COLORADO STATE UNIVERSITY
EXPERIMENTAL RAINFALL-RUNOFF FACILITY

Summary of Experiments and preliminary Results of an Experimental Investigation on the Kinematic Theory of Overland Flow

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Initial Data Analyses

The first series of experimental runs were performed during Sept. and Oct., 1969. The primary objective of these experiments was to test the hypothesis that the kinematic wave equations are an adequate mathematical model for overland flow on a linearly converging surface. A second objective was to investigate the effect of spatially non-uniform roughness on the watershed response. The experimental runs completed in 1969 are listed in Table I.

The mathematical model upon which the data analysis is based is the kinematic model for overland flow on a converging surface (Woolhiser, 1969). A definition sketch of the problem is shown in Fig. (1). The equations describing converging overland flow are:

The continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial \, uh}{\partial \, x} = q + \frac{uh}{(L_o - x)} \qquad (1)$$

And the friction relationship

$$u = \partial h^{N-1} \qquad (2)$$

where u is the local velocity, h is the local depth L_o is the radius, q is the lateral inflow rate and ∂ and N are parameters. If the Chezy formula is used $\partial = C\sqrt{S_o}$ and $N = 3/2$ when S_o is the slope and C is the Chezy coefficient.

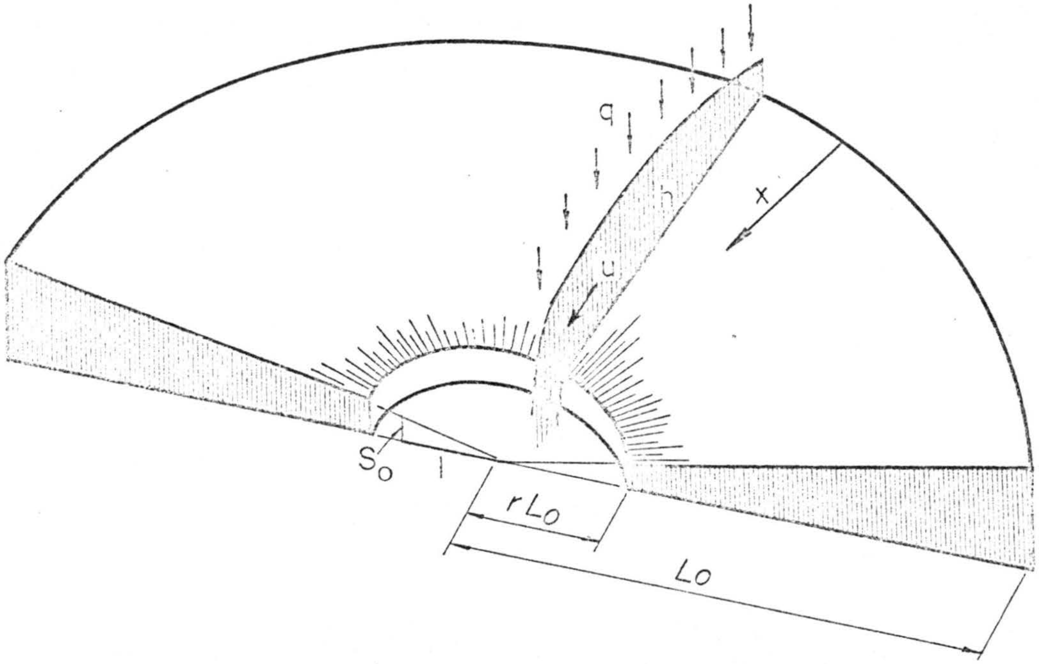


Figure 1. Geometry of Converging Section.

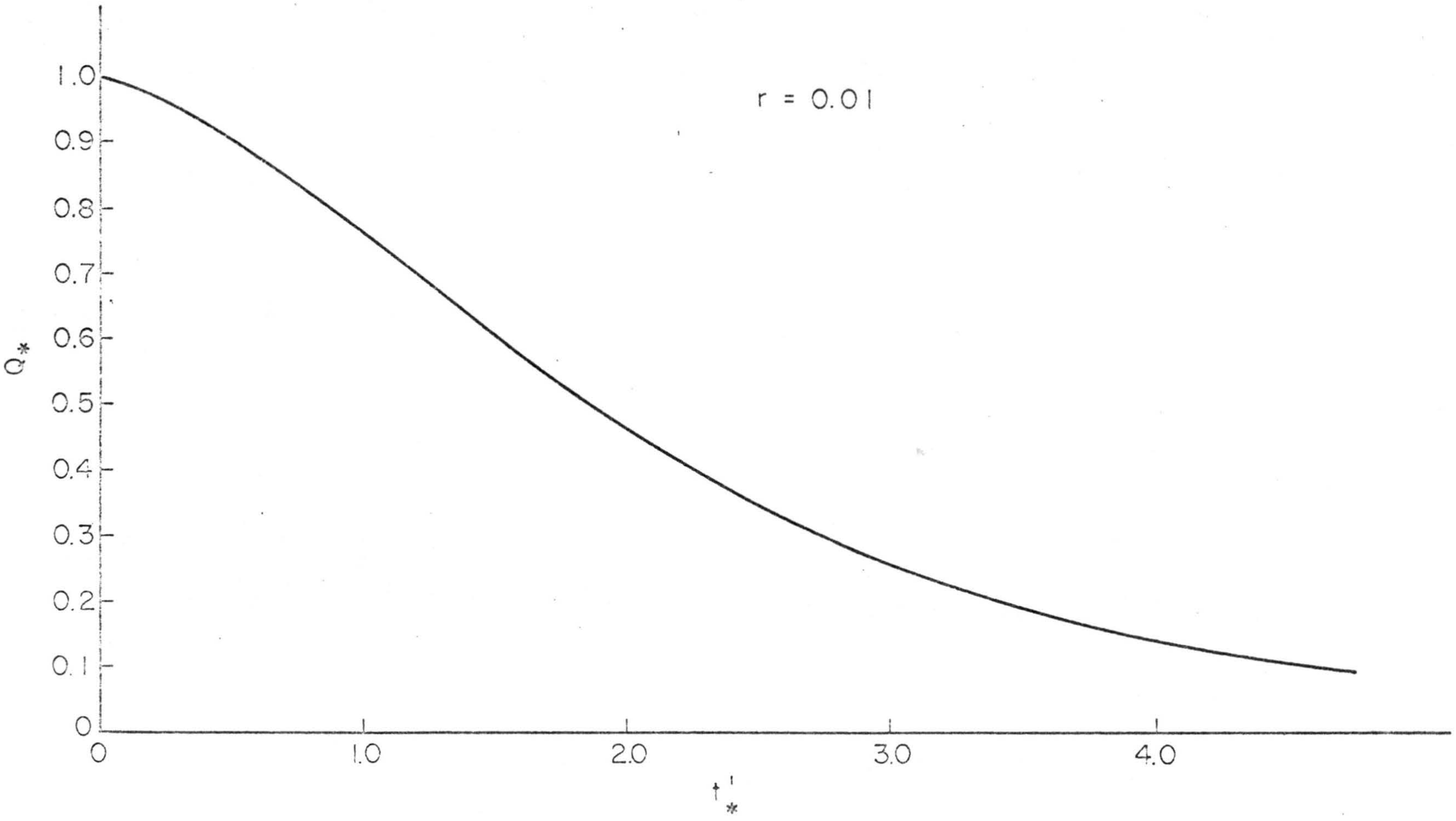


Figure 2. Dimensionless Recession Hydrograph.

where Q_* is the dimensionless discharge, r is the covergence parameter, X_o is the origin of a characteristic beginning at, the time inflow stops in the region $0 < X_o < 1$, t_*' is the time after lateral inflow stops until a discharge Q_* appears at the downstream boundary and N is 3/2 for the Chezy equation. This recession hydrograph is shown in Fig. (2). In Fig. (2) note that $t_*^1 = 1$ when $Q_* = 0.76$, $t_*^1 = 2$ when $Q_* = 0.46$ and $t_*^1 = 3$ when $Q_* = 0.26$. Let the time after lateral inflow stops until the dimensionless discharge Q_* is reached be designated as t_{Q_*}. Then an estimate of T_o is given by the average:

$$T_o = 1/3 \left[t_{0.76} + (1/2)\ t_{0.46} + (1/3)\ t_{0.26} \right] \qquad (7)$$

Normalizing times were computed using Eq. (7) and the experimental equilibrium hydrographs were normalized on this basis. Non-dimensional experimental hydrograph are compared with the solution to Eq. (3) in Fig. 3(a) and 3 (b). Agreement between the hydrographs appears quite good, however, the Chezy parameterestimated from Eq. (4) appears not to be constant depending only upon the surface characteristics but appear to vary with the equilibrium flow rate (see Fig. 4). This may be an indication that the Chezy formulation is not appropriate over the range of intensities tested. Undoubtedly flow is initially laminar for all cases and may become turbulent over a substantial portion of the surface as flow rates increase. The Manning formulation may give a more accurate representation for the rough surfaces and this formula will be used in future analysis.

The data analysis reported herein are not complete so no definite conclusions can be made. However, it appears that the Kinematic Model is accurate for the converging flow case with a slope of 5%. The problem of estimating roughness parameters is an important one and will be investigated throughly. The size of the experimental watershed makes it uniquely suitable for studying effects of spatially variable roughness. The results from the exploratory studies on effects of spatial variations in roughness will assist in the design of new experiments for next summer.

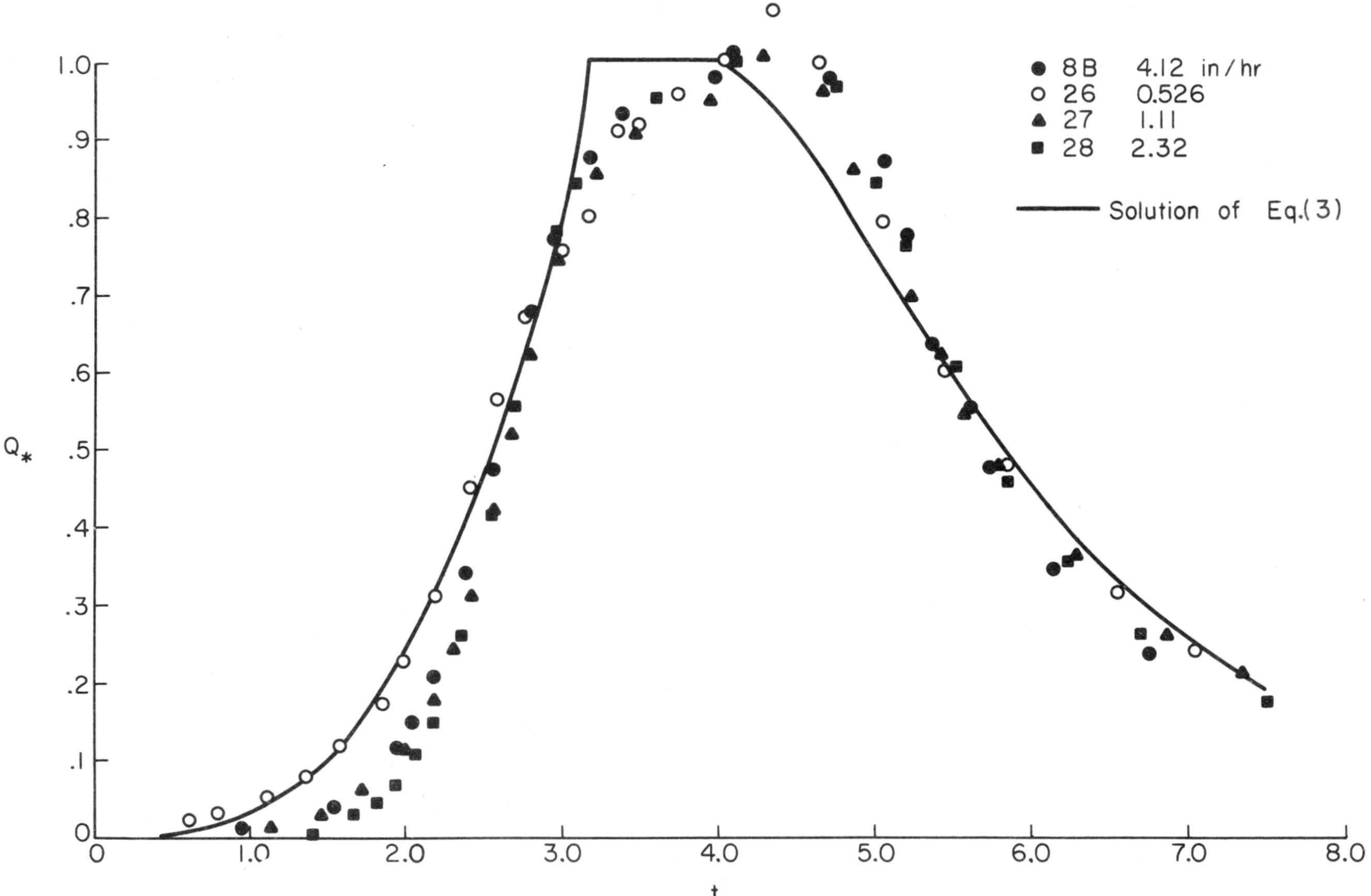


Figure 3A Theoretical and Observed Dimensionless Hydrographs for Butyl Surface

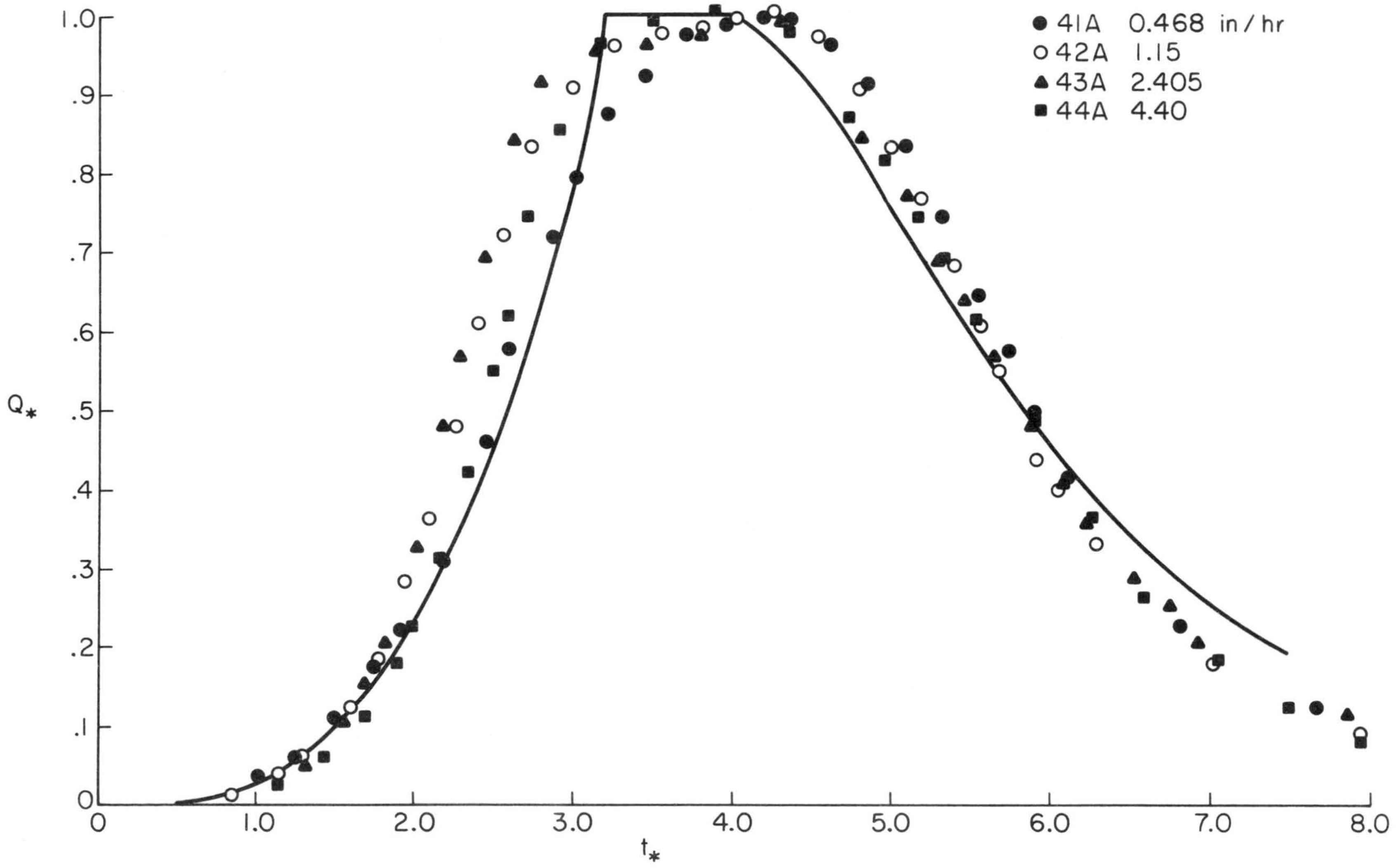


Figure 3B Theoretical and Observed Hydrographs for Graveled Surface

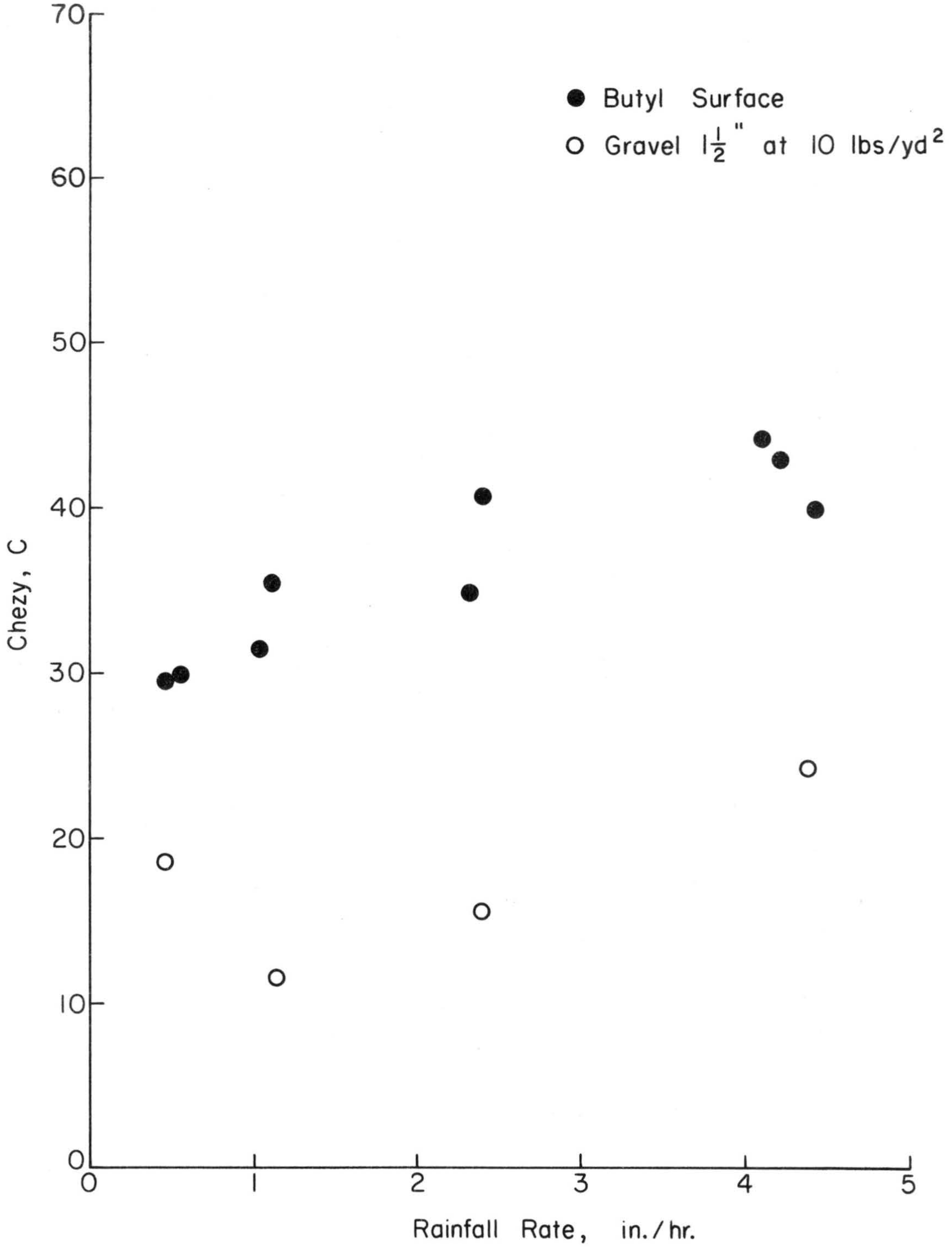
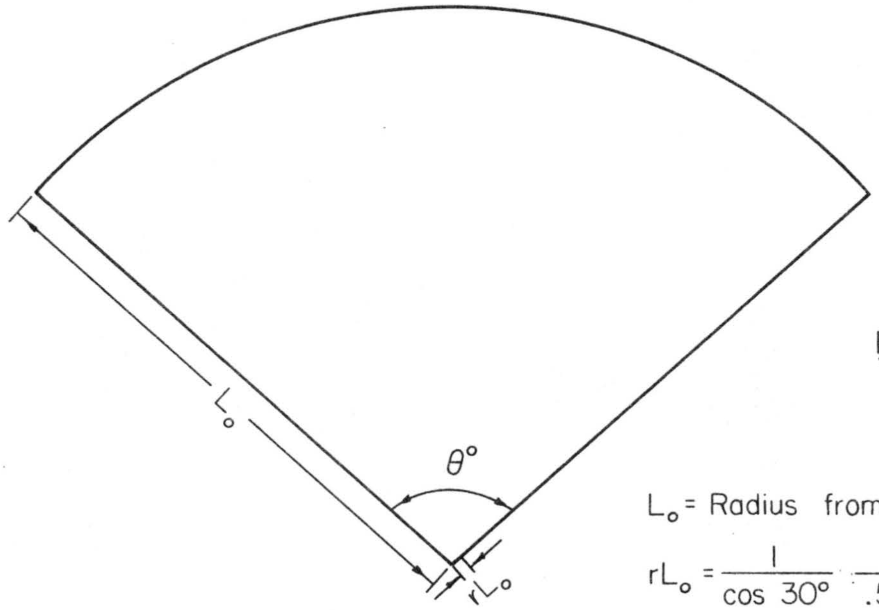
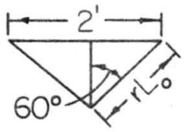


Figure 4 Chezy C vs Rainfall Rate



General Configuration



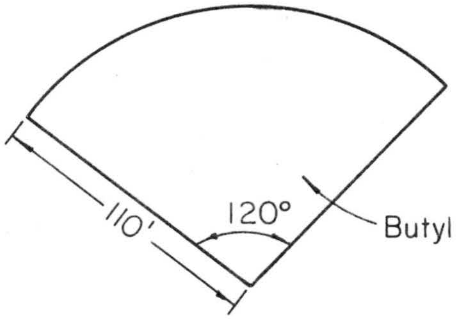
L_o = Radius from Outlet to Rim

$$rL_o = \frac{1}{\cos 30°} \quad \frac{1}{.557} = 1.17'$$

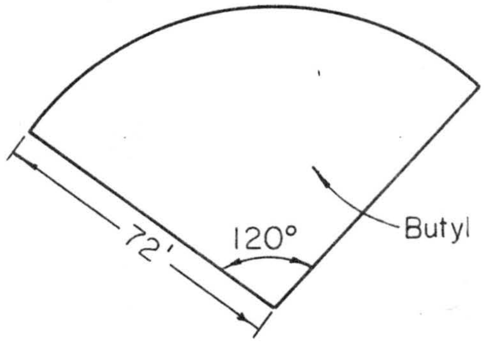
$$r_1 = \frac{1.17}{110} = .01063$$

$$r_2 = \frac{1.17}{72} = .0163$$

$$r_3 = \frac{1.17}{36} = .0325$$



Configuration 1



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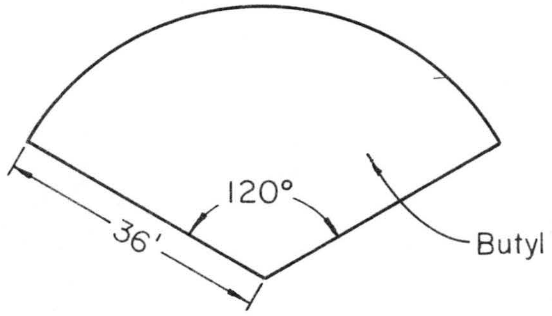

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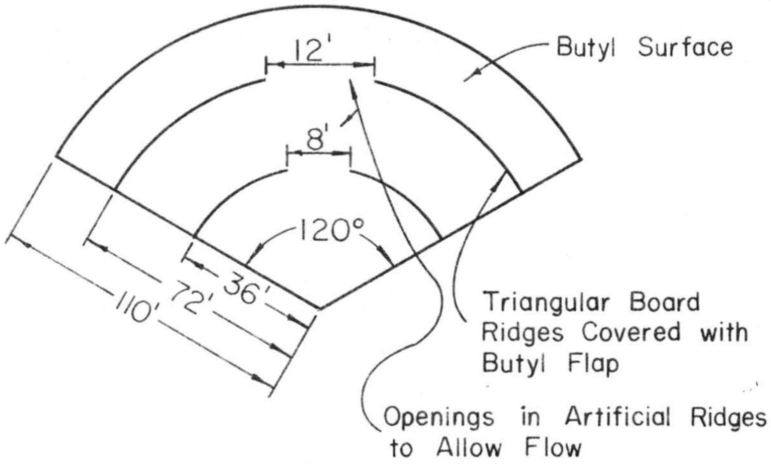

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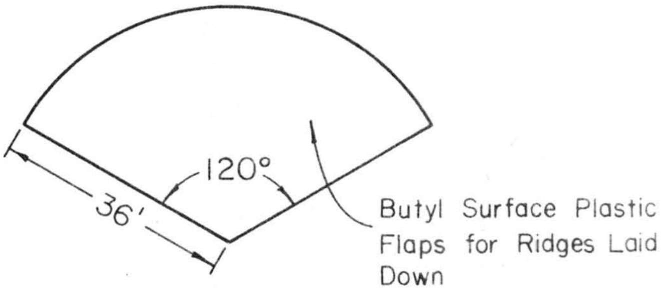

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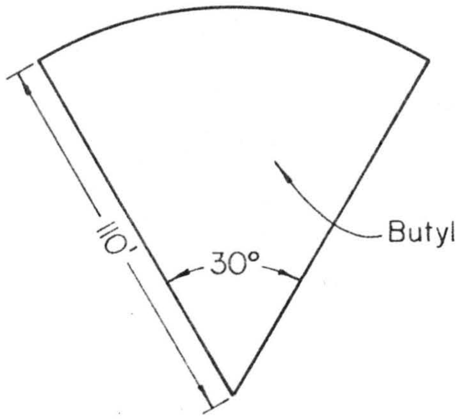

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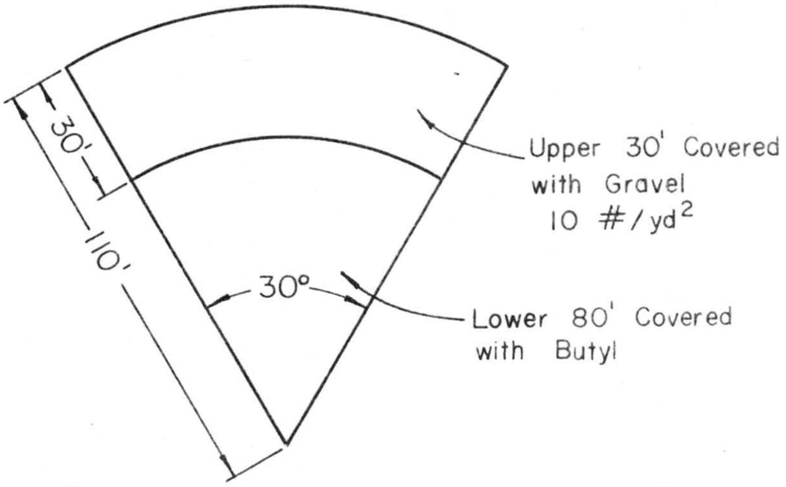

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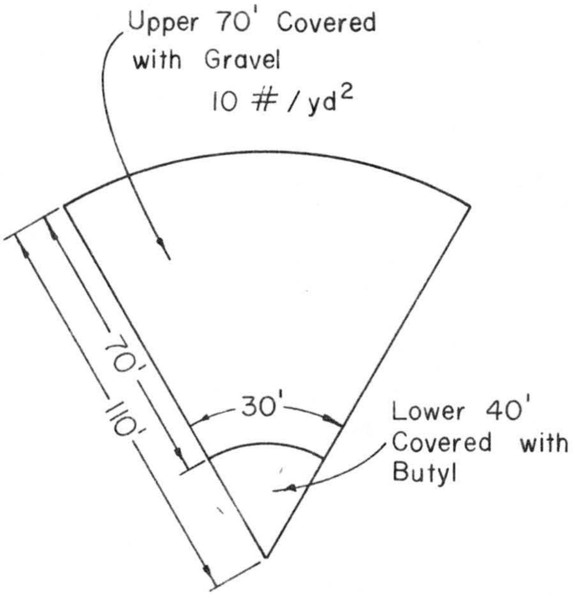

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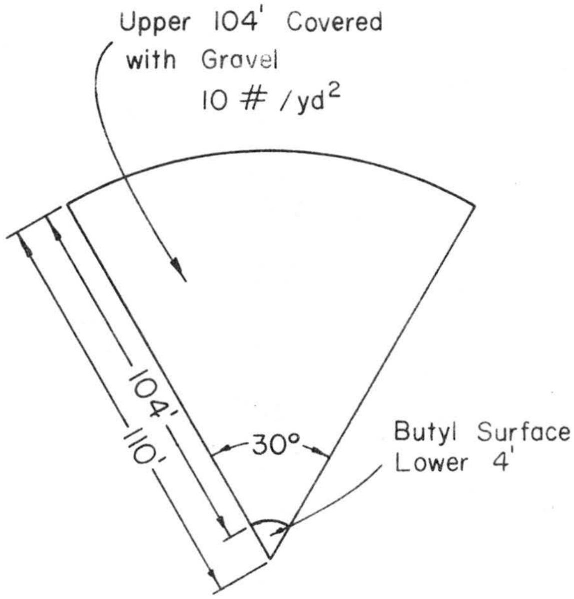

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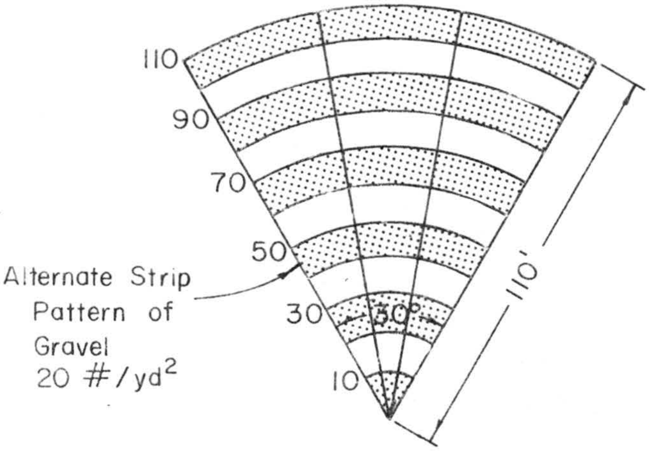

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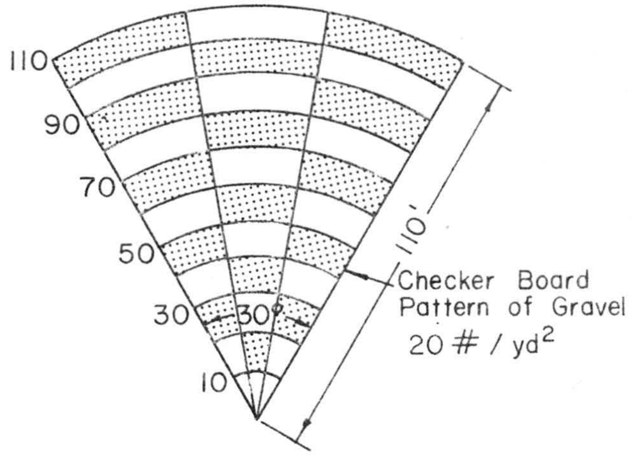

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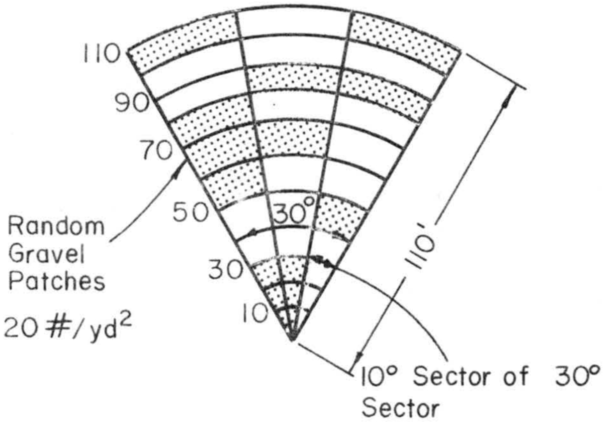

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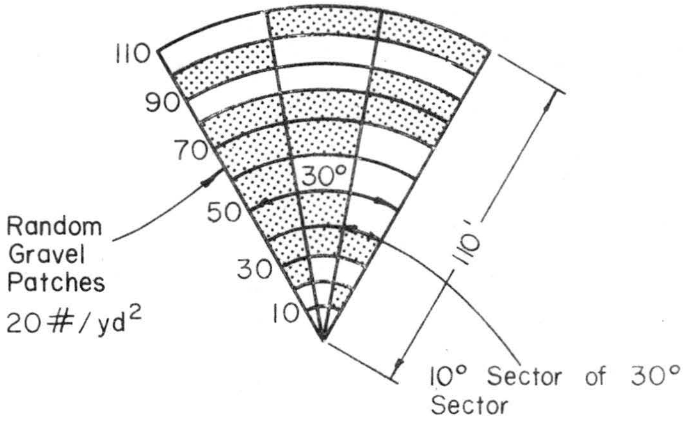

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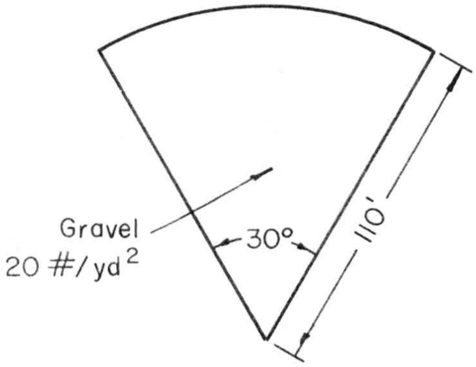

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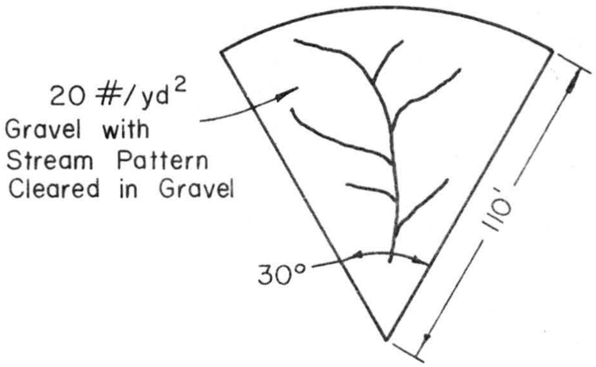

Configuration 15

TABLE I

Colorado State University
Experimental Rainfall-Runoff Facility

EXPERIMENTAL RUNS COMPLETED

Run No.	*Configuration	Surface	! Intensity	Duration-Secs.	Remarks
8A	1	Butyl	RYBG	300	Nozzle Pressure variation significant factor.
8B			RYBG	45	
			RYBG	600	
9	1	Butyl	R	30	
			R	60	
			RY.	60	
			RYG	60	
			R	60	
			RY	60	
10	1	Butyl	R	30	
			RYB	60	
			RYB	60	
			RY	60	
			R	60	
11A	1	Butyl	G	15	Few secs of B rathe than G at start of 11B.
				300	
			G	10	
11B				90	
12	1	Butyl	G	10	5mph wind
			G	900	
13	1	Butyl	R	10	
			R	60	
			RY	60	
			RYG	60	
			RYB	60	
14	1	-Butyl	R	20	
			RYB	60	
			RY	60	
			RYB	60	
15	1	Butyl	R	15	
			RYB	60	
			RY	60	
			RYB	60	
16	2	Butyl	RY	300	Windy day; test stilling well lag
17	2	Butyl	Y	135	
			Y	600	
			Y	20	
			Y	45	
			Y	15	
			Y	300	

Run No.	*Configuration	Surface	Intensity	Duration-Secs.	Remarks
18	2	Butyl	RY	30	
			RY	300	
			RY	75	
			RY	300	
19			RYG	20	
			RYG	300	
			RYG	60	
			RYG	300	
20	2	Butyl	RYGB	10	Very poor response.
			RYGB	300	
			RYGB	60	
			RYGB	300	
21	3	Butyl	RY	35	
			RY	300	
			RY	75	
			RY	300	
22	3	Butyl	RYG	22	
			RYG	300	
			RYG	75	
23	3	Butyl	RYGB	14	
			RYGB	300	
			RYGB	75	
24A	4	Butyl	RY	30	Problem with storage behind the border; should be filled with the wet down stage. Board ridges covered with butyl flap & center opening.
			RY	720	
24B			RY	30	
			RY	300	
24C			RY	30	
			RY	720	
25	4	Butyl	RYG	20	Board ridges covered with Butyl flap & center opening.
			RYG	720	
			RYG	120	
26	5	Butyl	R	20	Plastic flaps laid down.
			R	300	
			R	20	
			R	90	
27	5	Butyl	RY	30	Plastic flaps laid down.
			RY	300	
			RY	90	
28	5	Butyl	RYG	20	Plastic flaps laid down.
			RYG	300	
			RYG	10	
			RYG	75	
29	6	Butyl	R	85	Plastic flaps laid down.
			R	300	
			R	15	
			R	90	

Run No.	*Configuration	Surface	Intensity	Duration-Secs.	Remarks
30	6	Butyl	RY RY	360 90	Wind calm.
31	6	Butyl	RYG RY	300 75	Surface wet evaporation no wet down.
32	6	Butyl	RYBG RYBG	300 45	No wet down needed
33	7	Gravel & Butyl	R R	420 90	Gravel$_2$for top 30' 10#/yd^2
34	7	Gravel & Butyl	RY RY	300 90	Gravel$_2$for top 30' 10#/yd^2
35	7	GRavel & Butyl	RY RYG RYG	25 360 75	Gravel$_2$for top 30' 10#/yd^2
36	7	Gravel & Butyl	RYBG RYBG RYBG	10 240 45	Gravel$_2$for top 30' 10#/yd^2
37	8	Gravel & Butyl	R R	420 120	Gravel$_2$for top 70' 10#/yd^2
38	8	Gravel & Butyl	RY RY	60 120	Gravel$_2$for top 70' 10#/yd^2
39	8	Gravel & Butyl	RYG RYG	360 90	Gravel$_2$for top 70' 10#/yd^2
40	8	Gravel & Butyl	RYGB RYGB	300 60	Gravel$_2$for top 70' 10#/yd^2
41	9	Butyl & Gravel	R R	120 120	10#/yd^2 for top 104' Little or no wind.
42	9	Butyl & Gravel	RY RY	480 120	10#/yd^2 top 104'
43	9	Butyl & Gravel	RYG RYG	360 90	10#/yd^2 for top 104' wind calm
44A 44B	9	Butyl & Gravel	RYGB RYGB RYGB	300 60 60	10#/yd^2 for top 104' Run fouled up
45	10	Butyl & Gravel	RYG RYG RYG RYG	365 720 210 75	partial that becomes equilibrium
46	10	Butyl & Gravel	RYBG RYBG	300 90	
47	10	Butyl & Gravel	RY RY	360 120	

Run No.	*Configuration	Surface	!Intensity	Duration	Remarks
48	10	Butyl & Gravel	R	420	
			R	120	
49	11	Butyl & Gravel	RYG	720	
			RYG	90	
50	11	Butyl & Gravel	R	420	Repeat partial equilibrium
			R	120	
			R	120	
51	11	Butyl & Gravel	RY	360	
			RY	120	
52	11	Butyl & Gravel	RYBG	305	
			RYBG	90	
53	12	Butyl & Gravel	R	540	
			R	120	
54	12	Butyl & Gravel	RY	360	wind calm
			RY	10	
			RY	120	
55	12	Butyl & Gravel	RYG	10	
			RYG	300	
			RYG	10	
			RYG	90	
56	12	Butyl & Gravel	RYGB	10	
			RYGB	300	
			RYGB	90	
57	13	Butyl & Gravel	R	420	
			R	120	
58	13	Butyl & Gravel	RY	10	
			RY	360	
			RY	120	
59	13	Butyl & Gravel	RYG	10	
			RYG	300	
			RYG	90	
60	13	Butyl & Gravel	RYBG	300	
			RYBG	90	
61	14	Butyl & Gravel	R	540	
			R	120	
62	14	Butyl & Gravel	RY	420	
			RY	120	
63	14	Butyl & Gravel	RYG	420	
			RYG	90	
64	14	Butyl & Gravel	RYGB	420	
			RYGB	90	
65	15	Butyl & Gravel	R	480	
			R	120	

Run No.	*Configuration	Surface	!Intensity	Duration	Remarks
66	15	Butyl & Gravel	RY RY	360 120	
67	15	Butyl & Gravel	RYG RYG	420 90	
68	15	Butyl & Gravel	RYGB RYGB	420 90	

* See attached Configuration sketches at end of Table 1.

! See attached coding Table 2 at end of Table 1.

Coding Scheme for Rainfall Intensity

CODE	RAINFALL INTENSITY
R	Approx. 0.5 inches per hour
RY	Approx. 1.0 inches per hour
RYG	Approx. 2.0 inches per hour
RYGB	Approx. 4.0 inches per hour

Equations (1) and (2) can be combined by eliminating u and written in the following dimensionless form:

$$\frac{\partial h*}{\partial t*} + Nh*^{N-1} \frac{\partial h*}{\partial x*} = q* + \left[\frac{(1-r)\ h*^{N}}{1-x*)1-r)} \right] \qquad (3)$$

where

$$h* = h/H_o \ , \quad t* = \frac{Lo\,(1-r)}{Vo}, \quad X* = \frac{x}{L\,(1-r)}$$

and

$$q* = ql_{qo} = \frac{q\, L_o\,(1-r)}{Ho\ Vo}$$

The normalizing quantities are defined as follows: H_o is the normal steady-state depth at $x = L_o(1-r)$ V_o is the normal steady-state velocity at $x = L_o(1-r)$, and $L_o(1-r)$ is the length of the converging section.

Equation (3) has only one parameter, r, which is related to the degree of convergence. This indicates that when r is constant and if the kinematic model is adequate there will be a unique equilibrium hydrograph if experimental data are normalized by dividing the discharge by the steady-state discharge and by dividing the observed time by a normalizing time t_o. The normalizing time will be chosen such that it minimizes an error criterion between observed and computed dimensionless hydrographs. In choosing such an optimized t_o we are in fact obtaining an optimized estimate of the Chezy parameter C through the following relationship:

$$C = \left[\frac{L_o\,(1-r)}{T_o} \right]^{3/2} (S_o\, Q_o)^{-1/2} \qquad (4)$$

Where Q_o is the steady-state discharge per foot of width at the outlet.

Two sets of experimental runs with different roughness but the same value of the parameter r have been analyzed so far. The series with a smooth butyl surface are 8B, 26, 27, and 28. The second series, runs 41A, 42A, 43A, and 44A, had a uniform layer of 1-1/2 diameter gravel spread over the butyl surface at a rate of approximately 10 lbs. per square yard.

Experimental runs were performed at each of four rainfall intensities and consisted of two parts: an equilibrium run to established the steady-state input rate and a partial equilibrium run. Each run was started with approximately the same initial condition by turning on the sprinklers for a short time to wet the surface before each test began. Because of the rapid response of the system, accurate timing is of utmost importance. Although the stage recording equipment at the H-flume measuring device had a time resolution of five seconds some of the early runs were subject to substantial timing errors because of procedural problems. These problems were eliminated after sufficient experience was gained and are not present after the first ten runs.

T_o was estimated from the recession side of the equilibrium hydrographs in the following manner. The discharges were first normalized by dividing by the steady state discharge. The analytical recession from equilibrium can be obtained in the following parametric form

$$Q_* = \frac{X_o\left[2-(1-r)\,X_o\right]}{(1+r)} \qquad (5)$$

$$t_*^{1} = \left(\frac{1+r}{r}\right)\frac{\frac{N-1}{N}\left\{\left[1-(1-r)\,X_o\right]^{\frac{2N-1}{N}} - (r)^{\frac{2N-1}{N}}\right\}}{(2N-1)\,(1-r)\left\{X_o\left[2-(1-r)\,X_o\right]\right\}^{\frac{N-1}{N}}} \qquad (6)$$