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The Mathematical Simulation of the Hydrology of Small Watersheds

L. F. Huggins

E. J. Monke

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THE MATHEMATICAL SIMULATION OF THE HYDROLOGY OF SMALL WATERSHEDS

by

L. F. Huggins
E. J. Monke

August 1966

PURDUE UNIVERSITY
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THE MATHEMATICAL SIMULATION
OF THE HYDROLOGY OF SMALL WATERSHEDS

by
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E. J. Monke

Purdue University Water Resources Research Center
Technical Report No. 1
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ABSTRACT

The determination of the volume and rate of surface runoff 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 facilities is based. Numerous methods for predicting the surface runoff hydrograph resulting from the application of real or hypothetical storms to a given watershed have been proposed. However, because of the complexity of this process, these methods have generally consisted of grossly simplified relationships between average conditions within the entire watershed, the applied storm and the resulting hydrograph. The computational effort required to describe the detailed mechanics of the hydrologic phenomena occurring within the watershed boundaries has, until recently, made any other approach unreasonable.

The rapid development of large, high speed electronic computers has made feasible the development of mathematical models which integrate the relationships for the various hydrologic components of the runoff process at all points in the watershed to obtain the runoff hydrograph for the complete area. Such a model is proposed herein. Basically, the procedure consists of the development of relationships describing the runoff dynamics for very small elemental areas or points within the watershed. Quantitative relationships are suggested for five of the basic hydrologic components which describe the runoff processes:
interception, infiltration, depression storage or surface retention, surface detention and surface runoff. A general purpose digital computer program, written in FORTRAN IV, is developed to evaluate the resulting mathematical watershed model.

The ability of the proposed watershed model to simulate observed runoff hydrographs from small (two acre) watersheds was investigated for several storm events. In general, with appropriate component relationships, the model is capable of simulating complex storm events very satisfactorily. A comparison between the runoff hydrograph predicted for each storm event by the synthetic hydrograph analysis and the proposed model was made.

The sensitivity of the predicted hydrographs of selected storm events to changes in the values of the assumed initial parameters is reported. Such results can be very useful as a guide in determining the critical components of the model which need further study.
INTRODUCTION

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. Some means of quantitatively describing the rate and path of movement of a rain droplet after it strikes the ground surface is essential for the rational development and efficient utilization of our nation's water resources.

Basically, a method is needed whereby, for known or assumed conditions within a watershed, the runoff hydrograph resulting from any real or hypothetical storm can be predicted with a high degree of reliability. Such a method must be sufficiently general to allow the determination of the change in system response that would result from proposed water management projects within the watershed. Only with this type of analysis can such projects be designed on a rational basis to produce optimum conditions for a minimum cost.

Some of the more common methods of describing the hydrologic performance of a watershed have been based upon statistical studies of long-term rainfall records and the runoff resulting from each storm. Very satisfactory results may be obtained by these techniques when applied to relatively large watersheds where the necessary historical records are available. However, a great number of water control
projects must be designed and installed on smaller watersheds where little or no past hydrologic record exists. The cost and time required for such studies prohibit their application to these many small watersheds.

Several methods have been developed and refined in an effort to solve this highly complex problem. In order to reduce the scope of the problem to a manageable size these methods have been based upon numerous simplifying assumptions as discussed in the following section. Such approximations have significantly limited the reliability of these relationships. The resulting uncertainty in the predicted runoff hydrograph requires that large factors of safety be incorporated into the prediction method and the subsequent engineering design. Any method capable of modeling the surface runoff phenomenon with greater accuracy will permit a reduction of these safety factors and a corresponding reduction in the cost of such projects.

With these factors as background, this dissertation has the following objectives:

I. To develop a mathematical watershed model capable of simulating the surface runoff hydrograph from small (up to several hundred acres) ungaged watersheds. The input data required for the model must consist of information available from maps, generalized tables, etc., rather than being obtained from an extended data collection period on the actual watershed.

II. To study the relative importance of the various components such as infiltration, surface slope and
roughness, and watershed shape in the determination of the runoff hydrograph predicted by the model.

III. To investigate the ability of the model to predict the observed runoff hydrograph resulting from actual storm events on a limited number of natural watersheds.
CURRENT METHODS OF RUNOFF ANALYSIS

The necessity of estimating the hydrologic performance of a watershed and the numerous complexities of this problem have resulted in many proposed methods of analysis. The more popular methods currently used in engineering design are discussed below. For discussions of past methods, the reader is referred to the works of Carter\(^1\) and of Nash\(^2\).

The more common engineering applications of hydrologic data are normally concerned with extreme and infrequent conditions which might be expected to occur within the life of a structure. Fortunately, under almost all conditions, the maximum rate and volume of surface runoff are bounded by the maximum rate and volume of rainfall. Thus, comparatively simple prediction methods have often provided estimates large enough to result in a design safe from failure due to hydrologic conditions in excess of design values. Such results do not provide conclusive evidence of the accuracy of the analytical method employed; they only imply one or a combination of the following possibilities: (1) the method of analysis employed was satisfactory, (2) because of the stochastic nature of rainfall a storm of the expected magnitude did not occur during the period of observation or, (3) the procedure


employed predicts conditions in excess of those actually resulting from the design storm. Only extended gaging periods on several different watersheds can determine the accuracy of a particular method of analysis.

For the following discussion, current analytical techniques may be subdivided into two broad categories: (1) methods developed primarily for use on watersheds where a period of historical record of rainfall and the resulting runoff exists and (2) methods developed for use where no such data are available. A comprehensive and very penetrating discussion of many of these techniques has been given by Amorocho and Hart.3

Methods Suitable for Gaged Areas

For certain types of problems the engineer needs information concerning only the peak rate and/or volume of runoff rather than the entire hydrograph. Two general methods are currently employed for this purpose. Conceptually, the simpler of these two is one of the several extreme value theories which are available.4,5 Basically, these methods consist of completely ignoring the rainfall and watershed and considering the runoff as the stochastic element. Then, based on the extreme values of runoff which occurred during the period of historical record, one attempts to predict the probability of recurrence of an event of specified magnitude or vice versa. Theoretically, this basic approach


should be capable of providing estimates at least as reliable as any of the other methods discussed below.

The second general method for predicting extreme rate and/or volume of runoff is correlation analysis. With this procedure one attempts to establish a functional relation describing the manner in which the watershed transforms the rainfall into runoff. Watershed parameters which, for either theoretical or empirical reasons, can be expected to influence this transformation are formed into a mathematical model. Multiple regression techniques are then used to determine the values of coefficients for these parameters which result in the highest correlation between measured values and model predictions.6

Often information concerning the complete runoff hydrograph is needed rather than just peak rates or volumes. Undoubtedly the most commonly used technique for predicting a complete runoff event is the unit-hydrograph or the instantaneous unit-hydrograph. These complementary methods have been so well discussed it would be redundant to go into their details here.7,8,9 Basically, they provide a technique whereby one assumes that the manner in which the watershed transforms a particular storm event into runoff can be used to describe the transformation for a storm of different magnitude.

---


The recently developed Stanford Watershed Model\(^{10}\) provides one of the most detailed means of describing the entire hydrologic output of a watershed for long periods of time. This digital computer model uses a large number of parameters related to the various components of the run-off phenomenon to generate extended periods of synthetic records of watershed output. A five year (or more) period of detailed hydrologic data from the watershed to be synthesized is normally required. This record is used to determine numerical values of the various coefficients for the model which result in the "best fit" between observed and computed runoff for the period of record.

A method which has recently been receiving increased attention is system identification, sometimes called general systems analysis or non-linear analysis. A detailed discussion of this general technique has been presented by Amorcoho and Orlob.\(^{11}\) These techniques, in their most general form, do not require any understanding of the mechanics of the run-off phenomenon within the watershed. The procedure involves the development of a general mathematical model or transfer function capable of appropriately modifying a known input function (precipitation) into a known output function (runoff). The general method does not require a prior knowledge of the form of this transfer function. If a sufficiently long period of record is available, along with adequate computational capabilities, it is theoretically possible to obtain a


function which will result in the exact duplication of the output for the period of record under analysis.

Methods Developed for Ungaged Areas

Until recent years, one of the most widely used formulas for predicting peak rates of runoff, particularly from small areas, was the rational formula. In fact, this method is still used in some areas of engineering design. Certainly one of the reasons for this popularity is the relative simplicity of the method. In essence, this formula simply states that the peak rate of runoff is a percentage (between 0 and 100) of the rate at which water is being supplied to the watershed. The appropriate supply rate is determined from general rainfall rate-duration-frequency relationships and from certain shape characteristics of the watershed. The percentage factor, or runoff coefficient, is normally selected from tables of "typical" values thereby avoiding the requirement of any hydrologic records from the watershed. Larson recently recommended the use of a modified form of the rational formula. His relationship was developed from periods of synthetic records generated by the Stanford Watershed Model.

A second procedure currently used when estimates of only peak instantaneous flow rates are required is called Cock's method. This procedure, developed completely on the basis of empirical data, is even


simpler to apply than the rational formula. Runoff rates are predicted by reading appropriate numbers off a family of curves. Because the original data utilized was collected from a limited geographical region this method is recommended for use only in the Upper Mississippi Valley region.

The most popular and complete method of runoff prediction currently used for ungaged areas has been developed by the Soil Conservation Service. Although the basic curves used by the synthetic hydrograph procedure are, like Cook's method, based on empirical data, the method is much more comprehensive than Cook's procedure. Unlike either the rational formula or Cook's method, this procedure produces a complete design runoff hydrograph that is dependent upon the time distribution of the rainfall. A detailed explanation of this method may be found in Design of Small Dams.\textsuperscript{15}

Recently, Laurensen\textsuperscript{16} proposed a mathematical model for predicting the complete runoff hydrograph on the basis of applying the continuity equation to the detailed runoff processes within the watershed boundaries. Although the method is based on comparatively firm fundamental concepts, lack of presently available data for defining some of the relationships used would require that a period of hydrologic record be available from a watershed before applying the method.


Critique of Current Methods

All of the methods discussed above which are based on the use of a period of hydrologic records to predict possible future events have several characteristics in common. The most obvious of these is their dependence on the availability of a long term (the longer the better) period of hydrologic records. Implicit in the use of historical records to predict future events is the assumption that the hydrologic system has been invariant with time during the period of record and will continue to be so during the future period for which predictions are desired. This assumption of time invariance is required for both the rainfall input and the watershed itself. Therefore, these techniques cannot be used to evaluate the influence of proposed water management systems on the hydrologic performance of the watershed.

The use of the methods developed for gaged watersheds to predict runoff from ungaged areas is, in general, unsatisfactory. Such a procedure necessitates analysis of data from a gaged area which is hydrologically similar to the ungaged area and which has been subjected to similar precipitation patterns. The success of such an endeavor is highly dependent upon a combination of experience, judgment and luck. In addition, no means is available to test the suitability of the gaged area to model the ungaged watershed.

All of the methods developed for use on ungaged areas and most of those for gaged areas assume a "lumped" hydrologic system for their analysis. This means that the areal distribution and variability of the rainfall and watershed parameters are assumed to have no influence on the runoff. The magnitude of error introduced by this approach is obviously a function of the degree and distribution of the nonuniformities;
thus it would vary from one watershed to another and even between storms on a given watershed.

Excluding the newer methods such as the Stanford and Laurencen models and general system synthesis which are still in developmental stages, extensive efforts to refine the methods of analysis outlined above do not appear to be justified. In order to substantially improve the reliability of current methods, techniques which avoid the gross over-simplifications characteristic of these methods are necessary.
DEVELOPMENT OF A WATERSHED MODEL

Before proceeding to formulate explicit mathematical expressions describing the dynamic process of runoff, a detailed qualitative description of the phenomenon would seem desirable. The purpose of such a description is to delineate the parts of the process for which quantitative relations are required and, hopefully, to indicate a suitable form for these expressions. This qualitative description, or conceptual model, may then serve as the basis upon which to develop the fundamental form of a mathematical watershed model.

All of the methods currently used to predict watershed runoff, since they consist of quantitative relationships concerning hydrologic events, represent various types of mathematical watershed models. In contrast with the lumped parameter approach commonly employed in the development of such relationships, the model developed below was based upon the philosophy that only a description of the many dynamic factors influencing the hydrologic process at each point in the watershed could adequately model such a complex event.

A Conceptual Model

Figure 1 represents a typical or average profile of a very small area or element within a watershed. Because of the small size of the element, areal variations of hydrologic parameters within its boundaries may be neglected. The maximum rate at which water can enter the
soil profile at a given time, i.e., the infiltration capacity, is assumed to be of the form shown in Figure 2. The infiltration rate is equal to the infiltration capacity if the combined supply of rainfall, surface runoff from adjacent areas and surface storage is adequate to sustain this maximum rate; otherwise it is equal to the supply rate.

Figure 1. Average Profile of a Watershed Element

Figure 2. Assumed Form of the Infiltration Capacity Relationship
The general form of the surface runoff hydrograph that can be expected to result from the application of a steady rate of rainfall to this hypothetical watershed element is shown in Figure 3. At time = 0, when rainfall begins, a portion of the water is intercepted by plant surfaces and never reaches the ground. Generally, the rate of interception can be expected to decrease quite rapidly with time as indicated in Figure 3. The interception rate could be expected to depend mainly upon the density of vegetal cover (and therefore season of the year), type of vegetation, wind velocity and rainfall intensity.

Water that reaches the ground surface at $t = 0$ begins to infiltrate into the soil and to fill the micro- and macro-depressions in the surface. Water normally will be unavailable for runoff until at least a portion of the depression storage volume has been filled. The total volume of depression storage within a particular element would depend primarily upon the cultural practices, the vegetation (as it influences cultural practices) and the soil erosion or deposition which occurs during the storm event. The amount and pattern of soil erosion could be expected to depend upon the rate of runoff, energy of the falling rain (intensity), soil type and slope steepness of the element.

As indicated in the preceding paragraph, infiltration begins when the rain first reaches the ground surface. The rate of infiltration will be equal to the rate of supply as long as this supply rate does not exceed the infiltration capacity. Water begins to collect on the soil surface to become either surface runoff or to satisfy the volume of depression storage when the rate of supply exceeds the infiltration capacity. Infiltration is one of the most complex and often one of the more important components of the runoff process. Its rate and volume
can be expected to depend upon the following parameters: soil type, antecedent moisture conditions, rainfall intensity, soil moisture content and distribution during the storm event, season of the year, vegetal cover, previous cropping history, cultural practices and any erosion or deposition of soil which might occur during the runoff event.

Once the composite demands for interception, depression storage and infiltration have decreased to a level below the rainfall rate, water becomes available for surface runoff. However, before this water can begin to move off the surface it must accumulate to some finite depth. In general, the rate of surface runoff can be expected to increase with increasing depths of water. The "film" or volume of water that must accumulate to produce a given rate of runoff is often referred to as the surface detention component of the runoff process. Except for that portion which infiltrates, it eventually becomes surface runoff when the rain ceases and the rate of surface runoff decreases. Thus, the volume of surface detention depends upon the rate of runoff, the slope of the element, the effective hydraulic roughness of the element, and the degree of turbulence in the flow.

In order to expand this conceptual model to encompass an entire watershed additional factors neglected in the preceding discussion must be considered. One of the more important considerations omitted in the development of the elemental area hydrograph was the ultimate destination or flow path of water which infiltrates into the soil profile. This water will normally either percolate through the soil to become a part of the general groundwater level or it may move laterally through the soil to later reappear on the surface at some other point within the watershed boundaries. That which ultimately becomes groundwater and
does not reappear within the boundaries of the watershed is of no concern to the problem of surface runoff hydrology. The other phenomenon of lateral movement and reappearance, normally called interflow, is of definite importance and concern. The magnitude and rate of this interflow component will be a function of the subsurface geology of the watershed and of the soil moisture distribution.

The assumption that the rainfall rate is steady for a period of time sufficiently long to permit the establishment of a constant runoff rate is normally not valid on a watershed scale. Likewise, the areal distribution of this rainfall is likely to be an important factor, particularly on the larger watersheds. The various parameters which were discussed as influencing the elemental runoff hydrograph can also be expected to vary within the watershed boundaries. Thus, the runoff hydrograph from a composite watershed will depend upon the highly complex interaction between these nonuniform and unsteady relationships for the many elements of which the area is composed. Therefore, in order to be able to describe this process accurately, a mathematical watershed model must be capable of quantitatively describing not only the components applicable to a small elemental area, but also the various interactions which occur between these many small areas.

**A Mathematical Model**

A fundamental limitation of almost all of mathematical relationships that have been proposed and used to predict runoff from a known or assumed rainfall input is their dependence upon the concept of a "lumped" system. Thus, regardless of the number of components used in building the model, the parameters employed must represent an average
or net effect of the particular component over the entire watershed. To obtain such a value requires knowledge of not only the particular component itself, but of its complex interactions between all other components as well. In addition, unless all elements within the watershed are linear, a final or overall average coefficient will depend upon the magnitude and the time distribution of the system input. Such an average 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. Such a capability eliminates the need for the original lumped system model.

The development of means of predicting the hydrologic response of a watershed to a given rainfall input without using lumped parameters requires relationships describing the dynamics of the process at every point within the watershed. A mathematical watershed model which avoids the use of lumped parameters 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 beginning of the storm event, depth of flow and rainfall intensity (to the extent that it affects flow turbulence and topography) at that point.

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

On the basis of the above hypothesis, a mathematical watershed model may be developed upon the concept of subdividing a composite watershed into a finite number of small, independent elements as shown
Figure 4. Hypothetical Watershed Showing Subdivision into Elements.

in Figure 4. The various components of the runoff phenomenon within each element may then be delineated as independent mathematical functions of the pertinent watershed and rainfall parameters and of time. In order to model the essential characteristics of the complete watershed the elements must be of sufficiently small size that:

All hydrologically significant parameters, e.g. slope magnitude and direction, vegetation, rainfall and infiltration rates, etc., are uniform within the boundaries of the element. These parameters may, however, vary in a completely unrestricted manner between adjacent watershed elements.

Considering the entire watershed to be composed of a composite group of essentially independent elements, it is apparent that the runoff

\footnote{It is computationally convenient to require that the slope direction of all boundary elements be such that their entire outflow enters an element within the watershed. Likewise, the outlet element should be given a slope direction such that none of its outflow enters adjacent watershed elements.}
water or outflow from one element is a source of supply or inflow to its adjacent elements. On the basis of the above requirement of a uniform slope within an element, the following assumption was made in order to quantitatively determine the distribution of the outflow into adjacent elements:

All water flowing across an element moves parallel to the direction of steepest slope of the element. The percentage of the total outflow moving into each of the two adjacent elements receiving this water is simply the percentage that the shaded areas shown in Figure 5 represent of the total area of the element.

Basically, then, the proposed mathematical watershed model requires the development of a runoff hydrograph for each element in the watershed, as developed on a qualitative basis in the preceding section, and the integration of these responses over the entire area.

\[ Q_1 = \frac{A_1}{A_1 + A_2} Q \]

\[ Q_2 = \frac{A_2}{A_1 + A_2} Q \]

Figure 5. Surface Flow Conditions Within an Element
The time distribution of runoff from each watershed element may be determined by combining the various component relationships outlined above with the equation of continuity:

\[ I - O = \frac{dS}{dt} \]  

(1)

where:  
\( t \) = time  
\( I \) = inflow rate  
\( O \) = outflow rate  
\( S \) = volume of water in storage.

In order to utilize Equation (1) the volume of water in storage and the rate of surface runoff are normally expressed in parametric form with the depth of water in the element as the parameter. Equation (1) may be solved numerically in the following finite difference form:

\[ I_1 + I_2 - O_1 + \frac{2S_1}{t} = O_2 + \frac{2S_2}{t} \]  

(2)

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

The composite runoff hydrograph from the entire watershed is obtained by starting at a known initial condition and applying Equation (2) to determine conditions at all points in the system one time increment later. This process is simply repeated until the complete hydrograph at the outlet of the watershed has been defined.

The conceptual model of surface runoff from a small watershed element developed above resulted in a subdivision of the runoff cycle
into several components. Each of these components can be independently incorporated into the general mathematical model with little difficulty. For example, the component of interception can be viewed as an abstraction from the rainfall before it reaches the ground surface. Thus, computationally, it is necessary only to subtract the rate at which water is being intercepted from the total rainfall rate to obtain an "effective" rate. The interception rate could, of course, differ for various parts or elements of the watershed.

Infiltration, like interception, can also be considered as a component which modifies the effective rainfall rate. Defining the rainfall excess as that portion of the total rainfall which is available to either satisfy depression storage requirements or to become runoff, the instantaneous rainfall excess rate is simply the instantaneous total rainfall rate minus the sum of the instantaneous interception and infiltration rates. The component of interflow can be treated, for computational purposes, simply as a negative infiltration rate.

As developed in the conceptual model, at least a portion of the depressional storage would normally be satisfied before water became available for runoff. This component must therefore be incorporated as a part of the required functional relationship between the rate of runoff and the depth of water, i.e., a runoff function, for each watershed element.

The component of surface detention storage is already incorporated into the model as the storage volume in the continuity equation. A storage relationship which relates the volume of water being detained to the depth of water within the element is, of course, required.
The above description indicates how all the components of the
detailed conceptual model are incorporated in the mathematical watershed model. Before such a model can actually be useful for quantitatively predicting surface runoff hydrographs, explicit functional relationships for each of these components must be developed.

Critique of Mathematical Model

Before proceeding to develop detailed mathematical relations for the components of the watershed model some of the broader limitations and advantages of this method of analysis need to be considered. Such a discussion at this point requires the tacit assumption that acceptable relationships can be developed for each of the hydrologic components of the runoff process outlined above.

The most obvious result of using the proposed type of watershed model is the tremendous increase in computational effort required to obtain a predicted runoff hydrograph in comparison to methods currently in use. Fortunately, modern electronic computers have so completely changed computational capabilities that methods of engineering analysis no longer need to be severely restricted for this reason. In fact, the general method of analysis proposed above can be very flexible in this regard. Depending upon the cost that can be justified by the ultimate use of the output, the number and size of the elements can be varied to adjust the computational requirements. There is, of course, a limit to the maximum size of element which will still give results representative of the area being modeled.

In addition to the much larger computational effort demanded by a detailed model, it appears, upon a cursory examination, to require a
great volume of detailed quantitative data regarding conditions at each point within the watershed. If such data were not available for a particular watershed requiring a runoff analysis considerable expense and effort could be involved in obtaining accurate information for the several components. Although the reliability of the hydrographs predicted by any such model is certainly dependent upon the basic data supplied, a lack of accurate and detailed information concerning all pertinent hydrologic components does not preclude its use. Engineering estimates of parameter values can be made just as readily for a detailed model as for the current lumped system models. In fact, estimates for such an analysis should be easier to make for independent point values of the parameters than for a lumped system model requiring complex weighted averages as discussed in detail in the preceding section. For the same degree of quantitative data, better results should be expected from the more complete model than from the lumped system model.

The analysis of watershed runoff on the basis of a combination of elements has several rather fundamental advantages. One such advantage has been alluded to above; namely, the ability to isolate the various component parts of the runoff process. The complex interactions between unsteady and nonuniform components are inherently obtained during the stepwise computational procedure. This physical and mathematical independence of the parameters means that known or assumed physical constraints can easily be placed on the component relationships. In addition to eliminating the need for lumped system parameters this also makes possible an evaluation of the sensitivity of the watershed to ranges in parameter values for the various components. Thus, the components requiring the greatest expenditure of money and effort for
additional research and/or collection of field data for engineering application of the model can be determined.

The nature of a detailed watershed model is such that it should be capable of predicting the runoff hydrograph or the lack of such runoff resulting from any storm. Therefore, the validity of the model reproductions can be evaluated on the basis of every storm event to which a watershed is subjected rather than just the few storms which produce large runoff rates. Thus, any length of hydrologic record with any degree of complexity of the rainfall hydrograph can be useful. In fact, even storms which produce no runoff can provide a check on assumed parameters of interception, infiltration, etc.

A detailed model is very easily adapted to investigate the influence of proposed structures and/or watershed programs on the total runoff from an area. Such a capability is essential to the utilization of systems design techniques currently coming into use to determine the optimum design for complex water control projects.

Finally, a detailed analysis inherently accounts for the effects of areal shape and general surface topography on the runoff hydrograph. Likewise the influence of the areal variations as well as the time distribution of the rainfall can be studied with almost no additional computational effort. For example, the influence of such phenomenon as the path of movement of a storm across a watershed could be evaluated with little difficulty. Such complex concepts as Betson's\(^2\) "partial area contribution" phenomenon are generated as a natural result of the assumed areal distribution patterns for the various hydrologic components just as such conditions develop in a natural watershed.

DEVELOPMENT OF COMPONENT RELATIONSHIPS

The accuracy with which the watershed model developed in the previous section can predict a particular runoff hydrograph depends upon the ability of the mathematical relationships representing the individual hydrologic components to describe their respective phenomenon. Ideally, the best method of establishing quantitative relations for these components would have been a series of experiments designed to study each component separately. Unfortunately, such an ambitious program was beyond the scope of this research program.

The relations below, with the exception of the infiltration phenomenon for which the results of several independent investigations are available, were developed mostly from theoretical and intuitive considerations of the processes involved. The only means available for testing the adequacy of such relationships was a comparison between measured and predicted runoff hydrographs from a complete watershed. Although such comparisons are the ultimate means of testing the validity of the complete watershed model they do not permit the source(s) of any observed discrepancies to be isolated. This dissertation will indicate the basic feasibility of the fundamental approach rather than attempt to develop thoroughly tested relationships describing the dynamics of each hydrologic component.
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 prevailing 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. Horton\(^1\) 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 precipita-
tion 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 recom-
mended 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:

\[ V = A(B + C \cdot P)h \]  \hspace{1cm} (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.
Table 1. Interception Constants Recommended by R. E. Horton

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

O. R. Clark\(^2\) reported the results of interception studies made on several field crops. Interception measurements on almost all crops and grasses were found to be in excess of 50 percent of the total rainfall for storms with up to 2 inches of precipitation. These values are so much higher than those reported by any other investigator that their validity is questionable.

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 Haynes\(^3\). 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, 25 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

<table>
<thead>
<tr>
<th>Crop</th>
<th>Condition of Growth</th>
<th>Projected Area -- %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>8 ft. high, 42 in. rows with 14 inch hill spacing</td>
<td>55-65</td>
</tr>
<tr>
<td>Oats</td>
<td>maximum stage of growth, drilled in 6 inch rows</td>
<td>55-65</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>18-20 inches high</td>
<td>90-100</td>
</tr>
<tr>
<td>Soybeans</td>
<td>38 inches high, drilled in 8 inch rows</td>
<td>95</td>
</tr>
</tbody>
</table>

Stoltenberg and Wilson 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

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acre to be 0.025 inches of rain. These data are in general agreement with that of Horton as given in Table 1.

Burgy and Pomeroy have recently reported results of interception measurements under grass cover. However, their results, like those of Haynes, are given in terms of the total volume of interception from a combination of storms.

Several studies have reported on the interception losses under various types of forest canopies. Because none of the watersheds modeled in this study had this type of cover, their results are not reported.

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 is 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

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could be neglected and (2) the rate at which water is intercepted prior to the satisfaction of interception storage could be computed as the ratio of the horizontal projected leaf surface area 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 important because the rate of surface runoff from an element depends upon the depth of flow.
In order to develop a surface storage-depth relationship consider the ground surface profile sketched in Figure 6 to represent the average profile for a particular square watershed element.

![Diagram of ground surface profile]

**Figure 6. 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:

\[
A(h) = \Delta x \sum_{i=1}^{n} l_i \tag{h}
\]

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

\[
S(h) = \Delta x \int_{h=0}^{h=h_u} L(h) \cdot dh \tag{5}
\]

where:

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

\(^{10}\) This assumption is not basic to the derivation; however, the location of the water surface must be a specified function of depth. Any explicit storage-depth relationship may be used in the watershed model outlined previously.
For \( h \geq h_u \):

\[
S(h) = S_u + (\Delta x)^2 (h - h_u)
\]  

(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 7.

![Figure 7. Typical Shape of a Storage-Depth Function for a Flat and a Rough Surface](image)

Most of the reported research on micro-relief has concerned the effects of tillage operations on surface conditions.\(^{11}\)\(^{12}\) 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 a limited number of field surface profiles taken in the spring of 1966. 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:

\[ \frac{S}{(\Delta x)^2 h_u} = f(h/h_u) \]  \hspace{1cm} (7)

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 Figures 8 and 9, and 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.
Figure 8. Sample Surface Roughness Profiles as Measured in the Field

\[ \frac{S}{S_u} = 0.54 \left( \frac{h}{h_u} \right)^{2.2} \]

Figure 9. Combined Surface Roughness Data From All Conditions
### Table 3. Summary of Surface Storage Relationships

<table>
<thead>
<tr>
<th>Condition</th>
<th>( h_u )</th>
<th>( B )</th>
<th>( A )</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowed Ground</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring -- smooth</td>
<td>4.0</td>
<td>.81</td>
<td>.75</td>
<td>1.9</td>
</tr>
<tr>
<td>Spring -- normal</td>
<td>5.3</td>
<td>1.26</td>
<td>.55</td>
<td>2.1</td>
</tr>
<tr>
<td>Spring -- rough</td>
<td>5.2</td>
<td>1.45</td>
<td>.40</td>
<td>1.7</td>
</tr>
<tr>
<td>Spring -- very rough</td>
<td>7.2</td>
<td>2.12</td>
<td>.55</td>
<td>2.2</td>
</tr>
<tr>
<td>Fall -- smooth</td>
<td>2.5</td>
<td>.51</td>
<td>.47</td>
<td>2.7</td>
</tr>
<tr>
<td>Fall -- normal</td>
<td>4.2</td>
<td>.86</td>
<td>.31</td>
<td>2.2</td>
</tr>
<tr>
<td>Fall -- normal</td>
<td>2.7</td>
<td>.52</td>
<td>.81</td>
<td>3.0</td>
</tr>
<tr>
<td>Fall -- normal</td>
<td>3.5</td>
<td>.91</td>
<td>.44</td>
<td>1.9</td>
</tr>
<tr>
<td>Fall -- rough</td>
<td>5.1</td>
<td>1.11</td>
<td>.56</td>
<td>2.2</td>
</tr>
<tr>
<td>Disked and Harrowed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very smooth</td>
<td>1.4</td>
<td>.33</td>
<td>.55</td>
<td>2.4</td>
</tr>
<tr>
<td>Rather rough</td>
<td>2.3</td>
<td>.46</td>
<td>.59</td>
<td>2.3</td>
</tr>
<tr>
<td>Corn Stubble</td>
<td>4.5</td>
<td>1.25</td>
<td>.67</td>
<td>1.7</td>
</tr>
<tr>
<td>All data</td>
<td></td>
<td></td>
<td>.54</td>
<td>2.2</td>
</tr>
</tbody>
</table>

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. The works of Philip, Hanks and Bowers, Rubin and Steinhardt, and of Whisler and Klute are representative of this latter group. 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,\textsuperscript{17} while primarily empirical, have strongly influenced much of the research involving hydrologic applications of infiltration data. In 1939, Horton\textsuperscript{18} suggested the following widely used relationship for infiltration capacity:

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

(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.

Philip\textsuperscript{19} proposed an equation of the form:

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

(9)

\textsuperscript{17}Horton, R. E. 1933. The Role of Infiltration in the Hydrologic Cycle. Trans. AGU 14:446-460.


where: \( \mu \) = 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 \( t \).

The potential application of relationships such as Equations (8) and (9) in a watershed runoff model is greatly 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. In order to eliminate this area of difficulty, Holtan\(^{20}\) and Overton\(^{21}\) proposed an infiltration capacity relationship with soil moisture content as the independent variable. This equation has the form:

\[
f = f_c + A(S - P)^P
\]

\( (10) \)


where: \( A \) and \( P \) = coefficients

\[ S = \text{storage potential of a soil above the impeding strata (total porosity minus antecedent soil moisture)}. \]

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

\[ f = f_c + A \left( \frac{S - F}{T_p} \right)^P \]  \( (11) \)

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 practical as well as
theoretical advantages. 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 a 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.

Sufficient data have not yet been analyzed to allow typical values of the infiltration constants of Equation (11) to be published for a variety of soils. Fortunately, unpublished data from a series of sprinkling infiltrometer\textsuperscript{22} tests conducted by the Agronomy Department at Purdue University were made available so that estimates could be made for the predominant soil type needed for this study. These data were collected during 1960 and 1961 from a Sidell silt loam\textsuperscript{23} soil on the Purdue Throckmorton Farm located approximately eight miles south of the University. The study from which the data were taken involved the determination of the influence of various surface conditions, i.e., different types of tillage versus "crusted" conditions, on the infiltration rates. Thus, the data afforded an opportunity to measure the order of magnitude of variation of the infiltration capacities which might be expected within one soil type. Infiltration coefficients for soil types for which no data were available were estimated on the basis of the values obtained for the Sidell soil.


\textsuperscript{23}A map of the Throckmorton watersheds showing the distribution of the soils is given in Appendix B.
Figure 10. Sample Infiltration and Subsurface Drainage Curves

The evaluation of the coefficients for Equation (11) from an observed infiltration-time relationship as shown in Figure 10 requires a knowledge of the rate at which water drains from the "control zone" used to determine the soil moisture content. For the analyses reported herein the following assumptions were used: (1) when the moisture content within the control zone was less than field capacity, the drainage rate was taken to be zero; (2) the soil within the control zone was assumed to be completely saturated when the rate of infiltration became constant; (3) the drainage rate was assumed to be equal to the infiltration rate, as required by continuity considerations, when the infiltration rate became constant; and (4) when the water content was
between field capacity and saturation, the drainage rate was computed according to the relation:

\[
\text{Drainage rate} = f_c \left(1 - \frac{P IV}{GWC}\right)^3
\]

where: \( P IV \) = unsaturated pore volume
\( GWC \) = maximum volume of gravitational water, i.e., total porosity minus field capacity.

The above assumptions, while rather arbitrary, were not considered to be critical for the intended use of the results. More complicated, and perhaps more realistic, assumptions would simply result in different values for the infiltration constants calculated from a particular observed infiltration curve. However, provided a consistent set of assumptions are employed for both the analysis and the application of the resulting coefficients, predicted infiltration capacity rates within the range of the observed values should be expected.

The determination of the infiltration constants for Equation (11) from observed data also requires that the depth of the control zone be specified. However, this depth may be determined, by trial and error, from the data by requiring that the volume of water represented by the area between the infiltration and drainage curves shown in Figure 10 be equal to the initial moisture deficiency, i.e., the product of the control depth with the difference between total porosity and antecedent soil moisture.

The infiltration constants, \( A \) and \( P \), were determined by least square regression techniques using \( f - f_c \) and \( [(S - F)/T_p] \) as the dependent and independent variables. Two types of regression analyses were made: first, a standard linear regression of the logarithms of
the data and secondly, an analysis which minimized the sum of the actual squared deviations. The latter analysis resulted in equations for several of the tests which appeared to more closely describe the observed infiltration rates, especially for the initial portion of the curve, than the equations derived using the log-transformations. Figure 10 is a rather extreme example of a test for which the two analyses gave widely differing results.

Despite the apparently better agreement between the data and the computed regression relationships obtained without transforming the data, the results obtained from fitting a linear equation to the logarithms of the variables were used for the watershed model. This decision was based upon the conclusion that, for many of the tests, the non-transformed relationships predicted unrealistically high infiltration capacities in the lower ranges of soil moisture. The data collection techniques employed to determine the infiltration capacity rates with the sprinkling infiltrometer consistently overestimate the infiltration capacity rates actually occurring during the early portion of a test. Forcing the regression line to fit these early points very closely and then extrapolating the resulting curve to moisture contents much lower than included in the range of the data was unrealistic. The log-transformations minimize the influence of this early portion of the data on the resulting regression coefficients.

The results of the analysis of the available infiltrometer data are summarized in Table 4. In general, the measured steady-state infiltration rates were considerably higher than anticipated on the
basis of rates suggested for large watersheds. They were, however, of
the general order of magnitude expected as a result of tests on less
permeable soils by Sharp, Holten and Musgrave using small scale
sprinkling type infiltrometers. The primary influence of a surface
crust was to substantially reduce the depth of the control zone. Wheel-
track planting, in comparison with the corresponding surface condition
for more conventional tillage practices, increased both the depth of the
control zone and the steady-state infiltration rate.

Interflow

As indicated above, the reappearance of groundwater onto the surface
to become runoff may be treated, for computational purposes, simply as
a negative infiltration rate. While the inclusion of this hydrologic
component in the basic watershed model is an easy task, specifying its
distribution and rate at all points within many watersheds could be
extremely difficult. The geology of the area where the experimental
watersheds used herein were located is such that interflow was assumed
to be negligible.

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Printing Office, pp. 151-159.

tration in Relation to Runoff on Small Watersheds. Soil Cons. Service
Table 4. Summary of Infiltration Capacity Data

<table>
<thead>
<tr>
<th>Control Depth</th>
<th>$f_c$ (in./hr)</th>
<th>Log-transformation A (in./hr)</th>
<th>Log-transformation P</th>
<th>No Transformation A (in./hr)</th>
<th>No Transformation P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Condition -- Crusted (10 tests)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>3.7</td>
<td>.86</td>
<td>4.7</td>
<td>.70</td>
<td>16.5</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.1</td>
<td>.13</td>
<td>1.2</td>
<td>.04</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Surface Condition -- Freshly Cultivated (7 tests)

| Mean         | 12.0 | 1.09                          | 5.0                  | .58                          | 6.1               | .65               |
| Standard Deviation | 3.0  | .26                           | 1.0                  | .18                          | 1.1               | .26               |

Wheel Track Cultivation

Surface Condition -- Crusted (2 tests)

| Mean         | 6.7  | 1.58                          | 3.8                  | .69                          | 10.1              | 1.21              |
| Standard Deviation | 1.8  | .32                           | 1.1                  | .11                          | 2.0               | .08               |

Surface Condition -- Cultivated (2 tests)

| Mean         | 20.3 | 1.85                          | 3.6                  | .61                          | 4.0               | .61               |
| Standard Deviation | 10.3 | .32                           | 1.0                  | .04                          | 2.3               | .93               |
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 11. Figure 11a 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, $d_p$. The more complex relationship shown in Figure 11b corresponds to an element located in a depressional area. The depth $d_p$ 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.

A large amount of research has been devoted to the development of relationships describing the flow of thin sheets of water over plane surfaces. On the basis of the assumption that two-dimensional overland flow could be characterized by an equation of the form:
(a) Normal Relationship

(b) Relationship for an Element Subject to Flooding

Figure 11. Qualitative Runoff Functions
with slope or flow rate was found, the spray from the simulated rainfall caused the depth of flow to increase from 8 to 28 percent.

Parsons found the flow usually began to deviate from laminar conditions for Reynolds numbers in excess of 500 with a transition zone ranging to approximately 2000. The value of Manning's roughness coefficient was found to be essentially constant for the completely turbulent flows.

Recent research has emphasized the development and solution of the differential equations which describe the mechanics of overland flow. 30,31,32,33 Yu and McNown34 obtained very good correlation between experimental observations and numerical solutions for the runoff hydrographs from a 500 foot concrete surface subjected to simulated rainfall. They concluded the anomalous "pip" often observed in such hydrographs at the cessation of rainfall was the result of a change from conditions of high turbulence caused by raindrop impact to more laminar conditions when the flow was not disturbed by raindrops.


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 hydrodynamic 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 to allow the feasibility of the proposed watershed model to be tested.

The extensive experimental program required to determine the validity of the hypothesized runoff function or to develop alternative relationships was beyond the scope of this dissertation.

Figure 12. Typical Cross-Section of a Watershed Element

Let Figure 12 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:

\[
\bar{d} = \frac{(S - S_r)}{A}
\]  

(15)

where:  
\( A \) = area of the element  
\( S_r \) = volume of water for a depth = \( d_r \).

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 seems reasonable:

\[
V = K \bar{d}^m
\]  

(16)

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.

Utilizing the earlier hypothesis that the flow within a watershed element moves parallel to the direction of maximum slope and Equation (16), the total discharge may be computed as:

\[
q = V_x \bar{d} \cdot DX + V_y \bar{d} \cdot DX \\
= \bar{d} \cdot DX \cdot V(|\cos \theta| + |\sin \theta|) \\
= K' \bar{d}^{m+1}
\]  

(17)

where:  
\( K' = K \cdot DX(|\cos \theta| + |\sin \theta|) \)  
\( \theta \) = the angle of flow across an element.
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.:

\[ K = \frac{1.486 \sqrt{S}}{n} \]

\[ m = 2/3 \]

where: \( S \) = slope of watershed element

\( n \) = hydraulic roughness coefficient.

Despite some experimental evidence to the contrary\(^{35}\) 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.

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\(^{35}\) Schiff, L. 1951. Surface Detention, Rate of Runoff, Land Use, and Erosion Relationships on Small Watersheds. Trans. AGU 32:57-65.
Figure 14. The Effect of Grid Orientation on the Runoff Hydrograph

Figure 15. The Influence of Hydraulic Roughness on Surface Runoff
watersheds four and eleven for a particular roughness coefficient. The flatter topography of watershed eleven results, as expected, in a slower rate of rise of the hydrograph, and a longer delay in the hydrograph peak after rainfall ceases.

**Analysis of Actual Storm Events**

The significance of such hydrologic components as interception, surface retention and infiltration can be effectively evaluated only by simulating actual storm events and studying their influence on the predicted runoff hydrograph. Likewise, hydraulic roughness influences are most pronounced when unsteady phenomenon are being modeled. In order to study these effects under a range of conditions, thirteen storm events from the period of record on the Throckmorton watersheds were chosen for simulation. The storms were selected to obtain a wide variety of rainfall and runoff conditions.

Because of the aforementioned difficulty in obtaining quantitative data regarding the antecedent values of the various hydrologic parameters of a detailed watershed model the values used herein represent only estimates of actual conditions. The antecedent soil moisture was estimated on the basis of the available record of rainfall which had occurred prior to the storm being analyzed. For this purpose it was assumed that moisture conditions varied between the permanent wilting point and field capacity of the soil. An exception to these limits was made when large amounts of rainfall occurred within the 24 hours immediately preceding the storm being investigated. The potential volume of interception was determined on the basis of qualitative estimates of the crop cover recorded for each storm event and the results of the
interception research already discussed. Two levels of infiltration capacity rates were permitted: a "high" rate summarized for the various soils in Table 5 and a "low" rate corresponding to one-half the magnitude of \( f_c \) and \( A \) as given in Table 5.

Table 5. Infiltration Capacity Parameters for the Throckmorton Soils

<table>
<thead>
<tr>
<th>Soil</th>
<th>Total Porosity Volume %</th>
<th>Field Capacity % of Saturation</th>
<th>( f_c ) in./hr.</th>
<th>( A ) in./hr.</th>
<th>( F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sidell si. lo.</td>
<td>46.</td>
<td>72.</td>
<td>1.00</td>
<td>4.90</td>
<td>.65</td>
</tr>
<tr>
<td>Chalmers si. cl. lo.</td>
<td>49.</td>
<td>80.</td>
<td>0.50</td>
<td>3.00</td>
<td>.75</td>
</tr>
<tr>
<td>Raub si. lo.</td>
<td>51.</td>
<td>73.</td>
<td>0.80</td>
<td>4.50</td>
<td>.65</td>
</tr>
<tr>
<td>Dana si. lo.</td>
<td>53.</td>
<td>66.</td>
<td>0.90</td>
<td>4.75</td>
<td>.65</td>
</tr>
</tbody>
</table>

Physical data which might have been useful in estimating parameter values for the surface retention volume and hydraulic roughness were not available. Likewise, information to determine the depth of the infiltration control zone, although shown in the infiltrometer study to depend significantly on surface crusting, was unavailable. Therefore, these values, subject to the constraints indicated below, were selected so that the peak runoff rate of the simulated hydrograph approximated the observed rate. The various parameters were arbitrarily limited to the following ranges: the hydraulic roughness coefficient from 0.02 to 0.6, the surface retention volume from 0.00 to 0.14 inches, and the infiltration control depth from 3.0 to 16.0 inches. In addition, identical antecedent soil moistures and infiltration capacity relationships were assumed for both watersheds on a given date.
The results of the model simulation of the selected storm events are shown in Figures C1 and C2 of Appendix C. The assumed parameter values for the various hydrologic components for each storm are given in Table C1.

While the selected parameter values do not, in general, represent the particular combination of values capable of best reproducing the observed runoff hydrograph, little significance can be attached to the close agreement between observed and predicted peak runoff rates. An indication of the ability of the watershed model to simulate the runoff from natural storms may be obtained by observing the accuracy with which it reproduces multiple peaks and transient features of runoff hydrographs. Unfortunately, no generally accepted standard of comparison exists to determine what constitutes satisfactory agreement between observed and modeled hydrographs. In order to provide a comparison of the predictions obtained from the detailed watershed model with current techniques, a synthetic hydrograph analysis was made of each storm event. These results are also shown in Appendix C.

A synthetic hydrograph analysis predicts the surface runoff hydrograph from a storm event on the basis of the observed rainfall hydrograph, the time of concentration for the watershed and the values of the runoff curve number assigned for the particular event. The selection of an appropriate runoff curve number is based upon the soils present in the watershed, the vegetation, the type of farming operations, the antecedent soil moisture and the classification of the "hydrologic condition" of the watershed, i.e., an evaluation of whether or not conditions within the watershed are conducive to high runoff rates and volumes. Because of the comparatively high infiltration rates observed on the
Throckmorton soils, the hydrologic condition was assumed to be not conducive to runoff. The quantitative relationship used to select a curve number for a particular antecedent soil moisture level is shown in Figure 16. The broken vertical lines represent the soil moisture levels assumed to correspond to antecedent conditions designated I through III by the Soil Conservation Service. The time of concentration for the watersheds was determined by adding the estimated travel times for both overland\(^2\) and channel\(^3\) flow conditions. The resulting times of concentration for watersheds four and eleven were 9.9 and 11.4 minutes, respectively.

Several conclusions may be drawn from the results presented in Appendix C. First, in comparison with the synthetic hydrograph procedure, the detailed watershed model was capable of simulating the observed runoff hydrographs from the Throckmorton watershed quite well for most of the storms. For those storms where a relatively constant time lag existed between the observed and simulated hydrographs, such as the storm of September 21, 1950, on watershed four, it is strongly suspected that an error existed in either the observed rainfall or runoff hydrograph or that the time of occurrence of rainfall differed between the watershed and recording raingage record.


Figure 16. Relationships Between the Antecedent Soil Moisture and Runoff Curve Number

The two storms of April 7, 1948, on watershed eleven represent an exception to the pattern of agreement between the predicted and observed hydrographs. Apparently the infiltration capacity relations employed were not representative of conditions prevailing on the watershed on that date. A comparison of the observed rainfall and runoff hydrographs for the first of the two storms of April 7 also indicates that an additional source of discrepancy between the observed and predicted runoff hydrograph was the probable inaccuracy with which the raingage record described the actual storm pattern on the watershed.

In general, for conditions on the Throckmorton watershed, the synthetic hydrograph analysis produced a rather poor prediction of the observed runoff hydrographs. While the assumed runoff curve number
could be adjusted to provide a better reproduction of the peak runoff rates, the predicted hydrographs would still not satisfactorily reproduce the multiple peaks and transient phenomenon for many of the storms.

The use of a variable hydraulic roughness coefficient for the runoff function in the detailed watershed model would further improve its ability to simulate observed hydrographs for many of the storms. However, such a refinement would be justified only on the basis of an experimental study to quantitatively define the manner in which such variation occurs.

A comparison of the assumed antecedent conditions between watersheds four and eleven indicate the latter generally required deeper infiltration control depths, a larger volume of surface retention storage, and a larger hydraulic roughness coefficient. These results are in agreement with the observations of Stoltenberg and would be expected when comparing a watershed subjected to "conservation farming" in contrast to the "conventional farming" practiced on watershed four.

**Sensitivity Analysis**

One of the advantages claimed for the detailed watershed model outlined above was its ability to determine the relative importance of the various hydrologic components of which it was composed. Three of the previously analyzed storm events on watershed four which represented divergent antecedent conditions were selected for this purpose. The

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influence on the simulated hydrographs of a change in the various parameter values was determined by calculating the hydrographs predicted as a result of modifying each factor individually.

The results of the sensitivity analysis are shown in Figures 17, 18 and 19. The labels for the various curves in these figures are defined in Appendix A. The runoff hydrographs resulting from infiltration capacity rates determined by the coefficients in Table 5, rates one-half as large and rates one-fourth as large are designated, respectively, in these figures by the letters H, M and L.

Storm of June 30, 1945

This storm occurred when the antecedent soil moisture in the watershed was very low. Although the main portion of the storm was an advanced type, a brief period of rather intense rain near the end of the storm resulted in a complex, double-peaked runoff hydrograph as shown in Figure C1 of Appendix C.

The relative influence of the different hydrologic components on the calculated runoff hydrograph from this storm may be observed in Figure 17. When the various parameters were allowed to range over their respective plausible limits, only the interception storage volume proved to be of relatively minor importance.

The predicted hydrographs were most sensitive to those parameters influencing the infiltration rate, i.e., infiltration capacity coefficients and antecedent soil moisture. Relatively small changes in the depth of the infiltration control zone were also quite important; however, the maximum influence of this control depth occurred, as expected, during the later portion of the runoff hydrograph.
(a) Influence of Manning's Coefficient

(b) Influence of Surface Retention Volume

Figure 17. Parameter Sensitivity Analysis for Storm of June 30, 1945
(c) Influence of Antecedent Soil Moisture

(d) Influence of Infiltration Control Depth

Figure 17 (cont'd.)
(c) Influence of Infiltration Capacity Rates

(f) Influence of Interception Storage

Figure 17 (cont'd.)
Storm of June 7, 1947

The rainfall and runoff hydrographs from this storm are shown in Figure C1 of Appendix C. In contrast to the storm of June 30, 1945, the antecedent soil moisture conditions were very high for this storm with runoff having occurred within the 24-hour period immediately preceding the storm. Corn had been planted in the watershed on May 26 so the likely absence of a significant surface crust suggested the rather deep infiltration control depth assumed for the basic hydrograph prediction. The sensitivity of the simulated hydrographs to changes in the antecedent parameters is illustrated in Figure 18.

Although the interception conditions were obviously zero when this storm occurred, the influence of the assumption of a storage volume of 0.04 inches could not be detected in the runoff hydrograph. This was primarily a consequence of the early, low intensity portions of the storm which produced no runoff.

Substantial changes in the hydraulic roughness coefficient did not produce large changes in the predicted runoff hydrograph. However, the smaller "n" value did increase the sensitivity of the hydrograph to the rather numerous fluctuations in the rainfall intensity which were characteristic of this storm.

The predicted runoff hydrograph from this storm were, as for the storm of June 30, 1945, most sensitive to the assumed antecedent soil moisture and the infiltration capacity coefficients. However, because of the high soil moisture level, much larger changes in the infiltration control depth were required to produce a significant hydrograph response than were necessary for the prior storm.
(a) Influence of Manning's Coefficient.

(b) Influence of Surface Retention Volume

Figure 18. Parameter Sensitivity Analysis for Storm of June 7, 1947
(c) Influence of Antecedent Soil Moisture

(d) Influence of Infiltration Control Depth

Figure 18 (cont'd.)
(e) Influence of Infiltration Capacity Rates

Figure 18 (cont'd.)
Storm of July 19, 1950

This storm, illustrated in Figure C1j of Appendix C, occurred when the soil moisture conditions in the watershed were intermediate between the levels for the two previous storms. Although the rainfall intensity was not constant, a very smooth, single peaked runoff hydrograph was recorded. The hydrographs which resulted from changes in the various parameter values are shown in Figure 19.

As for the 1947 storm, the relatively long period of low intensity rainfall prior to runoff caused the influence of interception to be negligible for storage volumes less than 0.06 inches.

The importance of the hydraulic roughness coefficient on the values of the peak runoff rate was greater for this storm than the two prior storms. This was a consequence of the particular storm distribution, i.e., the fact that the peak rate of runoff was determined by a brief period of very high intensity rain. For such conditions the runoff rate changes very rapidly and the hydraulic roughness coefficient is quite important in controlling the rate of this change.

As for the other two storms, the runoff hydrographs were most sensitive to the watershed parameters which determine the infiltration capacity and to the antecedent soil moisture. The depth of the infiltration control zone influenced the peak rate of runoff and the recession curve substantially.

Generalizations

The results shown in Figures 17 through 19 permit several generalizations. First, for the highly permeable soils found on the Throckmorton watersheds, the infiltration capacity relationship
(a) Influence of Manning's Coefficient

(b) Influence of Surface Retention Volume

Figure 19. Parameter Sensitivity Analysis for Storm of July 19, 1950
(c) Influence of Antecedent Soil Moisture

(d) Influence of Infiltration Control Depth

Figure 19 (cont'd.)
(e) Influence of Infiltration Capacity Rates

Figure 19 (cont'd.)
represented the most critical hydrologic component in the model. For these soils, data from sprinkling infiltrometer studies and Holtan's infiltration capacity relationship appeared to provide a suitable estimate of the rate of infiltration during a storm event. The influence of the infiltration control depth on the resulting runoff hydrograph was greater for low antecedent soil moisture levels than for high levels.

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.

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.
SUMMARY AND CONCLUSIONS

A generalized mathematical watershed model has been developed to simulate the surface runoff hydrology of small watersheds. The model was based upon the subdivision of the watershed to be modeled into a grid of small, independent elements. The composite runoff hydrograph from the entire watershed was determined by delineating the various hydrologic processes occurring within each element and applying the equation of continuity to integrate the responses from each individual element. A general purpose digital computer program corresponding to the proposed watershed model was written.

The ability of the model to simulate observed runoff events on two small, experimental watersheds was investigated. The runoff hydrographs predicted by the proposed model and by the most popular current design technique, the synthetic hydrograph analysis, were compared for the storm events which were studied.

The sensitivity of the predicted runoff hydrographs to variations in the values of assumed initial condition parameters was determined for selected storm events. The influence of finite difference effects were also investigated under conditions of zero infiltration and a constant rainfall rate.

On the basis of the results obtained from the above studies, 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, as noted above, the agreement between observed and predicted hydrographs does not offer conclusive evidence of the validity of the watershed model.

For the watersheds and storms studied, the synthetic hydrograph procedure generally estimated the peak rates and total volumes of runoff rather poorly. This may have resulted from the selection of an inappropriate relationship between the runoff curve number and the assumed antecedent soil moisture as given in Figure 16. However, a modification of this relationship to produce a better correlation between observed and predicted peak runoff rates would not result in an accurate prediction of the runoff hydrograph for many of the storms.

The parameter sensitivity analysis indicated that, for the Throckmorton watersheds, the most critical parameters were those factors which influenced the calculated infiltration capacity rates during the storm. Interception storage had a negligible influence on the simulated runoff hydrograph. The assumed surface retention volume had an appreciable influence on the predicted peak runoff rates; however, this influence was much less than for the infiltration parameters. The hydraulic roughness coefficient controlled the shape and time lag of the predicted hydrographs as well as the peak runoff rate. The
influence of the roughness coefficient was greatest during periods when the rate of runoff was changing most rapidly.
RECOMMENDATIONS

On the basis of the results obtained in simulating natural storms on the Throckmorton Farm watersheds and the potential flexibility of the watershed model proposed above, additional research to further develop and refine the basic model would be desirable. Research is particularly needed to better define the hydrologic component relationships required by the model.

It is recommended that an experimental investigation of the runoff function be given a high priority in the selection of the components to receive further study. Such work would likely require, in addition to a laboratory model to study flow conditions in interconnected rills, the development of greatly improved techniques to measure and quantify field micro-relief.

Additional information on the infiltration capacity coefficients of Equation (11) is needed for a variety of soil conditions. The possibility of utilizing the large volume of data available from portable rainfall simulators for this purpose should be investigated. Such data might also be useful in the development of an improved runoff function.

An effort to further improve the computational efficiency of the computer program required by the watershed model offers potentially significant financial benefits. When these efforts have been completed, watersheds considerably larger than those studied in this research
should be modeled to determine the accuracy with which observed hydrographs from such areas may be simulated.

The basic engineering application of a watershed model is the prediction of the magnitude of possible future runoff events from a watershed. Therefore, work should be initiated to define probabilistic relationships which will describe the likelihood of occurrence of combinations of antecedent conditions of the parameters for the several hydrologic components of the watershed model. Such relationships are required in order to permit the model to simulate the occurrence of probable future hydrologic events.
BIBLIOGRAPHY


NOTE!!

The computer program listings discussed in Appendix A are those used to generate the results discussed in this report; however, subsequent research in this area has resulted in much improved and more comprehensive simulation programs dealing with both hydrologic and non-point source pollution phenomena. These new versions are available by contacting the authors of this report.

April, 1980
APPENDICES

APPENDIX A

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 interactive 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.

The program was processed on an IBM 7094 computer and required approximately 55,000 words of memory. Execution times for a simulation using 150 watershed elements and a five second time increment ranged from approximately one-tenth to one-thirtieth of the storm duration time.

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.

The various hydrologic components of the watershed model were incorporated into the computer program as separate function subprograms. The influence of micro-relief on the volume of detention storage is evaluated by the subprogram STOR. 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 runoff function, which incorporates the influence of surface retention, is evaluated by the RUNF 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 data consists of: (1) the observed rainfall and runoff hydrographs; (2) the antecedent watershed conditions including the crop being grown and the amount of cover it provides, the potential volume of interception storage, the micro-relief category and the maximum height of this relief, the volume of surface retention, the antecedent soil moisture and the depth of the control zone used to determine infiltration capacity rates; (3) the basic characteristics of each watershed element including its size, location, slope, slope direction and soil type number; and (4) the information required for the synthetic hydrograph analysis including the area of the watershed,
its time of concentration and the curve number assigned for each storm event on the basis of the antecedent soil moisture conditions and vegetation present in the watershed. 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 OUTPUT subroutine controls the printing of supplemental results including the hydrograph of rainfall and simulated runoff as well as the observed runoff hydrograph, when available, and the hydrograph predicted by the synthetic hydrograph analysis with the subroutine SHYD. The results are printed in graphical form by a general purpose subroutine, PLOT, not included in the program listing below.

A sample of the output produced by the program is given on page 105. 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.
AN = 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.

CN = Curve number utilized in the synthetic hydrograph analysis.

CONST = A constant = 2. DX.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.

D(I) = Depth of water in the I-th element -- ft.

DD(I) = Change in depth between iterations for the I-th element -- ft.

DEPTH = Depth of water in an element -- ft.

DF = Derivative of the discharge relationship with respect to depth -- ft.²/sec.

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.

DS = Derivative of the storage relationship with respect to depth -- ft.²/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 -- in./hr.; J = 4 to "A" in Equation (11) -- in./hr.; and J = "P" 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.

NCOL(I,1) = Column number of first element in row I.

NCOL(I,2) = Column number of last element in row I.

NEXP = Drainage exponent used in infiltration calculations.

NI = Number of rows of elements in the watershed.

NIOUT = Row number for watershed outlet element.

NJ = Number of columns of watershed elements.

NJOUT = Column number for watershed outlet 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.

PFIN(I,J,K) = Percentage of discharge from adjacent elements entering element I, J: K = 1 corresponds to the element to the right of I, J; K = 2 to the element above; K = 3 to the element to the left; and K = 4 to the element below.

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) = Used in the subroutine OUTPUT to store the rates of runoff from the observed hydrograph -- in./hr.
Q(I,J) = Discharge rate from the element in the I-th row and J-th column -- ft.³/sec.
QMAX(I) = Maximum discharge for I-th triangular hydrograph -- 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.
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.
RUNOFF = Observed volume of runoff -- in.
S = Slope of a watershed element -- ft./ft.
SC = Coefficient for computing the volume of storage for a rough surface.
SOIL(I) = Soil type number of the I-th element.
SP = Exponent for computing the volume of storage for a rough surface.
SSTOR = Twice the volume of water in storage divided by the time increment, DT, -- ft.³/sec.
SU = Twice the storage volume divided by DT when depth is equal to HU -- ft.³/sec.
SUPP = Rate at which water is being supplied to satisfy infiltration capacity -- ft.³/sec.
\textbf{SUR(I,J)} = Constants for the storage function for the I-th soil; \( J = 1 \) corresponds to "A" in Table 3; \( J = 2 \) to "B" in Table 3.

\begin{itemize}
\item \textbf{T} = Time -- min.
\item \textbf{TB} = Base time for the triangular hydrographs -- min.
\item \textbf{TC(I)} = The time at which a change in rainfall intensity occurred -- min.
\item \textbf{TCON} = Time of concentration of the watershed -- min.
\item \textbf{TE(I)} = Ending time of I-th triangular hydrograph -- min.
\item \textbf{TM(I)} = Time of peak for I-th triangular hydrograph -- min.
\item \textbf{TO(I)} = Starting time of I-th triangular hydrograph -- min.
\item \textbf{TP} = Time to peak for the triangular hydrographs -- min.
\item \textbf{VOL} = Total volume of runoff predicted by simulation -- in.
\end{itemize}
Program Listing

MATHEMATICAL MODEL OF A SMALL WATERSHED
L. E. HUGGINS ** 06/20/66

DIMENSION G(31,31), PFIN(31,31), FLIN(300), RC(100), TC(100), NCOL(3
10+2), X(300), Y(300), T(300), PFIN(300), P(300), FC(300), GWC(300), R(300)
2X(301), X(101), IDATE(2)
1 CALL DATA(NUM, DATE, CONST, DT, NDT, KPR, NJ, NJOUT, CONV, CU, PER, PI)
11 = X1, PFIN, FC, GWC, NEXP, FLIN, G, D, DD, PFIN, TC, RC, NCOL, HUSU, SC, SF, RI, D
2 TR = RAIN
10 ITR = 1
VOL = 0
PREC = 0
G(I) = 0
DTM = DT/60
T(I) = TC(I)
11 IF (ITR = RAIN) 12
10 ITR = ITR + 1
12 RATE = RC(ITR)*CU
PREC = PREC + RC(ITR)*(TC(ITR) - TC(ITR-1))/60
13 M = 0
R = RAIN(RATE + PER)
DO 50 I = 2, N1
NS = NCOL(I+1)
NF = NCOL(I-1)
DO 50 J = NS, NF
K = 0
M = M + 1
DEPT = D(M) + DD(M)
SSTOR = SSTOR + DEPTH*HUSU*CONST*DS*SC*SP
FLIN = PFIN(I+1)*G(I+1)*PFIN(I)*G(I-1) + PFIN(I)*G(I-1)*PINF(I)*G(I+1)
FLN(I) = FLN - FLIN + PFIN(I)*PFIN(M)*FC(I)*GWC(I)*SSTOR/2*FLIN*DT
1 NEXP
FHS = FLINS(M) + FLIN
IF (FHS < 1.E-25) 43, 47
20 SSTOR = SSTOR + DEPTH*HUSU*CONST*DS*SC*SP
22 Q2 = RUNOFF(STOR, SSTOR, DEPTH, DF, DIR, 0)
F5 = Q2 + SSTOR
IF (ABS(F5/FHS) = 1.E-06) 45, 45
30 DEPT = DEPTH - F5/DS + DF
K = K + 1
40 IF (K = 10) 20, 24
43 DEPT = 0
SSTOR = 0
Q2 = 0
46 DO I = 1, NS
50 DO (M) = DEPTH - D(M)
51 G(I) = DEPTH
FLINS(M) = FLIN + SSTOR - Q2
G(I) = G(I)*GOUT + NJOUT)/CONV
DO 51 (I, L) = 1, 10, 51 + 60 + 60
51 IF (DATE) 60, 52, 60
56 CALL DRY(N, NCOL, M, D, A, P, P, FC, GWC, NEXP, DT, T(L+1), TCT, RC, NCOL, HUSU, SC)
60 WRITE (46, 6) T(L+1), D(I, L+1)
65 FORMAT (20X, F9.2, 16X, F6.3)
10 CT = 1
67 VOL = (VOL + X1*T)*DT*FLOAT(KPR)/3600
WRITE (46, 70) VOL, PREC*VOL
73 FORMAT (1HO 4X 3H10.6 THE RUNOFF VOLUME PREDICTED FROM F5 = 2.18 INCHES
15 OF RAINFALL = 6.34 INCHES)
80 CALL OUTPUT(L, T, 1, ITR, RC, NCOL, NUM, DATE)
GO TO 1
END
FUNCTION STOR(DEPTH+HU*SU*CONST*DS*SC*SP)
  O = DEPTH = HU
  IF (D) 5*10.20
  5 DEPTH = O
  STOR = O
  GO TO 25
  8 STOR = O
  DS = SC/10.
  RETURN
  10 STOR = SC*DEPTH**SP
  DS = SP*STOR/DEPTH
  RETURN
  20 STOR = SU + CONST*D
  25 DS = CONST
  RETURN
END

FUNCTION FILT(A*PIV*P*FC*GWC*SUPP*DT*NEXP)
  IF (PIV) 45*0.0
  5 FILT = 4*PIV**P + FC
  IF (FILT = SUPP) 15*15*8
  8 FILT = SUPP
  15 IF (PIV = GWC) 25*20*20
  20 PIV = PIV = FILT*DT
  GO TO 27
  25 PIV = PIV = (FILT = FC*E*(1* - PIV/GWC)**NEXP)*DT
  27 IF (PIV) 30*80*80
  30 PIV = 0*
  RETURN
  45 WRITE (6,46) PIV
  46 FORMAT (52H WATER CONTENT OF SOIL EXCEEDS TOTAL POROSITY, PIV = FP
  1 E15.7)
  50 IF (FC = SUPP) 75*75*65
  65 FILT = SUPP
  PIV = (FC - FILT)*DT
  IF (PIV = GWC) 27*80*70
  70 PIV = GWC
  RETURN
  75 FILT = FC
  80 RETURN
END

C DETERMINATION OF RUNOFF DISCHARGE BASED ON MANNING'S EQUATION
FUNCTION RUNF($STOR*B*DF*DIR*DS)
  O = $STOR = DIR
  IF (D) 10*10*20
  10 RUNF = O*
  DF = O*
  RETURN
  20 RUNF = B*DF*1*66667
  DF = 1*66667*RUNF/5*DS
  RETURN
END
12 NCOL(1+2) = J
M = AN/90 + 1
AN = AN + 2
GO TO 14
14 IF (AN = 435791) AN = 435791
16 PFIN(1+J+1) = -S*TAN(1+J+1) - AN
PFIN(1+J+4) = 1
GO TO 30
17 PFIN(1+J+4) = -S*TAN(AN)
PFIN(1+J+3) = 1
GO TO 30
18 IF (AN = 435791) AN = 435791
19 PFIN(1+J+1) = S*TAN(AN)
PFIN(1+J+4) = 1
GO TO 30
20 PFIN(1+J+4) = S*TAN(AN)
PFIN(1+J+3) = 1
GO TO 30
21 IF (AN = 435791) AN = 435791
23 PFIN(1+J+1) = -S*TAN(AN)
PFIN(1+J+4) = 1
GO TO 30
24 PFIN(1+J+1) = S*TAN(AN)
PFIN(1+J+4) = 1
GO TO 30
22 IF (AN = 435791) AN = 435791
26 PFIN(1+J+1) = S*TAN(AN)
PFIN(1+J+4) = 1
GO TO 30
27 PFIN(1+J+4) = S*TAN(AN)
PFIN(1+J+3) = 1
GO TO 30
30 B(N) = 1
32 PFIN(1+J+1) = -S*TAN(AN)
PFIN(1+J+4) = 1
GO TO 30
33 AREA = FLOAT(N)*DX*DX/43560
CONV = FLOAT(N)*CCU
IF (N = 500) CCU = CCU + 10
40 P = RC(2)(1)*PERCCU
CF = FN1:RN/DNT/J/DNT)*1:6667
DO 41 J = 1
41 D(J) = 0
DO 41 J = 1
IS = SDO(J)
B(J) = B(J)*CF1
P(J) = FLOTJ(IS+5)
FC(J) = CU*FLOTJ(IS+3)
TFOR = FLOTJ(IS+1)*CU*WIND
P1(J) = 1
ANM*TFOR
riers(J) = CU*FLOTJ(IS+4)/TFOR
WJ = WJ + FLOTJ(IS+1)*P(J)
FC(J) = WJ/J/1:4 + NC
GO 42 J = 1
42 WJ = WJ/J/1:4
WRITE (5,50) IDATE,NUM,AREA,N,DT,DX,DXCROP,PER,ROUGHP,FIT,RN,HU
RN = RN
DT = DT
HU = HU12
FPT = FPT*UC/DT
SP = SUR(ROUGH*2)
CONST = 2/DT/ES
SU = SUR(ROUGH*1)*HUCONST
KFR = FFC(5) = TC(1)/DT/FLOT(42)+60 + 1
IF (HU = 4746467
46 SC = 0
GO TO 48
47 SC = SU/4*SP
48 DIA = DIA*12, HU = HUCONST+DSC/5
49 DIA = DIA/CONST*12
WRITE (5,60) DIA,ADP*3/16
IF (DIA < 1) WRITE (6,69)
RETURN
50 FORMAT (11H1 13X 52X MATHEMATICAL SIMULATION OF SMALL WATERSHED HYDROLOGY/370 TO PREDICT THE OUTFLOW FROM STORM OF 24H 30H ON THE \PORT
FORTN PORTION WATERSHED NO. ABD/107/07/089127 OF WATERSHED = POISSON AGGREGATES 0 X 2544N/2544C ELEMENTS USED = F16/17H TIME INCREMENT = 1F4H 0H 9 9060 FT X 6X11 AN FT X 1611 CROP D
4F440 9X 17H SIZE OF ELEMENT = 9X11 060 FT X 6X11 AN FT X 1611 CROP D
5F440 SEED GROWN IS AB1600 38PERCENT OF GROUND COVERED BY FOLIAGE1 = 2P
65) OF 29H SURFACE ROUGHNESS CATEGORY = 12) 6X 32H MAXIMUM POTENTIAL 7 INTERCEPTION = OPG + 3.4H INCH 24H MAXIMUM HEIGHT = F6 + 1.4H INCH
51 FORMAT (4X 32F10.4) 57 FORMAT (4X 32F10.4)
62 FORMAT (4X 32F10.4)
63 FORMAT (4X 32F10.4)
64 FORMAT (4X 32F10.4)
65 FORMAT (4X 32F10.4)
66 FORMAT (4X 32F10.4)
67 FORMAT (4X 32F10.4)
68 FORMAT (4X 32F10.4)
69 FORMAT (4X 32F10.4)
70 WRITE (6,66)
71 STOP
72 WRITE (6,67)
73 STOP
74 WRITE (6,68)
75 STOP
76 WRITE (6,69)
77 STOP
78 WRITE (6,70)
79 STOP
80 RETURN
81 END

SUBROUTINE DU(N) INCOL*M+0*A+PIV*FC*GWC*NEXP+DT+TII+H+SU+CON
1ST=SC+SPDO+FLNS)
DIMENSION NCOL(30), G(30), Q(30), I(30), P(30), S(30), FC(30)
1ST=SC+SPDO+FLNS)
DO 10 I = 3, N
10 CONTINUE
N = (TI - T)/5 + 1
DTI = (TI - T) * 60 / FLOAT(N)
DO 35 K = 1, N
35 CONTINUE
S = STORED(I), H, SU, CON1D, SC, SP)
IF (S) 21, 22, 23
21 IF (S) 24, 25, 26, 27, 28, 29, 30
22 S = 2* S* P*(1+P)**(I/I)+FC(1)+GWC(I)+O*DTI+NEXP
1) DTI
30 = S+O2*30
1 23 FLNS(I) = S
24 IF (S) 27, 28, 29, 30
25 CONTINUE
T = TI
27 RETURN
100 FORMAT (14)
END
SUBROUTINE OUTPUT(N1,T1,Q1,N2,TG,RC,NUM,IDATE)
DIMENSION T(1:101),Q1(1:101),TC(1:100),RC(100),Q(100),ST(75),SO(175),IDATE(2),IDAT(2)
DATA C1,C2,6H SYNTH,6H ORSE/
READ (5,50) TEST
IF (C2.EQ.TEST) GO TO 5
IF (N.EQ.NUM.OR.IDAT(1).NE.IDATE(1).OR.IDAT(2).NE.IDATE(2)) GO TO 1
15 I = 1
IF (1.EQ.2) 15,16,12
5 BACKSPACE 5
M = 1
READ (5,65) N*IDAT(1)*Q(1)
IF (N.NE.NUM.OR.IDAT(1).NE.IDATE(1).OR.IDAT(2).NE.IDATE(2)) WRITE
16(66,56) N*IDAT
RUNOFF = 0
1 = 1
8 I = I + 1
READ (5,65) C(I),T(I),Q(I)
10 FORMAT (12X,E5*2,E10*6)
RUNOFF = RUNOFF + (Q(I) + Q(I-1))*(T(I) - T(I-1))*1200.
IF (I) 11,12,65
11 READ (5,65) TEST
12 WRITE (4,70) RUNOFF
IF (I) 100,17,18
15 I = 2
Q(I) = 0
Q(I+2) = 0
T(I) = T(1)
S(I) = T(1)
16 M = 2
17 IF (C1.NE.TEST) GO TO 20
M = 1
READ (5,65) AREA,CN,TCON
18 FORMAT (16X,E5*2,2X,E8*0,25X,ES*0)
CALL SHC (AREA,CN,TCON,M2,TC,RC,ST,SO,NSO,IDATE,NUM)
GO TO 21
20 NSO = 2
C(0) = 0
S(0) = 0
ST(1) = TC(1)
ST(3) = TC(1)
BACKSPACE 5
21 WRITE (4,24) IDATE,NUM
25 FORMAT (1H4,6X,2AHYDROGRAPH, FROM STORM OF A4,3DH ON THROCKMOR
1T1,HATERSHD NO. A5/25H0, *- SIMULATID RUNOF 8X 19XH = OBSERV
2ED RUNOF 8X 19XH = RAINFAL4 PATF/33X PHALL RATES IN IN./HR)
CALL PLOT (51,3,41,T1,C(1),M2,TC,RC,ST,SO,0,0,X,Y)
WRITE (4,33)
30 FORMAT (1H4,37X,11H TIME = MIN.)
GO TO (32*6), M
32 WRITE (6,73) IDATE,NUM
33 FORMAT (1H11,1X,47H COMPARISON OF RUNOFF HYDROGRAPHS FROM STORM OF A4
1425X/25THROCKMORTON WATERSHD NO. A5/190X14H* = SIMULATION 10X13H
200 - SYNTHETIC 10X12H = OBSERVED 25X20HALL RATES IN IN./HR*)
40 FORMAT (144H RUNOFF DATA EXCEEDS DIMENSION SPECIFICATION )
CALL PLOT (51,3,111,T1,C(1),NSO,ST,SO,0,0,X,Y)
WRITE (4,33)
50 FORMAT (65)
55 FORMAT (1H4,9X,37X RUNOFF DATA HAS WATERSHED NO. OF A5,13H AND DA
1T1,HATERSHD NO. A4)
60 FORMAT (45X,12X,PA4,2X,EB,2X,E10*0)
70 FORMAT (22X,PHOBSERVED RUNOF VOLUME = F6.3,4H IN)
80 WRITE (6,40)
STOP
END
SUBROUTINE SHYD (AREA, CN, TCON, N2, TC, RC, ST, S2, NUM, IDATE, N)
DIMENSION T(ST), S(T), TC(200), TM(200), TE(200), GM(200), TC(100), RC(100), IDATE(100)
DIMENSION T(ST), S(T), TC(200), TM(200), TE(200), GM(200), TC(100), RC(100), IDATE(100)

C1 = 43200.435560.5 AREA
S = 1000.5 CN = 10.5
P = P
D = D
T = T + 6.5 TCON
T = T + 6.5 TCON
K = 2
P = P
S0(1) = 0.5
RUNO = 0.5
TIME = TC(1)
L = TC(N2) - TC(1)/D
OP = 43.5 AREA TP/640.5*60.5
DC = 50 = 1.4

20 TIME = TIME + D
25 IF (TIME - TC(K)) .LT. 40.40.527
27 IF (K = N2) 37, 46, 28
29 GM(1) = 0.5
33 P = P + RC(K)*(TC(K) - TC(K-1))/60.5
37 K = K + 1
40 GM(1) = GM(1) + 1
44 WRITE (*, 50)
45 IF (GM(1)) .GT. 21, 44, 46
48 S0 = S0 - S0
52 GM(1) = GM(1) + 1
54 IF (GM(1)) .LT. 30, 54, 55
58 NUM = (TC(K) - TO(1))/20
60 IF (NUM .LT. 75) 64, 65, 55
64 GM(1) = GM(1) + 1
68 IF (GM(1)) .LT. 30, 68, 69
72 GM(1) = GM(1) + 1
76 GM(1) = GM(1) + 1
80 WRITE (*, 50) ST(1), S0(1)
84 WRITE (*, 50) ST(1), S0(1)
90 FORMAT (F8.6) S0(1), ST(1)
100 RETURN
END
<table>
<thead>
<tr>
<th>Rainfall Data for Throckmorton Storm of 8/16/45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>06/16/45</td>
</tr>
<tr>
<td>06/16/45</td>
</tr>
<tr>
<td>06/16/45</td>
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<tr>
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<tr>
<td>06/16/45</td>
</tr>
<tr>
<td>06/16/45</td>
</tr>
<tr>
<td>06/16/45</td>
</tr>
</tbody>
</table>

Crop being grown is Wheat. Portion of Watershed covered by foliage = 0.60. 
Maximum potential interception = 1.06 in. Surface roughness category = 2. 
Maximum surface roughness height = 0.00 in. Antecedent moisture = 0.45 red. 
Filtration constant depth = 0.00 in. Manning's Roughness = 0.04. 
Surface detention depth = 0.158 in. Time increment = 0.01 sec. 
Number of lines of hydrograph output = 100. 

Drainage Exponent = 0.7. 
Rec. = 1.00 (per) 
Prec. = 0.60 (per) 
Surf. = 0.00 (per) 
CI = 0.00 (per) 
Storm = 1.00 (per) 
Overland Flow = 1.00 (per) 
R = 0.00 (per) 

Simulation of Throckmorton Watershed No. 4-3. 
Orientation No. 

<table>
<thead>
<tr>
<th>Y1</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
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<tr>
<td>6</td>
<td>20000</td>
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</tr>
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<tr>
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</table>

4-3-
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<th>Time</th>
<th>Runoff</th>
<th>Rundoff Data</th>
</tr>
</thead>
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<tr>
<td>0</td>
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<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>0.20</td>
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</tr>
<tr>
<td>0.3</td>
<td>0.30</td>
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</tr>
<tr>
<td>0.4</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.50</td>
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</tr>
<tr>
<td>0.6</td>
<td>0.60</td>
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</tr>
<tr>
<td>0.7</td>
<td>0.70</td>
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</tr>
</tbody>
</table>

Synthetic hydrograph analysis data is on the following card.

Watershed Area = 2.0, Assumed Curve No. = 50, Time of Concentration = 0.0
### Infiltration Parameters

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Porosity Vol. Percent</th>
<th>Porosity Percent Saturation</th>
<th>Field Capacity FC - IN/HR.</th>
<th>Infiltration Constants</th>
<th>Drainage Rate DR is Proportional to the 3 Power of the Gravitational Water Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46.</td>
<td>10.</td>
<td>0.50</td>
<td>2.45</td>
<td>0.050</td>
</tr>
<tr>
<td>2</td>
<td>47.</td>
<td>8.</td>
<td>0.75</td>
<td>1.50</td>
<td>0.750</td>
</tr>
<tr>
<td>3</td>
<td>51.</td>
<td>7.</td>
<td>0.45</td>
<td>2.25</td>
<td>4.650</td>
</tr>
<tr>
<td>4</td>
<td>49.</td>
<td>6.</td>
<td>0.45</td>
<td>2.45</td>
<td>0.650</td>
</tr>
</tbody>
</table>

### Surface Roughness Parameters

<table>
<thead>
<tr>
<th>Roughness Category</th>
<th>SG</th>
<th>SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.400</td>
<td>1.73</td>
</tr>
<tr>
<td>2</td>
<td>0.340</td>
<td>2.15</td>
</tr>
<tr>
<td>3</td>
<td>0.810</td>
<td>2.47</td>
</tr>
<tr>
<td>4</td>
<td>1.000</td>
<td>1.0</td>
</tr>
</tbody>
</table>
MATHEMATICAL SIMULATION OF SMALL WATERSHED HYDROLOGY

PREDICTION OF RUNOFF FROM STORM OF 6/16/45 ON THROCKMORTON WATERSHED NO. 4-2

SIZE OF WATERSHED = 2.18 ACRES  
NUMBER OF ELEMENTS USED = 30

TIME INCREMENT = 2.2 SEC.   
SIZE OF ELEMENT = 50.0 FT. x 50.0 FT.

CROP BEING GROWN IS WHEAT  
PERCENT OF GROUND COVERED BY FOLIAGE = 96.

SURFACE ROUGHNESS CATEGORY = 2   
MAXIMUM POTENTIAL INTERCEPTION = 0.010 IN.

WAINING'S COEFFICIENT = 0.040  
MAXIMUM SURFACE ROUGHNESS HEIGHT = 1.0 IN.

MAX. SURFACE DETENTION DEPTH = 0.162 IN. = AN AVERAGE DEPTH OF 0.610 IN.
ANTICIPATED SOIL MOISTURE = 85% PERCENT OF SATURATION
INfiltration CONTROL DEPTH = 3.2 IN.

RUNOFF HYDROGRAPH

<table>
<thead>
<tr>
<th>TIME - MIN.</th>
<th>DISCHARGE - IN./HR.</th>
</tr>
</thead>
<tbody>
<tr>
<td>836.0</td>
<td>0.0</td>
</tr>
<tr>
<td>838.2</td>
<td>0.064</td>
</tr>
<tr>
<td>840.7</td>
<td>0.143</td>
</tr>
<tr>
<td>893.1</td>
<td>0.333</td>
</tr>
<tr>
<td>900.6</td>
<td>0.401</td>
</tr>
<tr>
<td>906.1</td>
<td>0.464</td>
</tr>
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<tr>
<td>912.5</td>
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</tr>
<tr>
<td>914.4</td>
<td>0.657</td>
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<tr>
<td>916.6</td>
<td>0.614</td>
</tr>
<tr>
<td>915.6</td>
<td>0.531</td>
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<td>915.6</td>
<td>0.417</td>
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<td>917.1</td>
<td>0.313</td>
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<tr>
<td>917.1</td>
<td>0.268</td>
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<tr>
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<td>0.280</td>
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<tr>
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<td>924.4</td>
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<td>0.000</td>
</tr>
<tr>
<td>935.4</td>
<td>0.000</td>
</tr>
</tbody>
</table>
THE RUNOFF VOLUME PREDICTED FROM 0.52 INCHES OF RAINFALL = 0.094 IN.
OBSERVED RUNOFF VOLUME = 0.143 IN.
SYNTHETIC RUNOFF HYDROGRAPH

STORM OF 6/16/45 ON WATERSHED NO. 4-7

RUNOFF CURVE NO. = 89.0  TIME OF CONCENTRATION = 9.90 MIN.
MAXIMUM POTENTIAL DIFFERENCE BETWEEN RAINFALL AND RUNOFF = 1.24 IN.
ANALYSIS IS BASED UPON A TIME INTERVAL OF 2.5 MIN.

<table>
<thead>
<tr>
<th>TIME (MIN)</th>
<th>DISCHARGE (IN./HR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.004</td>
</tr>
<tr>
<td>15.0</td>
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<tr>
<td>45.0</td>
<td>0.004</td>
</tr>
<tr>
<td>60.0</td>
<td>0.004</td>
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<tr>
<td>75.0</td>
<td>0.004</td>
</tr>
<tr>
<td>90.0</td>
<td>0.004</td>
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<td>105.0</td>
<td>0.004</td>
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<td>120.0</td>
<td>0.004</td>
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</tr>
<tr>
<td>165.0</td>
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<tr>
<td>210.0</td>
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<tr>
<td>225.0</td>
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<tr>
<td>240.0</td>
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<tr>
<td>255.0</td>
<td>0.004</td>
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<tr>
<td>270.0</td>
<td>0.004</td>
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<tr>
<td>285.0</td>
<td>0.004</td>
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<tr>
<td>300.0</td>
<td>0.004</td>
</tr>
<tr>
<td>315.0</td>
<td>0.004</td>
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<tr>
<td>330.0</td>
<td>0.004</td>
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<tr>
<td>345.0</td>
<td>0.004</td>
</tr>
<tr>
<td>360.0</td>
<td>0.004</td>
</tr>
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</table>

THE RUNOFF VOLUME PREDICTED FROM 0.52 INCHES OF RAINFALL = 0.048 IN.
HYDROGRAPHS FROM STORM OF 7/1/45 ON THRACMorton WATERSHED NO. 4-2

- Simulated Runoff
- Observed Runoff
- Rainfall Rate

All rates in in/hr.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>7:00</th>
<th>7:10</th>
<th>7:20</th>
<th>7:30</th>
<th>7:40</th>
<th>7:50</th>
<th>8:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
COMPARISON OF RUNOFF HYDROGRAPHS FROM STORM OF 6/16/45
THORCKMORON WATERSHED NO. 4-2

* - SIMULATION
O - SYNTHETIC
X - OBSERVED

ALL RATES IN IN./HR.

TIME = MIN.
COMPUTER TIME REQUIRED FOR THIS SIMULATION = 94.05 SEC.
APPENDIX B

THROCKMORTON WATERSHED CHARACTERISTICS

During the period from 1940 to 1953 the Agricultural Research Service, in cooperation with Purdue University, conducted an intensive study of the surface runoff and erosion which occurred from sixteen small, single crop, natural watersheds located on the Purdue Throckmorton Farm.¹ Twelve of these watersheds were used to determine the influence of a combination of several conservation practices upon the runoff and erosion from the watersheds.

The conservation treatments included contour tillage, the application of manure and greatly increased amounts of commercial fertilizers, the addition of alfalfa and alsike to the meadow seeding mixture and the return to the soil of increased crop residues resulting from the high level of fertilization. The "prevailing practice" treatment consisted of moderate levels of fertilization, straight-row farming and the use of red clover-timothy meadows.

Each experimental watershed on the 300 acre farm was instrumented with an H-type flume and a water-level recorder. Several recording rain gages were strategically located over the area. A continuous record of

the precipitation and the resulting runoff and erosion from all watersheds over the thirteen year period of study was obtained.

Of the twelve watersheds used in the study of the effects of conservation practices, numbers 4 and 11 were selected to investigate the ability of the watershed model outlined above to simulate the observed runoff hydrographs from several natural storms. These particular watersheds were chosen to illustrate the influence of their several dissimilar characteristics upon the resulting hydrographs. Topographic maps of both watersheds are shown in Figures B1 and B2.

Both watersheds 4 and 11 have essentially the same total area, 2.01 and 2.04 acres, respectively, and were planted in a corn-soybeans-wheat-meadow rotation during the study. However, watershed 4 was farmed using the prevailing practice treatment while watershed 11 received the conservation treatment during the period of record. Watershed 4 is composed almost entirely of a Sidell silt loam soil with average slopes of 5.1 percent. Approximately one-fourth of watershed 11 is composed of a Chalmers silty clay loam soil with the remainder being about equally divided between a Sidell and a Raub silt loam. The slopes on this watershed average 2.2 percent.

Detailed descriptions of the soil types found on the watersheds are available elsewhere. The total volume porosity and the moisture content at field capacity for the various soils were estimated from data supplied by H. N. Holtan.

---


Figure B1. Topographic Map of Throckmorton Watershed No. 4

Figure B2. Topographic Map of Throckmorton Watershed No. 11
(a) Orientation No. 1; 37, 50.0 foot Elements

(b) Orientation No. 2; 38, 50.0 foot Elements

Figure B3. Subdivision of Watersheds into Elements
(c) Orientation No. 1; 236, 19.7 foot Elements

(d) Orientation No. 2; 236, 19.7 foot Elements

Figure B3 (cont'd.)
(e) Orientation No. 2; 146, 25.0 foot Elements

(f) Watershed No. 11; 143, 25.0 foot Elements

Figure B3 (cont'd.)
APPENDIX C
STORM HYDROGRAPHS

The material below represents a summary of the assumed antecedent condition of the various hydrologic parameters required to simulate a storm event and the calculated surface runoff hydrographs resulting from these conditions. The storm of July 27, 1943, on watershed eleven was very light and produced no runoff. Runoff records for watershed eleven were not available for storms after 1949.

The solid lines in Figures C1 and C2 represent observed conditions while the broken lines correspond to predicted runoff hydrographs. The short broken lines represent the hydrographs predicted by the watershed model outlined herein while the dash-dot lines correspond to the predictions of the synthetic hydrograph analysis.
Table C1. Assumed Antecedent Watershed Conditions

<table>
<thead>
<tr>
<th>Date</th>
<th>Infiltration Rate</th>
<th>ASM**</th>
<th>DINF</th>
<th>CROP</th>
<th>PER</th>
<th>PIT</th>
<th>ADIR</th>
<th>RN</th>
<th>CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/19/42</td>
<td>H</td>
<td>55.</td>
<td>11.0</td>
<td>Timothy</td>
<td>90.</td>
<td>.020</td>
<td>.00</td>
<td>.100</td>
<td>61.</td>
</tr>
<tr>
<td>6/16/45</td>
<td>L</td>
<td>85.</td>
<td>3.0</td>
<td>Wheat</td>
<td>80.</td>
<td>.010</td>
<td>.00</td>
<td>.055</td>
<td>89.</td>
</tr>
<tr>
<td>6/30/45</td>
<td>L</td>
<td>45.</td>
<td>3.5</td>
<td>Wheat</td>
<td>80.</td>
<td>.020</td>
<td>.02</td>
<td>.120</td>
<td>56.</td>
</tr>
<tr>
<td>8/14/45</td>
<td>H</td>
<td>60.</td>
<td>8.5</td>
<td>Clover</td>
<td>60.</td>
<td>.010</td>
<td>.02</td>
<td>.230</td>
<td>63.</td>
</tr>
<tr>
<td>9/22/45</td>
<td>H</td>
<td>50.</td>
<td>7.0</td>
<td>Clover</td>
<td>85.</td>
<td>.020</td>
<td>.02</td>
<td>.200</td>
<td>54.</td>
</tr>
<tr>
<td>6/07/47</td>
<td>L</td>
<td>90.</td>
<td>16.0</td>
<td>New Corn</td>
<td>00.</td>
<td>.000</td>
<td>.14</td>
<td>.070</td>
<td>95.</td>
</tr>
<tr>
<td>4/07/48</td>
<td>L</td>
<td>80.</td>
<td>3.0</td>
<td>Corn Stubble</td>
<td>00.</td>
<td>.000</td>
<td>.00</td>
<td>.085</td>
<td>87.</td>
</tr>
<tr>
<td>4/07/48</td>
<td>L</td>
<td>90.</td>
<td>3.0</td>
<td>Corn Stubble</td>
<td>00.</td>
<td>.000</td>
<td>.00</td>
<td>.050</td>
<td>95.</td>
</tr>
<tr>
<td>7/27/48</td>
<td>L</td>
<td>65.</td>
<td>8.0</td>
<td>Beans</td>
<td>25.</td>
<td>.000</td>
<td>.06</td>
<td>.045</td>
<td>80.</td>
</tr>
<tr>
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<td>70.</td>
<td>7.0</td>
<td>Clover</td>
<td>80.</td>
<td>.020</td>
<td>.01</td>
<td>.140</td>
<td>72.</td>
</tr>
<tr>
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<td>80.</td>
<td>4.0</td>
<td>Clover</td>
<td>80.</td>
<td>.020</td>
<td>.01</td>
<td>.140</td>
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<tr>
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<td>Fallow</td>
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<td>.00</td>
<td>.020</td>
<td>69.</td>
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<td>70.</td>
<td>3.0</td>
<td>Wheat</td>
<td>30.</td>
<td>.000</td>
<td>.03</td>
<td>.040</td>
<td>77.</td>
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</table>

Watershed #11

<table>
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<tr>
<th>Date</th>
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<th>DINF</th>
<th>CROP</th>
<th>PER</th>
<th>PIT</th>
<th>ADIR</th>
<th>RN</th>
<th>CN</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Timothy</td>
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<td>.03</td>
<td>.150</td>
<td>61.</td>
</tr>
<tr>
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<td>L</td>
<td>85.</td>
<td>12.0</td>
<td>Wheat</td>
<td>90.</td>
<td>.015</td>
<td>.06</td>
<td>.250</td>
<td>89.</td>
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<tr>
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<td>45.</td>
<td>16.0</td>
<td>Wheat</td>
<td>90.</td>
<td>.020</td>
<td>.14</td>
<td>.600</td>
<td>56.</td>
</tr>
<tr>
<td>8/14/45</td>
<td>H</td>
<td>60.</td>
<td>12.0</td>
<td>Clover</td>
<td>60.</td>
<td>.010</td>
<td>.12</td>
<td>.600</td>
<td>63.</td>
</tr>
<tr>
<td>9/22/45</td>
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<td>50.</td>
<td>16.0</td>
<td>Clover</td>
<td>95.</td>
<td>.025</td>
<td>.14</td>
<td>.600</td>
<td>54.</td>
</tr>
<tr>
<td>6/07/47</td>
<td>L</td>
<td>90.</td>
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<td>New Corn</td>
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*The letter "H" corresponds to the infiltration capacity rates given in Table 5 and the letter "L" to rates one-half as large.

**Column heading symbols refer to the programming symbols defined in Appendix A.
Table C2. Comparison of Hydrograph Analyses

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<th>Date</th>
<th>Observed Conditions</th>
<th>Predicted Conditions</th>
<th>Synthetic Hydrograph</th>
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<td>Peak Rate in./hr.</td>
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(a) Storm of 7/19/42

(b) Storm of 6/16/45

Figure C1. Observed and Predicted Hydrographs for Watershed No. 4
(c) Storm of 6/30/45

(a) Storm of 8/14/45

Figure C1 (cont'd.)
(e) Storm of 9/22/45

(f) Storm of 6/7/47

Figure CI (cont'd.)
(i) Storm of 7/27/48

(j) Storm of 7/19/50

Figure C1 (cont'd.)
(k) Storm of 9/21/50

(1) Storm of 6/17/51

Figure C1 (cont'd.)
(m) Storm of 6/10/53

Figure C1 (cont'd.)
Figure C2. Observed and Predicted Hydrographs for Watershed No. 11
(c) Storm of 6/30/45

(d) Storm of 8/14/45

Figure C2 (cont'd.)
(e) Storm of 9/22/45

(f) Storm of 6/7/47

Figure C2 (cont'd.)
(g) Storm of 4/7/48

(h) Storm of 4/7/48

Figure C2 (cont'd.)