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L. F. Huggins

E. J. Monke

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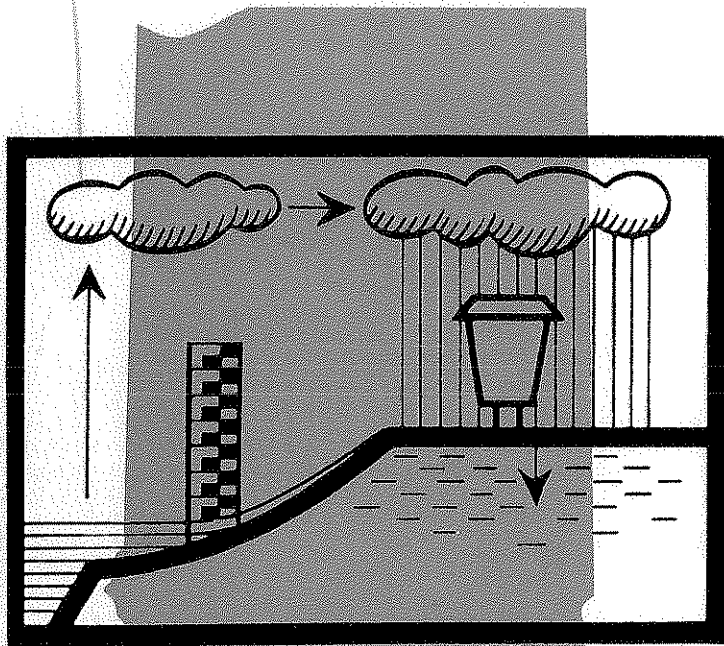
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TECHNICAL REPORT 14

MATHEMATICAL SIMULATION OF HYDROLOGIC EVENTS OF UNGAGED WATERSHEDS



by
L. F. Huggins
E. J. Monke

March 1970



PURDUE UNIVERSITY
WATER RESOURCES RESEARCH CENTER
LAFAYETTE, INDIANA

Department of Agricultural Engineering
Purdue University
Lafayette, Indiana

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INTRODUCTION

Numerous methods for predicting the surface runoff hydrograph resulting from the application of real or hypothetical storms to a given watershed have been proposed. The large number of proposed methods is the result of two primary factors. First, the determination of the volume and rate of movement of surface water within a watershed is the fundamental step upon which the design of reservoirs, channel improvements, erosion control structures and sewers as well as agricultural, highway and airport drainage systems is based. Secondly, the processes involved in describing the hydrological behavior of an area are extremely complex; therefore, numerous attempts have been made to develop methods based on simplifying assumptions concerning these physical processes, which can be used to characterize the behavior of a watershed with "acceptable" accuracy.

Historically, many of the methods proposed to predict the surface runoff hydrograph resulting from the application of real or hypothetical storms to a given watershed area have been based upon relationships between average conditions within the entire watershed, the applied storm and the resulting composite hydrograph. The computational effort required to describe the detailed dynamics of phenomena occurring within the watershed boundaries made other approaches unreasonable. The general approach of this research project was to utilize general modeling concepts and the computational capabilities of a large digital computer to attempt to describe the detailed physical processes occurring within the boundaries of a watershed and thereby more precisely characterize the behavior of the entire watershed. This general approach resulted in the following specific objectives:

1. To develop the fundamental mathematical relationships describing the mechanics of surface runoff within a watershed and the digital computer programs required to perform the integration of the resulting equations to produce a complete runoff hydrograph.
2. To investigate the adequacy of the mathematical model by applying it to gaged watersheds from which records were available and to compare predicted and observed hydrographs.
3. To use the mathematical model developed in objective 1 and available data to investigate the sensitivity of predicted hydrographs to variations in parameter values for the various hydrological components of the model.
4. On the basis of the results of objective 3, to initiate laboratory studies of the more important hydrological components not currently under investigation elsewhere in suitable detail in order to obtain more precise quantifying information about these processes.

WATERSHED MODEL CONCEPTS

Most of the methods proposed to date for describing the hydrological performance of a watershed have been based upon the concept of a "lumped" system, i.e. the parameters used to model the various hydrological processes are assumed to be representative of an average or net effect of the particular process over the entire watershed. The quantification of the resulting coefficients for such a system is not easy even for linear systems; unfortunately, it is many times more difficult for nonlinear systems because the coefficients for each lumped parameter vary with the magnitude and temporal distribution of the system inputs. To quantify such parameters, a knowledge is required of not only the particular component itself, but of its complex interaction with all other components as well. Furthermore, unless all the elements and processes within a watershed behave in a linear fashion, a final or overall average coefficient will depend upon the magnitude and the time distribution of the system input as well as the physical characteristics of the watershed. Such an average value may be determined only with previous knowledge of the system response or the ability to predict that response from which the average may be computed directly.

In order to develop a watershed model for predicting the hydrologic response for any specified input without using lumped parameters, it is necessary to describe the dynamics of the processes occurring at every point within the watershed boundaries. A mathematical watershed model designed to operate in this manner may be developed on the basis of the following hypothesis:

At every point within the watershed, a functional relationship exists between the rate of surface runoff (dependent variable) and the hydrologic parameters of topography, temperature, time from the beginning of the storm event, depth of flow and rainfall intensity (to the extent it affects flow turbulence and surface roughness).

This same hypothesis is fundamental, though usually implicit, to all mathematical models. The primary difference between implications for a lumped analysis and the one developed below is its use as a point relationship.

The necessity of attempting to describe the geometry and processes occurring within a watershed using partial differential equations may be avoided by relaxing the concept of a "point" application of the above hypothesis to refer instead to a finite-sized elemental area. Thus, a watershed may be viewed conceptually as being composed of a grid of elemental areas as shown in Figure 1.

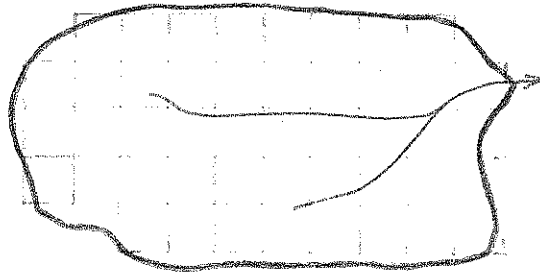


Figure 1. Hypothetical Watershed Showing Subdivision into Elements

In order to assure accurate modeling of the essential characteristics of a complete watershed, these physical elements must be of sufficiently small size that all hydrologically significant parameters, e.g., slope steepness and direction, vegetation, rainfall and infiltration rates, etc., are uniform within the boundaries of each element. However, these parameters may vary in a completely unrestricted manner between adjacent watershed elements. In the strictest sense, each of these elemental areas constitutes a lumped sub-area because the mechanics of the processes interior to its boundaries are not analyzed by distributed system equations. This is done primarily to reduce the computational effort required to analyze the model. The distinction between this concept and the more classical gross lumping of parameters over an entire watershed comes from the fact that, with this approach, parameter coefficients correspond to an entire elemental area because the relevant physical characteristics are constant within the boundaries of that element rather than because an effective or average value has been substituted for specially variable characteristics.

Assuming a watershed is composed of a composite group of essentially independent elements, it is apparent that the runoff water from one element is a source of inflow to its adjacent elements. Basically, the application of this concept to a watershed requires the development of a runoff hydrograph for each elemental area and the integration of these elemental responses over the entire watershed. The relationship between individual elemental responses and the composite watershed hydrograph is determined by the solution of the differential form of the continuity equation for each element:

$$I - Q = \frac{dS}{dt} \quad \dots(1)$$

where: I = inflow rate,
Q = outflow rate,
S = volume of water in storage,
t = time.

For application in the watershed model, the following finite-difference form of equation one was used:

$$I_1 + I_2 - Q_1 + \frac{2S_1}{\Delta t} = Q_2 + \frac{2S_2}{\Delta t} \quad \dots(2)$$

where: the subscripts 1 and 2 refer, respectively, to the values at the beginning and end of a time increment, Δt .

The runoff hydrograph from the entire watershed is obtained by applying equation two sequentially to all elements within the watershed

at time t_1 to ascertain conditions existing at time t_2 . This procedure is repeated until the complete hydrograph at the outlet of the watershed has been defined.

For an individual element, the net inflow rate, I , is composed of the algebraic sum of the rainfall rate, any interflow that resurfaces within its boundaries, the applicable surface runoff rates from adjacent elements and the rate at which water is being intercepted by plant surfaces. The outflow rate from an element, Q , is composed of the rates of infiltration and surface runoff. Surface retention effects resulting from microrelief must be incorporated in the relationship between the depth or volume of water in an element and the corresponding rate of surface runoff. The component of surface detention storage is obtained as a result of the integration of the continuity equation.

The accuracy with which a watershed model of the type outlined above can predict a particular runoff hydrograph depends both upon the size of the elemental areas into which the watershed is sub-divided and upon the ability of the mathematical relationships representing the various individual hydrologic components to describe their respective phenomena. The size of the element chosen depends upon the economics of a particular situation, i.e. the application for which the results are needed and the precision of the prediction required. The accuracy of the component relationships is not so controllable by the end user. These results depend primarily upon improved relationships and will come only from additional research results in the area of physical hydrology. Preliminary results in connection with the mechanics of overland flow are presented later in this report.

COMPONENT RELATIONSHIPS

The physical processes that require characterization by the watershed model include: interception, infiltration, interflow, depressional storage and surface flow. With the exception of interflow which was neglected in this project, the method used to characterize each process is described in detail below. The methods chosen are admittedly crude; however, one of the primary advantages of the modeling method outlined above is the ease with which improved component relationships can be introduced as they become available. Thus, these are proposed only as a starting point so that preliminary testing of the model may proceed.

Interception. Interception is that portion of the rainfall caught and retained by the vegetal canopy; it never reaches the ground surface to become part of the surface water hydrology. This component is often subdivided into two parts: interception storage and evaporation. Interception storage refers to the volume of water held on the plant surfaces due primarily to surface tension forces; this portion of the interception component is satisfied during the early stage of the more intense storms. Because of the tremendous surface areas that can be exposed in a dense vegetal cover, significant amounts of water may evaporate during a storm despite the high relative humidity conditions which normally prevail. This evaporation represents an abstraction from the rainfall rate which continues throughout the duration of the storm. For computational purposes in the mathematical

watershed model, the entire interception component can be incorporated by appropriately modifying the rainfall rate which would prevail under conditions of no vegetation.

A considerable amount of interception research, particularly with regard to woodland canopies, has been conducted. The classic work of R. E. Horton¹ reports the results of an extensive series of interception measurements under several species of trees. A limited number of observations under certain economically significant crops were also reported.

Horton found the interception storage volume for trees to vary from 0.02 inches to 0.07 inches and concluded that these values were approached for certain well-developed crops. By expressing the interception loss in terms of depth on the horizontal projected area shadowed by the vegetation, he found the loss for any shower of a given amount of rain to be very nearly the same for various broad-leaved trees during the summer season. The percentage of the total precipitation intercepted during a storm varied from nearly 100 percent for light showers where the total rainfall did not exceed the interception storage capacity to about 25 percent as an average constant amount for most large trees in heavy rains of long duration. Both the interception storage and evaporation were found to be greater for needle-leaved than broad-leaved trees.

On the basis of an analysis of rather extensive data taken under trees and limited observations made relative to crops, Horton recommended the relationships given in Table 1 be used to estimate the amount of interception to be expected from various crops. The constants given in Table 1 are applicable to an interception relationship of the form:

$$V = A(B + C \cdot P)h \quad (3)$$

where: h = height of crop in feet,
P = precipitation in inches,
V = interception volume in inches,
A, B, and C are constants dependent upon
the type of vegetal cover.

From the standpoint of physical significance, the B coefficient is associated with the interception storage potential of the crop while the C coefficient is a measure of the evaporation losses to be expected.

¹Horton, R. E. 1919. Rainfall Interception. Monthly Weather Review 47:603-623.

Table 1. Interception Constants Recommended by R. E. Horton

Crop	A	B	C
Oats	1	.007	.07
Corn	h/10	.005	.005
Grass	5/6	.005	.08
Pasture and meadow	1	.005	.08
Wheat, rye and barley	1	.005	.05
Beans, potatoes, and cabbage	h/4	.02	.15

Measurements of interception on several economically important crops and of the projected areas shadowed by the leaf surfaces of these crops have been made by Haynes². Unfortunately, only the total amount of interception that occurred during the three year period of record is reported; therefore, it is impossible to determine how the amount of interception might vary with the amount of rainfall. No rains in excess of 0.5 inches were recorded during the period of this study.

Expressing the total interception loss as a percent of the rain which fell during the period of study, Haynes' results can be summarized as follows: alfalfa, 22 percent; corn, 43 percent; and soybeans, (based upon only one year's data), 15 percent. The measurements of projected leaf surface areas are summarized in Table 2. Haynes concluded, as did Horton, that the amount of interception for any plant species increased almost directly with the percent of vegetal cover.

Table 2. Projected Leaf Surfaces of Various Crops Measured by Haynes

Crop	Condition of Growth	Projected Area -- %
Corn	8 ft. high, 42 in. rows with 14 inch hill spacing	55-65
Oats	maximum stage of growth, drilled in 8 inch rows	55-65
Alfalfa	18-20 inches high	90-100
Soybeans	38 inches high, drilled in 8 inch rows	95

²Haynes, J. L. 1940. Ground Rainfall Under Vegetative Canopy of Crops. J. of ASA 32:176-184

Stoltenberg and Wilson³ measured the interception storage capacity of corn plants by cutting the plant, bringing it to the laboratory, and then applying artificial rainfall. The amount of water intercepted was determined by weighing the plant before and after the applications of rainfall. They found that approximately 0.35 pounds of water was held on the surface of a mature corn plant. The amount of storage was essentially constant for rainfall rates between 2 and 10 inches/hour. Using these data from individual corn plants, Stoltenberg and Wilson computed the total interception capacity of a corn field with 15,000 plants per acre to be 0.025 inches of rain. These data are in general agreement with that of Horton as given in Table 1.

For direct use in a watershed runoff model an interception relationship describing the rate at which rainfall is being intercepted at any particular time is required. None of the reported work in this area provides such information. Fortunately, the magnitude of interception storage for runoff producing storms is generally small in comparison with the other hydrologic components. Thus, quantitative interception rate relationships were developed by combining the reported work with two assumptions: (1) the amount and rate of evaporation occurring during the intense runoff producing storm could be neglected and (2) the rate at which water is intercepted prior to the satisfaction of interception storage could be computed as the fraction of the total area covered by the horizontal projected leaf surfaces times the rainfall rate.

While the results of Horton indicate evaporation losses represent a significant portion of the total interception volume for a storm, the extension of these relationships to predict the rate of interception during the storm was not considered desirable. The linear relationship between evaporation and total precipitation implied by Equation (3) is theoretically very doubtful. Intuitively the amount of evaporation occurring per inch of rain would be expected to decrease with increasing rainfall intensity. Thus, evaporation would be of reduced significance for the more intense runoff producing storms. A probable reason for the relationship between evaporation and total rainfall which Horton found is the high correlation which exists between total rainfall and storm duration.

Surface Storage

The utilization of the equation of continuity to determine the time distribution of runoff from a watershed element requires, as indicated above, that the volume of surface storage be expressed as a function of the depth of water in the element. Such a relation is necessary to account for the influence of the surface micro-relief on the depth to which a given volume of water will rise on a specified surface area. Knowledge of this depth of water is also important because the rate of surface runoff from an element depends upon the depth of flow. The

³Stoltenberg, N. L. and Wilson, T. V. 1950. Interception Storage of Rainfall by Corn Plants. Trans. AGU 31:443-448

use of the total volume of water within an element instead of the depth relative to a datum can significantly reduce the subsequent calculational effort and can if carried throughout the infiltration relationships, eliminate the necessity of specifying an explicit surface storage relationship. However, for the purpose of completeness, a possible explicit form is developed herein.

In order to develop a surface storage-depth relationship consider the ground surface profile sketched in Figure 2 to represent the average profile for a particular watershed element.

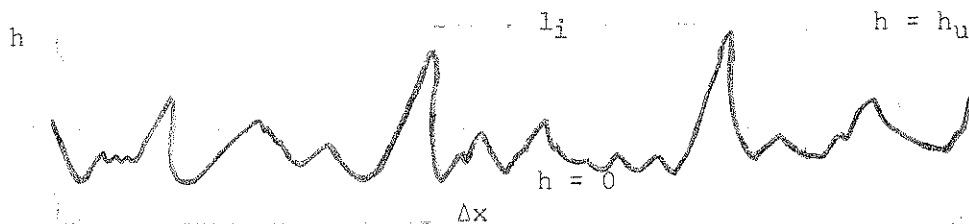


Figure 2. Typical or Average Ground Surface Profile

Assuming the water to be comparatively uniform over the entire element and defining the depth, h , to be zero at the lowermost point of the deepest depression, the water surface area is given by:

$$A(h) = \Delta x \sum_{i=1}^n l_i \quad (4)$$

Therefore, the storage volume, S , for $h \leq h_u$, the height of the highest roughness element in the profile, may be expressed as:

$$S(h) = \Delta x \int_{h=0}^{h=h_u} L(h) \cdot dh \quad (5)$$

where:

$$L(h) = \sum_{i=1}^n l_i$$

For $h \geq h_u$:

$$S(h) = S_u + (\Delta x)^2 (h - h_u) \quad (6)$$

where: S_u = the volume of water in-storage when $h = h_u$.

The general form of such a storage-depth relationship is shown in Figure 3.

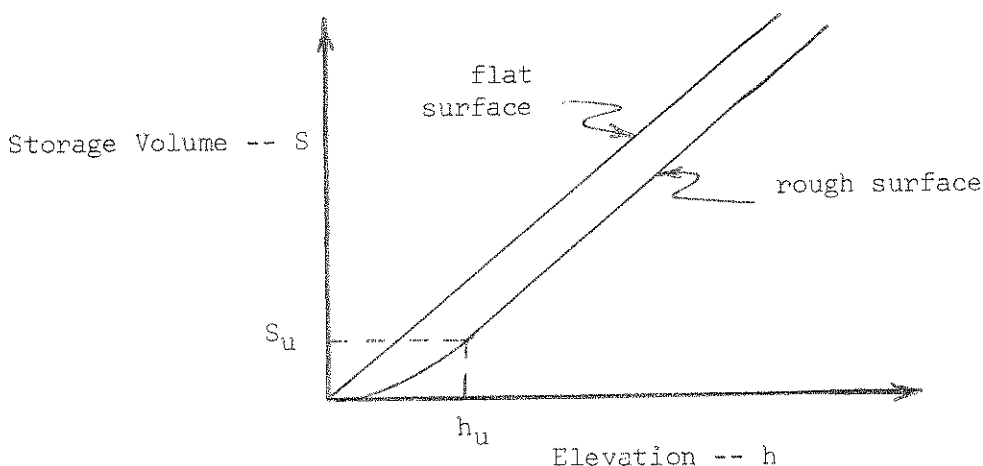


Figure 3. Typical Shape of a Storage-Depth Function for a Flat and a Rough Surface.

Most of the reported research on micro-relief has concerned the effects of tillage operations on surface conditions.^{4, 5} These studies have employed micro-relief meters which measure the surface elevation at fixed points in a uniform grid, usually two inches square. While data from such equipment may be used to determine the volume of water as a function of depth, the normal published results from these studies include only means and standard deviations of the roughness heights which are inadequate to define a storage-depth relationship.

Information concerning the order of magnitude of the influence of micro-relief on the storage-depth relationship was obtained from an analysis of a limited number of high-resolution field surface profiles. The tillage conditions selected were chosen to include extreme conditions: spring plowed ground before rainfall, fall plowed ground, corn stubble and disked and harrowed conditions after approximately one inch of rainfall. All conditions except the corn stubble were measured in more than one location.

The measuring procedure consisted of driving an 8 foot length of galvanized sheet metal into the ground at the desired location. The metal exposed above the ground surface was then sprayed with paint leaving a clear outline of the ground surface elevations on the metal. The profile was later analyzed to determine a dimensionless storage-depth relationship of the form:

$$\frac{S}{(\Delta x)^2 h_u} = f(h/h_u) \quad (7)$$

⁴Burwell, et al. 1963. A Field Measurement of Total Porosity and Surface Microrelief of Soils. Proc. SSSA 27:697-700.

⁵Allmaras, R. R., et al. 1966. Total Porosity and Random Roughness of the Interrow Zone as Influenced by Tillage. USDA ARS Conservation Research Report No. 7, 22 pp.

For most of the profiles this functional relationship could be approximated quite well with an equation of the form $y = Ax^B$, the coefficients of which were determined by a least-square regression of the logarithms of the observed data. These results are summarized in Table 3. Although not all of the profiles could be described equally well by one equation, no trend in the values of the A and B coefficients with the degree of roughness was evident from these observations.

Table 3. Summary of Surface Storage Relationships

Condition	h_u	$\sqrt{\frac{1}{n} \sum_{i=1}^n (h_i - \bar{h})^2}$	A	B	Correlation Coefficient r
Plowed Ground					
Spring -- smooth	4.0	.81	.75	1.9	.999
Spring -- normal	5.3	1.26	.55	2.1	.998
Spring -- rough	5.2	1.45	.40	1.7	.995
Spring -- very rough	7.2	2.12	.55	2.2	.999
Fall -- smooth	2.5	.51	.47	2.7	.997
Fall -- normal	4.2	.88	.31	2.2	.986
Fall -- normal	2.7	.52	.81	3.0	.996
Fall -- normal	3.5	.91	.44	1.9	.999
Fall -- rough	5.1	1.11	.56	2.2	.998
Disked and Harrowed					
Very smooth	1.4	.33	.55	2.4	.999
Rather rough	2.3	.46	.59	2.3	.999
Corn Stubble	4.5	1.25	.67	1.7	.999
All data			.54	2.2	.964

An assumption implicit in the above discussion was that topographic conditions measured at some arbitrary time would represent conditions during a storm event, i.e., the surface topography would not change appreciably during the storm. Such an assumption is obviously not valid when significant erosion or deposition occurs during a runoff event. In order to avoid neglecting the effects of erosion on runoff a storage-depth relationship which varied with time from the beginning of the storm event would be required. Such conditions could be incorporated in the proposed watershed model with little difficulty; however, specifying the manner, amount and distribution of soil moving into, out of, and within each watershed element is not possible with the present understanding of erosion mechanics.

Infiltration

Despite the comparatively large effort devoted to infiltration research over the past few decades, no widely accepted method of describing the infiltration process on a watershed scale has been developed. This is quite understandable in light of the tremendous complexity of the infiltration phenomenon and the infinite variety of soils which occur in nature.

Most of the past infiltration research can be subdivided into two broad classes: first, those efforts which have attempted to develop empirical relationships descriptive of observed field conditions and secondly, the more recent attempts to develop and solve the partial differential equations governing unsaturated flow through a porous media. Although the more rigorous approach holds considerable promise of ultimately providing more reliable infiltration relationships, present developments are not suitable for application to the proposed watershed model.

The basic concepts of the infiltration process outlined by R. E. Horton,⁶ while primarily empirical, have strongly influenced much of the research involving hydrologic applications of infiltration data. In 1939, Horton⁷ suggested the following widely used relationship for infiltration capacity:

$$f = f_c + (f_o - f_c)e^{-Kt} \quad (8)$$

where: K = a constant,
 e = base of natural logarithms,
 f_o = initial infiltration capacity,
 f_c = final or steady-state infiltration capacity,
 f = infiltration capacity at a particular time, t .

Equation (8) is an empirical relationship which describes the observed fact that the infiltration rate of most soils decreases somewhat exponentially with time when subjected to a supply rate in excess of the infiltration capacity.

Philip⁸ proposed an equation of the form:

$$\frac{dF}{dt} = \frac{k}{\mu} \left[1 + \frac{(m - m_o)(P + H)}{F} \right] \quad (9)$$

where: μ = viscosity of fluid,
 k = saturated permeability,
 F = total volume of water infiltrated,
 H = depth of water on the soil surface,
 m_o = initial moisture content of the soil,
 P = capillary potential at the wetting front,
 m = average moisture content to the depth of the wetting front at time t .

⁶Horton, R. E. 1933. The Role of Infiltration in the Hydrologic Cycle. Trans. AGU 14:446-460.

⁷Horton, R. E. 1939. Analysis of Runoff Plat Experiments with Varying Infiltration-Capacity. Trans. AGU 20:693-711.

⁸Philip, J. R. 1954. An Infiltration Equation with Physical Significance. Soil Science 77:153-157.

The potential application of relationships such as Equations (8) and (9) in a watershed runoff model is handicapped by the fact that infiltration capacity is expressed as a function of time. Such relationships are satisfactory provided the rate of water being supplied to the area exceeds the calculated infiltration capacity; however, difficulties arise with the occurrence of periods during a storm when the supply rate temporarily falls below the calculated infiltration capacity of the soil. Holtan and Overton¹⁰ proposed an infiltration capacity relationship which eliminates this difficulty by specifying the soil moisture content as the independent variable. This equation has the form:

$$f = f_c + A(S - F)^P \tag{10}$$

where: A and P = coefficients
S = storage potential of a soil above the impeding strata (total porosity minus antecedent soil moisture).

Equation (10) can be made dimensionally consistent and the coefficients A and P given a physical interpretation by the following modification:

$$f = f_c + A \frac{(S - F)^P}{T_p} \tag{11}$$

where: T_p = total porosity of the soil above the impeding layer.

With such a rearrangement, the coefficient, A, has the same units as f_c and represents the maximum potential increase of the infiltration capacity above the limiting or steady-state value. The dimensionless coefficient, P, is related to the rate of decrease in the infiltration capacity with increasing soil moisture content. Because the ratio of (S - F) to T_p is always less than unity, the larger values of P are associated with rapid rates of decrease of the infiltration capacity.

The infiltration volumes utilized in Equation (11) are determined by visualizing the value of the steady-state infiltration rate, f_c , as being limited by either the permeability of an impeding strata or the depth required for the hydraulic gradient to approach unity. This infiltration control depth is used to determine the initial storage capacity and total porosity of the soil. The initial and all subsequent infiltration capacity rates may then be computed directly.

Using soil moisture instead of time as the independent variable for infiltration capacity determinations offers a major practical advantage.

⁹Holtan, H. N. 1961. A Concept for Infiltration Estimates in Watershed Engineering. USDA ARS 41-51, 25 pp.

¹⁰Overton, D. E. 1964. Mathematical Refinement of an Infiltration Equation for Watershed Engineering. USDA ARS 41-99, 11 pp.

Handwritten notes:
∂f/∂t → ∞
∂f/∂t → 0
∂f/∂t → ∞
∂f/∂t → 0

For example, no difficulties are encountered in computing the infiltration capacity at any time during a storm event, even when the water supply does not at all times exceed the infiltration capacity. Assuming the soil drains at the specified rate proportional to its water content, Equation (11) will predict the "recovery" of the infiltration capacity observed in field studies as the result of a temporary interruption in the rainfall. Equation (11) was used in all tests of the watershed model that were conducted in this project.

Surface Runoff. The watershed model developed above is based upon the hypothesis of the existence of a functional relationship between the depth of water and the rate of surface runoff for every point within the watershed. Such a relationship would normally be expected to depend upon the general slope of the watershed element, the degree of turbulence in the flow, the micro-relief of the element and, in certain cases, the topographic conditions in adjacent elements.

The qualitative forms expected for a surface runoff-depth relationship, or runoff function, are shown in Figure 4. Figure 4a represents the more commonly expected form for such a relationship, i.e., the rate of surface runoff increases at an increasing rate for depths in excess of the surface retention demands, d_r . The more complex relationship shown in Figure 4b corresponds to an element located in a depressional area. The depth d_f represents the water depth at which the element becomes flooded due to the topography of adjacent elements. Flow would recommence at a depth, d_p , when the entire ponded area begins to overflow. The runoff function for depths greater than d_p would depend primarily upon the hydraulic characteristics of the entire pond and its outlet rather than the conditions prevailing in the particular element under consideration.

Numerous researchers have studied the flow of shallow depths of water over flat plains, i.e. classical overland flow. 11, 12, 13, 14, 15

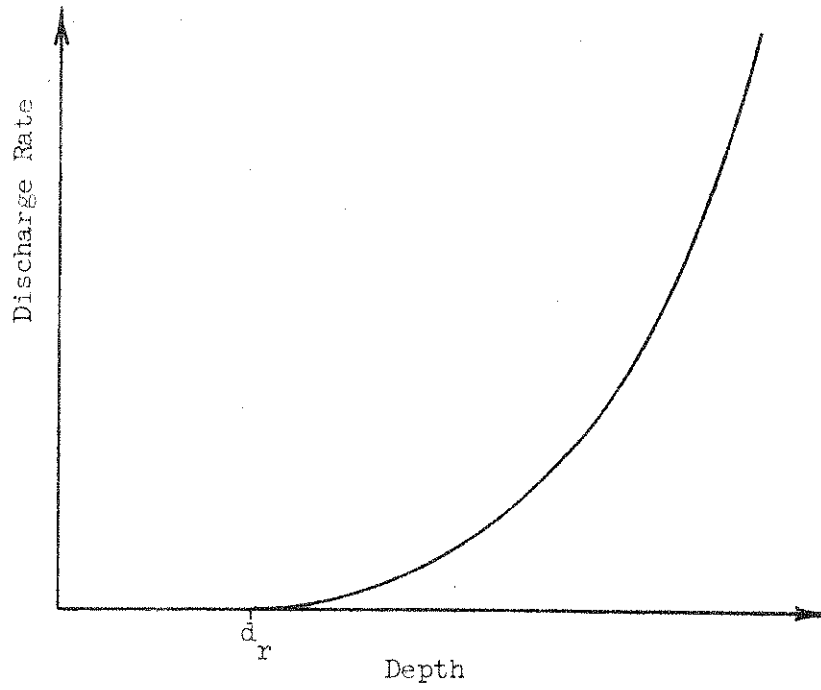
11 Horton, R. E. 1938. The Interpretation and Application of Runoff Plat Experiments with Reference to Soil Erosion Problems. Proc. SSSA 3:340-349.

12 Izzard, C. F. 1946. Hydraulics of Runoff from Developed Surfaces. Proc. Highway Research Board 26:129-150.

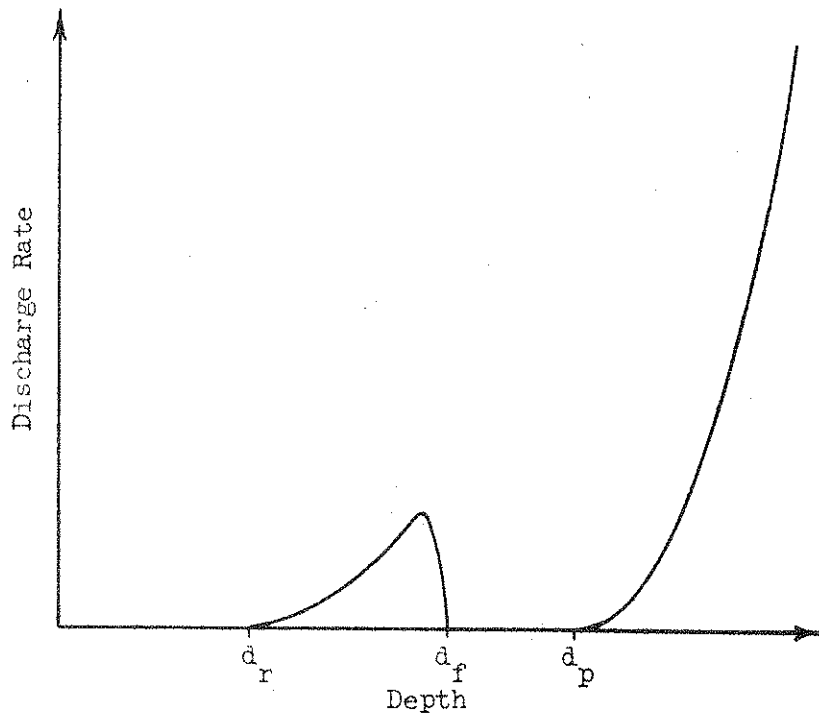
13 Woo, D. and Brater, E. F. 1962. Spatially Varied Flow from Controlled Rainfall. J. Hyd. Div. ASCE 88:HY6.

14 Ishihara, T. and Takasao, T. 1963. A Study on Runoff Pattern and Its Characteristics. Bulletin 65. Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan, 23 pp.

15 Yu, Y. S. and McNown, J. S. 1964. Runoff from Impervious Surfaces. J. IAHR 2:1-24.



(a) Normal Relationship



(b) Relationship for an Element Subject to Flooding

Figure 4. Qualitative Runoff Functions

In general, the relevance of much of the above research to the development of a runoff function of the type required by the proposed watershed model is questionable. The ability of relationships derived for the analysis of flow in thin, relatively uniform sheets to describe the phenomenon of flow in the myriad, interconnected rills and channels which compose the actual flow conditions in a watershed is very doubtful. Intuitively, a means of quantitatively describing the overall flow conditions of an element without analyzing the rigorous hydro-dynamic equations governing the flow in the tiny individual channels appears to be required. Such a relationship would be analogous to the manner in which the Darcy equation permits the analysis of groundwater flows without concern for the size and geometry of the actual flow paths through the porous media. Because no such relationship was found in the literature, the runoff function outlined below was developed for temporary use to allow the feasibility of the proposed watershed model to be tested.

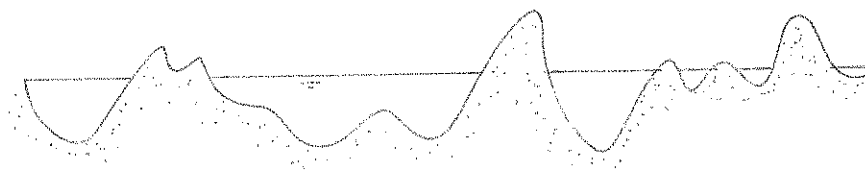


Figure 5. Typical Cross-Section of a Watershed Element

Let Figure 5 represent the average surface profile, taken perpendicular to the direction of flow, of a particular watershed element. The average cross-sectional flow depth, \bar{d} , can be determined for a given total depth, d , from the storage relationship for the element as:

$$\bar{d} = \frac{(S - S_p)}{A}$$

where: A = area of the element
 S_p = volume of water for a depth = d_p

On the basis of the experimental results obtained from the overland flow studies discussed above, the hypothesis of a relationship for the average velocity of flow within an element of the following form seemed reasonable:

$$V = K \bar{d}^m \tag{12}$$

where: V = average flow velocity
 K = a coefficient related to the slope and surface roughness of the element
 m = an exponent dependent upon the degree of turbulence in the flow.

For application in the watershed model it was assumed that the coefficients for Equation (16) could be determined by Manning's equation for open channel flow, i.e.:

$$K = \frac{1.486}{n} S$$

$$m = 2/3$$

where: S = slope of watershed element
n = hydraulic roughness coefficient

Despite some experimental evidence to the contrary¹⁶ and observations of the occurrence of a transition from laminar to turbulent conditions in overland flow studies, the coefficients for the runoff function were assumed to be constant for a given storm event. The assumption of more complex conditions was not justifiable without experimental validation of the basic form of Equation (16).

The assumption that the rate of discharge is proportional to the average depth of water within the element, i.e., the total volume of storage, makes the specification of the influence of micro-relief on surface storage unnecessary. For a given volume of retention storage, the runoff hydrographs predicted for a flat and a rough surface of the same hydraulic roughness are identical.

SIMULATION OF NATURAL WATERSHEDS

The ultimate method of determining the ability of a mathematical model to characterize a physical phenomenon is a comparison of the measured responses, for a variety of input functions, from the physical system being studied with those predicted by the model. In the case of a watershed model this means a comparison between observed and predicted runoff hydrographs resulting from measured rainfall hydrographs. Detailed records of the rainfall and runoff hydrographs, cropping history, and infiltration characteristics from a number of small, single crop, natural watersheds located on the Purdue Throckmorton Farm were made available to study the ability of the proposed watershed model to simulate the runoff hydrographs resulting from actual storm events. Two of these watersheds, shown in Figure 6 and each approximately two acres in size, were selected for this purpose.

The major difficulty with attempting to use actual storm events on natural watersheds to investigate the adequacy of a detailed mathematical model arises from the lack of quantitative data regarding the antecedent conditions of the several hydrologic model components at the time of occurrence of the storm being studied. For example, the soil moisture conditions, all of the surface roughness properties and the infiltration conditions must be estimated on the basis of primarily the antecedent rainfall and the season of the year. Because these estimates are all subject to substantial error it is impossible to determine whether discrepancies which may occur between the observed and predicted hydrographs are due to a poor model or the assumption of inaccurate boundary conditions. Fortunately, the ultimate engineering application of a watershed model, the prediction of possible future runoff events, does not require such quantitative data. For such applications the parameters are determined by probabilistic relationships rather than observable conditions.

¹⁶ Schiff, L. 1951. Surface Detention, Rate of Runoff, Land Use, and Erosion Relationships on Small Watersheds. Trans. AGU 32:57-65.

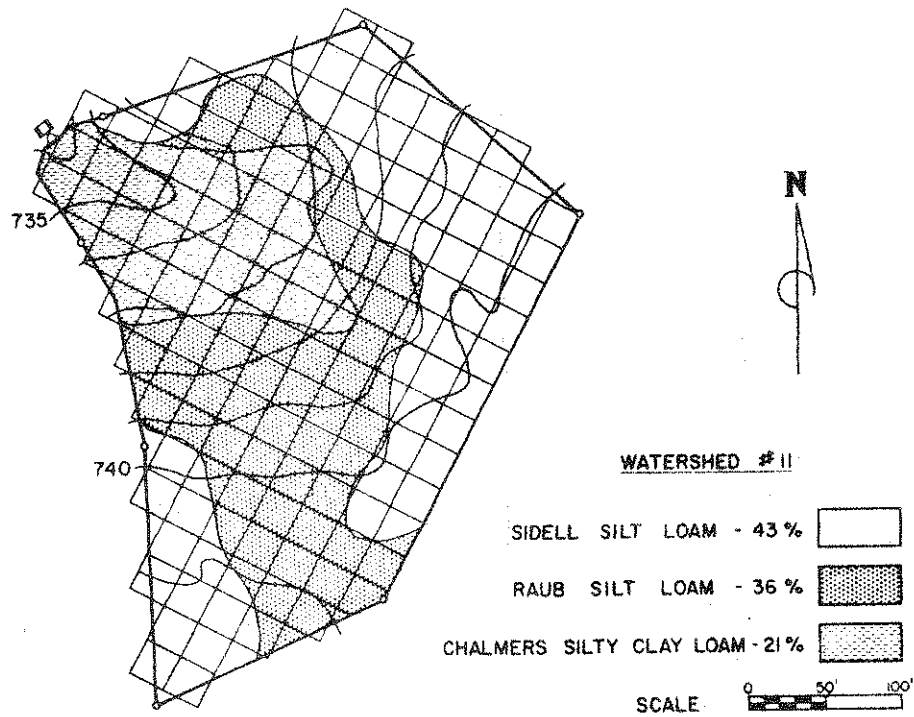
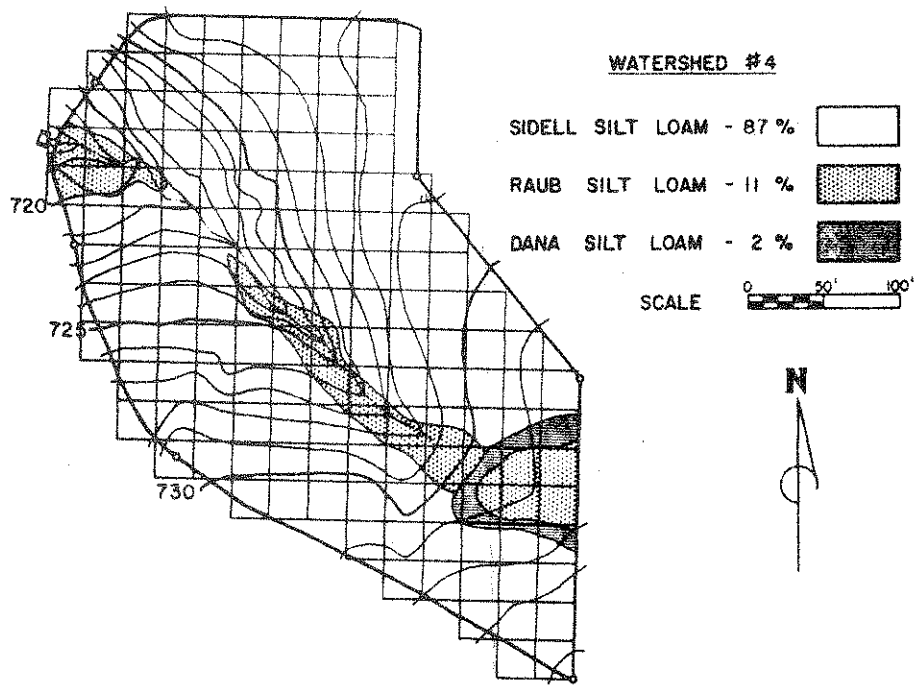


Figure 6. Topographic Map of Throckmorton Watershed

Numerous hypothetical and natural storm events were analyzed using the model to simulate the hydrologic behavior of the two Throckmorton watersheds. A detailed presentation of these results has been previously published.¹⁷ An example of the results obtained for a particularly complex storm is shown in Figure 7. On the basis of these results, the following conclusions were drawn:

For the limited range of conditions studied, the watershed model developed above, for appropriate values of initial parameters, was capable of simulating observed surface runoff hydrographs very well in comparison with techniques currently employed. However, because of the uncertainty in the magnitude of several of the watershed parameters at the beginning of a storm event, due to lack of sufficiently detailed historical data, the agreement between observed and predicted hydrographs cannot offer conclusive evidence of the validity of the watershed model.

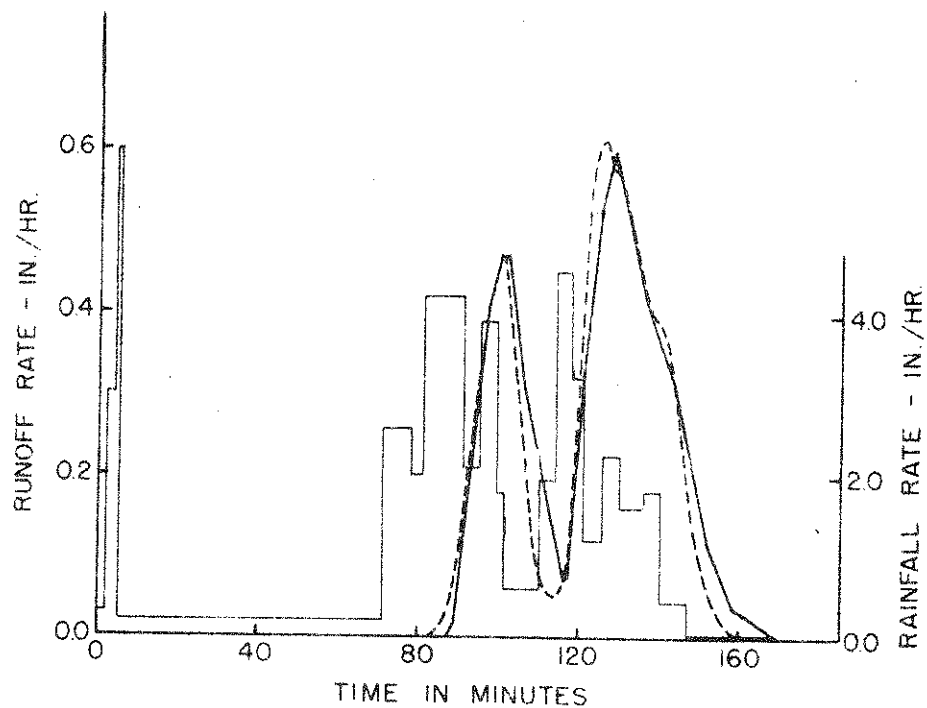
A parameter sensitivity analysis indicated that, for the Throckmorton watersheds, the most significant parameters were those factors which influenced the calculated infiltration capacity rates during the storm. This result was expected in view of the high infiltration rates of the soils found on the test watersheds. The infiltration parameters for these soils are given in Table 3.

Table 3. Infiltration Capacity Parameters for the Throckmorton Soils

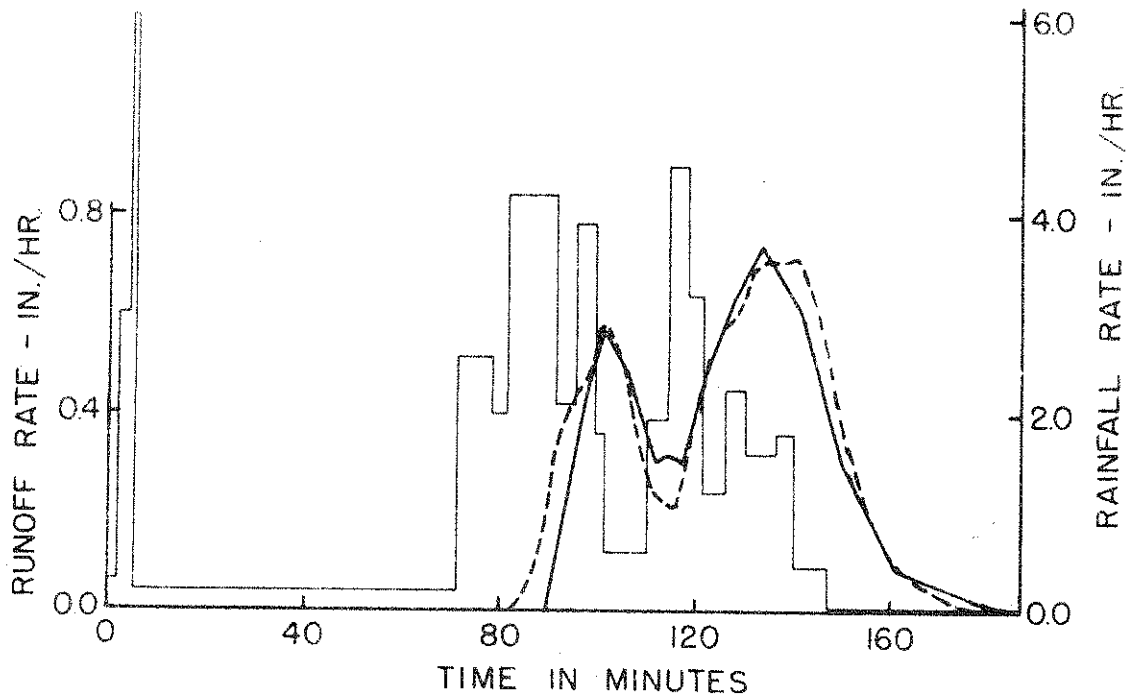
Soil	Total	Field Capacity			
	Porosity Volume %	% of Saturation	f_c in./hr.	A in/hr	P
Sidell si. lo.	46.	72.	1.00	4.90	.65
Chalmers si. cl. lo.	49.	80.	0.50	3.00	.75
Raub si. lo.	51.	73.	0.80	4.50	.65
Dana si. lo.	53.	66.	0.90	4.75	.65

The influence of interception storage on the predicted runoff hydrographs, for the magnitudes of storage capacity considered, was minor. The effect was discernible only when the runoff resulted from a storm wherein the runoff producing rainfall intensities occurred very early during the storm event.

¹⁷ Huggins, L. F. and Monke, E. J. 1966. The Mathematical Simulation of the Hydrology of Small Watersheds. Tech. Report 1. Purdue University Water Resources Research Center.



(a) Watershed #4.



(b) Watershed #11.

Figure 7. Observed and Predicted Hydrographs, 7/19/42.

The parameters in the runoff function, hydraulic roughness and surface retention volume, both appreciably influenced the predicted runoff hydrographs. Generally, the hydrographs were considerably more sensitive to the roughness coefficient than to the surface retention volume with the maximum influence of hydraulic roughness occurring during the unsteady flow periods of highest rainfall excess intensities.

The influence of the size and orientation of the elemental areas used to represent the watershed tended to become comparatively insignificant after a size was reached which resulted in about 150 elements for the entire watershed. The effect of the time increment used in the simulation became negligible for ratios of element area to time increment greater than 100 ft.²/sec.

THE MECHANICS OF OVERLAND FLOW

The result discussed in the previous section indicated the importance of being able to accurately describe the behavior of the surface flow over plane surfaces. The relative importance of this particular process to the overall problem of modeling the runoff from real watersheds can be expected to increase as the rate of infiltration for tighter soils tends to decrease. In view of this result, studies were initiated under this project to develop techniques for better characterizing the flow of water over surfaces which had roughness elements that were larger than the depth of flowing water, i.e., surfaces which could be expected to characterize the type of overland flow that would be found in most field situations. The first study completed in this connection was reported as an M.S. thesis by G. R. Foster¹⁸. The basic data for his study was provided by the Agricultural Research Service (ARS, USDA, at Purdue University). The data consisted of runoff hydrographs obtained from erosion plots subjected to simulated rainfall conditions. In excess of 10,000 plot-years of data were available from studies which involved a variety of soil types, slopes and cultural practices.

The overall objective of Foster's work was to determine the feasibility of using classical hydraulic equations to describe the movement of surface water from erosion plot studies. The specific objectives of his first studies were: to select an analytical model and to simulate actual field hydrographs; to determine the magnitude of the model parameters necessary to produce adequate simulations; to investigate the variations of the model parameters within a given hydrograph and from one surface condition to another; and, when possible, to correlate these parameters to either a qualitative description or a quantitative measure of the surface roughness.

The data available from the ARS studies, which were designed to obtain information concerning the mechanics of erosion by water, consisted of a surface runoff hydrograph measured at the downstream end of a plot

¹⁸Foster, G. R. 1968. Analysis of Overland Flow on Short Erosion Plots. M.S. Thesis. Purdue University.

and a known rate of application of artificially applied rainfall. The plot size for these studies, 35 feet long by 12 feet wide, was large enough that the unsteady effects of overland flow were significant; however, because no data were available concerning the instantaneous rate of infiltration, it was not possible to differentiate unsteady effects caused by changing infiltration rates from those resulting from overland flow dynamics. Since the primary objective of this study was concerned only with the mechanics of surface runoff, only those tests which were made under very wet soil moisture conditions in which it was reasonable to assume the rate of infiltration was constant during the period of rainfall application were used for subsequent analyses. All of the data used for this investigation were taken from fallow plots which had been tilled parallel to the slope of the plot.

The analytical model selected to simulate the observed hydrographs was obtained using a finite difference solution to the following equations:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = \sigma \quad S = \text{slope} \quad \dots(19)$$

$$y = \frac{fv^2}{8gS} \quad \gamma = \quad \dots(20)$$

where: q = discharge per unit width,
 v = velocity of flow
 σ = rainfall rate,
 f = Darcy-Weisbach coefficient of friction

These equations represent the kinematic method of analysis of overland flow and are derived by neglecting some of the smaller magnitude terms in the full momentum equation governing fluid flow. The particular solution generated by solving these equations depends upon the magnitude of the input parameters. Of the various parameters required, only the coefficient of friction could not be estimated from measured data. The "correct" value of the coefficient of friction was estimated by trial and error using a computer program written to solve equations 19 and 20 for each trial value of the friction factor. Values were chosen which resulted in good agreement between observed and simulated hydrographs. By analyzing the range of friction factors required to obtain good simulations for a large number of hydrographs and for a variety of surface roughnesses it was possible to estimate the feasibility of predicting the hydraulic roughness of a surface based upon some measure of the physical roughness. The magnitude of variation in the coefficient of friction required to obtain reasonable simulations for similar, yet individual, surface conditions determines the precision with which this term must be correlated to surface conditions and the detail that must be known about the flow surface if the above equations are used to model the behavior. Model simulations were also run using flow equations based upon Chezy's C and upon Manning's n to characterize the energy dissipation term of the flow equations.

On the basis of this study several conclusions were drawn. For the plot studies simulated in this work, the kinematic model was capable of providing an accurate simulation of the unsteady portions of the flow hydrograph when appropriate values for the frictional resistance of the flow were specified. A constant coefficient of friction, i.e. one which does not have to vary as a function of the Reynolds number of the flow, gave very satisfactory results for the rather small plot size and short flow lengths investigated. For most flow situations

typical of agricultural surfaces of short slope length, both Manning's and Chezy equations yield similar results. On the basis of this investigation it did not appear that the usually available qualitative description of the soil surface, e.g. rough fallow, would be sufficient to allow the selection of a quantitative coefficient of friction. Inadequate data were available to attempt a quantitative evaluation of the physical roughness of the plots.

Laboratory Investigations. At this point in the project a decision was made to initiate laboratory studies of overland flow situations in order to obtain a greater degree of control over the variables and to obtain more precise data. Conceptually, the laboratory equipment was designed to represent a full scale element of a watershed following the general concept outlined earlier. A detailed report concerning the design and construction of the laboratory facility and of the results of an investigation of three surface roughness conditions was presented by Das¹⁹. The final laboratory facility consisted of an apparatus to apply a very uniform, artificial rainfall of controllable intensity and momentum to a flow plane of variable slope and roughness. A flow surface 12 feet square was instrumented to measure instantaneous flow rates, drop and impact forces, shear forces and surface slope as well as the depth of water at various points on the surface. Extensive equipment was designed and constructed to interface the laboratory equipment with a remote analog/hybrid computer for on-line, automatic data acquisition, analysis, and feedback control of the experimental apparatus. Equipment was developed to record data from an experiment in both analog form for qualitative interpretation and in digital form for detailed, quantitative off-line analysis.

The equipment developed to generate an artificial rain over the flow surface was patterned closely after that developed by Chow and Harbaugh²⁰. The rainfall generator had 36 raindrop producing units. These units consisted of boxes made of 3/8-in. plexiglass having an outside dimension of 23-3/4 in. by 23-1/2 in. by 1-3/4 in. Polyethylene tubes of 0.023-in. inside diameter and 1-1/4 in. long were inserted and glued into the bottom of the box on 1-1/4 in. centers. There were 361 Polyethylene tubes installed in each box. The four sides of (1/4 in. thick) the boxes were glued to the bottom surface and the top surfaces were fastened to the four sides with screws. This was done to allow cleaning of the inside of the raindrop producers. The rate of flow into each rain producing module was controlled by 4 hypodermic tubes, the diameter and length of which served to control the rate of flow into each unit. The diameters and lengths were selected in such a manner that successive tubes increased the flow rate by a factor of 2; thus, by individually controlling the combination of 4 inflow tubes turned on at a particular time, it was possible to generate 16 intensities of rainfall ranging from 0 to nearly 7.0 inches per hour over the entire flow plane.

¹⁹Das, K. C. 1970. Laboratory Modeling and Overland Flow Analyses. Ph. D. Thesis. Purdue University.

²⁰Chow, V. T. and Harbaugh, T. E. 1965. Raindrop Production for Laboratory Watershed Experimentation. J. of Geo. Res. V. 70, n. 24.

The water supply to the individual hydrodermic tubes was controlled at a constant pressure of 25 psi and passed through a 50 micron filter before entering the raindrop producers. Flow in each of the four supply lines was controlled by solenoid valves. The entire system of raindrop producing modules was supported by a frame and could be raised a variable distance above the flow plane. This provided for the capability of controlling the momentum of the raindrops striking the flow surface by controlling the distance of fall of the raindrops.

A schematic view of the laboratory facility is shown in Figure 8. The initial flow surface was constructed from 1/4 inch aluminum sheets supported by a frame which was suspended at 4 points with load measuring devices. The load measuring devices permitted the total vertical force acting on the flow plane to be continuously monitored. They consisted of aluminum rods of .35 in. diameter to which foil-type strain gages were attached. The force measuring rods were supported by a large frame pivoted from fixed supports at the upstream end. Slope control of the entire surface was provided by 2 screw jacks located at the lower end of the support frame and driven by a common shaft and motor. This arrangement provided for longitudinal slopes ranging from 0 to 6.5 percent. No provision for cross-sloping of the surface was provided. Various types of roughness treatments could be applied to the aluminum surface in order to simulate a variety of conditions which might occur under normal field situations.

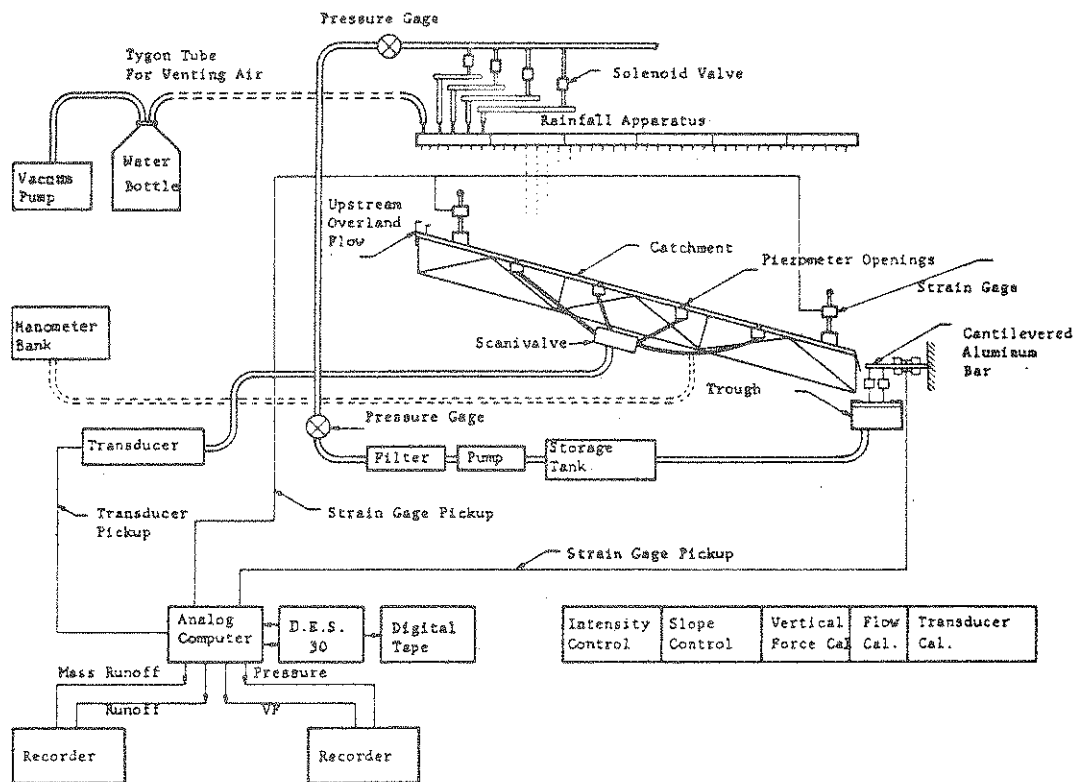


Figure 8. Schematic of laboratory equipment.

Runoff from the laboratory element was determined by measuring the rate of increase of the total mass runoff from the flow surface. Runoff was collected at the downstream of the flow plane in a metal trough. The trough was suspended from two cantilevered aluminum bars on which strain gauges had been mounted.

The depth of water at 20 points on the flow surface was measured by pressure transducer techniques. This was perhaps the most complex measurement in this investigation. Not only was the depth of water very small, but the effect of raindrop impact, the roughness of the surface and surface tension effects made precise measurements very difficult.

A technique was developed to determine the depth for both transient and steady cases at several points on the flow plane. It mainly utilized a pressure transducer, a manometer bank and a 24-point pressure scanning switch connected between the transducer and piezometer holes on the flow plane. The working range of the transducer was $\pm .5$ p.s.i. differential. The pressure scanning switch provided a means to record depths at different points on the flow plane using only one pressure transducer. At twenty locations on the flow plane $1/16$ -in. piezometer holes were drilled. Small pieces of brass tubes approximately 1" long with a $1/16$ inside diameter hole were glued on the bottom surface of the flow plane in alignment with the each of the piezometer holes. One-quarter inch Tygon tubing was used to connect the brass extension tubes on the piezometers to the scanning switch. Two points were connected to manometers filled to a known, constant water level approximating the full scale range of the pressure data. Transducer readings from these manometers provided calibration data for each complete pressure scan.

Each of the 20 depth measuring tubes was connected in parallel to a manometer tube on a central board. The manometer bank provided several advantages. First, it facilitated the removal of air from the pressure line by allowing water to be poured in each manometer tube just prior to the beginning of a test. This was particularly important when the slope was changed from low to high and air was drawn into the lines. Secondly, the manometers provided a means to damp any momentary changes in pressure due to impact of raindrops near a piezometer opening during a test. The ratio of diameters of manometer tube to piezometer hole on the flow plane was roughly 8. Thirdly, it was possible to physically see the elevation of each row of points on the flow plane. This greatly facilitated detecting trouble in the pressure lines during and after a test.

All of the electronic signals associated with the various measuring transducers were sent to a remote analog/hybrid computer over shielded, instrumentation-grade lines for amplification and preliminary analysis of the data. The data concerning the vertical force on the flow surface was amplified at the computer, digitized at periodic intervals and recorded on digital magnetic tape. In addition, after the signal was analyzed it was sent back to the laboratory for display on a recording oscillograph which provided the operator the convenience of monitoring the equipment during a test to verify that it was operating properly. The signal from the weighing tank which collected the mass

runoff during a test was amplified and then differentiated, using an analog circuit, to provide a signal proportional to the rate of runoff. Both accumulated mass runoff and the calculated rate of runoff were digitized and recorded periodically and, as with the vertical force, sent back to the laboratory for observation on the oscillograph.

The scanning and recording of the data from the pressure transducer merited special consideration in order to not require inordinate time periods and thereby degrade the overall system performance. A finite period of time was required for the pressure transducer output to stabilize the switching transients resulting from the scanning valve stepping from one piezometer to a successive one at a different pressure. Furthermore, the stabilization time depended upon the magnitude of pressure change between adjacent points. Because of large elevation changes between some piezometers on the sloping flow surface, the magnitude of pressure changes between points varied greatly. In order to reduce the overall scanning time to a minimum, the transducer signal was analyzed "on-line" and the results of this analysis were used to control the stepping rate.

A sample of the pressure transducer signal and the associated computer analysis signals for two full scale step inputs to the transducer is shown in Figure 9. The data in Figure 9 were recorded at a chart speed of 25 mm/sec and sensitivities of 5v/cm for the derivative and comparator signals and 2v/cm for the other signals. The basic analysis circuit to control the scan rate consisted of testing the time derivative of the pressure signal and accepting the signal as stable when this derivative decreased in magnitude below a predetermined "critical" value. However, as may be noted from the transient oscillations of the pressure signal in Figure 9, the transducer response was not that of a first order system. This meant the magnitude of the derivative of this signal would become zero even though the signal was not yet stable. Therefore, in order to prevent this condition from falsely indicating stability the transducer signal was passed through a first-order filter with a time constant of 0.1 seconds before being differentiated. This resulted in an output approximating a first-order system as can be seen from the sample output of Figure 9. Once the absolute value of the derivative had fallen below the critical value and remained there for a period longer than 68 milliseconds, the original transducer signal was digitized and recorded and the pressure scanning switch was advanced to the next position. With this type of analysis it was possible to scan and record the 20 flow depths on the surface in a period of 3 to 4 seconds. This time interval represented a reduction by a factor of 10 over the period required when using a fixed scanning rate.

Analysis of experimental results. An experimental investigation was conducted to determine if a functional relationship existed between the average depth of water within a finite-sized, uniform area and the rate of surface runoff from that area. Three uniform surface roughnesses described herein as smooth, rough and very rough, were used in the study. Aluminum was used to represent the smooth surface. It was treated with chemical to eliminate surface tension effects. The rough surface was formed by gluing sand on the aluminum surface. Sand particles screened between sieves number 14 (1.4 mm opening) and 20 (0.83 mm opening) with an average size of 1 mm in diameter were used. The very rough surface was formed by repeating the same procedure using gravel screened between sieves number 4 (4.70 mm opening) and 6 (3.33 mm).

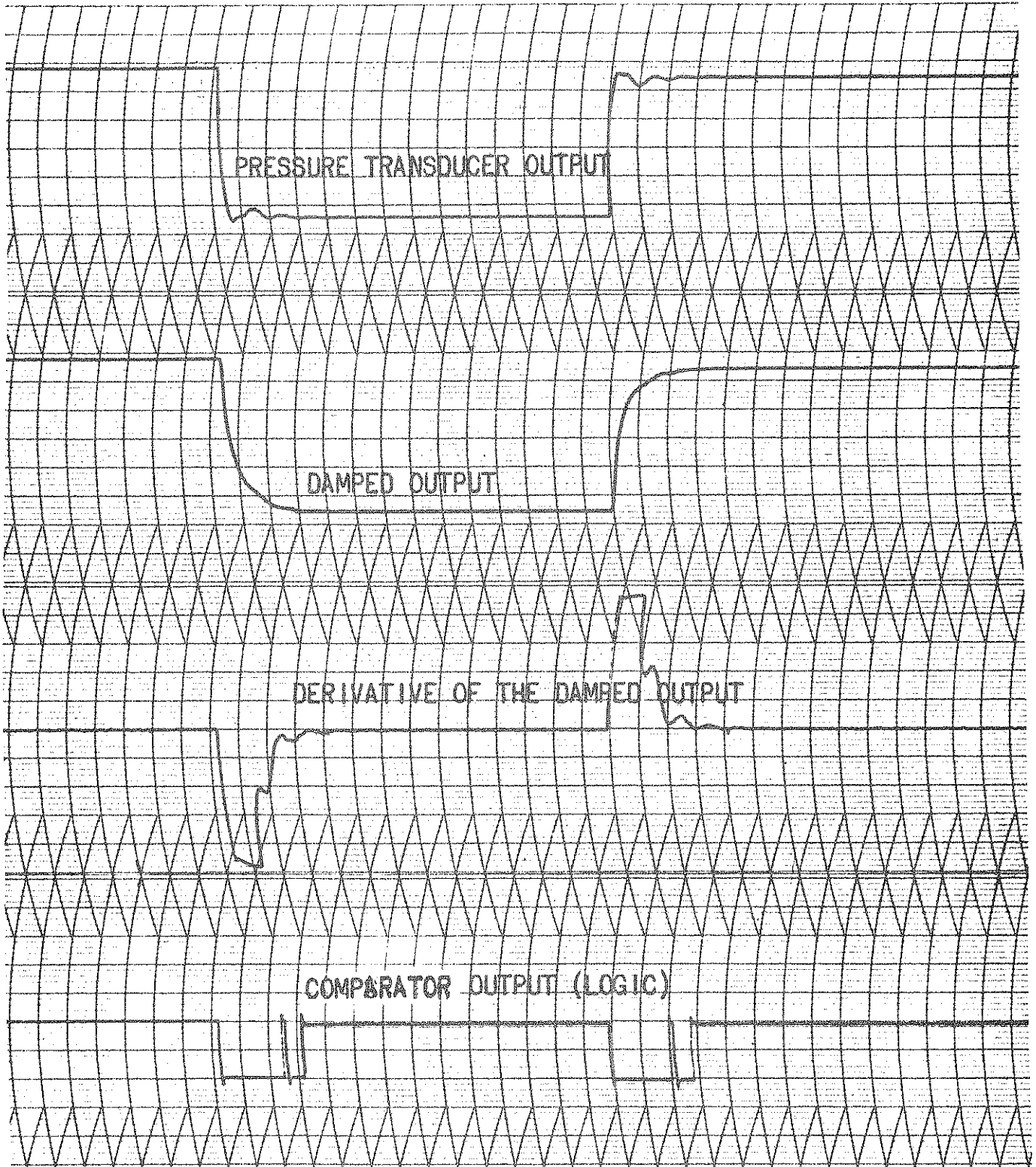


Figure 9. Transient Response of Pressure Transducer and the Associated Analysis Circuit.

To test the hypothesis of a function relationship between pertinent variables the following mathematical relationship was assumed:

$$d_{av} = F(S, K, I, Q_u, \mu, \rho, g) \quad (15)$$

where: S = slope of the plane (ft/ft),
K = roughness factor (dimensionless),
= f * R_e

(In order to quantify the physical surface roughness a factor K was used. The factor K was obtained separately for each of the surfaces from a plot of the Darch-Weisbach coefficient of friction (f) and Reynolds number (R_e) based on point depth measurement at steady state conditions. K = 23.64, 513.8, and 1860.96 represent smooth, rough, and very rough surfaces respectively).

I = intensity of rainfall (in/hr),
Q_u = upstream overland flow (in/hr),
μ = absolute viscosity of the input fluid (slug/ft-sec),
ρ = density of the fluid (slug/ft³),
g = acceleration due to gravity (ft/sec²).

In determining the relevant variables, certain basic assumptions and limitations were involved.

1. Surface tension was neglected.
2. Infiltration and interflow were neglected as the surface was impervious.
3. Raindrop impact effects were lumped into the roughness, intensity and slope terms.
4. Time was not considered a pertinent variable as the functional relationship was evaluated for steady state conditions.
5. An upstream flow was introduced in the experiment as a substitute for varying the length of the flow plane.

With the aid of Buckingham's homogeneity theorem, the following set of dimensionless products was obtained.

$$\Pi_1 = d_{av} \mu^{-2/3} \rho^{2/3} g^{1/3}$$

$$\Pi_2 = S$$

$$\Pi_3 = Q_u \mu^{-5/3} \rho^{5/3} g^{1/3}$$

$$\Pi_4 = I \mu^{-1/3} \rho^{1/3} g^{-1/3}$$

$$\Pi_5 = K$$

It is important to observe that the first variable d_{av} occurs only in Π_1 , the second variable S occurs only in Π_2 , the third variable Q_u occurs only in Π_3 , the fourth variable I occurs only in Π_4 , and the fifth variable K occurs only in Π_5 . All variables appearing in more than one term were not changed experimentally. This implies that the products were both linearly and statistically independent of each other.

On the basis of these variables an experiment was designed. Five treatment levels were chosen for each of the three independent variables Q_u , S , and I and three treatment levels for the variable K . Fifteen treatment combinations covering all permissible levels were chosen for the test. Due to several limitations it was not possible to randomize the surface within the experiments. Hence all tests were completed on one surface before it was changed. The fifteen different treatment combinations tested on each surface consisted of a 2^3 factorial supplemented by seven additional tests.

The fifteen treatment combinations were tested randomly with two replications for each surface. The objective of the statistical analysis was to establish a relationship between average depth (d_{av}) and other independent variables S , Q_u , I and K .

Initially various analyses of the data were made to determine the significance of main and interaction effects. The results of the analysis of variance of the 2^3 factorial part of the experiment indicated all main effects were significant for each of the three surfaces. For the smooth surface the only significant 2-way interaction was rain x upstream flow. The significant 2-way interactions in the case of rough surface were rain x slope and rain x upstream flow. The only significant 2-way interaction for the very rough surface was slope x rain. All the above tests were made at the five percent level of significance.

The presence of a significant level of interaction in the analysis of variance inferred that a nonlinear regression model would be required to correlate the dependent and independent variables. On the basis of these results and the general form of the classical hydraulic equations used to characterize open channel flows, the Mannings and Chezy equations, the mathematical model chosen was of the form:

$$\Pi_1 = a (\Pi_2^b \Pi_3^c \Pi_4^d \Pi_5^e)$$

Analyses were completed individually for each surface roughness and for the composite case with all tests combined. The results, as shown in Table 4, indicated the variation (R-squared) accounted for by the regression in each of the cases was rather high. The composite cases yielded relatively high R-squared values comparable to the values obtained for individual surfaces.

Table 4. Summary of Regression Analyses

Case	R ²	a	b	c	d	e
Smooth Surface	.93	20.7 x 10 ⁻²	-.387	.089	.265	-
Rough Surface	.92	4.44 x 10 ⁻²	-.308	.191	.362	-
V. Rough Surface	.92	1.57 x 10 ⁻²	-.423	.198	.517	-
Composite	.94	1.13 x 10 ⁻²	-.376	.181	.423	.164

SUMMARY AND CONCLUSIONS

The four project objectives outlined in the introduction of this report were completed during the duration of the project. The primary result of this project is the mathematical watershed model, programmed in FORTRAN IV, presented in the Appendix to this report. In its present form, this model must be viewed as a research model rather than a finished product ready for use as a design tool for water resources planning. Before the concepts presented in this report can be translated into a practical design method much additional research is needed to better define the equations governing the component hydrologic relationships, especially those concerning infiltration and surface runoff processes, for a variety of conditions which cover the range of normally occurring situations. Additional effort should also be devoted to improving the computational efficiency of the computer program and to developing a simplified method for characterizing the surface topography of watersheds to be modeled. Before the model can be recommended for use in engineering practice it will also be necessary to determine the range of watershed sizes for which it is applicable.

The laboratory facility developed under this project is capable of providing much of the data necessary to establish improved modeling equations and parameters to characterize overland flow. The rather long design and construction time required to develop this facility resulted in a severe restriction on the variety of surface conditions which could be tested during the project duration. Those experiments which were conducted indicated a need to improve the instrumentation used, especially that required to measure the point flow depths and the dynamic vertical forces acting on the flow plane.

Specific conclusions concerning the results of the various phases of the overall project have been presented previously in this report and are not repeated here. For these results the reader is referred to the closing remarks of each major section of the report.

Finally, one of the primary strengths of the conceptual watershed modeling approach developed herein concerns the ease with which it can be modified and improved as individual research advances are made in the areas associated with the various hydrologic components delineated in the model. It is hoped that this will encourage others working in the field of hydrology to incorporate their ideas concerning the modeling of component processes into the model and to test the effectiveness of their ideas with historical watershed data.

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APPENDIX

COMPUTER PROGRAMS

The following pages contain a listing of the computer program, written in FORTRAN IV, employed to simulate surface runoff conditions from natural watersheds. In order to facilitate possible future modifications and to better illustrate the programming logic, the program was segmented into various subprograms, each with a specific function. Considerable effort was devoted to increasing the computational efficiency of the routines used in the iterative portions of the program. Unfortunately, this endeavor often resulted in an increase in the complexity of the programming logic, the combining of several coefficients into a single numerical quantity with unfamiliar units and the storage of otherwise superfluous arrays of values for later computational use.

All of the basic control logic and the essential features of the mathematical watershed model developed above are contained in the program MAIN. Newton's method of finding the zero of a function by using its derivative to obtain successive approximations to the zero was employed to solve the equation of continuity recursively for each element within the watershed. As written, the program does not allow areal variations of rainfall, vegetal cover or surface roughness within the watershed boundaries. However, this feature could very easily be incorporated by changing the appropriate coefficients to subscripted variables and assigning values for all elements within the watershed.

Various hydrologic components of the watershed model were incorporated into the computer program as separate function subprograms. The rate of interception occurring during a storm event is determined by the subprogram RAIN which returns the value of the net rate of rainfall, the actual rate minus the rate of interception, to the main program. The infiltration rate is determined by the FILT function subprogram.

The purpose of the subroutine DATA is to input all of the basic data required to simulate a given hydrologic event on a particular watershed. This input data can be subdivided into four categories:

- A. The rainfall intensity-time distribution with the time expressed in minutes and the intensity expressed in inches / hour constitutes the first category. These data are required for the first and each subsequent new storm to be analyzed in a set of data. The effect of a given storm under a variety of antecedent watershed conditions and/or watershed may be analyzed by simply deleting this sub-section of data from data sets following the first set. The word PRINT starting in column 25 of the storm data card causes the storm hydrograph to be printed after being read. A non-zero value in column 1 of a card indicates the end of the rainfall data.
- B. Antecedent watershed condition data (a total of six data cards) are required for each analysis. The headings on these cards are intended to be self-explanatory. It is suggested that a roughness category of 4 be used for most analysis. Such a selection results in the average depth of surface retention agreeing with the value punched on the data card.

- C. Infiltration coefficients are required for each type of soil present within a watershed. Current dimension statements allow for only four soil types to be present in a watershed; however, this is easily increased by changing appropriate dimension and read/write statements in the program. These data need to be read only when the values of the coefficients from a preceding simulation must be changed. A DATA statement provides a default option.
- D. The last set of data concerns the topography of the watershed being simulated. The watershed must be subdivided into elements as shown in Figure 6. For each element the surface slope (percent), the slope direction and the soil type classification must be specified on a single card. The position of an element is determined by a row and column index. For best results, partitioning should begin with row one and column one corresponding to the most extreme, upper left portion of the watershed and progressing toward increasing column numbers, i.e., horizontally from left to right as normally viewed. The slope direction of an element is specified in degrees measured counter-clockwise from a directed line originating from the center of an element and projecting parallel to a row of elements. A non-zero value in column 8 of a card indicates the last element in the watershed. The slope direction of the watershed output element should be specified in such a manner that all outflow from the element leaves the watershed, i.e. either 0, 90, 180, 270 degrees.

The above set of data must be followed by data sets for subsequent simulations, or, if only one simulation is to be made, by an arbitrary additional card (END DATA was used in the example below). Several checks are made to assure the data are in a form which will allow the simulation to be completed. Parameter values for all elements of the model are evaluated from the input data and transferred back to the main program for subsequent calculations.

The subroutine DRY is used to greatly reduce the computational effort required during intermittent periods of complex storm events when the rainfall and runoff have temporarily ceased. The soil moisture conditions existing at all points in the watershed at the time of recurrence of rainfall are determined with this subprogram.

The physically significant programming symbols used are defined in the following list. Other symbols which appear in the programs were used only for programming convenience and have little or no physical significance.

Programming Symbols

- A(I) = Infiltration coefficient of Equation (10) for I-th element
- ADIR = Average surface retention depth -- in.
- ANG = Angle of the flow direction across an element--degrees (input).
- AREA = Area of the watershed--acres.

- ASM = Antecedent soil moisture--percent of saturation.
- B(I) = Coefficient for runoff function for I-th element.
- CONST = A constant = $2 \cdot DX \cdot DX/DT$ -- ft.²/sec.
- CONV = Constant to convert watershed outflow from ft.³/sec. to in./hr.
- CROP = Type of vegetation.
- CU = Constant to convert rates from in./hr. to ft.³/sec.
- CU1 = Constant for converting from inches per unit area to cubic feet.
- DINF = Depth of the control zone used in calculating the infiltration capacity rates -- in. (input).
- DIR = Twice the surface retention volume divided by DT--ft.³/sec.
- DIRM = Maximum surface retention depth at any point in the watershed--in.
- DR = Discharge₃ in a direction parallel to the elemental rows--ft.³/sec.
- DT = Time increment used in the analysis--sec.
- DT1 = Time increment used in a previous simulation--sec.
- DTM = Time increment used in the analysis--min.
- DX = Size of watershed element--ft.
- FC(I) = Steady-state infiltration capacity rate of I-th element--ft.³/sec.
- FILTC(I,J) = Constants for the infiltration capacity rates for the I-th soil; J = 1 corresponds to the total volume porosity--percent; J = 2 to the field capacity--percent of saturation; J = 3 to f_c-in./hr.; J = 4 to "A" in Equation (11)-in./hr.; and J = 5 to "P" in Equation (11).
- FLIN = Net rate at which water is flowing into an element--ft.³/sec.
- FLINS(I) = The sum of the inflow, outflow and rate of change of storage for the I-th element at the end of each iteration--ft.³/sec.
- GWC(I) = Gravitational water capacity of I-th element--ft.³
- HU = Maximum height of surface roughness influence on storage--in. (input).

IDATE = Date of storm event being analyzed.

MOUT = The position number of the outlet element.

NC(I) = Position number of the element to receive overland flow parallel to the column direction from I-th element.

NEXP = Drainage exponent used in infiltration calculations.

NIOUT = Row number for watershed outlet element.

NJ = Number of columns of watershed elements.

NJOUT = Column number for watershed outlet element.

NR(I) = Position number of the element to receive overland flow parallel to the row direction from the I-th element.

NUM = Watershed code number.

P(I) = Infiltration coefficient for Equation (10) for I-th element.

PER = Ground surface covered by foliage--percent of total area.

PIT = Potential interception storage volume--in. (input).

PIV(I) = Moisture deficiency (relative to saturation) for I-th element--ft.³

PREC = Total amount of rainfall--in.

Q1 = Watershed outflow rate--in./hr.

Q2 = Rate of discharge from an element--ft.³/sec.

Q(I) = Discharge rate from the I-th element--ft.³/sec.

QI(I) = Inflow rate from adjacent elements--ft.³/sec.

R = Effective rainfall rate. Actual rainfall rate minus rate of interception--ft.³/sec.

RATE = Rate at which water is being supplied to an element by rainfall--ft.³/sec.

RC(I) = The rainfall intensity corresponding to the I-th time interval--in./hr.

RFL(I) = The percentage of total outflow from I-th element which flow parallel to the rows of elements.

RIT = Rate of interception--ft.³/sec.

RN = Manning's roughness coefficient.

RN1 = Value of Manning's roughness coefficient used in a previous simulation.

ROUGH = Surface roughness category.

S(I) = Slope of I-th watershed element--ft./ft.; or twice the element storage volume divided by the time increment, DT,--ft.³/sec.

SOIL(I) = Soil type number of the I-th element.

SS(I) = The change in value of S(I) during an iteration.

SSTOR = Twice the volume of water in storage divided by the time increment, DT,--ft.³/sec.

SUPP = Rate at which water is being supplied to satisfy infiltration capacity--ft.³/sec.

SUR(I,J) = Constants for the storage function for the I-th soil.

T = Time--min.

TC(I) = The time at which a change in rainfall intensity occurred--min.

VOL = Total volume of runoff predicted by simulation--in.

Program Listing

C L. F. HUGGINS ** SECOND EDITION ** 10/68
C MATHEMATICAL MODEL OF A SMALL WATERSHED

```
PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
  DIMENSION Q(300),RFL(300),IDATE(2),FLINS(300),RC(100),TC(100),QI(3
  101),S(300),SS(300),A(300),PIV(300),P(300),FC(300),GWC(300),B(300)
  2,T(101),QI(101),NR(300),NC(300),NUM(20)
  COMMON NEXP,SUPP,DT
  DATA QI(1) /0./
  NEXP = 3
  READ (5,1) TEST
  1 FORMAT (A6)
  5 CALL DATA(NUM,IDATE,B,DIR,TC,NDT,KPR,N,NR,NC,QI,RFL,CONV,CU,PER,PI
  1T,A,PIV,P,FC,GWC,TEST,FLINS,Q,S,SS,RC,NRAIN)
  ITR = 1
  VOL = 0.
  PREC = 0.
  DTM = DT/60.
  T(1) = TC(1)
  WRITE (6,10) T(1),QI(1)
  10 FORMAT (1H0 31X 17HRUNOFF HYDROGRAPH / 1H0 20X 11HTIME - MIN. 9X 1
  19HDISCHARGE - IN./HR. / 20X F9.1, 18X F6.3)
  DO 60 L = 2,NDT
  T(L) = T(L-1)
  DO 50 J = 1,KPR
  T(L) = T(L) + DTM
  IF (T(L) - TC(ITR)) 13,11,11
  11 IF (ITR - NRAIN) 12,67,67
  12 ITR = ITR + 1
  RATE = RC(ITR)*CU
  PREC = PREC + RC(ITR)*(TC(ITR) - TC(ITR-1))/60.
  13 R = RAIN(RATE,PIT,PER)
  DO 50 M = 1,N
  SSTOR = S(M) + SS(M)
  FLIN = QI(M) + R
  SUPP = .5*SSTOR + FLIN
  FLIN = FLIN - FILT(A(M),PIV(M),P(M),FC(M),GWC(M))
  FHS = FLINS(M) + FLIN
  IF (FHS.GT.DIR) GO TO 22
  18 S(M) = FHS
  SS(M) = 0.
  FLINS(M) = FLIN + FHS
  IF (Q(M).EQ.0.) GO TO 50
  19 D = -Q(M)
  Q(M) = 0.
  GO TO 48
  22 X = FHS*1.E-4
  IF (SSTOR.GT.DIR) GO TO 28
  24 SSTOR = FHS
  GO TO 28
  26 SSTOR = SSTOR - FS/(1. + 1.66667*Q2/D)
  28 D = SSTOR - DIR
  Q2 = B(M)*D**1.66667
  FS = Q2 + SSTOR - FHS
  IF (FS.LT.-X.OR.FS.GT.X) GO TO 26
```

```
D = Q2 - Q(M)
Q(M) = Q2
SS(M) = SSTOR - S(M)
S(M) = SSTOR
FLINS(M) = FLIN + SSTOR - Q2
48 DR = D*RFL(M)
I = NR(M)
K = NC(M)
QI(I) = QI(I) + DR
QI(K) = D - DR + QI(K)
50 CONTINUE
QI(L) = QI(N+1)/CONV
VOL = VOL + QI(L)
IF (QI(L).LT..0005.AND.ITR.GT.2) CALL DRY (N,PIT,PER,S,CU,Q,A,PIV,
IP,FC,GWC,RATE,QI,T(L),TC,RC,ITR,NRAIN,FLINS,PREC)
60 WRITE (6,65) T(L),QI(L)
65 FORMAT (20X F9.1, 18X F7.4)
L = NDT + 1
67 VOL = (VOL - .5*QI(L-1))*DT*FLOAT(KPR)/3600.
WRITE (6,70) PREC,VOL
70 FORMAT (1H0 4X 32H THE RUNOFF VOLUME PREDICTED FROM F5.2, 21H INCHE
IS OF RAINFALL = F6.3, 4H IN. )
GO TO 5
END
```

```
FUNCTION FILT(A,PIV,P,FC,GWC)
COMMON NEXP,SUPP,DT
IF (PIV) 45,50,5
5 FILT = A*PIV**P + FC
IF (FILT.GT.SUPP) FILT = SUPP
IF (PIV.LT.GWC) GO TO 25
PIV = PIV - FILT*DT
RETURN
25 PIV = PIV - (FILT - FC*(1. - PIV/GWC)**NEXP)*DT
RETURN
45 WRITE (6,46) PIV
46 FORMAT (52H WATER CONTENT OF SOIL EXCEEDS TOTAL POROSITY, PIV = 1P
1 E15.7)
PIV = 0.
50 IF (FC.GT.SUPP) GO TO 65
FILT = FC
RETURN
65 FILT = SUPP
PIV = (FC - FILT)*DT
IF (PIV.GT.GWC) PIV = GWC
RETURN
END
```

C FUNCTION RAIN(RATE,PIT,PER)
DETERMINATION OF NET RAINFALL RATE ** CONSTANT INTERCEPTION RATE
IF (PIT) 40,50,10

```
10 RIT = PER*RATE
   IF (RIT - PIT) 15,15,20
15 RAIN = RATE - RIT
   PIT = PIT - RIT
   RETURN
20 RAIN = RATE - PIT
   PIT = 0.
   RETURN
40 WRITE (6,41) PIT
41 FORMAT (60H INTERCEPTION VOLUME EXCEEDS MAXIMUM POTENTIAL VOLUME,
  1PIT = 1PE15.7)
   PIT = 0.
50 RAIN = RATE
   RETURN
   END
```

```
      SUBROUTINE DATA(NUM, IDATE, B, DIR, TC, NDT, KPR, N, NR, NC, QI, RFL, CONV, CU,
  1PER, PIT, A, PIV, P, FC, GWC, TEST, FLINS, Q, S, SS, RC, K)
      DIMENSION Q(300), RFL(300), IDATE(2), FLINS(300), RC(100), TC(100), QI(3
  101), S(300), SS(300), A(300), PIV(300), P(300), FC(300), GWC(300), B(300),
  2FILTC(4,5), SUR(4,2), NC(300), NR(300), NUM(20)
      INTEGER ROUGH, SOIL(300)
      COMMON NEXP, SUPP, DT
      TAN(X) = SIN(X)/COS(X)
      DATA CHECK, C1, C2, PRI /4H  SO,4H  AN,4H  NE,4HPRIN/
      IF (TEST.EQ.C1) GO TO 3
      READ (5,66) IDATE, PR
      K = 1
  1 READ (5,58) J, TC(K), RC(K)
      K = K + 1
      IF (J) 2,1,2
  2 IF (K.GT.100) GO TO 85
      RC(K) = 0.
      TC(K) = TC(K-1) + .1*(TC(K-1) - TC(1))
      IF (PRI.EQ.PR) WRITE (6,53) IDATE, (TC(I), RC(I), I=1, K)
      READ (5,49) TEST
  3 READ (5,59) CROP, PER, PIT, ROUGH, HU, ASM, DINF, RN, DIRM, DT, NDT, TEST
      IF (NDT.GT.101) GO TO 70
      IF (TEST.NE.CHECK) GO TO 4
      READ (5,64) NEXP, ((FILTC(I, J), J = 1, 5), (SUR(I, L), L = 1, 2), I = 1, 4)
      WRITE (6,52) (I, (FILTC(I, J), J = 1, 5), I = 1, 4), NEXP, (I, (SUR(I, J), J
  1= 1, 2), I = 1, 4)
      READ (5,49) TEST
  4 IF (TEST.NE.C2) GO TO 40
      READ (5,49) NUM, NIOUT, NJOUT, DX
      RN1 = RN
      DT1 = DT
      CU1 = DX*DX/12.
      CU = DX*DX/43200.
      CONST = 1.486/RN*DX/(2./DT*DX*DX)**1.6667
      IC = 1
      N = 0
      NJ = 1
  6 JS = JBL + 1
      L = N
      N = N + 1
```

```
READ (5,54) I,JBL,NSTOP,S(N),QI(N),SOIL(N)
IF (I.EQ.NIOUT.AND.JBL.EQ.NJOUT) MOUT = N
IF (NSTOP) 12,10,12
10 IF (I - IC) 75,6,13
12 L = N
13 IC = I
DO 30 J = NJ,L
M = QI(J)/90. + 1.
ANG = (QI(J) - 90.*FLOAT(M - 1))*0.01745329
GO TO (20,21,21,20), M
20 NR(J) = J + 1
GO TO (23,23,24,24), M
21 NR(J) = J - 1
GO TO (23,23,24,24), M
23 NC(J) = J + JP
GO TO 25
24 NC(J) = J + JS - JBL
25 IF (ANG - .78539816) 26,26,27
26 RFL(J) = .5*TAN(ANG)
GO TO 28
27 RFL(J) = 1. - .5*TAN(1.5707963 - ANG)
28 GO TO (29,30,29,30), M
29 RFL(J) = 1. - RFL(J)
30 B(J) = CONST*SQRT(S(J))*(SIN(ANG) + COS(ANG))
JP = JBL - JS
NJ = N
IF (NSTOP) 35,6,35
35 AREA = FLOAT(N)*DX*DX/43560.
NR(MOUT) = N + 1
NC(MOUT) = N + 1
CONV = FLOAT(N)*CU
READ (5,49) TEST
IF (N - 300) 40,40,80
40 SUPP = RC(2)*(1. - PER)*CU
CF1 = RN1/RN/(DT1/DT)**1.6667
DT1 = DT
DT = 0.
DO 41 I = 1,N
Q(I) = 0.
S(I) = 0.
SS(I) = 0.
QI(I) = 0.
IS = SOIL(I)
B(I) = B(I)*CF1
P(I) = FILTC(IS,5)
FC(I) = CU*FILTC(IS,3)
TPOR = FILTC(IS,1)*CUI*DINF
PIV(I) = (1. - ASM)*TPOR
A(I) = CU*FILTC(IS,4)/TPOR**P(I)
GWC(I) = (1. - FILTC(IS,2))*TPOR
41 FLINS(I) = SUPP - FILT(A(I),PIV(I),P(I),FC(I),GWC(I))
DT = DT1
QI(N+1) = 0.
WRITE (6,50) I,DATE,NUM,AREA,N,DT,DX,DX,CROP,PER,ROUGH,PIT,RN,HU
RN1 = RN
PIT = PIT*CUI/DT
KPR = (TC(K) - TC(1))/DT/FLOAT(NDT)*60. + 1.
ADIR=SUR(ROUGH,1)*HU*(DIRM/HU)**SUR(ROUGH,2)
DIR = ADIR/6.*DX*DX/DT
WRITE (6,60) DIRM,ADIR,ASM,DINF
IF (DT.GT.60.) WRITE (6,69)
```

```
RETURN
49 FORMAT (20A4/ 19X 2(9X I4), 6X F6.1)
50 FORMAT (1H| 13X 52HMATHEMATICAL SIMULATION OF SMALL WATERSHED HYDR
10LOGY/18X 35HPREDICTION OF RUNOFF FROM STORM OF 2A4// 1X
2 20A4//20H0SIZE OF WATERSHED = F5.2,6H ACRES 6
3 X 25HNUMBER OF ELEMENTS USED = I4/17H TIME INCREMENT = F6.1, 5H S
4EC. 9X 17HSIZE OF ELEMENT =F6.1, 6H FT. X F6.1, 4H FT./21H CROP B
5EING GROWN IS A6.10X 38HPERCENT OF GROUND COVERED BY FOLIAGE = 2PF
65.0/ 29H SURFACE ROUGHNESS CATEGORY = I2, 6X 32HMAXIMUM POTENTIAL
7INTERCEPTION = 0PF6.3, 4H IN./ 24H MANNING'S COEFFICIENT = F6.3, 7
8X 34HMAXIMUM SURFACE ROUGHNESS HEIGHT = F5.1, 4H IN.)
52 FORMAT (/1H028X 23HINFILTRATION PARAMETERS / 21H0SOIL TYPE POROS
1ITY 7X 14HFIELD CAPACITY 9X 22HINFILTRATION CONSTANTS / 11X 48HVOL
2. PERCENT PERCENT SATURATION FC - IN./HR. 3X I1HA - IN./HR. 4X
3 1HP / 4(3X I3,8X 2PF5.0, 11X F6.0, 13X 0PF6.2, 9X F5.2, 3X F8.3/)
4, 37H DRAINAGE RATE IS PROPORTIONAL TO THE I2, 41H POWER OF THE
5GRAVITATIONAL WATER CONTENT / 1H0/1H0/1H0 26X 28HSURFACE ROUGHNESS
6 PARAMETERS / 1H0 20X18HROUGHNESS CATEGORY8X2HSC8X 2HSP / (28XI3,
713X F6.3, 4X F6.2))
53 FORMAT (1H| 30X 19HRAINFALL HYDROGRAPH / 32X 9HSTORM OF 2A4 / 1H0
1 20X 11HTIME - MIN. 7X 23HRAINFALL RATE - IN./HR. / (20X F9.1, 18X
1 F6.2))
54 FORMAT (2I3,I2,F3.3,F4.0,I2)
56 FORMAT (45HIDATA INPUT EXCEEDS RANGE OF DIMENSION SPECIFICATION )
58 FORMAT (I2,F8.0,F10.0)
59 FORMAT (21X A6, 47X F4.0/ 34X F4.3, 38X I2/ 35X F5.2, 25X F5.2/ 27
1X F5.1, 31X F5.3/ 26X F6.3, 24X F5.2/ 39X I4/ A4)
60 FORMAT (4X 31HMAX. SURFACE RETENTION DEPTH OF F6.3, 26H IN. = AN A
1VERAGE DEPTH OF F6.3, 4H IN. / 14X 26HANTECEDENT SOIL MOISTURE = 2
2PF5.0, 22H PERCENT OF SATURATION / 22X 28HINFILTRATION CONTROL DEP
3TH = 0PF5.1, 4H IN. )
62 FORMAT (34HISOME ERROR IN WATERSHED DATA. I = I3, 5H, J = I3)
64 FORMAT (21XI3/(6XF4.2, 9XF4.2, 7XF4.2, 6XF4.2, 6XE5.0, 7XE5.0, 7XF
14.3))
66 FORMAT (10X 2A4, 6X A4)
67 FORMAT (63H|NUMBER OF WATERSHED ELEMENTS TOO LARGE FOR DIMENSION S
1TATEMENT )
68 FORMAT (46H1RAINFALL DATA EXCEEDS DIMENSION SPECIFICATION )
69 FORMAT (74H0ANALYSIS IS NOT CORRECT IF RAINFALL INTENSITY INTERVAL
1S ARE LESS THAN DT. )
70 WRITE (6,56)
STOP
75 WRITE (6,62) I,JBL
STOP
80 WRITE (6,67)
STOP
85 WRITE (6,68)
STOP
END
```

```
SUBROUTINE DRY (N,PIT,PER,S,CU,Q,A,P|V,P,FC,GWC,RATE,QI,T,TC,RC,IT
1R,NRAIN,FLINS,PREC)
DIMENSION S(300),RC(100),A(300),P|V(300),P(300),FC(300),GWC(300),T
1C(100),FLINS(300),Q(300),QI(30)
COMMON NEXP,SUPP,DT
DQ = .0005*CU
```



```
DO 10 I = 1,N
10 IF (Q(I).GT.DQ) GO TO 80
   DTS = DT
   R = RAIN(RATE,PIT,PER)
   L = 1
11 GO TO (14,13). L
13 ITR = ITR + 1
   RATE = RC(ITR)*CU
   PREC = PREC + RC(ITR)*(TC(ITR) - TC(ITR-1))/60.
   L = 1
   R = RAIN(RATE,PIT,PER)
14 T = T + 5.
   DT = 300.
   IF (T.LT.TC(ITR)) GO TO 16
   DT = (TC(ITR) - T + 5.)*60.
   T = TC(ITR)
   L = 2
16 RATIO = DTS/DT/2.
   DO 35 I = 1,N
   FLINS(I) = PIV(I)
   QI(I) = Q(I)
   IF (S(I).LT.0.) S(I) = 0.
   SUPP = S(I)*RATIO + R
   Q(I) = FILT(A(I),PIV(I),P(I),FC(I),GWC(I)) - R
   S(I) = S(I) - Q(I)/RATIO
35 IF (Q(I).LT.0.) GO TO 38
   I = 0
   IF (T - TC(NRAIN)) 11,40,40
38 T = T - DT/60.
40 DO 60 J = 1,N
   IF (J.GT.I) GO TO 50
   PIV(J) = FLINS(J)
   S(J) = S(J) + Q(J)/RATIO
   FLINS(J) = S(J) - QI(J)
   GO TO 55
50 FLINS(J) = S(J) - Q(J)
55 Q(J) = 0.
60 QI(J) = 0.
   QI(N+1) = 0.
   DT = DTS
   WRITE (6,70)
70 FORMAT (25X 28HSIMULATION BY SUBROUTINE DRY )
80 RETURN
END
```

Example Data

```
1 RAINFALL DATA FOR THROCKMORTON STORM OF 05/21/40
STORM OF 5/21/40 PRINT
0 692. 0.000
0 694. .300
0 696. 3.000
0 697. 6.000
0 763. .020
0 770. 2.570
```

07/19/42
07/19/42
07/19/42
07/19/42
07/19/42
07/19/42

773.	2.000	07/19/42
783.	4.200	07/19/42
787.	2.100	07/19/42
791.	3.900	07/19/42
793.	1.800	07/19/42
802.	.600	07/19/42
806.	1.950	07/19/42
810.	4.500	07/19/42
813.	3.200	07/19/42
818.	1.200	07/19/42
822.	2.250	07/19/42
828.	1.600	07/19/42
832.	1.800	07/19/42
839.	.430	07/19/42
915.	.060	07/19/42

ANTECEDENT WATERSHED CONDITION DATA FOLLOW

CROP BEING GROWN IS TIMOTHY PORTION OF WATERSHED COVERED BY FOLIAGE = 0.90
 MAXIMUM POTENTIAL INTERCEPTION = .020 IN., SURFACE ROUGHNESS CATEGORY = 2 2
 MAXIMUM SURFACE ROUGHNESS HEIGHT = 1.0 IN., ANTECEDENT MOIST. = .55 PERC SAT3
 INFILTRATION CONT. DEPTH = 11.0 IN., MANNING'S ROUGHNESS = .100 4
 SURFACE RETENTION DEPTH = 0.000 IN., TIME INCREMENT = 5.0 SEC. 5
 NUMBER OF LINES OF HYDROGRAPH OUTPUT = 101

SOIL INFILTRATION AND SURFACE ROUGHNESS CONSTANTS FOLLOW

DRAINAGE EXPONENT = 3
 TP = .46, FCAP = .72, FC = 1.0, A = 4.90, P = .6500, SC = .4000, SP = 1.73
 TP = .49, FCAP = .80, FC = 0.50, A = 3.00, P = .7500, SC = .5400, SP = 2.19
 TP = .51, FCAP = .73, FC = 0.80, A = 4.50, P = .6500, SC = .8100, SP = 2.97
 TP = .53, FCAP = .66, FC = 0.90, A = 4.74, P = .6500, SC = 1.000, SP = 1.00

NEW WATERSHED DATA FOLLOWS

SIMULATION OF THROCKMONTON WATERSHED NO. 4-2 ,GRID SIZE NO.1,ORIENTATION NO. 2
 NI = 10, NJ = 8, NIOUT = 9, NJOUT = 8, DX = 50.0 FT.

2	2	28	270	1	4-2
3	2	30	304	1	4-2
3	3	33	270	1	4-2
4	2	55	331	3	4-2
4	3	33	294	4	4-2
4	4	37	270	1	4-2
4	5	38	264	1	4-2
5	2	30	0	1	4-2
5	3	60	343	3	4-2
5	4	36	302	3	4-2
5	5	50	264	1	4-2
5	6	50	261	1	4-2
5	7	50	264	1	4-2
6	2	31	0	1	4-2
6	3	40	0	1	4-2
6	4	40	0	1	4-2
6	5	40	314	3	4-2
6	6	60	261	1	4-2
6	7	60	270	1	4-2
7	3	45	9	1	4-2
7	4	46	13	1	4-2
7	5	55	13	1	4-2
7	6	21	314	3	4-2
7	7	42	270	1	4-2
7	8	42	270	1	4-2
8	4	40	7	1	4-2
8	5	50	13	1	4-2
8	6	45	13	1	4-2
8	7	22	324	1	4-2
8	8	45	270	1	4-2

9	4	31	0	1	
9	5	40	9	1	
9	6	50	32	1	
9	7	62	32	1	
9	8	50	333	3	
10	5	23	17	1	
10	6	29	51	1	
10	7	9	70	90	1

END DATA

4-
4-
4-
4-
4-
4-
4-
4-

Example Output

RAINFALL HYDROGRAPH
STORM OF 5/21/40

TIME - MIN.	RAINFALL RATE - IN./HR.
692.0	0.00
694.0	.30
696.0	3.00
697.0	6.00
763.0	.02
770.0	2.57
773.0	2.00
783.0	4.20
787.0	2.10
791.0	3.90
793.0	1.80
802.0	.60
806.0	1.95
810.0	4.50
813.0	3.20
818.0	1.20
822.0	2.25
828.0	1.60
832.0	1.80
839.0	.43
915.0	.06
937.3	0.00

INFILTRATION PARAMETERS

SOIL TYPE	POROSITY	FIELD CAPACITY	INFILTRATION CONSTANTS		
	VOL. PERCENT	PERCENT SATURATION	FC - IN./HR.	A - IN./HR.	P
1	46	72	1.00	4.90	.650
2	49	80	.50	3.00	.750
3	51	73	.80	4.50	.650
4	53	66	.90	4.74	.650

RAINAGE RATE IS PROPORTIONAL TO THE 3 POWER OF THE GRAVITATIONAL WATER CONTENT

SURFACE ROUGHNESS PARAMETERS

ROUGHNESS CATEGORY	SC	SP
1	.400	1.73
2	.540	2.19
3	.810	2.97
4	1.000	1.00

MATHEMATICAL SIMULATION OF SMALL WATERSHED HYDROLOGY
PREDICTION OF RUNOFF FROM STORM OF 5/21/40

1 SIMULATION OF THROCKMONTON WATERSHED NO. 4-2 ,GRID SIZE NO.1,ORIENTATION NO. 2

SIZE OF WATERSHED = 2.18 ACRES	NUMBER OF ELEMENTS USED = 38
TIME INCREMENT = 5.0 SEC.	SIZE OF ELEMENT = 50.0 FT. X 50.0 FT.
CROP BEING GROWN IS TIMOTH	PERCENT OF GROUND COVERED BY FOLIAGE = 90
SURFACE ROUGHNESS CATEGORY = 2	MAXIMUM POTENTIAL INTERCEPTION = .020 IN.
MANNING'S COEFFICIENT = .100	MAXIMUM SURFACE ROUGHNESS HEIGHT = 1.0 IN.
MAX. SURFACE RETENTION DEPTH OF 0.000 IN. = AN AVERAGE DEPTH OF 0.000 IN.	
ANTECEDENT SOIL MOISTURE = 55 PERCENT OF SATURATION	
INFILTRATION CONTROL DEPTH = 11.0 IN.	

RUNOFF HYDROGRAPH

TIME - MIN.	DISCHARGE - IN./HR.
692.0	0.000
SIMULATION BY SUBROUTINE DRY	
696.0	0.0000
SIMULATION BY SUBROUTINE DRY	
773.0	-0.0000
775.5	.0106
778.0	.0382
780.5	.0929
783.0	.1974
785.5	.2246
788.0	.2610
790.5	.3691
793.0	.3832
795.5	.2610
798.0	.1476
800.5	.0683
803.0	.0326
805.5	.0273
808.0	.0848
810.5	.2247
813.0	.4041
815.5	.4664
818.0	.4601
820.5	.4884
823.0	.4943
825.5	.4667
828.0	.4358
830.5	.4224
833.0	.3843
835.5	.2907
838.0	.2059
840.5	.1296
843.0	.0703
845.5	.0315
848.0	.0093
850.5	.0003
SIMULATION BY SUBROUTINE DRY	
937.3	-0.0000

THE RUNOFF VOLUME PREDICTED FROM 3.13 INCHES OF RAINFALL = .299 IN.

