The Hydraulics of Overland Flow On Hillslopes

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By WILLIAM W. EMMETT

DYNAMIC AND DESCRIPTIVE STUDIES OF HILLSLOPES

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CONTENTS

ILLUSTRATIONS

TABLES

SYMBOLS

A	Area in acres
C	Chezy coefficient, $C=(8g/f_f)^{1/2}$, in feet$^{1/2}$ per second
D	Average depth in feet
F	Infiltration rate in inches per hour
I	Rainfall intensity in inches per hour
K	Coefficient of runoff
L	Slope length in feet
M	Exponent reflecting the degree of turbulence
$\mathbf{F}$	Froude number, $\mathbf{F}=V/(gD)^{1/2}$
$\mathbf{R}$	Reynolds number, $\mathbf{R}=4VD/\nu$
Q	Discharge in cubic feet per second
R	Runoff rate in inches per hour
S	Slope in feet per foot
T	Temperature, °F and °C
V	Mean velocity, $V=q/D$, in feet per second
V_s	Surface velocity in feet per second
W	Width in feet
b	Exponent of width, $W \propto Q^b$
c	Constant
f	Exponent of depth, $D \propto Q^f$
f_f	Darcy-Weisbach friction factor, $f_f=8gDS/V^2$
g	Acceleration of gravity in feet per second squared
i	Maximum intensity of rainfall in inches per hour
k	Proportion of impervious surface
m	Exponent of velocity, $V \propto Q^m$
n	Manning resistance coefficient, $n=1.5D^{1/6}/C$, in feet $^{1/6}$
q	Unit discharge in cubic feet per second per foot
t	Time, in hours, minutes, and seconds
y	Exponent of friction, $f_f \propto Q^y$
z	Exponent of slope, $S \propto Q^z$
ν	Kinematic viscosity in square feet per second

DYNAMIC AND DESCRIPTIVE STUDIES OF HILLSLOPES

THE HYDRAULICS OF OVERLAND FLOW ON HILLSLOPES

By William W. Emmett

ABSTRACT

Overland flow resulting from rainfall on natural hillslopes responds to the downslope increase in discharge by increasing its depth and velocity. Depth absorbs about two-thirds of the increase in discharge; velocity absorbs about one-third. For straight slope segments investigated in the field, resistance to flow remains nearly constant in the downslope direction. The comparison of field data to laboratory data shows general agreement, but it illustrates the extreme influence of vegetation and topographic irregularities on resistance to flow over natural hillslopes. Values of resistance to flow expressed as Manning's n were as high as 1.0 and averaged about 0.5; this roughly corresponded to a Darcy-Weisbach friction factor of 100.

A theoretical model of overland flow on slopes was developed based on most probable statistical concepts. Evaluation of the model for laminar and turbulent flow, and the interpolation of these two cases, corresponds to overland flow on hillslopes from laminar at the hilltop to fully turbulent at some distance down the slope. The model is in general agreement with measured data on the downslope increase of depth and velocity and further shows that when no constraint is placed on slope, the slope for laminar flow increases downslope, the slope for turbulent flow decreases downslope, and a mixed or disturbed flow has an intermediate value or generally constant downslope gradient. This requires that a hillslope must have a convex upper segment, a straight middle segment, and a concave lower segment. This is the slope profile more often than not found in nature. Slope steepness and the length of each segment are controlled by the runoff rate and the initial gradient at the top of the slope. Thus the shape of each slope profile is related to its climatic and geologic environments.

ACKNOWLEDGMENTS

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The sediment concentration samples were analyzed by V. W. Norman and the size distribution of the soil samples was determined by A. B. Commings, both of the U.S. Geological Survey. For their review, comments, and suggestions, the author is indebted to W. O. Ree, L. D. Meyer, M. G. Wolman, C. B. Hunt, G. R. Foster, and R. F. Hadley.

INTRODUCTION

DESCRIPTION OF THE PROBLEM

Overland flow is the initial phase of surface runoff. It is sometimes referred to as sheet flow because the water is envisioned as moving in a sheet downslope over a plane surface to the nearest concentration point or channel. Nearly all surface runoff starts as overland flow in the upper reaches of a watershed and travels at least a short distance in this manner before it reaches a rill or channel. Once a known flow rate reaches a defined channel its action may usually be characterized adequately by standard hydraulic procedures.

In overland flow the variables are more difficult to define precisely and the use of a simple hydraulic procedure for predicting overland flow is beset with many difficulties. Overland flow is both unsteady and spatially varied since it is supplied by rain and depleted by infiltration, neither of which is necessarily constant with respect to time and location. Flow may be either laminar or turbulent or a mixture of these two conditions. Flow depths may be either below or above critical, or the depths may change from subcritical to supercritical. Under certain conditions the flow may become unstable and may give rise to the formation of roll waves. The action of raindrop impact on the sheet of flowing water further complicates the overland flow problem.

Although the ground surface over most of the plot areas was covered by surface detention during overland flow, most runoff occurred in several laterally-spaced concentrations of flow. These concentrations of flow wove anastomosing paths downslope. Over the short lengths of the runoff plots, the Reynolds number, a measure of fluid turbulence, remained in the regime normally considered laminar flow, but the flow was not truly laminar because of the disturbance by falling raindrops and the influence of topographic irregularities. Such a disturbed flow is capable of eroding and transporting sediments. Despite surface erosion by the runoff, no rilling was observed to have developed. It is suggested that the studied slopes are in dynamic equilibrium with other slopes in the drainage system. A complex interaction of vegetation, topography, and other friction terms provides a resistance to flow that maintains depths and velocities, and thus erosion is just sufficient to continue downcutting equilibrium with other slopes in the drainage system. Rilled slopes are in areas which require more rapid erosion to maintain equilibrium.

The need to accurately determine the hydraulic parameters characterizing overland flow and the role of overland flow as a landscaping agent led to the present experimental study directed toward quantitative evaluation of the variables associated with overland flow. The experimental study is still in progress, but sufficient data on the hydraulics of overland flow have been collected to enable the present analysis of that aspect.

REVIEW OF THE LITERATURE

In the course of the initial literature search it became apparent that many aspects of the hydraulics of overland flow have not been investigated. Early researchers tended to direct their studies toward individual aspects of overland flow. Little effort has been made to integrate various aspects into an attempt to quantify the hydraulics of overland flow. However, the individual aspects did serve to provide some of the important initial theories; for example, the behavior of laminar sheet flow and the theories of infiltration and detention were well documented. These writings were followed by a series of experiments in which investigators attempted to determine values for the constants in the earlier theories. Most of the more recent researchers have directed their attention to analytical and theoretical solutions to the hydraulics of overland flow.

Although his studies are not directly related to the present study, Kuichling (1889) made the first attempt to rationalize computations of surface runoff. The formula which he proposed, popularly known as the rational method, is expressed as

$$Q = kiA \tag{1}$$

in which Q is the discharge in cubic feet per second, k is the proportion of impervious surface, i is the maximum intensity of rainfall in inches per hour, and A is the area in acres. It is evident that the rational method contains many deficiencies; even Kuichling noted that it is "nothing more than a crude approximation * * *."

During the next half century following Kuichling's work, few studies were conducted to increase the knowledge of surface runoff computations. Most of these investigations were confined to filling the deficiencies in the rational formula or in applying the rational formula to special shapes of watersheds.

The first of the works utilizing details of the surface phase of the hydrologic cycle began in 1933, when R. E. Horton described his theories of infiltration capacity and surface detention (Horton, 1933). This work was closely followed by Horton, Leach, and Van Vliet (1934) in a study of the basic behavior of laminar sheet flow. In this study, values of depth and velocity associated with the shallow flow of water over sloping surfaces were predicted. Horton (1936, 1938) continued to be the pacesetter for a description of overland flow. His efforts resulted in a classical work on geomorphology (Horton 1945) in which he postulated that a condition of mixed flow exists in nature; that is, areas of fully turbulent flow are interspersed with areas of laminar flow. For turbulent flow, depth can be estimated by the Manning equation. Horton expressed this as

$$q = KD^{5/3} \tag{2}$$

in which q is the unit discharge in cubic feet per second, K is a coefficient of runoff reflecting among other things, slope and bed roughness for turbulent flow and slope and viscosity for laminar flow, and D is the depth in feet.

For laminar flow a form of the Poisseuille formula may be used to estimate the depth. This is expressed as

$$q = KD^3. \tag{3}$$

For either turbulent or laminar flow, depth can be expressed as

$$q = KD^M \tag{4}$$

in which M is an exponent reflecting in part the degree of turbulence. The value of M for fully turbulent flow is $5/3$ and is 3 for fully laminar flow. Thus, with increases in discharge, depth increases more rapidly in turbulent flow than laminar flow. For mixed flow, as Horton postulates occurs in nature, values of M would range between these two extremes. Horton continued his analysis with expressions for the downslope profile of overland flow and surface erosion by overland flow. Among those who determined the values of the constants in Horton's (1938) equations were Ree (1939) and Izzard (1943).

Keulegan (1944) employed a mathematical analysis to obtain a complete solution to spatially varied discharge over a sloping surface. One of his conclusions was that the direct resistance effect of falling rain is small, but the perturbing effect will give an increased velocity close to the bed of the channel.

Verifications of the Horton, Leach, and Van Vliet (1934) investigation of uniform laminar flow were conducted by Parsons (1949), Straub (1939), Owens (1954), and others. These studies were conducted in fully established uniform flow and were analyzed to show the dependence of resistance terms on Reynolds number. They further showed the presence of a transition region between laminar and turbulent flow. The transition region was variously reported to lie between Reynolds numbers of 2,500 to 12,000. Parsons (1949) further investigated the surface runoff resulting from the simulation of rainfall. One interesting aspect of Parsons' work was his determination of the ratio of measured depth to a theoretical depth calculated from a form of the Poisseuille formula. For uniform flows, the ratio ranged from 1.00 for a smooth surface to 1.25 for a rough and pitted mortar surface. For runoff from artificial rainfall, this depth ratio ranged from 1.46 for the rough and pitted mortar surface, 1.5 to 2.8 for bare soil, and up to 10.2 for bluegrass. These data illustrate the tremendous effect of surface roughness on extremely shallow flows. The rough and pitted mortar surface was evaluated for both uniform flow and runoff from artificial rain. Thus, the separate effects on the depth ratio caused by bed roughness and raindrop impact can be isolated. These data, collected at differing channel slopes and spray intensities, showed that raindrop impact increased depths from 8 to 28 percent over the theoretical depth, with the average increase being 17 percent. No consistent variation in relative increase with slope or spray intensity was noted.

Keulegan's (1944) conservation of momentum concept provided the base for a new series of overland flow experiments. Among these investigators were Izzard (1944, 1946), Parsons (1949), Behlke (1957), and Woo and Brater (1962). Izzard experimented with artificial rainfall over paved and turfed areas. From his empirical data, a nomograph was prepared for the solution of overland flow detention on a unit strip. Woo and Brater determined water surface profiles for combinations of rainfall intensity, surface roughness, and slope. The effect of rainfall impact was clearly expressed in terms of uniform flow condition, slope, and Reynolds number.

Richey (1954) and Chen (1962) theoretically derived the surface profile of overland flow by the methods of finite integration. The surfaces for which profiles were developed were smooth planes.

The above summary of the literature is by no means complete. However, it is representative of the development of knowledge of overland flow. References pertaining to overland flow in the geologic literature are included in subsequent sections of this report.

SCOPE OF THE INVESTIGATION

Many of the early studies involving the simulation of rainfall over small plots were concerned only with the bulk quantities of rainfall, infiltration, runoff, and the shape of the runoff hydrograph. Attention was seldom paid to a detailed characterization of the hydraulics of flow. Except with analytical models then, it has been impossible with the existing experimental data to completely describe the hydraulics of surface runoff from the moment a raindrop hits the ground until the time many drops collectively are established as channel flow in the nearest rill. The analytical models are also deficient in that there are insufficient field verifications to determine the constants in their equations.

Closely related to the hydraulic properties of overland flow is the ability of these extremely shallow flows to rework the ground surface over which they flow. Such reworking occurs in nature and is evidenced by the sheet erosion of hillslope sediments and the tranportation of these sediments, which are either deposited at some other location on the slope or are carried entirely out of the drainage system. Under certain conditions of flow and environment, more noticeable modifications of the ground surface appear. Included in this category is the formation of rills. Once a rill has been established, further modifications are controlled more by the laws governing concentrated channel flow than those by overland flow. Unfortunately, the present knowledge of overland flow as a landscaping agent is even more deficient than the knowledge of its hydraulic characteristics.

In an attempt to fill some of the gaps in the knowledge of overland flow, an experimental study was initiated to systematically evaluate the hydraulic parameters descriptive of overland flow. The study carried from the laboratory to the field.

In the laboratory, an impervious, smooth plane surface of adjustable slope was used to study uniform flow over a range of shallow depths from 0.0029 to 0.0435 foot (0.9 to 13.3 millimeters) and of five slope values from 0.0033 to 0.0775 foot per foot. At each slope position, spatially varied flow resulting from the uniform application of artificial rainfall was studied at five intensities of rainfall. These intensities were about 3.5, 4.7, 6.1, 8.5, and 11.5 inches per hour. After the completion of these smooth-surface tests, a uniform sand-grain roughness was applied to the flume floor and tests approximating those for the smooth surface were conducted as before. The principal measurements made include depth, surface velocity, discharge, and water temperature. Qualitative observations were also made by the diffusion of dye to determine whether the flow was laminar or turbulent and whether or not unsteady flow exemplified by roll waves was occurring. For the tests with artificial rainfall, depths and velocities were measured to determine the downslope changes and the total discharge measured was distributed over the runoff surface area to determine the average intensity of rainfall. The data collected allow the computation of additional hydraulic parameters describing the characteristics of the flow.

Seven field sites in west central Wyoming were selected for verification of the laboratory data.The field sites were 7 feet wide, about 45 feet long, and approximately represented four slope angles. These slope angles were about 0.003, 0.10, 0.20, and 0.33 foot per foot. To adequately describe the field sites, detailed topographic maps were prepared, surficial soil samples were analyzed for particle-size distribution, the relative density of different vegetation types was measured, and an estimate was made of overall vegetation density and overstory cover. Each field site was sprinkled with artificial rain at an intensity of approximately 8.5 inches per hour. About 10 percent of this amount was wind blown from the runoff area and, generally, runoff of 4 inches per hour was measured at the lower end of each plot. Beginning with the initial runoff, flow rate was recorded to determine the rising hydrograph and the infiltration characteristics. Periodic sampling of runoff water provided data on the sediment concentration of the flow. These data were analyzed for both the mineral and organic content. After the infiltration rate became constant, values of depth and surface velocity, and their downslope changes, were measured. Although the entire surface of the runoff plot generally glistened with standing water, most runoff occurred in concentrations of flow directed downslope. These flow concentrations, related mostly to the microrelief of the plot surface, were mapped by dye tracings to show the general pattern of flow. Finally, rain gages were placed over the plot area to check on the accuracy of the calibrated sprinkler system and to determine the uniformity of the rainfall distribution.

LABORATORY APPARATUS AND TECHNIQUES OF MEASUREMENT

LABORATORY EQUIPMENT

All laboratory tests reported in the present investigation were made in the Hydraulics Laboratory of the U.S. Geological Survey, Washington, D.C. A temporary flume was constructed to represent a segment of hillslope length. Water was supplied to the flume either from a 4-inch line from the laboratory's constant head system (uniform flow) or the city water supply (simulation of rainfall). Gate valves were used to regulate the discharge of water.

THE LABORATORY FLUME

The flume used in this investigation was constructed with a plywood bed supported by 2- by 4-inch timber beams. Flume walls were 3 inches high and made of clear plastic. The width was 4 feet and the length was 16 feet. Flume slope was adjustable by hydraulic jacks at the lower end and, to prevent sagging in the vertical, intermediate supports were placed under the 2- by 4-inch beams. The general arrangement of the equipment is shown in figure 1.

For a first series of tests, the plywood floor was sanded smooth and covered with two layers of enamel. In a second series of tests, a uniform sand roughness with a median grain diameter of 0.50 millimeter was glued to the flume floor by applying a heavy layer of varnish to the surface and then sprinkling the sand evenly onto the varnish after it had only partly dried. After the varnish had fully dried, the excess sand was swept from the surface leaving an applied roughness which was several grain diameters thick. This gave a firmly attached roughness without the surface of the

FIGURE 1.—General arrangement of the laboratory equipment. Upper: Looking upslope. Lower: Looking downslope.

top layer of grains being smoothed by excess varnish. The sand used as the roughness element was well sorted by sieving to give a uniform roughness; sorting characteristics were:

Grain size (mm)	*Percentage finer by weight than indicated size*
0.44	4
.50	45
.60	92
.71	99
.84	100

For the study of uniform flows at shallow depths, water was discharged from the supply line into a stilling-type of forebay. Uniform flow entered the flume over a rounded brink on the flume floor. Because all depths of flows investigated were extremely shallow (less than 0.05 ft.), there was no need for either upstream or downstream controls to promote uniform flow.

SIMULATION OF RAINFALL

Artificial rainfall was produced using a commercially available type of line sprinkler. This apparatus consisted of a ½-inch copper pipe equal in length to the length of the flume. A series of specially punched holes at 1-foot intervals along the pipe allowed the sprinklers to spray a fan of water in a narrow width along the line of sprinklers. Water was centrally supplied to each sprinkler unit through a gate valve and pressure gage. Each sprinkler unit was calibrated and rainfall intensity could be determined by the pressure gage indication. The distribution of rainfall over the sprinkled area was checked by randomly placing collecting gages over the area. It was determined that rainfall distribution was evenly divided over the area; individual gages indicated more or less than the average, but no systematic pattern could be detected over the entire area. Most likely, excess readings were due to higher concentrations of water in the tailing ends of each fan of water spray; deficient readings were due to a central location within the spray. Some details of the sprinkling apparatus and the appearance of artificial rainfall over the flume area are shown in figure 2.

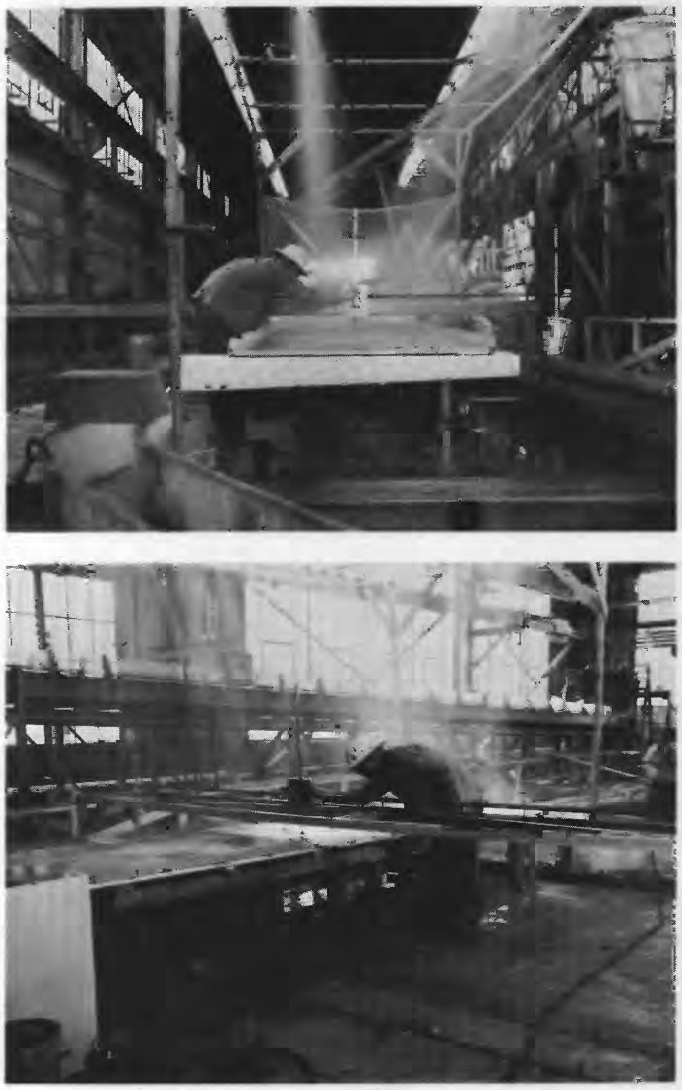

FIGURE 2.—Appearance of artificial rain over the flume area. Upper: Looking upslope. Lower: Looking downslope.

No attempt was made to determine the impact velocity or drop size of the falling rain droplets. Natural rainstorms at a given intensity include a wide range of drop sizes and the drop-size distribution varies with rainfall intensity. The size distribution by volume for different rainfall intensities shows mean drop sizes of 1, 2, and 3 millimeters for intensities of 0.01, 1.0, and 4.0 inches per hour, respectively (Laws and Parsons, 1943). However, the percentage by volume contributed by drop sizes within ⅛ millimeter of the sizes listed above are, respectively, only 28, 12, and 9 percent of the total rain, the remainder being about equally contributed between larger and smaller drops. Water drops falling through the air approach a terminal velocity which varies with drop size. The relation of distance of fall to drop-fall velocity was studied by Laws (1941) and Gunn and Kinser (1949). For drop sizes of 1.25, 2.0, and 3.0 millimeters, a respective fall distance of about 15, 30, and 40 feet was needed to obtain terminal velocity of 15.8, 21.6, and 26.5 feet per second, respectively.

In the laboratory, two sprinkler units were placed approximately 6 feet above the flume floor and pointed downward. Because of the initial acceleration in being sprayed downward, the impact velocity of the falling droplets was believed to be of reasonable acceptance. However, the average drop size in the present experiments was about 0.5 millimeter and varied little with the intensity of spray. This is considerably smaller than

368-391 O—70——2

the reported size of drops occurring in natural rainstorms. At the time the laboratory equipment was designed, this deficiency in attempting to simulate natural rainstorms was not believed to be an extremely important factor in the hydraulics of overland flow. Thus, Keulegan (1944) has reported that the retarding effect of falling rain is small. Apparently, however, the geomorphic or erosional effects of falling raindrops are related in part to the depth of flow into which they fall. Palmer (1965) investigated the soil loss by waterdrop impact forces for three drop sizes and with various depths of a water layer over the soil surface. Water layer depths were varied from 0 to 30 millimeters (0.10 foot). Maximum soil losses for drop sizes of 2.9, 4.7, and 5.9 millimeters occurred at a critical depth of the water layer of 2, 4, and 6 millimeters (0.007, 0.013, and 0.020 foot), respectively. Thus the critical depth occurs in a region where a 1:1 relationship exists between the drop diameter and the depth of the water layer.

DISCHARGE MEASUREMENTS

Total discharges below 0.10 cubic foot per second were measured volumetrically. All tests with artificial rainfall lie within this range. For discharges greater than 0.10 cubic foot per second, a calibrated bend meter in the 4-inch supply line was used.

DEPTH MEASUREMENTS

Measurements of flow depth and determination of flume slope were obtained with a point gage mounted on a precision leveled carriage which is independent of the flume structure. The point gage could be positioned anywhere over the flume surface. Depth determinations were recorded as the difference between the elevation of the flume floor and the water surface. The point gage could be read directly to 0.001 foot, and with discretion given to the flume-floor and water-surface elevation readings, the accuracy of the depth measurements was believed to be within 0.0005 foot.

Depth readings were recorded for 3 transverse locations for each 1-foot downslope position between 1 foot to 15 feet. The three transverse locations were at the quarter points (1 and 3 ft) and midpoint (2 ft) across the flume width. For each run then, 45 observations of depth were recorded. In the uniform flow tests, the 45 readings were averaged to give a mean depth, and for tests with artificial rain, each set of three transverse readings were averaged to give a mean depth for each downslope position.

For tests with the roughened surface, a mean flume floor elevation equal to the top of the roughness elements was used in depth determinations. The top of the roughness elements was measured by attaching a blunt ¾-inch-wide blade to the tip of the point gage. In all computations that follow, no correction that took into consideration the voids between sand particles was applied to depths as measured at the top of the roughness element.

Figure 2 also illustrates the point-gage arrangement and some of the problems involved with depth measurements in tests with artificial rain.

SURFACE-VELOCITY MEASUREMENTS

Surface velocity was measured by tracing the travel of dyes over specified downslope distances which had been marked out as a grid system on the flume floor. For most of the uniform flows, a liquid food coloring was used. As the dye advanced downslope, a dye streak was left behind as dye at the water surface moved downslope faster than dye settling downward in the flow. The leading edge of the dye streak was timed to assure that velocity at the water surface was being measured. The effect of impact from artificial rain was to hasten the diffusion of the liquid dye and it was difficult to trace the dye movement. Therefore, for tests with artificial rain, a nonwetting, brilliantly colored powder was sprinkled on the water surface and movement of the powder was timed over specified distances.

For uniform flow, the surface velocity was measured between downslope distances of 2 to 8 feet and 8 to 14 feet and at the three transverse positions of the quarter points and midpoint. These six readings were averaged to determine the mean surface velocity for each run. No systematic difference in velocities was detected between the six measuring reaches.

For tests with artificial rain, surface velocity was measured at the transverse quarter points and midpoint and between the downslope distances of 1 to 3 feet, 3 to 5 feet, 5 to 7 feet, 7 to 9 feet, 9 to 11 feet, 11 to 13 feet, and 13 to 15 feet. Each set of three transverse readings were averaged to give the mean surface velocity for each of the seven downslope positions.

OTHER MEASUREMENTS

In addition to the above measurements, at the time velocity for uniform flow was being determined by the dye measurements, visual observations were made of the amount of dye diffusion to determine if the flow was laminar, turbulent, or a mixture of the two.

Observations were made as to whether or not unsteadiness of flow as characterized by roll waves was occurring. Data from tests with roll waves were compared to data from tests without waves to determine if significant discrepancies were being caused in the measurements of depth and surface velocity. Some free-surface instability can be detected for the flow illustrated in figure 1 (lower photograph).

Water temperature was recorded for each test to determine the appropriate value of viscosity used in subsequent computations.

FIELD SITES AND DESCRIPTION OF MEASUREMENTS

GENERAL LOCATION

Seven sites were selected for field verification of the hydraulic characteristics of overland flow as determined in the laboratory investigation. All of the field sites were located in Sublette County, west-central Wyoming, near the town of Pinedale. This location was selected because it centers in the area where the author participates in other field research problems; the area has no particular advantages or disadvantages.

Individual sites were selected on the basis of several criteria including: the proximity to a source of water to facilitate the generation of artificial rain, a ground surface with a slope of essentially a smooth plane, and vegetation and surface features which have not been unduly influenced by man or animal.

FIGURE 3.—Pole Creek Site 1. Upper: Looking upslope. Lower: Runoff and surface detention immediately after rainfall.

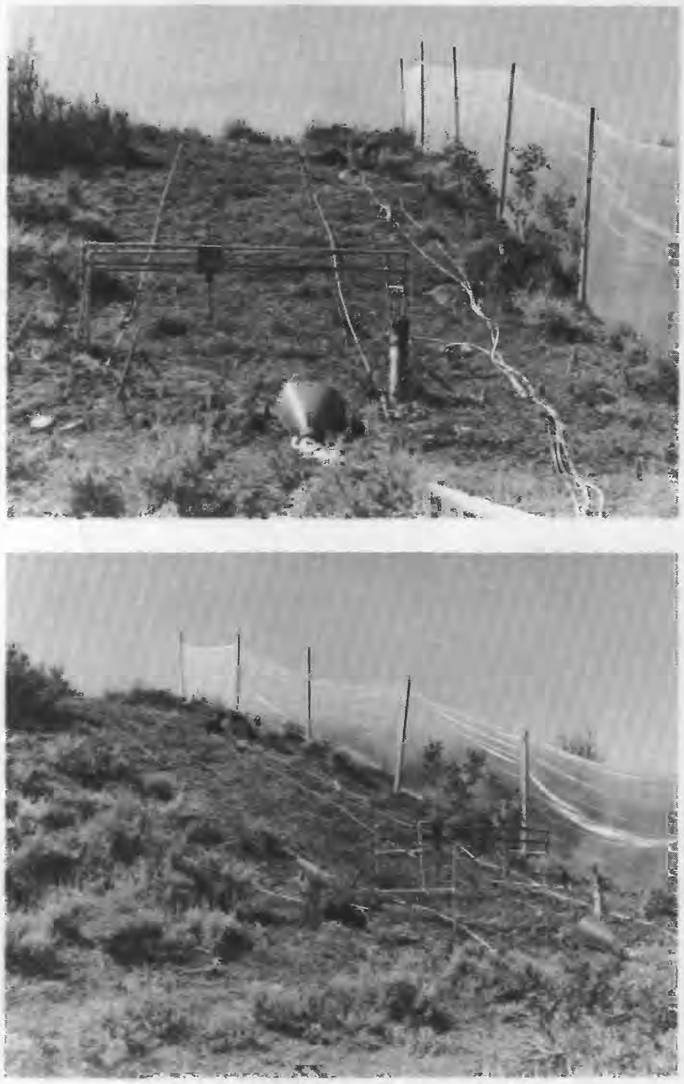

FIGURE 4.—Pole Creek Site 2. Upper: Looking upslope. Lower: Looking across slope.

The seven selected sites represented three geographical areas. Three sites were on slopes bordering Pole Creek at a reach about 2 miles downstream from Little Half Moon Lake, two sites were along the New Fork River about 1½ miles below the bridge crossing of State Highway 187, and two sites overlooked Boulder Lake near the upper end of the lake. The runoff plot established at each site was 7 feet wide and generally longer than 40 feet. The general appearance of the seven field sites is illustrated in figures 3 to 8. Some details of figures 3 to 8 are discussed in the following sections.

FIGURE 5.—Pole Creek Site 3. Upper: Looking upslope. Lower: Looking downslope.

GEOLOGY AND SOILS

The Pole Creek and Boulder Lake sites were on normally eroded morainal surfaces of sand, gravel, and boulders formed during the glaciation of the Wind River Range. Although boulders are common in the area, the sites selected included only a few small patches of exposed rock and no large protruding boulders. The ground surface at Pole Creek Sites 1 and 3 differed most from the general appearance of the morainal topography. These sites were located close to Pole Creek and infrequent high-water events in this creek have probably sent flowing water over these areas resulting in some smoothing of the surface and the deposition of fluvial sediments.

The two sites along the New Fork River were on a soil mantle developed from the Wasatch Formation of sandstone, claystone, and shale. Bedrock is within several feet of the ground surface.

Samples of the surficial soil at each site were analyzed for their particle-size distribution. The samples were obtained from the top 2 inches of soil at several random locations over each site. The analytical results of the size distribution are listed in table 1. Because the samples were skimmed from the ground surface with a shovel, a considerable amount of organic material was present in each sample. To eliminate the organics from the samples, the samples were treated with hydrogen peroxide (H_2O_2) and baked for 2 days in an oven. Conventional sieve and pipette analyses were conducted for the sediment residue. These analyses indicate that all sites were composed of very poorly sorted sediments ranging in size from clay particles to small gravel. The influence of the soil-size distribution on the hydraulics of overland flow is discussed in a later sec-

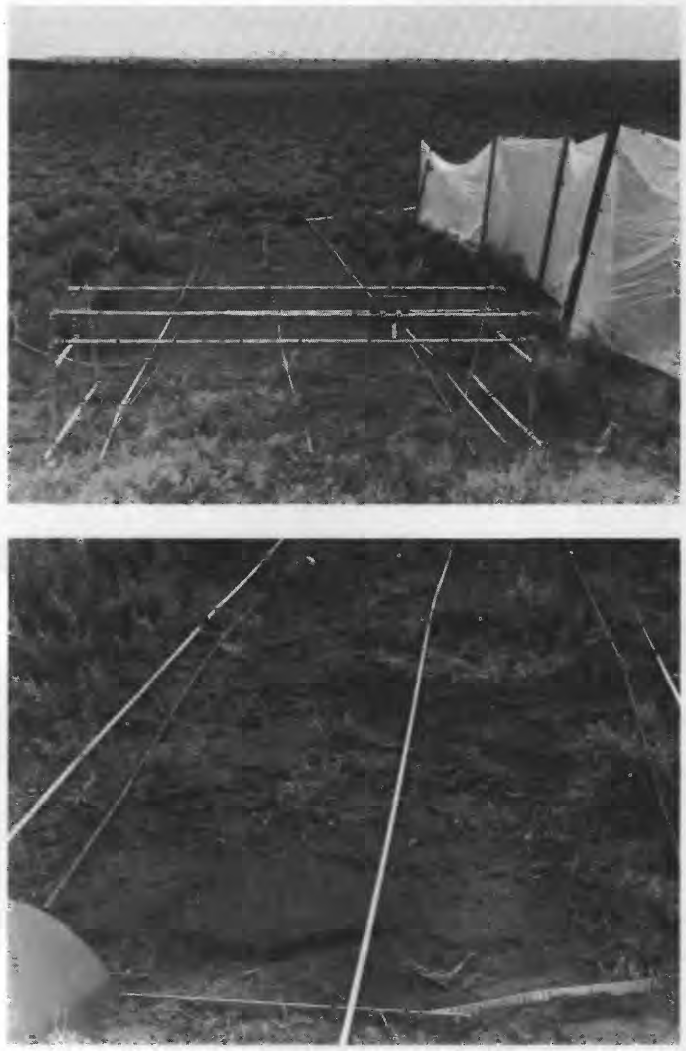

FIGURE 6.—New Fork River Site 1. Upper: Looking downslope. Lower: Delta formed of sediments eroded upslope.

TABLE 1.—*Analytical results of surficial soil samples from overland flow field sites*

[Diameter in millimeters. Site number: PC, Pole Creek; NF, New Fork River; and BL, Boulder Lake]

	Site number						
	PC-1	PC-2	PC-3	NF-1	NF-2	BL-1	BL-2
Percentage finer by weight than indicated size							
Grain diameter:							
0.002	5	5	8	7	10	8	6
.004	7	7	11	8	14	12	8
.008	10	10	14	10	20	15	11
.016	15	14	21	12	28	22	15
.031	22	20	30	16	37	30	21
.062	30	28	44	26	47	39	28
.125	36	34	52	42	53	47	35
.250	44	40	55	76	59	57	46
.500	54	51	60	97	66	70	58
1.00	64	64	68	99	72	84	70
2.00	72	73	77	100	75	95	82
4.00	75	80	84	--------	79	100	89
8.00	75	89	93	--------	81	--------	91
16.00	100	100	100	--------	100	--------	100
Diameter corresponding to particle class							
Particle class:							
D_{16}	0.018	0.021	0.010	0.030	0.005	0.009	0.018
D_{50}	.38	.48	.10	.15	.09	.16	.32
D_{84}	14.0	5.4	4.0	.30	11.0	1.0	2.3

tion. Pole Creek Site 1 and New Fork River Site 2 had the greatest number of coarse-sized particles as indicated by the large percentage of sediment weight in particles 8 to 16 millimeters. New Fork River Site 1 was characterized by a near absence of particle sizes greater than ½ millimeter. New Fork River Site 1 had the highest percentage of fine-sized particles followed closely by Boulder Lake Site 1 and Pole Creek Site 3. The large number of fine particles at Pole Creek Site 3 may help confirm that this site has, at times, been flooded by Pole Creek.

VEGETATION

At each site, detailed studies were conducted to determine plant species and the relative density of cover of each species. To determine these vegetation parameters, a 1-foot square metal grid was randomly tossed on the ground at about every 5-foot downslope distance. Within the 1-foot grid, each plant species was identified and the density of each occurring plant, on a relative scale of one to five, was observed. Observed plant species and the value of their relative density are listed in table A of the "Summary of data." The usual assortment of western range grasses, herbs, and shrubs predominate. An estimate of overall vegetation density for each site, expressed as a percentage of the total area, is given below the table. The New Fork River sites, located on soils weathered from the Wasatch Formation, exhibit the fewest number of species and also the lowest overall density of cover.

At most sites, a measure of the overstory vegetation was made by summing in tenths of a foot the footage of overstory lying below a 100-foot tape. These measures of overstory, expressed as a percentage of the total length of the transect, are also listed below table A in the "Summary of data." All but two sites had a characteristic overstory of sagebrush. One exception, Pole Creek Site 1, had no overstory on the site despite the general occurrence of sagebrush in the area. The other exception, Pole Creek Site 3, supported a sparse stand of young aspen in addition to sagebrush.

In order to observe and measure the hydraulic parameters of over land flow adequately, a clear and unobstructed view of the ground surface is necessary. To achieve this criterion, all overstory vegetation at the sites was cleared by cutting at the ground surface. Special care was taken not to disturb the ground surface during the clearing. Stems preferably were cut by clippers to minimize organic debris, but occasionally were cut with a saw. Figures 3 to 8 illustrate characteristics of the vegetation cover and the appearance of the sites after overstory vegetation was cleared.

FIGURE 7.—New Fork River Site 2. Upper: Looking upslope. Lower: Runoff collector.

FIGURE 8.—Boulder Lake Site 2. Upper: Looking upslope. Lower: Details of vegetation cover.

TOPOGRAPHY

The initial topographic survey at each site was to determine the most direct downslope distance. The eye is deceiving in this judgment and it is important to lay out the runoff plot perpendicular to the slope. After this direction had been determined, the general area was cleared of overstory vegetation as described above. Within this general area, the 7-foot-wide test plot was delineated over a length dependent on the continuity of the slope.

The topography of each site was surveyed on a 1- by 1-foot grid system. An exception was Pole Creek Site 1 which was mapped on a 1-foot-transverse by a 2-foot-downslope grid system. In lieu of presenting actual elevation data (all original data are on file with the U.S. Geological Survey), topographic maps of each site were prepared with contour intervals of either 0.05, 0.10, or 0.20 foot. These maps are presented in a later section of this report.

Eight surveyed elevations comprise transverse data at each downslope position. These eight readings were averaged to give a mean elevation. Mean elevations are plotted in figure 9 and show the hillslope profile at each site. The average ground slope was determined by visually fitting a straight line to the plotted data.

Figure 9 shows that the seven field sites represent only four different slope gradients of approximately 0.03, 0.10, 0.20, and 0.33 foot per foot. Thus, data can be analyzed holding slope constant to show the influence of other factors on values of the hydraulic parameters.

Table 2 summarizes some of the physical characteristics of the field sites.

TABLE 2.—*Characteristics of overland flow field sites*

Site name	Avg elev (ft)	Slope aspect	Ground slope (ft per ft)	Ground slope (degrees)	Estimated vegetation cover (percent)
New Fork River Site 2	7,150	S. 60° E.	0.0290	1°40′	8
Pole Creek Site 1	7,220	N. 75° W.	.0960	5°31′	20
New Fork River Site 1	7,160	S. 50° E.	.1000	5°44′	10
Boulder Lake Site 1	7,315	N. 30° W.	.1880	10°53′	28
Pole Creek Site 3	7,320	N. 40° W.	.2080	12°00′	35
Boulder Lake Site 2	7,330	N. 30° W.	.3315	19°21′	22
Pole Creek Site 2	7,240	N. 05° E.	.3320	19°23′	28

ARTIFICIAL RAINFALL

The same type of line sprinkler used in the laboratory investigation was also used to simulate rainfall in the field. One major difference in the field arrangement of the sprinklers was the placing of the sprinklers on the ground rather than have them suspended above the plot. Within the 7-foot-wide plot, the sprinklers were placed 6 inches inward from each side of the plot and ran continuously along the length of the plot, the total length being made up of 16-foot units placed end to end. Each unit was centrally supplied with water through a gate valve and pressure gage and was calibrated in the laboratory so that the total discharge from each unit was indicated by the pressure gage reading. With the sprinklers placed on the ground, the spray of water was pointed upward and reached a height of more than 10 feet before falling downward over the plot. As in the laboratory, neither drop size distribution nor terminal fall velocity for the applied rainfall intensity was achieved. However, because of the collision and meshing of drops within the spray, more larger drops were produced in the field arrangement than in the laboratory. The distribution of rainfall was generally uniform over the plot area, but there was a slight tendency for the heaviest concentration of water to be along the centerline of the plot which received overlapping spray from the laterally spaced sprinklers. The sprinkler arrange-

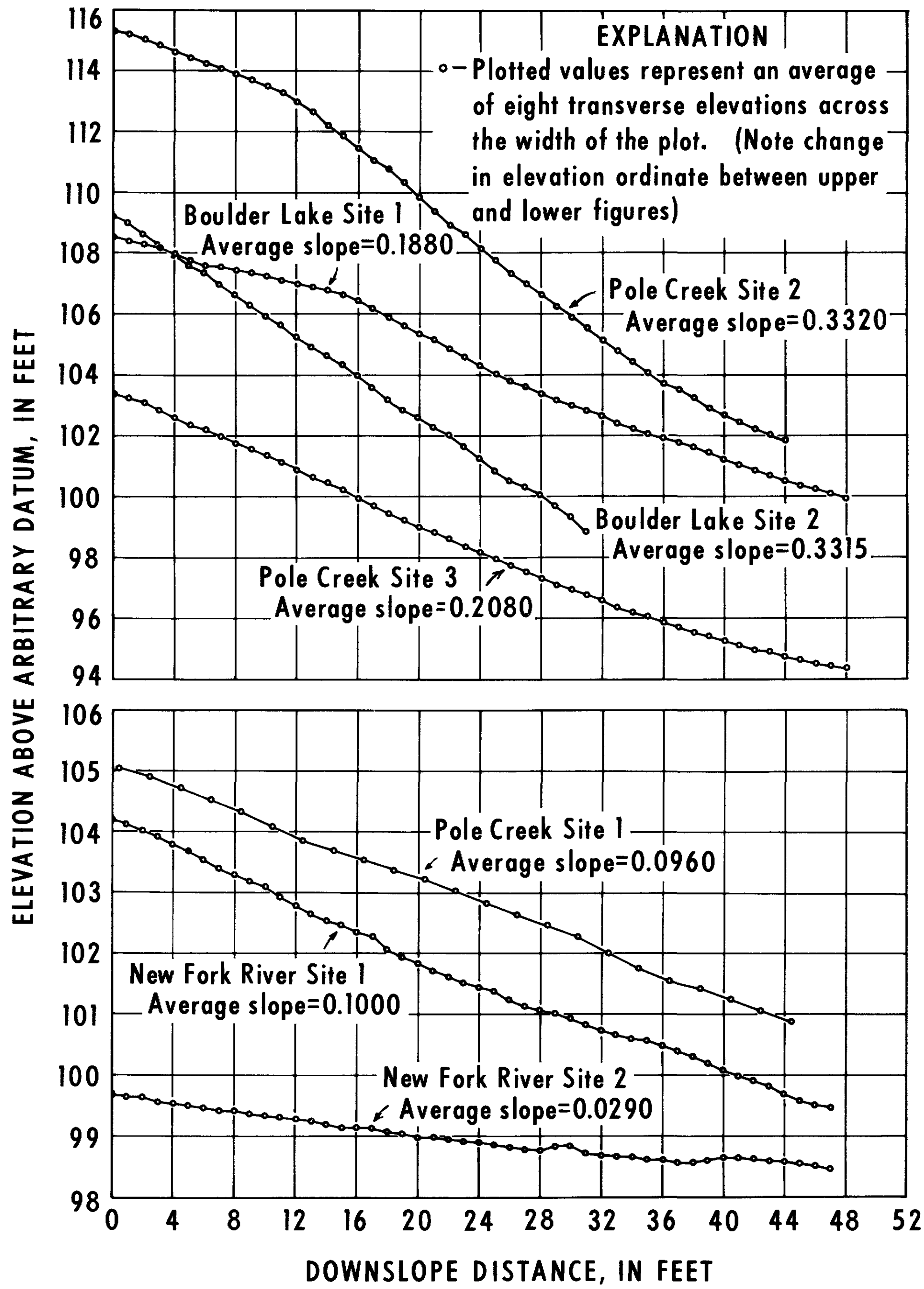

FIGURE 9.—Hillslope profiles of field sites.

ments and the general appearance of the artificial rainfall over the test plots can be seen in figures 3 to 8.

Water was pumped to the sprinkler units from a nearby stream or lake source. The pump had sufficient capacity to maintain a constant pressure gage reading at each sprinkler. Throttling of water was achieved with the gate valve at each pressure gage. The suction line of the pump was placed above the stream or lake bed to eliminate pumping any sediments to the sprinklers. Sediments could clog the sprinkler openings and also supply extraneous sediment to the runoff water and thus influence analyses of sediment concentrations in the runoff.

The first two plots (Pole Creek Sites 1 and 2) were sprinkled at a pressure gage reading of 25 pounds per square inch (7.80 in. per hr). The other five plots were sprinkled at a gage reading of 30 pounds per square inch (8.50 in. per hr). Fourteen rain gages placed over the sprinkled area were used to check the uniformity of rainfall distribution and to compare the actual intensity with that indicated by the pressure gage reading. At most sites some of the artificial rain fell outside the boundaries of the plot, largely from wind. At four sites, this loss of water was severe enough to warrant the construction of 7-foot high windscreens on the windward side of the plots. The windscreens successfully minimized the windblown loss of water. At each site, an estimate was made of any water falling outside the plot. At four sites, sufficient water fell outside the plot boundaries to warrant a reduction in rainfall intensity from the calibrated intensity. The calibrated rainfall intensity and a weighted rainfall intensity for each site is listed in table 3. The maximum difference in the two intensities is for Pole Creek Site 1 where a 10 percent correction was made.

TABLE 3.—*Rainfall and runoff rates at overland flow field sites*

Site name	Calculated rainfall [1] (in. per hr)	Measured runoff (in. per hr)	Weighted rainfall [2] (in. per hr)	Weighted runoff [2] (in. per hr)	Runoff / rainfall (percent)
New Fork River Site 2	8.5	4.5	8.1	4.1	51
Pole Creek Site 1	7.8	1.8	7.0	3.0	42
New Fork River Site 1	8.5	3.9	8.5	4.5	53
Boulder Lake Site 1	8.5	4.4	8.5	4.5	53
Pole Creek Site 3	8.5	5.0	8.5	4.5	53
Boulder Lake Site 2	8.5	4.2	8.1	4.1	51
Pole Creek Site 2	7.8	2.5	7.4	3.4	46

[1] From laboratory calibration using pressure gage readings.
[2] Weighted values used in all computations. Note that the weighted values indicate an infiltration rate of 4 in. per hr.

RUNOFF MEASUREMENTS

Runoff water was directed into a funnel-shaped collector at the lower end of each runoff plot. On the entering end, the funnel collector had a 1-inch lip which protruded into the ground and prevented flow losses under the collector. Depending on the topography of each site, 3-inch-high aluminum stripping of the type commonly used as flower garden borders was placed in a slit in the ground surface and further directed the flow to the runoff collector. (See, for example, figure 7 (lower photograph).) In a few instances, short lengths of the stripping were placed at locations along the sides of the plots. Care was taken not to divert any of the flow leaving the plot back onto the plot but rather to direct it downslope outside the plot and include it in the collection of total runoff. Without extensive sidewalls at each site, it was impossible to collect all of the runoff in the downslope collector. And, in some instances, runoff water was collected which fell as rain outside the plot. As in the determination of effective rainfall, a weighting of the measured runoff was made based on field observations of the effectiveness of collecting total runoff. Although these observation are only estimates, they are considered more factual than the measured values. Measured values of runoff and the weighted values of runoff are listed in table 3. Weighted values of runoff are used in later computations of hydraulic parameters.

At the instant that artificial rainfall application began, a clock timer was started and all data are referenced to this as zero time. Beginning with the first runoff, the rate of runoff passing through the funnel collector was volumetrically measured. The successive collection of runoff rates allows the shape of the rising hydrograph and the eventual constancy of runoff to be determined. An example of runoff hydrographs for New Fork River Site 1 is illustrated in figure 10. Figure 10 shows the rapid achievement of a constant runoff rate and the effects of sprinkling on a previously wetted surface and of increasing the rainfall intensity. Figure 10 and table 3 show that the infiltration capacity of all sites was about 4 inches per hour. This value of infiltration may seem high, but investigations by Smith and Leopold (1942) and Hadley, McQueen, and others (1961) report values of infiltration comparable to those found in the present investigation. Smith and Leopold showed a correlation of infiltration rates with vegetation density, but the present data, with only a limited range in density of cover, failed to show any correlation. The data of Hadley were observed on surfaces of the Wasatch Formation, one of the geologic formations underlying the present sites.

All measurements of velocity and depth were made after the runoff rate became constant.

SEDIMENT SAMPLES

Periodically, the containers used to measure runoff rate were put aside after filling for analysis of the sediment concentration. The samples were later filtered through filter paper and the trapped sediments were analyzed. Total sediment and organic content, expressed as milligrams per liter by weight of the total sample weight was first measured and then the organic content of the total sample was removed by hydrogen peroxide (H_2O_2). Thus, a separate measure of both the organic and sediment contents was obtained. The data are presented in a later section of this report.

SURFACE-VELOCITY MEASUREMENTS

Surface velocity was measured for two trials at each site. One trial was essentially over the left half of slope and the other over the right half. A liquid dye (food coloring) was poured over the ground surface at the upper end of the runoff plot (0-foot downslope position). As the dye touched the ground, one observ-

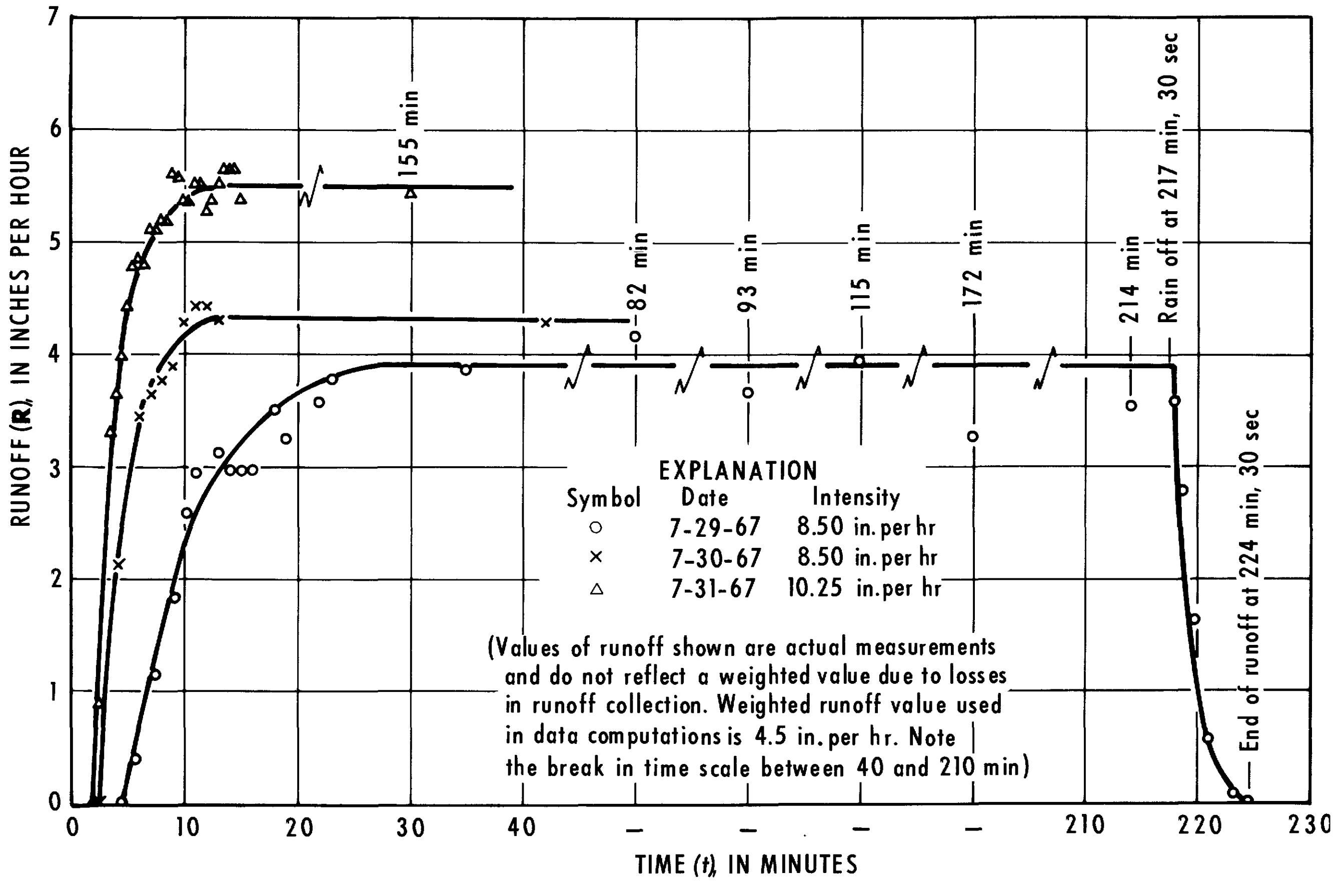

FIGURE 10.—Hydrographs of runoff for New Fork River Site 1.

er, watching the dye trace, called for a second observer, with stop watch and note pad, to start the watch. As the dye front passed each successive 1-foot downslope distance, the first observer notified the second who recorded the time. Increments of time provided the average velocity over each 1-foot reach of slope. As the dye trace became faded, it was reinforced with a new slug of dye. Always, the leading edge of the dye trace was used in timing its movement. Since the flow tends to accumulate in particular transverse concentrations, and in these concentrations velocity is highest, measurements of surface velocity were considerably higher than the actual average velocity. An example of the actual velocity measurements for Pole Creek Site 3 is included in the "Summary of data," table B. For the other sites, velocity measurements are listed in the "Summary of data," table F.

FLOW PATTERN OF OVERLAND FLOW

As previously mentioned, surface runoff within the plot area tended to accumulate in several lateral concentrations. Dye tracings used to measure the surface velocity clearly demonstrated this tendency. On nearly flat slopes, microrelief features on the order of only 0.10 foot appeared to dictate the paths of the flow concentrations. However, on steeper slopes, small microrelief features did not appreciably alter the downslope gradient and their influence on concentrations of flow was masked. Since detailed topography was surveyed for each site, a mapping of the pattern of flow concentrations was made to determine if any relation could be established between these concentrations and any of the other measured variables. Maps of the flow patterns are included in a later section.

The food coloring dye was introduced as a line source at the upper end of the plot and the stringers of dye left behind as concentrated flow advanced downslope more rapidly than the general sheet of water were mapped. The dye was reinforced every several feet downslope with new line sources of dye to detect new concentrations as they formed downslope.

DEPTH MEASUREMENTS

Depths were measured with the same type of point gage used in the laboratory investigation. A carriage was constructed of ¾-inch steel pipe to accommodate the point gage. The carriage was constructed such that measurements at two slope stations could be made with one positioning of the carriage and then the carriage was positioned at another upslope position. Depth measurements began at the downslope end of the plot and the observer worked from the downslope side of the carriage. In this manner, the area not yet measured had not been influenced by trampling.

The vertical-positioning mechanism of the point gage was loosened so that only slight resistance to lowering the point would cause slippage in the mechanism rather than to continue to lower the point. A blunt, ¾-inch-wide tip was affixed to the lower end of the point to offer additional resistance as the point touched the ground surface. Along with this sensitivity in locating the position of the ground surface, close visual observation as the point was lowered assured accuracy in determining the elevation of the ground surface. A second point-gage reading at each location determined an elevation of the water surface. The difference in ground-surface and water-surface elevations was recorded as depth. Observations were read directly to the nearest 0.001 foot.

Depths were measured on a 1-foot-transverse by a 2-foot-downslope grid system. Over the 7-foot-wide test plot, eight depths were thus recorded for each downslope position. These eight depths were averaged to give the mean depth as a function of downslope distance. Depth measurements at Pole Creek Site 3 are included in the "Summary of data," table C. For the other sites, only the average depth for each downslope position is listed in the "Summary of data," table F.

ANALYSIS OF RESULTS AND DISCUSSION

GENERAL

The presentation and analysis of hydraulic data follow a theme analogous to the hydraulic geometry of streams introduced by Leopold and Maddock (1953). The general technique in hydraulic geometry is to relate changes in the hydraulic parameters of flow to changes in discharge. This method of analysis is similar to the technique used by Horton (1945) except that Horton plotted discharge along the ordinate axis rather than the more conventional manner of plotting discharge along the abscissa axis. Thus data from the present investigation can be easily compared to both Horton's studies and the more voluminous collection of data for flow in river channels.

Because water temperature (and therefore values for the viscosity of water) varied in the present investigation, the Reynolds number, **R**, has generally been substituted for discharge in the analysis of data. The Reynolds number, here proportional to the discharge per unit width, is a nondimensional parameter relating the effect of viscosity to inertia and is defined as

$$\mathbf{R}=\frac{4VD}{\nu}$$

in which V is the mean velocity in feet per second, D is the average depth in feet, and ν is the kinematic viscosity having dimensions of feet squared per second. Depths of flow in the study were sufficiently small that depth rather than hydraulic radius could be used in computations of the Reynolds number. Use of the Reynolds number does not influence the comparison of data with other studies of hydraulic geometry and the use of the Reynolds number is convenient in visualizing whether the flow is laminar or turbulent.

For uniform flows in the laboratory flume, the analysis is similar to at-a-station hydraulic geometry because for a given discharge, depths are constant downslope. Generally, data are also plotted against depth, as well as Reynolds number (discharge), to show the importance of geometric similarity on values of the hydraulic parameters.

For tests with artificial rainfall, and thus with increasing downslope discharge, the analysis is similar to the case of downstream hydraulic geometry. At-a-station relations may also be developed by considering only data collected at the same downslope position.

Because the mass of collected and computed data is so large, it has been placed in the "Summary of data." All data collected are included in these tables, but in some of the illustrations which follow, only examples are plotted and summary curves describe the remainder of data. Throughout this section of the report, the data are presented with limited discussions. A more complete discussion follows after all data have been introduced.

Some of the results reported herein are not always in agreement with previous experiments in hydraulics and seemingly violate some of the known laws of hydraulics. Rather than a violation of the laws, the explanation is that the present investigation was conducted at an extreme end of the spectrum for which conventional hydraulic formulas are applicable. It is emphasized even before the data are introduced that many of the relationships indicated by the following analysis are unique to the flow of very shallow depths of water over sloping surfaces. Serious error could be incurred by the extrapolation of the present data to conditions beyond those investigated. It is as equally inapplicable to apply open channel hydraulics to the analysis of overland flow as it is to apply the present data to studies of river channels.

LABORATORY TESTS WITH UNIFORM FLOW

Detailed data from the laboratory tests with uniform flow are included in the "Summary of data," table D. Graphical representation of the data is illustrated with the next series of figures.

Figure 11 illustrates the relationship between the depth of uniform flow and the Reynolds number. The two most apparent observations are the break in the relationship at a certain critical value of Reynolds number between 1,500 and 6,000 and the increase in depth with decreasing slope. The critical Reynolds number marks a change in regime from laminar flow at smaller Reynolds numbers to turbulent flow at greater Reynolds numbers. For both smooth and roughened surfaces, the critical value of Reynolds number increases with increased slope. This indicates that the shallower flows on the steeper slopes are somewhat more stable against change to turbulent flow.

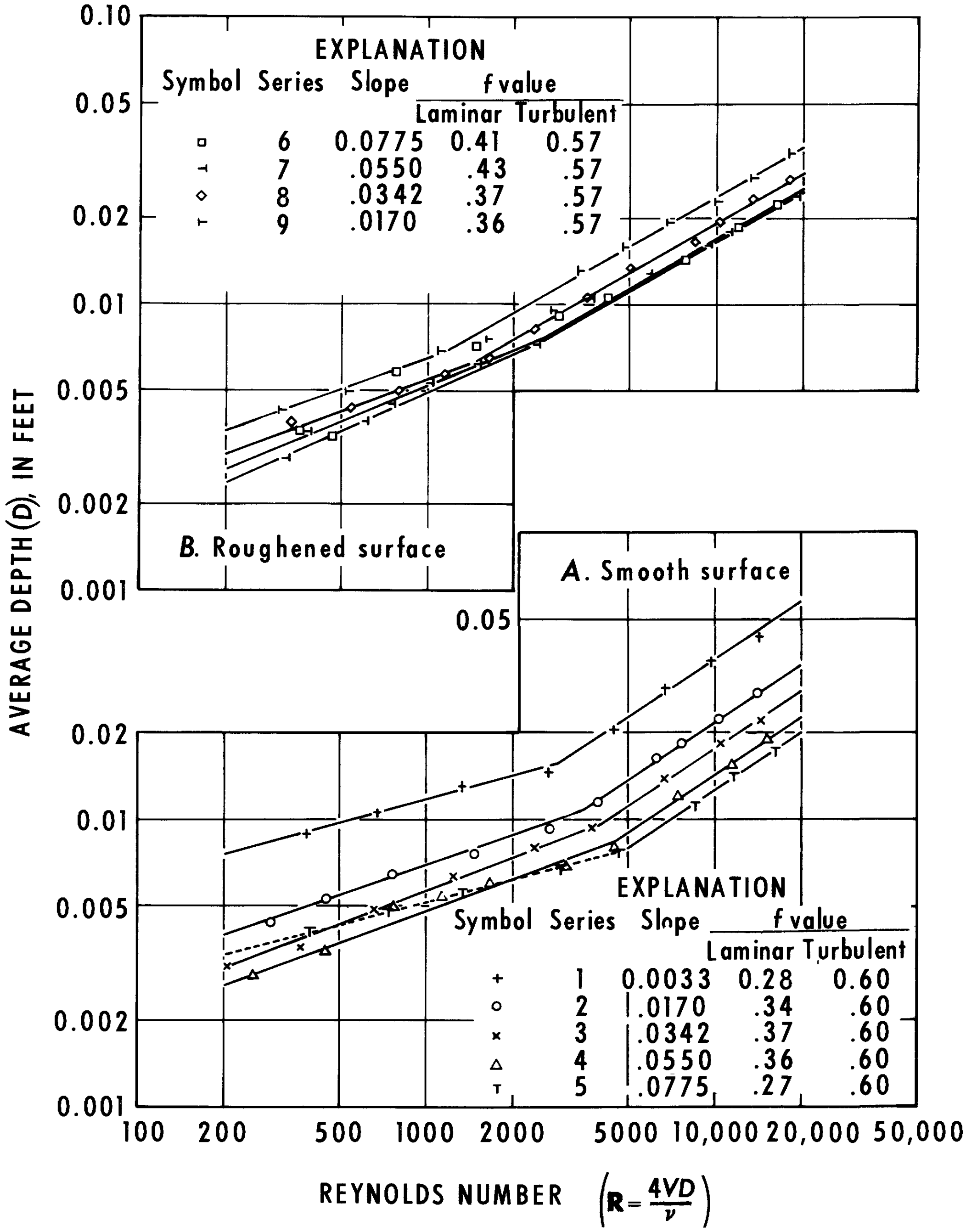

FIGURE 11.—Depth of uniform flow as a function of Reynolds number.

In terms of hydraulic geometry, the depth may be expressed as

$$D \propto Q^f. \tag{5}$$

A similar expression for the present analysis is

$$D \propto \mathbf{R}^f. \tag{6}$$

The values of f are the reciprocal of the M values (refer to=4) used by Horton (1945). Values of f are tabulated in the explanation blocks in figure 11. For turbulent flows over the smooth surface, the value of f is 0.60 for all slopes. As well as the lines can be fitted to the data (all curves in this report were fitted by eye), this value is equal to the theoretical value of $3/5$ or, in the Hortonian expression (see=2), $M=5/3$ for fully turbulent flow. For laminar flow over the smooth surface, values of f range from 0.27 to 0.37. These values tend to center around the theoretical value of $1/3$ ($M=3$; see eq 3). The scatter of values around a central value is attributed to the accuracy of data rather than any trend that might be suggested. Considering that errors of only a few ten-thousandths of a foot would appreciably alter the plotting position of the data, the plotted points appear to be satisfactory.

For the roughened surface, the value of f for turbulent flow is 0.57. Values of f less than $3/5$ would indicate flow less than fully turbulent. The effect of a roughened surface is to retard the flow near the bed of the flume. In flows as shallow as those investigated, that which is considered to be flow near the bed actually may represent a considerable part of the entire depth. Thus, it is quite reasonable to expect extremely shallow flows over roughened surfaces to exhibit some tendencies of laminar flow.

The laminar flow regime for the roughened surface produces values of f ranging from 0.36 to 0.43. One explanation for the values slightly higher than the theoretical value of $1/3$ is that no correction was applied to values of depth as measured from the top of the roughness element. At the extremely shallow depths for flows in the laminar region (generally less than 0.007 foot), a correction that allows for the voids between bed roughness particles and is added to the measured depths would, percentagewise, increase the shallowest depths most; the effect would be to decrease the value of f. For depths as large as those in the turbulent flow region, the effect would be negligible.

The effect of roughness on values of depth is both general and complex. Because of the additional resistance to flow, roughness increases the depth of flow for a given discharge. The maximum influence of roughness appears near the transition from laminar to turbulent flow. In this region, depths on the roughened surface are from 15 percent greater (for the less steep slopes) to 30 percent greater (for the steeper slopes) than depths on the smooth surface. In the turbulent region of flow for roughened surfaces, depth increases with increases in discharge less rapidly than for a smooth surface. Therefore, for flows at the highest Reynolds numbers investigated, increase in depth due to roughness is less pronounced. At a Reynolds number of 20,000 this increase in depth ranges from zero for the less steep slopes to about 25 percent for the steeper slopes. These data demonstrate that relative roughness for a given surface decreases as flow depths increase. At depths of flow somewhat greater than those investigated, further increases in depth would only negligibly decrease relative roughness and the influence of roughness on depth would be minimal.

In the laminar flow region, f values are higher for roughened surfaces than for smooth surfaces although as explained above, this is probably true only because no correction was made for measurements of depth for the roughened surface. Using the data as plotted, as Reynolds number decreases, the percentage influence of roughness on depth decreases. At a Reynolds number of 200, there are actually smaller depths reported for the roughened surface than for the smooth surface. For a low Reynolds number, a certain finite depth must exist regardless of further decreases in the Reynolds number. Thus for Reynolds numbers lower than those reported in this investigation, the relationship shown in figure 11 must begin to tail off to the left and the lines for all flume slopes would merge into a single curve at some small given value of depth. Likewise, as depths and Reynolds numbers increase above those reported in this investigation, the f value for the roughened slopes would approach a value of $3/5$ as effects of roughness diminish.

The effect of flume slope on depth is to decrease depth for increasing slopes. The relationship is hyperbolic; that is, as slope approaches zero, depth approaches infinity and as slope approaches high gradients, depths approach some minimum value. A roughened surface tends to dampen this effect. That is, the approach to some minimum depth regardless of further increases in slope occurs at a smaller gradient for the roughened surface. Thus, for flume slopes of 0.0775 and 0.0550 foot per foot, data on the roughened surface nearly describe a single curve while for the smooth surface, the data are still separate by a small distance.

A measure of the resistance to flow, the Darcy-Weisbach friction factor, is plotted in figure 12 as a function of Reynolds number and average depth.

The Darcy-Weisbach friction factor is defined as

$$f_f = \frac{8gDS}{V^2} \tag{7}$$

in which g is the acceleration of gravity in feet per second squared and S is the flume slope in feet of drop per foot of slope length.

The expression for velocity in terms of hydraulic geometry is

$$V \propto Q^m \tag{8}$$

or

$$V \propto \mathbf{R}^m. \tag{9}$$

The friction factor, in terms of hydraulic geometry, may be written as

$$f_f \propto Q^y \tag{10}$$

or

$$f_f \propto \mathbf{R}^y. \tag{11}$$

When slope, S, is constant, equation 7 may also be written

$$f_f \propto \frac{D}{V^2} \tag{12}$$

or

$$f_f \propto \frac{\mathbf{R}^f}{\mathbf{R}^{2m}}. \tag{13}$$

Thus for a constant gradient, the slope, y, of the friction line as a function of the Reynolds number is $f-2m$. Also, since $VD=q$, then $f+m=1$ or $m=1-f$. For turbulent flow, the slope of the line is $0.60-2\ (0.40)=-0.20$ and for laminar flow it is $0.33-2(0.67)=-1.0$. Negative values of y indicate a decrease in resistance to flow with increasing Reynolds number. For laminar flow in smooth rectangular channels, the equation of the line with a slope of -1.0 is

$$f_f = \frac{96}{\mathbf{R}}. \tag{14}$$

For rough channels, values of the friction factor would be higher and would plot above the lower limits defined in equation 14.

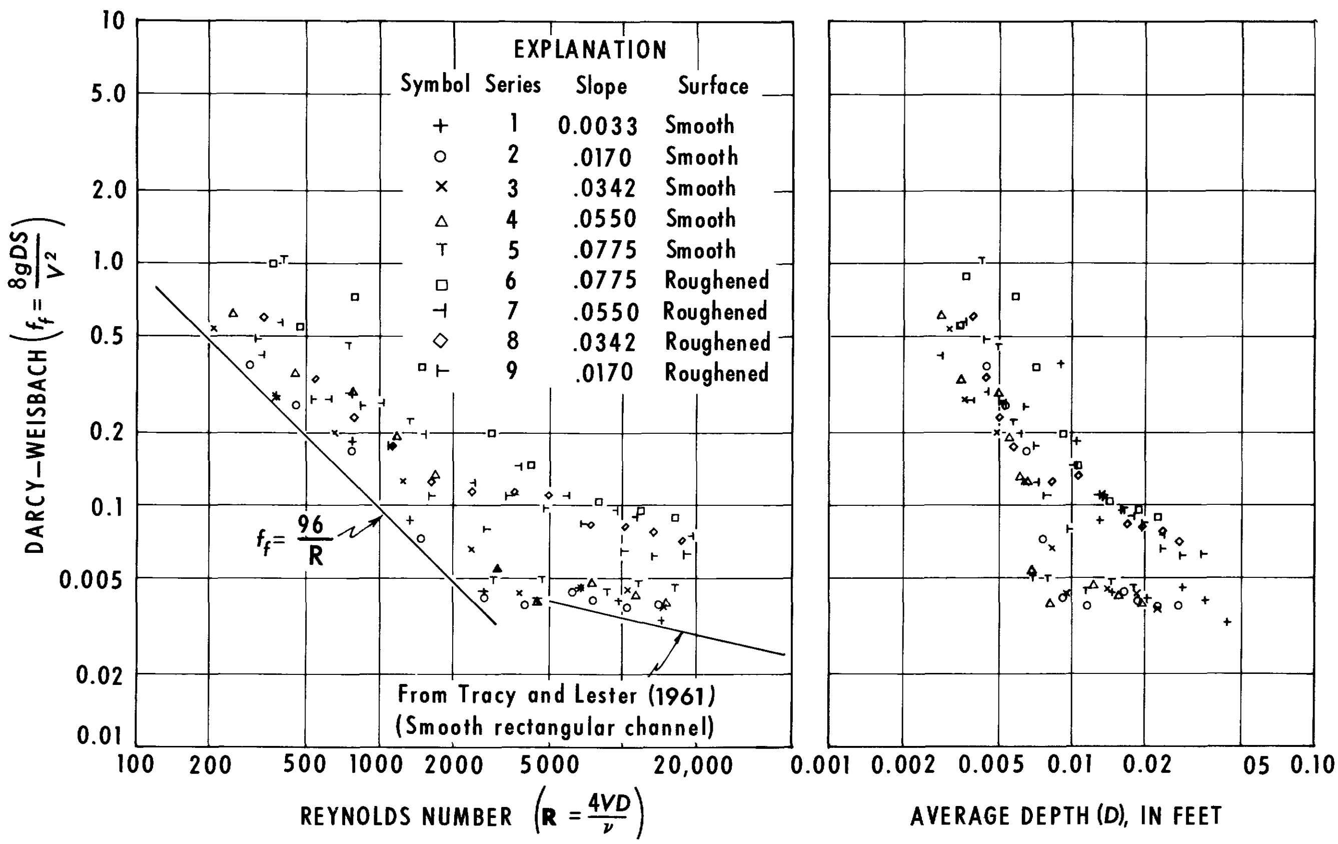

FIGURE 12.—Darcy-Weisbach friction factor for uniform flow as a function of Reynolds number and average depth.

For turbulent flows, the friction factor-Reynolds number relation has a slope of −0.20. For a smooth surface flume, this value is indicated in figure 12 with a line representing data from experiments by Tracy and Lester (1961).

The data of figure 12 plot higher than the limits indicated by the equations applicable to a smooth surface. This illustrates the pronounced effect of channel roughness on the friction factor. The smooth flume in the present investigation was in fact not completely smooth as indicated by the data plotting higher than the equations for a smooth surface.

Using the average value of the friction factor at a Reynolds number of 20,000, reference to a Stanton or Moody diagram gives a relative roughness of 0.03 for the roughened surface and 0.002 for the smooth(er) surface. At an average depth of 0.03 foot for a Reynolds number of 20,000, a computed absolute roughness is 0.0009 foot for the roughened surface and 0.00006 foot for the smooth surface. One-half the diameter of the 0.5 millimeter grain roughness used on the flume is 0.00082 foot. This is very close to the computed roughness for the roughened surface. The computed value for the smooth surface is not unreasonable for sanded plywood with a paint finish.

Only two roughnesses are involved with the two surfaces but because each plotted point in figure 12 has a different depth, the data include many values of relative roughnesses. For a Reynolds number of 300, depths are approximately 0.003 foot and the relative roughness is 0.3 for the roughened surface. This is 10 times rougher than at a Reynolds number of 20,000. If points representing equal depths were connected, one would find the beginnings of a family of curves, each representing a given relative roughness. The curves are not drawn in figure 12 because the data are too sparse. However, it is interesting to note that most of the data lie in a range of friction factors and relative roughnesses much greater than those included on conventional Moody diagrams. This again illustrates the tremendous influence of even small surface roughnesses on flows as shallow as those investigated and that occur in overland flow.

The right half of figure 12 again illustrates that plotted points represent differing depths. To maintain geometric similarity between the depth of flow and scale of roughness, friction factors are plotted against depth. The tendency to converge into a single curve for laminar flow and into two curves, one for each roughness, at higher Reynolds numbers is apparent. The remaining scatter in data is most likely within the accuracy of the experiment. From equation 7 and the relation $V=q/D$, the friction factor may be expressed as

$$f_f=\frac{8gD^3S}{q^2} \quad (15)$$

from which it can be seen that the percent error in friction factor is three times the percent error in depth. Using a nominal depth of 0.005 foot (typical of depths at low Reynolds numbers), an error of only 0.0005 foot (one-half the direct reading accuracy of the point gage) in the measurement of depth yields a 30 percent error in friction factor.

A commonly used uniform flow formula is the Chezy formula,

$$V=C(DS)^{1/2}, \quad (16)$$

where C is a factor of flow resistance called Chezy's C. Normally, hydraulic radius would be used rather than depth, but in the present investigation, depth and hydraulic radius are practically identical. Substitution of equation 7 into equation 16 gives a solution for Chezy's C in terms of the Darcy-Weisbach friction factor:

$$C=\left(\frac{8g}{f_f}\right)^{1/2}. \quad (17)$$

Figure 13 illustrates values of Chezy's C as a function of Reynolds number and of average depth. The slope of the Chezy C-Reynolds number relation is equal to $m-(1/2)f$ or 0.5 for laminar flow and 0.1 for turbulent flow. Upper limits for values of C are shown in the same manner as for friction factor in figure 12. The influence of laminar, transitional, and turbulent flow, as well as roughness and geometric similarity, are analogous to those in the previous discussion of the Darcy-Weisbach friction factor.

Another popular open channel formula is the Manning equation:

$$V=\frac{1.5}{n}D^{2/3}S^{1/2} \quad (18)$$

in which n is a coefficient of roughness known as Manning's n. In terms of Chezy's C:

$$n=\frac{1.5D^{1/6}}{C}. \quad (19)$$

Computed values of Manning's n are plotted in figure 14 as a function of Reynolds number and average depth. In terms of hydraulic geometry, Manning's n can be expressed by

$$n\propto\frac{D^{2/3}}{V}\propto\frac{Q^{2/3f}}{Q^m}\propto\frac{\mathbf{R}^{2/3f}}{\mathbf{R}^m}. \quad (20)$$

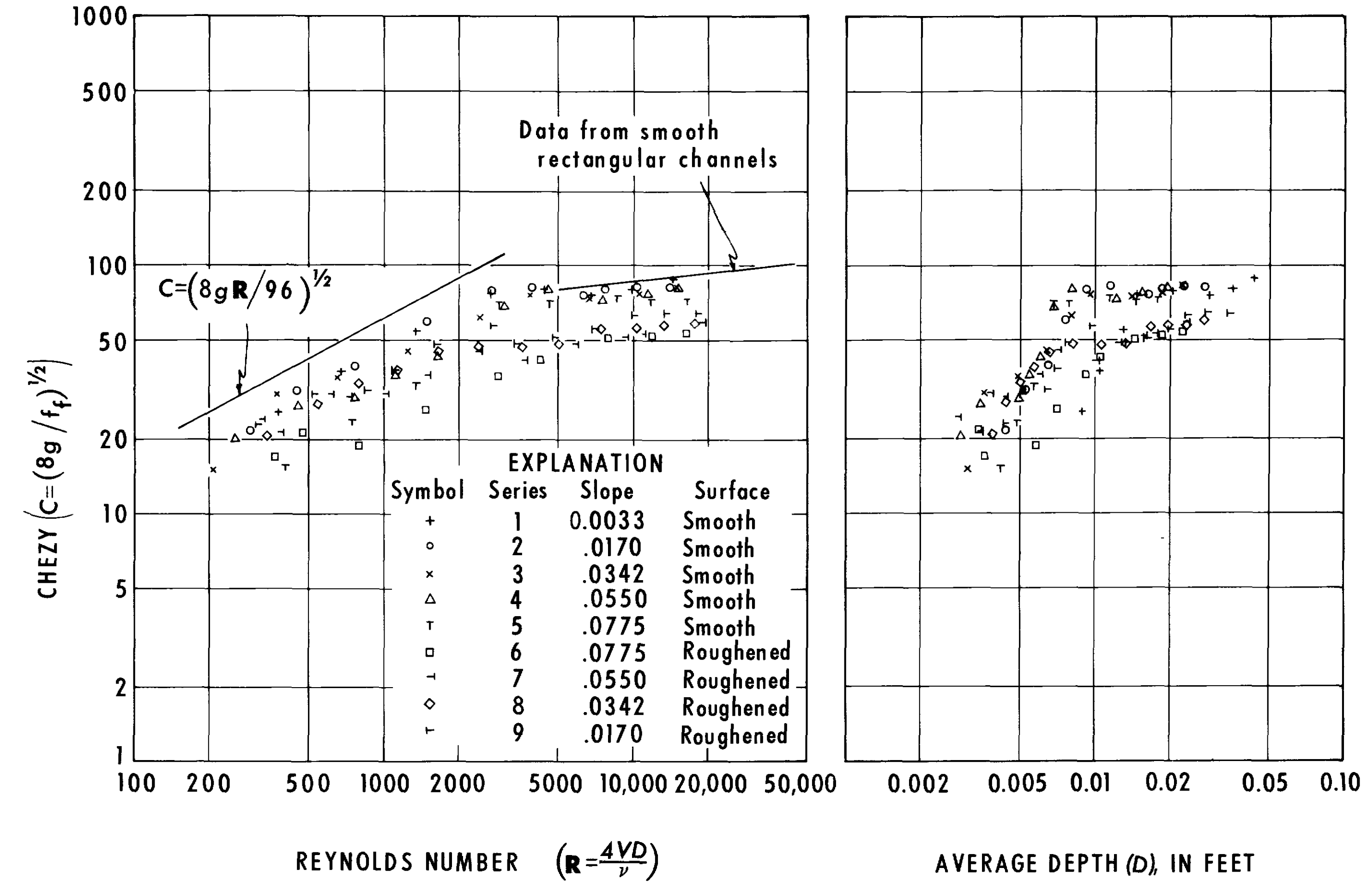

FIGURE 13.—Chezy's C for uniform flow as a function of Reynolds number and average depth.

Thus the slope of the Manning's relation as a function of the Reynolds number is $(\frac{2}{3})f-m$ or -0.45 for laminar flow and 0.0 for turbulent flow. The data closely follow these values. The previous discussion concerning the Darcy-Weisbach friction factor is again applicable to both plots of figure 14.

Figure 15 is a plot of the ratio of mean velocity to surface velocity, V/V_S, as a function of Reynolds number and average depth. In the turbulent region of flow, the velocity ratio is very close to the theoretical value of 0.8. In the laminar flow region, the theoretical velocity ratio of 0.67 tends to define an upper limit to the measured data. Most likely, the explanation for the lower measured values is the extreme retardance of flow of shallow depths by surface friction. This argument is supported by the plot of velocity ratio as a function of average depth. The close grouping of the plotted data and the variation with depth suggest that depth of flow is an influencing factor.

LABORATORY TESTS WITH ARTIFICIAL RAIN

All of the measured and computed data for the laboratory experiments with artificial rainfall are included in the "Summary of data," table E. As will be shown, the maximum Reynolds numbers which occurred with flows from artificial rain were less than 1,500. The data from uniform flow tests indicate this is entirely within the region of laminar flow. The effect of falling rain sufficiently disturbed the flow of water that injections of dye were rapidly dispersed. Although this flow has some characteristics of turbulent flow, it exhibits most of the properties of laminar flow. This type of flow does not belong to any of the classifications of laminar, transitional, or turbulent flow. In this report, runoff from artificial rain will be called disturbed flow.

The downslope change in depth of nonuniform flows resulting from a uniform increase in discharge is illustrated in the lower half of figure 16 by two examples of the tests with artificial rain. The data are for five intensities of rainfall on both the smooth and roughened surface. The same depth data are plotted on the lower half of figure 17 as a function of Reynolds number. The effect of plotting against Reynolds number is to eliminate the influence of increasing rainfall intensities. The single line drawn through the data of figure 17 represents the average downslope increase in depth due to increasing discharge. The single line relationship

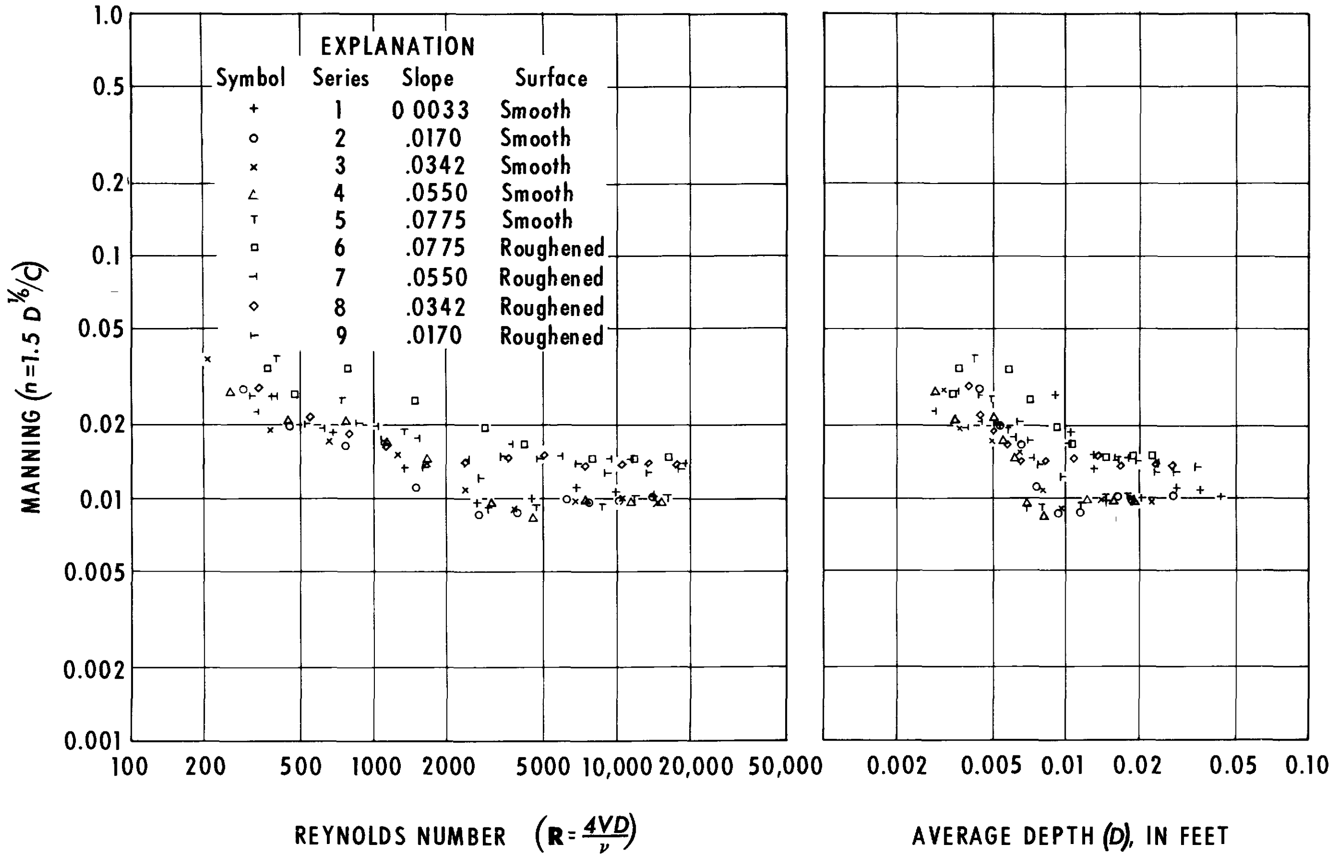

FIGURE 14.—Manning's n for uniform flow as a function of Reynolds number and average depth.

from figure 17 is shown on figure 16 as the downslope profiles for each intensity of rainfall.

One effect of the falling rain is to increase the variability in depths and possibly to decrease the accuracy in measurement. The irregularities in the downslope profiles of figure 16 are not consistent and indicate that the variability in depth is random and not related to the experimental apparatus. The downslope profiles in figure 16 suggested by the single line relation of figure 17 are not unreasonable representations of the measured profiles. This indicates that for increasing discharge, the at-a-station changes in hydraulic parameters are identical or close to the downslope changes in parameters.

An at-a-station type of analysis may be conducted by connecting points from equal downslope distance from the depth profile plot in figure 17. That is, if each of the first plotted various symbols were connected, followed by the second, third, fourth, and so on, the slope of these short line segments would describe the at-a-station relations of hydraulic geometry. The variability of the data is such that no distinction can be made between the at-a-station and downslope hydraulic geometries. Thus for the analysis of laboratory data with increasing discharge, at-a-station and downslope changes in the hydraulics of flow are considered analogous.

The most important effect of the falling raindrops is to retard the flow and increase the depth for a given discharge. Consideration of the momentum exchange between the mass of falling water and the mass of water as surface flow would predict this increase in depth. The momentum of the falling rain has little downslope component compared to the surface runoff. One would expect that the increase in depth would be least for the lowest intensities of rainfall and the highest rates of surface runoff. The present data do not entirely confirm this hypothesis. The effects of rainfall intensities are masked because lowest intensities are accompanied by lowest runoff rates, highest intensities by the highest runoff rates, and the overall effect is a balancing of the momentum exchange so that the percentage effect is roughly equal to all intensities of rainfall. For a constant intensity of rainfall, greater depths downslope should be less effected by raindrop impact than shallower upslope depths. The depth profile for the smooth surface in figure 17 illustrates this by a convergence of the plotted data to the line representing depths from the uniform flow test. That is, the f value for the runoff from rainfall is less than

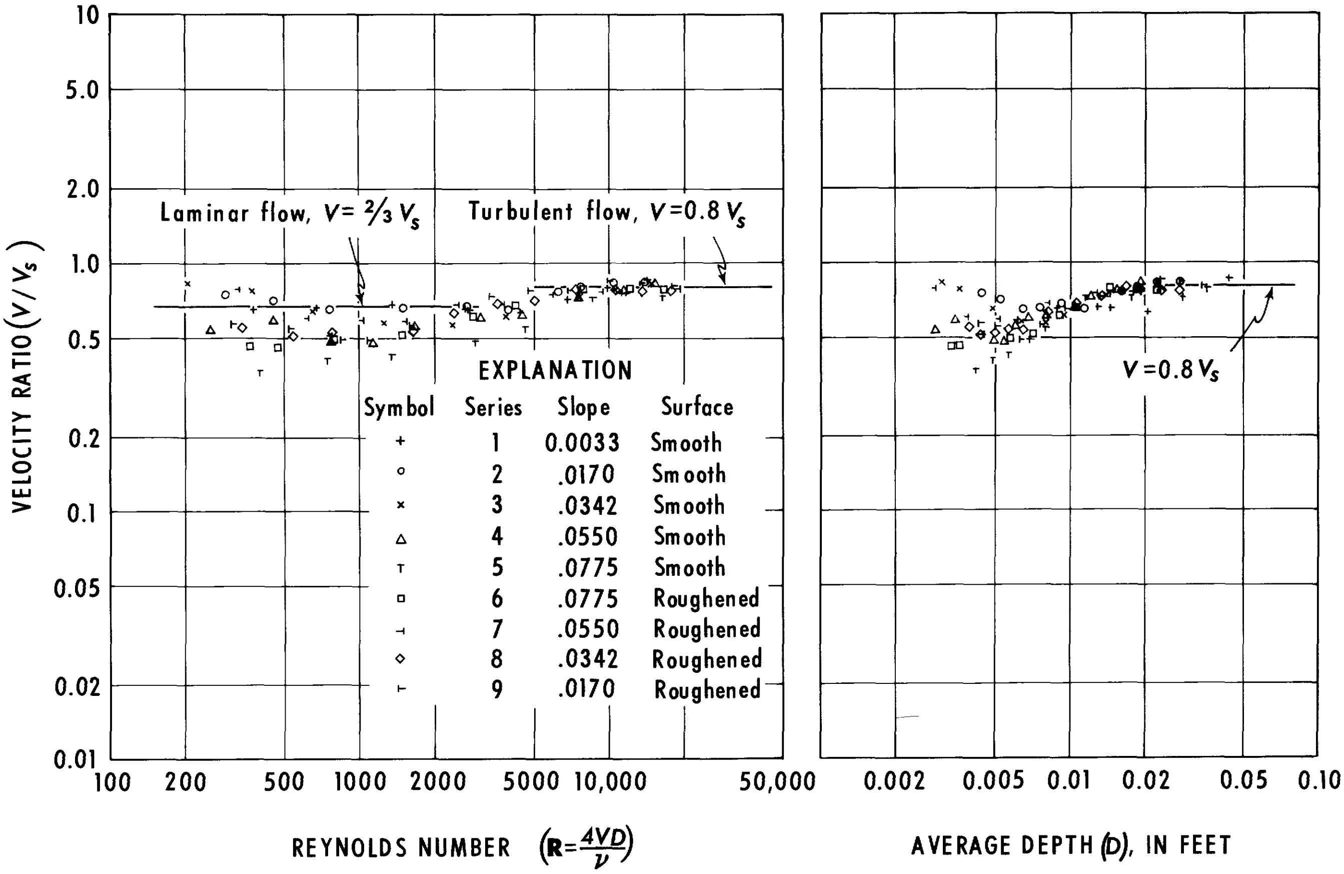

FIGURE 15.—Ratio of mean velocity to surface velocity for uniform flow as a function of Reynolds number and average depth.

the f value for uniform flow. The data for test series 3 (smooth surface) plotted in figure 17 indicate that the percentage increase in depth over uniform flow depth is about 60 percent at a Reynolds number of 100 and decreases to about 35 percent at a Reynolds number of 1,000. This increase in depth due to rainfallim pact is considerably greater than the average of 17 percent reported by Parsons (1949).

The data for test series 8 plotted in figure 17 does not show a reduction in the increase of depth with an increase in Reynolds number. However, if a correction in depth to allow for the voids between grains in the roughness was added to the measured depths, the data would more closely conform to that from the smooth surface. For the uncorrected data from the rough surface plotted in figure 17, the increase in depth is about 50 percent at a Reynolds number of 200 and about 65 percent at a Reynolds number of 1,000.

Summary curves describing the relation between average depth and Reynolds number for all tests are shown on the lower graphs of figure 18. For all tests, the depth profiles with artificial rain showed greater depths than for uniform flow. No test data differed greatly from the examples plotted in figure 17. For smooth surface tests, the f values with artificial rain are slightly less than the f values for uniform laminar flow. Conversely, the f values for artificial rain on the roughened surface are slightly greater than the f values for uniform laminar flow.

Unlike the present study of shallow flows in a constant width flume, most rivers are also free to change their width with changes in discharge. This change in width may be expressed as

$$W \propto Q^{b} \propto \mathbf{R}^{b}. \qquad (21)$$

Since $VDW=Q$, then $m+f+b=1$. It is of interest to briefly summarize and compare values of the exponents m, f, and b from the present laboratory data with values from rivers and a constant width flume with greater depths than those in the present study. This summary is shown in table 4; river and flume data are after Langbein (1965).

It is apparent from the data of table 4 that the constraint of constant width for overland flow imposes additional requirements for depth and velocity to absorb changes in discharge. The nearly comparable cases are the roughened surface sprinkled tests and the down-

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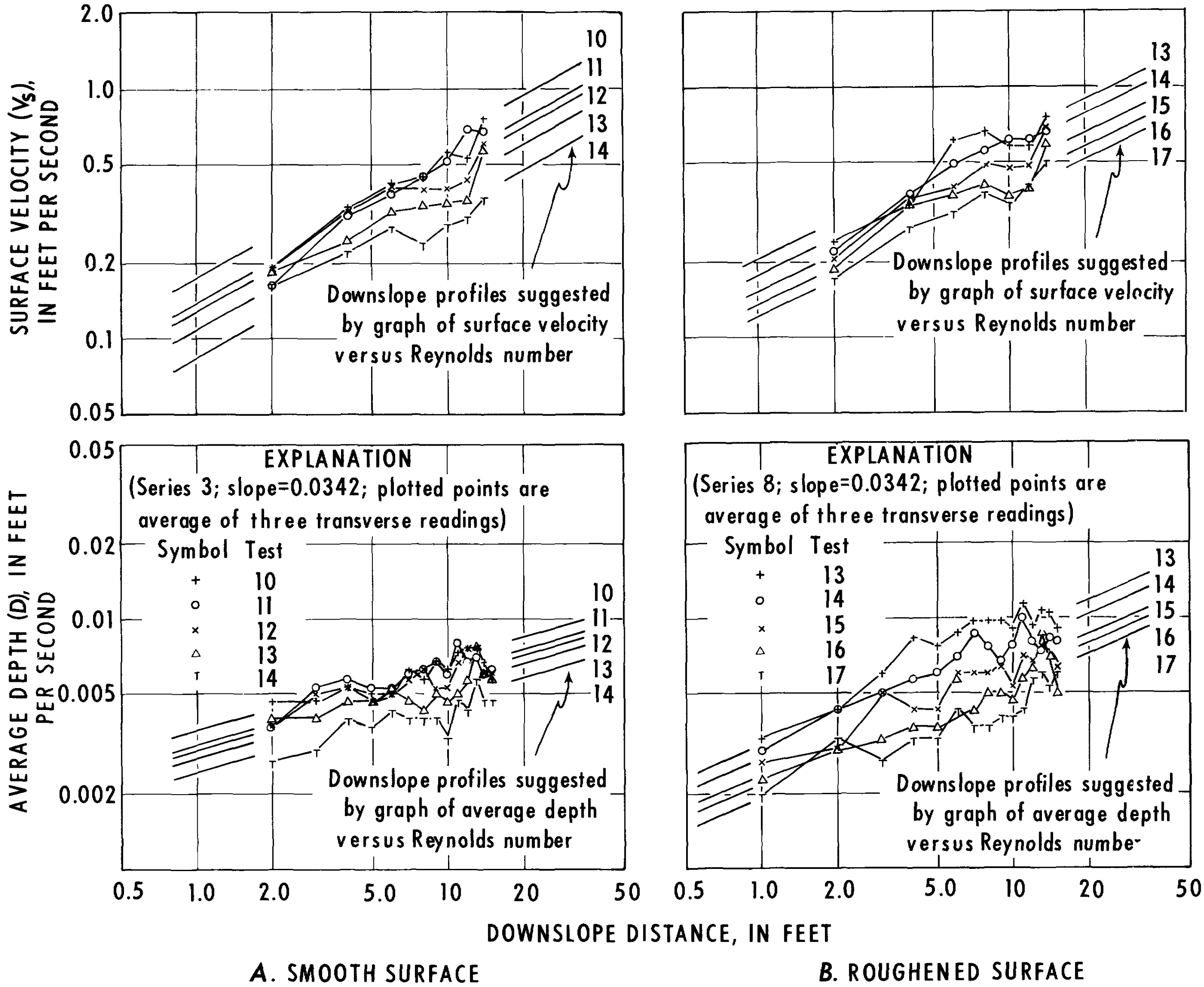

FIGURE 16.—Downslope profiles of depth and surface velocity for sprinkled tests.

stream river channel. The river channel absorbs half of the increase in discharge by an increase in width, but for the constant width, roughened surface, overland flow in the laboratory, the increase in discharge is about equally absorbed between increase in depth and velocity. The constant width flume data for uniform sediment concentration compare with reasonable agreement to the present data for uniform turbulent flow.

Measurements of the downslope changes in surface velocity are shown in the upper parts of figures 16 and 17 by two examples from the nine-test series. The actual downslope profiles are illustrated in figure 16 and the same data are plotted as a function of Reynolds number in figure 17. A straight line relation of surface velocity to Reynolds number was determined for the data in figure 17 and this relation is used in figure 16 to suggest the downslope surface velocity profiles for each rainfall intensity. For all laboratory tests, there appears to be some reduction in surface velocity, when compared

TABLE 4.—*Summary and comparison of exponents in hydraulic geometry*

Type of channel	Values of exponents in hydraulic geometry					
	Depth (*f*)		Velocity (*m*)		Width (*b*)	
	Theory	Data	Theory	Data	Theory	Data
Laboratory Shallow Flows:						
Uniform Flow:						
Smooth, turbulent	0.60	0.60	0.40	0.40	0	0
Smooth, laminar	.33	.33	.67	.67	0	0
Roughened, turbulent		.57		.43		0
Roughened, laminar		.39		.61		0
Sprinkled Tests:						
Smooth, disturbed		.26		.74		0
Roughened, disturbed		.48		.52		0
Rivers, at-a-station:						
Cohesive	.43	.40	.32	.34	.25	.26
Noncohesive	.27		.23		.50	
Rivers, downstream	.37	.40	.13	.10	.50	.50
Flume, constant width, uniform sediment concentration	.67	.67	.33	.33	0	0

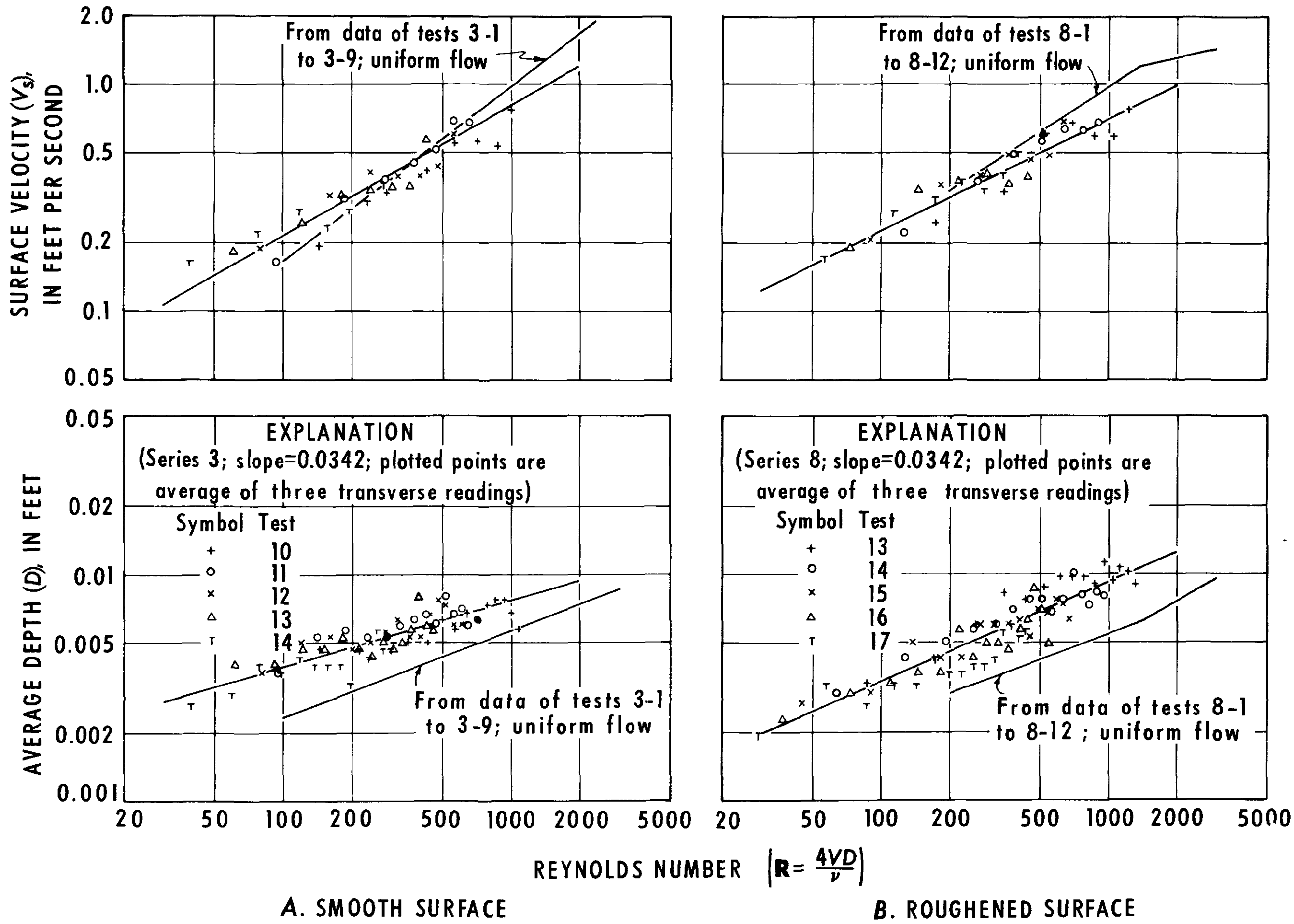

FIGURE 17.—Depth and surface velocity as a function of Reynolds number for sprinkled tests.

to the suggested profiles, in the upstream reaches of the flume and especially for the flows at higher rainfall intensities. In figure 16, this gives the appearance of the radial family of curves rather than the suggested parallel profiles. The apparent upslope reduction in velocity is attributed to the greater retarding effects of high rainfall intensities in the region where surface velocities and momentum of flow is initially small. This influence is not as noticeable in figure 17 where surface velocities are plotted against Reynolds number.

As partly supported by figure 17, surface velocities in flows from artificial rain are generally lower than surface velocities in uniform flow. Summary curves for all tests are shown on the upper part of figure 18. The slope, or m value, for the downslope profiles of surface velocity is approximately the same for smooth and roughened surfaces and it averages about 0.60. The range in values about this average is not systematic with flume slope and apparently is related to measurement accuracy in timing surface velocities over 2-foot reaches. The m values for surface velocity as shown in figure 18 do not have to be identical to the m value for mean velocity. By the law of continuity for constant-width channels, the m value for mean velocity is 1.0 minus the f value.

The Darcy-Weisbach friction factor for two of the test series is plotted in figure 19 as a function of Reynolds number. Summary curves for all tests are shown in figure 20. The same discussion of the friction factor for uniform flow is applicable to the friction factors plotted in figure 19. Thus, much of the scatter in data is related to the effects of relative roughness.

The lines of best fit to the data of figure 19 average a value of resistance to flow about four times greater than the theoretical value of $f_f=96/\mathbf{R}$ for uniform flow on a smooth surface. However, in the present experiment, friction factors for uniform flow tests (see figure 12) were also greater than the theoretical value ($f_f=96/\mathbf{R}$) by about a factor of 2. Therefore, the isolated effect of the type of artificial rainfall used in the present investigation is to about double the friction factor over that for flows without rainfall.

The line of best fit to the data in figure 19 is a computed line from the relation established between

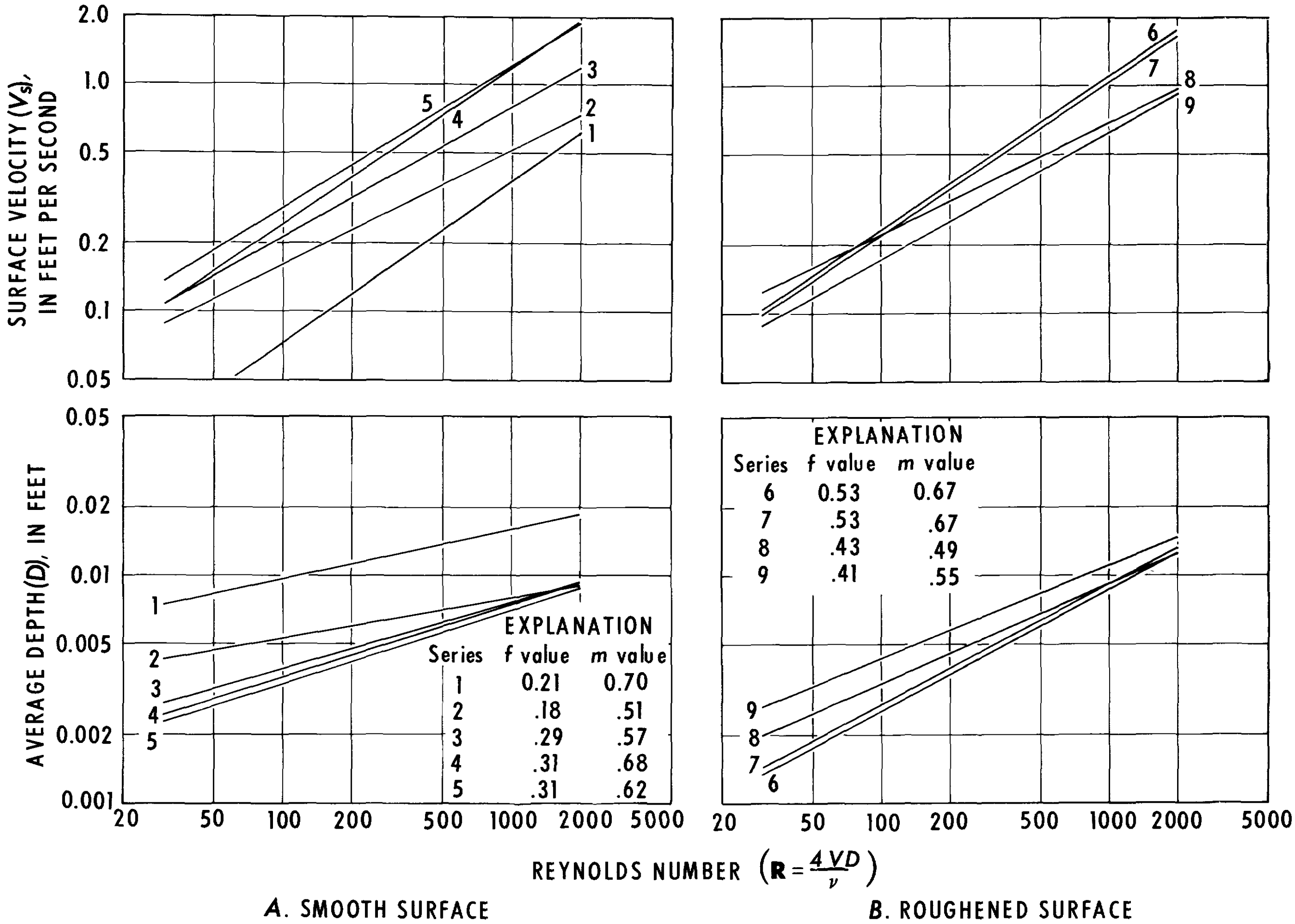

FIGURE 18.—Summary curves of depth and velocity as a function of Reynolds number for sprinkled tests.

depth and Reynolds number in figure 17. Computed lines of best fit are used in the analysis because any percentage errors in the original depth measurements are multiplied in the computations of hydraulic parameters. This enlarges the scatter of points on plots of computed data and increases the difficulty of curve fitting. The relation of depth to Reynolds number can be accurately determined from graphs with little scatter to the data and computed lines of best fit to other graphs are equally good fits. The computed lines of best fit are used for the summary curves in figure 20.

The resistance terms in the Chezy and Manning formulas are plotted for the same two examples in figure 21 and summary curves for all tests are shown in figure 22. Because these terms are related to the Darcy-Weisbach friction factor, they follow the same pattern as figures 19 and 20. The inclusion of graphs for all three resistance terms is to facilitate the visualization of the behavior of these terms. Each of the three most common resistance terms is presented inasmuch as individual hydrologists are more familiar and have customarily preferred to use one expression rather than another.

The examples of data in figure 23 and the summary curves in figure 24 show the relation of the Froude number and the ratio of mean velocity to surface velocity as functions of the Reynolds number. The Froude number is defined as the ratio of inertial forces to gravitational forces; flows with a Froude number greater than 1 are supercritical, flows with a Froude number less than 1 are subcritical. Within the range of conditions investigated, most of the flows observed in the smooth channel and all of those observed in the roughened surface channel were in subcritical flow. Over longer slopes, however, supercritical flows could be expected. Theoretically, the slope of the line relating the Froude number to Reynolds number is 0.5 for laminar flow. The present data for the smooth surface tests indicate a value slightly higher than 0.5 and the roughened surface tests have a value somewhat less than 0.5. This difference is related to the difference in

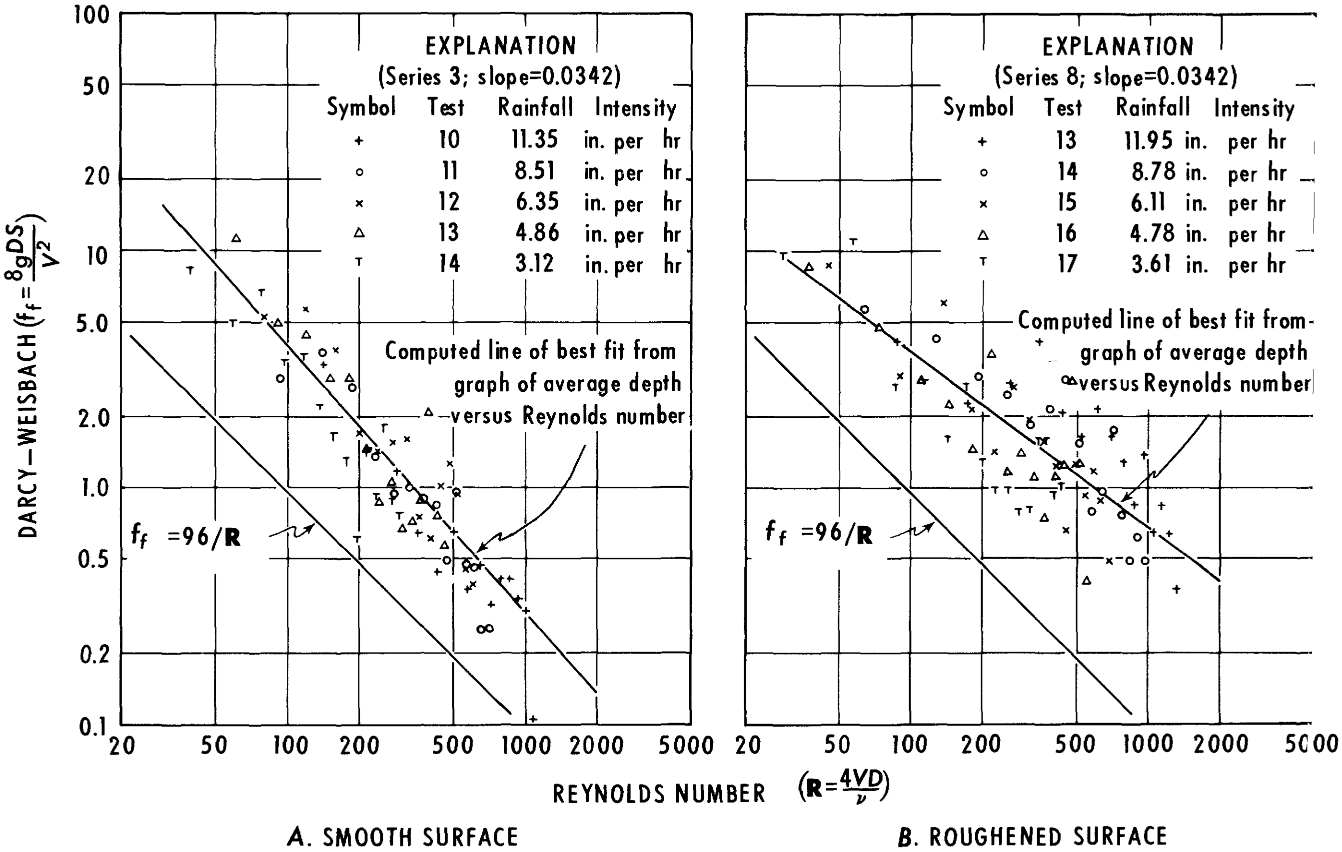

FIGURE 19.—Darcy-Weisbach friction factor as a function of Reynolds number for sprinkled tests.

f values shown in figure 18. (Lest the reader jump to early conclusions, it will be shown in the next section that the Froude number for natural slopes is nearly constant with increasing discharge and generally stays below a value of 0.2.)

The upper parts of figures 23 and 24 show values of the ratio of mean velocity to surface velocity. Nearly all values of the ratio are smaller than 0.67, the theoretical value for uniform laminar flow. This indicates that mean velocity is retarded more than surface velocity and this influence is greatest at the lower Reynolds numbers. For seven of the nine test series, the slope of the line relating the velocity ratio to Reynolds number is positive. The slope of this line is determined by the ratio of the computed m value for mean velocity ($m=1-f$) to the m value for measured surface velocity. The actual slope is this ratio minus 1.0. From the information in figure 18, the value of $1-f$ is greater than the surface velocity m value in all test series except numbers 6 and 7.

FIELD INVESTIGATION OF OVERLAND FLOW

The results of the field verification studies are illustrated by an example of data from one site, Pole Creek Site 3, and summary curves representing the data from all sites. All of the measured and computed data from the field sites are included in the "Summary of data," table F.

Topographic maps were prepared from the detailed surveying at each site. These maps are shown as part A of figures 25 to 31. All of the maps show the general downslope orientation of the runoff plots and because of the close contour interval, many details of the microrelief on the slopes are apparent. Supplementing each topographic map is a grid layout covering the area of the runoff plot. At each field site, physical features influencing the runoff of water were observed and located on the grid layout. These layouts are shown as part B in figures 25 to 31. The mapped features influencing flow include vegetation mounds, exposed rock surfaces, the aluminum stripping used as a barrier to direct runoff, and the position of the collecting trough. The vegetation mounds were generally less than 0.1 foot high and normally occurred at places where sagebrush overstory was removed. Most likely, the sagebrush had protected mound areas from erosion by wind, rain, and the trampling of livestock.

As explained earlier, the flow rarely occurred as a uniform sheet of water and the majority of water travelled downslope in several lateral concentrations of

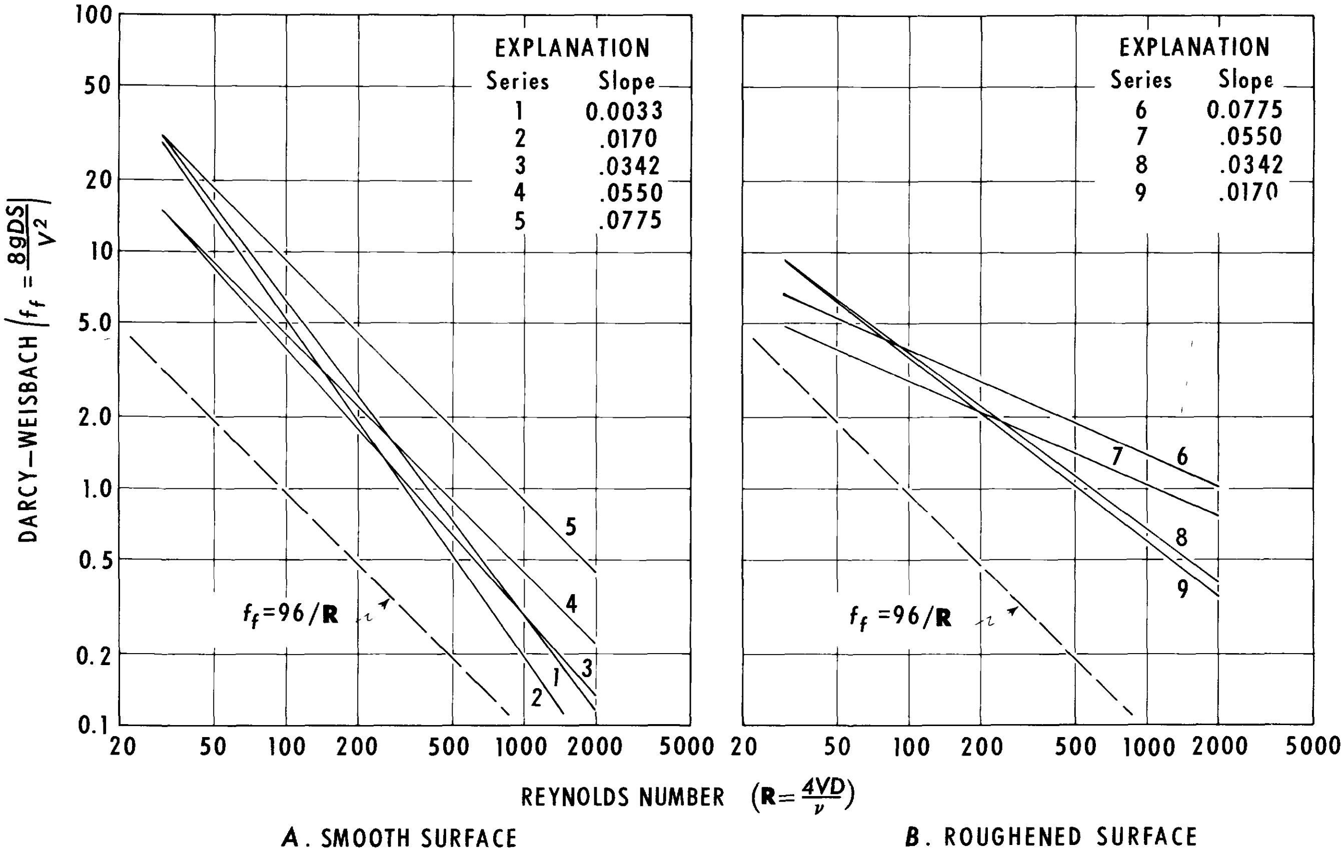

FIGURE 20.—Summary curves of Darcy-Weisbach friction factor as a function of Reynolds number for sprinkled tests.

flow; however, these concentrations were not considered rill flow. Dye tracings were mapped to determine the patterns of flow illustrated in part *B* of figures 25 to 31. Each site exhibited a unique flow pattern dependent mostly on the physical characteristics of the slope.

It is emphasized that not all the runoff occurs in the concentrations of flow shown in figures 25 to 31. The general appearance of runoff at most field sites was one of omnipresent surface detention, easily detected by the glistening of the sheet of water in sunlight. Dye tracings showed that this sheet of water moved slowly downslope and often it moved laterally to join the concentrated areas of flow. Few areas approached stagnation because continuing rainfall forced runoff. Therefore, the flow patterns shown represent only the concentrations of flow and not all the flow. A number of flow lines uniformly spaced, as in the lower fourth of the plot shown in figure 27*B*, indicate depths of flow great enough that runoff is uniform over the entire width.

Pole Creek Site 1 is shown in figure 25. This site was relatively free of topographic irregularities and surface runoff was essentially downslope. Note in figure 25 the trending of the flow pattern in the lower half of the plot in response to the curvature of the contour lines. Runoff from this site and some of the other sites was also characterized by surface detention in a series of puddles formed by barrier dams of organic debris. These miniature lakes are illustrated in figure 3 (lower photograph). Surface runoff occurs, in part, by a succession of failures of these barriers.

The slope of Pole Creek Site 2 was great enough to override the influence of minor topographic irregularities. As shown in figure 26, the general pattern of flow is directly downslope with little anastomosing of the flow concentrations. A similar flow pattern is noted in figure 27*B* for Pole Creek Site 3. However, the less steep slope of Pole Creek Site 3 begins to show the influence of small topographic features and the curve of flow lines around topographic highs. In the lower fourth of the runoff plot at Pole Creek Site 3, depths of flow are sufficiently great and are evenly enough distributed so that flow was nearly uniform across the plot. Note also the shift in direction of the flow pattern in this area in response to a curvature in slope direction.

The ground slope at New Fork River Site 1 is flat enough that small topographic features are obvious in the topographic map in figure 28 and are visible in the

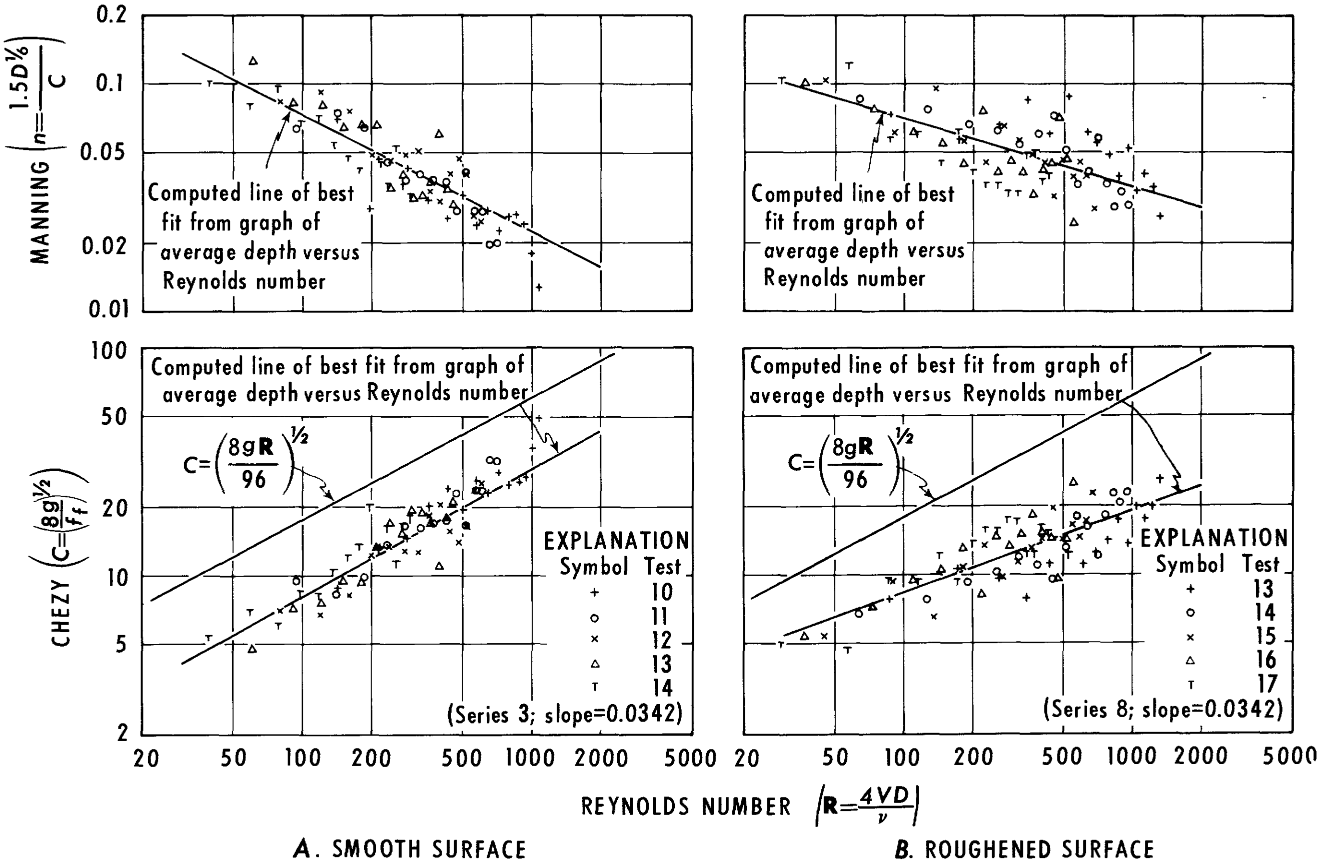

FIGURE 21.—Chezy's C and Manning's n as a function of Reynolds number for sprinkled tests.

upper photograph of figure 6. The flow pattern responding to this topography is shown in figure 28*B*. The gradient at the lower end of the plot was such that water ponded in the lower 2 feet of slope. In this ponded area, sediment was deposited as a delta. The size of the delta, shown in the lower photograph of figure 6, indicates the effectiveness of overland flow to erode and transport sediments. The eroded sediments apparently were derived as sheet wash since no rilling was observed. The ponding had no effects on the upslope hydraulics of flow and affected only the analysis of sediment concentrations.

The flattest slope of the sites investigated was for New Fork River Site 2. Irregular surface features are unmistakeable in the topographic map in figure 29*A* although they stand out only slightly in the photographs of figure 7. The pattern of flow over this topography is shown in figure 29*B*. The flow is definitely directed around the topographic highs and follows the microvalleys indicated by the contour map. Water in the lower 8 feet of this site was also ponded and there was some deposition of sediment in this area. The deposition was distributed over the area and did not form a delta as at New Fork River Site 1.

Figures 30 and 31 illustrate the topography and flow patterns for the two Boulder Lake sites. The appearance and behavior of flow at these sites are similar to those just described for the other sites.

Examples of downslope profiles of depth and surface velocity are shown in figure 32 for Pole Creek Site 3. This site was chosen as an example because it represented an intermediate slope in the range of slopes investigated. Measurements listed in the "Summary of data," table C, were used to construct the downslope profile of depth. With little variation, the data can be described with a straight line having a slope of 0.80 on the log-log plot. Surface-velocity measurements are plotted as the downslope profile in the right half of figure 32. Part *B* of this figure is a plot of the actual individual measurements and part *A* is an attempt to smooth the data by using a running 3-foot average of the measured velocities. The data can be adequately expressed with a straight line of slope 0.25.

Summary curves of downslope profiles of depth and surface velocity are shown in figure 33 for all field sites. Values of f for the exponent of depth range from 0.40 to 1.00 and m values of velocity range from 0.25 to 1.00. More will be said about these values of f and m later.

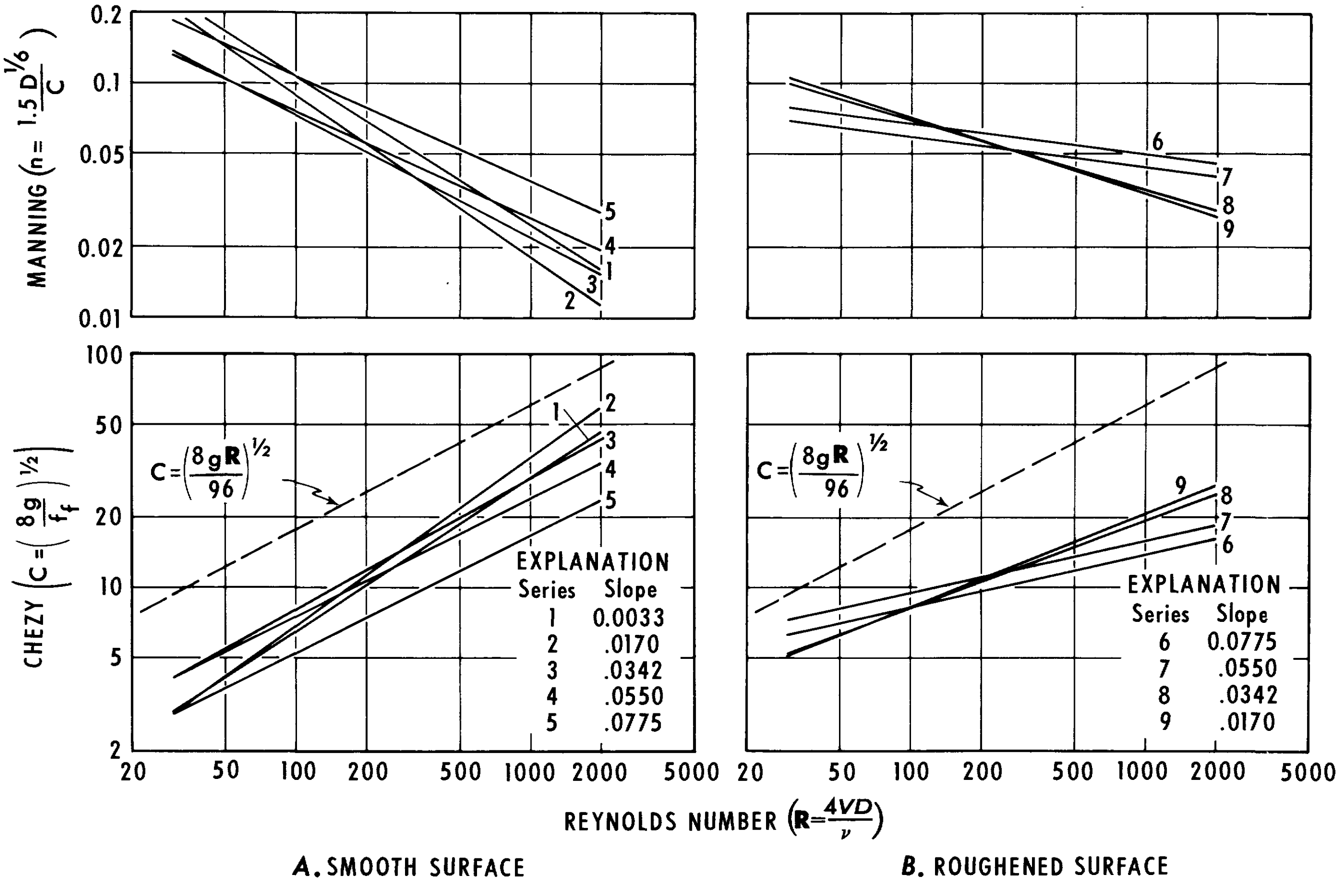

FIGURE 22.—Summary curves of Chezy's C and Manning's n as a function of Reynolds number for sprinkled tests.

Depth data are also plotted as a function of Reynolds number on the left of figure 34. The same line of fit for figure 32 is also shown in figure 34. Summary curves of depth as a function of Reynolds number are shown in the left graph in figure 35.

Values of the Darcy-Weisbach friction factor for Pole Creek Site 3 are plotted in the right graph of figure 34. The scatter of data shows the tremendous effect of small depth discrepancies in the computation of friction factors. The suggested straight line relationship is a computed line of best fit taken from the opposite graph in the figure. The slope of the straight line relationship, as determined from equation 13, is equal to $f—2m$ or $f—2(1—f)$. For a value of f equal to 0.67, the slope of the friction factor relationship is 0; smaller values of f yield negative slopes, and greater values of f give positive slopes. Since f=0.80 for Pole Creek Site 3, the slope of the friction factor relationship is 0.40 and this indicates the friction factor increases in the downslope direction. Summary curves of the friction factor-Reynolds number relation are shown in the right half of figure 35 for all field sites. The wide range in values of slope for the friction factor relation are due to the range in values of f for the depth relations.

Values of Chezy's C and Manning's n for Pole Creek Site 3 are plotted as a function of Reynolds number in figure 36. Summary curves for all plots are shown in figure 37. The appearance of these curves is similar to those for the Darcy-Weisbach friction factor.

The relation of the Froude number to Reynolds number is shown in the left graph of figure 38 for the data of Pole Creek Site 3. Positive or negative slopes for the straight line relation depend on whether the f value is greater or less than 0.67. The summary curves for Froude number as a function of Reynolds number are shown in the left graph in figure 39.

The ratio of mean velocity to surface velocity for Pole Creek Site 3 is shown as a function of Reynolds number in the right graph of figure 38 and summary curves are shown in the right graph of figure 39. The near horizontal to negative range in slopes of the lines in figure 39 indicate a relatively more rapid downslope increase in surface velocity than mean velocity.

COMPARISON OF FIELD RESULTS TO LABORATORY DATA

The most apparent difference in field and laboratory data is the greater depths occurring in the field run-

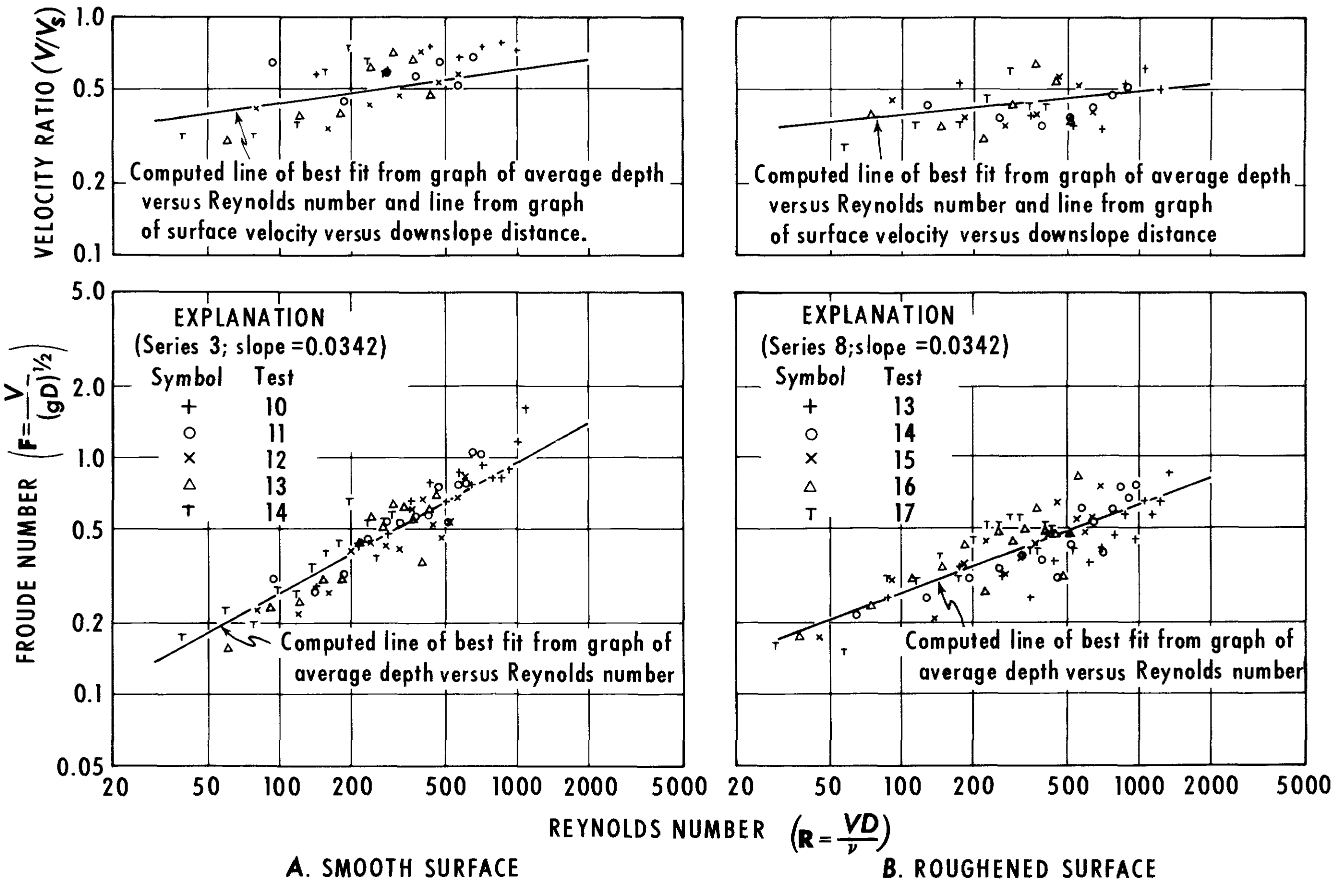

FIGURE 23.—Froude number and velocity ratio as a function of Reynolds number for sprinkled tests.

off. This was not an unexpected observation. The laboratory data indicated that the effect of roughness is to retard the flow and increase the depth; the sand grain roughness in the laboratory increased the depths up to 30 percent over those on a smooth surface. Surface roughness of the field sites is difficult to estimate. The roughness of field sites consists of both particle roughness (sand grain roughness in bare areas and plant sprouts in vegetated areas) and form roughness (topographic irregularities). Mean grain sizes of the soil particles at the field sites are smaller than those in the laboratory roughness so that the increase in depths is due primarily to vegetation and topographic characteristics of the field sites. Depths at the upslope end of the field plots were comparable to depths at the upstream end of the flume in the laboratory. Thus the downslope rate of increase in depths is greater for the field sites. Figure 33 shows f values for field sites range from 0.40 to 1.00, average 0.69, and compare to an average f value of 0.48 for the rough surface tests in the laboratory.

Higher f values are related both to the magnitude of relative roughness (degree of overall retardance) and the character of the runoff (for example, ponding as at Pole Creek Site 1, lower photograph in figure 3). The f values for the field sites show no correlation with ground slope, or, at least, the data indicate that other characteristics of the field plots override the influence of slope. Since no correlation could be established between vegetation cover in percent (or type of vegetation) and f value, the increase in f values at field sites is attributed to topographic form and, dependent on form, the character of runoff. No two field sites are identical in form and no two depth profiles are the same.

Values of f in the relation $D \propto q^f$ are related to downslope changes in resistance to flow. Resistance to flow, expressed in this report as the Darcy-Weisbach friction factor f_f, Chezy's C, and Manning's n, describe bulk resistance to flow rather than resistance attributable to grain roughness alone. With increasing downslope discharge, one would expect resistance to flow to decrease downslope as relative roughness decreased (as in all laboratory cases). Overriding influences, such as ponding, are analogous to tremendous retarding forces. Thus, depending on topographic form, relatively smoother surfaces may show higher resistance to flow and different rates in downslope changes in roughness.

The average of the downslope changes in roughness at the field sites is approximately zero, this indicates a

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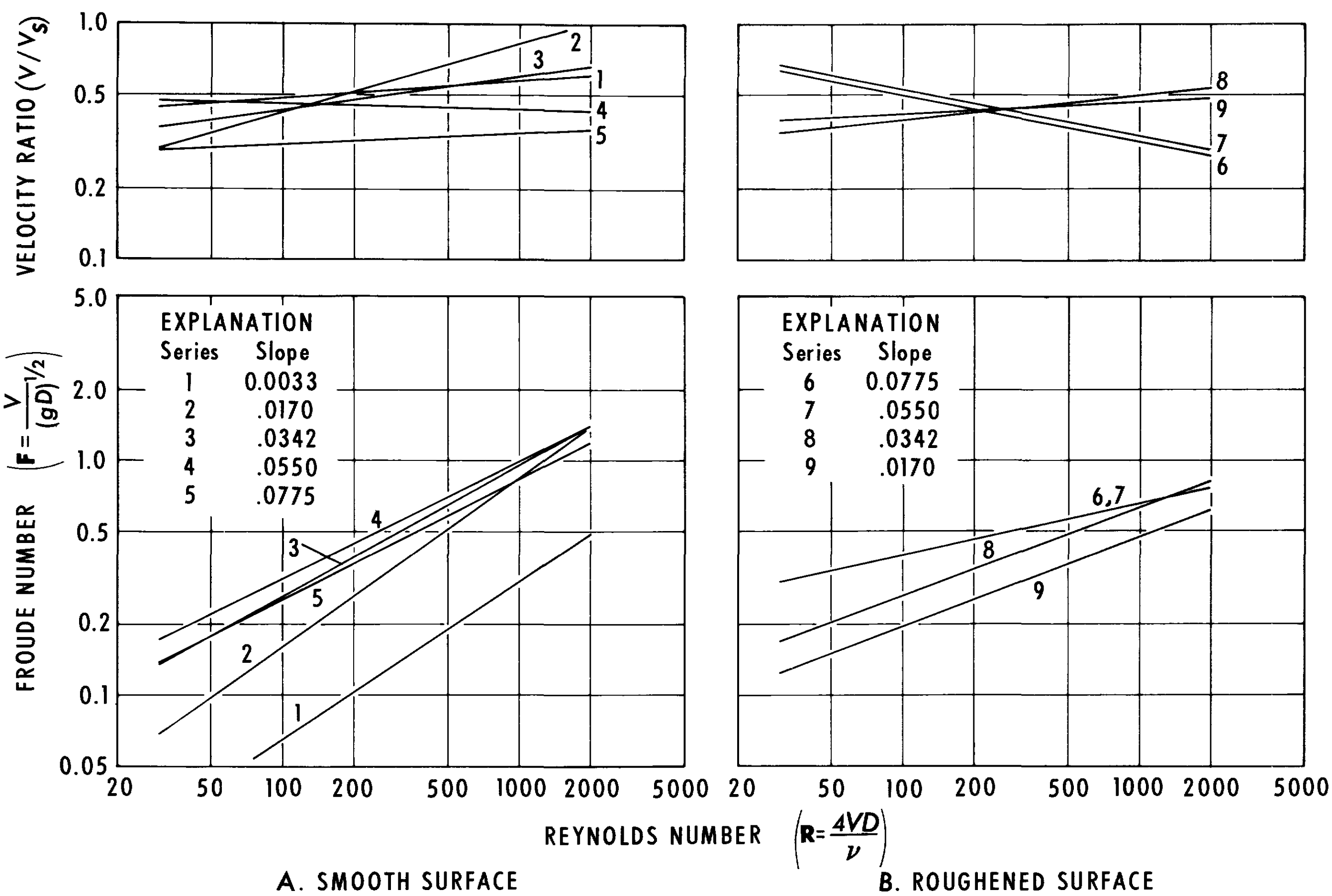

FIGURE 24.—Summary curves of Froude number and velocity ratio as a function of Reynolds number for sprinkled tests.

downslope increase in relative roughness. Absolute roughness is probably not increasing, so the apparent increase in roughness is due to a decrease in runoff efficiency and is related to the microtopography of the site. As a first approximation to overland flow on natural ground surfaces, an f value of 0.67 and no downslope change in roughness may be used to estimate the hydraulic parameters. Absolute values of depth and the resistance term may be approximated from figures 35 and 37. Values of relative roughness corresponding to values of the Darcy-Weisbach friction factor are beyond those shown on conventional Moody diagrams, but they would appear in some instances to have a value greater than 1. This is not unreasonable comparing the shallow depths of flow to the magnitude of vegetation and topographic barriers.

It is difficult to compare values of the friction factor at field sites to values from the laboratory tests. However, in general, the field data indicate a tenfold increase in resistance on the natural field plots compared to the laboratory surfaces.

Values of m for surface velocity are generally less for the field sites than for the laboratory flume (compare figure 33 to figure 18). As depth enlarges its role in absorbing downslope increases in discharge, mean velocity must absorb less of the change. Graphs of the velocity ratio in figure 24 indicate that the velocity ratio is nearly constant. This is approximately true for the field data. (See figure 40.) Thus, m values for surface velocity in the field must be lower than laboratory values. An average value of the ratio of mean velocity to surface velocity is about 0.4 to 0.5. One reason for this low value of the velocity ratio is that a maximum surface velocity was measured in the field. The leading edge of the dye trace was measured and as the dye merged into concentrated areas of flow, the velocity timed was greater than an average surface velocity over the width of the plot. Still, values of the velocity ratio from field data were not substantially lower than values from laboratory data.

The downslope change in Froude number for field data varied, but on the average it was nearly constant down the slope and was considerably lower than values from laboratory data. This behavior is related to the differences in depths of field runoff compared to labora-

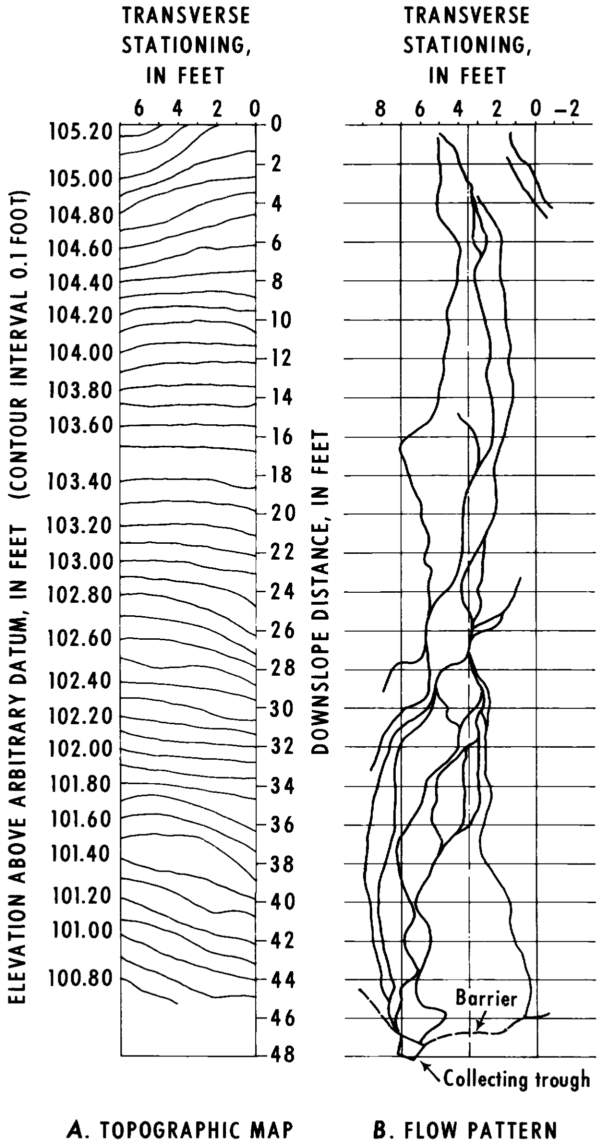

FIGURE 25.—Topography and flow pattern at Pole Creek Site 1.

tory tests. An average value of the Froude number is 0.1, which is well within the regime of subcritical flow.

PROBABILISTIC APPROACH TO OVERLAND FLOW AND THE SHAPE OF HILLSLOPES

In accommodating the downslope increase in discharge from rainfall, overland flow on hillslopes can change velocity, depth, and slope. These are the factors which describe the hydraulic geometry. The exponents of hydraulic geometry are indices of the deviations of the dependent factors for any change in the independent factor, discharge. The variability of the dependent factor is minimized when the variance of the factor is minimized. Such minimization of the variability of the dependent factors provides the most probable relations among the factors. When variability of dependent factors are jointly minimized, the sum of the variance of the factors is minimized.

HYDRAULIC CHANGES DOWNSLOPE

In the presentation of data in earlier sections of this report, hydraulic geometry was used to describe the downslope changes in depth, velocity, and resistance to flow. Exponents in the hydraulic geometry equations, summarized here,

$$D \propto Q^f \propto \mathbf{R}^f, \qquad (5, 6)$$
$$V \propto Q^m \propto \mathbf{R}^m, \qquad (8, 9)$$

and

$$f_r \propto Q^y \propto \mathbf{R}^y, \qquad (10, 11)$$

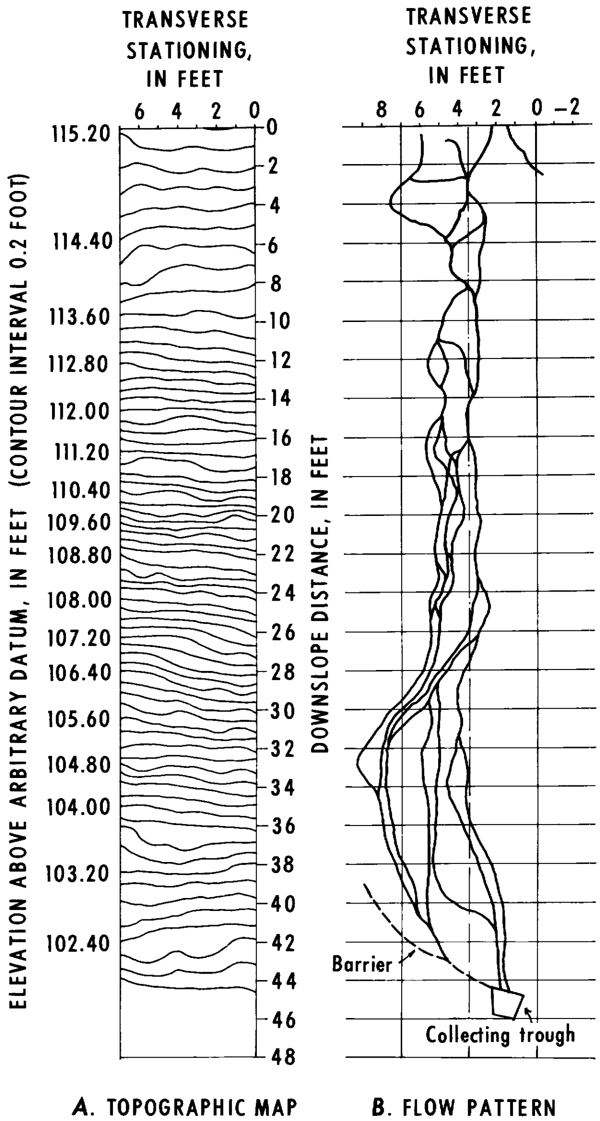

FIGURE 26.—Topography and flow pattern at Pole Creek Site 2.

were computed for the condition of constant slope. More generally, slope can also be expected to vary with discharge:

$$S \propto Q^{z} \propto \mathbf{R}^{z}. \qquad (22)$$

Thus, it can be seen that quantification of four variables, f, m, y, and z is needed to describe the hydraulics of flow with increasing discharge.

The known laws of hydraulics do not provide sufficient physical relations to offer a solution to the above equations. However, in a clever reasoning of the most probable energy distribution and expenditure within a river system, Leopold and Langbein (1962) were able to supply additional equations needed for a solution to flow in river channels. Namely, they postulated that energy expenditure per unit of surface area

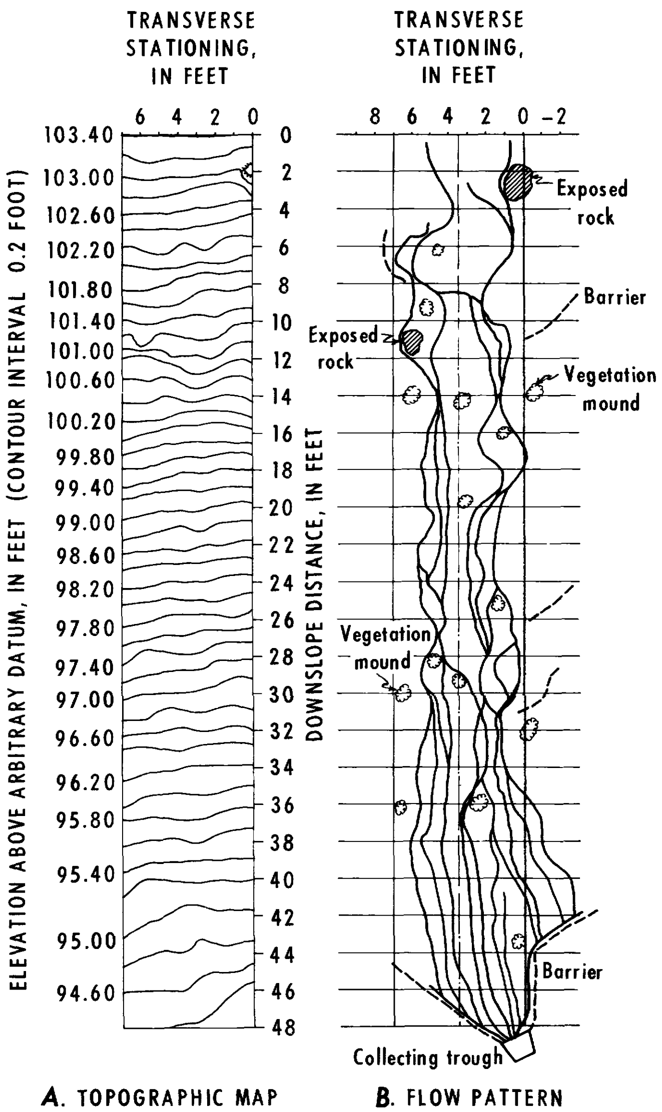

FIGURE 27.—Topography and flow pattern at Pole Creek Site 3.

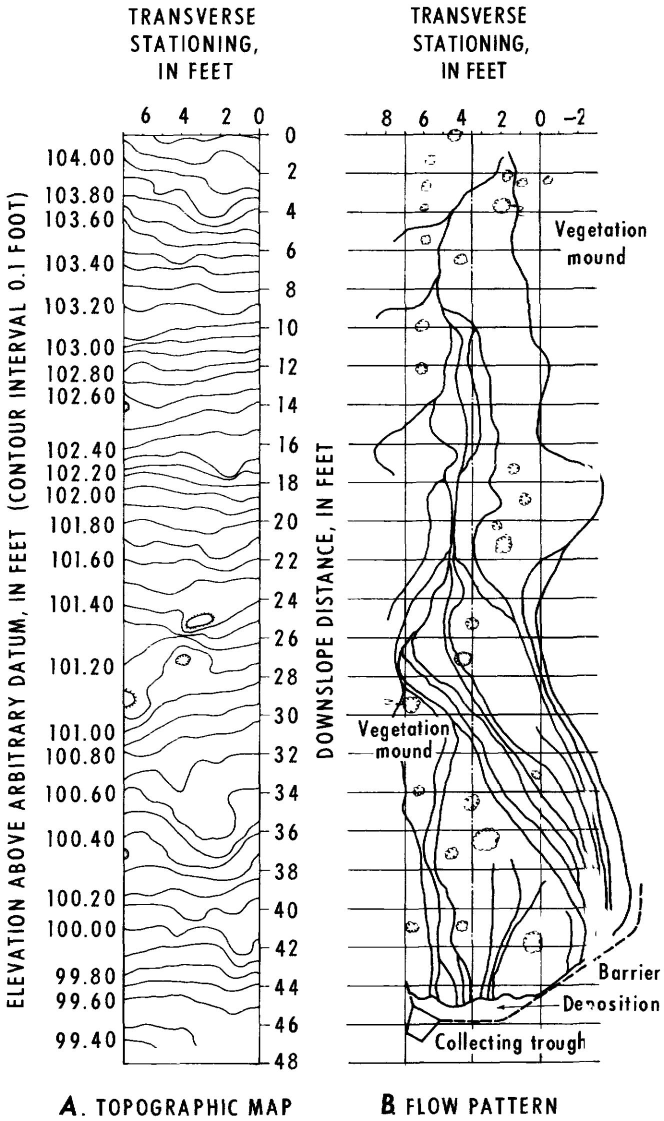

FIGURE 28.—Topography and flow pattern at New Fork River Site 1.

is equal throughout the river system and that total energy expenditure in the system is a minimum. Langbein (1964) elaborated on this pioneering work; Emmett and Leopold (1964) presented graphical solutions for Langbein's equations, and Langbein (1965), in a closure to his 1964 paper, demonstrated the validity of this new concept through the agreement between theory and data for many examples of flow in rivers, canals, and flumes. Although controversy still exists about the applicability of "most probable" statistical concepts to hydraulics, there is increasing acceptance and elaboration of the basic ideas. For example, Maddock (1969) has applied these concepts to sediment transport in alluvial channels. It would be interesting to apply these statistical techniques to an analysis of overland flow.

For overland flow, width may be considered constant, $b=0$, and increase in discharge is absorbed through the interaction of depth and velocity and in turn is reflected in shear and friction. The variability of each of these dependent factors is its exponent in hydraulic geometry and the variance of each of these terms is the square of the exponent relating that variable to discharge. Thus the variance of depth may be expressed as f^2, velocity as m^2, shear as $(f+z)^2$, and friction as $(f+z-2m)^2$. The most probable way that an increase in discharge can be met is given by the condition that the sum of these variances is minimized:

$$f^2+m^2+(f+z)^2+(f+z-2m)^2\rightarrow 0. \qquad (23)$$

Minimization of equation 23 will be considered for two cases: (1) turbulent flow and (2) laminar flow.

The theoretical value of f for turbulent flow is 0.60; the theoretical value of f for laminar flow is 0.33. These are the same values illustrated in figure 11 for relation between depth and Reynolds number for uniform flow. For constant widths, $m=1-f$. Thus, for turbulent flow, $f=0.60$ and $m=0.40$, and for laminar flow, $f=0.33$ and $m=0.67$. With these values of f and m for equation 23, minimization of equation 23 gives a value of $z=-0.20$ for turbulent flow and $z=+0.33$ for laminar flow. Thus for turbulent flow, slope decreases downslope and for laminar flow, slope increases downslope. It may be supposed that flows intermediate between laminar and turbulent (as those in the transition region or, in the present investigation, a disturbed type of

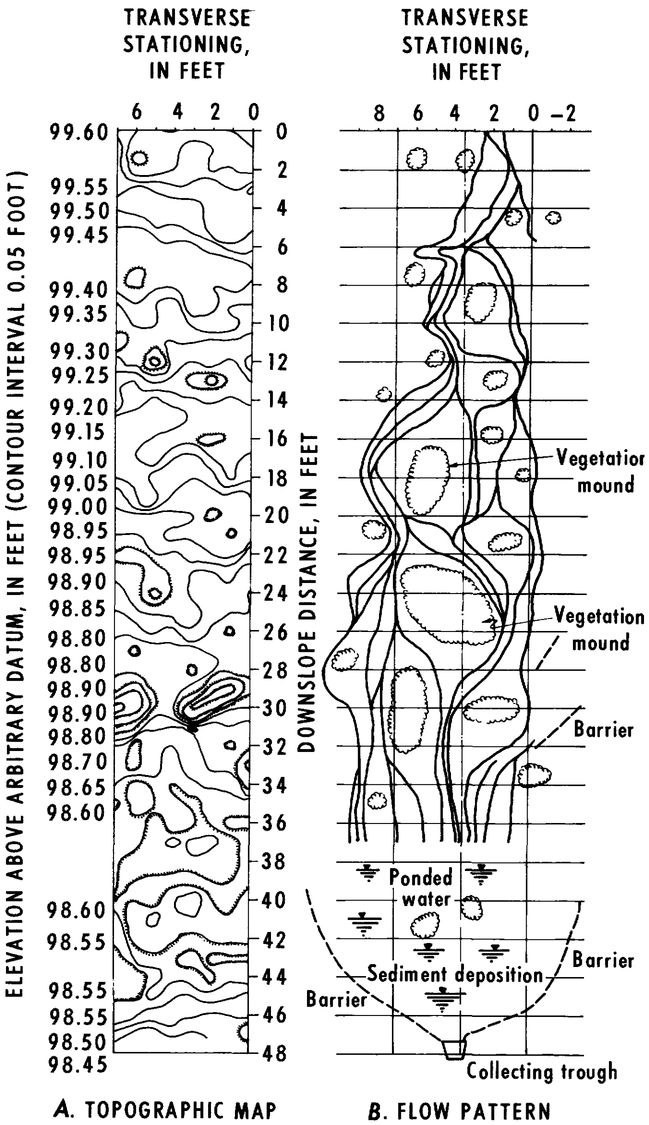

FIGURE 29.—Topography and flow pattern at New Fork River Site 2.

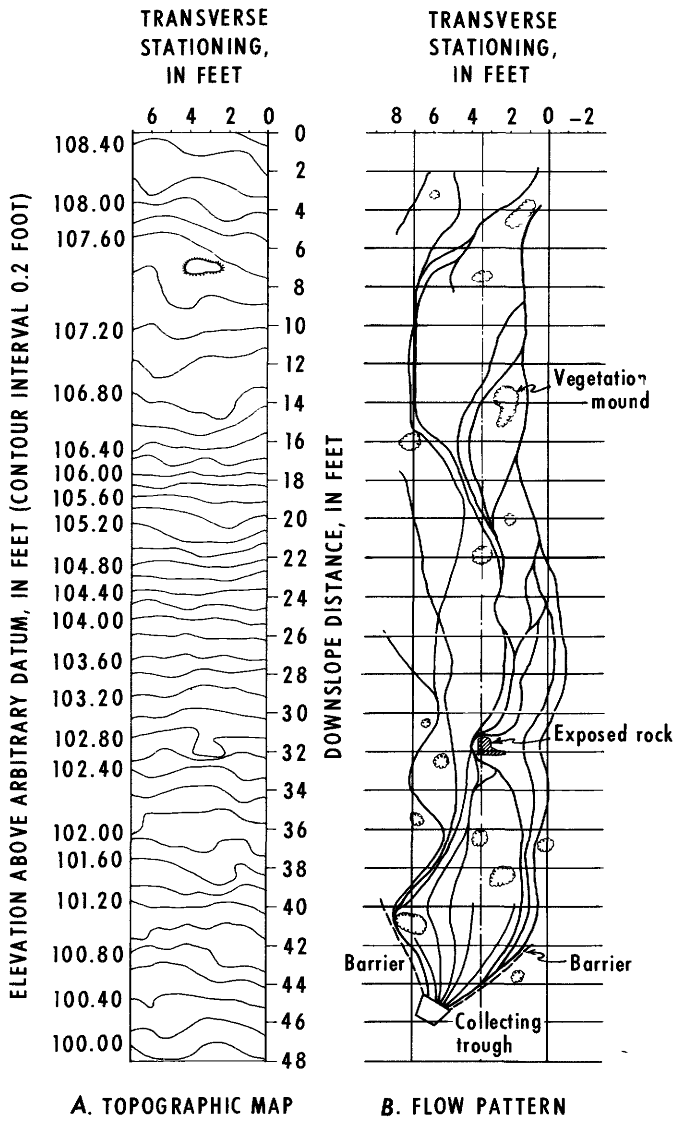

FIGURE 30.—Topography and flow pattern at Boulder Lake Site 1.

flow caused by raindrop impact and the anastomosing of flow concentrations) would show intermediate values of downslope changes in slope. In the present probabilistic approach to overland flow, an intermediate value (or value for flows somewhere between laminar, $z=+0.33$, and turbulent, $z=-0.20$) is approximated by a zero downslope change in slope, $z=0.0$.

From the computed values of z above, values of the roughness exponent, y, can be computed from the Darcy-Weisbach formula (eq 7): $y=f+z-2m$ or $y=-0.40$ for turbulent flow, and $y=-0.67$ for laminar flow. From figure 12 and its discussion, it has been shown that for uniform flow on a constant slope, the exponent y should have a value of -1.0 for laminar flow. The less negative value (-0.67) in the present analysis indicates a relative increasing downslope resistance to flow. That is, when slope is relaxed and allowed to change in the downslope direction, the resistance to laminar flow decreases downslope less rapidly than for a fixed slope. Conversely, for turbulent flow, the data of figure 12 indicate that y should have a value of -0.20 for fully turbulent flow. The more negative value (-0.40) in this analysis indicates decreasing resistance to turbulent flow in the downslope direction.

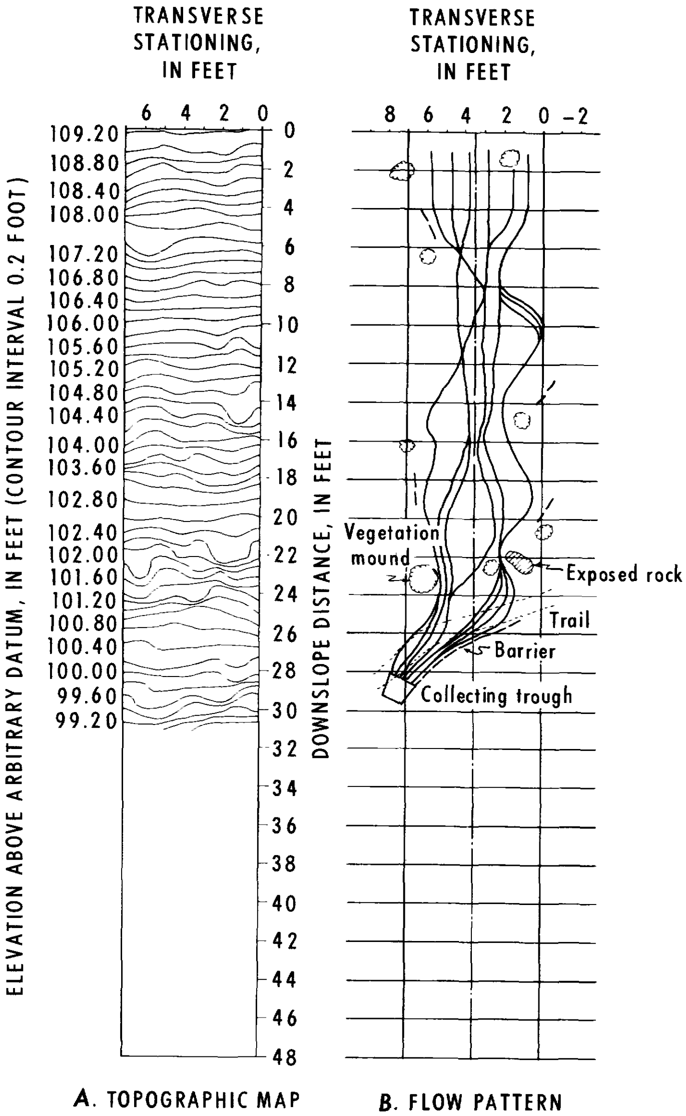

FIGURE 31.—Topography and flow pattern at Boulder Lake Site 2.

APPLICATION TO THE SHAPE OF HILLSLOPE PROFILES

It is of interest to apply the results of this analysis to flow over a long length of hillslope. Without any external factors affecting the downslope runoff of unconcentrated sheet flow resulting from rainfall, Reynolds number increases in the downslope direction. For uniformity of rainfall and infiltration, Reynolds number increases uniformly downslope from a value of zero at the hilltop to a maximum at the base of the slope. For sufficiently long slopes, overland flow at the foot of the hill could be expected to be fully turbulent. It should be noted, however, that the Reynolds number is dependent on the runoff rate. The Reynolds number, $\mathbf{R}=4VD/\nu$, may also be expressed as

$$\mathbf{R}=cRL \tag{24}$$

where c is a coefficient including the value of kinematic viscosity of water, R is the runoff rate in inches per hour, and L is the length of slope in feet. For an average value of viscosity of 1×10^{-5} feet squared per second, the following tabulation shows for several intensities of runoff the length of slope required to obtain the given Reynolds number:

Reynolds number	Length of slope, L, in feet		
	0.5 in. per hr	1.0 in. per hr	2.0 in. per hr
500	108	54	27
1,000	216	108	54
2,000	432	216	108
3,000	648	324	162
4,000	864	432	216

Doubling the runoff rate would halve the length of slope needed to obtain the same Reynolds number.

The preceding analysis would indicate that an upper reach of slope, characterized by laminar overland flow, should be convex (z is positive). A middle reach of slope with mixed flow should be nearly straight (z is approximately zero) and a lower reach of slope with turbulent overland flow should be concave (z is negative). From the tabulated slope lengths above for one inch per hour of runoff, such a slope profile may be convex for about

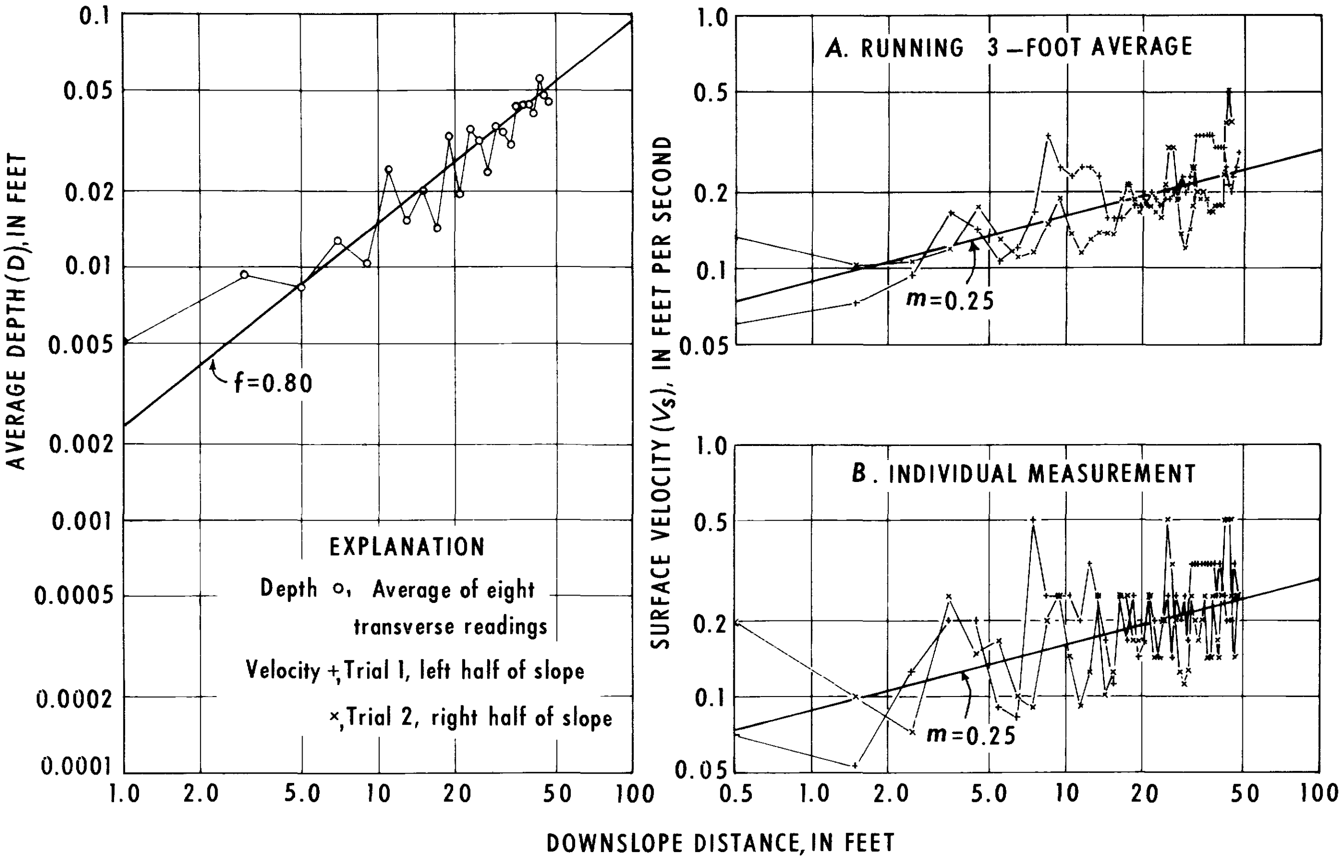

FIGURE 32.—Downslope profiles of depth and surface velocity for Pole Creek Site 3.

the first 100 feet, straight for the next 200 feet, and concave for the remainder of the profile. Such convex, straight, concave hillslope profiles are schematically shown in figure 40 for three intensities of runoff on slopes with the same initial gradient. The steepening of the straight segment of slope with decreasing runoff rates may not be significant because the slope of the straight segment depends primarily on the initial gradient at the top of the hill. The influence of initial gradient is schematically shown in figure 41 for a constant runoff intensity.

White (1966) has shown that many hillslopes are indeed characterized by a convex, straight, and concave profile. The length of each of the three slope segments is dependent on the runoff rate which in turn relates to rainfall intensity and infiltration, and short slopes may not be long enough to develop all of the three segments. The steepness of the straight segment is dependent on a number of possible combinations of initial gradient and runoff intensity. As one possibility, the initial gradient might be associated with a runoff intensity (a combination of figs. 40 and 41) in such a way that slope steepness is constant and only the length of each slope segment is different for differing rates of runoff. But regardless of the slope steepness, the rate of downslope change of gradient in the convex and concave segments should be similar between most slopes, an observation verified by measurements of hillslopes by White (1966). It appears likely that the overall hillslope profile (lengths of each of the three slope segments) is dependent on the climate which defines the rainfall intensity and the geologic structure, especially rock type, which controls the infiltration rate. Differing rainfall intensities sculpture the ground surface in proportions different than those of the observed profile, but the general shape of the hillslope is that profile determined by a dominant runoff rate. Slopes with different infiltration rates (differing geologic structure and rock type) in the same climatic environment may have different lengths of each slope segment as may slopes of the same geologic structure and rock type in different climatic environments. But all slopes subject to overland flow would tend towards a characteristic convex, straight, and concave profile.

It is emphasized that the profile suggested by the above analysis is not characteristic of any given slope, but it is a most probable profile toward which all hillslopes tend to develop. And, of course, an implicit

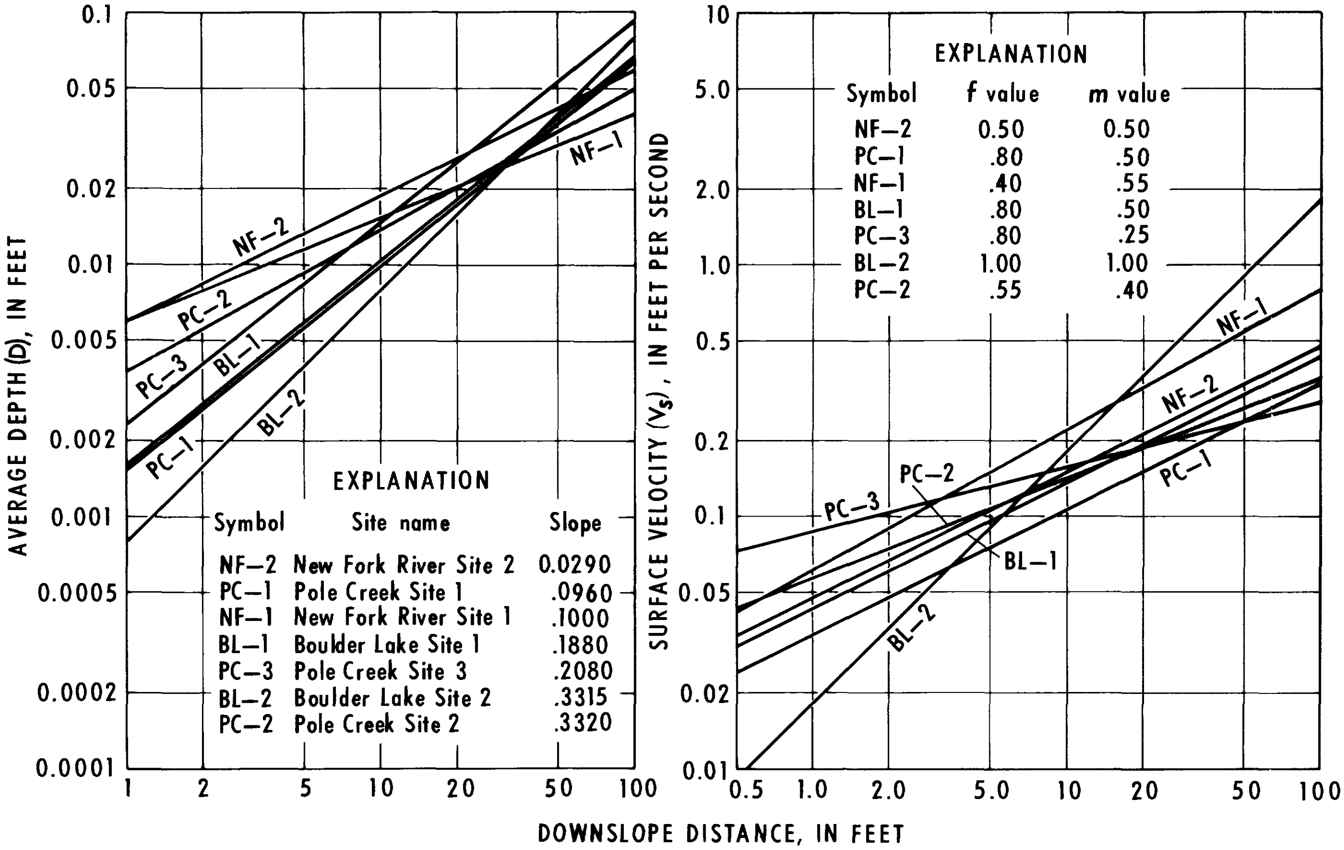

FIGURE 33.—Downslope profiles of depth and surface velocity at field sites.

assumption is that overland flow is the only operative process developing the profile. Other processes, for example mass movement, might serve to alter a profile developed only from the flow of unconcentrated runoff.

EROSION AND SEDIMENT TRANSPORT

RILLS AND DYNAMIC EQUILIBRIUM

One of the most ubiquitous processes occurring on hillslopes is the erosion, transportation, and deposition of debris by running water. The formation of rills is one consequence of the flow of water. However, some slopes may show no rills and may be undergoing uniform degradation by sheet erosion. The question may be logically asked why some slopes develop rills and others do not? Since the development of rills is widespread, the question extends beyond the field sites of this study and is pertinent to the general science of geomorphology.

Both rills and sheet erosion are the products of overland flow. However widespread overland flow may be, it is one of the most elusive processes to observe and measure. This fact has made difficult the collection of quantitative data to help resolve the questions of why and how rills develop. In fact, little is known of the general mechanics of slope erosion by overland flow.

The author and others (Leopold and others, 1966) have measured hillslope erosion for nearly 10 years in a semiarid area of New Mexico. Despite efforts to observe overland flow from thunderstorms occurring during the several weeks of residence at the project area each year, overland flow was never observed in the field. Yet, during the period of measurement, surface erosion on unrilled slopes yielded 13,600 tons per square mile per year or 98 percent of the sediment production from all sources. Obviously, surface erosion on these unrilled slopes must be the work of unconcentrated overland flow, but without the detailed measurements of hillslope erosion, the full importance of overland flow was not apparent in the field. Still, the question remains; why did the slopes degrade by sheet erosion rather than develop rills?

The presence of rills was not observed at any of the field sites of the present investigation and rilling is not common in the general area. Flow concentrations occurring at the sites were dictated by microtopographic features, but the paths followed by concentrations of flow were not in discernible rills. Nor, during the course of sprinkling at each site (generally about 6 hours or longer), were rills observed to be formed by flow concen-

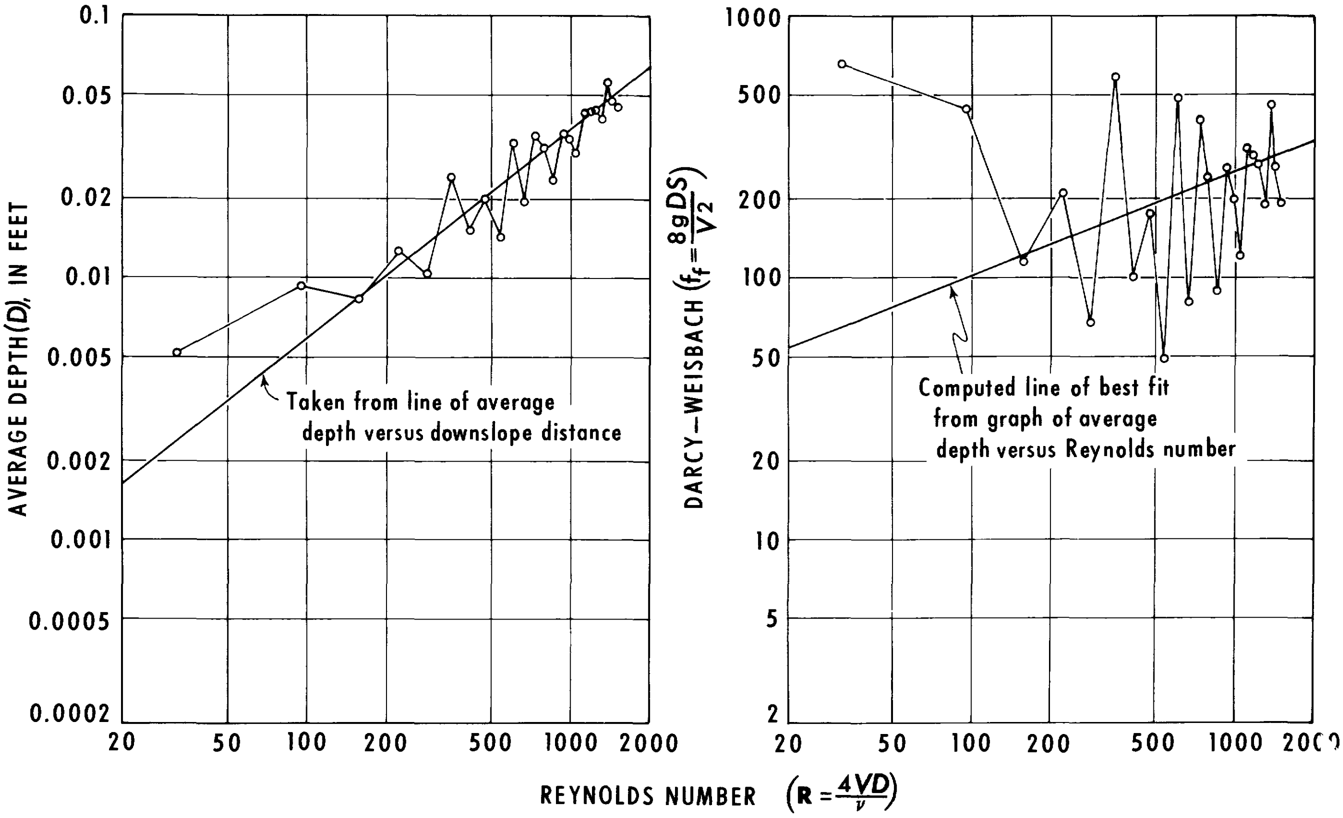

FIGURE 34.—Depth and Darcy-Weisbach friction factor as a function of Reynolds number, Pole Creek Site 3.

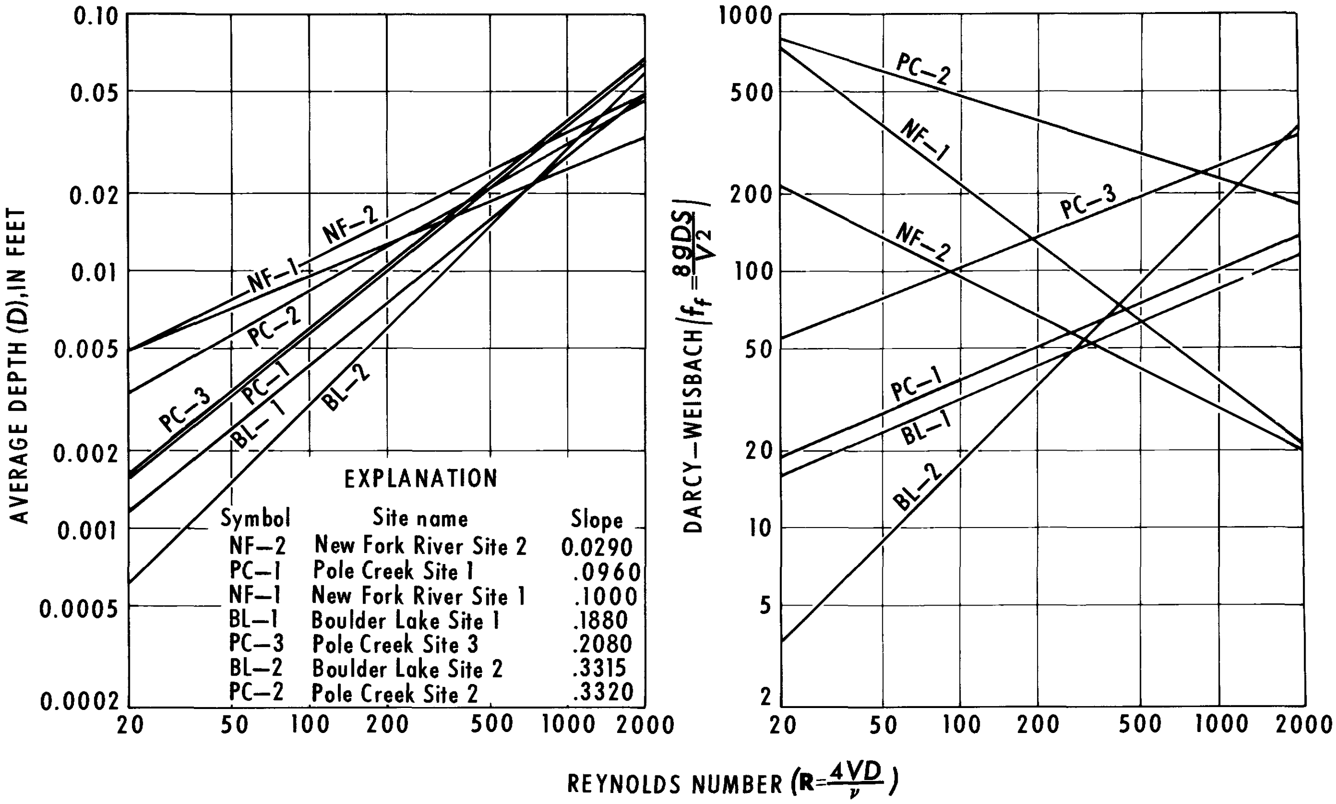

FIGURE 35.—Summary curves of depth and Darcy-Weisbach friction factor as a function of Reynolds number, field sites.

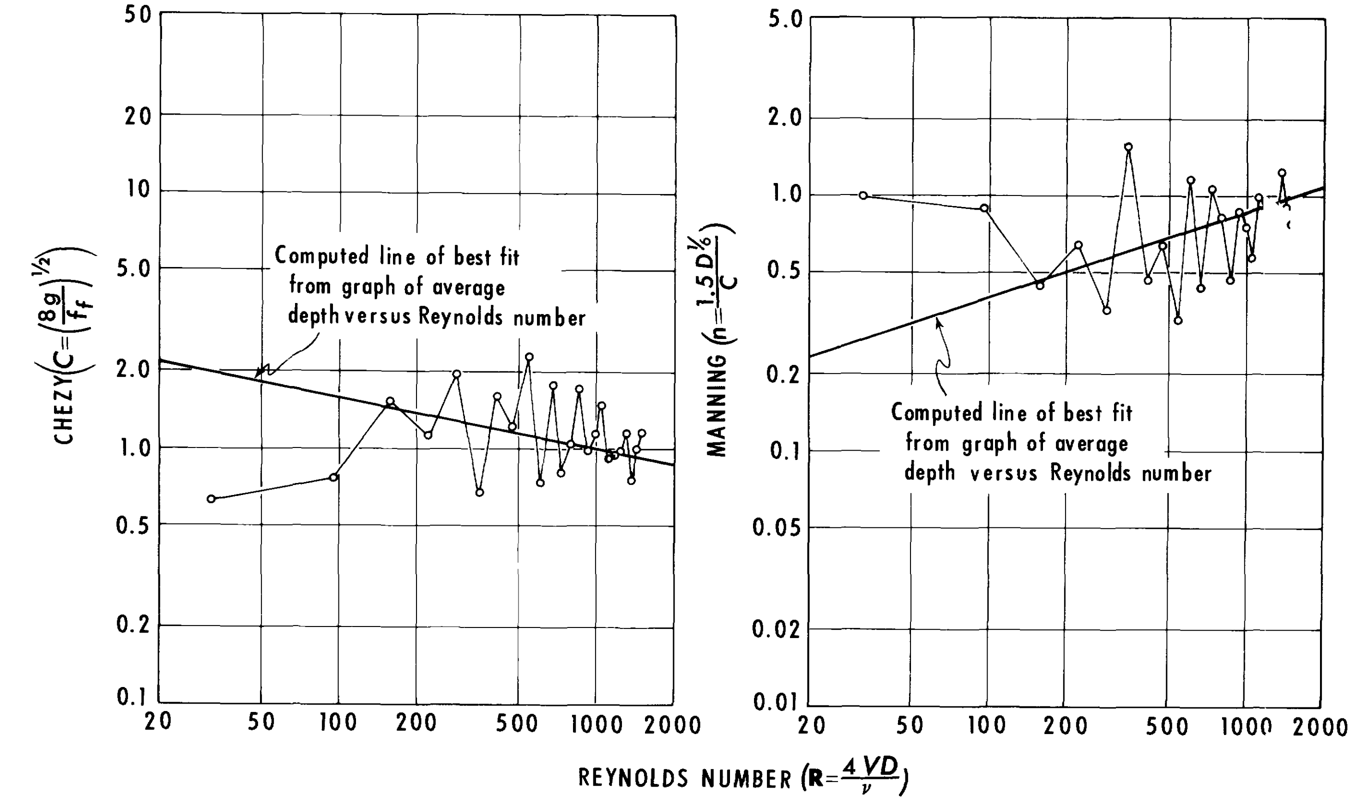

FIGURE 36.—Chezy's C and Manning's n as a function of Reynolds number, Pole Creek Site 3.

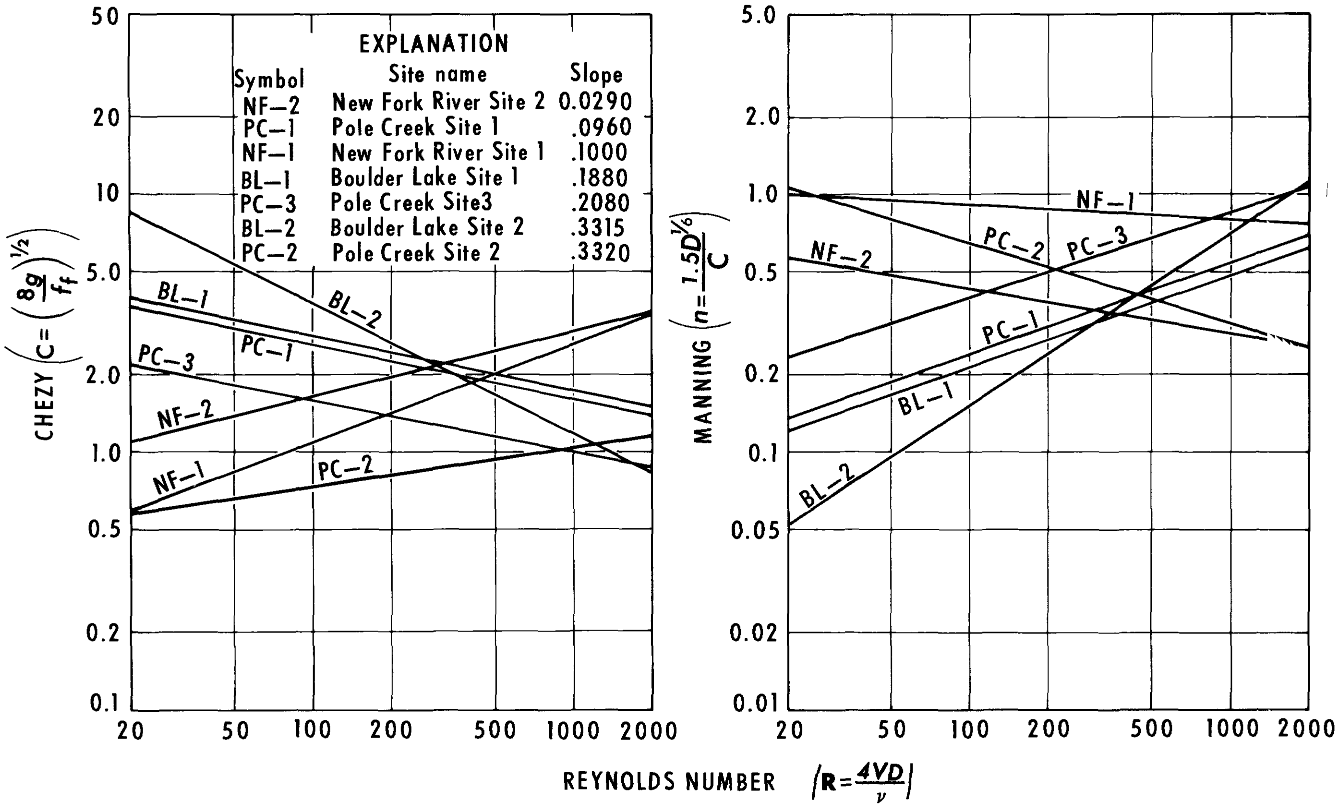

FIGURE 37.—Summary curves of Chezy's C and Manning's n as a function of Reynolds number, field sites.

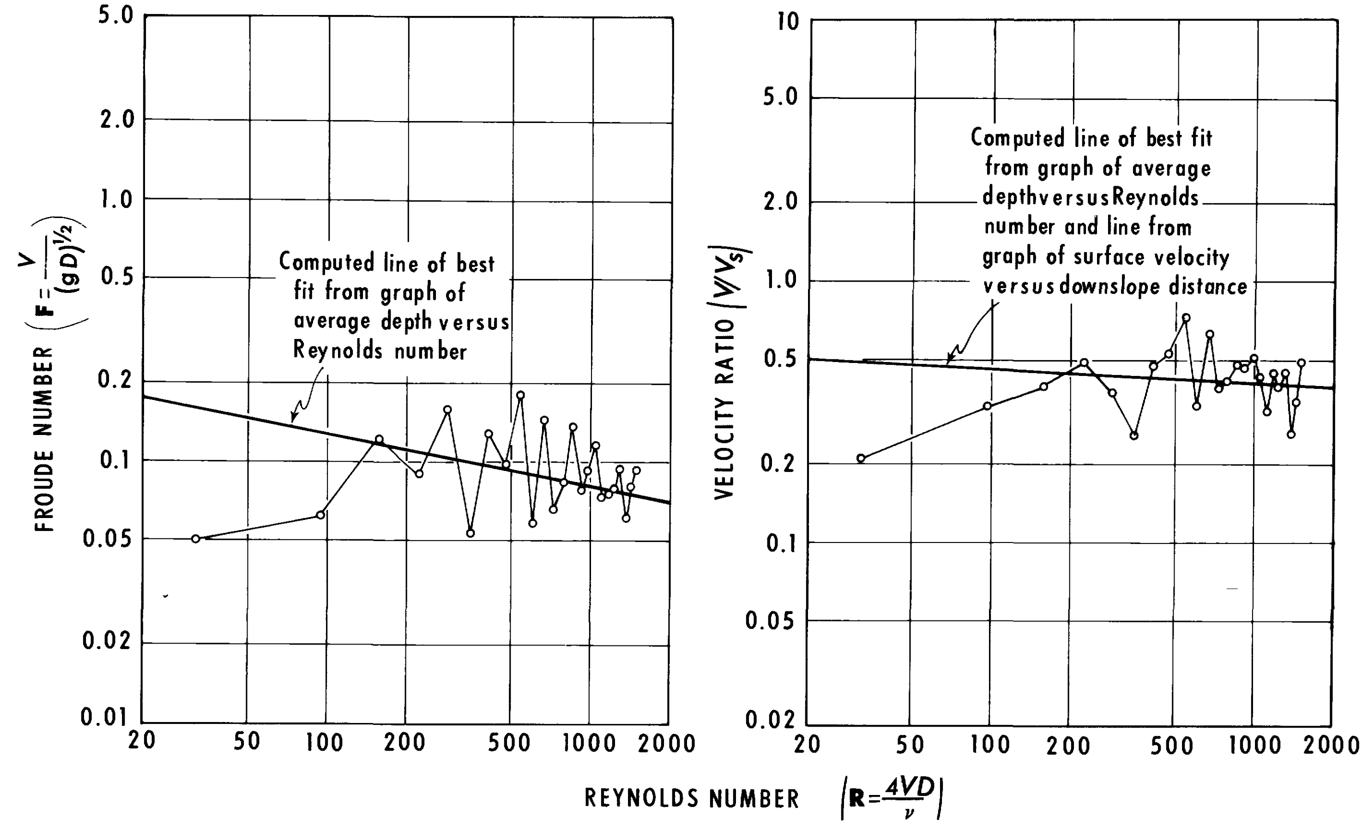

FIGURE 38.—Froude number and velocity ratio as a function of Reynolds number, Pole Creek Site 3.

trations. Rilling is generally considered to be evidence of more accelerated erosion than sheet erosion. Sediment concentrations at New Fork River Site 1 were the highest observed at that time in the investigation and rilling was considered most likely to occur at this site. However, after nearly 10 hours of sprinkling at an intensity of 8.5 inches per hour, no observable rills had been formed. The sprinkling intensity was raised to 10.5 inches per hour and continued for over 6 hours. Still no rills were formed by the increased runoff.

The appearance of rills on a soil surface during overland flow as influenced by slope steepness, runoff rate, and presence or absence of rainfall was reported by Meyer and Monke (1964) for a laboratory investigation using glass spheres as a noncohesive bed material. They reported erosion occurs predominately by rilling and the intensity of erosion increases with increasing slope steepness and runoff rates. Rainfall tended to level the bed surface, thereby smoothing its rill-roughened surface. For a 10 percent slope, the same as the slope steepness at New Fork River Site 1, Meyer and Monke report that erosion was rapid and rilling was pronounced. Rills were long narrow chutes and were directed predominately downslope. As erosion rates increased with increased runoff rates, they report that erosion tended to be uniform since potential rills were filled by the great rates of soil movement before they could fully develop.

Using the reasoning of Meyer and Monke, it could be argued in the present investigation that rilling should be the predominate erosion process but that rills were obliterated by deposition of sediments from interrill areas. However, the lack of rilling on both the less steep and more steep field sites and the lack of rilling in the general field area indicate that rilling need not occur where there is erosion and may be related to some broader aspect of geomorphology. Such an aspect might be the "equilibrium concept of landscape" elaborated by Hack (1960). Briefly, Hack postulates that for landforms in dynamic equilibrium, all topographic elements are eroding vertically at an equal rate with no change in time of slope form or areal arrangement of the topography. Such equilibrium landforms would be completely adjusted to the processes presently acting on them. The concept of dynamic equilibrium is supported by the most probable model analysis in the preceding section which suggests that hillslopes tend to adjust to and to maintain certain highly regular, geometric forms.

Utilizing Hack's thesis, it can be argued that the gen-

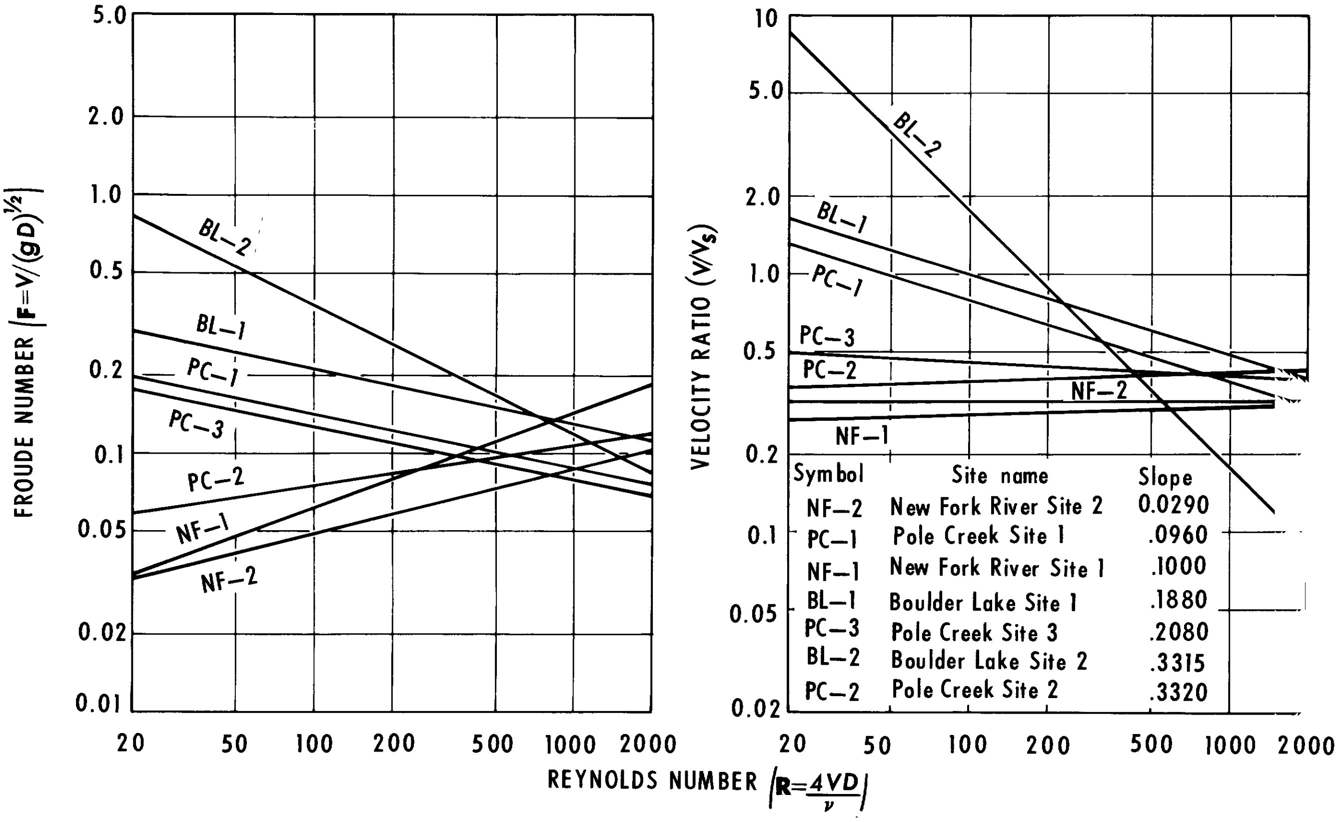

FIGURE 39.—Summary curves of Froude number and velocity ratio as a function of Reynolds number, field sites.

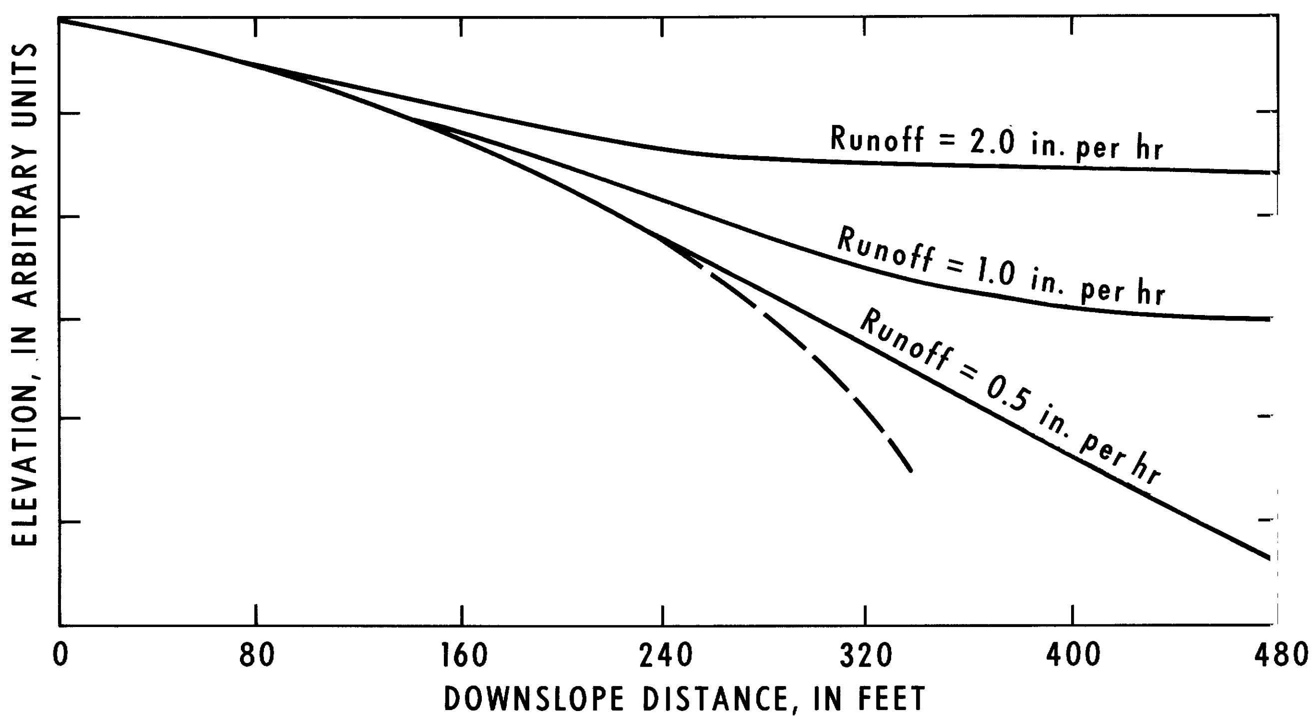

FIGURE 40.—Hillslope profiles for various runoff rates; downslope distance shown is approximate for values of runoff shown.

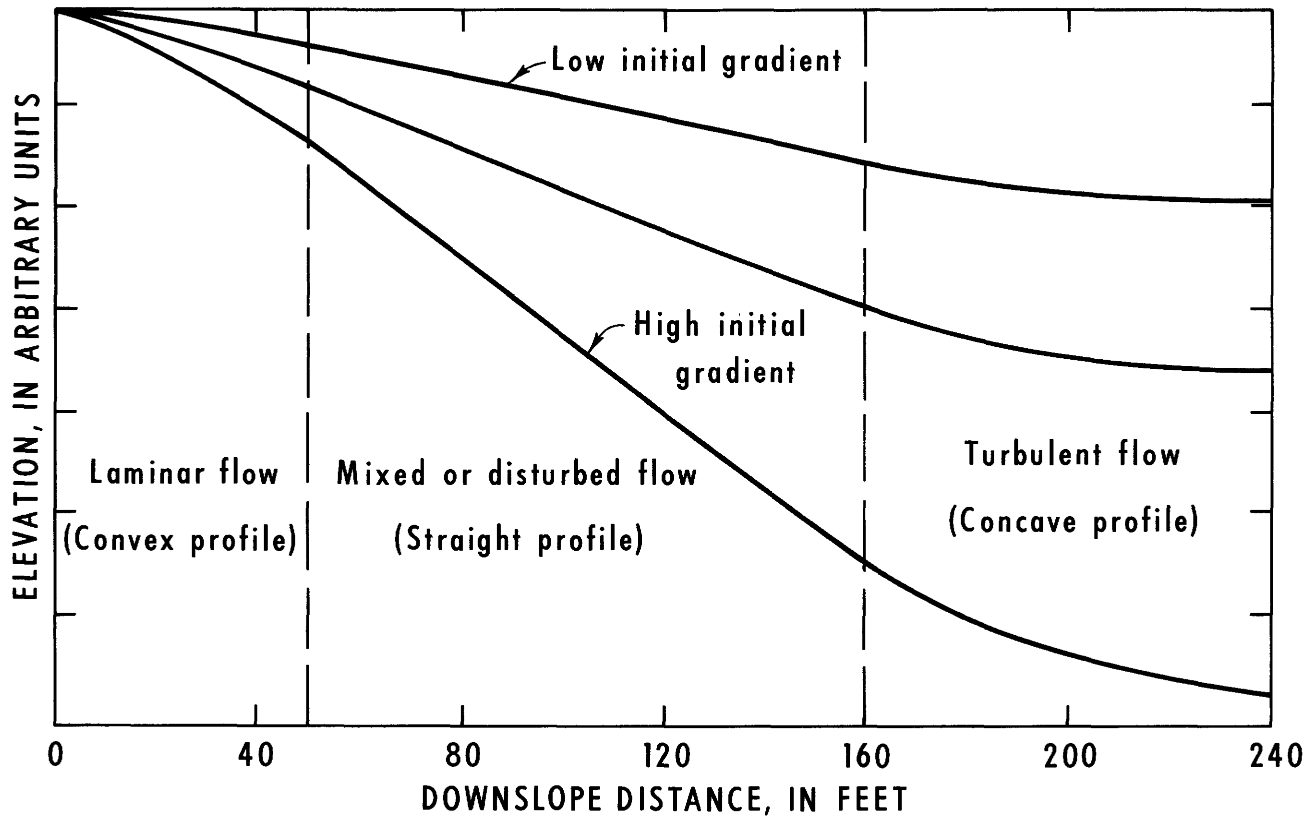

FIGURE 41.—Hillslope profiles for various initial gradients; downslope distance shown is approximate for a runoff rate of 2.0 inches per hour.

eral absence of rilling in the field area is related to the erosion rate necessary on the reach of slope investigated to keep in downcutting equilibrium with other slopes within the drainage system. Under conditions of dynamic equilibrium, the behavior of individual hydraulic parameters need not be elaborated. The requirement is that there is an interaction among all of the variables to promote those flow conditions of depth and velocity to maintain equilibrium. Data for the present investigation indicate that velocities sufficient to cause rilling never occurred, and figure 33 illustrates well that velocities in overland flow are indeed low. But the principle involved is that velocities were low because depths were relatively great; the increase in depth is related to its role in the interaction of all variables.

Rills may or may not develop on unrilled surfaces if some threshold is exceeded which causes a change in the degradation rate. Such a threshold may be exceeded, for example, because of climatic change, but equilibrium could be maintained by equally altering the erosion rate throughout the drainage system. It is interesting to note that even at the high intensity of rainfall applied to the test plots, a threshold was not exceeded with an external variable (rainfall intensity and duration) which was sufficient to cause rilling. This would imply that the potential for increased erosion (supplied by greater rainfall intensities and durations than are probably natural) was absorbed by increased depths of flow rather than by higher velocities and accelerated erosion by rilling. To maintain this equilibrium, each slope had developed both a form and a resistance to flow, manifested in a complex interaction of vegetation and microtopographic form, to which the depth and velocity components of overland flow must adjust.

Schumm (1962) discussed the development of resistance to flow to maintain equilibrium between pediments and hillslopes in an analysis of miniature pediments developed on badland topography in South Dakota. Using the Manning formula (eq 16) to estimate velocity, Schumm applied a value of Manning's n to the rougher but more steep hillslopes which was three times greater than the value of n for the smoother pediment surfaces. (The actual values of n used by Schumm were probably low, but the relative order of magnitude appears reasonable.) The pediment slopes were about eight times less steep than the hillslopes. Assuming that the depth of the sheet of water moving over the hillslope was the same as that over the pediment, the computed value of velocity was the same for the hillslopes as for the pediments. Thus, in the case of the pediment, the decrease in roughness apparently compensates for the decrease in slope angle. Such mutual adjustment of the component variables is the key to equilibrium.

This example by Schumm and the data from figure 39 of this report showing values of the Froude number and its downslope change should serve to discredit the existance of a hydraulic jump as overland flow on natural hillslopes passes from a steep slope to a moderate or flat slope. A hydraulic jump occurs as flow goes from supercritical to subcritical, but Schumm's example shows no decrease in velocity at the base of the steep slope because changes in resistance to flow compensate for the smaller value of slope. And the data of figure 39 show that the value of the Froude number for natural slopes, even steep slopes, is on the order of 0.1 and is essentially constant over the length of the slope. Although it is possible to have supercritical flow in river channels, especially with flash flooding in ephemeral channels, it is unlikely that overland flow is ever supercritical and thus never offers the opportunity for a hydraulic jump.

EROSION AND LAMINAR FLOW

The sediment concentrations observed in the samples taken during this study illustrate the ability of overland flow to erode and transport sediments. The analytical results of the several sediment samples from each site are included in table 5 and are summarized as averages for each site in table 6. The average values of sediment and organic content from table 6 show no apparent correlation with the ground slope at the site (table 6) or with the rainfall and runoff rates (table 3). The range of runoff rates in the present study is perhaps too limited to show a correlation. However, it has been shown (for a summary of investigations, see Smith and Wischmeier, 1962) that a few high intensity storms cause a high proportion of total soil erosion. That is, erosion is caused more by the number of high intensity storms than by the total volume of runoff. Although the present data show no apparent correlation of sediment concentration with slope, other investigators (see Smith and Wischmeier, 1962) have shown soil erosion to increase with increasing slope. The upper limit of slopes reported by Smith and Wischmeier was 18 percent (about 10 degrees).

In the present investigation, resistance to flow was such that downslope profiles of depth and velocity were only negligibly influenced by slope. The similarity between field plots in the downslope profiles of depth and velocity is responsible in part for the lack of correlation of erosion rates to slope. Also responsible is the differences in vegetation density between sites. The average values of sediment concentration from table 6 correlate well with the density of vegetation except for the data of New Fork River Site 2. Ponding occurred in the lower 8 feet of this site and much of the sediment load of the runoff settled out as velocities were lowered. The correlation of sediment concentrations with vegetation density at the other six sites, however, illustrates the importance of ground cover for prevention of erosion. Smith and Wischmeier (1962) summarize some earlier investigations on the relation of plant cover to erodibility and generally report decreasing soil losses for increasing densities of vegetation. It becomes apparent that the interaction of variables may mask the effects of any one variable. For example, a nearly flat bare surface may contribute as much sediment as a steeper, more vegetated slope. For the present data, if vegetation is held constant, ground slope does appear related to sediment concentrations. Comparison of Boulder Lake Site 1 to Pole Creek Site 2 and Pole Creek Site 2 to Boulder Lake Site 2 illustrates that for the same vegetation density, sediment concentrations in the runoff increase with increased slope angle.

One important observation is the higher concentrations of sediment in the initial runoff and the relatively rapid decrease in concentrations during the remainder of the runoff. Unfortunately, the data of table 5 do not entirely confirm this observation because of a deficient number of samples collected during the early stages of runoff. Within the limitations of the present investigation, this observation is best illustrated by the data of New Fork River Site 1 included

TABLE 5.—*Analytical results of sediment samples from overland flow field sites*

Site No.[1]	Date (1967)	Time[2] (minutes)	Total sediment and organic content (mg/l)[3]	Sediment content of total sample		Organic content of total sample	
				(percent)	(mg/l)[3]	(percent)	(mg/l)[3]
PC-1	6-27	35	31	33	10	67	21
	6-27	65	113	38	42	62	71
	6-27	129	68	20	14	80	54
	6-28	25	43	23	9.7	77	33
	6-28	85	83	38	31	62	52
2	7-14	80	35	86	30	14	4.8
	7-14	85	24	79	19	21	5.0
	7-15	25	75	88	66	12	9.3
3	7-19	----------	25	12	3.0	88	22
	7-19	----------	24	8	2.0	92	22
	7-19	----------	29	24	6.9	76	22
NF-1	7-29	24	288	90	260	9.9	28
	7-29	34.7	184	92	170	7.6	14
	7-29	82	41	94	39	5.8	2
	7-29	119	36	89	32	11	4
	7-30	15	160	94	150	6.4	10
	7-31	150	49	90	44	9.6	5
2	8-18	48	24	82	20	18	4
	8-18	79	10	70	7	30	3
	8-18	176	45	96	43	4	2
	8-18	270	9	75	7	25	2
BL-1	9-27	56	10	68	7	32	3
	9-27	80	14	69	10	31	4
	9-27	128.5	7	62	4	38	3
	9-27	232	4	50	2	50	2
2	9-28	30	81	88	71	12	10
	9-28	45	87	83	72	17	15
	9-28	87	93	89	83	11	10

[1] Site numbers: PC, Pole Creek, NF, New Fork River, and BL, Boulder Lake.
[2] Time is from beginning of rainfall application.
[3] Milligrams per liter by weight.

TABLE 6.—*Average values of sediment sample analyses compared to ground slope and vegetation cover at overland flow field sites*

[Content in milligrams per liter by weight]

Site name	Ground slope (ft per ft)	Estimated vegetation cover (percent)	Total sediment and organic content (mg/l)	Sediment content of sample (mg/l)	Organic content of sample (mg/l)
New Fork River Site 2	0.0290	8	22.1	19.3	2.8
Pole Creek Site 1	.0960	20	67.6	21.3	46.2
New Fork River Site 1	.1000	10	126.3	115.8	10.5
Boulder Lake Site 1	.1880	28	8.8	5.8	3.0
Pole Creek Site 3	.2080	35	26.0	4.0	22.0
Boulder Lake Site 2	.3315	22	87.3	75.3	11.7
Pole Creek Site 2	.3320	28	44.7	38.3	6.4

in table 5. From a sediment concentration of 228 milligrams per liter after 24 minutes of runoff, the concentration decreases to 184 milligrams per liter at 35 minutes, 41 milligrams per liter at 82 minutes, and 36 milligrams per liter at 119 minutes. Similar results were found by Lowdermilk and Sundling (1950). Their studies indicate that the erosion rate decreases throughout a simulated rainstorm as the finest particles were removed in surficial flow. Their removal led to the domination of the soil surface by larger particles until ultimately an erosion pavement was formed. Similar results were also found by Swanson, Dedrick, and Weakly (1965). However, the present data do not strictly support the pavement theory. Using the data of Pole Creek Site 2 and New Fork River Site 1 from table 5, comparison of sediment concentrations observed early in the runoff from a second day of sprinkling to the concentrations at the end of the previous day's sprinkling shows the second day's initial concentration to be considerably higher than the preceding day's final concentration. Since a new number of fine-grained particles could not be produced in the short interval between sprinklings, higher initial sediment concentrations appear to be related to some process making soil particles ready for transport. Over a single night, as in the present investigation, the responsible process is most likely a wetting-drying effect on the soil. Between natural storms, processes making soil ready for transport would include wetting-drying, wind, frost action, churning by animals, and even weathering where intervals are long.

Splash erosion by raindrop impact before a protecting layer of surface detention is built up is also important in the initial high sediment concentrations (Borst and Woodburn, 1942). However, the present data do not fully confirm the conclusion of Borst and Woodburn that raindrop splash, not runoff, is responsible for soil loss. A number of other investigators have shown the importance of raindrop impact on erosion (for a summary, see Smith and Wischmeier, 1962). However, raindrop impact with very little transporting medium by runoff is not likely to be an effective agent of erosion. As surface detention builds up everywhere and depths increase downslope, the effect of waterdrop impact lessens. The data of Palmer (1965) indicate that for the size of waterdrops and depths of flow in the present investigation, there was probably little splash erosion due to raindrop impact.

The values of sediment concentration in table 5 are adequate proof that overland flow can be effective as an eroding and transporting agent. It is interesting to note that the values of Reynolds numbers from all field tests were well within the regime of laminar flow as defined in figure 11. As previously mentioned, overland flow is disturbed by rainfall and flow in the concentrations of water have higher Reynolds numbers than the average Reynolds number for a given downslope distance. The actual characteristics of flow are somewhere between laminar and turbulent and as indicated earlier in this report; the flow is primarily laminar in upslope reaches and becomes more turbulent as slope length increases. Regardless of the exact characteristics of overland flow, sediment was being eroded and transported.

Sediment transport occurring at the low values of Reynolds number are in agreement with Bagnold's (1955) observation that turbulence is not an essential requisite of sediment transport. The present data tend to invalidate King's (1953) canon 27 of landscape evolution that laminar flow is nonerosive. That a large volume of material is indeed eroded and transported by overland flow is strikingly illustrated by the lower photograph in figure 6 of the delta formed by deposition of sediments eroded upslope in the plot at New Fork River Site 1. The photograph, taken after about 6 hours of simulated rainfall at an intensity of 8.5 inches per hour, does not show all of the eroded and transported sediment as sediment concentration data of table 5 show high concentrations in the runoff water.

The average values of sediment content in table 6 show great variability between different field sites. Although the values shown are valid only for the observed conditions of plot size and the hydrologic, geologic, and vegetation characteristics of the sites, a sediment production corresponding to the observed sediment concentrations of runoff can be computed. Using an average value of 55 milligrams per liter sediment content, runoff of 1 inch per hour for 1 hour would yield 4 tons of sediment per square mile. The extrapolation of plot data to watersheds is questionable and the above computation should be considered only illustrative of the large amount of sediment production from overland flow with small sediment concentrations.

SUMMARY OF FINDINGS

Extremely shallow uniform flows over sloping planes are characterized by laminar flow at Reynolds numbers less than 1,500 (or somewhat greater) and turbulent flow at Reynolds numbers higher than 6,000 (or somewhat less). For constant widths and smooth surfaces, increases in depth absorb about one-third of increases in discharge for laminar flows, two-thirds for turbulent flows, and velocity absorbs the remainder. Transitional flow exists between laminar and turbulent flow; the range in Reynolds number accompanying transitional flows is dependent on depth of flow and nature of surface roughness. Surface roughness tends to increase depth and, for the shallow flows investigated, even apparently smooth surfaces impart an element of roughness. For laminar flow on constant slopes, resistance to flow (expressed by the Darcy-Weisbach friction factor) decreases exponentially by a factor of 1 with increases in discharge, but for turbulent flows, resistance to flow decreases only slightly with increases in discharge. Transitional flows show values of resistance to flow intermediate between laminar and turbulent flow. Absolute values of resistance to flow are dependent on the magnitude of the relative roughness of the flume surface. The ratio of the mean velocity to surface velocity is equal to the theoretical values of 0.8 for turbulent flow and 0.67 (or somewhat less) for laminar flow.

For shallow flows with increasing downslope discharge due to uniform simulated rainfall over the flume area, depths of flow are increased because of the retarding influence of falling raindrops. The amount of the increase in depth varies, but for the laboratory conditions investigated the depths of flow due to simulated rainfall averaged about a 50 percent increase over depths of uniform flow. For the short lengths of slopes investigated in the laboratory, all sprinkled tests are in the laminar regime of flow as defined by the Reynolds number criterion established by uniform flow tests. However, the flows are not truly laminar because of the disturbing effect of falling raindrops. For this disturbed type of flow, data indicate that depth absorbs somewhat less of the increase in discharge for smooth surfaces and somewhat more for roughened surfaces when compared with uniform flows in the same channel. For disturbed flow compared to uniform flow, falling raindrops roughly doubles the resistance to flow. For these same disturbed (but nearly laminar) flows, the Froude number increases exponentially as the square of the increase in downslope discharge. Generally, the ratio of the mean velocity to surface velocity is about 0.5, which is less than the theoretical value of 0.67 for laminar flow. Thus, mean velocity is retarded more than surface velocity, but this effect decreases as depths increase.

Overland flow resulting from rainfall on natural slopes is characterized by several lateral downslope concentrations of flow rather than uniform sheet flow. These concentrations of flow are dictated by the resistance to flow (obstacles) developed on each slope. The downslope increases in depth that resulted with increasing discharge varied between field sites, but they averaged an exponential value of about ⅔. Increases in velocity absorbed the remainder of the increases in discharge. Values of resistance to flow for the several field sites ranged from positive to negative downslope changes in downslope frictional resistance, but the average value indicates no change in downslope resistance to flow. Values of resistance to flow are of a magnitude approximated by a Darcy-Weisbach friction factor of 100, a Manning *n* of 0.5, or a Chezy *C* equal to 2.0. Actual values of resistance vary between sites and between downslope distances, but the average values listed above for the field experiments are of a magnitude 10 times greater than the laboratory data for sprinkled tests. On the average, Froude numbers in overland flow were less than 0.2 and averaged close to 0.1. From these values of Froude number, it appears unlikely that supercritical flow ever occurs as overland flow on natural hillslopes. The ratio of the mean velocity to surface velocity is somewhat suppressed below laboratory data and generally remains below a value of 0.5.

A theoretical model of overland flow, based on most probable statistical concepts of minimizing the variance in depth, velocity, shear, and friction, was evaluated for the condition of no constraint on slope and yielded (1) a downslope decrease in slope gradient for turbulent flow and (2) a downslope increase in slope gradient for laminar flow. The application of these two cases to overland flow on natural hillslopes, and the interpolation of intermediate conditions of flow, indicate that hillslope profiles should be convex at the top, straight in a middle segment of slope, and concave in lower reaches of slope. The length of the convex, straight, and concave segments of slope, and the steepness of slope, are related to the runoff rate and the initial slope gradient. Thus the shape of hillslope profiles is controlled by their climatic and geologic environments.

It is suggested that each slope within a drainage system is in dynamic equilibrium with other slopes within the system. Downcutting of slopes in equilibrium maintain erosion rates which are comparable with other slopes in the system. On unrilled slopes, the resistance to flow develops such that depths absorb most of the downslope increase in discharge and velocities remain small enough to prevent rilling. Although no rilling occurred on the field test plots, analysis of sediment samples shows that overland flow at low Reynolds numbers is capable of eroding and transporting sediment.

In summary, it appears that overland flow may be described by a downslope increase in depth which is proportional to about the two-thirds power of downslope increase in discharge. Increase in downslope velocity absorbs the remainder of the increase in discharge. When the variance of the parameters of hydraulic geometry are jointly minimized, the slope profile of overland flow should be convex at the hilltop, straight in a middle reach of slope, and concave for the remainder of the slope length. The dimensions (relief and length) of each slope segment are related to the climatic and geologic environvent of the drainage system. It is suggested that all slopes in a drainage system are in dynamic equilibrium; that is, all slopes are vertically downcutting at the same rate. This too is controlled by the climatic and geologic environments of the slope.

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SUMMARY OF DATA

A.—*Vegetation type and relative density of cover at field sites*

[Values of density shown are based on a relative scale of 1 to 5 for each quadrat. T represents trace and is scored as 0.5]

Plant	Common name	Quadrat No. 1	2	3	4	5	6	7	8	9	10	Total	Percent
Pole Creek Site 1 [1]													
Antennaria		2	2				3					7	15.7
Eriogonum	Buckwheat			1		2		1	1		2	7	15.7
Poa secunda	Bluegrass	1		1	1			2	1			6	13.4
Stipa comato	Needlegrass	2	T	1			1	1				5.5	12.3
Taraxacum officinale	Dandelion	1		T			T				1	3	6.7
Artemisia tridentata	Sagebrush	1	T								1	2.5	5.6
Agropyron dasystachum	Wheatgrass				1		1					2	4.5
Agoseris	Agoseris							1				1	2.2
Sitanion hystrix	Bottlebrush									1		1	2.2
Astragalus	Pea										T	.5	1.1
Misc. annuals		1	1	1	T	1	1	1	1	T		8	17.9
Unknown forb									1			1	2.2
Pole Creek Site 2 [2]													
Antennaria			2	1	2	T	1	3	3	1	2	15.5	26.3
Sestuca idahoensis	Festuca		2	3	2		1	2	2	2	1	15	25.4
Stipa lettermani	Needlegrass				1		1	2	1	2	1	8	13.6
Agropyron spicatum	Wheatgrass		2			1						3	5.1
Poa secunda	Bluegrass					1	1				1	3	5.1
Taraxacum officinale	Dandelion				T	1			T	1		3	5.1
Artemisia tridentata	Sagebrush		1		T							1.5	2.5
Achillea lanulosa										1	T	1.5	2.5
Agoseris	Agoseris			1							T	1.5	2.5
Stipa comata	Needlegrass		1	T								1.5	2.5
Bidens cernua		T					T					1	1.7
Kosa spp								1				1	1.7
Lupinus	Lupine										T	.5	.8
Misc. annuals			T				T	T		1	T	3	5.1
Pole Creek Site 3 [3]													
Carex	Sedge			2	1	3	1	1	1	1	1	11	18.0
Taraxacum officinale	Dandelion		1	1	2	2	T	2	T	T	1	10.5	17.2
Stipa lettermani	Needlegrass		2		2	2				2	1	9	14.8
Festuca idahoensis	Festuca			1	1			T	1	1	1	5.5	9.0
Poa canbyi	Bluegrass					1		2	1			4	6.6
Stipa comata	Needlegrass	1		2			1					4	6.6
Antennaria		1	1						T	T		3	4.9
Astragalus	Pea			T	T	T			T	T	T	3	4.9
Lupinus	Lupine						1				1	2	3.3
Achillea lanulosa											1	1	1.6
Agropyron spicatum	Wheatgrass		1									1	1.6
Artemisia tridentata	Sagebrush					T						.5	.8
Misc. annuals		1			1	1	T	T	1	T	1	6.5	10.7
New Fork River Site 1 [4]													
Artemisia tridentata	Sagebrush	2	3	3	2	2	1	1	4	2	T	20.5	44.1
Agropyron dasystachum	Wheatgrass	2	3	3	1	1	1	1	2	1	1	16	34.4
Carex	Sedge		1		1	1	T			2		5.5	11.8
Castilleja	Paintbrush	1										1	2.2
Blitum capitatum					T		T	T	T	T		2.5	5.4
Chrysanthemum		1										1	2.2
New Fork River Site 2 [5]													
Agropyron dasystachum	Wheatgrass	3	1	1	1	1	2	2	1	1		13	60.5
Carex	Sedge		1			1		1				3	13.9
Sitanion hystrix	Bottlebrush					T				1	2	3.5	16.3
Poa	Bluegrass			1	1							2	9.3

See footnotes at end of table.

A.—*Vegetation type and relative density of cover at field sites*—Continued

Plant	Common name	Quadrat No. 1	2	3	4	5	6	7	8	9	10	Total	Percent
Boulder Lake Site 1 [6]													
Poa canbyi	Bluegrass	2	2	3	2	1	2	T	4	4	1	21.5	40.6
Stipa lettermani	Needlegrass	2		1	1	1	1	1		3	3	13	24.5
Antennaria				1	2		1	1		1	1	7	13.2
Carex	Sedge	T				T		1	T	1		3.5	6.6
Eriogonum	Buckwheat		T						T		1	2	3.8
Misc. annuals				1	2	1	1	T	T			6	11.3
Boulder Lake Site 2 [7]													
Poa	Bluegrass	2	3	3	2	2	1	1	2	2	3	21	47.8
Antennaria			1	1		1	2	2	3	1		11	25.0
Sedum stenopetalum	Stonecrop	T	1					1				2.5	5.7
Paranychia depressis		2										2	4.6
Agropyron spicatum	Wheatgrass				1							1	2.3
Eriogonum	Buckwheat	T					T					1	2.3
Juncus	Rushes								T			.5	1.1
Misc. annuals				1	T	T	T	T	1		1	5	11.3

[1] Estimate of overall average density, 20 percent. No overstory cover on site.
[2] Estimate of overall average density, 28 percent. Overstory of *Artemisia tridentata* (sagebrush), 42.6 percent.
[3] Estimate of overall average density, 35 percent. Overstory of *Artemisia tridentata* (sagebrush) and *Populus tremuloides* (aspen), 23.6 percent.
[4] Estimate of overall average density, 10 percent. Overstory of *Artemisia tridentata* (sagebrush), 49.9 percent.
[5] Estimate of overall average density, 8 percent. Overstory of *Artemisia tridentata* (sagebrush) not measured.
[6] Estimate of overall average density, 28 percent. Overstory of *Artemisia tridentata* (sagebrush) not measured.
[7] Estimate of overall average density, 22 percent. Overstory of *Artemisia tridentata* (sagebrush) not measured.

B.—*Example of data from measurements of surface velocity, Pole Creek Site 3*

Downslope stationing (ft)	Velocity (fps)	
	Trial 1	Trial 2
0		
1	0. 071	0. 200
2	. 053	. 100
3	. 125	. 072
4	. 200	. 250
5	. 200	. 148
6	. 091	. 167
7	. 083	. 100
8	. 500	. 091
9	. 250	. 200
10	. 250	. 250
11	. 250	. 148
12	. 200	. 091
13	. 333	. 125
14	. 250	. 250
15	. 167	. 100
16	. 111	. 125
17	. 250	. 250
18	. 167	. 250
19	. 250	. 167
20	. 143	. 167
21	. 167	. 167
22	. 250	. 250
23	. 200	. 143
24	. 143	. 143
25	. 200	. 200
26	. 250	. 500
27	. 143	. 333
28	. 250	. 200
29	. 200	. 125
30	. 250	. 111
31	. 167	. 125
32	. 333	. 250
33	. 333	. 200
34	. 333	. 167
35	. 333	. 200
36	. 333	. 250
37	. 333	. 143
38	. 333	. 143
39	. 333	. 250
40	. 250	. 167
41	. 333	. 143
42	. 333	. 250
43	. 250	. 500
44	. 200	. 500
45	. 200	. 500
46	. 200	. 250
47	. 333	. 143
48	. 250	. 250

C.—*Example of data from depth measurements, in feet, Pole Creek Site 3*

Transverse stationing (ft)	Downslope stationing (ft),											
	1	3	5	7	9	11	13	15	17	19	21	23
0	0. 000	0. 000	0. 000	0. 010	0. 013	0. 055	0. 023	0. 002	0. 004	0. 026	0. 014	0. 014
1	. 000	. 010	. 010	. 014	. 000	. 061	. 040	. 095	. 013	. 024	. 020	. 040
2	. 000	. 000	. 010	. 004	. 003	. 000	. 012	. 019	. 003	. 028	. 013	. 020
3	. 000	. 013	. 000	. 011	. 009	. 000	. 000	. 000	. 006	. 019	. 000	. 111
4	. 014	. 021	. 000	. 000	. 042	. 014	. 034	. 008	. 043	. 066	. 030	. 011
5	. 010	. 010	. 015	. 004	. 00C	. 021	. 009	. 017	. 010	. 042	. 020	. 024
6	. 012	. 020	. 025	. 017	. 000	. 000	. 047	. 004	. 012	. 034	. 024	. 014
7	. 005	. 000	. 006	. 042	. 015	. 035	. 036	. 015	. 018	. 024	. 033	. 046
Avg	. 0051	. 0093	. 0083	. 0128	. 0103	. 0243	. 0151	. 0200	. 0142	. 0329	. 0193	. 0350

Transverse stationing (ft)	25	27	29	31	33	35	37	39	41	43	45	47
0	0. 022	0. 038	0. 047	0. 012	0. 000	0 069	0. 029	0. 073	0. 037	0. 044	0. 027	0. 092
1	. 075	. 021	. 062	. 094	. 047	. 054	. 084	. 065	. 061	. 056	. 034	. 057
2	. 028	. 034	. 008	. 042	. 057	. 056	. 023	. 041	. 059	. 067	. 055	. 064
3	. 018	. 028	. 046	. 026	. 058	. 052	. 054	. 051	. 027	. 102	. 078	. 012
4	. 034	. 026	. 037	. 017	. 030	. 022	. 042	. 040	. 045	. 067	. 045	. 011
5	. 013	. 020	. 026	. 055	. 005	. 033	. 053	. 044	. 037	. 026	. 065	. 032
6	. 031	. 013	. 035	. 012	. 033	. 043	. 036	. 023	. 049	. 050	. 038	. 058
7	. 029	. 008	. 004	. 012	. 009	. 013	. 025	. 012	. 005	. 033	. 038	. 027
Avg	. 0313	. 0235	. 0356	. 0338	. 0299	. 0428	. 0433	. 0436	. 0400	. 0556	. 0475	. 0441

D.—*Summary of laboratory data for uniform flow*

[Flow: T, turbulent; L, laminar; r, roll waves (R, more pronounced)]

Series and test	Discharge q (cfs/ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, V/V_s	Temp, T (° C)	Kinematic viscosity $\times 10^{-5}$, μ (sq ft per sec)	Reynolds number, **R**	Froude number, **F**	Slope, S (ft per ft)	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n	Flow
1-1	0.0460	0.0435	1.057	1.235	0.86	13.5	1.29	14257	0.89	0.0033	0.0330	88.3	0.0101	T
2	.0310	.0357	.868	1.093	.79	14.0	1.28	9760	.83	.0033	.0402	80.0	.0108	T
3	.0208	.0286	.727	1.007	.72	15.0	1.23	6762	.76	.0033	.0460	74.6	.0110	T
4	.0133	.0205	.650	1.033	.63	16.0	1.20	4442	.80	.0033	.0413	79.0	.0099	L, T
5	.0078	.0146	.531	.820	.65	17.0	1.17	2650	.78	.0033	.0439	76.5	.0097	L
6	.0046	.0130	.366	.527	.68	11.0	1.38	1341	.55	.0033	.0870	54.5	.0133	L
7	.0023	.0104	.219	.330	.66	11.5	1.36	670	.38	.0033	.1840	37.4	.0187	L
8	.0013	.0089	.140	.215	.65	12.5	1.32	378	.26	.0033	.3860	25.8	.0264	L
2-1	.0493	.0279	1.768	2.118	.84	10.0	1.41	13968	1.87	.0170	.0390	81.2	.0102	T
2	.0366	.0227	1.610	1.923	.84	10.0	1.41	10362	1.88	.0170	.0384	81.9	.0098	T
3	.0264	.0186	1.419	1.770	.80	11.0	1.38	7650	1.84	.0170	.0405	79.7	.0097	T
4	.0209	.0164	1.273	1.653	.77	12.0	1.34	6232	1.75	.0170	.0443	75.7	.0100	T
5	.0131	.0115	1.141	1.765	.65	12.0	1.34	3917	1.88	.0170	.0387	81.5	.0087	T, L
6	.0091	.0092	.984	1.439	.68	12.0	1.34	2702	1.81	.0170	.0417	79.5	.0086	L, T
7	.0049	.0076	.646	.977	.66	12.5	1.32	1492	1.30	.0170	.0728	59.7	.0111	L, r
8	.0026	.0065	.409	.628	.65	11.0	1.38	765	.90	.0170	.1685	39.1	.0166	L, r
9	.0016	.0053	.297	.421	.71	11.0	1.38	453	.72	.0170	.2610	31.4	.0199	L
10	.0010	.0044	.226	.302	.75	11.0	1.38	290	.60	.0170	.3795	21.6	.0282	L
3-1	.0508	.0223	2.281	2.756	.83	11.0	1.38	14710	2.70	.0342	.0376	82.7	.0096	T
2	.0361	.0186	1.947	2.466	.79	11.0	1.38	10471	2.52	.0342	.0431	77.3	.0100	T
3	.0255	.0140	1.643	2.222	.74	11.0	1.38	6659	2.45	.0342	.0456	75.2	.0098	T
4	.0130	.0095	1.378	2.273	.61	11.0	1.38	3776	2.50	.0342	.0438	76.6	.0090	T
5	.0082	.0080	1.025	1.794	.57	11.0	1.38	2378	2.02	.0342	.0662	62.3	.0108	T, R
6	.0043	.0064	.669	1.149	.58	11.0	1.38	1237	1.48	.0342	.1253	45.3	.0152	L, T, R
7	.0023	.0049	.463	.719	.65	12.0	1.34	654	1.17	.0342	.2000	35.9	.0170	L, R
8	.0013	.0036	.341	.439	.78	12.0	1.34	370	.99	.0342	.2760	30.6	.0192	L, r
9	.0007	.0031	.224	.269	.83	12.0	1.34	205	.71	.0342	.5390	15.1	.0379	L
4-1	.0508	.0193	2.629	3.125	.84	12.0	1.34	15149	3.34	.0550	.0395	80.2	.0096	T, r
2	.0354	.0156	2.266	2.913	.78	15.0	1.23	11496	3.20	.0550	.0428	77.5	.0097	T, r
3	.0231	.0122	1.893	2.586	.73	15.0	1.23	7504	3.02	.0550	.0479	73.2	.0098	T, R
4	.0138	.0081	1.698	2.740	.62	15.5	1.22	4506	3.33	.0550	.0399	80.4	.0084	T, r
5	.0092	.0069	1.334	2.230	.60	16.0	1.20	3050	2.84	.0550	.0546	68.6	.0096	T, L, r
6	.0050	.0061	.805	1.449	.56	16.5	1.19	1663	1.81	.0550	.1341	43.7	.0147	L, r
7	.0035	.0055	.640	1.345	.48	14.5	1.25	1131	1.52	.0550	.1920	36.6	.0172	L, R
8	.0025	.0050	.487	1.005	.49	14.0	1.27	770	1.21	.0550	.2990	29.4	.0211	L, R
9	.0014	.0035	.386	.660	.59	16.0	1.20	453	1.15	.0550	.3350	27.7	.0211	L, R
10	.0008	.0029	.259	.481	.54	16.0	1.20	253	.84	.0550	.6197	20.4	.0278	L, R
5-1	.0492	.0179	2.753	3.750	.73	16.0	1.20	16392	3.63	.0775	.0470	74.0	.0104	T
2	.0354	.0146	2.435	3.209	.76	16.0	1.20	11783	3.56	.0775	.0492	72.4	.0102	T, r
3	.0258	.0115	2.247	3.061	.73	16.0	1.20	8600	3.70	.0775	.0455	75.2	.0095	T, R
4	.0139	.0079	1.766	3.226	.55	16.0	1.20	4625	3.50	.0775	.0503	71.5	.0094	T, r
5	.0088	.0069	1.284	2.620	.49	16.0	1.20	2945	2.73	.0775	.0503	71.5	.0092	T, L
6	.0040	.0057	.705	1.635	.43	16.0	1.20	1337	1.65	.0775	.2290	33.5	.0195	L, R
7	.0022	.0049	.456	1.111	.41	16.0	1.20	738	1.16	.0775	.4650	23.7	.0260	L, R
8	.0012	.0042	.282	.770	.37	16.0	1.20	396	.77	.0775	1.0570	15.6	.0388	L, R
6-1	.0505	.0225	2.244	2.913	.77	15.0	1.23	16423	2.64	.0775	.0893	53.7	.0149	T
2	.0367	.0186	1.969	2.532	.78	15.0	1.23	11935	2.56	.0775	.0950	52.0	.0148	T, r
3	.0243	.0144	1.681	2.166	.78	15.0	1.23	7886	2.46	.0775	.1020	50.2	.0147	T, r
4	.0126	.0105	1.198	1.796	.67	16.0	1.20	4192	2.06	.0775	.1461	42.0	.0167	T
5	.0087	.0091	.956	1.571	.61	16.0	1.20	2884	1.60	.0775	.1975	36.1	.0192	T, L
6	.0044	.0071	.616	1.215	.51	16.5	1.19	1475	1.29	.0775	.3750	26.2	.0251	L, T
7	.0023	.0058	.398	.808	.49	17.0	1.17	784	.91	.0775	.7250	18.8	.0340	L, T, r
8	.0012	.0034	.353	.775	.46	21.5	1.03	470	1.05	.0775	.5480	21.6	.0270	L, T, R
9	.0011	.0036	.285	.619	.46	17.5	1.15	361	.83	.0775	.8950	17.0	.0346	L, R
7-1	.0510	.0240	2.125	2.727	.78	21.0	1.04	19615	2.42	.0550	.0753	58.4	.0139	T
2	.0303	.0180	1.681	2.206	.76	20.5	1.06	11415	2.19	.0550	.0902	52.8	.0145	T
3	.0251	.0162	1.551	2.041	.76	20.5	1.06	9481	2.15	.0550	.0954	51.9	.0146	T
4	.0166	.0129	1.289	1.729	.75	19.0	1.11	5992	2.00	.0550	.1100	48.3	.0150	T
5	.0103	.0104	.997	1.478	.68	19.5	1.10	3755	1.73	.0550	.1471	41.8	.0168	T
6	.0067	.0073	.914	1.345	.68	20.0	1.08	2469	1.89	.0550	.1233	45.7	.0144	T
7	.0042	.0062	.667	1.149	.58	20.0	1.08	1535	1.48	.0550	.1977	36.1	.0178	L, T, r
8	.0028	.0053	.530	.896	.59	20.0	1.08	1043	1.28	.0550	.2680	31.4	.0199	L, T, r
9	.0022	.0045	.488	.946	.51	19.0	1.11	775	1.28	.0550	.2900	29.8	.0204	L, T, R
10	.0018	.0039	.451	.748	.60	19.0	1.11	631	1.28	.0550	.2708	30.8	.0193	L, r
11	.0011	.0036	.301	----------	----------	19.0	1.11	395	.80	.0550	.5680	21.3	.0276	L, r
12	.0009	.0029	.317	.404	.78	18.5	1.12	332	1.03	.0550	.4150	24.9	.0228	L
8-1	.0505	.0275	1.835	2.390	.77	18.0	1.14	17719	1.95	.0342	.0719	59.8	.0138	T
2	.0383	.0235	1.629	2.135	.76	18.0	1.14	13421	1.87	.0342	.0780	57.5	.0139	T
3	.0288	.0197	1.459	1.875	.78	18.5	1.12	10268	1.83	.0342	.0815	56.3	.0139	T
4	.0207	.0168	1.337	1.700	.79	18.5	1.12	7376	1.82	.0342	.0826	55.8	.0136	T
5	.0138	.0134	1.034	1.463	.71	19.0	1.11	4986	1.58	.0342	.1100	48.3	.0150	T
6	.0098	.0107	.913	1.330	.69	19.5	1.10	3556	1.55	.0342	.1132	47.6	.0147	T
7	.0066	.0082	.800	1.268	.63	19.5	1.10	2377	1.56	.0342	.1125	47.8	.0141	T
8	.0044	.0065	.629	1.271	.53	20.0	1.08	1641	1.48	.0342	.1246	45.5	.0142	T, L, r
9	.0031	.0057	.534	1.003	.53	20.0	1.08	1125	1.25	.0342	.1760	38.3	.0166	L, T, r
10	.0022	.0050	.437	.844	.52	19.0	1.11	786	1.09	.0342	.2305	33.4	.0186	L, r
11	.0015	.0044	.340	.661	.51	19.0	1.11	542	.90	.0342	.3365	27.6	.0220	L, r
12	.0009	.0039	.239	.436	.55	19.5	1.10	339	.67	.0342	.6030	20.7	.0288	L
9-1	.0524	.0340	1.541	1.935	.80	17.0	1.17	17906	1.47	.0170	.0627	64.0	.0133	T
2	.0388	.0277	1.398	1.695	.83	17.0	1.17	13248	1.48	.0170	.0621	64.5	.0128	T
3	.0287	.0230	1.248	1.463	.85	17.0	1.17	9812	1.45	.0170	.0648	63.0	.0127	T
4	.0192	.0194	1.003	1.302	.77	17.5	1.15	6753	1.27	.0170	.0843	55.4	.0140	T
5	.0135	.0159	.849	1.117	.76	17.5	1.15	4690	1.19	.0170	.0965	51.6	.0146	T
6	.0095	.0131	.725	.998	.73	18.0	1.14	3318	1.12	.0170	.1086	48.7	.0150	T
7	.0069	.0095	.723	1.113	.65	22.5	1.03	2674	1.31	.0170	.0797	56.9	.0121	T, r
8	.0042	.0076	.551	.988	.56	21.5	1.05	1588	.85	.0170	.1091	48.5	.0137	L, T, r
9	.0029	.0069	.413	.843	.49	21.5	1.05	1083	.88	.0170	.1760	38.2	.0172	L, T, r
10	.0022	.0063	.344	.704	.49	22.0	1.04	837	.73	.0170	.2555	31.7	.0204	L, r
11	.0014	.0050	.281	.509	.55	20.0	1.08	519	.70	.0170	.2710	30.8	.0201	L
12	.0009	.0043	.197	.347	.57	19.5	1.10	307	.53	.0170	.4850	23.0	.0263	L

E.—*Summary of laboratory data for artificial rainfall*

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
Test 1-9										
[I=11.61 in. per hr; S=0.0033 ft per ft; T=9.5° C; ν=1.43×10^{-5} sq ft per sec]										
1	0.00027	0.0170	0.016			76	0.017	56.45	2.14	0.3554
2	.00054	.0117	.046	0.10	0.46	150	.075	4.70	7.40	.0966
3	.00081	.0110	.074			225	.124	1.707	12.28	.0576
4	.00108	.0113	.096			301	.159	1.042	15.72	.0495
5	.00134	.0133	.102			376	.156	1.087	15.39	.0474
6	.00161	.0143	.113	.16	.70	451	.167	.952	16.45	.0438
7	.00188	.0133	.142			526	.217	.561	21.43	.0341
8	.00215	.0153	.141			601	.201	.654	19.85	.0377
9	.00242	.0153	.158			676	.225	.521	22.24	.0336
10	.00269	.0173	.155	.32	.49	752	.208	.612	20.52	.0348
11	.00296	.0177	.167			827	.221	.610	20.55	.0373
12	.00323	.0153	.211			902	.301	.292	29.70	.0252
13	.00349	.0163	.214			977	.295	.303	29.16	.0259
14	.00376	.0150	.251	.42	.60	1052	.361	.202	35.71	.0210
15	.00403	.0113	.357			1127	.592	.075	58.61	.0121
Test 2-11										
[I=11.56 in. per hr; S=0.170 ft per ft; T=12.0° C; ν=1.34×10^{-5} sq ft per sec]										
1	0.00027	0.0060	0.045			80	0.102	12.97	4.46	0.1435
2	.00054	.0063	.085	0.246	0.35	160	.189	3.82	8.21	.0785
3	.00080	.0070	.115			240	.242	2.32	10.54	.0632
4	.00107	.0073	.147	.339	.43	319	.303	1.480	13.19	.0501
5	.00134	.0070	.191			399	.402	.840	17.51	.0375
6	.00161	.0067	.240	.372	.65	479	.517	.510	22.49	.0290
7	.00187	.0073	.257			559	.530	.484	23.07	.0286
8	.00214	.0070	.306	.387	.79	639	.644	.327	28.05	.0234
9	.00241	.0077	.313			719	.629	.344	27.35	.0244
10	.00268	.0067	.399	.442	.90	799	.860	.184	37.39	.0174
11	.00294	.0087	.338			878	.733	.334	27.79	.0245
12	.00321	.0073	.440	.531	.83	958	.907	.165	39.49	.0167
13	.00348	.0087	.400			1038	.756	.238	32.89	.0207
14	.00375	.0067	.559	.625	.89	1118	1.205	.094	52.38	.0124
15	.00401	.0077	.521			1198	1.260	.124	45.54	.0146
Test 2-12										
[I=8.60 in. per hr; S=0.0170 ft per ft; T=11.0° C; ν=1.38×10^{-5} sq ft per sec]										
1	0.00020	0.0053	0.038			58	0.092	16.08	4.00	0.1565
2	.00040	.0073	.055	0.128	0.43	115	.113	10.57	4.94	.1338
3	.00060	.0060	.100			173	.227	2.63	9.90	.0646
4	.00080	.0070	.114	.293	.39	231	.240	2.36	10.45	.0628
5	.00100	.0067	.149			288	.321	1.322	13.96	.0467
6	.00119	.0073	.164	.316	.52	346	.338	1.189	15.17	.0435
7	.00139	.0060	.232			404	.527	.488	22.98	.0278
8	.00159	.0070	.227	.349	.65	461	.478	.595	20.81	.0315
9	.00179	.0077	.233			519	.468	.621	20.37	.0327
10	.00199	.0067	.297	.359	.83	577	.640	.333	27.91	.0234
11	.00219	.0087	.252			634	.476	.600	20.72	.0328
12	.00239	.0067	.356	.444	.80	692	.767	.232	33.32	.0195
13	.00259	.0090	.287			750	.533	.479	23.19	.0295
14	.00279	.0077	.361	.444	.81	808	.725	.259	31.54	.0211
15	.00299	.0070	.426			865	.897	.169	39.04	.0168

E.—*Summary of laboratory data for artificial rainfall*—Continued

Test 2-13

[I=6.09 in. per hr; S=0.0170 ft per ft; T=10.5° C; $\nu=1.40\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0. 00014	0. 0047	0. 030			40	0. 077	22. 87	3. 36	0. 1829
2	. 00028	. 0053	. 053	0. 115	0. 46	81	. 128	8. 26	5. 58	. 1122
3	. 00042	. 0053	. 080			121	. 194	3. 63	8. 43	. 0743
4	. 00056	. 0060	. 094	. 230	. 41	161	. 214	2. 97	9. 31	. 0687
5	. 00070	. 0067	. 105			201	. 226	2. 66	9. 84	. 0662
6	. 00085	. 0073	. 116	. 268	. 43	242	. 239	2. 38	10. 41	. 0635
7	. 00099	. 0060	. 164			282	. 373	. 977	16. 24	. 0394
8	. 00113	. 0060	. 188	. 295	. 64	322	. 427	. 744	18. 61	. 0344
9	. 00127	. 0057	. 222			362	. 518	. 507	22. 54	. 0281
10	. 00141	. 0053	. 266	. 323	. 82	403	. 644	. 328	28. 02	. 0223
11	. 00155	. 0073	. 212			443	. 437	. 711	19. 03	. 0347
12	. 00169	. 0080	. 211	. 292	. 72	483	. 416	. 787	18. 09	. 0371
13	. 00183	. 0083	. 221			523	. 427	. 744	18. 61	. 0363
14	. 00197	. 0070	. 282	. 444	. 64	564	. 594	. 386	25. 83	. 0254
15	. 00211	. 0067	. 315			604	. 679	. 296	29. 50	. 0221

Test 2-14

[I=4.63 in. per hr; S=0.0170 ft per ft; T=10.5° C; $\nu=1.40\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0. 00011	0. 0053	0. 020			31	0. 048	58. 04	2. 11	0. 2972
2	. 00021	. 0053	. 040	0. 162	0. 25	61	. 097	14. 51	4. 21	. 1486
3	. 00032	. 0057	. 056			92	. 131	7. 96	5. 69	. 1115
4	. 00043	. 0060	. 071	. 202	. 35	122	. 161	5. 21	7. 03	. 0910
5	. 00054	. 0060	. 089			153	. 202	3. 32	8. 81	. 0726
6	. 00064	. 0067	. 096	. 250	. 38	184	. 207	3. 18	9. 00	. 0724
7	. 00075	. 0057	. 132			214	. 308	1. 433	13. 41	. 0473
8	. 00086	. 0050	. 171	. 262	. 65	245	. 426	. 749	18. 55	. 0334
9	. 00096	. 0053	. 182			276	. 441	. 701	19. 17	. 0327
10	. 00107	. 0057	. 188	. 306	. 61	306	. 439	. 706	19. 10	. 0332
11	. 00118	. 0077	. 153			337	. 307	1. 441	13. 37	. 0499
12	. 00129	. 0067	. 192	. 294	. 65	367	. 414	. 796	17. 99	. 0362
13	. 00139	. 0087	. 160			398	. 302	1. 489	13. 15	. 0517
14	. 00150	. 0070	. 214	. 324	. 66	429	. 451	. 669	19. 63	. 0334
15	. 00161	. 0067	. 240			459	. 517	. 509	22. 50	. 0290

Test 2-15

[I=3.25 in. per hr; S=0.0170 ft per ft; T=9.0° C; $\nu=1.46\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0. 00008	0. 0047	0. 016			21	0. 041	80. 41	1. 79	0. 3430
2	. 00015	. 0040	. 038	0. 147	0. 26	41	. 106	12. 13	4. 61	. 1297
3	. 00023	. 0037	. 061			62	. 177	4. 36	7. 69	. 0767
4	. 00030	. 0053	. 057	. 145	. 39	82	. 138	7. 16	6. 00	. 1043
5	. 00038	. 0047	. 080			103	. 206	3. 22	8. 95	. 0686
6	. 00045	. 0053	. 085	. 200	. 43	124	. 206	3. 21	8. 95	. 0699
7	. 00053	. 0053	. 099			144	. 240	2. 37	10. 43	. 0601
8	. 00060	. 0040	. 150	. 201	. 75	165	. 418	. 799	18. 19	. 0329
9	. 00068	. 0050	. 135			185	. 337	1. 202	14. 64	. 0424
10	. 00075	. 0043	. 175	. 210	. 83	206	. 470	. 615	20. 47	. 0296
11	. 00083	. 0060	. 165			226	. 411	. 804	17. 90	. 0347
12	. 00090	. 0060	. 150	. 184	. 82	247	. 341	1. 168	14. 85	. 0431
13	. 00098	. 0060	. 163			268	. 370	. 989	16. 14	. 0396
14	. 00105	. 0050	. 210	. 219	. 96	288	. 524	. 497	22. 77	. 0273
15	. 00113	. 0057	. 198			309	. 463	. 637	20. 11	. 0315

E.—*Summary of laboratory data for artificial rainfall*—Continued

Test 3–10

[I=11.35 in. per hr; S=0.0342 ft per ft; T=7.0° C; $\nu=1.47\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
2	0.00053	0.0047	0.112	0.194	0.58	143	0.288	3.301	8.83	0.0685
3	.00079	.0047	.168			214	.432	1.467	13.25	.0463
4	.00105	.0053	.198	.333	.60	286	.479	1.191	14.71	.0426
5	.00131	.0050	.263			357	.656	.637	20.11	.0308
6	.00158	.0050	.315	.417	.46	429	.786	.444	24.09	.0257
7	.00184	.0063	.292			500	.649	.651	19.89	.0324
8	.00210	.0057	.369	.545	.68	572	.862	.368	26.43	.0240
9	.00236	.0067	.353			643	.761	.474	23.32	.0279
10	.00263	.0063	.417	.556	.75	715	.927	.319	28.41	.0237
11	.00289	.0073	.396			786	.816	.410	25.06	.0264
12	.00315	.0077	.409	.526	.78	857	.821	.406	25.20	.0265
13	.00341	.0077	.444			929	.892	.344	27.36	.0244
14	.00368	.0067	.549	.760	.72	1000	1.183	.196	36.27	.0180
15	.00394	.0057	.691			1072	1.614	.105	49.48	.0128

Test 3–11

[I=8.51 in. per hr; S=0.0342 ft per ft; T=4.0° C; $\nu=1.68\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
2	0.00039	0.0037	0.106	0.164	0.65	94	0.307	2.90	9.42	0.0626
3	.00059	.0053	.112			141	.271	3.72	8.32	.0753
4	.00079	.0057	.138	.314	.44	188	.322	2.64	9.88	.0641
5	.00099	.0053	.186			235	.450	1.350	13.81	.0453
6	.00118	.0053	.223	.380	.59	281	.540	.939	16.56	.0378
7	.00138	.0060	.230			328	.523	.999	16.06	.0398
8	.00158	.0063	.250	.447	.56	375	.556	.888	17.03	.0378
9	.00177	.0067	.265			422	.571	.841	17.51	.0372
10	.00197	.0060	.328	.509	.64	469	.745	.491	22.90	.0279
11	.00217	.0080	.271			516	.533	.960	16.38	.0409
12	.00236	.0067	.353	.690	.51	563	.761	.474	23.32	.0279
13	.00256	.0070	.366			610	.771	.460	23.65	.0277
14	.00276	.0060	.460	.673	.68	657	1.045	.250	32.11	.0199
15	.00296	.0063	.469			704	1.042	.252	31.95	.0202

Test 3–12

[I=6.36 in. per hr; S=0.0342 ft per ft; T=7.0° C; $\nu=1.47\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
2	0.00029	0.0037	0.079	0.190	0.42	80	0.229	5.22	7.02	0.0841
3	.00044	.0050	.088			120	.219	5.69	6.73	.0922
4	.00059	.0053	.111	.326	.34	160	.269	3.79	8.24	.0760
5	.00073	.0047	.156			200	.401	1.701	12.31	.0499
6	.00088	.0050	.176	.411	.43	240	.439	1.422	13.46	.0461
7	.00103	.0057	.180			280	.421	1.550	12.89	.0492
8	.00117	.0063	.186	.392	.47	320	.413	1.604	12.67	.0509
9	.00132	.0053	.249			360	.603	.753	18.50	.0339
10	.00147	.0053	.277	.394	.70	399	.671	.609	20.58	.0304
11	.00161	.0067	.241			439	.519	1.016	15.92	.0409
12	.00176	.0077	.229	.432	.53	479	.460	1.294	14.11	.0472
13	.00191	.0073	.261			519	.538	.944	16.52	.0400
14	.00206	.0060	.343	.601	.57	559	.780	.449	23.94	.0267
15	.00220	.0060	.367			599	.834	.393	25.62	.0250

E.—*Summary of laboratory data for artificial rainfall*—Continued

Test 3-13

[I=4.86 in. per hr; S=0.0342 ft per ft; T=7° C; $\nu=1.47\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
2	0.00023	0.0040	0.056	0.186	0.30	61	0.156	11.24	4.79	0.1249
3	.00034	.0040	.084			92	.234	4.99	7.18	.0832
4	.00045	.0047	.096	.248	.39	122	.247	4.49	7.57	.0811
5	.00056	.0047	.120			153	.308	2.88	9.47	.0649
6	.00068	.0053	.127	.323	.39	184	.308	2.90	9.43	.0664
7	.00079	.0047	.168			214	.432	1.467	13.25	.0463
8	.00090	.0043	.209	.341	.61	245	.562	.867	17.23	.0351
9	.00101	.0050	.203			276	.506	1.069	15.52	.0400
10	.00113	.0047	.249	.353	.71	306	.640	.668	19.64	.0313
11	.00124	.0050	.248			337	.618	.716	18.97	.0327
12	.00135	.0057	.237	.359	.66	367	.554	.894	16.98	.0373
13	.00146	.0080	.183			398	.360	2.105	11.06	.0606
14	.00158	.0060	.263	.571	.46	429	.598	.764	18.36	.0348
15	.00169	.0057	.296			459	.692	.573	21.20	.0299

Test 3-14

[I=3.12 in. per hr; S=0.0342 ft per ft; T=7.0° C; $\nu=1.47\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
2	0.00014	0.0027	0.053	0.164	0.32	39	0.180	8.47	5.52	0.1015
3	.00022	.0030	.072			59	.232	5.10	7.11	.0802
4	.00029	.0040	.072	.221	.33	78	.201	6.80	6.16	.0971
5	.00036	.0037	.097			98	.281	3.46	8.62	.0684
6	.00043	.0043	.101	.281	.36	118	.272	3.71	8.33	.0726
7	.00050	.0040	.126			137	.351	2.22	10.77	.0555
8	.00058	.0040	.144	.240	.60	157	.401	1.699	12.31	.0486
9	.00065	.0040	.162			177	.451	1.343	13.85	.0432
10	.00072	.0033	.218	.287	.76	196	.669	.612	20.52	.0282
11	.00079	.0047	.169			216	.434	1.450	13.33	.0461
12	.00087	.0043	.201	.303	.66	235	.540	.938	16.57	.0365
13	.00094	.0057	.164			255	.383	1.867	11.75	.0540
14	.00101	.0047	.215	.366	.59	275	.553	.896	16.96	.0362
15	.00108	.0047	.230			294	.591	.783	18.14	.0338

Test 4-11

[I=11.19 in. per hr; S=0.0550 ft per ft; T=13.0° C; $\nu=1.31\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0.00026	0.0040	0.065			79	0.181	13.42	4.38	0.1364
2	.00052	.0043	.120	0.287	0.42	158	.323	4.23	7.80	.0775
3	.00078	.0050	.155			237	.387	2.95	9.35	.0664
4	.00104	.0047	.220	.496	.44	316	.566	1.376	13.68	.0449
5	.00130	.0057	.227			395	.530	1.567	12.82	.0495
6	.00155	.0053	.293	.612	.48	475	.709	.875	17.16	.0365
7	.00181	.0067	.271			554	.584	1.293	14.12	.0461
8	.00207	.0063	.329	.823	.40	633	.731	.825	17.67	.0365
9	.00233	.0063	.370			712	.822	.652	19.88	.0324
10	.00259	.0070	.370	.800	.46	791	.779	.725	18.86	.0348
11	.00285	.0087	.327			870	.618	1.153	14.95	.0455
12	.00311	.0067	.464	1.036	.45	949	1.000	.441	24.17	.0269
13	.00337	.0070	.481			1028	1.013	.429	24.51	.0268
14	.00363	.0080	.453	1.307	.35	1107	.892	.552	21.60	.0311
15	.00389	.0070	.555			1186	1.168	.322	28.28	.0232

E.—*Summary of laboratory data for artificial rainfall*—Continued

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient n
Test 4-12										
[I=8.69 in. per hr; S=0.0550 ft per ft; T=12.0° C; $\nu=1.34\times10^{-5}$ sq ft per sec]										
1	0. 00020	0. 0037	0. 054			60	0. 157	17. 98	3. 79	0. 1559
2	. 00040	. 0043	. 094	0. 245	0. 38	120	. 253	6. 90	6. 11	. 0990
3	. 00060	. 0043	. 140			180	. 376	3. 11	9. 10	. 0665
4	. 00080	. 0050	. 161	. 345	. 47	240	. 401	2. 73	9. 71	. 0639
5	. 00101	. 0047	. 214			300	. 550	1. 454	13. 31	. 0461
6	. 00121	. 0050	. 241	. 551	. 44	360	. 601	1. 220	14. 53	. 0427
7	. 00141	. 0047	. 300			420	. 771	. 740	18. 66	. 0329
8	. 00161	. 0053	. 304	. 690	. 44	480	. 736	. 813	17. 81	. 0352
9	. 00181	. 0043	. 421			541	1. 132	. 344	27. 37	. 0221
10	. 00201	. 0060	. 335	. 707	. 47	601	. 761	. 758	18. 44	. 0347
11	. 00221	. 0067	. 330			661	. 711	. 872	17. 19	. 0379
12	. 00241	. 0063	. 383	. 881	. 44	721	. 851	. 609	20. 57	. 0313
13	. 00262	. 0070	. 374			781	. 787	. 709	19. 06	. 0344
14	. 00282	. 0060	. 469	1. 070	. 44	841	1. 066	. 387	25. 82	. 0248
15	. 00302	. 0057	. 529			901	1. 236	. 289	29. 88	. 0212
Test 4-13										
[I=6.38 in. per hr; S=0.0550 ft per ft; T=10.0° C; $\nu=1.41\times10^{-5}$ sq ft per sec]										
1	0. 00015	0. 0030	0. 049			42	0. 158	17. 70	3. 81	0. 1494
2	. 00030	. 0037	. 080	0. 210	0. 38	84	. 322	8. 19	5. 61	. 1052
3	. 00044	. 0043	. 103			126	. 170	5. 74	6. 70	. 0903
4	. 00059	. 0050	. 118	. 402	. 29	167	. 294	5. 09	7. 12	. 0872
5	. 00074	. 0053	. 139			209	. 337	3. 89	8. 14	. 0769
6	. 00089	. 0050	. 177	. 509	. 35	251	. 441	2. 26	10. 67	. 0581
7	. 00103	. 0047	. 220			293	. 566	1. 376	13. 68	. 0449
8	. 00118	. 0043	. 275	. 536	. 51	335	. 455	. 806	17. 88	. 0338
9	. 00133	. 0050	. 266			377	. 663	1. 001	16. 04	. 0387
10	. 00148	. 0040	. 369	. 509	. 73	419	1. 028	. 416	24. 88	. 0240
11	. 00162	. 0047	. 345			461	. 887	. 560	21. 45	. 0286
12	. 00177	. 0060	. 295	. 631	. 47	502	. 670	. 977	16. 24	. 0394
13	. 00192	. 0053	. 362			544	. 877	. 573	21. 20	. 0295
14	. 00207	. 0053	. 390	. 660	. 59	586	. 944	. 494	22. 84	. 0274
15	. 00221	. 0050	. 443			628	1. 105	. 361	26. 71	. 0232
Test 4-14										
[I=4.53 in. per hr; S=0.0550 ft per ft; T=10.0° C; $\nu=1.41\times10^{-5}$ sq ft per sec]										
1	0. 00010	0. 0027	0. 039			30	0. 132	25. 15	3. 20	0. 1749
2	. 00021	. 0027	. 078	0. 228	0. 34	59	. 264	6. 29	6. 40	. 0875
3	. 00031	. 0033	. 095			89	. 291	5. 18	7. 05	. 0821
4	. 00042	. 0037	. 113	. 326	. 35	119	. 328	4. 11	7. 92	. 0745
5	. 00052	. 0033	. 159			149	. 488	1. 850	11. 80	. 0491
6	. 00063	. 0037	. 170	. 442	. 39	178	. 493	1. 814	11. 92	. 0495
7	. 00073	. 0043	. 170			208	. 457	2. 108	11. 05	. 0547
8	. 00084	. 0040	. 209	. 438	. 48	238	. 582	1. 298	14. 09	. 0424
9	. 00094	. 0037	. 259			267	. 751	. 782	18. 15	. 0325
10	. 00105	. 0037	. 283	. 455	. 62	297	. 821	. 655	19. 83	. 0298
11	. 00115	. 0047	. 245			327	. 630	1. 110	15. 23	. 0403
12	. 00126	. 0053	. 237	. 504	. 47	356	. 574	1. 337	13. 88	. 0451
13	. 00136	. 0043	. 317			386	. 853	. 606	20. 62	. 0293
14	. 00147	. 0050	. 293	. 593	. 49	416	. 731	. 825	17. 67	. 0351
15	. 00157	. 0050	. 314			446	. 783	. 719	18. 93	. 032[illegible]

E.—*Summary of laboratory data for artificial rainfall*—Continued

Test 4-15

[I=3.47 in. per hr; S=0.0550 ft per ft; T=13.5° C; $\nu=1.29\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0.00008	0.0020	0.040			25	0.158	17.71	3.81	0.1396
2	.00016	.0027	.059	0.132	0.45	50	.200	10.99	4.84	.1156
3	.00024	.0027	.089			75	.302	4.83	7.30	.0767
4	.00032	.0033	.097	.308	.32	100	.298	4.97	7.20	.0804
5	.00040	.0030	.144			124	.463	2.05	11.21	.0508
6	.00048	.0033	.146	.351	.42	149	.448	2.19	10.84	.0534
7	.00056	.0037	.152			174	.441	2.27	10.66	.0554
8	.00064	.0037	.174	.390	.45	199	.504	1.732	12.20	.0484
9	.00072	.0033	.219			224	.672	.975	16.25	.0356
10	.00080	.0033	.243	.419	.58	249	.745	.792	18.04	.0321
11	.00088	.0047	.188			274	.483	1.884	11.69	.0525
12	.00096	.0043	.224	.398	.56	299	.602	1.214	14.57	.0415
13	.00104	.0037	.282			324	.817	.659	19.77	.0298
14	.00112	.0037	.304	.417	.73	349	.881	.567	21.32	.0277
15	.00120	.0040	.301			373	.838	.626	20.29	.0295

Test 5-10

[I=11.77 in. per hr; S=0.0775 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0.00027	0.0043	0.063			86	0.169	21.63	3.45	0.1753
2	.00054	.0043	.127	0.372	0.34	172	.341	5.32	6.96	.0869
3	.00082	.0050	.163			257	.406	3.76	8.28	.0749
4	.00109	.0057	.191	.600	.32	343	.446	3.12	9.09	.0698
5	.00136	.0060	.227			429	.516	2.32	10.53	.0607
6	.00163	.0063	.259	.791	.33	515	.576	1.875	11.72	.0550
7	.00191	.0067	.284			600	.612	1.658	12.47	.0523
8	.00218	.0070	.311	.939	.33	686	.655	1.445	13.35	.0491
9	.00245	.0070	.350			772	.737	1.141	15.03	.0437
10	.00272	.0080	.340	1.156	.29	858	.669	1.381	13.66	.0491
11	.00300	.0077	.389			943	.781	1.016	15.92	.0419
12	.00327	.0080	.408	1.036	.39	1029	.803	.959	16.39	.0409
13	.00354	.0077	.460			1115	.936	.726	18.84	.0354
14	.00381	.0080	.477	1.460	.33	1201	.939	.702	19.16	.0350
15	.00408	.0083	.492			1286	.952	.684	19.41	.0348

Test 5-1ı

[I=8.43 in. per hr; S=0.0775 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0.00020	0.0033	0.059			61	0.181	18.92	3.69	0.1569
2	.00039	.0040	.098	0.274	0.36	123	.273	8.31	5.57	.1074
3	.00059	.0040	.146			184	.407	3.75	8.29	.0721
4	.00078	.0047	.166	.531	.31	246	.427	3.40	8.70	.0706
5	.00098	.0050	.195			307	.486	2.63	9.91	.0626
6	.00117	.0047	.249	.567	.44	369	.640	1.513	13.05	.0470
7	.00137	.0053	.258			430	.625	1.589	12.73	.0492
8	.00156	.0060	.260	.714	.36	492	.591	1.771	12.06	.0530
9	.00176	.0063	.279			553	.620	1.615	12.63	.0510
10	.00195	.0063	.310	.733	.42	614	.689	1.309	14.03	.0459
11	.00215	.0070	.307			676	.646	1.482	13.18	.0498
12	.00234	.0067	.349	.870	.40	737	.752	1.098	15.32	.0425
13	.00254	.0070	.362			799	.762	1.066	15.55	.0422
14	.00273	.0080	.341	1.176	.29	860	.671	1.373	13.70	.0490
15	.00293	.0073	.401			922	.827	.906	16.86	.0392

E.—*Summary of laboratory data for artificial rainfall*—Continued

Test 5-12

[I=6.07 in. per hr; S=0.0775 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0.00014	0.0030	0.047			44	0.151	27.11	3.08	0.1848
2	.00028	.0040	.070	0.267	0.26	88	.195	16.29	3.98	.1504
3	.00042	.0037	.114			133	.330	5.68	6.73	.0876
4	.00056	.0047	.119	.531	.22	177	.306	6.63	6.74	.0984
5	.00070	.0047	.149			221	.383	4.23	7.81	.0786
6	.00084	.0050	.168	.571	.29	265	.419	3.54	8.54	.0727
7	.00098	.0053	.185			310	.448	3.09	9.13	.0686
8	.00112	.0057	.197	.714	.28	354	.460	2.93	9.37	.0676
9	.00126	.0053	.238			398	.576	1.868	11.74	.0533
10	.00140	.0067	.210	.741	.28	442	.453	3.032	9.21	.0707
11	.00154	.0063	.245			486	.544	2.095	11.09	.0581
12	.00168	.0067	.251	.791	.32	531	.541	2.126	11.01	.0592
13	.00183	.0067	.272			575	.586	1.808	11.94	.0546
14	.00197	.0070	.281	1.093	.26	619	.592	1.769	12.07	.0544
15	.00211	.0063	.334			663	.742	1.127	15.12	.0426

Test 5-13

[I=4.64 in. per hr; S=0.0775 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]

1	0.00011	0.0023	0.047			34	0.173	20.78	3.52	0.1548
2	.00021	.0040	.054	0.217	0.25	68	.150	27.38	3.07	.1949
3	.00032	.0037	.087			101	.252	9.76	5.14	.1149
4	.00043	.0040	.107	.428	.25	135	.298	6.97	6.08	.0984
5	.00054	.0040	.134			169	.373	4.45	7.61	.0785
6	.00064	.0043	.150	.560	.27	203	.403	3.82	8.22	.0736
7	.00075	.0047	.160			237	.411	3.67	8.38	.0732
8	.00086	.0040	.215	.536	.40	271	.599	1.727	12.13	.0493
9	.00097	.0047	.206			304	.530	2.211	10.79	.0569
10	.00107	.0047	.229	.612	.37	338	.589	1.789	12.00	.0512
11	.00118	.0047	.251			372	.645	1.489	13.15	.0467
12	.00129	.0060	.215	.645	.33	406	.489	2.591	9.97	.0641
13	.00140	.0050	.279			440	.696	1.282	14.18	.0438
14	.00150	.0057	.264	.823	.32	474	.617	1.632	12.56	.0505
15	.00161	.0057	.283			507	.661	1.421	13.46	.0471

Test 6-10

[I=10.85 in. per hr; S=0.0775 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]

1	0.00025	0.0030	0.084			79	0.270	8.49	5.51	0.1074
2	.00050	.0040	.126	0.271	0.46	158	.351	5.03	7.16	.0835
3	.00075	.0040	.183			237	.524	2.26	10.69	.0560
4	.00100	.0053	.189	.504	.38	316	.458	2.96	9.33	.0672
5	.00126	.0063	.199			395	.442	3.18	9.01	.0716
6	.00151	.0063	.239	.714	.34	474	.531	2.20	10.82	.0596
7	.00176	.0073	.241			553	.497	2.51	10.13	.0652
8	.00201	.0077	.261	.909	.29	632	.524	2.26	10.69	.0624
9	.00226	.0060	.377			711	.857	.843	17.48	.0367
10	.00251	.0077	.326	.844	.39	791	.655	1.446	13.35	.0499
11	.00276	.0090	.307			870	.571	1.906	11.63	.0588
12	.00301	.0083	.363	1.156	.31	949	.702	1.257	14.32	.0471
13	.00326	.0087	.375			1028	.709	1.235	14.44	.0471
14	.00351	.0097	.362	1.156	.31	1107	.648	1.477	13.21	.0525
15	.00377	.0093	.405			1186	.740	1.132	15.09	.0456

E.—*Summary of laboratory data for artificial rainfall*—Continued

Test 6-11

[I=8.20 in. per hr; S=0.0775 ft per ft; T=18.0° C; $\nu=1.14\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0.00019	0.0017	0.112			67	0.479	2.70	9.76	0.0531
2	.00038	.0030	.127	0.251	0.51	133	.408	3.71	8.33	.0684
3	.00057	.0037	.154			200	.446	3.11	9.10	.0649
4	.00076	.0040	.190	.462	.41	267	.529	2.21	10.79	.0553
5	.00095	.0043	.221			333	.594	1.757	12.11	.0500
6	.00114	.0043	.265	.576	.46	400	.712	1.222	14.52	.0417
7	.00133	.0043	.309			466	.831	.899	16.93	.0304
8	.00152	.0057	.266	.749	.36	533	.621	1.608	12.66	.0501
9	.00171	.0060	.285			599	.648	1.474	13.22	.0484
10	.00190	.0070	.271	.755	.36	666	.571	1.902	11.64	.0564
11	.00209	.0083	.252			733	.487	2.609	9.94	.0679
12	.00228	.0083	.274	.851	.32	799	.530	2.207	10.80	.0625
13	.00247	.0100	.247			866	.436	3.373	8.87	.0785
14	.00266	.0093	.286	1.053	.27	932	.523	2.269	10.66	.0646
15	.00285	.0097	.294			999	.526	2.240	10.72	.0646

Test 6-12

[I=5.95 in. per hr; S=0.0775 ft per ft; T=18.0° C; $\nu=1.14\times11^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0.00014	0.0020	0.069			48	0.272	8.39	5.54	0.0960
2	.00028	.0023	.120	0.236	0.51	97	.441	3.19	8.99	.0606
3	.00041	.0030	.138			145	.444	3.14	9.05	.0629
4	.00055	.0040	.138	.500	.28	193	.384	4.19	7.84	.0762
5	.00069	.0037	.186			242	.539	2.14	10.98	.0537
6	.00083	.0040	.207	.468	.44	290	.577	1.863	11.76	.0508
7	.00096	.0040	.241			338	.671	1.375	13.69	.0437
8	.00110	.0047	.235	.612	.38	387	.604	1.699	12.31	.0499
9	.00124	.0047	.264			435	.679	1.346	13.83	.0444
10	.00138	.0047	.293	.625	.47	484	.753	1.093	15.35	.0400
11	.00152	.0050	.303			532	.756	1.087	15.39	.0403
12	.00165	.0057	.290	.612	.47	580	.678	1.353	13.80	.0459
13	.00179	.0063	.284			629	.631	1.559	12.85	.0501
14	.00193	.0070	.276	.844	.33	677	.581	1.834	11.85	.0554
15	.00207	.0067	.309			725	.666	1.401	13.56	.0480

Test 6-13

[I=4.72 in. per hr; S=0.0775 ft per ft; T=16.5° C; $\nu=1.19\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0.00011	0.0017	0.064			37	0.274	8.28	5.58	0.0929
2	.00022	.0017	.128	0.192	0.67	73	.547	2.07	11.15	.0465
3	.00033	.0027	.121			110	.410	3.68	8.37	.0669
4	.00044	.0027	.162	.375	.43	147	.549	2.05	11.20	.0500
5	.00055	.0027	.202			184	.685	1.321	13.96	.0401
6	.00066	.0033	.199	.366	.54	220	.610	1.663	12.45	.0465
7	.00076	.0050	.153			257	.382	4.26	7.73	.0798
8	.00087	.0040	.218	.560	.39	294	.607	1.680	12.38	.0483
9	.00098	.0040	.246			330	.685	1.319	13.98	.0428
10	.00109	.0047	.232	.645	.36	367	.596	1.743	12.16	.0505
11	.00120	.0043	.279			404	.750	1.103	15.28	.0396
12	.00131	.0057	.230	.639	.36	440	.537	2.151	10.94	.0579
13	.00142	.0070	.203			477	.427	3.39	8.72	.0753
14	.00153	.0073	.209	.870	.24	514	.431	3.34	8.79	.0752
15	.00164	.0050	.328			551	.818	.928	16.66	.0372

E.—*Summary of laboratory data for artificial rainfall*—Continued

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, $\mathbf{R}$	Froude number, $\mathbf{F}$	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
Test 7–13										
[I=11.70 in. per hr; S=0.0550 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]										
1	0.00027	0.0030	0.090			85	0.289	5.25	7.01	0.0313
2	.00054	.0040	.135	0.324	0.42	171	.376	3.11	9.10	.0657
3	.00081	.0057	.142			256	.332	4.01	8.02	.0791
4	.00108	.0057	.190	.484	.39	341	.444	2.24	10.73	.0591
5	.00135	.0070	.193			426	.406	2.66	9.84	.0667
6	.00162	.0070	.232	.673	.35	512	.488	1.843	11.82	.0551
7	.00189	.0090	.211			597	.392	2.86	9.48	.0721
8	.00216	.0093	.233	.697	.33	682	.426	2.43	10.30	.0668
9	.00244	.0077	.316			767	.635	1.093	15.35	.0434
10	.00271	.0080	.338	.760	.45	853	.665	.992	16.12	.0416
11	.00298	.0083	.359			938	.694	.913	16.80	.0402
12	.00325	.0090	.361	1.036	.35	1023	.671	.979	16.22	.0422
13	.00352	.0097	.363			1108	.649	1.043	15.72	.0441
14	.00379	.0100	.379	1.504	.25	1194	.668	.986	16.16	.0431
15	.00416	.0097	.419			1279	.750	.783	18.14	.0382
Test 7–14										
[I=8.46 in. per hr; S=0.0550 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]										
1	0.00020	0.0020	0.098			62	0.386	2.95	9.34	0.0570
2	.00039	.0037	.106	0.153	0.69	123	.307	4.67	7.43	.0794
3	.00059	.0053	.111			185	.269	6.10	6.50	.0963
4	.00078	.0057	.137	.314	.44	247	.320	4.30	7.74	.0819
5	.00098	.0053	.185			308	.448	2.19	10.84	.0578
6	.00117	.0053	.222	.375	.59	370	.538	1.524	13.00	.0482
7	.00137	.0060	.228			431	.518	1.636	12.55	.0510
8	.00157	.0070	.224	.673	.33	493	.472	1.977	11.42	.0575
9	.00176	.0063	.280			555	.434	1.139	15.04	.0429
10	.00196	.0067	.292	.690	.42	616	.629	1.113	15.21	.0428
11	.00215	.0073	.295			678	.608	1.189	14.72	.0449
12	.00235	.0087	.270	.844	.32	740	.510	1.691	12.34	.0551
13	.00254	.0077	.330			801	.663	1.002	16.03	.0416
14	.00274	.0077	.356	1.070	.33	863	.715	.861	17.30	.0385
15	.00294	.0087	.337			925	.637	1.085	15.41	.0442
Test 7–15										
[I=6.07 in. per hr; S=0.0550 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]										
1	0.00014	0.0020	0.070			44	0.276	5.78	6.67	0.0798
2	.00028	.0027	.104	0.186	0.56	88	.353	3.54	8.53	.0656
3	.00042	.0037	.114			133	.330	4.03	7.99	.0738
4	.00056	.0043	.131	.353	.37	177	.352	3.55	8.52	.0710
5	.00070	.0047	.149			221	.383	3.00	9.27	.0663
6	.00084	.0047	.179	.468	.39	265	.460	2.08	11.13	.0552
7	.00098	.0057	.172			310	.402	2.73	9.71	.0653
8	.00112	.0050	.225	.513	.44	354	.561	1.400	13.57	.0457
9	.00126	.0047	.269			398	.692	.920	16.73	.0367
10	.00140	.0050	.281	.571	.49	442	.701	.897	16.95	.0366
11	.00154	.0067	.231			486	.498	1.779	12.03	.0541
12	.00168	.0070	.241	.606	.40	531	.507	1.708	12.28	.0534
13	.00183	.0077	.237			575	.476	1.943	11.51	.0579
14	.00197	.0073	.269	.858	.31	619	.555	1.430	13.42	.0492
15	.00211	.0077	.274			663	.550	1.453	13.32	.0501

E.—*Summary of laboratory data for artificial rainfall*—Continued

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
Test 7-16										
[I=4.77 in. per hr; S=0.0550 ft per ft; T=14.5° C; ν=1.25×10^{-5} sq ft per sec]										
1	0.00011	0.0020	0.055			35	0.217	9.37	5.24	0.1015
2	.00022	.0023	.096	0.222	0.43	71	.353	3.54	8.54	.0639
3	.00033	.0027	.123			106	.417	2.53	10.09	.0555
4	.00044	.0033	.134	.271	.49	141	.411	2.60	9.95	.0582
5	.00055	.0030	.184			177	.592	1.256	14.32	.0398
6	.00066	.0037	.179	.390	.46	212	.519	1.636	12.55	.0470
7	.00077	.0040	.193			247	.538	1.522	13.01	.0459
8	.00088	.0047	.188	.435	.43	283	.483	1.884	11.69	.0525
9	.00099	.0043	.231			318	.621	1.142	15.02	.0403
10	.00110	.0040	.276	.435	.63	353	.769	.744	18.61	.0321
11	.00121	.0053	.229			389	.554	1.432	13.41	.0467
12	.00132	.0057	.232	.496	.47	424	.542	1.501	13.10	.0484
13	.00144	.0077	.186			459	.373	3.15	9.04	.0738
14	.00155	.0073	.212	.619	.34	495	.437	2.30	10.58	.0625
15	.00166	.0053	.312			530	.755	.772	18.27	.0343
Test 7-17										
[I=3.67 in. per hr; S=0.0550 ft per ft; T=15.0° C; ν=1.23×10^{-5} sq ft per sec]										
1	0.00008	0.0017	0.050			28	0.214	9.64	5.17	0.1002
2	.00017	.0017	.100	0.178	0.56	55	.427	2.41	10.34	.0501
3	.00025	.0017	.150			83	.641	1.071	15.51	.0334
4	.00034	.0023	.137	.211	.65	110	.504	1.736	12.18	.0447
5	.00042	.0027	.157			138	.532	1.552	12.88	.0435
6	.00051	.0030	.170	.332	.51	165	.547	1.471	13.23	.0431
7	.00059	.0037	.160			193	.464	2.04	11.22	.0526
8	.00068	.0033	.206	.398	.52	221	.632	1.102	15.29	.0379
9	.00076	.0033	.231			248	.709	.876	17.15	.0338
10	.00085	.0033	.257	.419	.61	276	.788	.708	19.08	.0303
11	.00093	.0037	.252			303	.730	.826	17.66	.0334
12	.00102	.0047	.217	.455	.48	331	.558	1.414	13.50	.0455
13	.00110	.0047	.235			359	.604	1.206	14.62	.0420
14	.00119	.0047	.253	.560	.45	386	.650	1.040	15.74	.0390
15	.00127	.0053	.240			414	.581	1.304	14.06	.0446
Test 8-13										
[I=11.95 in. per hr; S=0.0342 ft per ft; T=14.0° C; ν=1.27×10^{-5} sq ft per sec]										
1	0.00028	0.0033	0.084			87	0.258	4.12	7.91	0.0732
2	.00055	.0043	.129	0.244	0.53	174	.347	2.28	10.64	.0569
3	.00083	.0060	.138			261	.314	2.78	9.63	.0664
4	.00111	.0083	.133	.339	.39	348	.257	4.13	7.89	.0850
5	.00138	.0077	.180			435	.361	2.09	11.09	.0601
6	.00166	.0087	.215	.619	.35	523	.406	1.658	12.47	.0883
7	.00194	.0097	.200			610	.358	2.14	10.98	.0631
8	.00221	.0097	.228	.673	.34	697	.408	1.644	12.52	.0553
9	.00249	.0097	.257			784	.460	1.294	14.11	.0491
10	.00277	.0090	.307	.583	.53	871	.571	.841	17.50	.0391
11	.00304	.0113	.269			958	.446	1.376	13.68	.0519
12	.00332	.0093	.357	.583	.61	1045	.653	.643	20.02	.0344
13	.00359	.0107	.336			1132	.572	.835	17.56	.0401
14	.00387	.0103	.376	.760	.50	1219	.653	.642	20.03	.0349
15	.00415	.0090	.461			1306	.857	.373	26.28	.0260

E.—*Summary of laboratory data for artificial rainfall*—Continued

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
Test 8-14										
[I=8.78 in. per hr; S=0.0342 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]										
1	0.00020	0.0030	0.068			64	0.219	5.71	6.71	0.0849
2	.00041	.0043	.095	0.221	0.43	128	.255	4.20	7.83	.0772
3	.00061	.0050	.122			192	.304	2.96	9.33	.0665
4	.00081	.0057	.143	.372	.38	256	.334	2.46	10.24	.0619
5	.00102	.0060	.169			320	.384	1.851	11.80	.0542
6	.00122	.0070	.174	.496	.35	384	.366	2.16	10.92	.0601
7	.00142	.0087	.163			448	.308	2.89	9.45	.0720
8	.00163	.0077	.211	.560	.38	512	.424	1.524	13.00	.0513
9	.00183	.0067	.273			576	.607	.792	18.04	.0361
10	.00203	.0077	.264	.625	.42	640	.530	.973	16.27	.0410
11	.00224	.0100	.224			704	.395	1.756	12.11	.0575
12	.00244	.0080	.305	.619	.49	768	.600	.758	18.44	.0364
13	.00264	.0073	.362			832	.746	.491	22.91	.0288
14	.00284	.0083	.343	.667	.51	896	.663	.622	20.35	.0332
15	.00305	.0080	.381			960	.750	.486	22.02	.0291
Test 8-15										
[I=6.11 in. per hr; S=0.0342 ft per ft; T=14.5° C; $\nu=1.25\times10^{-5}$ sq ft per sec]										
1	0.00014	0.0027	0.052			45	0.176	8.80	5.41	0.1035
2	.00028	.0030	.094	0.208	0.45	90	.302	2.99	9.28	.0614
3	.00042	.0050	.085			136	.212	6.10	6.50	.0954
4	.00057	.0043	.132	.362	.37	181	.355	2.17	10.89	.0556
5	.00071	.0043	.164			226	.441	1.408	13.53	.0447
6	.00085	.0060	.141	.398	.35	271	.320	2.66	9.84	.0650
7	.00099	.0060	.165			317	.375	1.942	11.52	.0555
8	.00113	.0060	.189	.491	.39	362	.430	1.479	13.20	.0485
9	.00127	.0063	.212			407	.471	1.234	14.45	.0446
10	.00141	.0053	.267	.465	.57	452	.646	.655	19.83	.0316
11	.00156	.0070	.222			498	.467	1.215	14.35	.0458
12	.00170	.0067	.253	.484	.52	543	.545	.922	16.72	.0390
13	.00184	.0077	.239			588	.480	1.180	14.73	.0453
14	.00198	.0073	.271	.683	.40	633	.559	.876	17.15	.0385
15	.00212	.0063	.337			679	.749	.489	22.95	.0281
Test 8-16										
[I=4.78 in. per hr; S=0.0342 ft per ft; T=16.0° C; $\nu=1.20\times10^{-5}$ sq ft per sec]										
1	0.00011	0.0023	0.048			37	0.176	8.80	5.41	0.1007
2	.00022	.0030	.074	0.191	0.39	74	.233	4.83	7.31	.0780
3	.00033	.0033	.101			111	.310	2.85	3.51	.0609
4	.00044	.0037	.120	.347	.35	147	.348	2.26	10.67	.0553
5	.00055	.0037	.149			184	.432	1.468	13.25	.0445
6	.00066	.0057	.116	.375	.31	221	.271	3.73	8.31	.0763
7	.00077	.0043	.180			258	.484	1.169	14.85	.0407
8	.00088	.0050	.177	.408	.43	295	.441	1.406	13.54	.0458
9	.00100	.0050	.199			332	.496	1.112	15.22	.0408
10	.00111	.0047	.235	.370	.64	369	.604	.750	18.53	.0331
11	.00122	.0057	.213			406	.498	1.107	15.26	.0416
12	.00133	.0063	.211	.394	.54	442	.469	1.247	14.37	.0448
13	.00144	.0087	.165			479	.312	2.82	9.58	.0710
14	.00155	.0070	.221	.600	.37	516	.465	1.263	14.28	.0459
15	.00166	.0050	.332			553	.828	.400	25.38	.0244

E.—*Summary of laboratory data for artificial rainfall*—Continued

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
Test 8-17										
[I=3.61 in. per hr; S=0.0342 ft per ft; T=17.0° C; $\nu=1.17\times10^{-5}$ sq ft per sec]										
1	0. 00008	0. 0020	0. 042			29	0. 165	9. 99	5. 08	0. 1048
2	. 00017	. 0033	. 051	0. 172	0. 30	57	. 156	11. 18	4. 80	. 1206
3	. 00025	. 0027	. 093			86	. 315	2. 75	9. 68	. 0578
4	. 00033	. 0033	. 101	. 279	. 36	114	. 310	2. 85	9. 51	. 0609
5	. 00042	. 0033	. 127			143	. 390	1. 639	12. 54	. 0462
6	. 00050	. 0043	. 117	. 319	. 37	171	. 315	2. 77	9. 65	. 0627
7	. 00058	. 0037	. 158			200	. 458	1. 306	14. 05	. 0420
8	. 00067	. 0037	. 181	. 380	. 48	228	. 525	. 995	16. 09	. 0367
9	. 00075	. 0040	. 188			257	. 524	. 997	16. 07	. 0372
10	. 00084	. 0040	. 209	. 345	. 61	285	. 582	. 807	17. 87	. 0335
11	. 00092	. 0043	. 214			314	. 575	. 827	17. 65	. 0343
12	. 00100	. 0057	. 176	. 402	. 44	343	. 411	1. 621	12. 61	. 0503
13	. 00109	. 0060	. 181			371	. 411	1. 614	12. 63	. 0506
14	. 00117	. 0053	. 221	. 504	. 44	400	. 535	. 956	16. 42	. 0382
15	. 00125	. 0057	. 220			428	. 514	1. 038	15. 75	. 0402
Test 9-13										
[I=11.40 in. per hr; S=0.0170 ft per ft; T=15.0° C; $\nu=1.23\times10^{-5}$ sq ft per sec]										
1	0. 00026	0. 0060	0. 044			86	0. 100	13. 57	4. 36	0. 1468
2	. 00053	. 0067	. 079	0. 165	0. 48	172	. 170	4. 70	7. 40	. 0880
3	. 00079	. 0070	. 113			257	. 238	2. 40	10. 36	. 0633
4	. 00106	. 0083	. 127	. 297	. 43	343	. 246	2. 25	10. 69	. 0631
5	. 00132	. 0080	. 165			429	. 325	1. 287	14. 15	. 0474
6	. 00158	. 0090	. 176	. 357	. 49	515	. 327	1. 273	14. 23	. 0481
7	. 00185	. 0100	. 185			601	. 326	1. 280	14. 19	. 0491
8	. 00211	. 0087	. 243	. 522	. 47	687	. 459	. 645	19. 98	. 0340
9	. 00238	. 0090	. 264			772	. 491	. 566	21. 33	. 0321
10	. 00264	. 0087	. 303	. 560	. 54	858	. 573	. 415	24. 91	. 0273
11	. 00290	. 0107	. 271			944	. 462	. 638	20. 09	. 0350
12	. 00317	. 0117	. 271	. 645	. 42	1030	. 441	. 698	19. 21	. 0372
13	. 00343	. 0117	. 293			1116	. 477	. 599	20. 77	. 0344
14	. 00369	. 0130	. 284	. 800	. 36	1201	. 439	. 706	19. 10	. 0382
15	. 00396	. 0117	. 338			1287	. 550	. 449	23. 95	. 0298
Test 9-14										
[I=8.44 in. per hr; S=0.0170 ft per ft; T=14.5° C; $\nu=1.25\times10^{-5}$ sq ft per sec]										
1	0. 00020	0. 0043	0. 045			62	0. 121	9. 30	5. 26	0. 1149
2	. 00039	. 0063	. 062	0. 131	0. 47	125	. 138	7. 18	5. 99	. 1076
3	. 00059	. 0063	. 093			187	. 207	3. 19	8. 99	. 0717
4	. 00078	. 0080	. 098	. 252	. 39	250	. 193	3. 65	8. 40	. 0798
5	. 00098	. 0077	. 127			312	. 255	2. 09	11. 10	. 0601
6	. 00117	. 0057	. 206	. 335	. 62	375	. 481	. 588	20. 93	. 0303
7	. 00137	. 0073	. 187			437	. 386	. 914	16. 79	. 0394
8	. 00156	. 0077	. 203	. 442	. 46	500	. 408	. 818	17. 75	. 0376
9	. 00176	. 0070	. 251			562	. 528	. 487	23. 00	. 0394
10	. 00195	. 0077	. 254	. 419	. 61	625	. 510	. 523	22. 19	. 0300
11	. 00215	. 0110	. 195			687	. 328	1. 267	14. 26	. 0496
12	. 00234	. 0100	. 234	. 462	. 51	750	. 413	. 800	17. 94	. 0388
13	. 00254	. 0107	. 237			812	. 404	. 834	17. 58	. 0401
14	. 00273	. 0110	. 249	. 588	. 42	875	. 418	. 777	18. 21	. 0389
15	. 00293	. 0080	. 366			937	. 720	. 262	31. 36	. 0214

E.—*Summary of laboratory data for artificial rainfall*—Continued

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
				Test 9-15						
				[I=5.93 in. per hr; S=0.0170 ft per ft; T=14.0° C; $\nu=1.27\times10^{-5}$ sq ft per sec]						
1	0.00014	0.0043	0.032			43	0.086	18.39	3.74	0.1617
2	.00027	.0040	.069	0.143	0.48	86	.192	3.68	8.37	.0714
3	.00041	.0053	.078			130	.189	3.82	8.21	.0762
4	.00055	.0050	.110	.313	.35	173	.274	1.810	11.93	.0520
5	.00069	.0063	.109			216	.242	2.32	10.53	.0612
6	.00082	.0077	.107	.323	.33	259	.215	2.95	9.35	.0713
7	.00096	.0080	.120			302	.236	2.43	10.29	.0652
8	.00110	.0070	.157	.345	.46	345	.331	1.244	14.39	.0456
9	.00123	.0067	.184			389	.397	.867	17.24	.0378
10	.00137	.0057	.241	.364	.66	432	.563	.430	24.48	.0259
11	.00151	.0087	.173			475	.327	1.273	14.23	.0478
12	.00165	.0093	.177	.309	.57	518	.324	1.300	14.08	.0489
13	.00178	.0103	.173			561	.300	1.507	13.07	.0535
14	.00192	.0100	.192	.438	.44	605	.339	1.188	14.73	.0473
15	.00206	.0070	.294			648	.619	.355	26.94	.0244
				Test 9-16						
				[I=4.95 in. per hr; S=0.0170 ft per ft; T=14.5° C; $\mu=1.25\times10^{-5}$ sq ft per sec]						
1	0.00011	0.0043	0.027			37	0.073	25.84	3.16	0.1915
2	.00023	.0050	.046	0.150	0.31	73	.115	10.35	4.99	.1243
3	.00034	.0047	.073			110	.188	.386	8.17	.0752
4	.00046	.0050	.092	.203	.45	147	.229	2.59	9.98	.0622
5	.00057	.0053	.108			183	.262	1.990	11.38	.0550
6	.00069	.0077	.089	.234	.38	220	.179	.426	7.78	.0857
7	.00080	.0070	.115			257	.242	2.32	10.54	.0622
8	.00092	.0057	.161	.328	.49	293	.376	.963	16.36	.0388
9	.00103	.0060	.172			330	.391	.848	17.43	.0367
10	.00115	.0050	.229	.341	.67	366	.571	.418	24.83	.0250
11	.00126	.0073	.173			403	.357	1.068	15.53	.0425
12	.00137	.0073	.188	.313	.60	440	.388	.905	16.87	.0392
13	.00149	.0100	.149			476	.263	1.973	11.43	.0609
14	.00160	.0083	.193	.447	.43	513	.373	.976	16.25	.0415
15	.00172	.0067	.256			550	.552	.448	23.98	.0272
				Test 9-17						
				[I=3.57 in. per hr; S=0.0170 ft per ft; T=13.0° C; $\mu=1.23\times10^{-5}$ sq ft per sec]						
1	0.00008	0.0040	0.021			27	0.058	39.73	2.55	0.2348
2	.00017	.0047	.035	0.168	0.21	54	.090	16.81	3.92	.1568
3	.00025	.0027	.092			81	.312	1.397	13.58	.0412
4	.00033	.0040	.083	.193	.43	107	.231	2.54	10.07	.0594
5	.00041	.0047	.088			134	.226	2.66	9.85	.0624
6	.00050	.0057	.087	.246	.35	161	.203	3.30	8.84	.0717
7	.00058	.0047	.123			188	.316	1.361	13.76	.0446
8	.00066	.0040	.165	.248	.67	215	.460	.644	20.01	.0299
9	.00074	.0047	.158			242	.406	.825	17.68	.0347
10	.00083	.0043	.192	.270	.71	269	.516	.511	22.46	.0269
11	.00091	.0053	.171			295	.414	.794	18.01	.0348
12	.00099	.0057	.174	.281	.62	322	.407	.825	17.68	.0359
13	.00107	.0073	.147			349	.303	1.480	13.19	.0501
14	.00116	.0073	.158	.372	.43	376	.326	1.281	14.18	.0466
15	.00124	.0060	.207			403	.470	.613	20.49	.0729

F.—*Summary of field data for overland flow sites*

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
Pole Creek Site 1										
[I=7.02 in. per hr; R=3.0 in. per hr; S=0.0960 ft per ft; T=10° C; $\nu=1.41\times10^{-5}$ sq ft per sec]										
1	0. 00007	0. 0004	0. 174	0. 026	6. 67	20	1. 529	0. 33	27. 98	0. 0146
3	. 00021	. 0066	. 032	. 032	. 98	59	. 068	164. 48	1. 25	. 5187
5	. 00035	. 0071	. 049	. 090	. 55	98	. 102	73. 46	1. 87	. 3511
7	. 00049	. 0081	. 060	. 122	. 49	138	. 117	55. 65	2. 15	. 3123
9	. 00062	. 0046	. 136	. 119	1. 14	177	. 353	6. 17	6. 46	. 0944
11	. 00076	. 0106	. 072	. 167	. 43	217	. 123	50. 56	2. 26	. 3128
13	. 00090	. 0143	. 063	. 148	. 43	256	. 093	88. 82	1. 70	. 4336
15	. 00104	. 0214	. 049	. 111	. 44	295	. 059	224. 03	1. 07	. 7373
17	. 00118	. 0180	. 066	. 084	. 78	335	. 086	103. 74	1. 58	. 4870
19	. 00132	. 0204	. 065	. 064	1. 01	374	. 080	120. 87	1. 46	. 5372
21	. 00146	. 0176	. 083	. 101	. 82	413	. 110	63. 48	2. 01	. 3797
23	. 00160	. 0136	. 117	. 146	. 80	453	. 177	24. 41	3. 25	. 2255
25	. 00173	. 0151	. 115	. 144	. 80	492	. 165	28. 28	3. 02	. 2470
27	. 00187	. 0265	. 071	. 255	. 28	532	. 077	131. 08	1. 40	. 5841
29	. 00201	. 0249	. 081	. 165	. 49	571	. 090	94. 31	1. 65	. 4908
31	. 00215	. 0246	. 088	. 244	. 36	610	. 098	79. 45	1. 80	. 2424
33	. 00229	. 0189	. 121	. 275	. 44	650	. 155	31. 83	2. 85	2724
35	. 00243	. 0209	. 116	. 248	. 47	689	. 142	38. 28	2. 59	. 3037
37	. 00257	. 0361	. 071	. 175	. 41	728	. 066	176. 58	1. 21	. 7147
39	. 00271	. 0280	. 097	. 190	. 51	768	. 102	74. 04	1. 87	. 4434
41	. 00285	. 0380	. 075	. 219	. 34	807	. 068	167. 45	1. 24	. 7012
43	. 00298	. 0486	. 061	. 204	. 30	847	. 049	318. 78	. 90	1. 0075
Pole Creek Site 2										
[I=7.41 in. per hr; R=3.4 in. per hr; S=0.3320 ft per ft; T=13° C; $\nu=1.31\times10^{-5}$ sq ft per sec]										
1	0. 00008	0. 0011	0. 072	0. 127	0. 56	24	0. 380	18. 40	3. 74	0. 1288
3	. 00024	. 0006	. 394	. 109	3. 60	72	2. 831	. 33	27. 90	. 0156
5	. 00039	. 0052	. 076	. 128	. 59	120	. 185	77. 60	1. 82	. 3427
7	. 00055	. 0182	. 030	. 147	. 21	168	. 040	1695. 50	. 39	1. 9726
9	. 00071	. 0095	. 075	. 122	. 61	216	. 135	145. 99	1. 33	. 5198
11	. 00087	. 0184	. 047	. 119	. 39	264	. 061	712. 34	. 60	1. 2824
13	. 00102	. 0119	. 086	. 130	. 66	312	. 139	136. 60	1. 37	. 5220
15	. 00118	. 0199	. 059	. 147	. 40	360	. 074	483. 98	. 73	1. 0697
17	. 00134	. 0160	. 084	. 168	. 50	409	. 116	195. 79	1. 15	. 6565
19	. 00150	. 0201	. 074	. 172	. 43	457	. 092	310. 54	. 91	. 8586
21	. 00165	. 0098	. 169	. 175	. 96	505	. 300	178. 10	1. 20	. 5768
23	. 00181	. 0249	. 073	. 189	. 39	553	. 081	402. 91	. 80	1. 0132
25	. 00197	. 0266	. 074	. 204	. 36	601	. 080	415. 42	. 79	1. 0413
27	. 00212	. 0203	. 105	. 195	. 54	649	. 130	158. 37	1. 28	. 6145
29	. 00228	. 0295	. 077	. 250	. 31	697	. 079	421. 13	. 78	1. 0662
31	. 00244	. 0230	. 106	. 286	. 37	745	. 123	174. 73	1. 21	. 6589
33	. 00260	. 0228	. 114	. 250	. 46	793	. 133	150. 30	1. 71	. 4660
35	. 00275	. 0299	. 092	. 260	. 35	841	. 094	301. 45	. 92	. 9044
37	. 00292	. 0240	. 121	. 225	. 54	889	. 138	139. 50	1. 36	. 5928
39	. 00307	. 0284	. 108	. 207	. 52	937	. 113	207. 84	1. 11	. 7444
41	. 00323	. 0206	. 157	. 265	. 59	985	. 192	71. 89	1. 89	. 4147

F.—*Summary of field data for overland flow sites*—Continued

Pole Creek Site 3

[I=8.50 in. per hr; R=4.5 in. per hr; S=0.2080 ft per ft; T=13° C; $\nu=1.31\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0. 00010	0. 0051	0. 020	0. 097	0. 21	32	0. 050	656. 71	0. 63	0. 9041
3	. 00031	. 0093	. 034	. 101	. 33	95	. 061	441. 40	. 76	. 9004
5	. 00052	. 0083	. 063	. 160	. 39	159	. 121	112. 76	1. 51	. 4467
7	. 00073	. 0128	. 057	. 116	. 49	223	. 089	211. 09	1. 11	. 6565
9	. 00094	. 0103	. 091	. 242	. 38	286	. 158	66. 64	1. 97	. 3559
11	. 00115	. 0243	. 047	. 184	. 26	350	. 053	584. 43	. 66	1. 5421
13	. 00135	. 0151	. 090	. 190	. 47	414	. 129	100. 55	1. 60	. 4661
15	. 00156	. 0200	. 078	. 147	. 53	477	. 097	175. 24	1. 21	. 6448
17	. 00177	. 0142	. 125	. 173	. 72	541	. 184	48. 93	2. 30	. 3216
19	. 00198	. 0329	. 060	. 182	. 33	605	. 058	486. 42	. 73	1. 1663
21	. 00219	. 0193	. 113	. 182	. 62	668	. 144	80. 42	1. 79	. 4340
23	. 00240	. 0350	. 069	. 177	. 39	732	. 065	399. 66	. 80	1. 0684
25	. 00261	. 0313	. 083	. 201	. 41	795	. 083	242. 27	1. 03	. 8168
27	. 00281	. 0235	. 120	. 250	. 48	859	. 138	87. 88	1. 71	. 4689
29	. 00302	. 0356	. 085	. 184	. 46	923	. 079	264. 63	. 99	. 8717
31	. 00323	. 0338	. 096	. 187	. 51	986	. 092	198. 16	1. 14	. 7482
33	. 00344	. 0299	. 115	. 267	. 43	1050	. 117	121. 14	1. 46	. 5732
35	. 00365	. 0428	. 085	. 267	. 32	1114	. 073	315. 92	. 90	. 9825
37	. 00386	. 0433	. 089	. 200	. 45	1177	. 075	292. 89	. 94	. 9476
39	. 00406	. 0436	. 093	. 238	. 39	1241	. 079	268. 94	. 98	. 9090
41	. 00427	. 0400	. 107	. 238	. 45	1304	. 094	187. 90	1. 17	. 7491
43	. 00448	. 0556	. 081	. 312	. 26	1368	. 060	458. 57	. 75	1. 2872
45	. 00469	. 0475	. 099	. 288	. 34	1432	. 080	261. 26	. 99	. 9091
47	. 00490	. 0441	. 111	. 225	. 49	1495	. 093	191. 43	1. 16	. 7686

New Fork River Site 1

[I=8.50 in. per hr; R=4.5 in. per hr; S=0.1000 ft per ft; T=13° C; $\nu=1.31\times10^{-5}$ sq ft per sec]

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
1	0. 00010	0. 0018	0. 058	0. 000	----------	32	0. 240	13. 83	4. 32	0. 1212
3	. 00031	. 0070	. 045	. 110	0. 40	95	. 094	90. 25	1. 69	. 3884
5	. 00052	. 0104	. 050	. 169	. 30	159	. 087	106. 74	1. 55	. 4510
7	. 00073	. 0139	. 052	. 223	. 24	223	. 078	129. 91	1. 41	. 5224
9	. 00094	. 0138	. 068	. 261	. 26	286	. 102	76. 88	1. 83	. 4014
11	. 00115	. 0178	. 064	. 261	. 25	350	. 085	110. 56	1. 53	. 5023
13	. 00135	. 0176	. 077	. 286	. 27	414	. 102	76. 47	1. 84	. 4169
15	. 00156	. 0255	. 061	. 261	. 23	477	. 068	174. 81	1. 21	. 6703
17	. 00177	. 0203	. 077	. 273	. 28	541	. 095	88. 20	1. 71	. 4584
19	. 00198	. 0195	. 102	. 317	. 32	605	. 128	48. 76	2. 30	. 3885
21	. 00219	. 0209	. 105	. 375	. 28	668	. 128	49. 11	2. 29	. 3438
23	. 00240	. 0233	. 103	. 465	. 22	732	. 119	56. 69	2. 13	. 3760
25	. 00261	. 0269	. 097	. 375	. 26	795	. 104	73. 95	1. 87	. 4400
27	. 00281	. 0221	. 133	. 402	. 33	859	. 158	30. 59	2. 90	. 2738
29	. 00302	. 0233	. 130	. 375	. 35	923	. 150	35. 68	2. 69	. 2983
31	. 00323	. 0215	. 150	. 429	. 35	986	. 181	24. 55	3. 24	. 2442
33	. 00344	. 0283	. 122	. 438	. 27	1050	. 127	49. 38	2. 29	. 3624
35	. 00365	. 0385	. 095	. 500	. 19	1114	. 085	110. 59	1. 53	. 5712
37	. 00386	. 0200	. 193	. 514	. 37	1177	. 240	13. 86	4. 31	. 1813
39	. 00406	. 0219	. 186	. 550	. 34	1241	. 221	16. 38	3. 97	. 2001
41	. 00427	. 0263	. 162	. 625	. 26	1304	. 176	25. 69	3. 17	. 2585
43	. 00449	. 0214	. 209	. 714	. 29	1368	. 252	12. 57	4. 53	. 1746

F.—*Summary of field data for overland flow sites*—Continued

Downslope distance (ft)	Discharge, q (cfs per ft)	Average depth, D (ft)	Mean velocity, V (fps)	Surface velocity, V_s (fps)	Velocity ratio, $\frac{V}{V_s}$	Reynolds number, **R**	Froude number, **F**	Darcy-Weisbach friction factor, f_f	Chezy coefficient, C	Manning resistance coefficient, n
New Fork River Site 2										
[I=8.08 in. per hr; R=4.1 in. per hr; S=0.0290 ft per ft; T=13° C; $\nu=1.31\times10^{-5}$ sq ft per sec]										
1	0.00009	0.0155	0.006	0.042	0.15	29	0.009	3112.50	0.29	2.6007
3	.00028	.0114	.025	.067	.38	87	.041	136.25	1.38	.5175
5	.00047	.0155	.031	.125	.25	145	.043	123.66	1.44	.5191
7	.00066	.0341	.020	.163	.12	203	.019	669.98	.62	1.3777
9	.00085	.0111	.077	.163	.47	261	.129	14.02	4.29	.1653
11	.00104	.0124	.084	.184	.46	319	.133	13.07	4.44	.1625
13	.00123	.0148	.083	.160	.52	377	.120	15.90	4.02	.1845
15	.00142	.0280	.051	.146	.35	435	.054	81.05	1.78	.4636
17	.00161	.0164	.098	.158	.62	493	.104	12.65	4.51	.1676
19	.00180	.0234	.077	.223	.35	551	.089	29.41	2.96	.2710
21	.00199	.0294	.068	.190	.36	609	.070	47.78	2.32	.3591
23	.00218	.0296	.074	.204	.36	664	.075	40.71	2.52	.3314
25	.00237	.0154	.154	.232	.66	724	.219	4.84	7.29	.1026
27	.00256	.0664	.039	.183	.21	782	.026	332.91	.88	1.0847
29	.00275	.0398	.069	.207	.33	840	.061	62.27	2.03	.4309
31	.00294	.0250	.118	.429	.28	898	.131	13.48	4.37	.1856
33	.00313	.0418	.075	.429	.18	956	.065	65.66	2.15	.4108
35	.00332	.0706	.047	.244	.19	1014	.031	238.74	1.04	.9281
37	.00351	.0945	.037	.101	.37	1072	.021	510.13	.71	1.4238
39	.00370	.0941	.039	.071	.55	1130	.023	455.15	.75	1.3450
41	.00389	.0486	.080	.103	.78	1188	.064	56.58	2.13	.4246
43	.00408	.0905	.045	.125	.36	1246	.026	332.37	.88	1.1421
Boulder Lake Site 1										
[I=8.50 in. per hr; R=4.5 in. per hr; S=0.1880 ft per ft; T=10° C; $\nu=1.41\times10^{-5}$ sq ft per sec]										
1	0.00010	0.0026	0.040	0.082	0.49	30	0.139	78.31	1.81	0.3067
3	.00031	.0144	.022	.090	.24	89	.032	1481.29	.42	1.7743
5	.00052	.0025	.208	.129	.61	148	.153	2.78	9.61	.0575
7	.00073	.0164	.045	.129	.35	207	.061	401.10	.80	.9439
9	.00094	.0188	.050	.130	.38	266	.064	365.66	.84	.9220
11	.00115	.0206	.056	.165	.34	325	.068	322.73	.89	.8795
13	.00135	.0146	.093	.165	.56	384	.135	82.11	1.77	.4187
15	.00156	.0103	.152	.132	1.14	443	.263	21.68	3.45	.2030
17	.00177	.0055	.322	.136	2.37	503	.765	2.57	10.02	.0629
19	.00198	.0125	.158	.177	.89	562	.250	24.13	3.27	.2212
21	.00219	.0195	.112	.181	.62	621	.142	75.02	1.85	.4200
23	.00240	.0180	.133	.141	.94	680	.175	49.21	2.29	.3356
25	.00261	.0148	.176	.130	1.35	739	.255	23.14	3.34	.2227
27	.00281	.0343	.082	.197	.42	798	.078	247.05	1.02	.8374
29	.00302	.0191	.158	.236	.67	857	.202	36.96	2.64	.2938
31	.00323	.0310	.104	.173	.60	916	.104	138.28	1.37	.6159
33	.00344	.0204	.169	.252	.66	975	.208	34.76	2.72	.2881
35	.00365	.0389	.094	.268	.35	1035	.084	214.12	1.10	.7959
37	.00386	.0293	.132	.263	.50	1094	.135	81.94	1.77	.4697
39	.00406	.0349	.116	.270	.43	1153	.110	124.75	1.44	.5967
41	.00427	.0422	.101	.336	.30	1212	.087	199.55	1.14	.7791
43	.00448	.0281	.160	.338	.47	1271	.168	53.49	2.19	.3840
Boulder Lake Site 2										
[I=8.08 in. per hr; R=4.1 in. per hr; S=0.3315 ft per ft; T=10° C; $\nu=1.41\times10^{-5}$ sq ft per sec]										
1	0.00009	0.0008	0.119	.051	2.35	27	0.739	4.86	7.28	0.0628
3	.00028	.0026	.110	.057	1.92	81	.378	18.52	3.73	.1491
5	.00047	.0051	.093	.073	1.28	135	.229	50.35	2.26	.2751
7	.00066	.0041	.162	.101	1.61	188	.446	13.34	4.39	.1366
9	.00085	.0139	.061	.198	.31	242	.092	314.84	.91	.8127
11	.00104	.0123	.085	.204	.42	296	.135	145.71	1.33	.5419
13	.00123	.0128	.096	.198	.49	350	.150	117.62	1.48	.5009
15	.00142	.0144	.099	.258	.38	404	.145	125.71	1.43	.5170
17	.00161	.0139	.116	.365	.32	458	.174	88.06	1.71	.4301
19	.00180	.0178	.101	.500	.20	512	.134	148.12	1.32	.5811
21	.00199	.0215	.093	.625	.15	565	.111	213.64	1.10	.7203
23	.00218	.0129	.169	1.125	.15	619	.263	38.48	2.59	.2808
25	.00237	.0185	.128	1.333	.10	673	.166	96.12	1.64	.2424

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