paper 82. 1949.

Ree, W. O. "Some Experiments on Shallow Flows Over a Grassed Slope." <u>Transactions, American Geophysical Union</u>. 20: pp. 653-656. 1939.

Staub, Lorenz G. "Studies of the Transition-Region Between Laminar and Turbulent Flow in Open Channels." <u>Transactions, American Geophysical Union</u>. 20: pp. 649-653. 1939.

Turner, A. K. Unpublished Report to the Agricultural Engineering Department, Oklahoma State University, on Project 758, Overland Flow. 1963.

Wischmeier, W. H. and Dwight D. Smith. "Rainfall Energy and its Relationship to Soil Loss." <u>Transactions, American Geophysical Union</u>. 39: No. 2. pp. 285-291. 1958.

Woo, Dah-Cheng. <u>Study of Overland Flow</u>. Ph.D. Dissertation. University of Michigan Library, January, 1956.

Woo, D. C. and E. F. Brater. "Laminar Flow in Rough Rectangular Channels." <u>Transactions, American Geophysical Union</u>. 66: No. 12. pp. 4207-4217. 1961.

Woo, D. C. "Spatially Varied Flow from Controlled Rainfall." <u>Journal of the Hydraulics Division - Proceedings of the American Society of Civil Engineers</u>. 88: No. HY-6, pp. 31-56. 1962.

Yu, Y. S. and J. S. McKnown. <u>Runoff from Impervious Surfaces</u>. Contract Report No. 2-66, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. February, 1963.

APPENDIX A

SYMBOLS AND NOTATIONS

SYMBOLS AND NOTATIONS

ρ - mass density, lbm/ft^3

q_o - initial inflow per foot of width, cfs/ft

q - flow rate per foot of width, cfs/ft

u - average velocity of flow, ft/sec

r - rain intensity, ft/sec

ℓ - distance down the channel, ft

v - velocity of raindrops, vertical, ft/sec

p - pressure, psf

y - depth, ft

g - local gravitational acceleration, ft/sec^2

θ - channel slope, degrees

S_o - channel slope, ft/ft

S_f - friction slope, ft/ft

W - weight, lb_f

f - Darcy-Weisbach resistance coefficient

τ - unit shearing force per foot of width, $lbs/ft^2/ft$

x - horizontal distance, ft

F - friction force, lb_f

ν - kinematic viscosity, ft^2/sec

σ - rain intensity, iph

APPENDIX B

COMPUTER SOLUTION FOR STEADY STATE OVERLAND FLOW PROFILES

COMPUTER SOLUTION FOR STEADY STATE OVERLAND FLOW PROFILES FOR USE ON IBM 1620 BY AL ROBERTSON

SIGMA = RAINFALL RATE, FT./ SEC.
VISC = KINEMATIC VISCOSITY, SQ FT / SEC.
COFT = COEFFICIENT IN DARCY WEISBACH RESISTANCE EQUATION.
POWR = EXPONENT IN DARCY WEISBACH RESISTANCE EQUATION
QO = INITIAL INFLOW, CFS/FT.
DELX = INCREMENT OF DISTANCE, FT.
BITE = INCREMENT OF DEPTH, FT.
DIST = DISTANCE DOWN THE CHANNEL, FT.
DEPA = ASSUMED DEPTH, FT.
DEPC = CALCULATED DEPTH, FT.
REN = REYNOLDS NUMBER

```
1      READ 38, SIGMA, VISC, COFT, POWR, QO, DELX, BITE
2      IF(SENSE SWITCH 1)3, 6
3      TYPE 39
4      TYPE 40
5      GO TO 8
6      PUNCH 39
7      PUNCH 40
8      U = 0.0
9      BIT = 0.0
10     UH = 0.0
11     DIST = 0.0
12     FRICT = 0.0
       IF(QO)1, 36, 13
13     UH = (SIGMA*DIST) + QO
14     BIT = BITE
15     L = 0
16     REN = UH/VISC
17     FRICT = COFT/(REN**POWR)
18     DEPA = 0.0001
19     U = UH/DEPA
20     DEPC = FRICT*(U*U)/12.7728
21     DIFF = DEPC - DEPA
22     IF(DIFF)26, 31, 23
23     IF(DIFF - 0.0001)31, 31, 24
24     DEPA = DEPA + BIT
25     GO TO 19
26     IF(DIFF + 0.0001)27, 31, 31
27     DEPA = DEPA - BIT
```

```
28    BIT = BIT/2.0
29    L = L + 1
30    IF(10 - L)31, 31, 24
31    IF(SENSE SWITCH 1)32, 34
32    TYPE 41, DIST, DEPA, DEPC, REN
33    IF(100.0 - DIST)1, 1, 36
34    PUNCH 41, DIST, DEPA, DEPC, REN
35    GO TO 33
36    DIST = DIST + DELX
37    GO TO 13
38    FORMAT (1X,E10.3,E11.3, F8.4,F8.4, F9.6,F6.1,F7.3)
39    FORMAT (28H  SURFACE    NOZZLE     RUN    ,/)
40    FORMAT (30H  DIST     DEPA     DEPC    REN     ,)
41    FORMAT (F6.1,1X,F7.4,1X,F7.4,1X,F6.0)
42    END
```

APPENDIX C

INPUT DATA FOR PROFILE COMPUTATION

INPUT DATA FOR PROFILE COMPUTATION

SURFACE 1 NOZZLE 1

RUN	SIGMA	VISC	COFT	POWR	QO	DELX	BITE
1	1.773E-04	0.930E-05	0.5303	0.1524	0.0	10.0	0.008
2	1.662E-04	0.930E-05	0.5303	0.1524	0.02134	10.0	0.016
3	1.752E-04	0.876E-05	0.5303	0.1524	0.0	10.0	0.008
4	1.708E-04	0.876E-05	0.5303	0.1524	0.01788	10.0	0.016

SURFACE 1 NOZZLE 2

RUN	SIGMA	VISC	COFT	POWR	QO	DELX	BITE
1	1.341E-04	0.930E-05	0.5303	0.1524	0.0	10.0	0.008
2	1.388E-04	0.930E-05	0.5303	0.1524	0.01839	10.0	0.016
3	1.469E-04	0.930E-05	0.5303	0.1524	0.0	10.0	0.008
4	1.421E-04	0.930E-05	0.5303	0.1524	0.01512	10.0	0.016

SURFACE 2 NOZZLE 1

RUN	SIGMA	VISC	COFT	POWR	QO	DELX	BITE
1	1.771E-04	0.876E-05	4.2177	0.3897	0.0	10.0	0.008
2	1.771E-04	0.876E-05	4.2177	0.3897	0.0	10.0	0.008
3	1.780E-04	0.876E-05	4.2177	0.3897	0.02176	10.0	0.016
4	1.780E-04	0.930E-05	4.2177	0.3897	0.02163	10.0	0.016

SURFACE 2 NOZZLE 2

RUN	SIGMA	VISC	COFT	POWR	QO	DELX	BITE
1	1.418E-04	0.930E-05	4.2177	0.3897	0.0	10.0	0.008
2	1.389E-04	0.930E-05	4.2177	0.3897	0.0	10.0	0.008
3	1.335E-04	0.930E-05	4.2177	0.3897	0.01677	10.0	0.016
4	1.328E-04	0.876E-05	4.2177	0.3897	0.02050	10.0	0.016

SURFACE 3 NOZZLE 1

RUN	SIGMA	VISC	COFT	POWR	QO	DELX	BITE
1	1.865E-04	0.930E-05	1.1123	0.2223	0.0	10.0	0.008
2	1.722E-04	0.930E-05	1.1123	0.2223	0.01751	10.0	0.016
3	1.934E-04	0.991E-05	1.1123	0.2223	0.0	10.0	0.008
4	1.816E-04	0.991E-05	1.1123	0.2223	0.01726	10.0	0.016

SURFACE 3 NOZZLE 2

RUN	SIGMA	VISC	COFT	POWR	QO	DELX	BITE
1	1.356E-04	0.991E-05	1.1123	0.2223	0.0	10.0	0.008
2	1.296E-04	0.991E-05	1.1123	0.2223	0.01606	10.0	0.016
3	1.388E-04	0.991E-05	1.1123	0.2223	0.0	10.0	0.008
4	1.241E-04	0.991E-05	1.1123	0.2223	0.01606	10.0	0.016

APPENDIX D

THEORETICALLY PREDICTED OVERLAND FLOW PROFILES

THEORETICALLY PREDICTED OVERLAND FLOW PROFILES

SURFACE 1 NOZZLE 1 RUN 1

DIST	DEPA	DEPC	REN
10.0	.0039	.0038	190.
20.0	.0059	.0059	381.
30.0	.0076	.0076	571.
40.0	.0091	.0091	762.
50.0	.0104	.0104	953.
60.0	.0117	.0116	1143.
70.0	.0128	.0129	1334.
80.0	.0139	.0139	1525.
90.0	.0150	.0150	1715.
100.0	.0160	.0160	1906.

SURFACE 1 NOZZLE 1 RUN 2

DIST	DEPA	DEPC	REN
.0	.0179	.0179	2294.
10.0	.0188	.0187	2473.
20.0	.0196	.0196	2652.
30.0	.0204	.0204	2830.
40.0	.0212	.0212	3009.
50.0	.0220	.0219	3188.
60.0	.0227	.0227	3366.
70.0	.0234	.0235	3545.
80.0	.0242	.0242	3724.
90.0	.0249	.0249	3903.
100.0	.0256	.0255	4081.

SURFACE 1 NOZZLE 1 RUN 3

DIST	DEPA	DEPC	REN
10.0	.0038	.0038	200.
20.0	.0059	.0058	400.
30.0	.0075	.0076	600.
40.0	.0090	.0090	800.
50.0	.0103	.0103	1000.
60.0	.0116	.0115	1200.
70.0	.0127	.0127	1400.
80.0	.0138	.0138	1600.
90.0	.0148	.0149	1800.
100.0	.0158	.0159	2000.

SURFACE 1 NOZZLE 1 RUN 4

DIST	DEPA	DEPC	REN
.0	.0161	.0160	2041.
10.0	.0169	.0170	2236.
20.0	.0179	.0178	2431.
30.0	.0187	.0187	2626.
40.0	.0196	.0196	2821.
50.0	.0204	.0203	3015.
60.0	.0212	.0213	3210.
70.0	.0220	.0220	3405.
80.0	.0227	.0228	3600.
90.0	.0235	.0235	3795.
100.0	.0242	.0243	3990.

SURFACE 1 NOZZLE 2 RUN 1

DIST	DEPA	DEPC	REN
10.0	.0032	.0032	144.
20.0	.0050	.0049	288.
30.0	.0064	.0064	432.
40.0	.0076	.0077	576.
50.0	.0087	.0088	720.
60.0	.0098	.0098	865.
70.0	.0108	.0108	1009.
80.0	.0117	.0117	1153.
90.0	.0126	.0126	1297.
100.0	.0134	.0135	1441.

SURFACE 1 NOZZLE 2 RUN 2

DIST	DEPA	DEPC	REN
.0	.0164	.0163	1977.
10.0	.0171	.0171	2126.
20.0	.0179	.0178	2275.
30.0	.0186	.0186	2425.
40.0	.0192	.0193	2574.
50.0	.0199	.0199	2723.
60.0	.0206	.0206	2872.
70.0	.0212	.0213	3022.
80.0	.0219	.0218	3171.
90.0	.0226	.0225	3320.
100.0	.0232	.0231	3469.

SURFACE 1 NOZZLE 2 RUN 3

DIST	DEPA	DEPC	REN
10.0	.0034	.0034	157.
20.0	.0052	.0053	315.
30.0	.0067	.0068	473.
40.0	.0081	.0081	631.
50.0	.0093	.0092	789.
60.0	.0104	.0104	947.
70.0	.0114	.0114	1105.
80.0	.0124	.0124	1263.
90.0	.0134	.0133	1421.
100.0	.0142	.0142	1579.

SURFACE 1 NOZZLE 2 RUN 4

DIST	DEPA	DEPC	REN
.0	.0145	.0145	1625.
10.0	.0153	.0154	1778.
20.0	.0161	.0161	1931.
30.0	.0169	.0168	2084.
40.0	.0177	.0176	2236.
50.0	.0184	.0184	2389.
60.0	.0191	.0191	2542.
70.0	.0198	.0198	2695.
80.0	.0205	.0205	2848.
90.0	.0212	.0211	3000.
100.0	.0218	.0219	3153.

SURFACE 2 NOZZLE 1 RUN 1

DIST	DEPA	DEPC	REN
10.0	.0051	.0050	202.
20.0	.0073	.0073	404.
30.0	.0091	.0091	606.
40.0	.0106	.0107	808.
50.0	.0120	.0120	1010.
60.0	.0132	.0132	1213.
70.0	.0144	.0144	1415.
80.0	.0154	.0155	1617.
90.0	.0165	.0164	1819.
100.0	.0174	.0174	2021.

SURFACE 2 NOZZLE 1 RUN 2

DIST	DEPA	DEPC	REN
10.0	.0051	.0050	202.
20.0	.0073	.0073	404.
30.0	.0091	.0091	606.
40.0	.0106	.0107	808.
50.0	.0120	.0120	1010.
60.0	.0132	.0132	1213.
70.0	.0144	.0144	1415.
80.0	.0154	.0155	1617.
90.0	.0165	.0164	1819.
100.0	.0174	.0174	2021.

SURFACE 2 NOZZLE 1 RUN 3

DIST	DEPA	DEPC	REN
.0	.0195	.0194	2484.
10.0	.0203	.0203	2687.
20.0	.0211	.0211	2890.
30.0	.0219	.0219	3093.
40.0	.0227	.0226	3296.
50.0	.0234	.0234	3500.
60.0	.0241	.0242	3703.
70.0	.0248	.0249	3906.
80.0	.0256	.0255	4109.
90.0	.0262	.0262	4312.
100.0	.0269	.0268	4515.

SURFACE 2 NOZZLE 1 RUN 4

DIST	DEPA	DEPC	REN
.0	.0196	.0196	2325.
10.0	.0204	.0204	2517.
20.0	.0212	.0212	2708.
30.0	.0221	.0220	2900.
40.0	.0228	.0228	3091.
50.0	.0236	.0235	3282.
60.0	.0242	.0243	3474.
70.0	.0250	.0249	3665.
80.0	.0257	.0257	3856.
90.0	.0264	.0263	4048.
100.0	.0270	.0270	4239.

SURFACE 2 NOZZLE 2 RUN 1

DIST	DEPA	DEPC	REN
10.0	.0045	.0045	152.
20.0	.0066	.0065	304.
30.0	.0081	.0082	457.
40.0	.0095	.0095	609.
50.0	.0107	.0107	762.
60.0	.0118	.0119	914.
70.0	.0129	.0128	1067.
80.0	.0138	.0138	1219.
90.0	.0147	.0147	1372.
100.0	.0156	.0156	1524.

SURFACE 2 NOZZLE 2 RUN 2

DIST	DEPA	DEPC	REN
10.0	.0044	.0045	149.
20.0	.0065	.0064	298.
30.0	.0081	.0080	448.
40.0	.0094	.0094	597.
50.0	.0106	.0106	746.
60.0	.0117	.0117	896.
70.0	.0127	.0127	1045.
80.0	.0137	.0136	1194.
90.0	.0146	.0146	1344.
100.0	.0154	.0154	1493.

SURFACE 2 NOZZLE 2 RUN 3

DIST	DEPA	DEPC	REN
.0	.0171	.0170	1803.
10.0	.0178	.0177	1946.
20.0	.0185	.0184	2090.
30.0	.0191	.0192	2233.
40.0	.0198	.0198	2377.
50.0	.0204	.0204	2520.
60.0	.0211	.0210	2664.
70.0	.0216	.0217	2808.
80.0	.0222	.0222	2951.
90.0	.0228	.0228	3095.
100.0	.0234	.0234	3238.

SURFACE 2 NOZZLE 2 RUN 4

DIST	DEPA	DEPC	REN
.0	.0189	.0188	2340.
10.0	.0195	.0195	2491.
20.0	.0201	.0202	2643.
30.0	.0207	.0207	2794.
40.0	.0214	.0213	2946.
50.0	.0219	.0219	3098.
60.0	.0225	.0225	3249.
70.0	.0231	.0230	3401.
80.0	.0236	.0236	3552.
90.0	.0241	.0242	3704.
100.0	.0247	.0246	3856.

SURFACE 3 NOZZLE 1 RUN 1

DIST	DEPA	DEPC	REN
10.0	.0045	.0045	200.
20.0	.0068	.0068	401.
30.0	.0087	.0086	601.
40.0	.0102	.0103	802.
50.0	.0117	.0117	1002.
60.0	.0131	.0131	1203.
70.0	.0143	.0143	1403.
80.0	.0155	.0155	1604.
90.0	.0166	.0166	1804.
100.0	.0177	.0177	2005.

SURFACE 3 NOZZLE 1 RUN 2

DIST	DEPA	DEPC	REN
.0	.0171	.0170	1882.
10.0	.0181	.0180	2067.
20.0	.0190	.0189	2253.
30.0	.0199	.0199	2438.
40.0	.0207	.0208	2623.
50.0	.0216	.0216	2808.
60.0	.0224	.0225	2993.
70.0	.0232	.0233	3178.
80.0	.0241	.0241	3364.
90.0	.0249	.0248	3549.
100.0	.0256	.0256	3734.

SURFACE 3 NOZZLE 1 RUN 3

DIST	DEPA	DEPC	REN
10.0	.0046	.0046	195.
20.0	.0070	.0069	390.
30.0	.0089	.0089	585.
40.0	.0106	.0105	780.
50.0	.0121	.0120	975.
60.0	.0134	.0134	1170.
70.0	.0147	.0147	1366.
80.0	.0159	.0159	1561.
90.0	.0171	.0171	1756.
100.0	.0182	.0181	1951.

SURFACE 3 NOZZLE 1 RUN 4

DIST	DEPA	DEPC	REN
.0	.0170	.0170	1741.
10.0	.0181	.0180	1924.
20.0	.0191	.0190	2108.
30.0	.0200	.0200	2291.
40.0	.0209	.0209	2474.
50.0	.0218	.0219	2657.
60.0	.0227	.0228	2841.
70.0	.0236	.0236	3024.
80.0	.0244	.0244	3207.
90.0	.0252	.0252	3390.
100.0	.0261	.0260	3574.

SURFACE 3 NOZZLE 2 RUN 1

DIST	DEPA	DEPC	REN
10.0	.0037	.0037	136.
20.0	.0056	.0057	273.
30.0	.0072	.0072	410.
40.0	.0086	.0085	547.
50.0	.0097	.0097	684.
60.0	.0109	.0108	820.
70.0	.0119	.0118	957.
80.0	.0129	.0129	1094.
90.0	.0138	.0139	1231.
100.0	.0147	.0147	1368.

SURFACE 3 NOZZLE 2 RUN 2

DIST	DEPA	DEPC	REN
.0	.0163	.0162	1620.
10.0	.0171	.0170	1751.
20.0	.0178	.0177	1882.
30.0	.0185	.0185	2012.
40.0	.0192	.0192	2143.
50.0	.0199	.0198	2274.
60.0	.0206	.0206	2405.
70.0	.0212	.0212	2536.
80.0	.0219	.0219	2666.
90.0	.0225	.0225	2797.
100.0	.0231	.0231	2928.

SURFACE 3 NOZZLE 2 RUN 3

DIST	DEPA	DEPC	REN
10.0	.0038	.0037	140.
20.0	.0057	.0057	280.
30.0	.0073	.0072	420.
40.0	.0087	.0086	560.
50.0	.0099	.0099	700.
60.0	.0110	.0110	840.
70.0	.0121	.0121	980.
80.0	.0131	.0131	1120.
90.0	.0140	.0141	1260.
100.0	.0149	.0149	1400.

SURFACE 3 NOZZLE 2 RUN 4

DIST	DEPA	DEPC	REN
.0	.0163	.0162	1620.
10.0	.0170	.0170	1745.
20.0	.0177	.0177	1871.
30.0	.0184	.0184	1996.
40.0	.0191	.0190	2121.
50.0	.0197	.0198	2246.
60.0	.0204	.0203	2371.
70.0	.0211	.0210	2497.
80.0	.0217	.0216	2622.
90.0	.0222	.0223	2747.
100.0	.0229	.0228	2872.

APPENDIX E

EXPERIMENTAL DATA

PART A
UNIFORM FLOWS

SURFACE 1

DEPTHS ABOVE MEASURED BOTTOM (FT)

TEST NO	1	2	3	4	5
STATION					
0 + 20	0.026	0.014	0.009	0.008	0.013
0 + 30	0.028	0.018	0.013	0.007	0.018
0 + 50	0.028	0.017	0.017	0.009	0.018
0 + 60	0.024	0.012	0.009	0.006	0.016
0 + 80	0.027	0.014	0.009	0.007	0.015
0 + 90	0.026	0.014	0.007	0.004	0.015
AVE	0.026	0.015	0.011	0.007	0.016

FLOW RATE (CFS)

TEST NO	1	2	3	4	5
ORIFICE	0.1232	0.04961	0.02615	0.01430	0.04844
H-FLUME (IN)	-	0.04683	0.02254	0.01479	0.04856

SURFACE 2

DEPTHS ABOVE MEASURED BOTTOM (FT)

TEST NO	1	2	3	4	5	6	7
STATION							
0 + 20	0.021	0.020	0.022	0.022	0.020	0.026	0.033
0 + 30	0.010	0.014	0.016	0.017	0.017	0.021	0.025
0 + 50	0.008	0.011	0.014	0.015	0.015	0.018	0.024
0 + 60	0.006	0.010	0.011	0.013	0.014	0.019	0.023
0 + 80	0.011	0.017	0.018	0.020	0.019	0.024	0.029
0 + 90	0.003	0.007	0.013	0.013	0.013	0.017	0.020
AVE	0.008	0.012	0.014	0.017	0.017	0.020	0.024

TEST NO	8	9	10	11	12
STATION					
0 + 20	0.035	-	0.022	0.018	0.015
0 + 30	0.028	0.017	0.013	0.010	0.012
0 + 50	0.028	0.015	0.012	0.008	0.015
0 + 60	0.027	0.020	0.016	0.006	0.014
0 + 80	0.032	0.020	0.017	0.014	0.017
0 + 90	0.023	0.018	0.014	0.010	0.013
AVE	0.028	0.018	0.014	0.010	0.014

PART A (CTD)
SURFACE 2

FLOW RATE (CFS)

TEST NO	1	2	3	4	5
ORIFICE	0.01344	0.02589	0.03246	0.04219	0.04844
H-FLUME (IN)	-	-	-	-	-

TEST NO	6	7	8	9	10
ORIFICE	0.07622	0.1009	0.1248	0.05187	0.02970
H-FLUME (IN)	-	-	-	-	-

TEST NO	11	12
ORIFICE	0.01771	0.03566
H-FLUME (IN)	-	0.03510

SURFACE 3

DEPTHS ABOVE MEASURED BOTTOM

TEST NO	1	2	3	4	5
STATION					
0 + 20	0.006	0.013	0.015	0.030	0.016
0 + 30	0.011	0.015	0.018	0.028	0.018
0 + 50	0.009	0.014	0.014	0.026	0.020
0 + 60	0.008	0.012	0.015	0.024	0.017
0 + 80	0.011	0.015	0.018	0.029	0.017
0 + 90	0.010	0.013	0.017	0.028	0.018
AVE	0.009	0.014	0.016	0.028	0.018

FLOW RATE (CFS)

TEST NO	1	2	3	4	5
ORIFICE	0.01453	0.02557	0.04112	0.1035	0.04785
H-FLUME (IN)	0.01641	0.02391	0.04151	-	0.04822

PART B
SIMULATED RAIN INDUCED FLOWS

SURFACE 1 NOZZLE 1

OBSERVED DEPTH (FT)

TEST NO STATION	1	2	3	4
0 + 20	0.005	0.021	0.005	0.013
0 + 30	0.014	0.024	0.014	0.021
0 + 50	0.014	0.027	0.015	0.025
0 + 60	0.012	0.017	0.009	0.018
0 + 80	0.014	0.024	0.014	0.022
0 + 90	0.016	0.024	0.015	0.023

FLOW RATE (CFS)

TEST NO	1	2	3	4
ORIFICE	0.06724	0.1269	0.06724	0.1189
VOLUMETRIC	0.06849	0.06604	0.06574	0.06652
NTH GUTTER	0.00892	0.00844	0.00882	0.00918
STH GUTTER	0.00868	0.00968	0.00936	0.00975
INFLOW	-	0.06223	-	0.05216

SURFACE 1 NOZZLE 2

OBSERVED DEPTH (FT)

TEST NO STATION	1	2	3	4
0 + 20	0.005	0.016	0.003	0.014
0 + 30	0.009	0.021	0.010	0.019
0 + 50	0.012	0.021	0.013	0.020
0 + 60	0.010	0.020	0.010	0.020
0 + 80	0.011	0.020	0.011	0.019
0 + 90	0.011	0.019	0.011	0.018

FLOW RATE (CFS)

TEST NO	1	2	3	4
ORIFICE	0.04932	0.1012	0.04961	0.09266
VOLUMETRIC	0.05184	0.04993	0.04960	0.05236
NTH GUTTER	0.00684	0.00380	0.00319	0.00215
STH GUTTER	0.00492	0.00491	0.00529	0.00660
INFLOW	-	0.05364	-	0.04411

PART B (CTD)

SURFACE 2 NOZZLE 1

OBSERVED DEPTH (FT)

TEST NO STATION	1	2	3	4
0 + 20	0.009	0.013	0.021	0.020
0 + 30	0.008	0.008	0.019	0.023
0 + 50	0.015	0.015	0.023	0.026
0 + 60	0.012	0.010	0.019	0.018
0 + 80	0.017	0.017	0.029	-
0 + 90	0.015	0.016	0.025	0.025

FLOW RATE (CFS)

TEST NO	1	2	3	4
ORIFICE	0.06809	0.06724	0.1286	-
VOLUMETRIC	-	-	-	-
NTH GUTTER	-	0.00439	0.00203	0.00629
STH GUTTER	-	0.01326	0.01328	0.01136
INFLOW	-	-	0.06346	0.05823

SURFACE 2 NOZZLE 2

OBSERVED DEPTH (FT)

TEST NO STATION	1	2	3	4
0 + 20	0.008	0.007	0.018	0.019
0 + 30	0.010	0.010	0.022	0.027
0 + 50	0.012	0.011	0.019	0.024
0 + 60	0.011	0.009	0.019	0.020
0 + 80	0.018	0.017	0.025	0.027
0 + 90	0.012	0.016	0.021	0.021

FLOW RATE (CFS)

TEST NO	1	2	3	4
ORIFICE	0.04903	0.04844	0.09585	0.1066
VOLUMETRIC	0.04804	0.04714	0.04668	0.04625
NTH GUTTER	0.00632	0.00611	0.00282	0.00259
STH GUTTER	0.00300	0.00344	0.00674	0.00700
INFLOW	-	-	0.04892	0.05981

PART B (CTD)

SURFACE 3 NOZZLE 1

OBSERVED DEPTH (FT)

TEST NO STATION	1	2	3	4
0 + 20	0.008	0.018	0.006	0.019
0 + 30	0.014	0.023	0.014	0.024
0 + 50	0.015	0.020	0.016	0.025
0 + 60	0.010	0.019	0.015	0.020
0 + 80	0.017	0.027	0.017	0.027
0 + 90	0.017	0.024	0.020	0.027

FLOW RATE (CFS)

TEST NO	1	2	3	4
ORIFICE	0.07036	0.1189	0.06934	0.1182
VOLUMETRIC	0.06711	0.07481	0.07066	0.06810
NTH GUTTER	0.00690	0.00602	0.00423	0.00621
STH GUTTER	0.01125	0.01358	0.01095	0.01080
INFLOW	-	0.05107	-	0.05035

SURFACE 3 NOZZLE 2

OBSERVED DEPTH (FT)

TEST NO STATION	1	2	3	4
0 + 20	0.004	0.017	0.006	0.017
0 + 30	0.011	0.020	0.010	0.021
0 + 50	0.013	0.023	0.012	0.022
0 + 60	0.011	0.020	0.013	0.022
0 + 80	0.015	0.023	0.014	0.021
0 + 90	0.016	0.024	0.016	0.025

FLOW RATE (CFS)

TEST NO	1	2	3	4
ORIFICE	0.04633	0.09358	0.04874	0.09141
VOLUMETRIC	0.04600	0.04586	0.04581	0.04534
NTH GUTTER	0.00468	0.00192	0.00150	0.00121
STH GUTTER	0.00376	0.00854	0.00836	0.00863
INFLOW	-	0.04683	-	0.04683

PART C
ADJUSTED DEPTHS FOR RAIN INDUCED FLOWS

SURFACE 1

	NOZZLE 1				NOZZLE 2			
TEST NO	1	2	3	4	1	2	3	4
STATION								
0 + 20	0.006	0.022	0.006	0.014	0.006	0.017	0.004	0.015
0 + 30	0.012	0.022	0.012	0.019	0.007	0.019	0.008	0.017
0 + 50	0.011	0.024	0.012	0.022	0.009	0.018	0.010	0.017
0 + 60	0.014	0.019	0.011	0.020	0.012	0.022	0.012	0.022
0 + 80	0.015	0.025	0.015	0.023	0.012	0.021	0.012	0.020
0 + 90	0.018	0.026	0.017	0.025	0.013	0.021	0.013	0.020

SURFACE 2

	NOZZLE 1				NOZZLE 2			
TEST NO	1	2	3	4	1	2	3	4
STATION								
0 + 30	0.008	0.008	0.019	0.023	0.010	0.010	0.022	0.027
0 + 50	0.016	0.016	0.024	0.027	0.013	0.012	0.020	0.025
0 + 60	0.013	0.011	0.020	0.018	0.012	0.010	0.020	0.021
0 + 80	0.013	0.013	0.025	-	0.014	0.013	0.021	0.023
0 + 90	0.018	0.019	0.028	0.028	0.015	0.019	0.024	0.024

SURFACE 3

	NOZZLE 1				NOZZLE 2			
TEST NO	1	2	3	4	1	2	3	4
STATION								
0 + 20	0.009	0.019	0.007	0.020	0.005	0.018	0.007	0.018
0 + 30	0.013	0.022	0.013	0.023	0.010	0.019	0.009	0.020
0 + 50	0.015	0.020	0.016	0.025	0.013	0.023	0.012	0.022
0 + 60	0.012	0.021	0.017	0.022	0.013	0.022	0.015	0.024
0 + 80	0.016	0.026	0.016	0.026	0.014	0.022	0.013	0.020
0 + 90	0.017	0.024	0.020	0.027	0.016	0.024	0.016	0.025

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