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# Construction, Instrumentation, and Preliminary Verification of a Physical Hydrologic Model

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# CONSTRUCTION, INSTRUMENTATION, AND PRELIMINARY

# VERIFICATION OF A PHYSICAL HYDROLOGIC MODEL

by

Donald L. Chery, Jr.

# ABSTRACT

From theoretical considerations involving a rationalized

dimensional analysis of the rainfall-runoff phenomena, dimensionless

products of the pertinent variables are derived.  These dimensionless

products guided the design and construction of a rainstorm simulator

and topographic model.  The design and construction of these two basic

elements of the physical hydrologic model are described.  A description

of the instrumentation and several relevant calibration tests is followed

by a discussion of two preliminary verification test sets.  The tests

indicated that some necessary refinements in equipment  and instru-

mentation were needed before more precise experimental data could

be obtained.  Further, the tests produced results which encouraged

further investigation and would guide the design of further experimental

tests.

# PREFACE

This report comprises a thesis submitted by the author to Utah

State University in partial fulfillment of the requirements for the degree

of Master of Science in Civil Engineering. The author is Hydraulic

Engineer, USDA Agricultural Research Service, located at the

Southwest Watershed Research Station, Tucson, Arizona.

The physical hydrologic model study was a cooperative endeavor

of the Agricultural Research Service, Soil and Water Conservation

Research Division, and the Utah Water Research Laboratory, Utah

State University. The Agricultural Research Service initiated and

funded the project. Utah State University provided laboratory space

and facilities along with professional consultation and direction.

Special recognition must be accorded to R. V. Keppel, Research

Center Leader, Agricultural Research Service, who conceived the

initial project idea and promoted it. Of the Utah State University

faculty, Dr. Jay M. Bagley gave the patient and conscientious review

of research and writing that brought the project to its first terminal

point as reported herein.

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# INTRODUCTION AND OBJECTIVES

The occurrence of precipitation, its dispersion upon the earth's surface and its subsequent travels has become a grave concern to man who is so utterly dependent upon this commodity. The great amount of current and proposed research is evidence of the imperfect knowledge about the variables and their relationships on a watershed. The study of the rainfall-runoff relations has been approached in many ways. Within the last few years, the use of similitude and physical models has been proposed to augment these studies. The development of this approach has been retarded by the complexity of the physical phenomena and the limited understanding of applying the similitude theory. Nevertheless, there has been at least one attempt at physically modeling the hydrologic cycle, and the results of this effort were encouraging.

In the present study, a physical hydrologic model designates a mechanical apparatus which applies a simulated rainstorm to some sort of scaled watershed or natural basin. Such a physical model made by Mamisao (1952) was, as far as is known, the first attempt at this novel approach to hydrologic analysis. And, to the best of Mamisao's knowledge,

> ...no work of this kind has been done yet; and this is verified by statements of Jones (17), Ree (28), Blaisdell (3) and Oliver (26). All studies with the use of models that have been so far conducted have dealt primarily with hydraulic problems of river flows, but none with hydrologic behavior of watersheds. (Mamisao, 1952, p. 2)

No reference to physical hydrologic modeling, other than that of Mamisao, was located at the commencement of this study in 1960. Since that time, there have been many inquiries from individuals, both within the United States and in foreign countries, asking for information about the study and indicating similar interests. At present, the considerable number of hydrologic investigations being made with analogue and digital computer models is not directly related to a physical model study. Eventually, however, the exchange and feedback of information and knowledge from these various approaches will all contribute to understanding the hydrologic phenomenon.

If physical hydrologic modeling can be made feasible, it has some appealing features; the most appealing being that such a model would allow the investigator a degree of control not possible over a natural event. With a model, various combinations of the hydrologic variables could be held constant, measured, or eliminated so that their individual influences could be studied. Further, the time scale could be reduced, which would permit the investigation of many more events than would be possible with prototype investigations. These advantages, however, are contingent upon whether or not hydrologic modeling can be satisfactorily accomplished. Are the technological and theoretical means at hand to make a useful and meaningful physical hydrologic model? It will be tacitly assumed that the technological means are available. The first concern is with the interpretation of the model performance.

Is it possible to simulate prototype hydrologic mechanisms with a model

and to interpret the performance of the model as specific action in the

prototype? The question can only be answered by attempting the very

thing questioned. Mamisao (1952) has made an initial attempt and

encourages further such endeavors by concluding:

> It was found that there was a close similarity between
> the two hydrographs in each of the three rainfalls. These
> results strongly indicated the possibility of using the
> scale-model method in making hydrologic studies of water-
> sheds. (Mamisao, 1952, p. 100)

Encouraged by the research value of such models, but well aware

of the many difficulties to be surmounted, the author under-

took to further evaluate the possibility of physical hydrologic models

for basic hydrologic studies. The specific objectives of the study were:

1. To design a physical hydrologic model which would

include a topographical model of a basin and a rainstorm

simulator.

2. To construct the topographical model and rainstorm

simulator with the necessary instrumentation to control,

measure, and evaluate the model performance.

3. To make preliminary verification studies.

# THEORETICAL CONSIDERATIONS FOR MODEL DESIGN

Since its development, dimensional analysis has become an important tool in the analysis of physical phenomena as well as a guide in the design and interpretation of models. Logically then, dimensional analysis was employed to guide the design and to assist in the interpretation of the experimental results of this study.

Discharge from a watershed is governed by a complicated interaction of many variables. This interaction may be expressed by a functional relation of the form:

$$(Q_1, Q_2, Q_3, \ldots) = 0$$

The exact solution of the functional relationship between these many variables is not known, but as explained by Bridgman (1963, p. 81),

> Under these conditions dimensional analysis enables us to obtain certain information about the form of the results which could be obtained in practice only by experiments with an impossibly wide variation of the arguments of the unknown function. In order to apply dimensional analysis we merely have to know
> [1] what kind of physical system it is that we are dealing with and
> [2] what the variables are which enter the equation.

Also, the use of dimensional analysis assumes a complete equation; since dimensional analysis is valid only for complete equations. A complete equation is one in which the dimensional formulas of all the measured quantities and dimensional constants are known. Bridgman

(1963, p. 37) explains further that for the functional relation to be complete, it must be "of such a form that it remains true formally without any change in the form of the function when the size of the fundamental units is changed." To proceed in the analysis of the rainfall-runoff problem, three questions had to be considered:

(1) What was the physical system?

(2) What variables entered the functional relation?

(3) Would the functional relation be complete?

The discussion of each of these questions follows in the order in which they have been posed.

## Physical system

The objective of the study was to model a portion of a large natural flow system in which rain falls on a watershed and then either evapo-transpires, infiltrates, or accumulates on the ground. As the accumulation on the surface increases, storage fills, surface resistance is overcome, and the water moves over the surface to collect in small channels. The small channels convey the water to large channels until eventually the water flows past the outlet of the watershed. These phenomena have, for many years, been treated and studied under the discipline of hydrodynamics which is merely mechanics applied to liquids. Thus, the appropriate physical system for this problem is mechanics, with all the equations of mechanics applying to it.

## Variables

The most critical and difficult step in the analysis was the determination of the variables involved in the functional relation. As expressed by Ipsen (1960, p. 131).

> If one can decide what substantial variables are involved
> in a problem and can decide what dimensional relation-
> ships are pertinent, then the problem of determining what
> natural variables are appropriate for describing behavior
> is purely formal. But settling the initial question is often
> difficult.

Bridgman (1963, p. 48) has explained that an analysis is also concerned with "all the variables which can change in numerical magnitude under the conditions of the problem." These variables are of two kinds according to Bridgman--physical variables and dimensional constants. Physical variables are represented by numbers measuring certain physical quantities which may vary in magnitude over the domain to which the result applies. Other arguments in the functional relation may be of the nature of coefficients "which do not change in magnitude when the size of the fundamental measuring units changes." (Bridgman 1963, p. 49) Such coefficients have been defined as dimensional constants.

Criteria for selection of variables. How does one ascertain all the variables involved in a problem? In essence, this insight is gained through having a great amount of empirical experience with the phenomena.

> To answer this question (which variables are involved), one
> must understand enough about the problem to explain why and
> how the variables influence ¦ the phenomenon. Before one
> undertakes the dimensional analysis of a problem, he should
> try to form a theory of the mechanism of the phenomenon.
> Even a crude theory usually discloses the actions of the more

> important variables. If the differential equations that
> govern the phenomenon are available they show directly
> which variables are significant. (Langhaar, 1951, p. 14)

A review of many empirical and theoretical descriptions of the hydrologic

and hydraulic phenomena thus becomes necessary in order to ascertain

the pertinent variables. Such a review produces a myriad of variables

which have to be organized and scrutinized in some discriminating way

to reveal the relevant quantities. Such was the process employed--a

review of hydrologic studies and the variables, and scrutiny of the

tabulation for the relevant variables.

Variables associated with the rainfall-runoff process. One of the

earliest American investigators of rainfall-runoff relationships was

R. E. Horton who discussed the runoff phenomena as follows:

> It will readily be seen that for any given drainage basin
> the phenomena of direct surface runoff are governed
> jointly by the storage equation and by the law expressing
> the relation between the depth of surface detention and the
> rate of channel inflow. (Horton, 1935, p. 5)

Horton theorized that six factors determine surface runoff flow. Three

of his factors are dependent on the rainstorm and three are dependent

on physical characteristics of the area. The rainfall factors are:

(1) intensity, (2) distribution, and (3) duration. The physical factors

are: (1) initial detention, including depression storage, (2) velocity of

overland flow, and (3) infiltration capacity. If an area included both

surface flow and channel flow, Horton included the following additional

factors: (1) groundwater flow; (2) channel detention; (3) modification or

flattening of flood waves due to momentum, gravitation, and friction in traveling downstream; and (4) combination of wave crests from different subareas.

Horton's studies were only the beginning of many attempts to quantify and describe the runoff from a watershed. Many empirical developments of runoff relations are summarized by V. T. Chow (1962). His class of Elaborate Discharge Formulas contains the type of information desired for this analysis. As noted by Chow (1962, p. 67), "these formulas are generally developed by the rational formula or by the method of multiple correlation." The general form of the formulas is ---$Q_o = f(Q_1, Q_2, ...)$. Chow has listed 31 formulas in this group, but elimination of equations involving only one or two variables leaves 16 equations, listed in Appendix B, which give an indication of the rainfall-runoff variables considered important by several different investigations.

The Soil Conservation Service has estimated direct runoff by the relation

$$Q = \frac{(P - 0.2S)^2}{(P - 0.8S)}$$

in which

      Q  =  total direct runoff in inches (L)

      P  =  total storm rainfall in inches

      S  =  maximum potential difference between P and Q in

                   inches at the beginning of the storm

The SCS Engineering Handbook (Mochus, et al. n.d.) also comments that S is a function of (1) soil-water storage and (2) infiltration rates of the watershed. In making the determinations of Q for a given P by the plotted solution curves of the runoff equation (SCS Engr. Handbook, Figure 3.10-1), a specific curve is selected by giving consideration to the following factors:

1. Land use or cover

2. Treatment or practice (row, terrace, contoured, etc.)

3. Hydrologic conditions (relative stability of the ground surface)

4. Soil group (porous to impervious)

5. Antecedent soil moisture

Gray (1962) delineated the factors affecting runoff by analyzing three portions of the hydrograph. He divided the hydrograph into the rising limb, the crest segment, and the recession limb. He said that the rising limb represents the increase in discharge produced by an increase in storage or detention on the watershed. He contended that the rising limb is influenced by the distribution of the time-area histogram of the basin and the duration, intensity, and uniformity of the rain. In Gray's opinion, the peak represents the arrival of flow from the portion of the basin receiving the highest concentration of area-inches of runoff. The shape of the recession limb, according to Gray (1962, p.519), is "independent of time variations in rainfall or infiltration and is dependent essentially upon the physical features of

channel alone." In his discussion, Gray listed the topographical factors

which Sherman suggested as dominant.   They are:

1. Drainage, area, size, and shape

2. Distribution of the watercourses

3. Slope of the valley sides or general land slope

4. Slope of the main stream

5. Pondage resulting from surface or channel obstructions

   forming natural detention reservoirs

Gray followed his discussion with the development of a two-parameter

gamma function to describe the unit hydrographs of the watersheds he

picked for his analysis.   He contended that for the unit hydrograph of

a given basin, the gamma function parameters,

> ...are relatively independent of storm duration.  It would
> appear, therefore, that differences in the magnitude of
> these parameters for the unit hydrographs from different
> watersheds could be attributed mainly to differences in the
> physical characteristics of the watersheds.  (Gray, 1962,
> p. 533)

In the end, he related the gamma function parameters to (1) period of

rise, (2) length of the main stream, and (3) the channel slope.

Hickok, Keppel, and Rafferty (1959) reported a method of

hydrograph synthesis for small arid-land watersheds which

> ...involves (a) estimation of characteristic lag time from
> readily determined watershed parameters, (b) use of the
> watershed lag time to predict the hydrograph peak rate for
> an assumed total volume of runoff, (c) synthesizing the
> entire hydrograph using the lag time, the estimated peak
> rate, and a standard dimensionless hydrograph.  (Hickok,
> et al, 1959, p. 608)

In their analysis, the lag time was constant for a given watershed, independent of rainfall intensity, duration, and areal distribution. Thus, the lag time (time for limited block of intense rainfall to peak of hydrograph) was visualized as dependent on only physiographical characteristics of the watershed. By the technique of multiple correlation the authors related lag time to watershed area, average land slope, and drainage density for homogeneous semi-arid watersheds less than 1,000 acres in size. For larger watersheds with heterogeneous physiographic characteristics and where the rainfall excess comes from only a portion of the area, the lag time was related to length from outlet of the watershed to center of gravity of the source area, average land slope, and drainage density.

Reich (1962) pursued the description of the hydrograph by a mathematical function. He fitted a three-parameter Pearson type III function to the discharge hydrograph. The three parameters used to describe the function were $G$, the time between the center of mass of runoff and the peak discharge rate; $q_o$, the peak rate of discharge; and $W$, $W = \int_{-m}^{\infty} q \, dt$ = total runoff volume in inches. Reich undertook to relate these three parameters to variables involved in the rainfall-runoff phenomenon. From 36 variables, he made a stepwise multiple regression analysis and compared each equation with the others by the unbiased coefficient of determination. In this way he selected the variables which best described the parameters of the

mathematical model. These functions were:

$$W = 0.1315 - 0.5792 D_1 + 0.1902 T_9 + 0.4261 R_1$$

$$q_o = 0.2917 + 0.4600 R_{11} - 0.0004 T_3 + 0.00018 T_2$$

$$G = 7.314(10)^{-9} (D_5)^5 / (T_5)^{0.727} (T_6)^{0.939}$$

in which

$R_1$ = storm total, inches

$D_1$ = ASCE's infiltration capacity, inches per hour

$T_9$ = time of concentration from SCS nomograph, function of

    1. length of the longest waterway from the watershed outlet

       to the ridge, feet

    2. difference in elevation between the watershed outlet

       and the furthermost point, omitting drops due to

       gully overfalls, waterfalls, etc., feet

$R_{11}$ = $I_{30}$, the maximum average intensity for thirty consecutive

    minutes, inches per hour

$T_3$ = length along the main stream from the gaging station to

    the point nearest the mass center of the area, feet

$T_2$ = length of the longest collector from the gaging station

    carried out to the watershed perimeter, feet

$T_5$ = average main channel slope, feet per foot

$D_5$ = Cook's W, function of

    1. topographical relief

    2. soil infiltration

3. vegetal cover

4. surface storage

$T_6$ = average land slope, $S_a$, percent

Thus, the runoff hydrograph was correlated with six measurable variables of the watershed, two of the rainstorm, and three subjective measures of topographical relief, vegetal cover, and surface storage.

Chow (1962) developed a method to derive a design hydrograph which uses the parameters, (1) soil type, (2) vegetative cover, (3) surface condition, (4) total rainfall, (5) rainfall duration, (6) channel length, (7) channel slope, and (8) area. Chow also discussed the variables involved in rainfall-runoff relations and has summarized them as follows:

> From the hydrologic point of view, the runoff from a drainage basin can be considered as a product in the hydrologic cycle, which is influenced by two major groups of factors: climatic factors and physiographic factors. (Chow, 1962, p. 35)

Within the two major groups, Chow delineated the following components:

Climatic factors

    (1) Rainfall

        (a) Intensity

        (b) Duration

        (c) Time distribution

        (d) Areal distribution

        (e) Frequency

        (f) Geographic location

(2) Snow

(3) Evapotranspiration

Physiographic factors

(1) Basin characteristics

    (a) Geometric factors

        1. Drainage area

        2. Shape

        3. Slope

        4. Stream density

    (b) Physical factors

        1. Land use or cover

        2. Surface infiltration condition

        3. Soil type

        4. Geological condition, such as the permeability and capacity of groundwater reservoir

        5. Topographical condition, such as the presence of lakes and swamps

(2) Channel characteristics

    (a) Carrying capacity, considering size and shape of cross section, slope, and roughness

    (b) Storage capacity

(Chow, 1962, p. 35-36)

Additional variables may be added by a consideration of the overland and channel flow processes. Chow (1959) stated that, theoretically, the variables governing overland flow are the same as those governing ordinary hydraulic flow of the same type.

For turbulent overland flow, which is often the case in nature, these variables would be:

1. Slope of the ground

2. Surface roughness coefficient

3. Depth of water, which is dependent on the

(a) length of overland flow

(b) duration of excess rainfall

(c) rainfall intensity during the time of rainfall excess

(d) volume of depression storage

(e) infiltration capacity

(f) initial detention

If the overland flow is uniform, steady, and laminar, then it can be described by the equation,

$$q = gSy_m^3/3\nu$$

in which

$q$ = discharge per unit width

$g$ = acceleration of gravity

$S$ = ground slope

$y_m$ = mean water depth

$\nu$ = viscosity of the water (kinematic)

Chen (1962) developed differential equations of momentum and continuity for overland flow with the conditions and assumptions of: two dimensional flow, impervious surface, constant rainfall (spatially and temporally), constant slope, constant resistance, and turbulent flow. The general momentum equation is

$$\frac{\partial u}{\partial t} + \beta u \frac{\partial u}{\partial x} - (\beta - 1) \frac{u \partial y}{y \partial t} + g \cos \theta \left(1 + \frac{\zeta}{y}\right) \frac{\partial y}{\partial x} =$$

$$g (\sin \theta - S_f) + \left[ v \sec \phi \sin (\theta + \phi) - \beta u \right] \frac{r}{y}$$

The continuity equation is

$$\frac{\partial y}{\partial t} + y \frac{\partial u}{\partial x} + u \frac{\partial y}{\partial x} = r$$

These equations show the velocity, u, of the overland flow to be a function of

t = time

$\beta$ = momentum coefficient

x = length of flow

y = flow depth

g = acceleration of gravity

$\theta$ = ground slope

$\zeta$ = rainfall momentum flux

v = velocity of rainfall

$\phi$ = impinging angle of the rainfall in the direction of flow

r = rainfall intensity

$S_f$ = friction slope (proportional to surface roughness)

In a later development by Chen and Hansen (1963), the rainfall momentum was ignored and the ground slope, $S_o$, was considered as a good approximation of $\sin \theta$ ; but infiltration was considered, which gave differential equations of surface flow involving the quantity (r - i), rainfall intensity minus the infiltration rate.

Thomas (1937) gave a development of the differential equations for continuous unsteady flow in a rectangular channel. The equations are:

$$\frac{\partial y}{\partial x} + (\frac{v}{g}) \frac{\partial v}{\partial x} + \frac{1}{g}\frac{\partial v}{\partial t} = S_o - \frac{v^2}{C^2 R}$$

$$\frac{\partial y}{\partial t} + y \frac{\partial v}{\partial x} + v \frac{\partial y}{\partial x} = 0$$

in which

y = depth

x = length

v = velocity

g = acceleration of gravity

t = time

$S_o$ = slope of the bottom

C = Chezy's coefficient, a function of roughness and hydraulic

radius

R = hydraulic radius

The previous limitations of a rectangular channel have implied that channel shape is a variable affecting the flow. Neither is all channel flow continuous. Rather, discontinuous flows are the rule in the Southwest United States, a semiarid region, where the prototype watershed is located. In the ephemeral channels of this region, most flows are flash floods of overriding waves traveling rapidly down sandy, steep-banked channels. Rouse (1950) has explained that such wave fronts travel with a velocity proportional to $2\sqrt{gy}$ ( in which g is the acceleration of gravity and y is the depth of the flow); the component of the fluid weight in the direction of the channel slope, and the boundary resistance. The boundary resistance includes at least the shape and roughness of the channel and the perviousness of the channel bed, which governs the abstraction of water from the advancing wave. [1]

If there is sediment transport, other variables must be considered. Einstein and Chien (1954) included the following parameters in their model analysis of rivers with movable beds.

1.  D, grain diameter

2.  $(p_s - p_w)$ sediment density minus fluid density

3.  $q_B$, bed load rate

4.  $q_T$, total load rate

5.  $v_s$, sediment settling velocity

---

[1] ARS-SWCRD, Annual Report (1963, p. 78)

A listing by Murphy (1950) of the pertinent variables involved in open channel similitude studies also includes the fluid surface tension and viscosity.

Two previous dimensional analyses of the rainfall-runoff relationship are reported in the literature. An analysis by Erzen (Langhaar, 1951) included:

1.    Q, runoff at time t $(L^3T^{-1})$

2.    t, time (T)

3.    A, watershed area $(L^2)$

4.    H, the amount of rainfall (L)

5.    g, acceleration of gravity $(LT^{-2})$

6.    $\rho$, mass density of water $(ML^{-3})$

7.    $\nu$, kinematic viscosity of water $(L^2T^{-1})$

The model study by Mamisao (1952) designated the following as pertinent variables:

1.    Q, runoff $(L^3T^{-1})$

2.    I, rainfall intensity $(LT^{-1})$

3.    t, time (T)

4.    1, length (L)

5.    b, width (L)

6.    h, height (L)

7.    r, roughness of the surface and resistance of vegetation ( - )

8.    i, infiltration capacity of the soil $(LT^{-1})$

9. $\rho$, density of water $(ML^{-3})$

10. u, dynamic viscosity of water $(ML^{-1}T^{-1})$

11. $\delta$, surface tension of water $(MT^{-2})$

12. g, acceleration of gravity $(LT^{-2})$

The many analyses just reviewed have associated a great number of variables with the rainfall-runoff phenomenon. The many variables are summarized in Table 1.

Discussion of the variable tabulation and accumulation of the variables pertinent to the model study. In the tabulation the variables have been grouped in two major categories, rainstorm variables and physiographic variables. A third group includes fluid properties or those variables contributed by the theoretical analyses. The type of analysis in turn has been divided into two groups, empirical and correlation analyses, and theoretical and dimensional analyses. The number of variables used in each analysis has been summed beneath each category of variables. In a general way, the subtotal indicates the number of rainstorm and physiographic variables used by all analyses and also illustrates the group of variables introduced by the more theoretical considerations.

The tabulation (Table 1) illustrates two things--first, the complexity of the runoff phenomenon and second, the difficulty of describing the proper hydrologic parameters. As the tabulation is regarded further, it is realized that some of the terms are imprecise or that several are

**Table 1. Summary of variables associated with watershed discharge**

Column headers (left to right) under **Empirical and correlation analyses**: Rational Formula, Adams, Besson, Burkli-Ziegler & McMath, Craig, Cramer, Gregory & Arnold, Gregory, Grunsky, Hering, Lillie, Possenti, Protodiakonov, Rhind, USSR Academy, Walker, SCS, Chow; under **Theoretical and dimensional analyses**: Grey & Sherman, Grey (Gamma), Hickok ($T_L$), Reich, Horton, Overland flow, Channel flow, Erzen, Mamisao.

**Dependent variable**
1. Instant. discharge @ time, t, $Q_i$ — $L^3T^{-1}$
2. Max. or peak discharge, $Q_p$ — $L^3T^{-1}$
3. Total discharge/unit area, $Q_t$ — $L$

**Rainstorm variables**
1. Rainfall intensity @ time, t, $I_i$ — $LT^{-1}$
2. Intensity (average), $I_a$ — $LT^{-1}$
3. Intensity (maximum), $I_m$ — $LT^{-1}$
4. Intensity (max. in 30 min.), $I_{m30}$ — $LT^{-1}$
5. Rainfall duration, $t_R$ — $T$
6. Time distribution
7. Areal distribution
8. Total storm rainfall/area, R — $L$
9. Mean annual rainfall/unit area, $R_{ma}$ — $L$
10. Rainfall in 24 hr. period/area, $R_{24}$ — $L$
11. Critical time, cont. of rain, $t_{cr}$ — $T$
12. Ratio of rainfall to runoff, $R/Q_t$ — $-$
13. Rainfall momentum, $\zeta$ — $L$
14. Impinging angle, rainfall, $\phi$ — $-$
15. Snow & snow water content — $L$
(Subtotal of rainstorm variables) 2 1 1 1 1 1 3 1 2 0 1 1 1 1 2 1 1 4 2 0 0 2 3 4 - 1 1

**Physiographic variables**
1. Drainage area, A — $L^2$
2. Basin or ave. watershed slope, $S_w$ — $-$
3. Basin shape coefficient, S* — $-$
4. Basin width, W — $L$
5. Basin length, l — $L$
6. Dist., discharge pt. to cg. of area, $L_{cg}$ — $L$
7. Hilly area of basin, $A_H$ — $L^2$
8. Flat area of basin, $A_F$ — $L^2$
9. Ratio of total area to flat area, $A/A_F$ — $-$
10. Angle (°) @ outlet of basin sectors, $\theta$ — $-$
11. Sector length, $L\theta$ — $L$
12. Stream or drainage density, DD — $L$
13. Concentration time, $t_c$ — $T$
14. Period of rise, $t_p$ — $T$
15. Topo. coeff. (sur. cond., lake, etc.), — $-$
16. Surface roughness coeff., $r_s$ — $-$
17. Land use or veg. cover
18. Height or elev. difference, h — $L$
19. Channel slope, $S_c$ — $-$
20. Channel roughness, $r_c$ — $-$
21. Channel length, $L_c$ — $L$
22. Channel storage or detention
23. Initial detention
24. Volume of depression storage, $V_{ds}$ — $L^3$
25. Permeability (infiltration) rate, i — $LT^{-1}$
26. Impervious/pervious area — $-$
27. Shortest infiltration time
28. Antecedent moisture
29. Soil type
30. Soil or surface stability
31. Ratio of forested to total area — $-$
(Subtotal of physiographic variables) 2 2 3 3 2 5 6 3 4 3 2 3 4 3 7 6 5 6 6 3 5 7 4 4 3 3 5

**Variables intro. by theoretical or dimensional considerations**
1. Velocity of overland flow, v — $LT^{-1}$
2. Overland flow depth, y — $L$
3. Surface slope, $S_o$ — $-$
4. Length of overland flow, x — $L$
5. Time — $T$
6. Acceleration of gravity, g — $LT^{-2}$
7. Water density, $\rho$ — $ML^{-3}$
8. Water viscosity (dynamic), $\mu$ — $ML^{-1}T^{-1}$
9. Water viscosity (kinematic), $\nu$ — $L^2T^{-1}$
10. Water surface tension, $\sigma$ — $MT^{-2}$
11. Velocity of flow in channel, $v_c$ — $LT^{-1}$
12. Depth of channel flow, $y_c$ — $L$
13. Channel shape factor, $S_c$* — $-$
14. Hydraulic radius, R' — $L$
15. Perviousness of channel bed
16. Sediment grain diam., D — $L$
17. Sediment density, $\rho_s$ — $ML^{-3}$
18. Bed load rate, $q_B$
19. Total sed. rate, $q_T$
20. Sediment settling vel., $v_s$ — $LT^{-1}$
21. Combination of wave crests
22. Groundwater flow & reservoir
(Subtotal of additional variables) 0 0 0 0 1 0 1 0 0 1 0 0 2 0 0 0 0 0 0 0 0 - 6 7 14 4 5

different attempts at describing the same quantity. For instance, investigators have characterized the rainstorm by the average intensity, the maximum intensity, or the maximum intensity in thirty consecutive minutes, with or without consideration for the time duration of the particular intensity. However, one familiar with a rainstorm is aware that the total description of the event must be a history of the rainfall intensities with respect to time and space.

Essentially then, the myriad of listed variables involves replication and contains quantities which are, in many instances, merely indexes or effective descriptions of the input, losses, resistances, and driving forces acting at each point on the watershed.

The interest of the study was focused on description of watershed discharge; therefore, it has been isolated at the beginning of the tabulation as the dependent variable. The ultimate objective of a study such as this is to describe the instantaneous discharge. As the tabulation shows, only a few investigators have attempted to describe the instantaneous discharge. Such instantaneous discharges are generally described by a characteristic hydrograph (unit hydrograph) for a particular area. Some efforts have been made to generalize the characteristic hydrograph by relating it to basin parameters. To account for different sized storm events, the unit hydrograph is distorted linearly in proportion to the magnitude of the storm. The unit hydrograph method has been questioned in principle as not being a

general and fundamental description of the hydrologic system. Others,
listed in Table 1, have developed equations to describe the peak
discharge or the total discharge, depending upon specific needs.
However, if the entire history of the runoff could be described by a
basic, fundamental relationship, this relationship would suffice for all
needs. Thus, consistent with the basic needs, the watershed discharge
was thought of as an instantaneous volumetric discharge, $Q_i$ ($L^3 T^{-1}$),
at the watershed outlet. This instantaneous discharge may also be
described relative to the area, A, from which it issues, and as such,
it becomes unit discharge, $Q_i/A = q_i$ ($LT^{-1}$). The unit discharge, $q_i$,
was thus selected as the variable describing the discharge for this study.

The precipitation input at any point ($x_1$, $x_2$, $x_3$) on the watershed
surface must be described. The areal distribution or geographical
location of the storm is described by locating a point in space on the
watershed surface. The rate at which the water comes to this specific
point is described as the rainfall intensity, $I_i$ ($LT^{-1}$). If, then, the
instantaneous rainfall intensities were integrated with respect to time
and space, the total volumetric contribution of the storm would be
obtained. No further descriptions, such as average or maximum rain-
fall intensity, duration of rainfall, or the several descriptions of total
rainfall would be necessary. In light of the discussion, it was assumed
that the rainfall simulator constructed for this project would simulate
rainfall intensity and its areal and time distributions with sufficient

accuracy to be considered an adequate description of the rainstorm event.

The rainfall momentum flux ($\zeta$) and the impinging angle of rainfall are distinct aspects of the rainfall. If one is to simulate the rainfall input, these two factors should also be considered. For the present study, however, the assumption was made that compensations could be made for them by distortion of the resistance to flow-term, as was done by Chen and Hansen (1963).

The critical time for the continuance of rainfall is a parameter appearing in only one of the empirical formulas and does not contribute to a description of the instantaneous rainfall. The same criticism applies to the remaining rainstorm variables. As the study was limited to an input derived entirely from rainfall, snow and snow moisture content were irrelevant variables. Thus, the instantaneous rainfall intensity, $I_{ix}$, with its implied proper temporal and spatial distribution was selected as a pertinent rainstorm variable.

Many attempts have been made to describe the shape and topography of watersheds. The slope of a watershed surface at the configuration of the drainage system obviously influences the flow of water. For this study, assumption was made that a scaled topographic model would be a faithful conformal representation of the area, shape, slopes, and channel configuration. A similar argument was given by Strahler (1957). The topographical model is therefore the sum of all

the topographical variables and is the surface in space denoted by the coordinates $x_1$, $x_2$, $x_3$ (the general length variables selected as relevant).

In the list of variables for overland and channel flow, the velocity and the depth term constitute a description of the discharge at the arbitrary point, $x_1$, $x_2$, $x_3$. The slopes, lengths of flow, and channel shapes are reflected in the general description of the watershed surface. Development of the overland and channel flow equations introduced the liquid properties of dynamic viscosity and density (or the ratio of these two parameters, the kinematic viscosity) and the acceleration due to gravity. Murphy (1950) included surface tension when he made an open channel model analysis. Mamisao (1952), whose main source of reference was Murphy, also listed the surface tension as a pertinent fluid property in the dimensional analysis for his watershed model. None of the empirical relations nor the theoretical developments of overland and channel flow used the surface tension as a significant parameter in the runoff phenomenon. For this reason, surface tension was not considered as a pertinent variable in respect to the prototype. Nevertheless, because of the depths of flow which were to be encountered in the model, surface tension would be a significant parameter in the performance of the model. Since surface tension became important only in the operation of the model and acts as another factor in flow resistance, it was considered part of the indefinite resistance term.

Thus; the quantities of time, t, dynamic viscosity, $\mu$, density, $\rho$,
and acceleration due to gravity, g, were identified as significant
variables for the study.

The transport of sediment complicates the channel flow
phenomenon. Based on the assumption that sediment transport has
a negligible effect on the discharge from the selected prototype water-
shed, these variables were not modeled. Possibly, channel flow
resistance could be altered to compensate for any effects that do exist.

For the particular prototype watershed selected, the basin out-
flow is derived entirely from surface runoff. This selection was made
to eliminate the need for consideration of such variables as ground-
water flow and groundwater reservoir, listed at the end of category
D (Table 1).

The remaining variables in categories C and D are all of the
nature of an abstraction or storage and resistance to the flow. The
storage variables, such as channel storage or detention, initial
detention, volume of depression storage, land use or vegetative cover,
may be considered in two respects. A portion of the storage acts to
retard or modify the flow through the system and was used as another
element in the indefinite resistance term.

The remaining storage was then considered an absolute loss, or
an abstraction which extracts a portion of the input before it appears as
outflow. The abstraction portion of the storage was then combined with

the other abstraction variables (infiltration, etc.) and designated as a general time-and-space-dependent abstraction rate, $i_{ix}$, $(LT^{-1})$ for the purpose of the dimentional analysis.

The resistance to the flow was visualized as a time-space variable operating throughout the watershed. The total resistance is a composite of many factors which were characterized by the indefinite resistance term, $r_{ix}$ (no dimensions).

Subject to the conditions of selection, the variables which developed as pertinent for the study are listed below. To identify the variables with more precision, the time-dependent variables are subscripted with an "i" and the space-dependent variables with an "x". With the origin of the space coordinates located at the watershed outlet, the discharge at the outlet was designated as $q_{io}$.

| | | | | |
|---|---|---|---|---|
| 1. | $q_{io}$ | = | instantaneous unit discharge | $LT^{-1}$ |
| 2. | $I_{ix}$ | = | rainfall intensity | $LT^{-1}$ |
| 3. | $x_1$ | = | space coordinates of the | $L$ |
| 4. | $x_2$ | = | watershed surface | $L$ |
| 5. | $x_3$ | = | | $L$ |
| 6. | $t$ | = | time | $T$ |
| 7. | $\mu$ | = | dynamic viscosity | $ML^{-1}T^{-1}$ |
| 8. | $\rho$ | = | density of liquid | $ML^{-3}$ |
| 9. | $g$ | = | acceleration due to gravity | $LT^{-2}$ |

10. $i_{ix} =$ rate of abstration $\qquad LT^{-1}$

11. $r_{ix} =$ resistance $\qquad --$

These variables may be expressed in the general functional relation

$$(q_{io}, I_{ix}, x_1, x_2, x_3, t, \eta, p, g, i_{ix}, r_{ix}) = 0$$

## Completeness of the equation

The final question to be considered was, "Is the above functional relation complete?" The first condition for completeness is that the dimensional formulas for all the measured quantities and dimensional constants be known. The dimensions of the resistance term $r_{ix}$ have not been expressed; therefore, it cannot be said that the equation is complete. The condition of functional form invariance with changes in the size of the fundamental units is also necessary. Whether or not such invariance holds for the function just expressed is not known. Thus, the analysis made for this study cannot be considered an exact dimensional analysis, but rather a "quasi-dimensional" analysis. For the purposes of the model study, the functional relation was considered adequate and the eventual manipulation of distortions would have to be used to establish verification between the model and prototype.

# MODEL DESIGN

The design of the hydrologic model required the organization of the rainfall-runoff variables so that simulation could be accomplished. A knowledge of the magnitudes and ranges of the rainfall-runoff variables to establish specific sizes and dimensions for components of the model was necessary. These two aspects of the design are developed in the following discussion.

## Development of model-prototype dimensional relations

The process of combining variables of a system into dimensionless products and comparing the dimensionless products between two different systems (model and prototype) is a well-established modeling method. Such an approach invokes the Buckingham Pi Theorem, which states that it is possible to obtain a functional relation of the form

$$\phi \left( \pi_1, \pi_2, \ldots, \pi_{r-m} \right) = 0$$

in which

$r$ = number of derived units

$m$ = number of fundamental units

for suitable dimensionless power products $(\pi_1, \pi_2, \ldots, \pi_{r-m})$ of the derived units.

The variables assessed as relevant for this study give the functional relation

$$\phi \ (q_{io}, \ I_{ix}, \ t, \ \mu, \ \rho, \ i_{ix}, \ x_1, \ x_2, \ x_3, \ g, \ r_{ix}) \ = \ 0$$

which expressed in exponential form gives

$$C_\alpha q_{io}^{a_1} I_{ix}^{a_2} t^{a_3} \mu^{a_4} \rho^{a_5} i_{ix}^{a_6} x_1^{a_7} x_2^{a_8} x_3^{a_9} g^{a_{10}} r_{ix}^{a_{11}} \ = \ 1$$

and then, substituting the dimensions according to Murphy (1950), the relation becomes

$$C_\alpha \left(\frac{L}{T}\right)^{a_1} \left(\frac{L}{T}\right)^{a_2} (T)^{a_3} \left(\frac{M}{LT}\right)^{a_4} \left(\frac{M}{L^3}\right)^{a_5} \left(\frac{L}{T}\right)^{a_6} (L)^{a_7} (L)^{a_8} (L)^{a_9}$$

$$\left(\frac{L}{T^2}\right)^{a_{10}} (-)^{a_{11}} \ = \ 0$$

From this equation, several groups of pi-terms (the power products) can be developed. Three such groups are illustrated in Table 2.

The third group was selected for the modeling endeavor because the parameters, discharge, rainfall intensity, viscosity, abstraction, and gravity, were separate and appeared in a single pi-term. The relation was re-expressed with the pi-term containing the discharge variable as a function of the other dimensionless products

$$\frac{qt}{x_1} \ = \ f\left(\frac{It}{x_1}, \ \frac{\mu t}{\rho x_1^2}, \ \frac{it}{x_1}, \ \frac{x_2}{x_1}, \ \frac{x_3}{x_1}, \ \frac{g t^2}{x_1}, \ r_{ix}\right)$$

If the contemplated model were to be a true model (faithful in all respects), the following ratio would have to be maintained:

Table 2. Comparison of pi-terms for different selected groups of repeating variables

| $\phi(q_{io}, I_{ix}, t, \mu, \rho, i_{ix}, x_1, x_2, x_3, g, r_{ix}) = 0$ | | | |
|---|---|---|---|
| Group | 1 | 2 | 3 |
| Repeated variables | $x_1$, g, $\rho$ | I, t, $\mu$ | $x_1$, t, $\rho$ |
| $\pi_1$ | $\dfrac{q}{(x_1 g)^{1/2}}$ | $\dfrac{q}{I}$ | $\dfrac{qt}{x_1}$ |
| $\pi_2$ | $\dfrac{I}{(x_1 g)^{1/2}}$ | $\dfrac{I^2 t \rho}{\mu}$ | $\dfrac{It}{x_1}$ |
| $\pi_3$ | $\dfrac{t g^{1/2}}{x_1^{1/2}}$ | $\dfrac{i}{I}$ | $\dfrac{\mu t}{x_1^2 \rho}$ |
| $\pi_4$ | $\dfrac{\mu}{\rho (x_1)^{3/2} g^{1/2}}$ | $\dfrac{x_1}{It}$ | $\dfrac{it}{x_1}$ |
| $\pi_5$ | $\dfrac{i}{(x_1 g)^{1/2}}$ | $\dfrac{x_2}{It}$ | $\dfrac{x_2}{x_1}$ |
| $\pi_6$ | $\dfrac{x_2}{x_1}$ | $\dfrac{x_3}{It}$ | $\dfrac{x_3}{x_1}$ |
| $\pi_7$ | $\dfrac{x_3}{x_1}$ | $\dfrac{gt}{I}$ | $\dfrac{gt^2}{x_1}$ |
| $\pi_8$ | $r_{ix}$ | $r_{ix}$ | $r_{ix}$ |

$$\frac{\left(\dfrac{q\,t}{x_1}\right)\text{prototype}}{\left(\dfrac{q\,t}{x_1}\right)\text{model}} = \frac{f(\pi_2, \pi_3, \ldots, \pi_8)_p}{f(\pi_2, \pi_3, \ldots, \pi_8)_m}$$

which would require

$$\pi_{2p} = \pi_{2m}$$

$$\pi_{3p} = \pi_{3m}$$

$$\cdot$$

$$\cdot$$

$$\cdot$$

$$\pi_{8p} = \pi_{8m}$$

To satisfy these seven conditions simultaneously was impossible; therefore, some simplifications were made. In postulating that the topographical model would adequately represent the prototype geometry, the model-prototype equality of the fifth and sixth pi-terms $\left(\dfrac{x_2}{x_1} \text{ and } \dfrac{x_3}{x_1}\right)$ was satisfied. In assuming the rainstorm simulator to simulate the input storm event with sufficient accuracy, the model-prototype equivalence of the second pi-term $\left(\dfrac{It}{x_1}\right)$ was satisfied.

In this endeavor, the surface of the topographic model was made impervious, thus no abstraction of input could be made through the model surface. Further, no exact method of determining the amount of input into permanent surface storage could be known. With the speculation that the volumetric distortion of the outflow would not unduly

affect the time relationships of the model outflow, the requirement to have model-prototype equality of the fourth pi-term $\left(\frac{it}{x_1}\right)$ was neglected. The same treatment was made of the undefined resistance term $r_{ix}$. As postulated, many items; e.g., surface roughness, rainfall momentum, and non-permanent storage, were compounded into the general resistance term. To know the proper equality of this term between the model and the prototype was impossible. Further, it was speculated that proper manipulation of the input liquid physical properties, model surface-liquid interactions, and model surface textural characteristics would allow for a simulation of the net effects of the many prototype resistances to the flow. Thus these two terms became terms of distortion which would eventually have to be manipulated to establish verification of the model.

The two pi-terms $\left(\pi_3 = \frac{\mu t}{\rho x_1^2}\right.$ and $\left.\pi_7 = \frac{g t^2}{x_1}\right)$ remained to be equated between model and prototype. These two conditions cannot be satisfied simultaneously. Thus for the design and initial operation of the model, the hypothesis was made that the gravity parameter $\left(\frac{g t^2}{x_1}\right)$ expressed the dominating influence, and the design was made according to the equivalence between the model and prototype of this dimensionless ratio.

A dimensional analysis of watershed discharge in Langhaar (1951) and the endeavor of Mamisao (1952) provided some justification for assuming the predominence of the gravity term. The analysis in

Langhaar (1951) developed three dimensionless parameters

$$\left( \frac{Q}{g^{1/2} A^{3/4} H}, \quad \frac{t g^{1/2}}{A^{1/4}}, \quad \text{and} \quad \frac{\nu^2}{g A^{3/2}} \right)$$

in which

Q = discharge $(L^3 T^{-1})$

t = time (T)

A = area $(L^2)$

H = total rain (L)

g = acceleration of gravity $(LT^{-2})$

ρ = mass density $(ML^{-3})$

ν = viscosity $(L^2 T^{-1})$

The dimensionless ratio $(Q/g^{1/2} A^{3/4} H)$ was plotted as a function of the term $(t\, g^{1/2}/A^{1/4})$ for three watersheds, ranging in size from 334 square miles to 550 square miles. A close fit to the same curve was obtained for all three plots. Thus an initial relation was obtained between terms considering the gravity variable but not the viscosity variable.

Mamisao (1952) expressed runoff as a function of eleven variables. He transformed his twelve variables into nine dimensionless pi-terms and recognized that he would not be able to satisfy all eight design conditions. He remarked,

> Since difficulty would be encountered not only in evaluating the values of the other distortion factors but also in establishing the relationship of δ to all these distortion

factors, the roughness of the surface may be modified so
as to compensate for the effects of these five distortions.
This modification would result in making the value of $\delta$
unity, and the prediction equation would remain as:

$$\frac{Q}{I\,l^2} = \frac{Q_m}{I_m\,l_m^2} \quad \text{or} \quad Q = n^{5/2}\,Q_m$$

where $1/l_m = n$, the length scale, and $I/I_m =$ intensity
scale. (Mamisao, 1952, p. 28)

Mamisao derived his rainfall intensity scale ratio by first obtaining a

time scale ratio from the pi-terms containing the gravity variable. He

let $\dfrac{l_m}{gt_m^2} = \dfrac{l_p}{gt_p^2}$ and derived the time ratio $t_p/t_m = \sqrt{n}$. Here the

dimensionless term with the gravity variable was used as the basis for

design, and the results were claimed to be somewhat successful.

Comparison of the time ratios, as determined from the gravity

and viscosity pi-terms, also indicated that the time ratio according to

the gravity term is more reasonable than one obtained from the viscosity

term. If a length scale ratio of 1 : 175 is assumed, the gravity pi-term

would mean that one minute in the prototype would have been equivalent

to 4.54 seconds in the model. But according to the pi-term with the

viscosity variable, the time ratio would have been $t_p/t_m = (175)^2$

= 30,630 which would mean one minute in the prototype would have

been equivalent to approximately 0.00196 second in the model. The

gravity time relation is much more tenable than the viscosity time

relation and was used to make the design calculations.

In order to make the model as large as possible in the available laboratory space, a length scale ratio of 1 : 175 was chosen. The verticle scale was not distorted; therefore, the scale of 1 : 175 holds throughout the topographic model.

In summary,

1. The rainstorm simulator was considered a sufficiently accurate representation of the input event.

2. The topographic model was considered an adequate conformal representation of the prototype geometry.

3. The distortion of the abstraction pi-term as a consequence of the impervious surface was assumed to have no serious effect on the time relations of the model outflow.

4. The postulation that the "resistance" term could be manipulated as a compensating distortion was introduced.

5. The hypothesis that the time relationships of the model could be designed according to the gravity pi-terms was introduced.

With the selected scale ratio and the other conditions just summarized, the two major components of the hydrologic model, topographic model, and rainstorm simulator, were designed and constructed.

## Description of the prototype watershed and associated rainstorm event

The Montaño W-I watershed, a 97.2-acre semiarid basin, was

selected as the prototype. The watershed is located about 19 miles

west of Albuquerque, New Mexico, and has more than 25 years of

observational data. A contour map of the watershed is shown in Figure 1.

The information used to build the topographic model was taken from a larger

5-foot contour map.

On the watershed, 26 percent of the land has a slope of 3 to 10

percent. The other 74 percent has a slope of 10 to 35 percent. The

parent material of the watershed soil is sandstone and shale. Of the

area, 22 percent is soft, coarse, exposed sandstone outcrop; 23 percent

has a weak, fine-grained, gravelly loam approximately 5 inches deep;

19 percent is a gravelly, silty loam with a 3-inch profile; 20 percent

has a single grain, sandy loam, 24 inches deep, with a weak, coarse

prismatic subsoil; 10 percent has a loamy sand with a 24-inch profile;

and the remaining 6 percent is a single grain, sandy loam with a profile

depth of 60 inches.

The surface drainage is good with a principal waterway 3, 900

feet long. The drainage density is approximately 100 feet per acre.

Runoff from the flat upland area is retained by closed-end terraces

which artificially define the southern boundary of the watershed. In

short, the land is rough, broken badland, 77 percent of which is barren.

Typical of the vegetation on the watershed are the sort grasses

(Aristida spp. , Bouteloua gracilis and B. eriopoda, Hilaria Jamesii,

and Muhlenbergia Torreyi), tall grasses and shrubs (Sporobolus
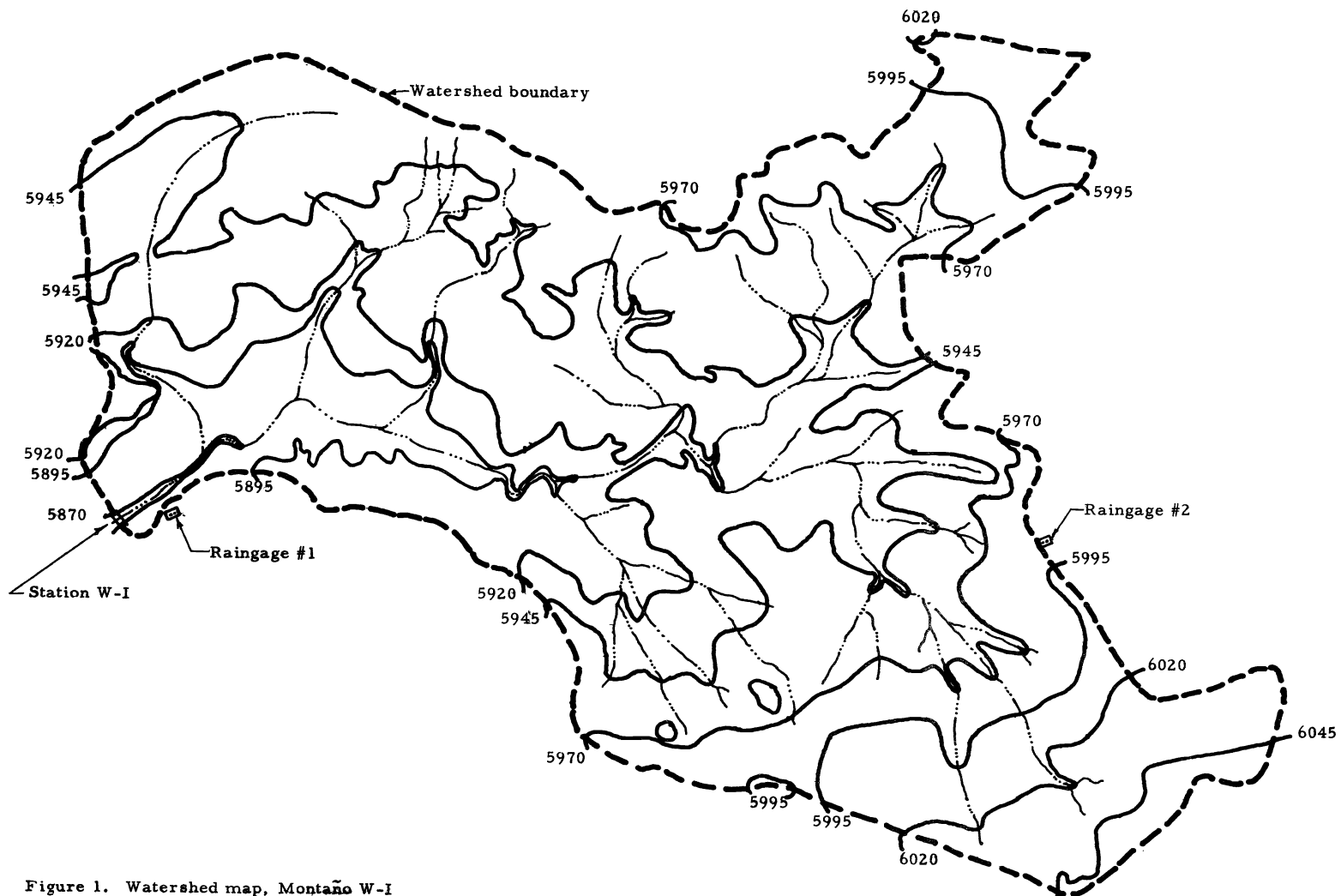
Figure 1. Watershed map, Montaño W-I

airoides, Artemsia filifolia, Chrysothamnus nauseosus, Yucca glauca, and Gutierrezia sarathrae) and a few trees (Juniperus spp. and Pinus edulis).

The description conveys the impression of a hot, desiccated area with very little vegetal ground cover. Indeed it is, and when precipitation falls on this basin, significantly, 30 to 50 percent of it runs off. This relatively high amount of runoff is principally a consequence of the high rainfall intensities, the barrenness of the land, and a good drainage system. The resulting runoff comes off in a flashy nature, with relatively high peak flow rates in proportion to the amount of rain and a short duration of flow. The runoff is derived predominatly from surface runoff with some interflow contributing to the flow recession. Abstractions occur mainly in the sandy fill of the channels and the mildly sloping sandy areas of the higher parts of the watershed.

Since August 1939, the runoff has been gaged by means of a 16-inch triangular concrete weir having 3 : 1 side slopes. The runoff is recorded on a 6-hour chart. Two weighing raingages (12-hour and 192-hour) at opposite ends of the basin record the precipitation.

Types and characteristics of rainstorms in western New Mexico. Sellers (1960) gives a good description of the weather typical of the location of the prototype. He notes that the Arizona and western New Mexico

> ...region receives most of its precipitation in either the
> winter or summer; the fall and particularly the spring are

quite dry. An average of barely more than 0.03 of an inch
of rain falls in May. The three wettest months of the year
are July, August, and September, which together account
for almost 45 percent of the period-of-record average annual
rainfall of 13.67 inches. The rains for these three months
come primarily from thunderstorms and convective showers
which form in moist tropical air, normally entering the region
from the Gulf of Mexico and the Atlantic Ocean. However, it
is not too unusual for late summer storms to be associated
with moisture drawn into the Southwest from distrubances cen-
tered in the tropical Pacific Ocean. (Sellers, 1960, p. 83)

Thus, thunderstorms or convective rainstorms are the predominant and

important storm events occurring at the prototype site, and of the many

forms of precipitation, the study was concerned with only rain (pre-

cipitation of water drops, ranging in size from 0.02 to 0.25 inch in

diameter).

From the list of variables obtained as relevant to the study the

rainfall intensity with its implied areal and temporal distribtuion was

the significant rainfall parameter. Thus, there was no concern with

reproduction of such aspects of rainfall as drop size, drop size distri-

bution, and rainfall energies. However, these aspects have been and

are of great concern in erosion and infiltration studies. Rainfall

simulators designed for these types of studies have not attempted to

scale down a rainstorm, but rather have attempted to make a true size

duplication of the raindrop size distribution, velocity, and energy.

Studies of rain drop size, shape, and size distribution have been made

by Bentley(1904), Atlas and Plank (1953), and Rigby et al. (1954) Horton (1948)

discussed these facets of a thunderstorm. Investigators, such as Laws (1941), Bernard in Meinzer (1942), and Blanchard (1950), included raindrop velocity with raindrop size and size distribution in their analyses of rainfall characteristics. Battan (1963) made some interesting observations of both particle size and velocity from radar surveillance of a thunderstorm. Schiff and Yoder (1941), Laws and Parsons (1943), and Wischmeier and Smith (1958) made specific investigations of rainfall energy and its characterization of rainfall. These are but a few of the many who have investigated these several aspects of rainfall. Their findings have contributed to the store of information by which laboratory rainfall simulators were developed and improved. The historical development and refinement of these simulators is interesting, but except for Mamisao's (1952) simulator, all were developed for a need different from that of this study. As a matter of interest, a summary of past rainfall simulator development has been given in Appendix B.

Thunderstorms in Southwest United States exhibit the distinctive features of short duration, low volume, and limited areal extent. Another and most distinctive characteristic of these storms is the bursts of heavy (high-intensity) rainfall. Storms with these relatively high intensities are runoff producing; that is, channel flow results from them. As a consequence of the heavy flows of water, such storms cause most of the floodwater damage, surface erosion, arroyo formation, and sediment deposition. On occasion they also contribute

to reservoir storage for downstream use.

What is the limited areal extent of these storms? With rather limited instrumentation, Leopold (1944) determined that the areal extent of ordinary summer thunderstorms in New Mexico and Arizona was extremely variable, but that the center of high intensity usually covered about 5,000 acres. From a plotting of thunderstorm size distribution based on 3 centimeter radar film records, Keppel and Fletcher (1959) determined that more than 80 percent of the storms have diameters less than 1.4 miles, with a majority having a mean diameter of 0.85 miles. Brancato (1943) measured the widths of two thunderstorm patterns perpendicularly to the direction of motion and found that they were approximately 8 miles and 4 miles wide at the widest place. He found that these measurements were in close agreement with the width of thunderstorm patterns measured at the Muskingum Watershed Project in Ohio where the width did not exceed 12 miles.

The 97-acre size of the prototype watershed is smaller than the normal thunderstorm; consequently, with each rainstorm recorded on the watershed, the probability that the entire watershed received precipitation is very high. However, the basin is large enough to reflect the areal distribution of intensities within a given storm. This aspect of the thunderstorms is discussed further on.

There is some question as to whether the movement of thunder-storms over the land is an actual lateral translation of the convective

storm cell or rather the effect of one cell generating a new cell, and so on. But whatever the movement mechanism, records taken on the ground indicate movement of the rainfall pattern. Brancato (1943) noted that the 15-minute maps of the isohyetal lines showed a storm advancing across the basin at about 8 miles per hour. The travel rate was in agreement with the direction and velocity of the air up to above 10,000 feet at the time. Horton (1948), Battan (1963), and others have discussed convective storm movement and the reasons for it.

In the vicinity of Tucson, Arizona, the length of rainfall time of thunderstorms was determined by Keppel and Fletcher (1959). Their analysis indicated that about 80 percent of the storms have total duration shorter than 4 hours with most of their water falling in periods of less than 30 minutes.

Since movement of convective rainstorms is evident, some account must be taken of this fact in the design of the rainfall simulator. The total duration of the storm events also has a bearing on the simulator design.

For the southwest, Dorroh (1954) noted that the time pattern of thunderstorm intensities remained somewhat consistent, regardless of changes in characteristic intensities from one location to another. Dorroh's estimation of the typical rainfall intensity pattern for 1, 2 and 3-inch thunderstorms is shown in Figure 2. He remarked that,
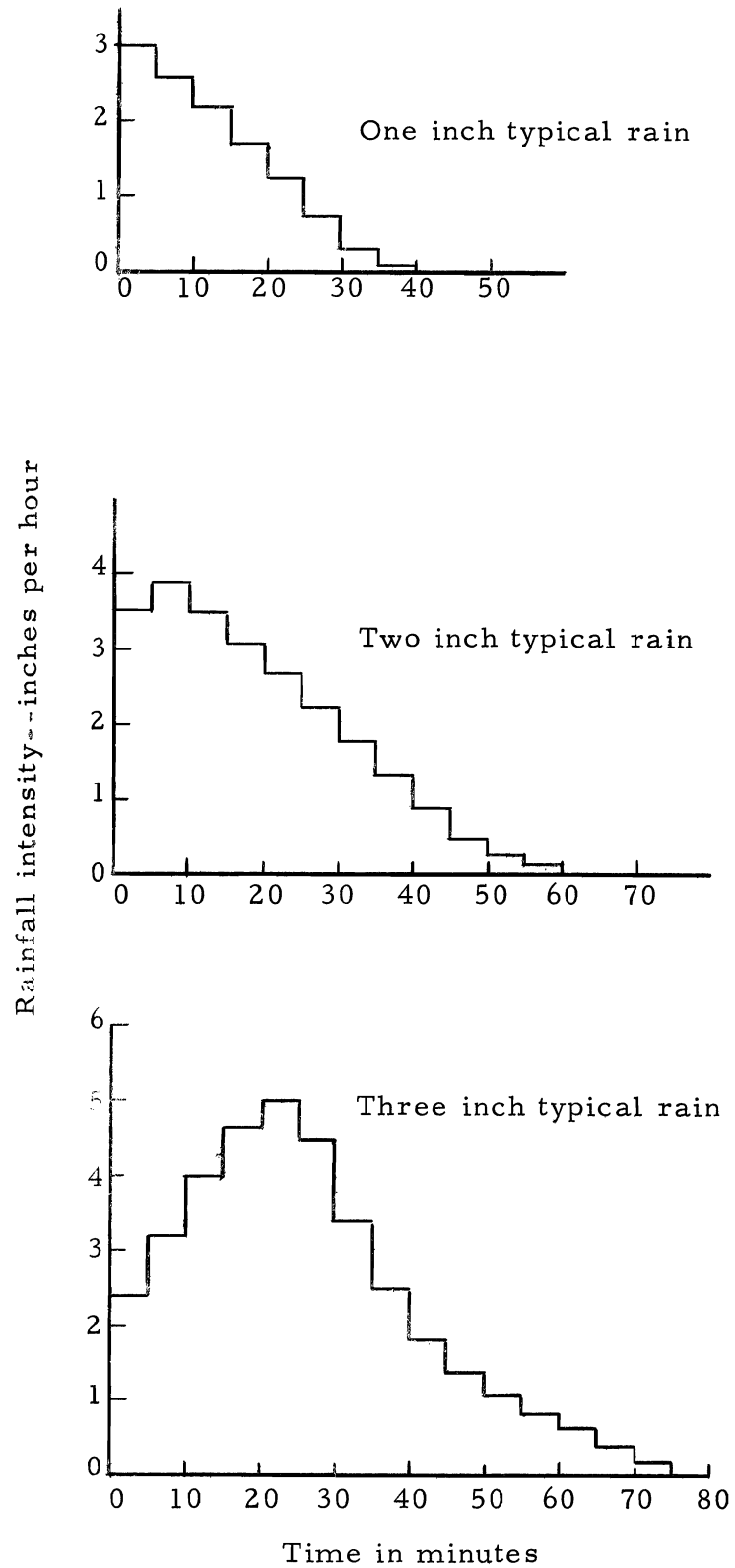
Figure 2. Typical thunderstorm rainfall intensity patterns according to Dorroh (1954, Figures 6, 7, and 8)

Although it is realized that individual storms may vary extremely in their patterns, it is believed that these histograms represent a reasonable approximation of what may be expected during a so-called "average" thunderstorm. It should be noted that these figures are further evidence of the characteristically short duration of runoff producing rainfall in this area. (Dorroh, 1954, p. 4)

The unusual rainstorm event, however, contributes most significantly to the runoff in the arid region of the prototype. A table of comparative high rainfall intensity values compiled by Osborn and Reynolds (1963) gives an idea of the magnitudes of intensity which the rainfall simulator may have to reproduce.

Table 3. Comparison of maximum point rainfall intensities of six storms, on four New Mexico and Arizona watersheds. (According to Osborn and Reynolds, 1963, p. 74)

| | Rainfall intensity (Inches/Hour) | | | | |
|---|---|---|---|---|---|
| Location | Time interval in minutes | | | | |
| | 5 | 10 | 15 | 30 | 60 |
| Alamogordo Creek, New Mex. | | | | | |
| Raingage 34, June 5, 1960 | 24.4 | 15.0 | 12.5 | 7.2 | 3.9 |
| (Raingage 21, June 5, 1960) | (7.4) | (7.0) | (6.0) | (4.0) | (2.3) |
| | | | | | |
| Alamogordo Creek, New Mex. | | | | | |
| Raingage 21, July 13, 1961 | 18.1 | 14.3 | 12.4 | 6.8 | 3.5 |
| (Raingage 34, July 13, 1961) | (5.9) | (5.1) | (4.0) | (2.6) | (1.7) |
| | | | | | |
| Montaño, New Mexico | | | | | |
| Raingage 1, August 24, 1957 | 6.7 | 6.2 | 5.4 | 3.2 | 1.8 |
| | | | | | |
| Safford, Arizona | | | | | |
| Raingage 5, August 2, 1939 | 8.2 | 7.0 | 6.6 | 4.9 | 3.1 |
| | | | | | |
| Walnut Gulch, Arizona | | | | | |
| Raingage 9, August 22, 1961 | 10.6 | 8.0 | 7.0 | 4.6 | 2.4 |

Table 3 indicates that the simulator must represent intensities of over 24 inches per hour for five minutes, and possibly even greater intensities for shorter durations, if it is to encompass the intensity extremes.

A great variation of intensity with respect to time and also with respect to position is evident. For those instances when extremely high intensities occur at a point, a steep gradient of decreasing intensity extends in all directions from the point of highest intensity. Dorroh (1954) comments on this situation by saying that

> Although intensity-duration relationships have been found to vary widely within the region, such has not been found to be the case with area-depth relationships. In other words, a storm with a given amount of rainfall at center will apparently cover about the same area, regardless of the location of its occurrence. (Dorroh, 1954, p. 3)

A reproduction of Dorroh's generalized area-depth relationship developed for storms of the southwest is given in Figure 3. An interesting analysis of the areal distribution of the intense European summer convective storms has been made by Kraijenhoff (1963). He has developed a double Gaussian expression for the relation between the isohyet and its enclosed area. The relation is

$$P = P_p \exp. (-A/\pi S_p) - P_b \exp. (-S/\pi S_b)$$

in which

P    is the depth of rain along an isohyet enclosing the area A

Pp   is the peak depth of rain

$P_b$ is the base depth of rain

$S_p$ and $S_b$ are typical areas denoting the spreading
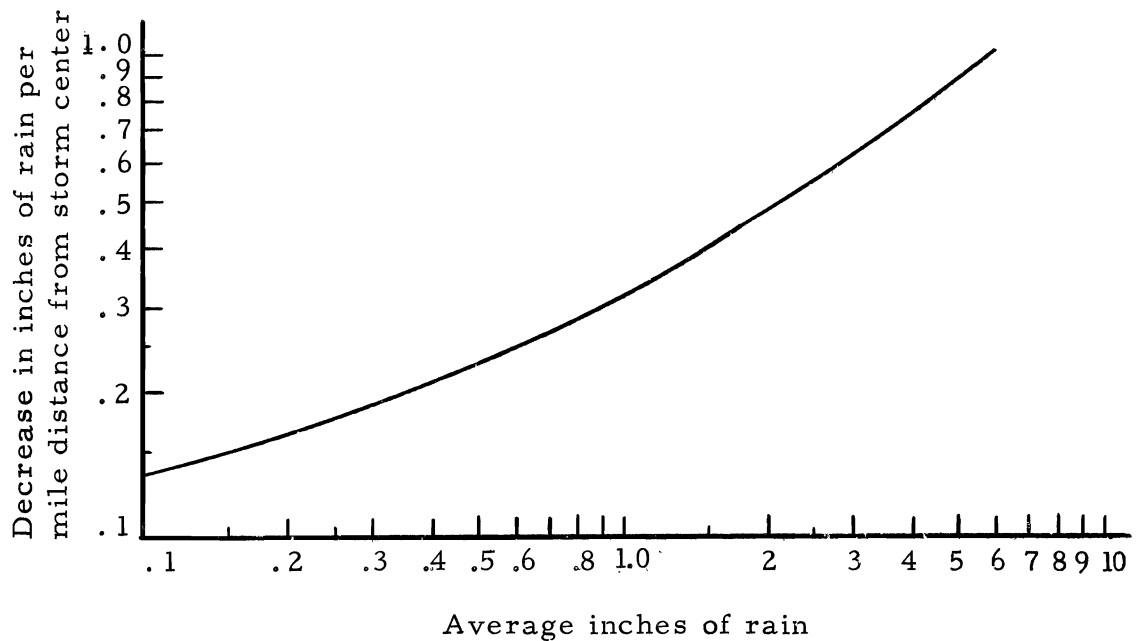


Figure 3. Area-depth relationship for thunderstorms according to Dorroh (1954, Figure 5)

For the present study, nothing is more descriptive of a storm's rainfall pattern than the record of the recording raingages. With the recorded information for the selected site and the information just reviewed, it was possible to design and construct the rainfall simulator and then program it.

Summary of precipitation and runoff data for Montaño W - I watershed. Analysis of the precipitation data from the prototype water-shed indicated the specific intensity magnitudes and durations which must be represented by the simulator. Comparison of the precipitation information with the runoff data indicated the percentage of runoff

produced. Osborn and Reynolds (1963) tabulated (for a 22-year recording period) 38 convective storms each of which had total rainfall of 0.65 inch or more. They further observed that the most intense storm was recorded on all five gages located on the three neighboring small watersheds (Montaño I, II, and III) and that it had an intensity of over 6 inches per hour for 10 minutes, over 5 inches per hour for 15 minutes, and over 4 inches per hour for 20 minutes. Intensities recorded for time periods through 60 minutes during this event far exceeded recorded intensities for any other event occurring on the three watersheds.

Dorroh (1954) has tabulated the rainfall and runoff information for 12 events on Montaño W-I, as shown in Table 4.

Table 4.    Rainfall-runoff relationships for Montaño W-I near Albuquerque, New Mexico, 98 acres. According to Table 3d Dorroh (1954)

| Date | Runoff volume inches | Maximum rate c.f.s. | c.f.s. per sq.mi. | Rainfall inches | Volume rainfall % |
|---|---|---|---|---|---|
| 7/23/49 | 0.2356 | 60 | 400 | 1.10 | 21.4 |
| 8/4/48 | 0.1690 | 63 | 420 | 0.42 | 40.2 |
| 8/4/48 | 0.1580 | 64 | 427 | 0.53 | 29.8 |
| 9/4/47 | 0.3046 | 97 | 647 | 0.94 | 32.4 |
| 9/8/47 | 0.4611 | 155 | 1033 | 1.16 | 39.8 |
| 10/4-5/46 | 0.1174 | 64 | 427 | 0.41 | 28.6 |
| 8/17-18/44 | 0.1044 | 29 | 193 | 0.74 | 14.1 |
| 6/28-29/43 | 0.1218 | 16 | 107 | 1.12 | 10.9 |
| 9/20/41 | 0.1226 | 54 | 360 | 0.45 | 27.2 |
| 10/3/41 | 0.1479 | 12 | 80 | 0.79 | 18.7 |
| 8/20/40 | 0.1622 | 49 | 327 | 0.82 | 19.8 |
| 9/14/39 | 0.2466 | 45 | 300 | 0.70 | 35.2 |

Seventeen storm events, occurring between 1939 and 1958, were selected

for the design and verification of the hydrologic model. The records of

the seventeen storms were retabulated, and a summary of the infor-

mation is presented in Table 5.[2] The storm intensity and duration

information from this table plus the range of values reviewed in the

previous section guided the design of the rainstorm simulator.

An intensity range of 0 to 10 inches per hour in increments of

0.01 inch per hour was adopted. If desired, a change of gear ratio

could double the range to 20 inches per hour with a parallel decrease

in increment accuracy. After counting the changes of intensities

during each storm event, provision for forty changes was considered

adequate to accomodate even an unusual event. With the initial

assumption on the time relation between model and prototype, the

rainstorm programming equipment was designed to represent:

    (a) 1/2-minute intensity changes for a total duration of 3 hours,

    (b) 1-minute intensity changes for a total duration of 6 hours,

    (c) or 2-minute intensity changes for a total duration of 12 hours.

---

[2] Discrepancies between Tables 4 and 5 result partially from the
author's effort in compiling the data in Table 5 to reflect possible
extremes, rather than most-probable actual rainfall and runoff
values as are tabulated from the field recorder charts by standard
procedures. Also, the data reported by Dorroh in 1954 as shown
in Table 4 were preliminary. The reader is referred to Hydrologic
Data for Experimental Agricultural Watersheds, USDA Misc. Publ.
Series, for the official audited data.

Table 5. Summary of storm and runoff data for seventeen significant storms on Montaño W - I

| | Storm date | Raingage R-1, high intensities Intensity In./hr. | Duration Min. | Gage R-1 total amount In. | Total length of storm Min. | Est. lag time Min. | Est. length of run Min. | Max. rate cfs | Runoff vol. In. | Vol. % rainfall |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9/14/39 | 1.80 | | 0.70 | 68 | 12.0 | 105 | 50.6 | 0.2547 | 36.4 |
| 2 | 9/20/41 | 3.60 | 1.0 | 0.38 | 15 | 14.0 | 75 | 66.3 | 0.1506 | 36.3 |
| | | 7.20 | 1.5 | | | | | | | |
| 3 | 10/4/46 | 4.35 | 4.0 | 0.41 | 40 | 7.5 | 72 | 76.0 | 0.1527 | 37.8 |
| 4 | 9/4/47 | 5.85 | 1.5 | 0.61 | 70 | 9.0 | 76 | 112.2 | 0.2740 | 39.4 |
| | | 2.90 | 6.0 | | | | | | | |
| 5 | 9/8/47 | 3.60 | 5.0 | 1.12 | 44 | 5.0 | 92 | 172.6 | 0.4900 | 46.1 |
| | | 2.40 | 11.0 | | | | | | | |
| 6 | 8/4/48 | 2.60 | 3.0 | 0.48 | 40 | 4.0 | 73 | 107.4 | 0.1821 | 35.8 |
| | | 1.80 | 2.0 | | | | | | | |
| 7 | 8/4/48 | 6.00 | 1.3 | 0.34 | 20 | 4.0 | 76 | 71.9 | 0.1617 | 46.9 |
| | | 3.20 | 1.5 | | | | | | | |
| 8 | 7/23/49 | 3.60 | 0.5 | 0.46 | 118 | 8.0 | 55 | 106.5 | 0.1532 | 27.7 |
| | | 3.36 | 2.5 | | | | | | | |
| 9 | 9/11/54 | 2.60 | 3.0 | 0.51 | 50 | 5.5 | 79 | 123.8 | 0.2482 | 41.1 |
| | | 2.40 | 1.5 | | | | | | | |
| 10 | 9/12/54 | 1.40 | 3.0 | 0.28 | 23 | 12.0 | 82 | 59.3 | 0.1488 | 45.8 |
| | | 1.20 | 5.0 | | | | | | | |
| 11 | 7/22/55 | 2.40 | 1.5 | 0.45 | 60 | 9.0 | 78 | 91.2 | 0.2223 | 44.6 |
| | | 1.65 | 4.0 | | | | | | | |
| 12 | 8/19/56 | 3.60 | 1.5 | 0.50 | 20 | 4.5 | 76 | 168.4 | 0.2000 | 53.4 |
| | | 2.92 | 3.5 | | | | | | | |
| 13 | 8/9/57 | 4.80 | 2.5 | 0.41 | 30 | 8.5 | 79 | 53.4 | 0.2053 | 42.8 |
| 14 | 8/24/57 | 7.32 | 1.8 | 1.73 | 70 | 6.0 | 92 | 230.4 | 0.6150 | 50.4 |
| | | 6.28 | 2.2 | | | | | | | |
| | | 5.71 | 8.5 | | | | | | | |
| 15 | 10/19/57 | 2.00 | 3.0 | 0.32 | 31 | 12.0 | 84 | 55.7 | 0.1591 | 49.7 |
| 16 | 8/21/58 | 2.57 | 3.5 | 0.54 | 37 | 5.0 | 80 | 151.8 | 0.2137 | 40.3 |
| 17 | 8/21/58 | 1.20 | 2.5 | 0.60 | 93 | 6.0 | 97 | 46.8 | 0.1698 | 29.3 |

# MODEL CONSTRUCTION

## Topographic model

A length scale ratio of 1 : 175 was selected, and a contour map, similar to Figure 1, was available to guide the construction of the topographic model. A preliminary investigation of fabricating materials indicated that a hand lay-up fiberglass shell would best fulfill the need. From a test section, it was decided to make the entire topographic model as one piece, which meant a single casting roughly 9 feet wide and 20 feet long.

The model was begun by making photographic slides of a 5-foot contour map of the prototype watershed. These slides were projected onto sheets of plywood which had been sanded to the proper thickness (0.343 inch) to represent a 5-foot contour interval in the model. Each contour in the map was traced onto separate sheets of plywood, and then the wood sheets were cut along the traced lines and positioned in a box encompassing the boundaries of the model watershed. This positioning of the coutour sheets is shown in Figure 4a. The cutting and positioning was the beginning of a negative mold of the basin surface. The plywood sheets representing each contour were stacked in reverse order, the lowest point in the mold representing the highest point of the watershed. When the plywood sheets were positioned, the steps between the contours were smoothed by filling the indentations with a prepared plaster mix.
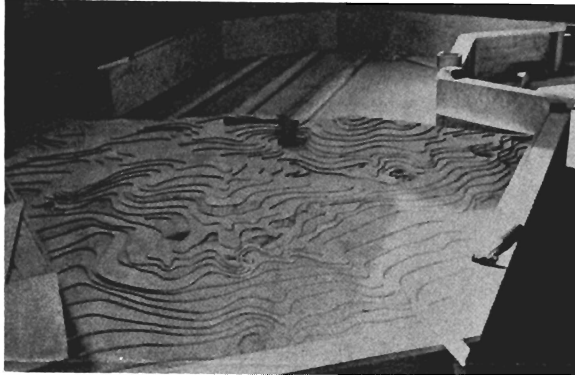
(a) Positioning the cut contour boards
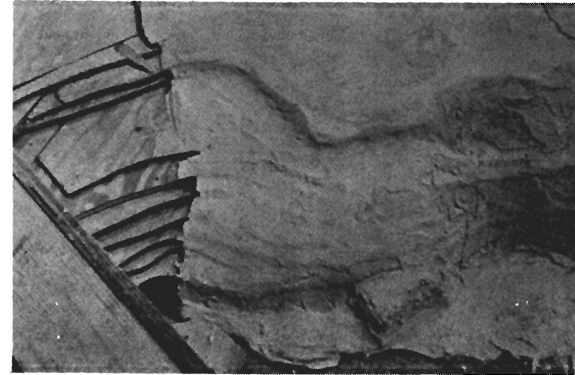


(b) Filling the indentations with plaster



(c) Saturating the fiberglass mat with resin
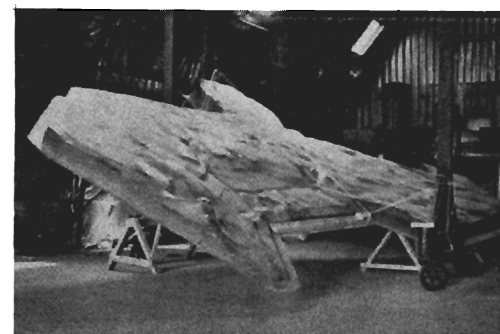


(d) Completed casting, broken from mold and turned right side up

Figure 4. Topographic model construction

This process is shown in Figure 4b. Care was used in the selection of the plaster mix so that it had a fine texture which gave a smooth durable surface when sanded.

The plaster was sanded until the edges of each contour were barely discernible. The plaster was then painted to toughen it and to make it impervious. A coat of plastic resin was applied over the painted surface. The plastic surface of the mold was then sanded and polished until it was glassy smooth and free of all blemishes. The prepared mold was coated with a bond-release to allow for easy separation of the casting from the mold. The model itself was begun by applying a coat of plastic resin (which became the finished surface of the model) over the bond-release. Fiberglass mat was then laid over the resin and saturated with additional resin, as illustrated in Figure 4c. When the resin within the fiberglass mat hardened, a stiff shell resulted. The shell was reinforced by running braces of fiberglass across the underside of the shell. When the resin had completely cured, the model was broken from the form, lifted up, turned over (Figure 4d) and set on a supporting frame. The frame holds the model about two feet above the floor on adjustable legs by which the model can be leveled.

## Rainstorm simulator

A rainstorm simulator capable of simulating the wide range of rainfall intensities and their areal distribution was essential to the project. Thus, proper input (simulated rainfall) to the model required:

1.  Control over the input rate so that it could be easily and quickly varied to represent the selected range of intensities.

2.  Coverage of particular portions of the topographic model and ability to change areal distribution of the input.

Control over the input rate (or storm intensity) was provided by small, positive displacement gear pumps which supplied the input liquid at a rate proportional to the speed at which they were turned. The pumps are driven by variable speed electric motors. The motor speed is automatically controlled by commercial speed controller units in conjunction with a specially designed switching circuitry.

Control over the areal distribution of the input was achieved by modular construction of the rainstorm simulator. Eleven modules, similar, but operating entirely independently from each other, supply input to only a fraction of the topographical model covered by the module. Thus, by operating the group of modules independently but relative to one and another, it is possible to simulate storm movement over the model watershed and different intensity distributions.

Ten of the modules were placed along the long axis of the watershed and one covers a small projecting arm of the watershed. Each module covers approximately 18 square feet, which is an area equivalent to 12.6 acres or about 1/8 of a square mile in the prototype. Compared with the areal extent of thunderstorms as discussed previously, such articulation should be sufficient to represent the distribution and movement of such storms reasonably well.

Uniform liquid application to the area covered by each module was approached by using small, equal lenght, uniformly spaced capillary tubes (0. 011 inch ID) to distribute the liquid, as shown in Figure 8, Item 12. Each module contains 676 tubes, each 2 feet long. The discharging ends of the tubes were positioned every 2 inches in a grid hanging over the topographic model.

The tubes were cut from spools of intramedic polyethylene tubing. Some of the tubing was severely stretched by the packaging methods. A check showed that some cut lengths shrank 1 3/4 inches in 24 inches after resting untensioned for several days. Tubing obviously distorted beyond use was discarded, but to avoid discarding all the tubing, some slightly distorted tubing was used.

Tests of the discharge from individual tubes confirmed that variation occurred in individual tube discharge where the stretched tubing had been used, As was desired, very uniform discharges occurred with groups of tubes that were carefully selected for no packaging damage. Figure 5 illustrates the slight spread of individual tube discharge when tubing was carefully selected; Figure 6 shows the spread in discharge typical of heads constructed with some stretched tubing.

The total discharge from each head (group of 169 producing tubes) for given time periods were measured. Then, to compensate for the

Figure 5. Distribution plot of individual tube discharge, Head No. 37 (group of 188 tubes)

Pressure: 8 psi

Duration of test: 5 min.

Figure 6. Distribution plot of individual tube discharge, Head No. 7 (group of 168 tubes)

Pressure: 15 psi

Duration of test: 2 min.
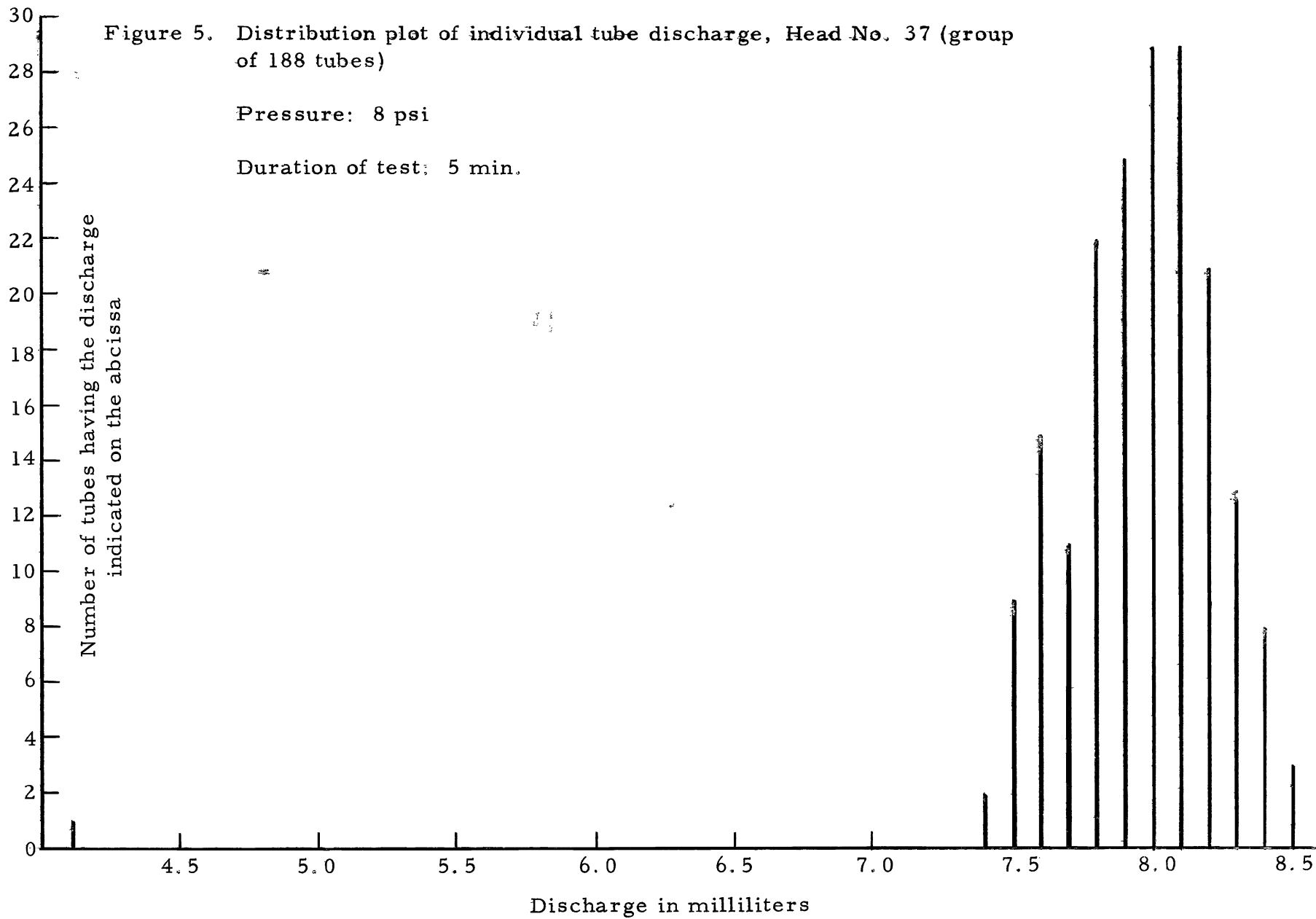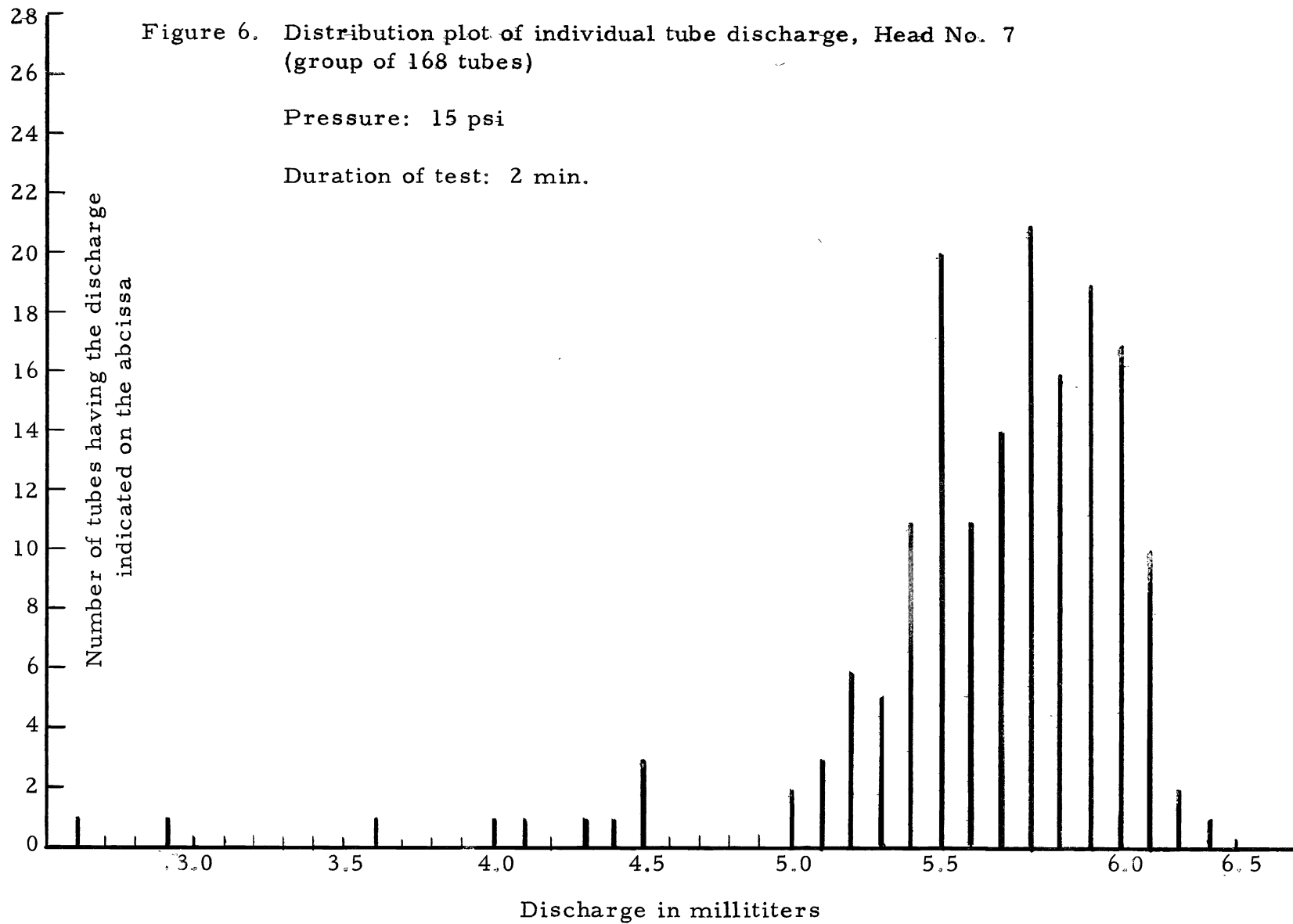
differences, the heads were grouped in sets of four according to the similarity of their total discharge (Table 6). This arrangement placed in each module tubes with nearly similar performance. Then each set of four heads is rated and operated independently of the others, which partially compensates for the differences. Still the desired uniformity of discharge from the individual tubes within a given module was not obtained. Each head was, however, provided with extra tubes so that abnormal performing tubes could be sealed off. Without investing in new tubing, the less than desired spread in individual tube discharge was tolerated for the time being.

The capillary tubes were inserted through holes punched in 1 1/2-inch-diameter circular disks and sealed on the inside with rubber and silicon mastic. These disks with 169 plus a few extra tubes were clamped in one end of a short 1 3/4-inch brass nipple by a pipe cap which had a large hole drilled in it for the bundle of tubes to pass through (Figure 8, Item 11). Four of these distribution heads constitute one module covering a rectangular area, 26 by 104 inches.

Equal-length, high-pressure hoses supply the four heads with liquid from a central manifold. High pressure hoses were used to minimize hose distortion as the pressure increased, and thus keep the system as responsive as possible to input rate changes. In this same regard, hose lengths were shortened and air traps eliminated. For this reason the pump was connected so that it pumped as directly

Table 6. Grouping of heads as to similar discharge

| No. | Head | Discharge in ml per 2 min. @ 15 psi | @ 8 psi | No. | Head | Discharge in ml per 2 min. @ 15 psi | @ 8 psi |
|---|---|---|---|---|---|---|---|
| 1. | 37 | 997 | 498 | 21. | 15 | 785 | 390 |
| 2. | 25 | 980 | 487 | 22. | 31 | 779 | 387 |
| 3. | 10 | 975 | 472 | 23. | 13 | 772 | 387 |
| 4. | 1 | 970 | 500 | 24. | 28 | 770 | 380 |
| 5. | 11 | 965 | 487 | 25. | 24 | 766 | 395 |
| 6. | 17 | 959 | 497 | 26. | 14 | 765 | 395 |
| 7. | 39 | 948 | 465 | 27. | 3 | 756 | 415 |
| 8. | 32 | 940 | 482 | 28. | 36 | 750 | 365 |
| 9. | 26 | 936 | 470 | 29. | 6 | 741 | 395 |
| 10. | 29 | 910 | 460 | 30. | 30 | 740 | 373 |
| 11. | 16 | 898 | 465 | 31. | 8 | 735 | 378 |
| 12. | 18 | 880 | 445 | 32. | 23 | 732 | 370 |
| 13. | 38 | 879 | 448 | 33. | 19 | 729 | 368 |
| 14. | 9 | 878 | 436 | 34. | 40 | 716 | 368 |
| 15. | 4 | 846 | 435 | 35. | 34 | 685 | 370 |
| 16. | 33 | 838 | 418 | 36. | 21 | 685 | 340 |
| 17. | 35 | 830 | 485 | 37. | 5 | 680 | 340 |
| 18. | 12 | 830 | 401 | 38. | 2 | 680 | 317 |
| 19. | 27 | 794 | 400 | 39. | 20 | 676 | 337 |
| 20. | 41 | 788 | 395 | 40. | 22 | 650 | 324 |
| | | | | 41. | 7 | 620 | 335 |

as possible into the junction manifold (Figure 8, Item 6). With this
arrangement, tests showed that the entire pressure change resulting
from full-range change in pump speed (either from 0 to 2,000 RPM
or from 2,000 to 0 RPM) was transmitted to the distribution head in
slightly over 4 seconds. This responsiveness was considered adequate.

The pump is driven at selected speeds by a one-twelfth horse-
power direct-current, shunt-wound motor. The speed of the motor is
controlled by a commercial motor controller. Various settings of a
potentiometer in the circuitry of the motor controller determined the
speeds of the motor. A line of forty potentiometers which can be
automatically switched in sequence into the motor controller gives
the ability to cause forty preset changes in pump speed. This system
would correspond to forty changes in storm intensity, which was
considered sufficient to model nearly all storm events. These
potentiometers are switched into the motor controller by a rotating
peg drum which instructs the on-off and duration of each simulated
storm intensity or pulse. Operating each module independently but in
proper sequence with the other modules provides for the simulation of
storm movement.

The pumps draw liquid from a 3/4-inch plastic pipe running the
length of the model. The liquid is supplied to the pipe from two 13-gallon
Teflon carboys placed at each end of the pipe. Breather tubes inserted

through the tops of the bottles regulate the pressure in the supply line.

The schematic drawing (Figure 7) illustrates how the various components were arranged into a complete simulator system. The characteristic and function of each component and its relation to the general system is given in the following explanation:

1. <u>Drum</u>. The drum is a 1/4-inch thick plastic cylinder, 18 inches long and 12 inches in diameter. Parallel to the axis of the cylinder, the drum is divided into eleven sections, each with three rings of holes. Each section controls the time instructions of one module. The circumference, or each ring, is divided 120 times and a hole drilled at each division. The drum is rotated about its axis by a variable speed motor, and the rotational speed controlled so that time increments of 2, 1, and 1/2 minutes can be simulated. The drum has the following simulation capacities:

(a) 3 hours at 1/2-minute increments

(b) 6 hours at 1-minute increments

(c) 12 hours at 2-minute increments

Pegs are inserted in a hole each time it is desired to change the input rate (storm intensity).

2. <u>Tripping switches</u>. As the drum rotates, the pegs trip the tripping switches, which activate the stepping switches.

3. <u>Stepping switches</u>. The stepping switches sequence various potentiometer settings into the motor speed controller circuitry.

2. Tripping switches    3. Stepping switches

1. Drum
(Time duration)

4. Potentiometers, 40
(intensity)

Liquid
supply

8. Pump

7. Gears

6. DC
motor

5. Speed
controller

11. Distribution
heads

9. Hose

10. Junction
manifold

12. Tubing
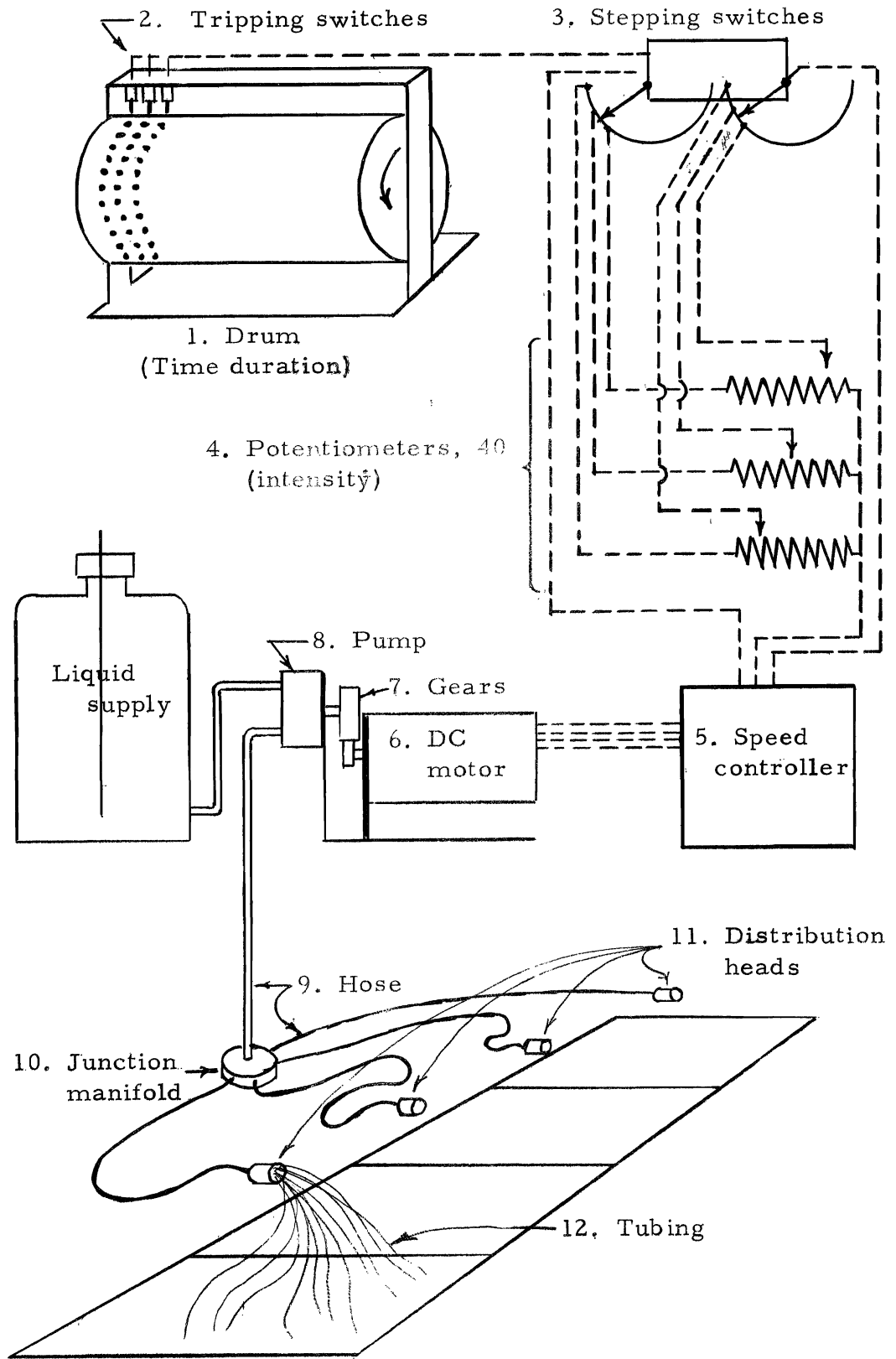
Figure 7. Schematic drawing of the rainstorm simulator, illustrated
for one of the eleven modules

4. _Potentiometers._ The potentiometers are Bourns Carbon deposit E-Z Trim potentiometers of 1 megohm resistance with a 15 turn screw adjustment. The potentiometers in connection with the speed controllers control the motor speed and consequently the input rate (storm intensities). A sequence of forty potentiometers allows for forty changes of input rate in each module for each operation of the simulator.

5. Speed Controller. This unit is a S-47 motor controller manufactured by the Gerald K. Heller Co. It operaters to control the speeds of the motors in connection with the potentiometers.

6. Motors. The controllers govern the speed of 1/12-horse-power, General Electric, direct-current, shunt-wound motors. The motors impose a limitation on the simulator by their speed range, which is 100 to 4, 000 rpm.

7. Gears. In connection with the rated pump displacement and the capabilities of the motor controllers, a gear reduction of 2 : 1 was considered advantageous.

8. Pump. A positive displacement of the fluid was desired so that as direct a ratio as possible could be obtained between motor speed and discharge. The small gear XMR-17220-BN Maisch Midget Pump with a displacement of 0. 836 cc per revolution was used.

9. and 10. Hose and junction manifolds. The supply system.

11. Distribution heads. The distribution heads are 1 1/2-inch

diameter brass nipples about 2 inches long. The brass cap on one end is drilled with a large hole, through which a bundle of polyethylene tubes is passed. The tubes are set in a perforated plate and sealed in place with silicon rubber cement. As the cap is tightened on the nipple the perforated plate is drawn up against the nipple and a watertight seal is made. The cap on the other end of the nipple is drilled and tapped for a hose fitting.

12. <u>Tubing</u>. Capillary polyethylene tubing (ID - 0.011 inch, 24 inches long) is used to distribute the input liquid uniformly over the module area. Ends of the tubing were placed in a 2-inch grid.
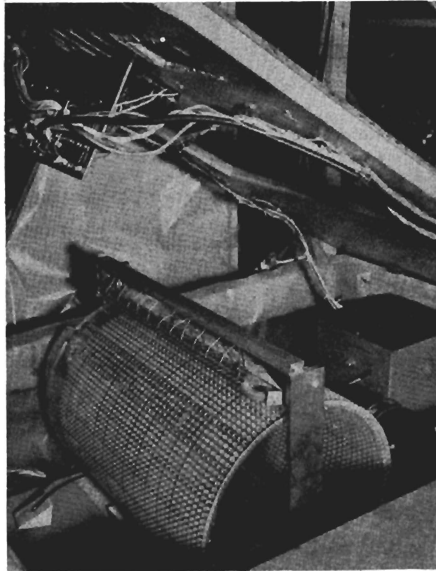
Items 1 and 2. Drum and tripping switches
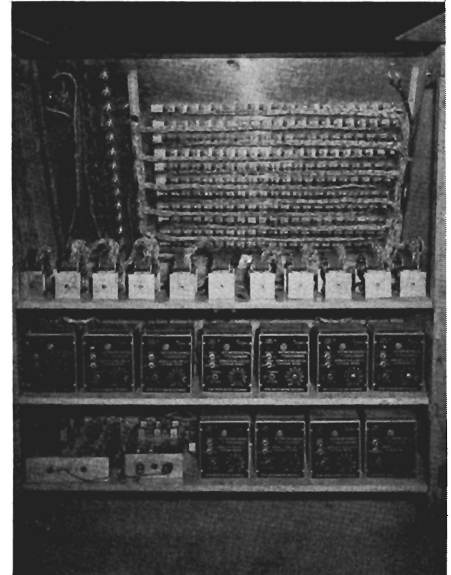


Items 3, 4, and 5. Stepping switches, potentiometers and speed controllers
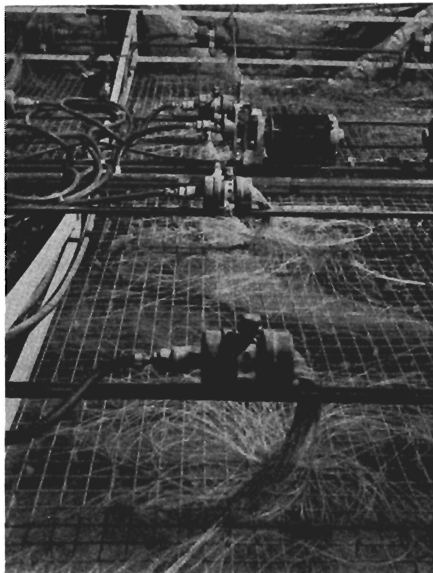


Items 6, 7, 8, 9, 10, 11, and 12. DC motor, gears, pump, hose, junction manifold, distribution head, and tubing



Items 11 and 12. Distribution head and tubing

Figure 8. The rainstorm simulator

# MODEL INSTRUMENTATION AND CALIBRATION

Outflow was monitored to reflect the performance of the model. The final apparatus used to measure and record the model's outflow is illustrated in the photograph of Figure 9.

The outflow from the model was funneled into a cup seated in the end of a pivoted arm. The arm was supported by a tension spring which stretched and allowed the arm to rotate about the pivot as water flowed into the cup. The rotation of the arm actuated a linear motion potentiometer which fed a signal to a Varian G-10 strip chart recorder. A curve of accumulated runoff versus time was recorded. With this system, the recorder had the capacity to record 100 grams of liquid. By changing cups, the range of the recording could be extended to any amount. The weight of the liquid was measured with an accuracy of $\pm$ 2 grams on a chart moving at a speed of 1 inch per minute. After making several tests, recorder performance was improved by installing a 4-inch per minute chart drive.

While operating the model, air temperature above and below the model and the temperatures of the input and outflow liquid were measured and recorded on a 4 pen, 6 hour, Trerice temperature recorder. Before and after each test, the air moisture content was measured with an Alnor Dew Pointer, type 7300.
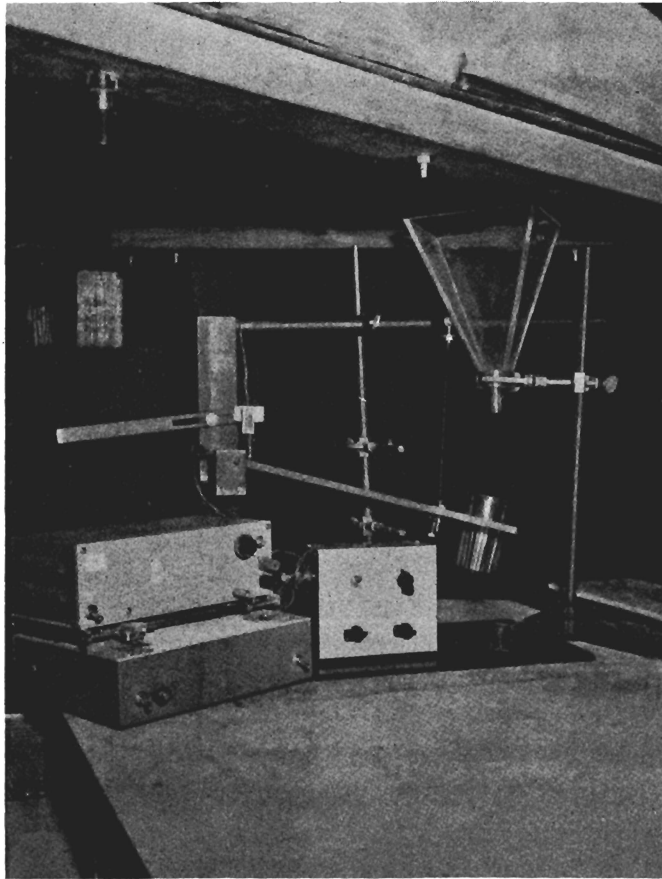
Figure 9.   The outflow measuring and recording apparatus

The input rate (simulated rainfall intensity) was calibrated against pump speed. The necessary pump speeds were measured by counting the revolutions per minute of the drive shaft to the pump. A disk with a hole in it was mounted on the drive shaft. A small light was placed on one side of the disk and a photo electric diode on the other. The diode was energized every time the hole passed between it and the light. This pulse was counted on a Deca counter for a given time period. The pump speed was then determined from the information obtained.

## Rating the rainstorm simulator

Prior to experimental testing, determination of the application rate versus pump speed relation for each module of the simulator was necessary. This relation was established by measuring the application rate and corresponding pump speed over the entire range of pump speeds.

Rating curves made using distilled water can be found in Appendix C.

## Programming the rainstorm simulator

Before each test or set of tests, the rainstorm simulator must be programmed to apply the desired input to the model. The liquid input is in the form of discrete pulses of different application rates and time durations. The form of this input is similar to a histogram record of a natural rainstorm, and, in fact, when actual storms were simulated,

their histograms were scaled. This information was used to prepare the simulator program. Particular application rates (rainfall intensity) and corresponding beginning and ending times of each input "pulse" were tabulated. From the pump rating curves, the corresponding pump speed was listed for the application rate of each pulse. Such a tabulation was prepared for each module and the several tabulations constituted the program for the rainstorm simulator.

The time information was programmed by inserting pegs at the proper locations on the circumference of the time drum (Figure 8, Item 1). The application rate (rainfall intensity) associated with a particular duration on the time drum was programmed by adjusting the corresponding potentiometer to give the proper pump speed. With the time drum set at the zero position and all the stepping switches moved to the beginning position, the simulator was ready to operate.

## Equipment operation tests

In the period of August 1963 to July 1964, a series of five tests (designated A, B, C, D, and E) were made to check the total per-formance of the model. The October 4, 1946, prototype rainstorm event (discussed in greater detail on page 80) was reduced by the design scale ratios and used as the program for the rainstorm simulator.

Mechanical problems of one degree or another were experienced in nearly all the tests. Nevertheless, these tests were valuable, for

they indicated where modifications were necessary and demonstrated the way the liquid would flow from the model's fiberglass surface. Information from these tests has been summarized in Table 7.

As is indicated in the summary, filtered city water (high in dissolved calcium) was used in tests A through D. A progressive change of the rainstorm simulator performance occurred and a major deteriorating effect was traced to flow restricting calcium deposits forming on the ends of the capillary tubes. This problem was corrected by purging the system with a weak acid solution and then using distilled water in the subsequent tests.

Operation of one module affected the water supply to a neighboring module. An improvement was made by installing a larger supply line and two supply sources, one at each end of the model.

Misalignment of the pump-to-motor mountings caused the pumps to bind and to perform erratically at slow speeds. To avoid rebuilding the mounts, adjustments were made and all the pump-motor units were checked and serviced before each test.

As the input water flowed onto the surface of the topographic model, it did not flow smoothly from the model's surface, but instead gathered as large beads of water, which periodically ran together and then came off the surface in spurts or small slugs of flow. These spurts or slugs quickly coalesced in the channel system, producing a continuous flow at the outlet. The wetting characteristic between the

Table 7.   Summary of the information from tests A-E

| | Trial A | Trial B 1 | Trial B 2 | Trial B 3 | Trial C | Trial D | Trial E | Montaño[g] W-I Reduced |
|---|---|---|---|---|---|---|---|---|
| 1. Runoff began in minutes | 5.67 | NR[a] | 10.56 | 5.95 | 5.81 | 5.63 | | 5.15 |
| 2. Runoff ended in minutes | 9.33 | | 19.50 | 20.00 | NR | 13.00 | | 10.28 |
| 3. Total runoff in cc | 537.4 | | 93.4 | 125 | 878 | 115 | None | 286 |
| 4. Storm volume in cc | | | | | | | | 758 |
| 5. Estimated input in cc | NR | | NR | NR | NR | NR | 870 | |
| 6. Type of liquid used | FCW[b] | | FCW | FCW | FCW | FCW | DW[c] | |
| 7. Model's surface condition | P&Dry[f] | | P&Dry | P&Dry | P&Dry | P&Dry | P&Dry | |
| 8. Level of model | Level | | Level | Tilt | Tilt | Tilt | Tilt | |
| 9. Outflow recording made | None | | L&N[d] | L&N | L&N | L&N | Varian[e] | |
| 10. Problems with test | None | Many | Many | Few | Few | None | None | |

[a] NR — No record
[b] FCW — Filtered city water containing a high percentage of dissolved calcium
[c] DW — Distilled water
[d] L&N — Leeds & Northrup AZAR recorder
[e] Varian — Varian G-10 recorder
[f] P&Dry — Polished and dry
[g] The corresponding points of the October 4, 1946 storm event on Montaño W-I (prototype reduced to the model scale)

model's surface and the liquid influenced the flow over the surface. Significantly, outflow occurred from the dry model when filtered city water was used. This result was quite a contrast to the results obtained when distilled water was put on the dry surface. When distilled water was used, all the input remained on the surface. While other unmeasured factors may have had their influence, the differences in the physical properties of the city water and the distilled water are thought to have influenced the reaction between the surface and liquid sufficiently to explain the contrasting performances.

After completing the modifications suggested by the previous tests, the simulator was reprogrammed with the October 4, 1946 storm. Two tests were made to check out the performance of the equipment. These tests revealed undesired speed fluctuations of the pump motors. Speeds varied to such an extent, after the controlling potentiometers had been set, that it was even possible to detect pitch changes in the sound from the running motors. This action suggested voltage fluctuations and caused an investigation of the problem.

A test of motor speeds versus time, console temperature, and power line voltage gave the information illustrated in Figure 10. Figure 10 shows that the motor speeds of two units dropped considerably during the first thirty minutes of operation and then fluctuated about a mean value the rest of the time. The temperature about the electronic equipment in the program console increased during the first forty minutes of
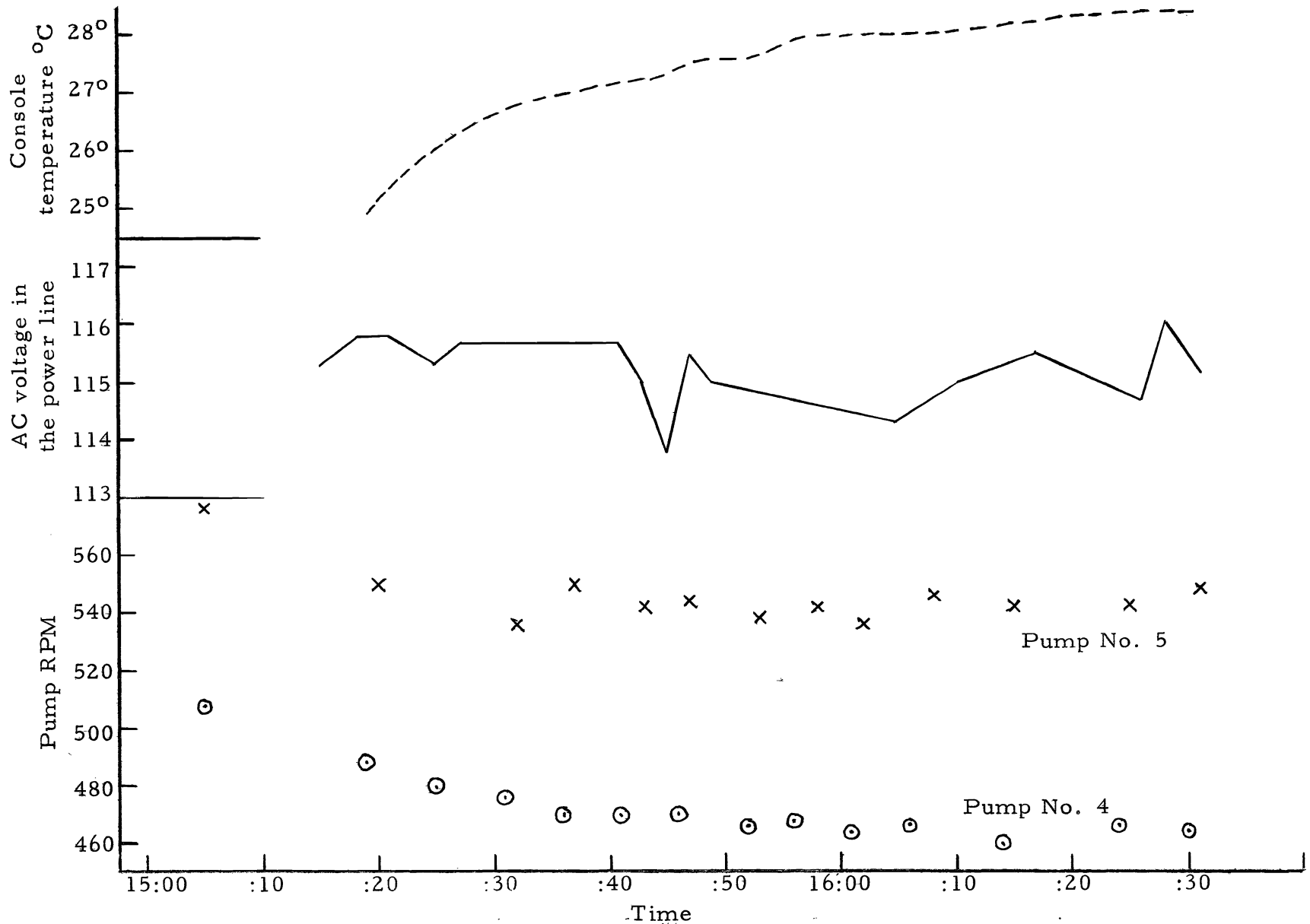
Figure 10. Plot of pump speeds, line voltage, and console temperature vs time

operation. The voltage fluctuated erratically during the entire test. This test showed that the line voltage should be stabilized and that the electronic equipment should be allowed a thirty minute warm-up before a program was set or the rainstorm simulator operated.

To check more precisely the influence of voltage change on the speed, a test was designed to determine the amount of speed change per volt when the line voltage was varied. The results of this investigation are graphed in Figure 11. The plot shows the speed of motor number 5 changing from about 660 to 530 rpm as the voltage fell from 124 to 115 volts, which is a change of 14.5 rpm per volt. The change may be interpreted as a percentage error of 29 percent per volt at the low end of the speed range (50 rpm) to 0.7 percent per volt at the top speed (2,000 rpm), if a linear change over the entire range is assumed. Nevertheless, the change was a good 2.4 percent per volt in the speed range tested. Since the simulator operated a major portion of the time at speeds around 500 rpm or lower, accurate reproduction of the lower speeds was important. Unfortunately the error increased as the speed was lowered.

A long-period test showed the line voltage varied between 114 volts and 124 volts in a six-hour period (8 p.m. to 2 a.m.) which could easily explain a 20 percent change in motor speed between the time the program was set and the model operated. Short-time period (10 minute) fluctuations of 2 volts were common, which easily varied the performance
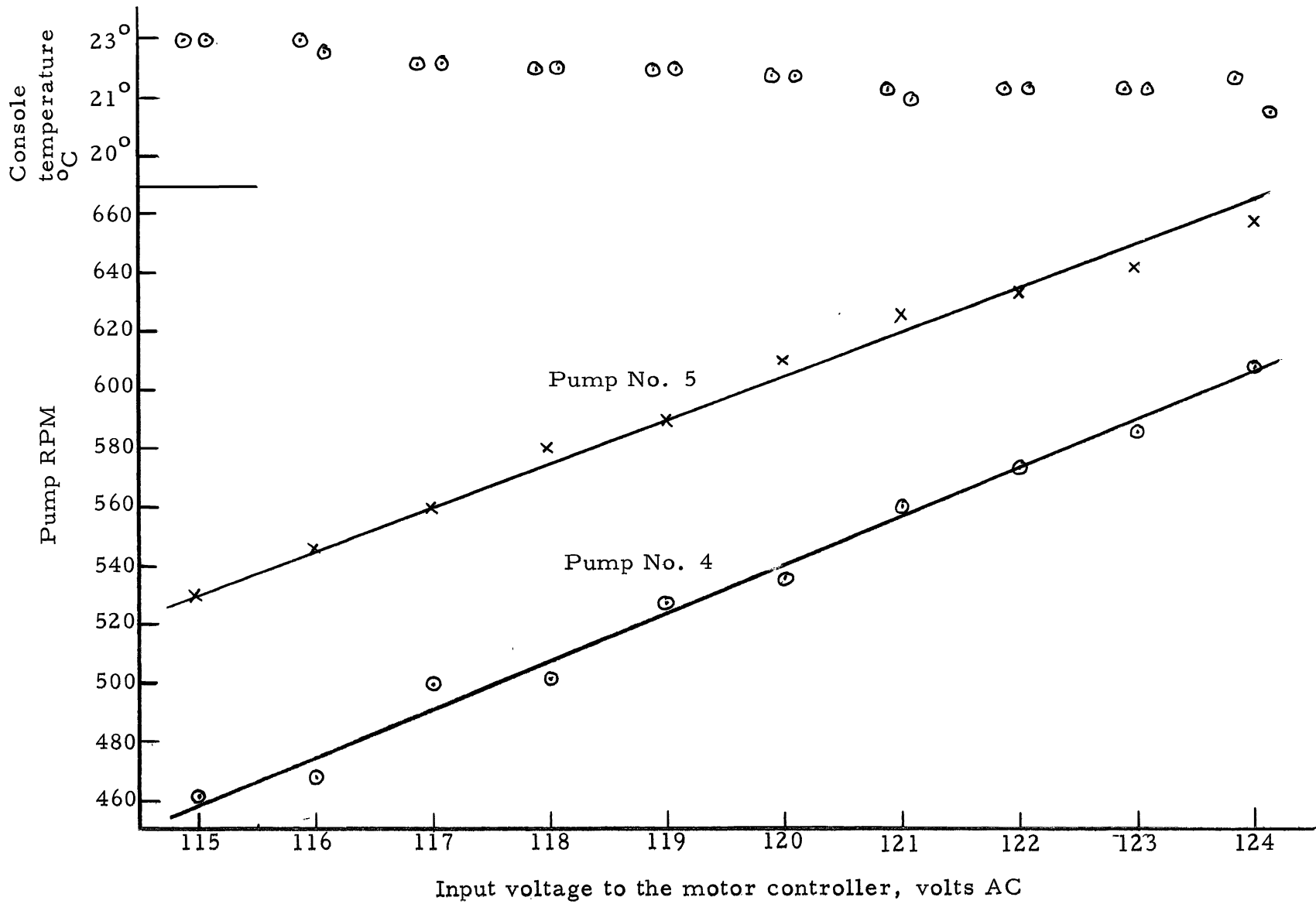
Figure 11. Plot of pump speed versus input voltage to the motor controller

of the simulator as it was running. In the speed range tested, voltage changes could easily have caused a 4.5 percent variation of the input rates during a test.

A test showed that temperature changes in the vicinity of the controlling potentiometers had no effect on the motor speeds. Thus, the conclusion was that power line voltage fluctuations were the main cause of the motor speed variation and would have to be corrected.

To reduce the voltage fluctuations, a simple circuit was prepared which properly loaded a voltage stabilizer. The installed stabilizer regulated the voltage to 115 volts with only a drift of about 1.5 volts occurring in a six-hour period (11 a.m. to 5 p.m.)

Test procedure

With information from the preceding tests, the following test procedure was established. The electronic equipment was allowed to warm up for a half hour. Drum rotation speed and pump speeds were rechecked and adjusted if necessary. All the pumps were operated for a short period of time to prime the system, purge air from the supply lines and tubing, and to satisfy the initial absorption of the dry model surface. If the test run was to be conducted with the surface storage satisfied (entire topographic model's surface covered with water at the point of incipient runoff), water was applied until all areas of the model were producing runoff. If a test was being conducted with a dry surface,

the surface was wiped dry. The water temperature, pressure in the supply line, the air moisture content, and the liquid supply levels were measured and recorded. After these measurements were taken, the rainstorm simulator was put into operation.

While the input was being applied automatically, photographs or general visual observations of the model's performance were made. At the end of the program, the equipment was turned off and the supply water temperature, air moisture content, and liquid supply levels were again measured.

When the outflow from the model had ceased, the recorder was stopped and the chart removed. Finally, the liquid remaining on the surface was carefully collected and measured.

# PRELIMINARY VERIFICATION TESTS

With the few modifications and improvements of the model completed, the ultimate project objective, model-prototype verification, could be approached. Verification is a trial-and-error process of programming the rainstorm simulator with a scaled prototype rainstorm event, comparing model outflow with the prototype hydrograph, and then manipulating the model until the model outflow is a scaled reproduction of the prototype hydrograph.

The first experimental tests with the model were of two types. The tests of one group were the initial effort to program the rainstorm simulator with a scaled prototype rainstorm event and to compare outflow with the prototype hydrograph. These tests are discussed in the section on simulation of a prototype rainfall-runoff event. The tests of the second group were made with an idealized input and are discussed in the section on idealized input tests.

These tests were made without the eleventh module of the rainstorm simulator functioning. Nevertheless, it was thought that useful outflow information could be obtained without the input contribution of this module which covered about 7.5 percent of the total model area. So in these initial tests, the effect of the incomplete simulator was thought inconsequential in the general model-prototype comparisons being investigated.

WEST END
OF MODEL

8

7    6

MODULE 11

AREA NOT CONTRIBUTING
TO FLOW

4

LOW, FLAT AREA
RETARDING FLOW

3

MODULE 10

5

MODULE 9

WATERSHED OUTLET
MEASURING WIER

MODULE 8

MODULE 7

MODULE 6

2

1

MODULE 5

EAST END
OF MODEL

MODULE 4

MODULE 3

MODULE 2

MODULE 1

━━━━ SUBWATERSHED BOUNDARY

━··━ DRAINAGE WAYS
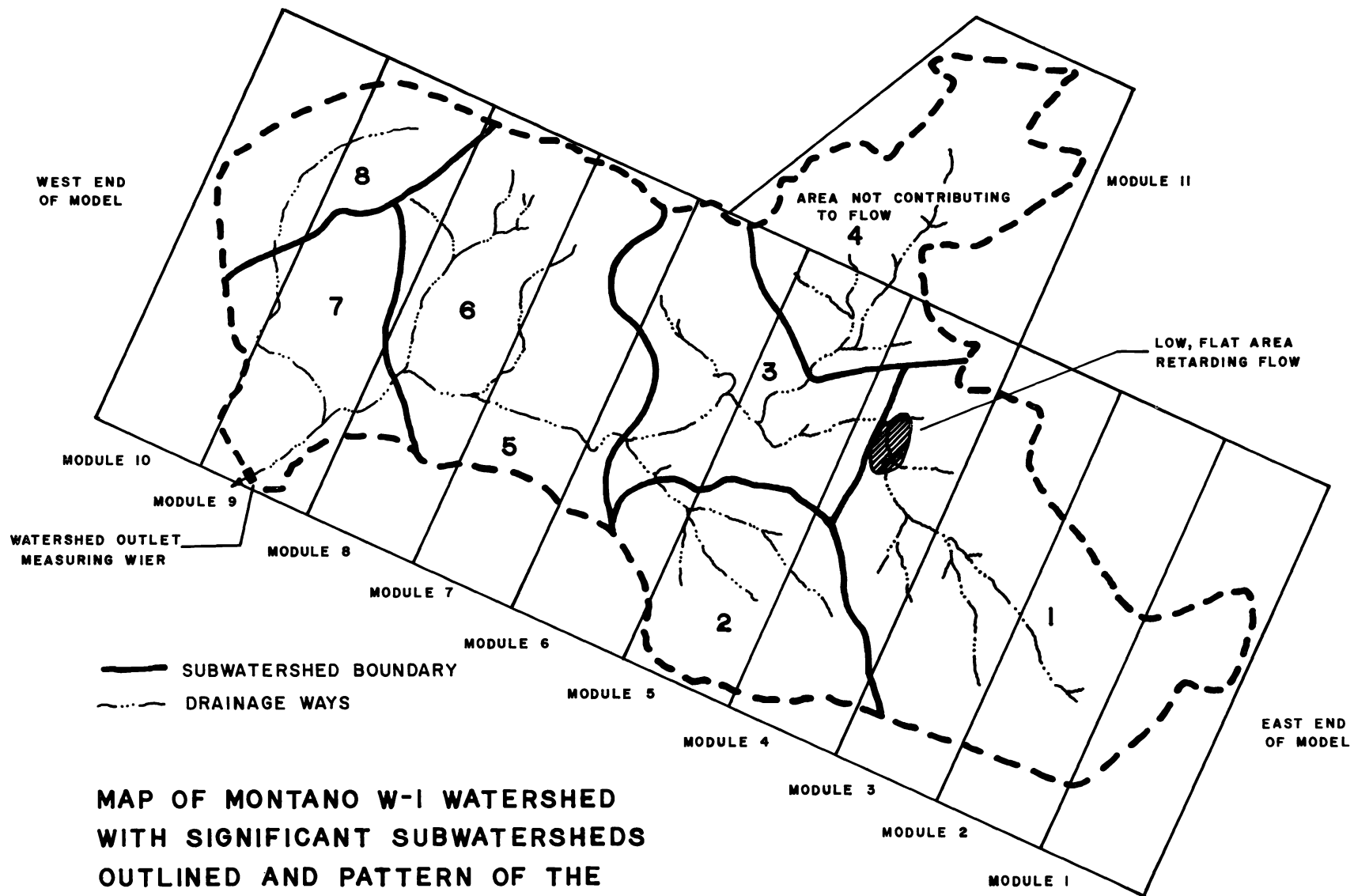
MAP OF MONTANO W-1 WATERSHED
WITH SIGNIFICANT SUBWATERSHEDS
OUTLINED AND PATTERN OF THE
SIMULATOR MODULES SUPERIMPOSED

FIGURE 12

80

The arrangement of the rainstorm simulator modules and the corresponding topographic model area to which they apply input is illustrated in Figure 12. The eight major subwatersheds and a low, flat area are also demarcated in Figure 12 for the use of coming discussion.

## Simulation of a prototype rainfall-runoff event

For the first verification tests, the October 4, 1946, prototype rainfall-runoff event was selected for modeling because of its simple rainfall intensity distribution and runoff hydrograph. Figure 13 presents the rainfall and runoff record of the selected prototype storm event. This event consisted of two essentially uniform intensity rain periods or pulses, the first of 1.20 inches per hour for 4 minutes, and the second of 4.35 inches per hour for 4 minutes. The smaller pulse occurred first and the larger came about 45 minutes later. The records also incidate that the storm began on the west end of the watershed and moved toward the east end of the watershed. This general movement is indicated in Figure 13 by the displacement along the time axis of the rainfall pulses measured at two raingage locations, one at the outlet of the basin (east end of the basin) and the other on the boundary near the top of the watershed (west end of the basin). The positions of the rain-gages are located on the map of Figure 1. The movement of an input pulse over the model has been indicated on the figures by showing the inputs for the first and tenth modules and connecting them with an arrow.
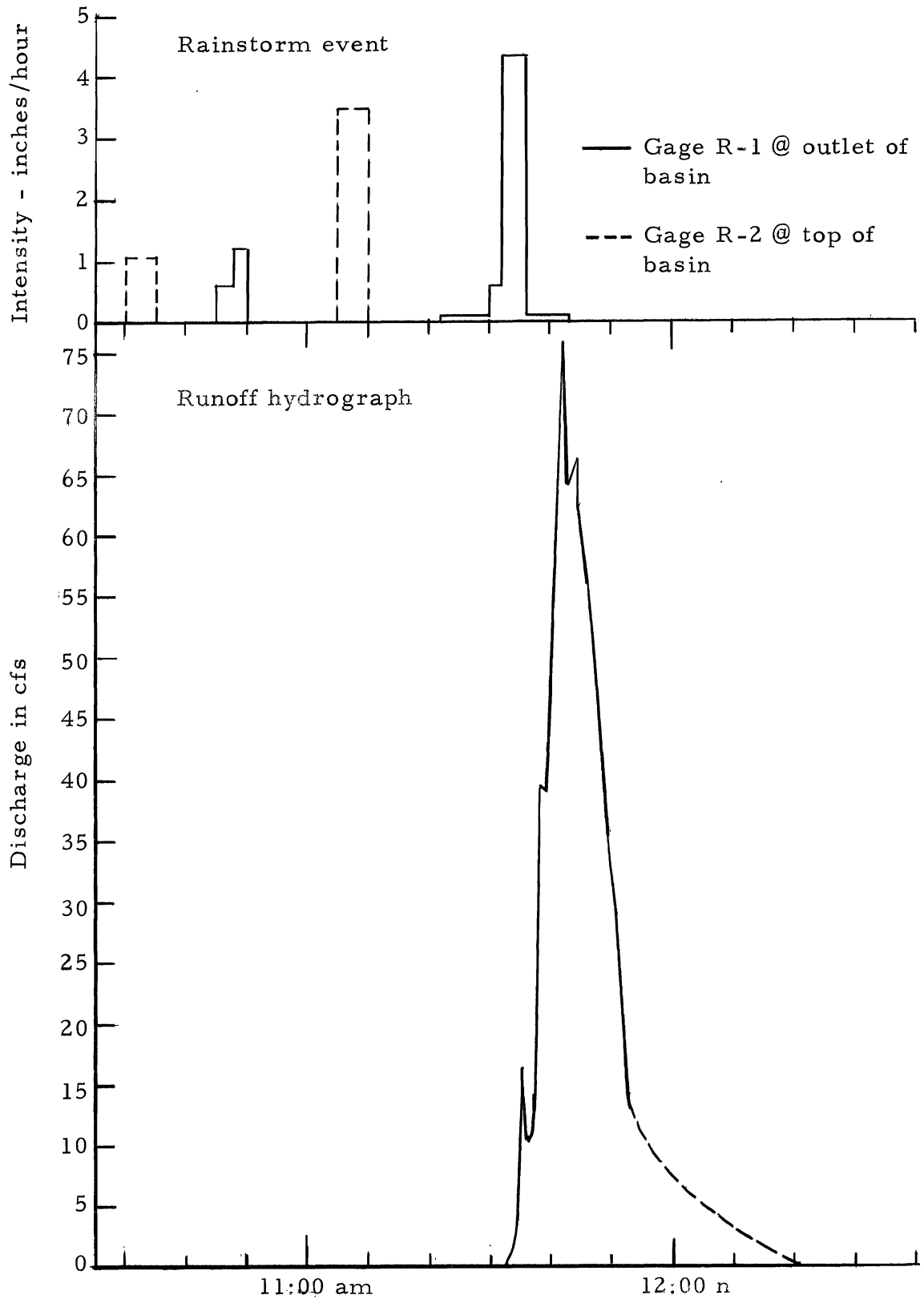
Figure 13. Histogram and hydrograph for the storm of October 4, 1946, Montaño Watershed W-I

Design of the test. Previous experience had indicated that no out-flow would come from the model if the scaled storm was applied to the dry model surface using distilled water as the model fluid. Under such conditions the entire input would be stored on the surface of the model. To assure that there would be an input (precipitation) excess and outflow from the model, two test variations were proposed. The variations were based on two apparent methods of compensating for the initial surface storage: (1) satisfy the storage and then apply the scaled storm, or (2) magnify the input rates of the scaled storm. Thus, four sets of tests were planned and performed. First, the scaled storm was applied to the dry-surface model as a check on the previous experience. This test set was designated F in the discussion and on the figures. Second, the scaled storm was applied to the model with the initial surface storage completely satisfied (G test set). Third, the application rates of the scaled storm were magnified three times and this input applied to the dry model. This test set was designated H. A final test set, I, was the application of the threefold magnified input to the model with the surface storage satisfied.

For these tests, the topographic model was leveled precisely and the accumulated outflow data were recorded on a recorder having a chart speed of one inch per minute.

Discussion of the test results. The discussion has been arranged so that the comparison of the average results from the four variations

is presented first. Then each test variation is discussed independently for its particular significance.

The average outflows resulting from the four test variations are presented in Figure 14. The plots of Figure 14 show all inputs and outflows plotted to the same scale for easy comparison. No outflow resulted in the F test set. The prototype runoff hydrograph has been reduced to the model scale and plotted with the F test set for comparison with the other test results. The outflow plots of the G and H tests are composites, formed from the records of several trials. The information of these composite records is described in the discussion of the G test results. The method of measuring outflow resulted in less measurement accuracy for higher amounts of flow. Consequently, results of the I tests are less precise than the other results and are shown by a dashed line in Figure 14. A detailed explanation of the recording problem is given in the discussion of the idealized input tests.

In spite of the difficulties encountered in reducing the records of accumulated outflow to flow rate information, the average outflow hydrographs do illustrate certain characteristics which have meaningful interpretation. From the observance of Figure 14, two major peaks and possibly a third lesser trailing peak appear as characteristic of the flow. This characteristic two peak distribution of the outflow holds consistently through the results of the idealized input tests, and appears to be determined by the fixed geometric configuration of the topographic
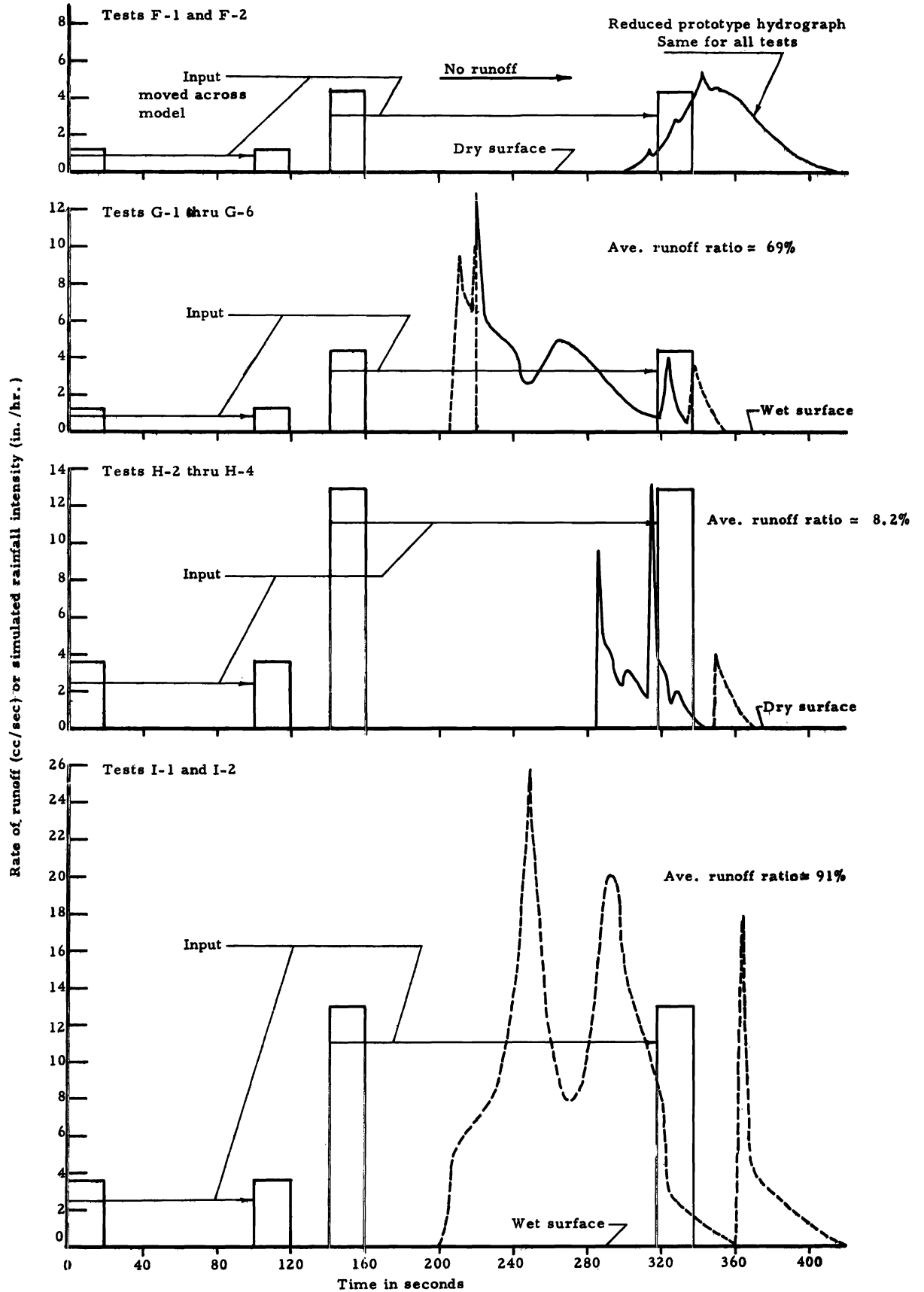
Figure 14  Summary of test results from the simulation of the October 4, 1946 prototype storm event

model. This point is developed further in the discussion of the idealized
input tests.

Maximum discharge rates of both the G and H tests were
approximately 12 cc per second, which was slightly more than twice
the maximum of the scaled prototype peak discharge. Further inspection
shows that the second peak rate of the G test (scaled input with surface
storage satisfied) results in approximately the same value as the peak
rate of the reduced prototype hydrograph. The second peak of the
results from the threefold magnified input on the dry surface (H tests)
is slightly more than twice the peak rate of the scaled prototype
hydrograph. If the second peak rate of the H test is reduced by three,
it would be on the same order of magnitude as the scaled peak of the
prototype. ·Thus, in the results of both tests, the second peak rate
was of the same order of magnitude as the peak rate of the reduced
prototype record. The magnified input on the wet model (I tests)
produced peak discharges on the order of 25 cc per second or over
four times as great as the scaled prototype peak discharge.

As is observed in Figure 14, the outflows from tests in which
the initial surface storage was satisfied began at almost the same time,
approximately 210 seconds after the start of the program. For the
test in which the model surface was initially dry, outflow began about
280 seconds after the start of the program. Thus, in the comparison
of the H test results with those of the G and I tests, the change in

the surface storage condition caused a 70-second shift of the outflow

beginning time. For these tests, the shift amounted to about a 28

percent adjustment of the model outflow beginning time. Possibly then,

the manipulation of storage singularly or in conjuction with other

variables, such as liquid physical property or liquid-surface inter-

action, would provide the distortion control needed to effect model-

prototype similarity.

Also, the outflow of the H tests began within 15 seconds of the

300-second beginning time of the prototype hydrograph scaled by the time

relation derived from the gravity criterion. However, these preliminary

results in no way assure the gravity-time relation as the proper model-

prototype time relation. The time relation must be investigated further.

Tests of scaled input on a dry model surface (F tests) confirmed

the earlier experience of no outflow when distilled water was used as

the model fluid. In contrast, the results of tests A to D recorded

in Table 7 showed that there was outflow from the initially dry model

when water high in dissolved calcium was used in the storm simulator.

Information from the F tests and all the subsequent tests showed that

the average total surface storage was 2,255 cc of distilled water. This

amount of storage is equivalent to approximately 1.16 inches of storage

in the prototype. Thus the estimated input for the F-2 test of approxi-

mately 900 cc (about 0.46 inch in the prototype) was easily stored on

the model surface. Also the variation in outflow results due to different types of model liquid suggests that changing the physical properties of the model liquid may give some latitude or control needed to establish similitude,

A description of the water flow on the model surface may give an appreciation for the great amount of initial surface storage. The water dropped from the rainstorm simulator and formed small puddles on the polished surface in the same way raindrops puddle on the waxed surface of an automobile. The puddles grew, and when they became of sufficient size (about 2.5 cm in diameter) they would suddenly leave their place and flow over the surface as a small slug of water. The storage was contained within all the small puddles. These globules or puddles which formed on the surface of the model are shown in Figure 15.

Six experimental trials were made in which the scaled storm was applied with the surface storage satisfied (G tests). The records of the outflow rate from these trials are plotted in Figure 16. All six records were originally plotted on individual sheets and then transferred to the superimposed plot. Although the outflow hydrographs were different in each trial, a consistency in general shape became more evident when the hydrographs were shifted slightly on the time scale until the major features of each hydrograph coincided as nearly as possible. From the shifted, superimposed plots of Figure 16, an average or composite plot was taken and is the plot of Figure 17. Such a development reduced

Figure 15. Puddles on the surface of the topographic model

Figure 16. Outflow rate plots of six trials at simulation of the October 4, 1946 prototype event (initial surface storage satisfied)

Peaks ≃ 12 - 13 cc/sec.

——— Test G-1
oooo Test G-2
,,,,, Test G-3
×××× Test G-4
——— Test G-5
——··— Test G-6

Figure 17. Plot of the composite outflow from the simulation of the October 4, 1946 prototype storm event with input and scaled prototype hydrograph superimposed
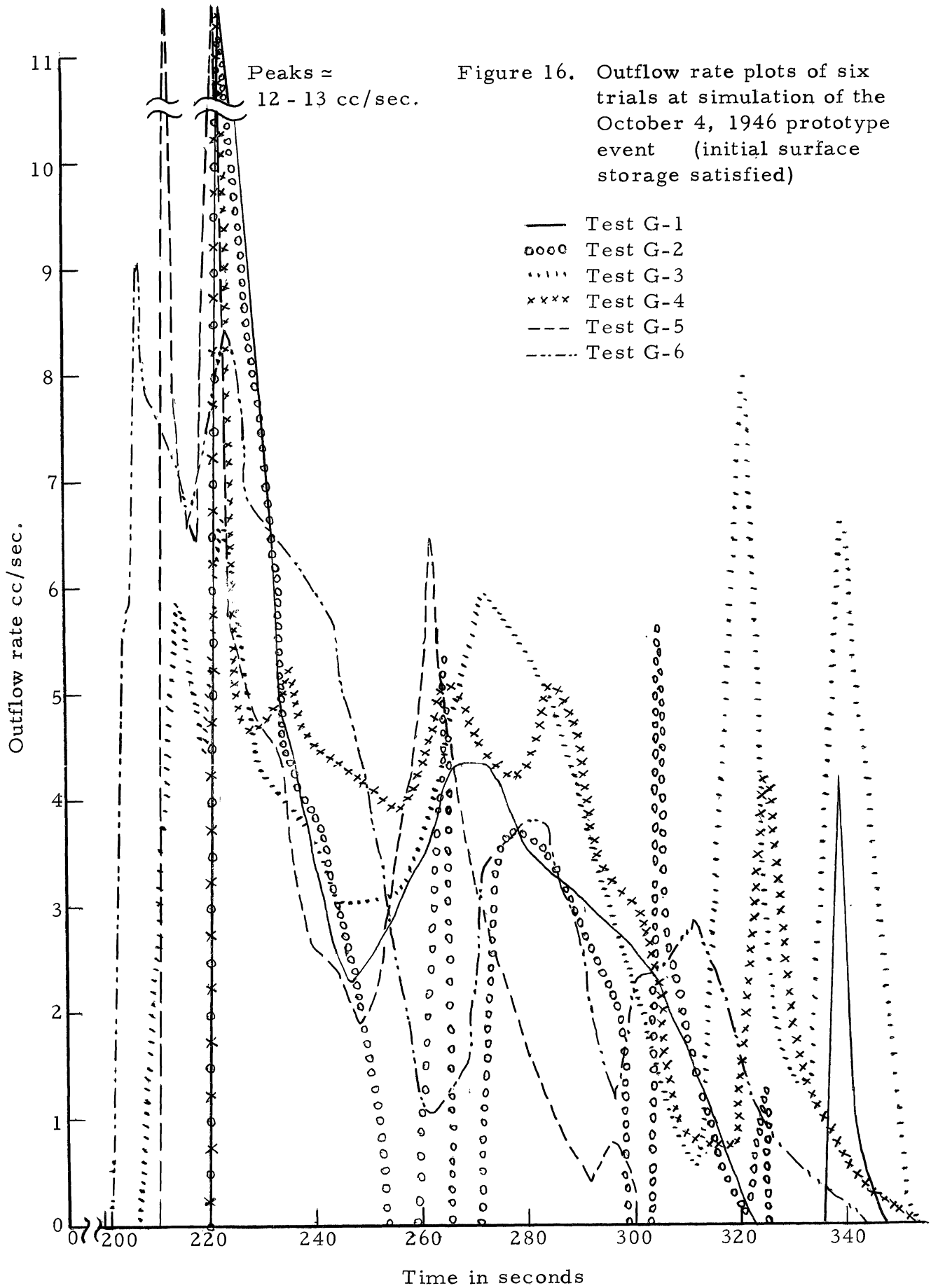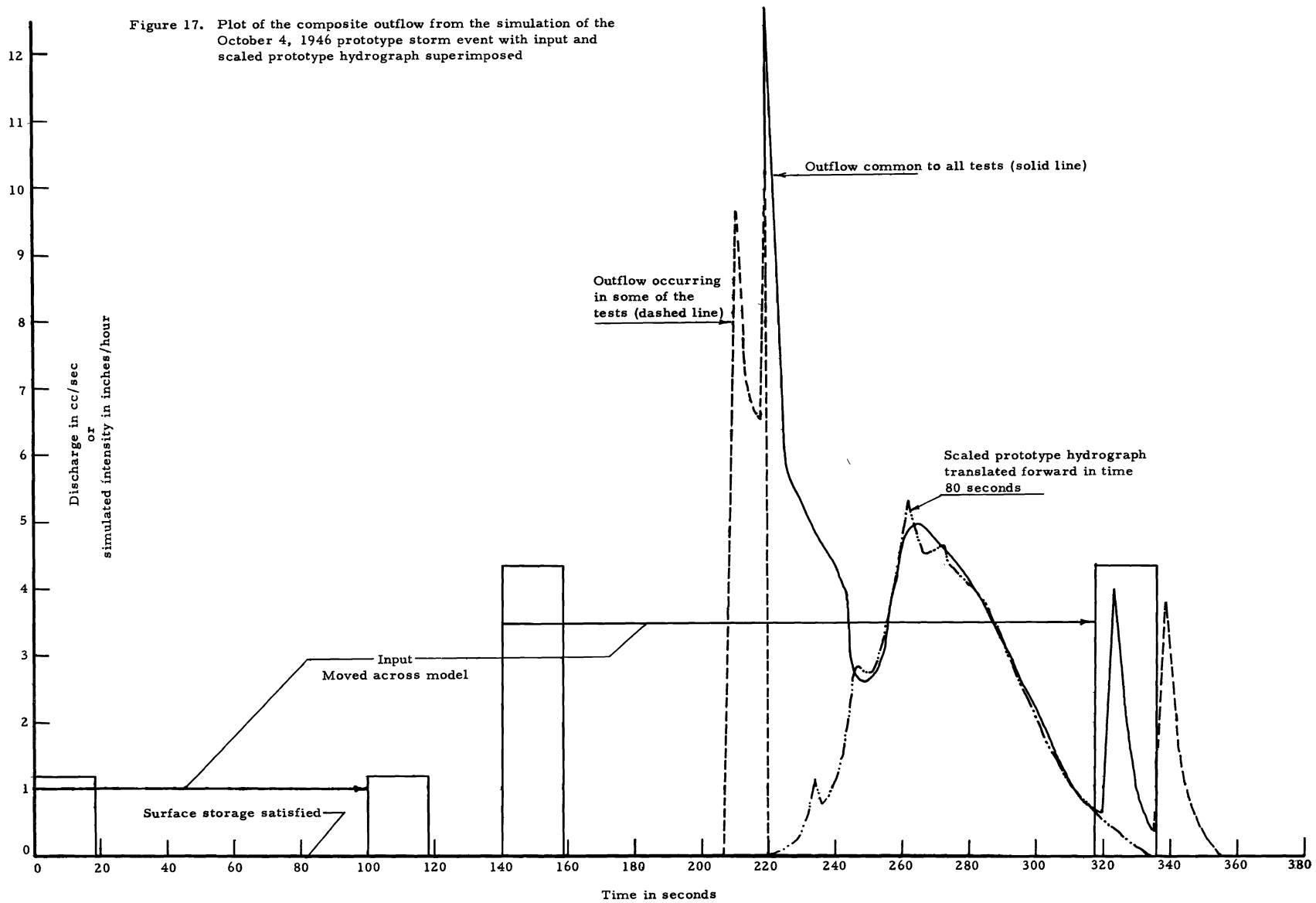
some of the recorded inconsistencies resulting from input variations and inadequate recording apparatus. The same technique was employed to develop the composite rate outflow graph for the H tests.

Three of the six trials in the G test set had an initial peak which occurred prior to the major peak common to all six trials. This initial peak is marked in Figure 17 by the dashed line. In some trials small peaks developed on the recession limbs of the hydrographs. The peak on the recession has also been indicated by a dashed line. The solid line represents the portion of the outflow common to all trials.

Reasons for the differences or inconsistencies are many and complex and were difficult to discover with the limited amount of test information gathered. Scrutiny of the records, however, gave some general explanations of the problems. The small spurts of outflow near the end of the recession were associated with the slug flow which tends to be erratic or at least exhibits some random tendencies. The flow would almost cease, and then some of the water drops on the surface would cascade down, coalesce in the channel and cause a small, quick outflow. A possible explanation for these random bursts of outflow is that the rainfall simulator continued to drip randomly after the program had ceased. The drops hit the surface filled with water in incipient motion and precipitated the movement of a water globule. The globule coalesced with others and the accumulation coursed down to the outlet and was

registered as a small burst of outflow. In succeeding tests, the input was positively shut off at the end of the programmed operation of the pumps. The results of those tests do not show the random recessional bursts of outflow.

In all but one of the  G  trials, the drag in the motor to pump linkage stopped the motor and, consequently, the pump in one or more modules during the application of the low intensity input pulse. In both the  G-2  and  G-6  trials, two motor-to-pump linkages jammed, interrupting the input contribution during the high intensity application. Thus there were obvious mechanical shortcomings, which caused variations in the programmed input.

Another apparent cause of the inconsistency was the different extents to which the initial surface storage had been satisfied. The differences between inputs and outflows for the six trials ranged from 84 to 407 cc, which meant that in each trial between 84 and 407 cc of the average input of about 690 cc went into surface storage. Such contributions to surface storage occurred even though the surface storage was, supposedly, completely satisfied and all the input should have appeared as outflow. However, the measurements of the inflow were not extremely accurate. Thus, the calculation of the input-outflow differences have a limited accuracy, but the range of differences was so great and their values so much more than zero that considerable variation in the initial surface storage was thought to have occurred.

Even though there was known variation in the input which had its
influence, the considerable variation of the initial storage was thought
to be a large contributor to the inconsistencies in the results of the
G trials. The initial storage was supposedly satisfied by operating the
rainstorm simulator until water was running freely from the surface.
The inconsistent results of the G tests indicate that this test procedure
must be improved to assure constant initial conditions.

An intriguing correspondence developed when the scaled prototype
hydrograph was superimposed on the composite result of the  G  tests.
This correspondence is illustrated by the superimposed plot in Figure
17. The prototype hydrograph corresponds closely with the second
low, rounded peak of the model hydrograph, and there is close
correspondence between the beginning and ending times of the two plots.
Since the model input was applied with the surface storage essentially
filled, immediate high rates of outflow occurred, whereas in the
prototype, the high rate of initial infiltration attenuated the first portion
of the flow. The model and prototype outflows approached closer
correspondence in the last three quarters of the outflow time when
either the influence of infiltration became rather constant, or the run-
off was essentially a drainage from storage. Under this condition,
the outflow was no longer a function of input but only of the geometric
basin characteristics. If the model is a faithful conformal represen-
tation of the prototype topography,  an  accurate  simulation

on the recession of the outflow can be expected. Thus, these test results indicate that the topographic model is performing as desired.

The composite outflow results from the scaled storm input with rates magnified three times and applied on the dry model surface are shown in Figure 18. The scaled prototype runoff record was again superimposed on the plot for comparison. The plot shows that for this situation the beginning time of the model outflow approached closely the beginning time calculated for the scaled prototype hydrograph.

The outflow to input ratio of the H trials was about 0.08. The same ratio for the prototype was 0.38 which indicated that almost five times more input appeared as outflow in the prototype than in the model. As a consequence, comparison between the model and prototype outflows was unlikely. Such expected results were found in these tests. The thin compressed double peaked model hydrograph is quite unlike the reduced prototype hydrograph. In these trials, the surface storage on the model varied between 1,550 to 1,664 cc and the input varied between 1,692 to 1,798 cc. The change in storage was not directly correlated with the increase or decrease of the input; consequently, the variation was also influenced by other factors, possibly ambient temperatures. However, the threefold magnification of the input rates was barely sufficient to cause outflow from the dry model surface. Further the model outflow which did occur came from the number two area (Figure 12) and areas adjacent to the main channels. It was therefore concluded

Figure 18. Plot of the composite outflow from the magnified simulation of the October 4, 1946 prototype storm event with input and scaled prototype hydrograph superimposed

Discharge in cc/sec or simulated intensity in inches/hour

Input
Moved across model

Surface dry

Composite result of model outflow

Scaled prototype hydrograph

Time in seconds
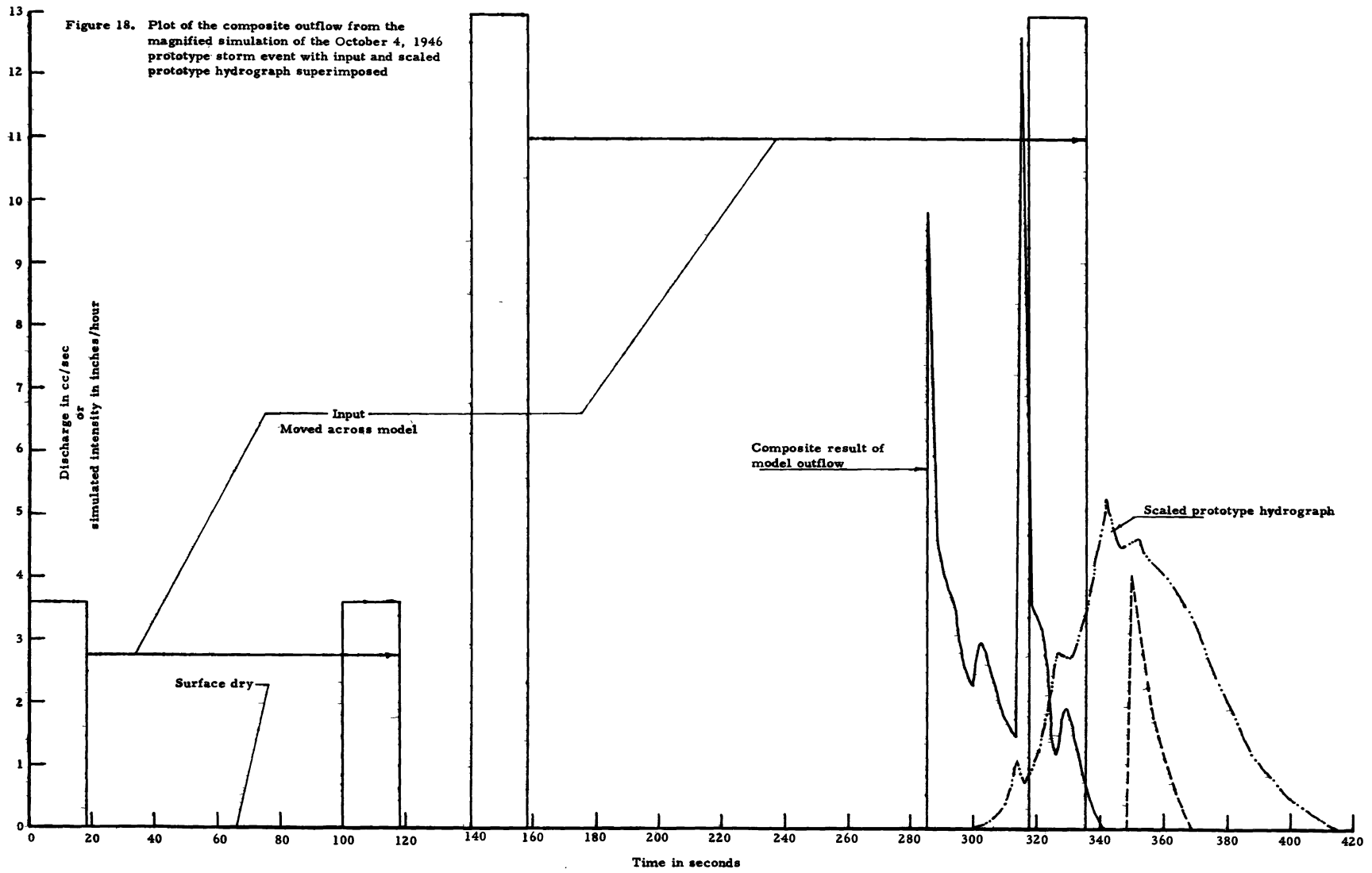
that if the model surface was initially dry either greater magnification of the input rates or alteration of the fluid-surface interaction would be needed to overcome the large initial surface storage. By reducing the effects of the initial storage, expanded areal contributions to outflow and greater outflow ratios would occur, and such results should be more comparable with the prototype situation.

The results of the F, G, and H tests suggest several continuing investigations. The contrast of the outflow produced from the dry model depending upon the type of liquid used in the storm simulator suggests using different input liquid physical properties as compensating distortions to accomplish model-prototype verification. Different input liquid properties may possibly be used to adjust the time orientation of the outflow. Manipulation of the input liquid physical properties may significantly influence the liquid-model surface interaction and consequently, the amounts stored on the model surface. Magnification of the model input rates combined with the already suggested manipulations may also be useful in obtaining simulation by reducing the effects of storage and the slug flow. Further, time relations may be developed to relate model outflow with the prototype outflow in establishing a verification. Regardless of what methods are investigated, the G and H tests show that consideration should be given to the distribution of the through-flow abstractions and the output to input ratio. All these aspects of simulation and verification will be studied more comprehensively in later investigations.

## Tests with an idealized input

The first trial runs of the model revealed the need for improved measurement of outflow and more consistent mechanical performance. Inconsistent performance could more easily be traced to particular components of the model system by using a more idealized situation, which would make the tests less complicated. If the causes could be isolated, mechanical modifications could be suggested which would result in improved performance and more faithful simulation. Also, the additional information, provided by the idealized tests, on the model input-outflow relation will be useful in determining and designing further model studies.

Design of the test. The effect of changing the magnitude of single input rate applied simultaneously over the entire model was assessed by comparing the outflow results of these four different test variations:

A simulated 5 inches per hour input pulse applied with the model surface initially dry.

A simulated 10 inches per hour input pulse applied with the model surface initially dry.

A simulated 5 inches per hour input pulse applied to the model with the initial surface storage satisfied, and a simulated 10 inches per hour input pulse applied to the model with the initial surface storage satisfied.

Three trials of each test variation were made and compared for consistency. The entire set of tests was identified by a 'J' and either a 5 or 10 was attached to the 'J' to designate a simulated 5 or 10 inches per hour input; the numbers following the 5 or 10 and a dash identify individual trials of the indicated test variation.

Data regarding the physical conditions about the model during each test were gathered and used, to the extent possible to determine causes for inconsistent model performance. This information has been tabulated on the comparative plots of each test variation (Figure 20, 21, and 22). The meaning of some tabulated items is apparent. Others may need additional explanation. The items are:

5. <u>Liquid supply temperature, E,</u> which is the temperature measurement of the liquid in the supply line at the east end of the model (Figure 12). The measurements were made with a mercury thermometer and were the values used to calculate the <u>liquid viscosity,</u> Item 7, and the <u>liquid surface tension,</u> Item 8, of the input liquid.

6. <u>Liquid supply temperature, W,</u> which is the temperature measurement taken by the Trerice temperature recorder which had a temperature probe in the supply bottle at the west end of the model.

9. <u>Estimate humidity during test,</u> which is the average value of before-and-after test, air humidity measurements.

10. <u>Volume measured under hydrograph,</u> which is the planimetered area under each outflow hydrograph expressed in cubic centimeters.

11. <u>Total outflow accumulated in the can,</u> which is the outflow volume in a container after the outflow passed through the recording apparatus. The process of collecting the outflow caused occasional spillage and thus could not be used as a standard.

12. <u>Total outflow accumulated on chart,</u> which is the total outflow as indicated on the accumulated mass record.

13. <u>Percentage difference in the volume of the hydrograph,</u> which is obtained by taking the difference between the total volume as recorded on the chart and the total volume as measured under the hydrograph and expressing this difference as a percentage of the total recorded volume. This value gives an indication of the accuracy with which the mass outflow record was transformed to an outflow rate graph and the error caused by the outflow recording device.

14. <u>Amount of liquid remaining on surface,</u> which is the volume of liquid stored on the model surface at the conclusion of each test.

15. <u>Estimate of input volume,</u> which is the estimate of the total input to the model for each trial. This estimate was obtained by measuring the total amount of liquid withdrawn from the supply and applying a correction for the amount which falls outside the model boundaries.

16. <u>Runoff ratio</u> is the ratio of the total outflow, as indicated on the chart, to the estimated input volume.
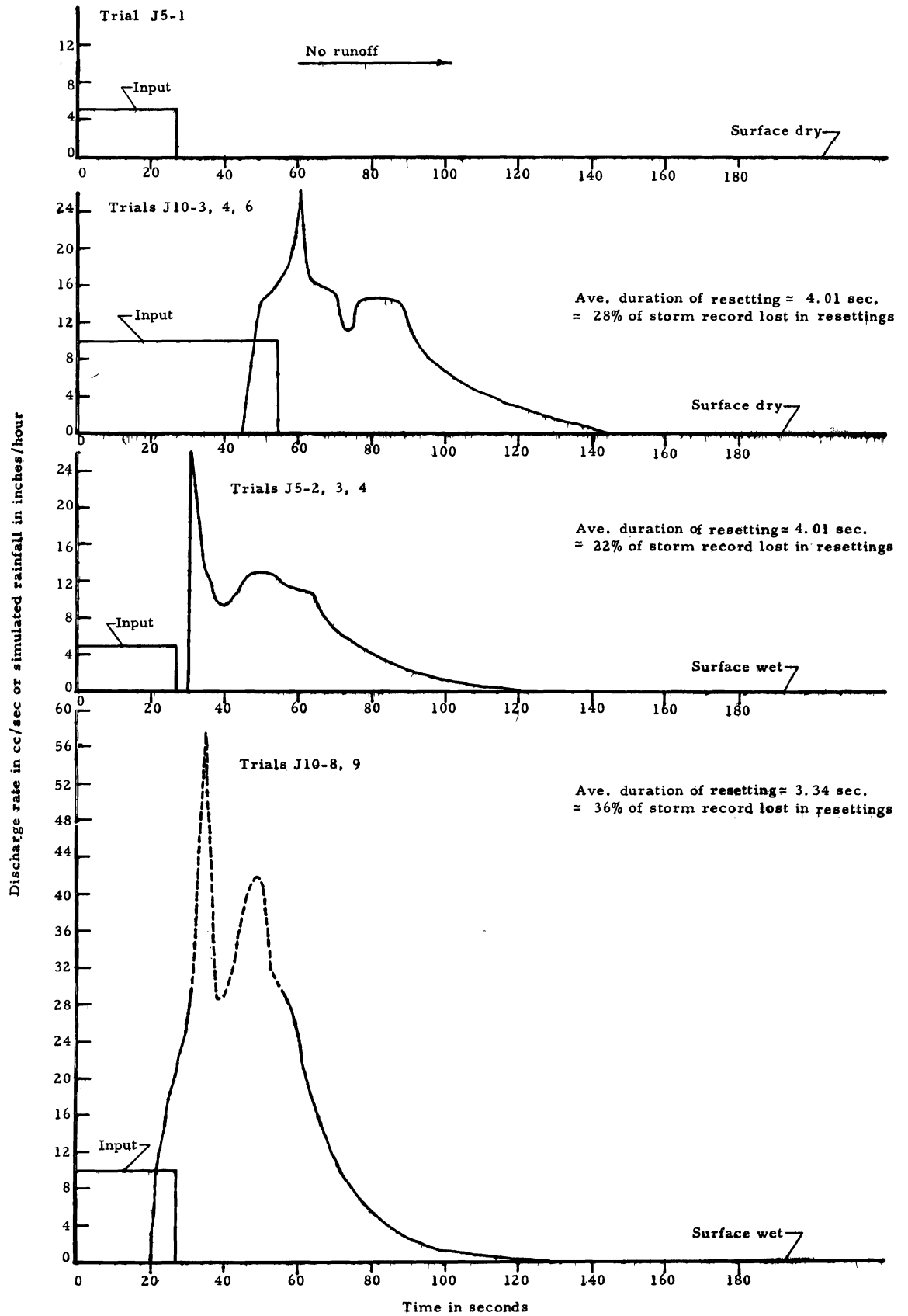
Figure 19. Summary of the outflow results from the idealized input tests

that Area 2 (Figure 12) drained more readily and in many tests

contributed the first runoff at the basin outlet. A low, flat area at the

outlet of the first area ponded and retarded the flow from this portion

of the model. Thus, it is thought that the first peak of all the hydrographs

represents the arrival of flow from Area 2 and that the second, rounded

peak represents the retarded contribution from Area 1. The observation

however, is only qualitative and suggests the desirability of tests to

isolate the contribution of various portions of the basin to the final

outflow.

As was expected, the outflow beginning time advanced when the

initial surface storage was completely satisfied. This time also

advanced slightly with increased application rate. From a comparison

of the J10-3, 4, 6, and J10-8, 9 plots in Figure 19, the beginning time

of outflow from the simulated 10 inches per hour input on the _wet_ model

occurred approximately 25 seconds before that of the outflow coming

from a simulated 10 inches per hour input on a _dry_ model. For these

two tests, the time the major peak occurred advanced the same amount

(25 seconds) as the beginning time of the outflow. If for these two tests,

the average base time of the flow is taken as 105 seconds, both the

beginning time of the outflow and the occurrence of the peak flow advanced

about 24 percent of this average base time when the input was applied with

the surface storage satisfied. For the simulated 5 inches per hour input,

applied uniformly and for approximately 27 seconds, to the dry model, no

runoff was produced. When this same input was applied to the wet

model, runoff began approximately 30 seconds after the start of the

program.

In the tests with the surface storage satisfied (J5-2, 3, 4 and

J10-8, 9), the outflow beginning time of the test using the higher input

rate advanced about 10 seconds ahead of that of the flow resulting from

the lesser input rate. This advance amounted to about 11 percent of the

90-second base flow time of the J5-2, 3, 4 tests. However, the time

and peak flow occurred did not respond in the same fashion. On the

contrary, the peak outflow from the higher input rate occurred a few

(3-5) seconds later than the peak of the lesser input rate. This move-

ment of the peak times amounted to about 4 percent of the 90 second

base time, which was not very significant. The situation does, however,

illustrate that the higher input rates began generating outflow more

quickly and in this particular comparison the higher input rates took

longer to build up to the maximum outflow rate.

Both the J10-3, 4, 6 and J5-2, 3, 4 tests had average peak

discharges of about 26 cc per second. Thus, doubling the duration

and input rate (a fourfold increase in volume) to a dry model surface

produced peak runoff rates of almost the same value as those resulting

from the lesser input on a wet surface. With the surface storage initially

satisfied (wet surface) an increase of input rate from a simulated 5

inches per hour to 10 inches per hour caused a little more than a two-

fold increase in the peak discharge rate, 26 to 58 cc per second.

The superimposed outflow hydrographs (comparative plots), with tabulated physical data, for the several trials of three test variations are shown in Figures 20, 21, and 22. Theoretically, repeated trials of the same test should produce identical results. The comparative plots show the extent to which results were duplicated. Although successive trials of the same test did not produce identical results, the several trials of the same test do exhibit similar shape characteristics and near correspondence at many points. Some reason for inconsistent performance can be found in an analysis of the information gathered during each trial.

In Figure 20, a good correspondence exists among the peak times. All three peaks occurred within a 2-second period. An obvious disparity is apparent among the outflow beginning times. Both the J10-3 and J10-6 outflows began approximately 10 seconds before the J10-4 outflow. Observers watching the model noticed that flow from the fifth and sixth areas of the model (as outlined in Figure 12) contributed the first runoff in the J10-3 and J10-6 trials. In the J10-4 trial, flow from the second area arrived at the outlet first.

The percent difference in the volume of the hydrograph (Item 13, Figure 20) indicates that the reduction to a rate curve of the J10-4 accumulated outflow record was the least accurate of the three reductions. This circumstance, however, has no bearing on the determination of the beginning time, because the inaccuracies of reduction accumulated after

| Item | Trials | | |
|---|---|---|---|
| | J10-3 | J10-4 | J10-6 |
| 1. Date of test | 6 Aug 64 | 6 Aug 64 | 6 Aug 64 |
| 2. Time of test | 10:55 | 11:47 | 15:42 |
| 3. Liquid used | DW | DW | DW* |
| 4. Air temperature ($^{o}$F) | 78.0 | 82.0 | 82.5 |
| 5. Liquid supply temp., E ($^{o}$F) | 77.5 | 80.0 | 84.0 |
| 6. Liquid supply temp., W ($^{o}$F) | 78.0 | 80.0 | 82.5 |
| 7. Liquid viscosity (centipoise) | 0.8881 | 0.8608 | 0.8380 |
| 8. Liquid surface tension (dynes/cm) | 71.93 | 71.71 | 71.35 |
| 9. Est. of humidity during test (dew pt.) | 64.5 | 66.0 | 69.0$^{o}$F |
| 10. Vol. measured under hydrograph (cc) | 811.5 | 689.2 | 830.8 |
| 11. Total outflow accum. in can (cc) | 752.0 | 613.7 | 768.6 |
| 12. Total outflow accum. on chart (cc) | 742.7 | 615.8 | 774.0 |
| 13. % difference in vol. of hydrograph | +9.3 | +11.9 | +7.4 |
| 14. Amt. liquid remaining on surface (cc) | NR | 1756.6 | 1752.0 |
| 15. Est. of input volume (cc) | 2480 | 2485 | 2460 |
| 16. Runoff ratio | 0.300 | 0.248 | 0.314 |
| 17. Amt. liquid on surface before test | 0 | 0 | 0 |
| 18. Rotation time of drum (min. & sec.) | NR | 4'30.8" | 4'26.1" |
| 19. Set rotation time (min. & sec.) | 4'32.4" | 4'32.4" | 4'32.4" |
| 20. Outflow liquid temp. ($^{o}$F) | 75.2 | 77.4 | 79.5 |

*Distilled water

Figure 20. Comparative plots of the outflows resulting from a simulated 10 in./hr. uniformly applied on a dry model.

| | | Trials | | |
|---|---|---|---|---|
| Item | | J5-2 | J5-3 | J5-4 |
| 1. | Date of test | 5 Aug 64 | 5 Aug 64 | 5 Aug 64 |
| 2. | Time of test | 10:34 | 11:26 | 12:20 |
| 3. | Liquid used | DW | DW | DW* |
| 4. | Air temperature ($^{\circ}$F) | 77$^{\circ}$F | 78.0$^{\circ}$F | 80.5$^{\circ}$F |
| 5. | Liquid supply temp., E ($^{\circ}$F) | 76.6$^{\circ}$F | 78.7$^{\circ}$F | 81.5$^{\circ}$F |
| 6. | Liquid supply temp., W ($^{\circ}$F) | 78.5$^{\circ}$F | 78.5$^{\circ}$F | 79.0$^{\circ}$F |
| 7. | Liquid viscosity (centipoise) | 0.9061 | 0.8749 | 0.8451 |
| 8. | Liquid surface tension (dynes/cm) | 72.01 | 71.82 | 71.57 |
| 9. | Est. of humidity during test (dew pt.) | 67$^{\circ}$F | 66$^{\circ}$F | 67$^{\circ}$F |
| 10. | Vol. measured under hydrograph (cc) | 465.2 | 563.2 | 574.4 |
| 11. | Total outflow accum. in can (cc) | 412.0 | 576.8 | 572.4 |
| 12. | Total outflow accum. on chart (cc) | 406.5 | 582.8 | 559.5 |
| 13. | % difference in vol. of hydrograph | +14.4% | -3.4% | +2.7% |
| 14. | Amt. liquid remaining on surface (cc) | 2,373.4 | 2,222.7 | 2,170.5 |
| 15. | Est. of input volume (cc) | 518 | 548 | 645 |
| 16. | Runoff ratio | 0.784 | 1.06 | 0.887 |
| 17. | Amt. liquid on surface before test | 2,450 | 2,285 | 2,202 |
| 18. | Rotation time of drum (min. & sec.) | 4'27.0" | ≈ 4'33" | 4'32.4" |
| 19. | Set rotation time (min. & sec.) | 4'32.4" | 4'32.4" | 4'32.4" |
| 20. | Outflow liquid temp. | 23.8$^{\circ}$C | 23.9$^{\circ}$C | 24.2$^{\circ}$C |

*Distilled water

Figure 21. Comparative plots of the outflows resulting from a simulated 5 in./hr. uniformly applied on the model with the surface storage satisfied.

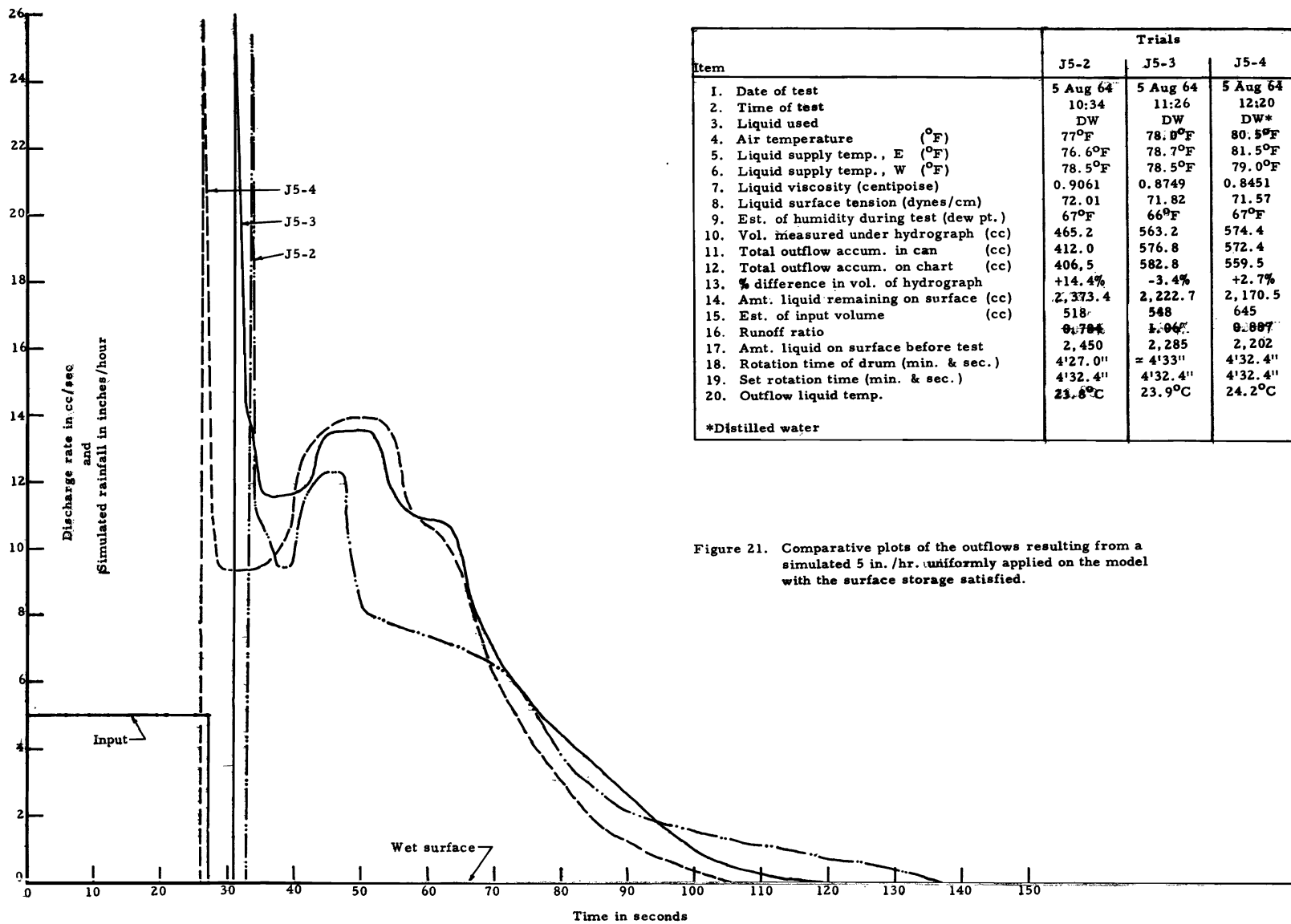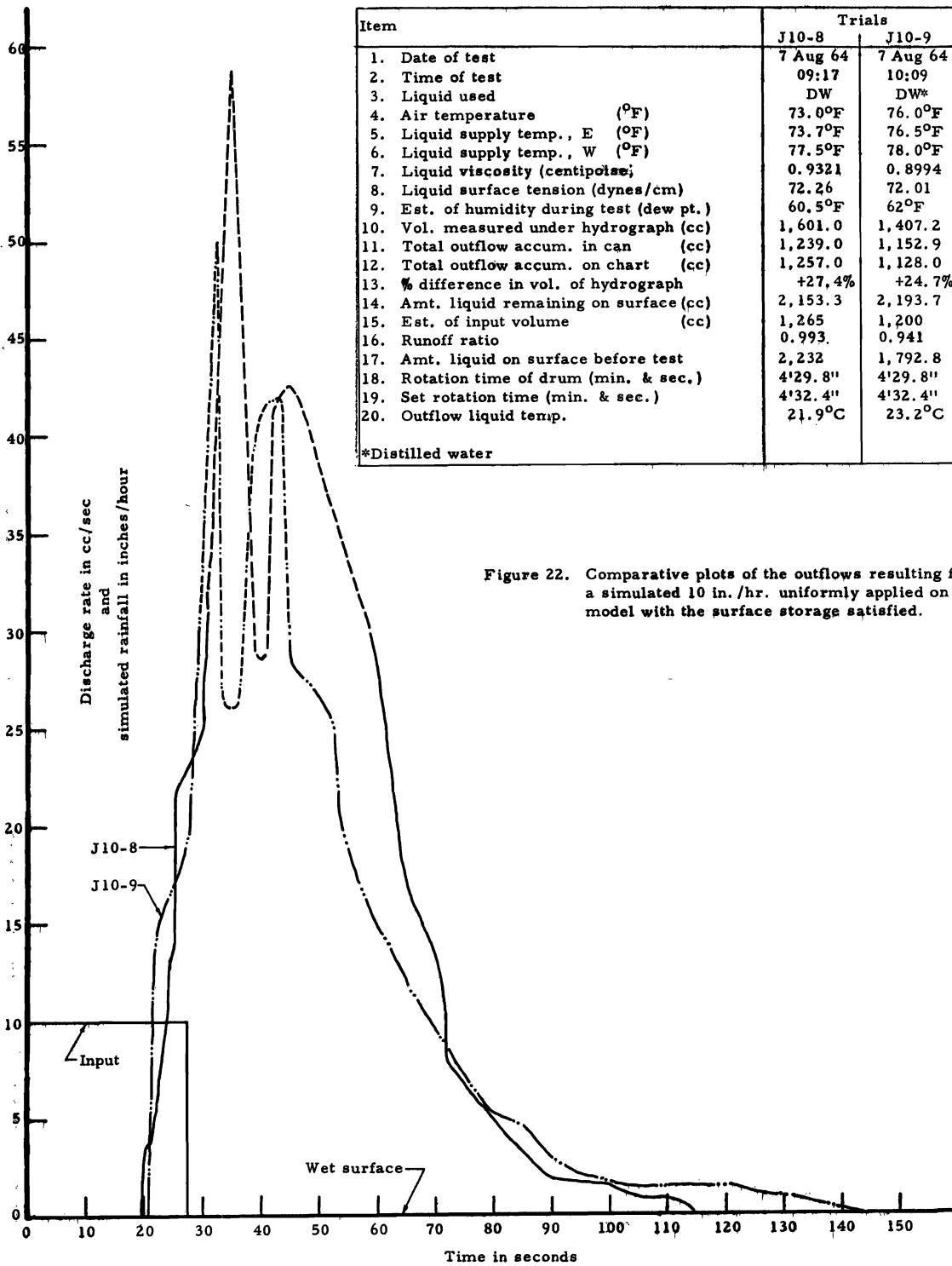| Item | Trials | |
|---|---|---|
| | J10-8 | J10-9 |
| 1. Date of test | 7 Aug 64 | 7 Aug 64 |
| 2. Time of test | 09:17 | 10:09 |
| 3. Liquid used | DW | DW* |
| 4. Air temperature ($^{\circ}$F) | 73.0$^{\circ}$F | 76.0$^{\circ}$F |
| 5. Liquid supply temp., E ($^{\circ}$F) | 73.7$^{\circ}$F | 76.5$^{\circ}$F |
| 6. Liquid supply temp., W ($^{\circ}$F) | 77.5$^{\circ}$F | 78.0$^{\circ}$F |
| 7. Liquid viscosity (centipoise) | 0.9321 | 0.8994 |
| 8. Liquid surface tension (dynes/cm) | 72.26 | 72.01 |
| 9. Est. of humidity during test (dew pt.) | 60.5$^{\circ}$F | 62$^{\circ}$F |
| 10. Vol. measured under hydrograph (cc) | 1,601.0 | 1,407.2 |
| 11. Total outflow accum. in can (cc) | 1,239.0 | 1,152.9 |
| 12. Total outflow accum. on chart (cc) | 1,257.0 | 1,128.0 |
| 13. % difference in vol. of hydrograph | +27.4% | +24.7% |
| 14. Amt. liquid remaining on surface (cc) | 2,153.3 | 2,193.7 |
| 15. Est. of input volume (cc) | 1,265 | 1,200 |
| 16. Runoff ratio | 0.993 | 0.941 |
| 17. Amt. liquid on surface before test | 2,232 | 1,792.8 |
| 18. Rotation time of drum (min. & sec.) | 4'29.8" | 4'29.8" |
| 19. Set rotation time (min. & sec.) | 4'32.4" | 4'32.4" |
| 20. Outflow liquid temp. | 21.9$^{\circ}$C | 23.2$^{\circ}$C |

*Distilled water

Figure 22. Comparative plots of the outflows resulting from a simulated 10 in./hr. uniformly applied on the model with the surface storage satisfied.

the first resetting on the chart. The nature and effect of the recording

problems are explained more fully in the discussion of the J10-8 , 9 tests.

The temperature of the model liquid is thought to influence the

pumping efficiency of the pumps, and the ambient temperature about

the entire apparatus is thought to influence the flow through the fine

capillaries. Ambient temperature effects on the liquid properties may

also vary the storage and movement of the liquid on the model surface.

The net effect of temperature changes has not been definitely established.

Temperatures during the tests were not purposely controlled or varied;

however, temperature changes which occurred were recorded. No

consistent variation of the J10-3, 4, 6 hydrographs (Figure 20)

relating to the slight but consistent increase in liquid and ambient

temperatures could be observed. In three trials conducted at low,

intermediate, and high temperatures, outflow in the intermediate

temperature trial began 9 to 10 seconds after the outflows of the other

two trials began.

Measurements showed that only 616 cc of water flowed from the

model in the J10-4 trial as compared with 743 and 774 cc in the other

two trials. As a result, the runoff ratio of the J10-4 trial was 0.25,

which was somewhat less than the runoff ratios of 0.30 and 0.31 for

the other two trials. Although, the J10-4 data differed from that of

the others in this one respect, the surface storage remaining at the

completion of the test was almost

identical with that of the J10-6 trial. The amounts were 1,757 and 1,752 cc respectively. This figure could not be compared with a like one for the J10-3 test, because an error in the shut-off procedure caused a loss of the information. Also, the J10-4 program ran 4.7 seconds longer than the J10-6 program. The storm simulator operated longer but produced about 150 cc (approximately 20 percent) less outflow than when the J10-6 trial was made.

The programmed input for the J10-3, 4, 6, trials was the constant single input pulse shown in Figure 20. Examination of the residual surface storage, total outflow, and drum rotation time data, however, makes it apparent that the inputs differed from trial to trial. The variation of input between trials naturally resulted in different time orientations and in different inflow histories. In the J10-4 trial the input was probably reduced, which caused the beginning time anomaly observed in Figure 20.

The change in input was undoubtedly caused by slight changes in component performance of the electrical-mechanical storm simulator. Slight voltage fluctuations may have caused the different drum rotation times and variations in motor speeds. Mechanical problems also contributed to the inconsistent performance, but because the data and observations of these experimental tests were limited, the isolation of the specific malfunctioning component was difficult.

The effect of operational and observational improvement can be clearly seen when the outflow results recorded in Figures 20 and 21 are compared with the outflow results shown in Figure 16. The comparison shows that a small change in the recording apparatus and a more careful operating procedure materially improved the performance of the model.

The hydrographs of the J5-2, 3, 4 trials resulting from a uniform input rate of a simulated 5 inches per hour applied for 27 seconds (both values were one-half those of the previous trials) are shown in Figure 21. The calculations showed that the mass records of these trials were, generally, the most accurately reduced to a discharge rate graph.

The 6.7-second time spread between the outflow beginning and peak times of the three trials is relatively large. Since no more than a one-second error could have been introduced by the procedure used to mark the beginning of the input on the outflow record, the operational procedure could not have accounted for the time spread of several seconds. The difference intime orientation may have been influenced by the temperatures. As the input water warmed from 76.6°to 81.5° F and the ambient temperature from 77° to 80.5°F, a proportional advance of the outflow hydrograph seemed apparent. The outflow beginning times and peak times advanced about 1.7 and then 6.7 seconds ahead of those of the first run. The ending times of succeeding trials were advanced in a corresponding manner but in somewhat greater proportion. Thus, the

time base of the hydrograph seemed to shorten somewhat with increasing ambient temperature. Further, the amount of liquid remaining on the surface at the end of each trial diminished with each successive test. This situation suggests that, as the ambient temperature increased, it so affected the liquid properties and resultant surface-liquid interaction so as to reduce the amount of water retained on the model surface. The temperature influence on the liquid-surface interaction, however, is not established and would need further verification.

In the trials in which the initial surface storage was to be satisfied, it developed that the initial surface storage never was completely satisfied thereby introducing another variable which complicated the analysis. The situation then became one of having a certain initial storage on the model and a given input which combined to give a measured output and the storage remaining on the model surface. Outflow and remaining storage were measured within 1 to 2 percent accuracy, whereas the input could only be estimated to within $\pm$ 200 cc or $\pm$ 30 to 40 percent of a 500-to 600-cc total input.

If for the J5-2, 3, 4 trials the outflow amounts accumulated in the can are added to the surface storage at the end of the test, totals of 2,785, 2,799, and 2,742 cubic centimeters are obtained. Thus there is only a maximum difference of 57 cc or about 2 percent between these summed amounts. These sums would be equal to the total input plus the storage on the model prior to the test input, and they indicate

that the sums of input plus initial storage could not have varied by more

than 2 percent. Aside from the different estimates of input that are

not reliable, it still can be inferred that the inputs varied because the

drum rotation times varied enough to cause difference in the inflow.

As a consequence, the amount of the initial storage also varied. Further,

some inconsistency in the distribution of the initial surface storage may

have occurred. Thus, variations in the total amount of input, input

rates, amount of storage, and distribution of the initial storage all

combined to produce the different outflow results which were recorded.

In these tests, the relative differences in outflow for each test appears

high, although it should be observed that with a low output relative

differences would be high even though absolute differences were small.

Again, the exact component responsible for the inconsistency

could not be isolated. Yet the information indicates that the problems

are largely physical and could be rectified with proper modification and

sophistication of the equipment. Many improvements became apparent

with the increasing experience with the model, and these improvements

are listed in the concluding section. The suggested improvements

reflect the many possible sources of error which, when accumulated,

could have produced the different experimental results.

The J10-8 and J10-9 trials (Figure 22) were the application of

the high input rate on the model with the surface storage satisfied. As

a consequence, high discharge rates (on the order of 60 cc/sec) and

nearly 100 percent runoff resulted. These records dramatically illustrate the limitation of the outflow recording device. The time required to change a catchment cup on the weighing arm and for the recorder to again begin recording was designated a resetting. The average resetting time for the J5 and J10-3, 4, 6 trials was 4.01 seconds. Thus, in considering the average number of resettings, five for the J5 trials and seven for the J10-3, 4, 6 trials, and the average duration time of the outflow, 22 percent of the record was obscured due to resettings in the J5 trials and 28 percent was obscured in the J10-3, 4, 6 trials. For the J10-8, 9 trials, the average resetting time was 3.34 seconds. Each trial had twelve resettings, therefore, 36 percent of the record was obscured by the resettings. Because two factors (flow rate and amount of record lost due to resettings) increased, the average hydrograph plotting difference (Item 13) increased from 6.8 percent for the J5 trials to 7.2 percent for the J10-3, 4, 6 trials to 26 percent for the J10-8, 9 trials. For the J10-8, 9 trials, it was most difficult to resolve into a rate curve the mass curves which had been so fragmented by resettings. As a result, some extrapolated portions of the rate curves are poorly defined. These portions of the curves have been indicated by a dashed line.

The recording problem had emerged in the very first tests. Consequently, the first recorder was replaced by one having a chart speed four times as fast (4 inches per minute) for this series of tests. Even this proved

to be insufficient for the high application rates.

Even though the outflow rate plots of the J10-8, 9 trials are of general poor quality, the portions of the curves recording the lower flow rates are reasonably good. Thus the middle portion of the two recessions diverge enough to indicate a characteristic variation in the outflow results. Also the total amounts of outflow collected in the can differ by 87 cc or about 7 percent. Both facts indicate different test conditions which may have been the result of different initial storage conditions, or inputs, or a combination of both. However, the tabulated information shows the rotation time of the timing drum to be the same for both trials. This fact would indicate no voltage fluctuation and near consistent operation of the pumping equipment. With the greater inputs, the estimates of input and surface storage become more useful. Both inputs were estimated to be about the same value, which is consistent with the timing drum rotation information. The estimates of the initial surface storage show a substantial difference. The storage of the J10-9 trials was about 400 cc or 18 percent less than that for the J10-8 trial. This situation indicates that different storage conditions were probably responsible for the differences in the J10-8, 9 results. However, this information does not preclude the event of physical differences between the pumps and discharging ends of the capillaries which would have varied the input.

# CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

A survey of empirical, rational, and theoretical rainfall-runoff relations guided the selection of variables relevant to the design of a physical hydrologic model. A "quasi-dimensional" analysis produced a set of dimensionless products, which guided the design of the hydrologic model. From the developed design, a topographic model and rainstorm simulator were constructed. Finally, two sets of preliminary verification tests were conducted.

The entire development was one of continuous evolution. Once the process of determining the relevant variables had been accomplished and the overall design criteria had been established, the problems of obtaining commercial components and designing other elements of the apparatus were confronted. Each step of the construction involved testing, experimentation, and adaptation. As the storm simulator was completed, attention was given to the development and procurement of instruments to monitor the performance of the model. The initial runs to test the actual performance of the model led to further reassessment and improvement of the entire apparatus. The entire development of the model and preliminary tests involved a process of plan, attempt, re-evaluate, improve and continue testing and improving.

Despite the problems, the model operation in the preliminary tests produced useful information, which encourages continued use of the model. A close correspondence between the outflow recessions of the G test results and the reduced prototype hydrograph may indicate that the topographic model accurately represents the prototype basin geometry as was desired. The fact that the outflow has reflected sensitivity to the input and other conditions is encouraging, because when the input and other conditions are accurately controlled, outflow from the model will reflect the influence of controlled adjustments in input and other variables. For the uniform, single pulse input, the model produced a characteristic double peak hydrograph, which was related to the watershed geometry. This result suggests the value of such models for investigations of sub-area contribution to the total hydrograph. The tests gave some indication of the time translations of the outflow hydrograph due to changes in the input rates and surface conditions. The tests also indicated that variations in the physical properties of the model liquid may allow for further latitude by which to establish verification.

The outflow beginning time for flow which resulted from a magnified scaled input on the initially dry model approached within 15 seconds the 300 second beginning time of the reduced prototype hydrograph. This result gave some assurance to the assumption that the gravity relation approximated the time relation. The time relation

was not exact, however, and thus development of time relations between the model and prototype which would give exact simulation is thought possible and worth investigating. The G and H tests indicated that further investigations should be made of the through-flow abstractions and outflow to input ratio in the search to establish verification. The tests have raised several questions which must be investigated as the process of verification continues and have also suggested some approaches which may help establish the verification. These tests are listed in the recommendations.

In the tests conducted, problems with consistent and accurate performance of the model were experienced. As well as could be assessed, nearly all unsatisfactory performance was associated with electrical-mechanical malfunction. Such mechanical and physical problems should be subject to rectification and as a consequence make the model valuable for basic research. Substantial encouragement to this effect is given by the material improvement of model performance between the first and second sets of tests (Compare Figures 20 and 21 with Figure 16). Between these tests, the installation of a different recorder, and careful priming of the supply system and preparation of the model surface, resulted in considerable improvement of the model performance. The exact cause for each recorded aberration could not be isolated, because several complex interactions were involved, and adequate measurements of the input were lacking. Nevertheless, voltage fluctuations, binding in the gear linkages, air

locks, air seepage into the pumping system, and temperature changes appear to be some of the causal factors. The entire list of recommended alterations and modifications indicates the many possible causes and sources of inconsistency. Improvement of all items would, undoubtedly, improve the model performance to a great extent.

## Recommendations

Recommendations for improvement of the model have been grouped in three categories. First, the needed mechanical and physical improvements; second, instrumentation for measurement; and finally, improved procedural arrangements. Future tests suggested by the test runs to date conclude the recommendations.

Mechanical improvements. Necessary or desirable improvements in the mechanical aspects of the model are:

1. Separate reservoirs to supply the liquid to each module. Individual reservoirs would eliminate the effect of the operation of one module on the supply to an adjoining module and would allow the input of each module to be measured.

2. Improved mechanical gear reduction mounting between the motors and pumps to eliminate binding and jamming.

3. New types of plastic tubing and stainless steel tubing to provide utmost uniformity in liquid distribution.

4. A system of leveling screws on the supports of the topographic model to provide easier and more accurate alignment of the model surface.

5. A stable and dependable power source to supply a constant voltage for the electronic equipment.

6. An air-conditioned, constant-temperature control room, isolated from the model to house the electronic control equipment.

7. A room in which the air temperature and humidity could be regulated and held at constant levels to enclose the model and rainstorm simulator. Such an enclosure would reduce the uncertainties introduced by temperature and humidity changes and slight air currents, which may have some effect. An air-filtering system would also maintain the immaculate conditions desirable for carefully controlled environmental conditions.

8. Items to improve the drum operation of the input program. Improvements may be made by

(a) Installation of a fast zero reset mechanism to reduce the time needed to set the program

(b) Installation of a higher resolution speed-controlling potentiometer than the one now in use to give more accurate control over the rotational speed of the drum

(c) Improvement of the mechanical drive system to eliminate the excessive play in the linkage.

(d) Redesign using such commercial units as the Tenor Impulse Stepping Switches or Sealectro Drum Actuated Switches.

9. Circuitry to automate the start and stop procedures.

10. Independent detachable rainfall simulator modules so that units of grid, tubing, pump and motors form individual units. Such redesigned modules would facilitate installation and servicing and would allow greater adaptability to a variety of hydrologic problems.

11. Distribution heads which would be lighter in weight, simpler and more easily constructed.

12. A new pumping system using diaphragm pumps driven by either a variable speed rotary motion or a variable frequency oscillation may merit consideration.

13. A liquid supply system which is constructed entirely of glass, plastic, and stainless steel to eliminate the possibility of corrosion and fouling of the system.

14. A commercial control unit, such as Controls Division's Data-Trak systems, could be considered in a redesign to control the input program of the rainfall simulator.

Instrumental improvements. Instruments which would improve the operation of the model and the quality of data gathered in operation of the model are:

1. A sensitive outflow rate measuring and recording device.

2. A more accurate means of metering the input liquid such as:

(a) Attach accurately calibrated level gages to the supply bottles.

(b)     Place the supply containers on weighing platforms

and make a continuous record of weight versus time.

3.     A recording voltmeter installed on the main power supply
line to indicate the voltage variations occurring during a test which
affect the operation of the equipment.

4.     An improved motor speed measuring system and possibly
provision for automatic recording of each motor's operation during a
test.

5.     Automatic photographic equipment to photograph the runoff
from the model and other aspects of model operation.

6.     General laboratory equipment and services so that needed
chemical analyses may be made, the needed mechanical services
readily supplied, and the proper electronic test and development
equipment be available.

Procedural improvements.     Incomplete and unsimilar surface
storage was concluded to be a cause of inconsistent model performance.
This situation dictates that operational procedures must be more
precisely standardized so as to provide more consistent initial
conditions.     One possible way to achieve the necessary precision will
be to program the initial storage as well as the input.

An additional observer (two were used) would make it easier to
operate the model and allow for less hurried observations.

<u>Continuing experimental tests.</u>   Tests suggested by the reported studies are:

1.   Tests to establish the influence of the surface storage on the model's outflow, and how manipulation of this variable might contribute to model-prototype verification.

2.   Tests to establish the contribution of each subarea to the composite hydrograph.

3.   Tests using various fluids or water mixtures with different physical properties to develop the compensating distortions needed to verify the model.

4.   Tests to verify or establish the time scale relation between the model and prototype.

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APPENDIXES

Appendix A

Summary of Elaborate Watershed

Discharge Formulas

(According to Chow, 1962, pp. 83-91)

1.  The Adams formula

$$Q = CAI^{12} \frac{S}{A^2 I^2}$$

in which

Q   =   peak discharge $(L^3 T^{-1})$ for all equations, unless other-

wise stated

C   =   constant (1.035)

A   =   drainage area $(L^2)$

I   =   maximum rainfall intensity $(LT^{-1})$

S   =   slope of the drainage area

2.  The Besson formula

$$Q = RTGA^n$$

in which

A   =   drainage area

R   =   total rainfall (L)

T   =   topographic factor

G   =   ground surface conditions

n   =   exponent, $0.5 < n < 0.83$

3.  The Burkli-Ziegler formula

$$Q = CAI \left(\frac{S}{A}\right)^{1/4}$$

in which

    C  =  function of 1) ground surface, 2) relative amount of

          pervious to impervious surface

    A  =  drainage area

    I  =  average rate of rainfall

    S  =  slope of the drainage area

4.  The Craig formula

$$Q = 440 \, C \, W \, \ln \left(\frac{8L^2}{W}\right)$$

in which

    C  =  function of

          1) rainfall (total depth)

          2) channel velocity

    L  =  mean length of the drainage area

    W  =  mean width of the drainage area

5.  The Cramer formula A

$$Q = \frac{C \, C_1 \, R \, A \, S^{1/3}}{57,000 - (27 \times 10^6 \, C_1 \, RA)^{1/3}}$$

in which

C = coefficient, function of

    1) topography

    2) relative perviousness of the ground surface

R = mean annual rainfall in inches

$C_1$ = coefficient function of

    1) ratio of total area to flat area

    2) mean annual rainfall, R

S = mean slope and declivity of the entire basin

A = area of the drainage basin

6. The Gregory and Arnold formula

$$Q = \frac{(3,600\ t)^{4nn_1}}{(1,000)^{2nn_1}} \left(\frac{C_1}{L}\right)^{4nn_1} (CAI)^{4c}\ (C_2)^{8nn_1}\ (S)^{1.5nn_1}$$

in which

C = coefficient representing the ratio of rainfall to runoff

$C_1$ = constant, function of shape of drainage area

$C_2$ = constant, function of

    1) shape of main channel

    2) condition of main channel

I = average rainfall intensity in t time

L = length water traverses in running from most remote

    point in drainage to outlet

S = slope of main channel

n = positive fractional exponent in rainfall intensity formula

$t$ = concentration time

$n_1$ = $1/(4-n)$

A = area

7. The Gregory formula

8. The Gregory and Hering formula

$$Q = CI\,S^{0.186}A^{0.86}$$

$$Q = CI\,S^{0.27}A^{0.833}$$

in which

C = coefficient, function of relative imperviousness of the

ground surface

A = drainage area

I = rainfall intensity

S = slope of the drainage area

9. The Grunsky formula A

$$Q = \frac{C_2\,IA}{t^n}$$

in which

$C_2$ and $n$ = coefficient and exponent function of

1) topography (hilly-flat)

2) relative imperviousness of the ground

I = maximum rainfall intensity

A = drainage area

t = critical time in minutes for continuance of rainfall

10. The Herring formula

$$Q = \frac{R\,V\,A}{640\,L} \quad \text{or} \quad \frac{R\,V\,A}{640\,t}$$

in which

A = drainage area

R = total runoff during a storm (inches)

V = mean velocity of the stream

L = length of the river

t = time of concentration

11. The Lillie formula

$$Q_p = VRC\,\Sigma\,(\theta\,L)$$

in which

V = standard mean velocity

R = 2 + annual rainfall / 15

C = 1.1 + log L

L = length of sectors of drainage area

θ = angle in degrees, at the discharge point, of the sections into which the catchment is divided. The sections are fan-shaped, having a common center meeting at the discharge point.

12. The Possenti formula

$$Q = C\,\frac{R}{L}\,\left(A_2 + \frac{A_1}{3}\right)$$

in which

C = constant (average = 1.72)

$A_1$ = flat area in acres

$A_2$ = hilly area in acres

R = depth of 24-hour rainfall (inches)

L = length of the stream from its source to point of

observation

13. The Protodiakonov formula

$$Q_m = 16.67 (I_d k - i) A_k$$

in which

$A_k$ = drainage area

$I_d$ = design rainfall intensity, which is selected with

consideration to:

1) length of channel in kilometers

2) half width of the drainage area

3) velocity of flow in the channel

4) velocity of overland flow

k = climatic factor equal to the ratio of the maximum rain-

fall intensity at the given watershed to that at the center

of European Soviet Union

i = permeability of the soil (cm./min.)

14.  The Rhind formula

$$Q = \frac{CSRD^n}{L}$$

in which

C = coefficient, function of R/L

S = slope of channel three miles above discharge point

R = greatest annual rainfall

L = greatest length of drainage basin

D = drainage area

n = a variable index

15.  The U.S.S.R. Scientific Academy formula

$$Q_m = \frac{CH^{5/4} r^{5/4} C_1^{3/4} I^{3/17} W^{1/4}}{3 t_c^{5/4} L^{3/4}} \quad (A_k)$$

in which

$Q_m$ = maximum discharge

C = coefficient for maximum discharge, $Q_{100}$, C - 1

H = average water content of snow in mm. before melting

$t_c$ = shortest time for infiltration during a 24-hour

intensive rainfall

r = parameter for forestation, computed by $1/(1 - A_k^1/A_k)$

$A_k^1$ = forested area

$C_1$ = roughness coefficient of the ground cover

$S$ = average slope of the main channel

$W$ = average width of the drainage area $W - A_k/L$

$L$ = length of the outlet channel from the edge of the

drainage area to the outlet

$A_k$ = drainage area

$I$ = rainfall intensity

16. The Walker formula

$$Q = \frac{CRD}{L^{5/6}}$$

in which

$C$ = coefficient, function of

1) relative imperviousness of ground

2) hilly and flat areas

3) channel configuration

$R$ = mean annual rainfall

$L$ = straight line distance from point of discharge to center

of gravity of basin

$D$ = drainage area

Appendix B

## Review of Rainfall Simulator Development

The desire for controlled studies of infiltration and erosion led to
the early development of sprinkling apparatus for small plot studies.
Wisler and Brater (1949) reported that before World War I, Horton was
using a sprinkling system consisting of a number of radial horizontal
pipes about six feet above the ground rotating about a vertical axis,
and driven by the reaction of a series of horizontal jets, to supply water
for infiltration studies.

Parr and Bertrand (1960) gave a rather extensive review of many
devices for sprinkling or applying water for infiltration and erosivity
studies. The first investigator to use a spray nozzle rainfall simulator
was Lowdermilk in his 1930 study of the influence of forest litter on
runoff, percolation, and erosion. He used special Skinner overhead
sprinkling nozzles fitted at 2-foot intervals on two horizontal pipes.
The nozzles were staggered so that the water jets were at 1-foot
intervals and so aimed that jets shot 15 to 20 feet in the air. In 1932,
Duley and Hays, and in 1934, Duley and Ackerman reported erosion
studies in which the water application was made by manually operated
sprinkling cans to field plots of 1/600 of an acre and producing rainfall
intensities of 1 and 2 inches per hour. Also in a 1932 study of soil
erosion, Nichols and Sexton applied artificial rainfall to their study

plots by a series of Skinner Catfish nozzles spaced 1 foot apart and 3 feet above the ground surface. They made no attempt to simulate natural rainfall characteristics.

Craddock and Pearse (1938) made two portable rainfall simulators; one to simulate 0.03 in./min. and a second to simulate 0.06 in./min. rainfall intensities. They used a 2-inch rotary gear pump to supply water under pressure to the sprinkler apparatus, which was a modification of the Skinner overhead irrigation system. The apparatus consisted of two 1-inch pipe lines each 54 feet long (on which nozzles with 1/32-inch orifices were fitted). The pipes were held above the ground on surveyor tripods. A uniform pressure of 19 to 21 psi was maintained in the pipes by using three intake, pressure regulators and gages. Each pipe was connected by a mechanical drive to each other pipe and both rotated simultaneously to give a more uniform application rate. The spray was directed into the air, rising above 25 feet and then falling back to the ground.

Beutner et. al. (1940) used a sprinkler device similar to the D-1 sprinkler apparatus of the Soil Conservation Service. This sprinkler had four stationary 1.5 "Mulsifyre" nozzles mounted on an overhead frame directing a spray of water to a 6 foot by 24 foot plot with an 18 inch border strip. With two nozzles operating, a constant rate of 3 in./hr. was supplied, and with all four nozzles operating, a constant rate of 6 in./hr. was supplied.

To make an analysis of sprinkled plot hydrographs, Sharp (1940) used a sprinkling device with two spray heads, each having seven specially designed spray-nozzles. A spray head was mounted on either side of the plot, and the spray from the nozzles was directed upward, letting the spray arch over and fall on the plot. The drops of this unit were rather large and they fell about seven feet. The distribution was reported to be good. The intensities depended on the number of nozzles being used, approximately 1.65 in./hr. with seven nozzles and 3.30 in./hr. with 14 nozzles. Covers, or caps, were arranged so that the nozzles could be covered or uncovered at will and practically instantaneously.

Duley and Kelly (1941) reported an infiltration study in which they used a sprinkling device consisting of an overhead supply pipe about 6 feet above the ground and fitted with fan-shaped, garden-sprinkler nozzles directed downward. The device was said to give reasonably even distribution of water over the 6-foot, 6-inch by 33-foot plot when the pipe carrying the nozzles was oscillated through an arc of about $60^{\circ}$.

Parsons (1943) gave some interesting notes on the development of the SCS infiltrometers from Type A to Type F. In September 1936, Dr. W. C. Lowdermilk instructed the group of SCS men at the Hydraulic Laboratory of the National Bureau of Standards to construct a suitable sprinkling apparatus for simulation of rainfall on experimental plots of 200 to 300 square foot size. The apparatus described by C. Kenneth Pearse of the Intermountain Forest and Range Experiment Station,

Ogden, Utah, in "Specifications for the construction and operation of a portable apparatus for measuring superficial runoff and erosion" (March 1936) was designated as Type A. Studies were then made of rainfall characteristics and the need to simulate these aspects of rainfall was recognized. A start at meeting these needs was the Type B simulator using Skinner ST50 nozzles. It was created and used in the field by V. J. Palmer and H. N. Holtan. Type C was used only in the laboratory for comparative tests of erosion and infiltration. It was called a "dripolator" or "stalactometer" type because it used a horizontal sheet of muslin with many short vertical strands of yarn hanging from the lower side from which the drops fell. Type D was developed by F. W. Blaisdell to give a large-drop, fairly evenly distributed spray, and to be portable. He used a Grinnel 1.5 "Mulsifyre" nozzle. This Type D simulator was the device used by the Virginia Agricultural Experiment Station and by E. L. Beutner and R. R. Gaebe at the Soil Conservation Experiment Station in Tucson, Arizona. Type E, developed by V. D. Young (Fayetteville, Ark.), used a special spray nozzle developed in Young's laboratory. Type F, also developed by Young, provided a high-energy spray of low intensity, with the minimum possible spray height. The drops fell almost vertically and were evenly distributed over a 6-foot wide area. The FA Type was made in 1939 at the request of G. W. Musgrave and R. A. Hertzler, then of the Flood-Survey Committee.

Wilm (1943) checked the application rates and uniformity of the application for Type FA and Type F infiltrometers, and he suggested improvements to give more uniform application rates and more accurate measurements of the simulated precipitation. Briefly, the Type FA rainfall simulator has three nozzles mounted on a supply pipe supported 30 inches above the ground and 4 inches from the infiltrometer-frame and tilted 4° toward the frame. The Type F simulator has two parallel pipes with 13 nozzles each. The nozzles are placed approximately 6 feet apart and are tilted from their vertical toward the other pipe by a few degrees. The pipes are placed along the side of the test plot and inclined at the same slope as that of the plot.

Ellison (1944) reported a rainfall simulator that he and several colleagues used for various infiltration studies. His device used a tank with 0.042-inch holes drilled on 4-inch centers in the bottom of the tank. The tank was supported at the top of a tower, and the water dripped on a 1-inch mesh chicken wire screen placed directly beneath the tank and loosely covered with cheesecloth. A short piece of yarn or thread was hung from each depression in the cheesecloth and water drops of uniform diameter dripped from these threads. Different yarn sizes were used to obtain different uniform drop sizes. In the studies, drop sizes of 3.5 mm and 5.1 mm $\pm$ 6 percent were produced. Drop velocity was controlled by varying the height of the screen. Intensity was controlled by varying the head of water or changing the size of the holes in the

supply tank. Natural rainfall characteristics were not simulated with this device.

Barnes and Costel (1957) modified the principle of Ellison's infiltrometer by using a full-cone nozzle to spray the water onto a circular drop screen. They mounted a full-cone nozzle at the top and centered in a cylindrical tower with the drop screen 4 feet below the nozzle. From the drop screen the drops fell 8 1/2 feet to the ground surface. With this device it was possible to simulate intensities of 1 to 6 in./hr. on a 13-square-foot circular plot.

Meyer and McCune (1958) developed a portable rainfall simulator, which approximately reproduced the kinetic energy of high-intensity natural rainfall. Referring to the raindrop fall velocities and raindrop size distribution studies of Laws (1941), these men designed a simulator using Spraying Systems Co. 80100 Veejet nozzles placed 8 feet above the ground. The nozzles were pointed downward with the water supplies at a pressure of 6 psi, thus giving a nozzle velocity of approximately 22 fps to the drops. The nozzles were placed in a grid, every 5 feet parallel to and every 6 feet perpendicular to the long dimension of the spray pattern. The nozzles reciprocated back and forth across the slope of the test plot, giving intensities of 2 1/2 in./hr. (nozzles spraying 20 percent of the time), and 5 in./hr. (nozzles spraying 40 percent of the time).

For an erosion study, Shachori and Seginer (1962) designed a rainfall simulator using various overlapping patterns of two-arm rotating sprinklers positioned 2 meters above the ground. Their analysis of the simulated rainfall showed that uniformity of application was reproduced within a 10 percent range lower than natural storms. Intensities were between 6 and 120 mm/hr. and within 10 percent of the designed intensity. Angles of impact of the simulator drops were found comparable to those of natural rain with velocities of 10 to 20 km/hr. The mode diameter of simulator drop size distribution was found to be 0.5 to 1.0 mm, which is lower than the mode for natural rain. Kinetic energy was 60 to 75 percent and momentum 70 to 80 percent of those of a natural storm.

To simulate hurricane rainstorms, a large device, described by Polovkas and Thompson (1952), was constructed at the University of Florida. A small building houses an aircraft engine driving a three prop propeller which simulates the hurricane winds. Behind the propeller in the airstream a grid of steel tubing releases water into the airstream to simulate the rain of a hurricane.

Several devices have been developed to form water drops for laboratory analysis. Rayner and Haliburton (1955) made a rotary device to produce uniform drops of liquids in the diameter range of 50 to 700 microns. A horizontally rotating blade detaches drops from a stabilized liquid jet fed under constant head through a stationary capillary. As the

blade passes through the stream of liquid, it detaches a drop which falls away in a characteristic trajectory. Magarvey and Taylor (1956) describe three drop generators based on the principle of the interrupted jet and on information from Lord Rayleigh's studies, which showed that the disturbance producing the greatest regularity in resolution was one which impressed upon the jet undulations of length approximately 4 1/2 times the diameter. Palmer (1962) reported "an apparatus for forming water drops" which is essentially a water column with an opening in the bottom to accept various gages and lengths of stainless steel tubing. Various static heads were maintained in the water column by a double syphon system. The drops were formed by the disintegration of the waterjet issuing from the small tubes. Syed (1963), reports in his literature review, a rainfall simulator developed by Sor and Bertrand, which was a lucite cylinder, 10 cm high and 14 cm inside diameter. A 2.5 cm thick lucite plate cemented to the bottom of the cylinder had a hundred holes drilled in it and was fitted with glass capillary tubes. A 0.051-inch diameter chromel wire placed in each of the capillary tubes aided in the formation of drops. Various intensities were obtained by varying the head of water in the cylinder.

Syed's (1963) rainfall simulator was a 3 foot by 4 foot wood frame lying horizontal and supported by ropes from the ceiling. In the long direction and down the center of the frame ran a 1 1/2-inch brass tubing water supply line. Smaller brass tubes emanated from both sides and

at right angles to the large pipe and extended to the edge of the frame.

Small polyethylene tubes were inserted at regular intervals along the

brass tubes, with opposite ends put through a masonite sheet tacked on

the bottom of the frame.  The tubing was thus held in a 2 by 2 or 1 by

1 inch grid.  As water was supplied in the main pipe it was distributed

to the small polyethylene tubes which dropped the water on the test

plot below the frame.  By using different lengths of polyethylene

tubing (ID = 0.011 in.) and by varying the head, Syed was able to

reproduce a range of intensities from 1 to 12 inches per hour.  The

drop size was variable, depending on the diameter and length of the

tubing and on the static head.

Keller (1963) used a "water applicator" employing 24-inch long,

0.011-inch inside diameter capillary tubes to study the effects of water

application rates on soil structure.  Keller's applicator had 34 capillary

tubes emitting from a manifold.  The discharging ends of the tubes were

fixed in a plastic lid which fitted over flower pots holding the soil samples.

The application rate was varied between 0.02 to 2.0 inches per hour by

adjusting the water pressure head and/or the percentage of time the

solenoid valve was open.

Appendix C
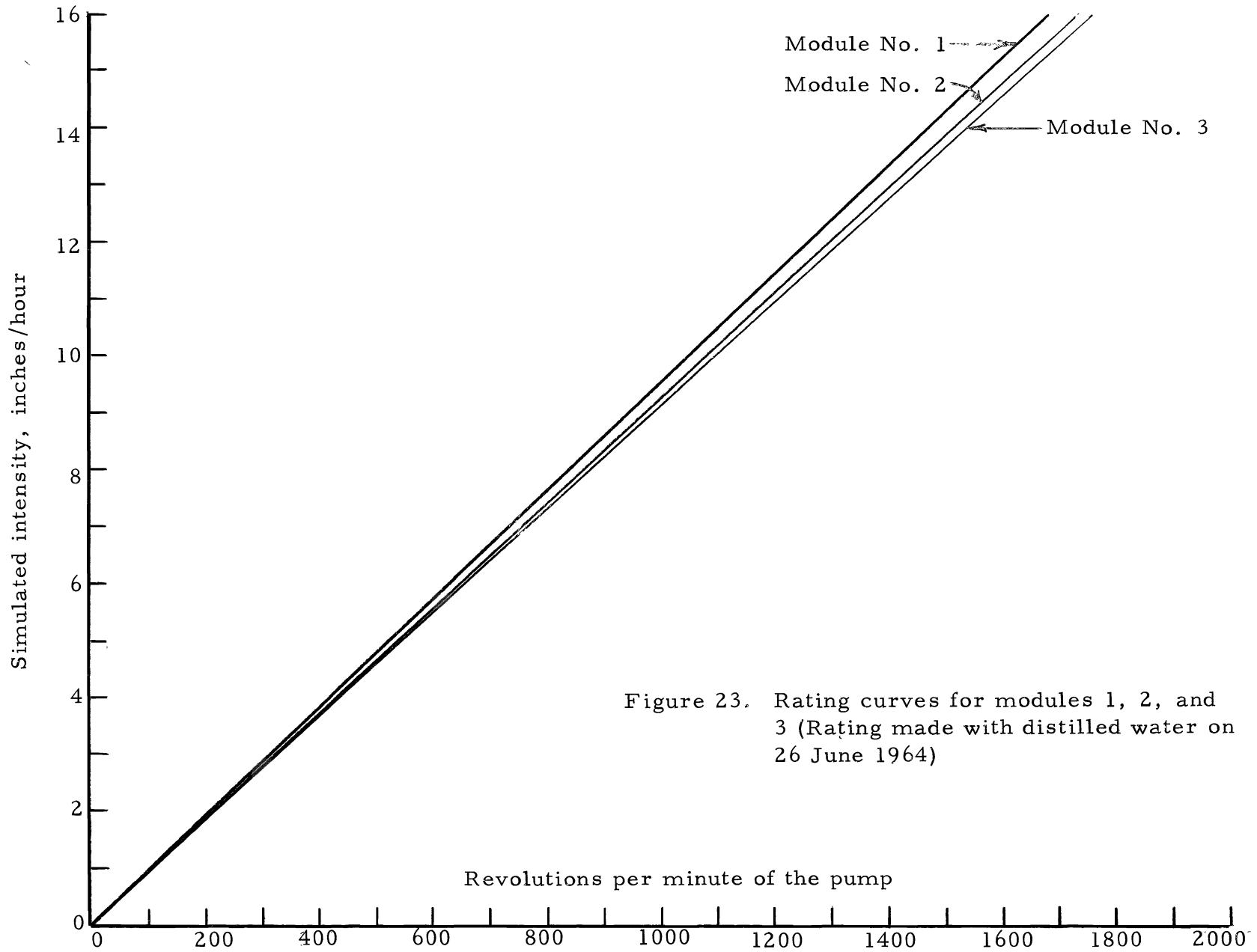
Rating Curves Prepared for the Rainstorm Simulator

Figure 23. Rating curves for modules 1, 2, and 3 (Rating made with distilled water on 26 June 1964)
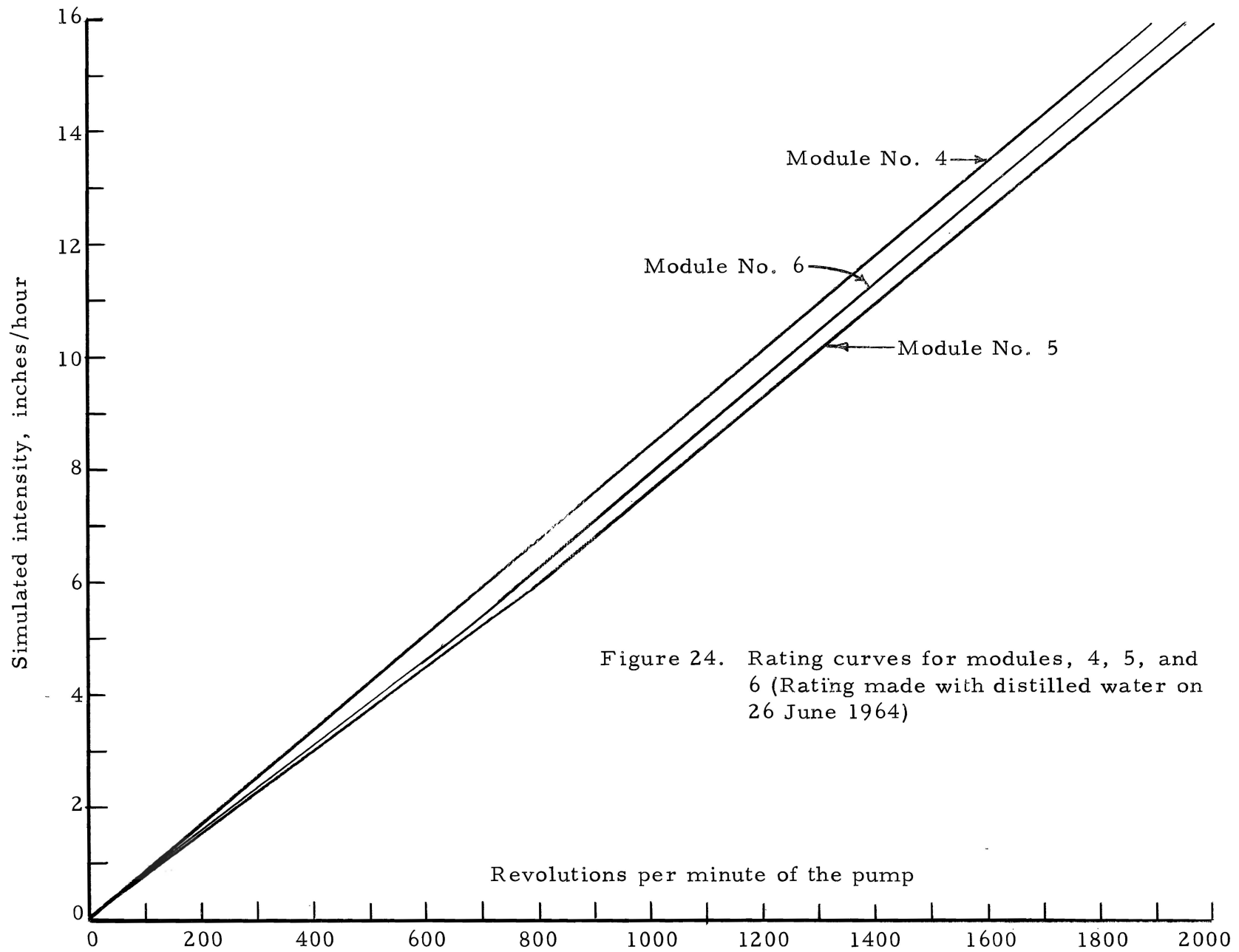
Figure 24. Rating curves for modules, 4, 5, and 6 (Rating made with distilled water on 26 June 1964)
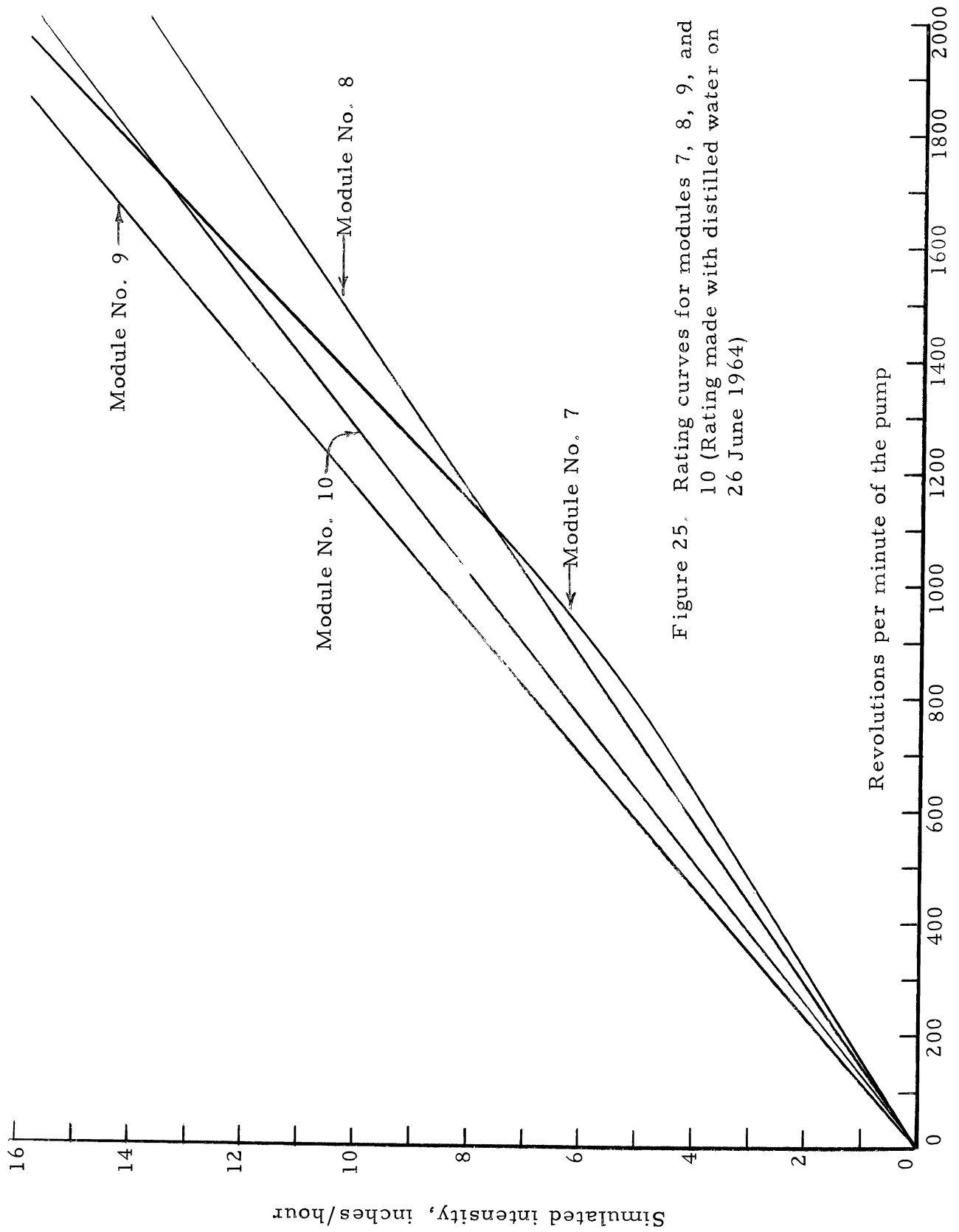
Figure 25. Rating curves for modules 7, 8, 9, and 10 (Rating made with distilled water on 26 June 1964)

Module No. 9

Module No. 10

Module No. 8

Module No. 7

Revolutions per minute of the pump

Simulated intensity, inches/hour