A SPATIALLY RESPONSIVE CATCHMENT MODEL FOR PREDICTING STORMWATER RUNOFF FROM UNGAGED WATERSHEDS

by

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CHAPTER I

INTRODUCTION

A basic problem facing modelers of natural watershed systems is that of accounting for the heterogeneities which are generally present. It has long been recognized that such factors as soil, land cover, management practice and slope contribute to the variability in the runoff response from one drainage basin to another.

Computer-based mathematical models that predict the runoff response of a watershed system have been the subject of much research in recent years. During the past decade, research efforts have focused on the development of hydrologic models that have the capability of simulating the flow response when a drainage area is subjected to some rainfall distribution. Many of these hydrologic models are lumped-parameter models in which non-uniform parameters, such as rainfall, soils, landuse and topographic characteristics, are weighted to obtain representative values for the entire drainage basin. These models are relatively easy to use when the necessary data requirements are available, but they are not readily adaptable to situations where spatial variations must be considered.

A spatially responsive model which has the capability of assembling and correlating non-uniform parameters and simulating the interaction of these parameters should, at least conceptually, provide a more reliable spatiotemporal history of overland and channel flows. Additionally, a spatially responsive model will provide the framework to better evaluate the effect of landuse change on the quality of storm water runoff. This premise is particularly relevant to the modeling of erosion and sediment transport. By improving the prediction of water quantity with a spatially responsive model, a better description of pollutant transport processes should be possible.

There is considerable concern over how to implement non-point source pollution controls as specified under Section 208 of the Clean Water Act (PL 92-500). Regulatory agencies can easily determine that poor water quality exists in a stream or lake, but can seldom determine the actual causes of the pollution when it occurs in a mixed landuse area. Efficient and effective pollution control is not possible without some understanding of cause-effect relationships. If, however, the runoff response of the watershed can be simulated with a spatially responsive model, it will be possible to specify which areas and landuses actually change the water quality status. In this manner, pollution control measures will be required only where they are necessary instead of "across the board". If such modeling techniques are not available, one can expect to see "across the board" regulation of landuse practice with no assurance of accomplishing water quality goals. The model described herein provides a rational framework for evaluation of management alternatives prior to implementation.

The most significant advantage of the spatially responsive modeling approach is its ability to incorporate many facets of the natural watershed system to answer specific questions about the system's response to perturbation. Properly constructed, the modeling system can be used with data at varying degrees of resolution. Thus, the system may economically be used to analyze single land units, entire basins, or the effect of a single land unit on a larger watershed.

Beasley, et.al. (1977) state, "The selection of a specific model for use as a planning tool is a difficult process complicated by the large number of different models developed in recent years. The most appropriate model to use will depend on the intended application, the type of input data available and the suitability of the output information generated. The accuracy of a model's simulation should also be an important consideration, but unfortunately this is very difficult to judge. Primarily this must be done intuitively by a thorough study of the relationships incorporated into a model." These statements tend to summarize the basic direction of this research effort.

Specific Objectives

The long range goal of the research program in hydrology in the Department of Agricultural Engineering at Virginia Polytechnic Institute and State University is the development of a spatially responsive watershed modeling system for use in all phases of soil and water management. A major part of this effort is the development of a computer-based model which will interact with a geographic information system that contains data on soils, topography and landuse. The modeling system will be organized for use at two levels: (1) the planning level for regional analysis of conservation and pollution control plans, crop growth forecasts and economic analyses, and (2) the field operational level to be accessed by farm managers and consultants for real-time analysis of the moisture and chemical status of specific field areas and for use as an aid in developing appropriate management practices.

The major objective undertaken in this study concerned the development of a Finite Element Storm Hydrograph Model (FESHM) to provide reliable flow prediction on ungaged areas. Primary emphasis was on this phase of model development since the most important aspect of simulating waterborne pollutants is the proper definition of runoff and its associated flow characteristics. It was not the intended purpose of this research effort to provide a rigorous evaluation of the many techniques for predicting water quality, but to provide a framework for successful simulation of water quality with a water quantity model of acceptable reliability.

The groundwork for this study was established by the initial work of Li (1975) and Ross (1975). Therefore, a major part of this effort has focused on the modification and integration of these basic concepts into a comprehensive hydrologic model which can be applied to any watershed. Specific objectives are summarized as follows:

1. The development of criteria for determing what constitutes a hydrologic response unit and a flow element,
2. The establishment of procedures for resolving the two levels of discretization which are encountered.
3. The selection of mathematical relationships to describe the hydrologic and hydraulic processes in the framework of the spatially variable data that is available.
4. To test the validity of the finite element numerical technique to the routing of overland and channel flow.
5. Determine the applicability of the kinematic wave approximation to channel flow routing.

6. Seek to eliminate errors inherent in the application of numerical methods to the governing differential equations such as convergence and stability errors.

Applications of the model included the following objectives:

1. Develop a user-oriented model for predicting storm water runoff from small ungaged watersheds.
2. Establish a framework by which the runoff model may be used in the prediction of water quality with a minimum of user effort.
3. Establish procedures in data preparation for the application of the runoff model to ungaged watersheds.
4. Incorporate sufficient flexibility into the runoff model to evaluate the effect of best management practices on water quantity and quality, including point controls and nonpoint controls such as vegetation and land cover.
5. Determine the sensitivity of those parameters driving the model to reveal the most crucial sources of error in the development of the data base.
6. Evaluate the effectiveness of the model in

predicting stormwater runoff from ungaged watersheds.

7. Apply the spatially responsive concept to the problem of simulating erosion and sediment transport.
8. Illustrate with specific examples, the applicability of the runoff model to the problem of erosion and sediment transport.

Research Approach

A procedure was developed by Li (1975) to use soil mapping units and landuse data to subdivide a watershed into homogeneous response units. Rainfall excess was determined from a soil moisture model. A parametric approximation was used in lieu of the more detailed numerical solution of the partial differential equations of unsaturated flow. The primary component of the soil moisture model was the simulation of infiltration.

In an earlier work by Ross (1975), the finite element numerical technique was used to solve the partial differential equations which describe overland and channel flow. A fundamental concept in finite element analysis is that a complex system can be subdivided to form a number of subareas which can be analyzed independently and the results collected to form the total system response. This concept provides a ready mechanism for routing surface flow contributions from subareas provided a reliable procedure exists to predict rainfall excess.

The above two routines were modified and interfaced to create a spatially responsive storm hydrograph simulation model with the capability of incorporating the many spatiotemporal variations that exist on a watershed.

The concepts for modeling spatial variations are discussed in Chapter II and the mathematical basis for the model is described in Chapter III. A description of the computer model, with emphasis on the procedures for creating the input data file for the inclusion of spatiotemporal properties of a given watershed, is given in Chapter IV. The application of the model to a hypothetical watershed and several natural watersheds is presented in Chapter V. The applicability of the FESHM concept to the problem of simulating erosion and sediment transport is presented in Chapter VI. Finally, Chapter VII discusses the conclusions and recommendations resulting from this research.

CHAPTER II

CONCEPTS FOR MODELING SPATIAL VARIABILITY

The development and/or utilization of a model that incorporates spatial variation requires an evaluation of the advantages of additional detail over more conventional parametric techniques and the criteria to be used in subdividing the watershed.

This chapter addresses these factors and presents the underlying concepts of a spatially responsive model. Particular emphasis is placed on the inclusion of spatial variation relative to the FESHM.

Spatially Responsive Models

Most approaches to watershed modeling in the past have been directed toward the development and/or utilization of a simplified, or lumped-parameter, input structure for creating an output hydrograph at a single point, generally the watershed outlet. Because of the "environmental crisis", the questions that require answers by watershed modeling demand an entirely new approach. It is no longer satisfactory to be able to determine quantity and quality of runoff from a drainage basin at some point far removed from critical influencing areas. It is now necessary to isolate these critical areas for the purpose of applying and evaluating corrective measures, due to governmental legislation resulting from environmental concerns.

The capability of a watershed model to perform the above task is important in light of landuse changes or management practices which affect the magnitude and timing of flood flows. More recently, the need to define the effects of land management practices on nonpoint source pollution has created greater interest in improving the prediction of flows from land surfaces. These phenomena have attracted the interest of hydrologists and others for many years.

Approximately fifty years ago Lowdermilk (1929) stated, "It appears that the factors operating in a large watershed are of sufficient complexity and interrelation to prevent the isolation of the influence of single factors by streamflow measurements alone. The evaluation of component elements is essential to an understanding of the phenomena of the water cycle."

Several years later, Bernard (1937) proposed that the summation of the runoff from relatively homogeneous subareas be used in predicting the total runoff from the larger watershed which they compose. He also suggested that this type of procedure would allow the effects of future landuse treatment to be evaluated.

More recently, Amerman and McGuiness (1967) noted that research on unit-source areas, including small plots, offers the only means of isolating factors affecting the hydrologic response of an area.

Huggins and Monke (1966) presented the underlying concept of a spatially responsive model by stating, "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."

The partial area concept represents one of the first attempts to accommodate the heterogenetic factors which contribute to the runoff from a natural drainage basin. Betson

(1964) examined this concept by the application of mathematical models to two small watersheds. He determined that a small portion of the overall watershed was largely responsible for the runoff contributions to the storm hydrographs and that these contributing areas were relatively consistent from one storm event to another.

Ragan (1968) conducted a spatially responsive numerical investigation of watershed runoff for the purpose of determining the partial area contributions of watershed response. His application of the partial area concept revealed that only a small portion of the watershed contributed flow to the storm hydrograph. Furthermore, he was able to isolate the localized zones of intense contribution and determined that the ranking of the magnitude of runoff from the contributing areas varied depending upon rainfall intensity.

Similar findings were obtained by other investigators, such as Betson and Marius (1969) who related source areas to the critical 'A' horizon depth factor. Kirkby and Chorley (1967) also found that a variation in watershed soils is primarily responsible for the non-homogeneity in runoff response.

Engman and Rogowski (1974) developed a storm hydrograph model which utilized contributing areas of response in determining surface runoff. The ability of the model to reliably predict runoff response on ungaged watersheds was concluded to be promising primarily because partial source areas could be identified with the model.

Hewlett and Troendle (1975) presented a brief treatise of the variable source area concept and the importance of including spatial variability in the simulation of runoff from small as well as large watersheds. It is, therefore, a well-known fact among hydrologists that significant spatial variability exists in most, if not all, watershed systems. As previously noted, a heterogeneous mixture of soils, landuse, slopes, etc. have been attributed by many investigators to be the primary contributors to the "noise" in runoff predictions. It appears logical, therefore, to use the above properties as the basis for incorporating more spatial variation in the modeling process.

Realization of these phenomena has led other investigators to seek the appropriate means by which a watershed may be discretized into its unit-source areas. The basic question, therefore, is what mechanism can be used to isolate areas that will respond similarly to a uniform rainfall input?

Amerman (1965) utilized unit-source areas, or areas consisting of a single cover and soil type, to subdivide a watershed into conceptual physically homogeneous unit-source watersheds.

England and Holtan (1969) state, "soil properties significant to processes of infiltration, moisture storage, drainage, and the hydraulics of surface flow are related to topographic position." England and Onstad (1968) offered a discretization scheme when they suggested that a complex drainage can be subdivided into an elevational sequence of upland, hillside and botton land. Later, England (1970) proposed the use of land capability classes to define these three land form sequences.

Rogowski (1972) evaluated soil variability criteria and concluded that the smallest area of significance, in heterogenetic terms, is likely to be a soil series. Beckett and Webster (1971) and Nielsen (1973) have conducted studies that confirm that significant spatial variability exists in the soil water properties of soils.

Very recently, investigators, such as Peck, et.al. (1977) and Warrick, et.al. (1977) have investigated soil variability in an effort to determine its effect upon water budget components.

It should be noted that whatever mechanism of subdivision is selected, homogeneity only implies a reduction in the heterogeneity of the original system. By proper categorization, however, one can hope to achieve a significant reduction in the heterogeneity of given units.

A complete accounting of the complex spatial variability in natural watersheds appears impracticable, if not impossible, with the present state of the art. This situation has confronted hydrologists for many years. What level of aggregation is possible to minimize data requirements and, concurrently, maintain a desired level of modeling predictability? Objective criteria for defining precisely when to and when not to aggregate soil properties, cover conditions, etc. are essentially nonexistent. [Research needs to be conducted that will develop objective criteria for defining reliable relationships between data aggregation and model predictability.]

As previously mentioned, if no data aggregation is performed, a large amount of data must be contended with, even for small watersheds. The extent of this problem has diminished somewhat in recent years with the accessibility of sophisticated mapping equipment, such as electronic planimeters, digitizers and graphics devices. Advances in the field of remote sensing will also facilitate the reduction and processing of non-aggregated data in the near future. These improved transferability techniques for data from maps to input files are closing the gap that once existed between the benefits derived from the lumping of watershed parameters and the cost of extensive data collection and manipulation. It should also be kept in mind that while it is a relatively simple task to aggregate a data base, it is essentially impossible to perform the reverse.

A model which integrates the spatial variability of soils, landuse, topography and rainfall, and minimizes the aggregation of those watershed-related properties that inherently can have tremendous spatial variability, should be capable of reproducing streamflows in the ungaged context. Investigators have for many years attempted to develop a hydrologic model with a reasonable degree of reliability in its output when applied to ungaged watersheds without prior optimization of model parameters. A model with this capability would have obvious benefits for application to watersheds which have not been monitored for streamflow. For a model to have this capability it appears logical that it would be due, in part, to the level at which watershed descriptors can be accurately defined.

Even though some weighting of hydrologic parameters is necessary, because of time and economic constraints, spatial uniqueness should be maintained on a relatively small scale. It is felt that this characteristic provides the strategy necessary in simulation to make a model sufficiently reliable for flood routing and water quality prediction on ungaged watersheds.

In developing this concept, an issue of primary importance is the correct selection of watershed descriptors, or combinations thereof, that will define the lowest level of finesse (e.g., soil-landuse combinations). The assumption is made, for example, that, if defined by the same criteria, a landuse labeled "woods" in a given watershed would have the same roughness characteristics as a "woods" landuse in an entirely different watershed. This circumstance would also be true for other watershed parameters which drive the model.

This same premise applies to the possibility of evaluating the effect of landuse change on the quantity and quality of storm water runoff from a watershed. Proper assignment of values to the descriptive parameters should indicate the effect of the change on both the runoff volume and the timing of flows. This concept will be further developed but it should be reemphasized that minimizing data aggregation should, in all likelihood, lend credence to the means of evaluating landuse changes.

Watershed Discretization

A primary objective of this research effort was the development of a comprehensive, yet generalized, model to simulate flood hydrographs. The development of the model resulted in a structure which consists of two distinct modules: a rainfall excess generator and a flood routing scheme. A significant problem is encountered in the coordinating of the two discretization techniques that are needed to provide optimal estimates of rainfall excess and subsequent routing of these quantities to downstream points of interest. This task must be performed in the interest of maintaining spatial variability and uniqueness.

This may be accomplished by defining flow sections or elements based upon flow patterns and topographic features solely for the purpose of routing flows. For use in computing rainfall excess, additional areas may be defined based upon soils, landuse and physiographic descriptors.

The basic procedures by which these subareas are defined are described below. The equations which govern the hydrologic and hydraulic occurrences on the subareas are reserved for discussion in Chapter III.

Defining Hydrologic Response Units

A procedure was outlined by Li (1975) to discretize a watershed into units that consist of soil mapping unit-landuse combinations. These unique combinations were referred to as hydrologic response units (HRU's). An HRU was defined as an area which responded similarly throughout when subjected to a given rainfall event, i.e., rainfall excess was assumed to be uniformly distributed over the corresponding land area.

The procedure for identifying HRU's and creating the basic data base for subsequent rainfall excess computations is a straightforward, but time-consuming, process. The use of electronic digitizing equipment with interactive graphics capability greatly facilitates the collection and manipulation of this data.

The first step is to develop two maps, with soil mapping units delineated on one and landuse on the other. The soils map is overlaid on the landuse map and each combination is identified. It is important to note that a given combination can occur at many different locations in a watershed and this position is always maintained.

This procedure is illustrated by Figure 1 where Figure 1a represents a soils map with two soil types and Figure 1b is a landuse map defining three land covers. Figure 1c results from the process described above and creates five

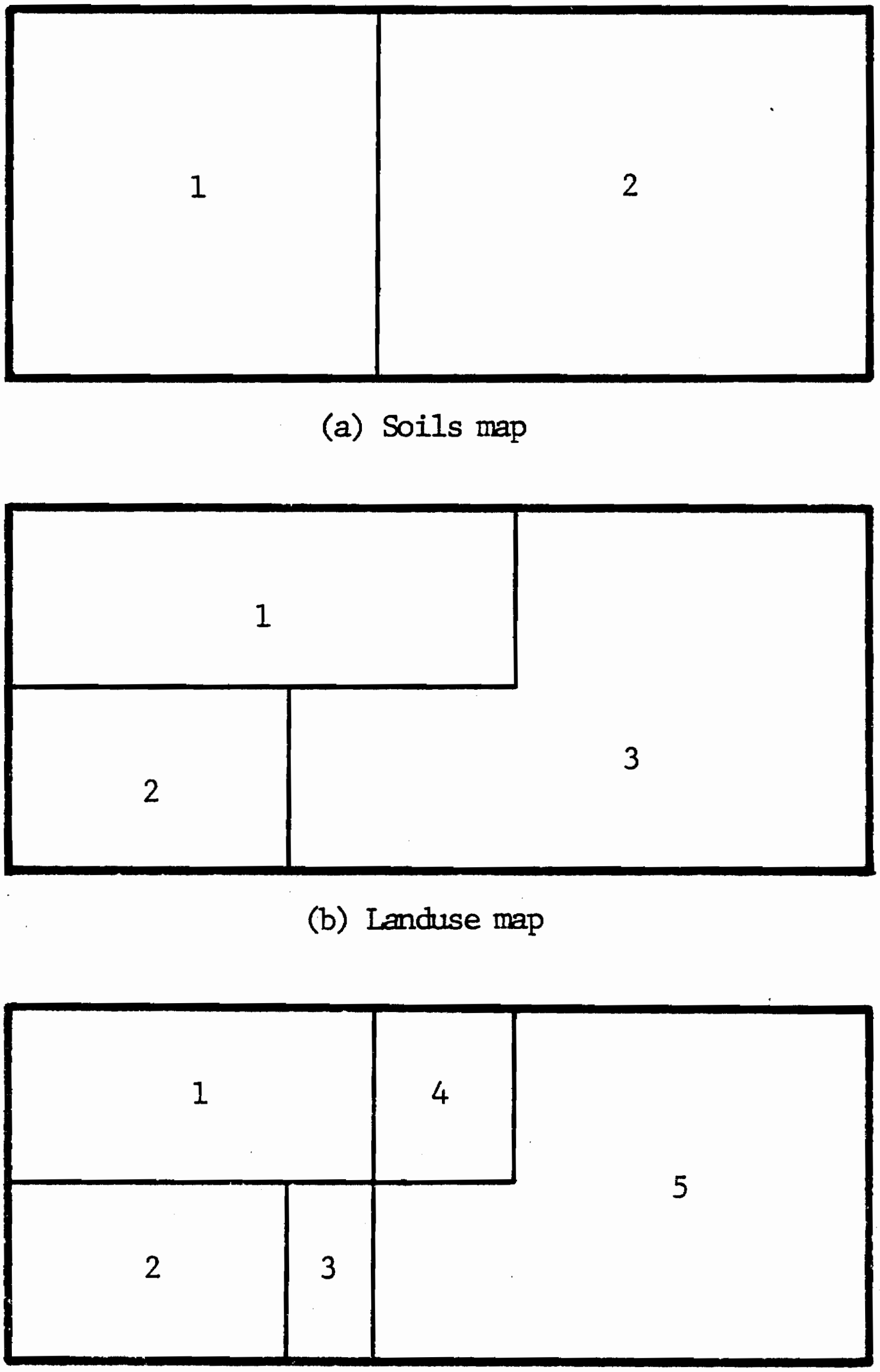


Figure 1. Schematic illustration of the procedure for determining hydrologic response units (from Li (1975)).

unique HRU's. Obviously, the number of HRU's can increase very rapidly as the drainage area is increased to include more mapping units and landuse types. The data necessary to identify each unit and, subsequently, to describe the hydrologic response from each area can rise to enormous proportions. Therefore, some degree of aggregation is necessary. This is better understood after the discretization procedure for flow elements has been discussed.

Defining Flow Elements

The primary assumption made in the discretization of the watershed is that of one-dimensional flow. The resulting element grid structure represents a quasi two-dimensional pattern where the arrangement of one-dimensional flow "strips" maintains an overall two-dimensional pattern of flow directions.

The first criterion in developing the finite element grid is that of discretizing the watershed in such a manner that significant flow paths are maintained. A watershed will usually consist of several subsheds, i.e., stream channels and their accompanying drainage areas. Each channel must then be subdivided into reaches, or elements, for the purpose of routing flow through the channel. The subareas of drainage (overland flow strips) into each channel element must be defined for routing overland flow and allocating the correct inflow to the corresponding channel element. Each of these overland flow strips may be further subdivided into a series of elements to define significant variations in slope, surface roughness, etc.

Figure 2 is a schematic illustration of the overland and channel flow pattern of strips. Figure 2 represents part of a typical watershed discretization consisting of five overland flow elements and two channel elements. For the purpose of simple illustration, rectangular boundaries are shown.

There are two overland flow strips shown. The first flow strip contains two elements and the second contains three elements. It should be noted that each flow strip is solved independently of the other flow strip in conformance with the one-dimensional method of solution. This procedure reduces internal computer core storage and allows large or small watersheds to be modeled with equal ease.

The steps by which flow is routed through the watershed are described as follows. A rainfall excess estimate is determined (see Chapter III) for each element and routed through each overland flow strip for each time step. The value of flow across the last node of an overland flow strip becomes input to the channel for each corresponding time step. Flow is routed along the entire channel as if it were

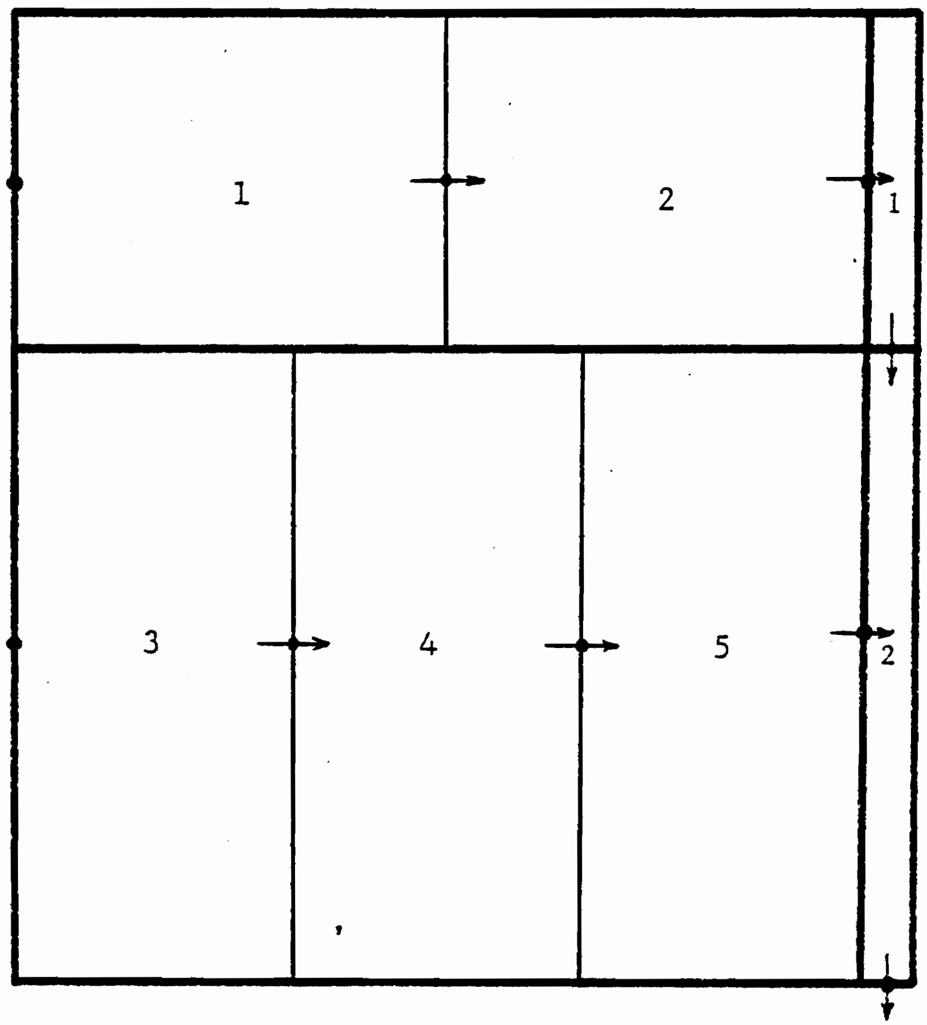


Figure 2. A typical rectangular discretization of an idealized watershed.

a single strip.

It is important to note that the usage of the one-dimensional approximation creates no additional problems in complexity when irregular overland flow element boundaries are encountered in natural watersheds. This is true because line elements result from the one-dimensional assumption and element areas are employed solely for the purpose of obtaining the quantity of the lateral flow that is concentrated along these elements. These considerations will be examined in detail when data preparation is discussed in Chapter IV.

Resolving Two Levels of Discretization

In the previous sections, two discretization procedures have been discussed which lead to land unit breakdowns whose boundaries will, in general, not coincide. This constitutes an immediate problem because excess rainfall will not be uniform across an element for a given time increment.

A procedure must then be developed whereby the properties of the two discretization procedures are integrated toward one common intention. This is necessary since a given flow strip can consist of many HRU's of varying size. Several alternative techniques that could be used to resolve this problem are discussed below.

One option is that of conceptualizing the HRU's within an overland flow strip into an ordered sequence of elements arranged such that hydraulic continuity is maintained in the one-dimensional context with each HRU defined as an element. An investigation in this direction would likely result in problems with numerical stability in the solution of flow through an overland flow strip. Unless the smallest of the HRU's were deleted from consideration, elements will be encountered that have very short lengths. To obtain a solution, very small time increments would be necessary. This would increase computer costs many orders of magnitude with no benefit discernible in the predicted hydrograph. This option also does not appear worth pursuing due to a lack of information on both the effect of ordering the HRU's and the effect of thresholding.

The primary advantage of the above method is the fact that hydraulic continuity may be maintained at the HRU level. This is important in light of transmission, or re-infiltration, losses which may occur as water moves, for example, from an impervious HRU across a highly pervious HRU. This may cause difficulty in predicting the volume of runoff for flood events with short return periods, however, for extreme flood events, re-infiltration would have less impact upon total runoff.

Despite inclinations to eliminate data aggregation, some integration must take place because a point will be reached where the cost for the inclusion of detail far exceeds potential gain. No exact line of demarcation or single set of criteria appears to be usable. Rather, the separation point is a function of an incredibly complex set of factors which includes not only physical properties of the drainage system but economic constraints, the problem being solved and possibly, most importantly, the model itself.

This aggregation is best attained by a weighting procedure which is generally necessary in all hydrologic models which attempt to describe the physical characteristics of a complex watershed system. Some of these methods involve an entirely new concept of what constitutes an HRU.

One possible weighting procedure is that of weighting the soil and landuse properties, within each element, that are needed to define corresponding parameters in the infiltration equation. This provides a unique HRU for each element. Rainfall excess can then be generated from the weighted properties of a given element.

The soil properties in a strip can be weighted to create a conceptualized soil type for each strip. Landuse types would then be defined on the watershed whereby each landuse, for the purpose of determining rainfall excess, would constitute a unique HRU. A single rainfall excess sequence would then be obtained for each element by weighting the generated excess as a function of the landuse areas.

The above method has obvious benefits because of the advantages in making landuse changes and subsequent evaluation of these changes. Since land management will affect the land cover but normally will not alter the soils, the weighted soils parameters for a strip will remain fixed entities. This is convenient for the purposes of mapping and planimetering landuse changes for evaluation and making the necessary input data adjustments necessary to describe such alterations.

The procedure which appears to retain the highest level of spatial uniqueness is that of defining elements in a strip by topographic indicators and, for a given storm event, determining the rainfall excess sequence for each HRU within an element. The rainfall excess values are then weighted to provide a single rainfall excess sequence for the entire element. These values are then inputted to the flow routing routines.

The weighting is performed as a function of area with the linear approximation,

$$P_e = \sum_{i=1}^{NH} a_i/A_e \; R_i \qquad (1)$$

where

P_e = weighted rainfall excess for an element,

A_e = element area,

a_i = area of the ith HRU

R_i = rainfall excess for the ith HRU, and

NH = number of HRU's within the element boundary.

This procedure is convenient from the viewpoint of both storage and efficiency. The primary advantage of this method, however, is that the individuality of the HRU's is maintained, i.e., hydrologic response is available for the smallest discernible area of the watershed. This may be helpful when it is desired to locate and isolate critical runoff-producing areas of a given element. Furthermore, the rainfall excess distribution across an element is available.

Two alternatives are possible by which the volume of data necessary for relating HRU's to elements may be reduced in order to facilitate the weighting process. In the work of Ross (1975) a thresholding technique was applied which omitted consideration of HRU's which fell under a certain predefined percentage of element area. This procedure was based on the premise that their inclusion had little effect upon the final weighted rainfall excess values per element and even less impact on the downstream discharge hydrograph. This was done primarily because manual data collection and manipulation proved to be a tedious, time-consuming process.

Another alternative is the optimal grouping of HRU's by lumping those that have a similar hydrologic response, even though they may have a different arrangement of soils, land cover, etc. Developing a relationship to predict the relative responses from different HRU's is difficult because of the many interacting factors which are not constant for a given HRU, such as antecedent moisture and rainfall intensity. Rankings of HRU response may result in different orders for different storm intensities.

Access to an electronic planimeter precludes any necessity of data reduction techniques of this type. Benefits derived from the application of improved data transferability techniques from the maps to input files are, in all likelihood, greater than those obtained by any data reduction techniques which may be implemented.

CHAPTER III

MATHEMATICAL DEVELOPMENT OF THE FESHM

All computer-based models must have a driving equation or set of equations which constitute the basis of the model's simulation capability. This section describes the equations used in the development of the FESHM and approaches taken in their solution by computer-adaptable methods. Tests are performed on the accuracy of the model in simulating runoff along with numerical stability and convergence tests of the resultant solutions.

Describing Hydrologic and Hydraulic Processes

Mathematical relationships must be defined to describe the hydrologic and hydraulic processes occurring on the watershed which the modeler desires to simulate. These are discussed below along with their applied solution techniques.

Determining Rainfall Excess

With the designation of HRU's, a method must be selected by which an estimate of rainfall excess may be obtained when an HRU is subjected to a given rainfall input. Many theoretical and empirical hydrologic models have been developed to simulate the process of infiltration. Two of these infiltration models were investigated by Li (1975) as possible methods for the prediction of rainfall excess for HRU's; the Mein and Larson equation {Mein and Larson (1971)} and the Holtan equation {Holtan (1961)}. It was concluded that the latter was easier to handle computationally with the information available from the HRU descriptors.

The Holtan equation has also been applied to a wide range of data with reasonable success by Shanholtz and Lillard (1970) and Holtan, et.al. (1975). It was selected for this study primarily because the data necessary to define model parameters closely parallel the concepts for subdividing a drainage area into HRU's.

Several forms of this equation are available in the literature, however, the following form was adopted for inclusion in the FESHM.

$$f = GI \; a \; S^{c} + f_{c} \qquad (2)$$

where

f is the infiltration rate, in inches per hour,

GI is the growth index of a crop expressed as a ratio of present growth to that at maturity,

a is a coefficient for indexing the effect of cover conditions,

S is the unfilled storage space to a restrictive layer, in inches, usually assumed to be the depth of the 'A' horizon,

f_c is the constant infiltration rate after prolonged wetting, in inches per hour, and

c is a coefficient that is assumed to be a function of the soil hydraulic characteristics and is defined as the ratio of potential available water to the potential gravitational water in the soil profile.

Equation (2) is the driving function of a soil moisture model that was structured to provide a continuous moisture update throughout a given storm for all HRU's that have been defined within a drainage area. A soil's infiltration potential, as defined by the Holtan infiltration model, is based upon the dynamic storage capacity of a given finite depth of soil. The storage capacity within a soil profile is defined as the percentage of pore space in a unit volume of soil that can be filled by air and/or water. Thus, any unit of soil can be relegated into the solid and pore space components shown in the schematic diagram of Figure 3.

The depth of soil that must be considered was defined by Holtan, et.al. (1975) as the depth to the impeding strata and is often assumed to be the depth of the 'A' horizon. Within this depth, the greatest range of hydrologic activity is assumed to exist between the saturation and wilting point levels. The water unavailable to plants (mostly hygroscopic water) is unaffected by the evapotranspiration process and, therefore, was considered insignificant in the modeling process.

Plant available water is defined as soil water readily available for use by plants and its upper level is termed field capacity. The upper layer of water in the soil profile is defined as gravitational water. When this compartment has been filled, saturation of the soil has occurred. Maximum storage, therefore, is considered to be the sum of the potential plant available water and the potential gravi-

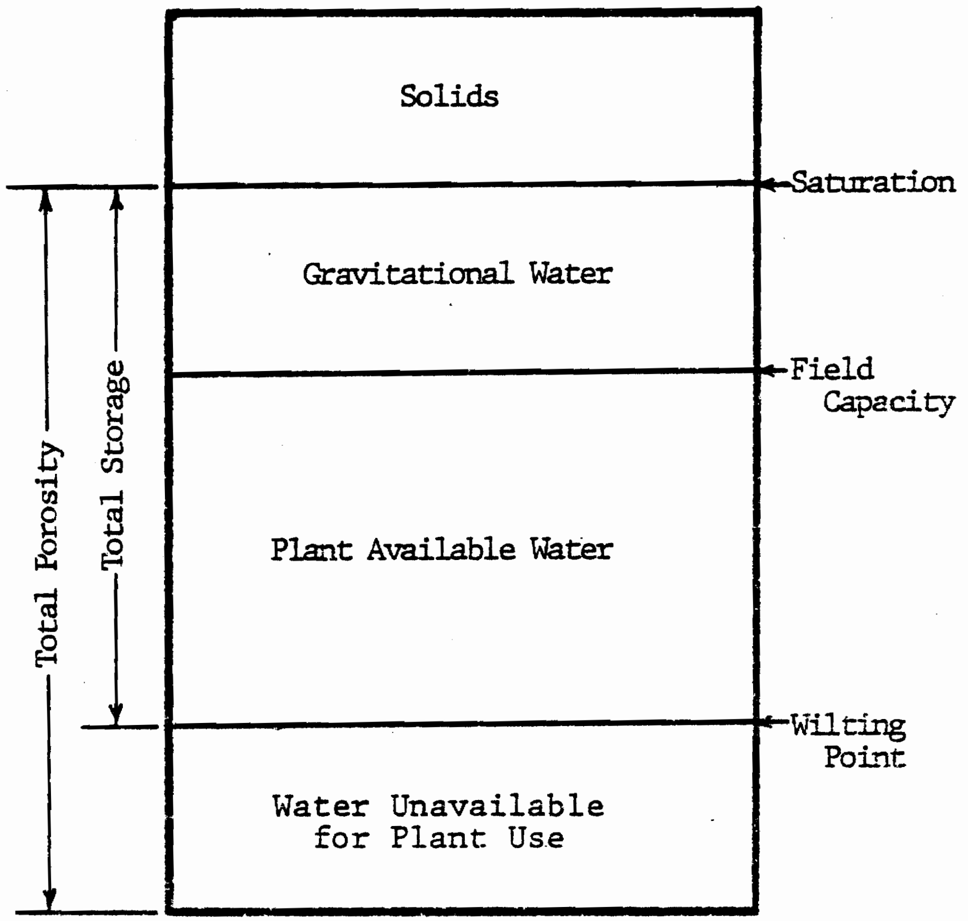


Figure 3. Schematic representation of the volume composition of soil {adapted from Li (1975)}.

tational water for a given soil profile. Unfilled storage space, S, is equal to the maximum storage minus the water existing in the soil profile at a given time.

The final infiltration rate, f_c, is a function of a soil's hydrology group and represents steady state infiltration for a given soil. It is theoretically equivalent to the soil's saturated hydraulic conductivity. During a storm event only gravitational water may be lost from the soil profile by deep seepage, i.e., f_c is assumed to be zero whenever the water level in the soil profile is below field capacity. When the water level is at field capacity or less, losses may be incurred only by evapotranspiration, which is assumed to be zero during precipitation. These constraints are maintained in the moisture accounting component of the FESHM during the course of a storm event.

Landuse factor 'a' is dependent primarily upon the vegetative characteristics of a land area. This is based on the premise that plant root density directly affects the capacity of a soil to infiltrate water. Values of 'a' are usually evaluated at plant maturity and are expressed as the fraction of the land area occupied by plant stems or root crowns.

The soil moisture accounting model in this study is based upon the model structure of Li (1975) where solutions proceed forward in discrete time steps. Computations are performed for each period during which the rainfall intensity is constant. The basic procedure is essentially a moisture accounting technique whereby infiltrated water during any time interval is subtracted from the available storage. The infiltration taking place does not affect the available storage until the end of that time step and the procedure is repeated for each rainfall interval. A major assumption of the soil moisture updating procedure is that the soil profile is assumed to be homogeneous although homogeneity does not, in reality, exist in any soil profile.

For each rainfall interval, rainfall intensity is compared to the computed infiltration rate. Runoff is simply the water available for infiltration less the water that can infiltrate during a given time interval and that retained as depression storage.

An understanding of the hydrologic processes which exist as rain falls to the earth results in the realization that there are many interacting factors which determine the amount of runoff which may occur. A continuous soil moisture budget model must consider many of these factors including seasonal vegetative growth, canopy interception, depression storage, evaporation and transpiration. With the exception of vegetative growth and depression storage, these factors have been neglected in this model. The primary reason for this is because the model was principally structured for routing storm events only. As storm intensity increases, the relative influence of the above phenomena on the volume and timing of runoff decreases. Cancpy interception usually represents a minimal quantity of water and, while evaporation must be considered in some context for any magnitude of storm, it is implied in the determination of antecedent moisture conditions.

Of the above factors, seasonal changes in vegetation and depression storage represent the factors that will exhibit the greatest influence on runoff. The former will do so specifically in the determination of the rate of infiltration by its effect on Holtan's 'a'. Notable examples of changes which are possible are the plowing of agricultural land in the Spring of the year and plant maturity during the Summer months, and the difference in forest litter during the Fall and other seasons of the year. The inclusion of these factors will allow greater variability in the range of landuse changes which can be presupposed to alter the face of a watershed. The model contains sufficient flexibility to incorporate the effects of vegetation on infiltration with a minimum of user effort through the inclusion of the crop growth index (GI) term in Eqn. (2).

Depression storage estimates for selected landuses may be relatively high and, therefore, may become an important factor as storm intensity decreases. This factor can be visualized as an additional storage component in the soil profile. While this factor decreases the amount of runoff it also provides water available for infiltration during the next storm interval in addition to precipitation. Thus, it may have a profound effect upon the moisture balance of the soil profile during a storm event.

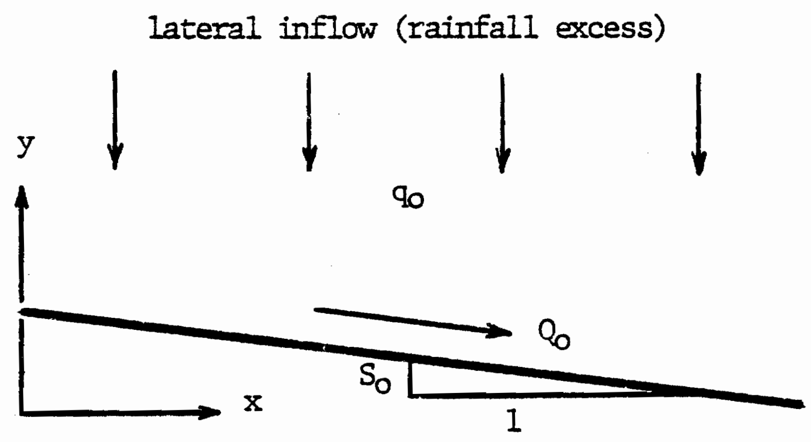
The approaches taken in dealing with the above factors will be described in a discussion of model parameters presented in Chapter IV.

Flood Routing

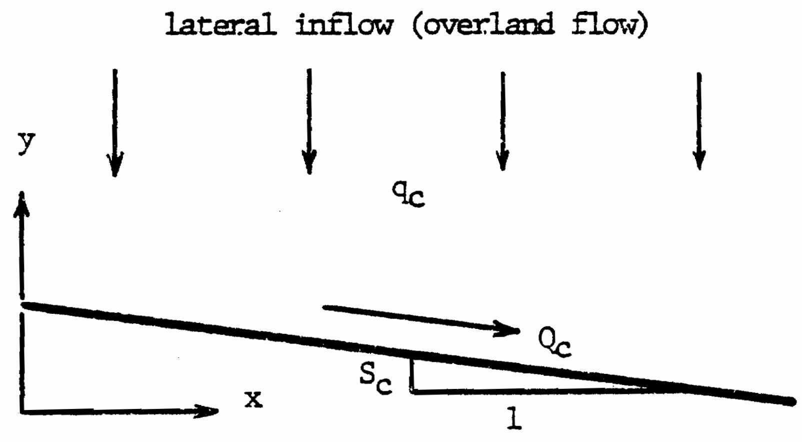
The hydrodynamic equations of continuity and momentum, referred to as the St. Venant equations, first appeared in 1871 and have remained essentially unchanged since that time. These equations have been demonstrated to be applicable to both overland and channel flow. Figure 4 shows the elevation views of the overland and channel flows that are represented by these equations. The similarity of these conceptualized flow planes should be noted.

The equation of continuity can be expressed as

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0 \tag{3}$$



(a) Representation of the overland flow plane



(b) Representation of the channel flow plane

Figure 4. Elevation views of a conceptualized overland and channel flow plane.

and the equation of momentum as

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) = g\ A\ (S - S_f) - g\ A\ \frac{\partial y}{\partial x} \qquad (4)$$

where

Q is the discharge in the overland flow plane or channel,

q is lateral inflow per unit length of flow plane (rainfall excess for the overland flow plane and overland flow output for the channel),

A is the area of flow in the overland flow plane or channel,

x is the distance in the direction of flow,

t is time,

g is the acceleration of gravity,

S is the bed slope of the flow plane,

S_f is the friction slope, and

y is the depth of flow.

Underlying assumptions and derivations leading to the St. Venant equations will not be repeated here since they are presented in many hydraulic texts (e.g., Viessman, et.al. (1972)). Approaches to the solution of these equations are discussed below.

Simplified Solution Forms

The solution of the unsteady flow equations presents an immediate problem to be resolved. The two equations, as nonlinear partial differential equations, can not be solved analytically, without the introduction of numerous simplifications which severely limit the applicability of the results. A review of several of these simplified methods are given by Yevjevich (1964).

One alternative solution to these equations is the application of numerical techniques to retain a general formulation applicable to a wide range of flow conditions. This type of approach requires a high-speed digital computer which, due to its current accessibility, reduces the need for simplified forms of the unsteady flow equations.

Expense of obtaining solutions by the numerical approach, however, may be prohibitive when the complete St. Venant equations are modeled. When applied under certain general physical conditions, assumptions may be made which still allow a wide range of unsteady flow conditions to be modeled. This leads to the application of the kinematic wave approximation (KWA).

Kinematic Wave Approximation

The concept of the kinematic wave implies that inertia forces are negligible relative to gravitational and frictional forces and that flow is a function of depth alone. This results in a numerical solution of the continuity equation and an analytical solution of the momentum equation, thus reducing the complexity and cost of obtaining a solution.

Lighthill and Whitham (1955), in a theoretical study of kinematic flow, set forth the justification for its application and cleared the way for its acceptance as an approach to flood routing. In doing so they established that, for flow to be classified as kinematic, the Froude number should be less than two. A discussion of the theory leading to the above conclusion may be found in Henderson (1966) and Eagleson (1970), as well as the original work of Lighthill and Whitham (1955).

An additional criterion was developed by Woolhiser and Liggett (1967) which utilizes a dimensionless kinematic flow number, K, defined as

$$K = \frac{L\ S\ g}{V^2} \qquad (5)$$

where

V is the velocity of flow.

When $K > 10$ the dynamic wave is small and the kinematic wave solution approximates the solution obtained by the complete equations. They were further able to determine that an error of approximately 10% results when $K = 10$ and that an increase in the value of K indicates a rapid decrease in the magnitude of the error.

Eagleson (1970) suggested that both of the above conditions be upheld for use of the KWA in unsteady flow simulation, however, Al-Mashidani and Taylor (1974) have shown that the Froude number can be greater than two provided that the value of K is large.

The applicability of the KWA to overland flow has been verified by many investigators {e.g., Woolhiser and Liggett (1967), Liggett and Woolhiser (1967), Kibler and Woolhiser (1970) and Overton and Brakensiek (1970)}. Liggett and Woolhiser (1967) have shown that for many overland flow conditions the value of K exceeds 1000. Wooding (1965a; 1965b; 1966) presented a convincing argument in favor of the KWA in a set of papers in which he applied the approach to a hypothetical V-shaped watershed and obtained good agreement between hydrographs generated by the simplified model and those generated by a natural catchment.

Successful applications of the KWA have been made to river flows (e.g., Sueishi (1955), Ishihara (1963) and Iwagaki (1955)}, and Henderson (1966) has stated that the KWA is generally applicable to natural floods in steep rivers with slopes of roughly 0.002 or greater. Henderson (1966) further classified rivers into one of three categories for routing by the St. Venant equations, based solely upon a slope criterion. Steep rivers were best simulated by the KWA, rivers with intermediate slopes should be modeled by the complete momentum equation and rivers with mild slopes can be simulated neglecting the local and convective acceleration terms. These three forms of the momentum equation will be solved and their results compared in the last major section of this chapter.

Numerical Methods and the Finite Element Technique

Numerical techniques have been applied to flow problems since the early days of the digital computer. Stoker (1953) performed the first important flood routing studies using a digital computer while working with floods on the Ohio River. His application involved an explicit scheme of the finite difference method. Many other investigators have utilized the explicit scheme while others have applied the implicit finite difference method and the method of characteristics. Several investigators have compared the solutions obtained by the various methods and discussed the advantages and limitations of each (e.g., Amein and Fang

(1970) and Price (1974)}.

High computation time, instability and convergence problems have been encountered with the use of the various numerical techniques. Complex geometric and boundary conditions have also been obstacles when working with these methods.

The recent introduction of the finite element method for solving flow problems has been encouraging since it has been demonstrated that some of the limitations encountered by the use other numerical methods can be avoided. Computation time can usually be reduced because the method requires less elements and can accommodate larger time steps. The method can also handle large spatial variations, complex geometry and complex boundary conditions.

Although finite element methods have been employed in the solid mechanics field since the 1950's, their use in flow problems did not become prominent until the late 1960's. One of the earliest applications of the finite element method to the solution of flow problems was made by Zienkiewicz and Cheung (1965) who conducted a seepage flow analysis. More recently, investigators such as Oden and Somogyi (1969) and Tong (1971) have applied the method to incompressible and compressible transient flow problems.

Judah, et.al. (1975) used the finite element method in conjunction with the Galerkin approximation to develop a model of overland and channel flow. The method was applied to the continuity equation alone since the KWA was assumed to apply to the momentum equation. Alterations were made in the input data describing the topography of a natural watershed and changes in the downstream hydrograph were noted. Fits between simulated and recorded hydrographs were good and it was reported that the model could easily handle complex geometry, diverse landuse and variable rainfall distribution.

Al-Mashidani and Taylor (1974) used the Galerkin form of the finite element method to solve the non-dimensional form of the St. Venant equations. When compared to other numerical methods the finite element approach was found to have more stability, more rapid convergence and to be computationally fast.

Cooley and Moin (1976) also used the Galerkin method to derive the finite element equations of continuity and momentum. They presented a comparison of results obtained with those of other numerical methods for several channel flow cases. It was also concluded that the linear forms of the approximating functions produced stable and convergent results.

Jayawardena and White (1977) discussed the basis of a distributed catchment flood routing model which utilized the Galerkin approximation for formulating the finite element solution. The KWA was assumed to be applicable and, therefore, the equation of continuity alone was solved numerically. Studies of parameter sensitivity were conducted and solutions obtained by different time integration schemes were compared. The model was applied to a hypothetical strip catchment and it was reported that future research would involve the application of the model to two natural catchments.

Derivation of the Finite Element Equations

The partial differential equations of continuity and momentum (Eqns. {3} and {4}) must be arranged into a form by which they can be solved algebraically. The derivation of the finite element continuity and momentum equations follows below.

Continuity Equation

The continuity equation (Eqn. {3}) is solved in its complete form in all three aforementioned approaches to obtain the cross-sectional area of flow, A. The parameters A and Q in Eqn. {3} are assumed to be variable while lateral inflow, q, is assumed to be constant over an element. When written in terms of the nodal point unknowns, A and Q can be assumed to be distributed with x in each element as follows:

$$A(x,t) \simeq A^{*}(x,t) = \sum_{i=1}^{NN} N_i(x)\; A_i(t) = [N]\;\{A\} \qquad \{6\}$$

$$Q(x,t) \simeq Q^{*}(x,t) = \sum_{i=1}^{NN} N_i(x)\; Q_i(t) = [N]\;\{Q\} \qquad \{7\}$$

where

$A_i(t)$ is area as a function of time only,

$Q_i(t)$ is discharge as a function of time only,

$N_i(x)$ is the interpolation function, and

NN is the number of nodes in an element.

For a one-dimensional line element, $NN = 2$, and

$$A^*(x,t) = N_1 \; A_1(t) + N_2 \; A_2(t) \tag{8}$$

$$Q^*(x,t) = N_1 \; Q_1(t) + N_2 \; Q_2(t) \tag{9}$$

The interpolation functions, N_1 and N_2, are often referred to as the coordinate functions since they define the relationship between the global and local, or natural, coordinates. Interpolation functions for line elements are adequately discussed in various finite element texts {e.g., Desai and Abel (1972) and Huebner (1975)}.

The derivation of the finite element equations involves the development of algebraic equations from the governing set of differential equations. The two procedures most commonly used are variational methods and weighted residual methods. The choice of Galerkin's residual method was made for this formulation because it has been demonstrated by others {e.g., Judah et.al. (1973) and Al-Mashidani and Taylor (1974)} to be a convenient formulation procedure for surface flow problems.

In Galerkin's residual method, the interpolation function is generally used as the weighting function of the trial function chosen to represent the field functions, which, in this case, are Eqns. {6} and {7}. Because the trial function is not the exact function, an error is introduced. It is this error which must be normalized by the weighting function.

Galerkin's method specifies that the integral

$$\int_D N_i \; R \; dD = 0 \qquad \{10\}$$

where

D is the element domain, and

R represents the residual to be weighted by the interpolation function, N_i.

While Eqn. {10} is specified for the entire solution domain, it may be applied to the individual elements as shown below where the trial function has been substituted into Eqn. {10} and the integral is taken over each element of the domain.

$$\sum_{e=1}^{NE} \int_{D_e} \left\{ N_i \left[\frac{\partial Q^*}{\partial x} + \dot{A}^* - q \right] \right\} dD_e = 0 \qquad \{11\}$$

where

NE is the number of elements in the solution domain,

A is the time differential of the area, and

D_e is the domain for a given element.

By considering one element only, the expansion of Eqn. {11} yields

$$\int_{D_e} \left[N_i \frac{\partial N_j}{\partial x} \{Q\} + N_i \{\dot{A}\} - N_i\, q \right] dD_e = 0 \qquad \{12\}$$

The three terms in the equation are then integrated over the length of the element to give the following well-known matrix terms for linear elements:

$$\int_{x_1}^{x_2} \left(N_i \frac{\partial N_j}{\partial x}\right) dx\ \{Q\} = \begin{bmatrix} -\frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2} & \frac{1}{2} \end{bmatrix} \{Q\}$$

$$\int_{x_1}^{x_2} (N_i\ N_j)\ dx\ \{\dot{A}\} = \ell \begin{bmatrix} \frac{1}{3} & \frac{1}{6} \\ \frac{1}{6} & \frac{1}{3} \end{bmatrix} \{\dot{A}\}$$

$$\int_{x_1}^{x_2} N_i\ dx\ q = \ell\ q \begin{Bmatrix} \frac{1}{2} \\ \frac{1}{2} \end{Bmatrix}$$

After combining these terms, the finite element equation becomes

$$\ell \begin{bmatrix} \frac{1}{3} & \frac{1}{6} \\ \frac{1}{6} & \frac{1}{3} \end{bmatrix} \begin{Bmatrix} \dot{A}_1 \\ \dot{A}_2 \end{Bmatrix} + \begin{bmatrix} -\frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix} - \ell q \begin{Bmatrix} \frac{1}{2} \\ \frac{1}{2} \end{Bmatrix} = 0 \qquad \{13\}$$

or

$$\ell [K] \{\dot{A}\} + [L] \{Q\} - \ell q \{M\} = 0 \qquad \{14\}$$

where, for an element,

$$[K] = \begin{bmatrix} \frac{1}{3} & \frac{1}{6} \\ \frac{1}{6} & \frac{1}{3} \end{bmatrix}$$

$$[L] = \begin{bmatrix} -\frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

$$\{M\} = \begin{Bmatrix} \frac{1}{2} \\ \frac{1}{2} \end{Bmatrix}$$

$$\{\dot{A}\} = \begin{Bmatrix} \dot{A}_1 \\ \dot{A}_2 \end{Bmatrix}$$

$$\{Q\} = \begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix}$$

Equation {13} represents the single element equation for this one-dimensional finite element analysis while Eqn. {14} expresses the general form of the equation.

If the time differential of the area is represented by a simple explicit time integration procedure,

$$\dot{A}(t) = \frac{A(t+dt) - A(t)}{dt} \qquad \{15\}$$

where dt = the time increment, the equation for one element becomes

$$\frac{\ell}{dt} [K] \{A\}_{t+dt} - \frac{\ell}{dt} [K] \{A\}_t + [L] \{Q\}_t - \ell q \{M\} = 0 \quad \{16\}$$

For the element equation to be adapted to a finite element grid consisting of more than one element, it must be arranged in a form that embodies the total number of elements. In this application an assembled equation must be provided for each strip and channel since the strips are routed independently.

The "direct stiffness" method is used to obtain the assembled matrices. This procedure is illustrated by the following example of an assemblage containing two elements and three nodes. The assembled element equation for this case is written as

$$\frac{1}{dt}\begin{bmatrix} \frac{\ell}{3}^{I} & \frac{\ell}{6}^{I} & 0 \\ \frac{\ell}{6}^{I} & (\frac{\ell}{3}^{I} + \frac{\ell}{3}^{II}) & \frac{\ell}{6}^{II} \\ 0 & \frac{\ell}{6}^{II} & \frac{\ell}{3}^{II} \end{bmatrix} \begin{Bmatrix} A_1 \\ A_2 \\ A_3 \end{Bmatrix}_{t+dt} - \frac{1}{dt}\begin{bmatrix} \frac{\ell}{3}^{I} & \frac{\ell}{6}^{I} & 0 \\ \frac{\ell}{6}^{I} & (\frac{\ell}{3}^{I} + \frac{\ell}{3}^{II}) & \frac{\ell}{6}^{II} \\ 0 & \frac{\ell}{6}^{II} & \frac{\ell}{3}^{II} \end{bmatrix} \begin{Bmatrix} A_1 \\ A_2 \\ A_3 \end{Bmatrix}_{t}$$

$$+ \begin{bmatrix} -\frac{1}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2} & 0 & \frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{Bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{Bmatrix}_{t} - \begin{Bmatrix} \frac{\ell^I q^I}{2} \\ \ell^I q^I + \ell^{II} q^{II} \\ \frac{\ell^{II} q^{II}}{2} \end{Bmatrix} = 0 \qquad (17)$$

where the subscripts of A and Q are the numbering of the nodes, and the superscripts, I and II, of variables l and q are the numbering of the elements.

The algebraic equations represented by the finite element equation must be solved as a set of simultaneous equations to obtain the unknown values of the field variables at the nodes. Gaussian elimination is one procedure by which the solution may be obtained.

A solution in time is performed by an iterative step approach where 'dt' is assigned a value and computations are made from t=0 to the desired duration of solution. In compliance with the "marching" procedure, values of A and Q solved for at one time step are used in Eqn. {16} for the solution of A and Q at the next time step. The values of $A_1(t+dt)$, $A_2(t+dt)$, $A_3(t+dt)$, $Q_2(t+dt)$ and $Q_3(t+dt)$ solved for at one time step would become $A_1(t)$, $A_2(t)$, $A_3(t)$, $Q_2(t)$ and $Q_3(t)$, respectively, at the next time step. This procedure would continue for as long as a solution is desired.

In a time-dependent problem of this type initial conditions must be specified in order to commence the time sequence of solution. For the example of a flow strip containing two elements and three nodes, initial flow can be assumed to be zero at all nodes. For both overland and channel flow at time, t=0, Eqn. {17} reduces to

$$\frac{1}{dt}\begin{bmatrix} \frac{\ell}{3}^{I} & \frac{\ell}{6}^{I} & 0 \\ \frac{\ell}{6}^{I} & (\frac{\ell}{3}^{I} + \frac{\ell}{3}^{II}) & \frac{\ell}{6}^{II} \\ 0 & \frac{\ell}{6}^{II} & \frac{\ell}{3}^{II} \end{bmatrix} \begin{Bmatrix} A_1 \\ A_2 \\ A_3 \end{Bmatrix} = \begin{Bmatrix} \frac{\ell^{I} q^{I}}{2} \\ \ell^{I} q^{I} + \ell^{II} q^{II} \\ \frac{\ell^{II} q^{II}}{2} \end{Bmatrix} \quad \{18\}$$

For solutions after time, $t=0$, boundary conditions need to be specified. Discharge at the upper node of a flow strip, Q_1, is zero at all times, t, for both the overland and channel flow strips. However, in the case of channel flow when the number of subsheds exceeds one, the upper node of certain channels may be located downstream of the confluence of two upstream channels. When this occurs, the boundary condition is specified that upstream discharge of the channel being considered is the sum of the discharges at the downstream nodes of the two upstream channels.

Boundary conditions may also be specified at the interior nodes of a flow strip. An example of the necessity of doing this is when a structure which tends to impede flow, such as a weir or culvert, exists at a channel node. In this case a function relating flow area, or depth, to discharge through the structure must be available. The value of Q at the node being considered is solved by this function and not by the momentum equation.

Momentum Equation

The three aforementioned solution approaches to the momentum equation (Eqn. {4}) are presented below.

Complete Momentum Equation

The equation of momentum (Eqn. {4}) can be rewritten for solution as

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} + \frac{V}{A}q + g S_f - g S = 0 \qquad \{19\}$$

The finite element equation can be obtained by considering V, y, A and S_f to vary linearly while the parameters n, S , q and g are constant within a given element. Consequently, the following relationships may be established.

$$A^*(x,t) = N_1 A_1(t) + N_2 A_2(t) \qquad \{20\}$$

$$V^*(x,t) = N_1 V_1(t) + N_2 V_2(t) \qquad \{21\}$$

$$y^*(x,t) = N_1 y_1(t) + N_2 y_2(t) \qquad \{22\}$$

$$S_f^*(x,t) = N_1 S_{f1}(t) + N_2 S_{f2}(t) \qquad \{23\}$$

It may be further assumed that the following is true:

$$\left(\frac{V}{A}\right)^{*}(x,t) = N_1 \frac{V_1}{A_1}(t) + N_2 \frac{V_2}{A_2}(t) \quad \{24\}$$

The similarity between terms in the above equations and those in Eqns. {8} and {9} is evident, therefore, the derivation of element matrices is not presented for the momentum equation. The finite element momentum equation, with an explicit time integration procedure and with known quantities on the right side, can be written as

$$\frac{1}{dt}[K]\{V\}_{t+dt} + g[K]\{\frac{V}{A}\}_{t+dt} + g[K]\{S_f\}_{t+dt} = \frac{1}{dt}[K]\{V\}_t$$

$$- \frac{\overline{V}}{\ell}[L]\{V\}_t - \frac{g}{\ell}[L]\{y\}_t + g\,S\,\{M\} \quad \{25\}$$

where

$$\overline{V} = \frac{V_1 + V_2}{\ell}$$

Factoring out the "stiffness" matrix and summing the known quanitites on the right side of the equation,

$$[K]\ \{V + dt\ q\ \frac{V}{A}\ + dt\ g\ S_f\} = \{P\} \qquad \{26\}$$

where

$$\{P\} = \begin{Bmatrix} P_1 \\ \\ P_2 \end{Bmatrix}$$

Equation {26} contains four unknowns, V_1, V_2, S_{f1} and S_{f2} and only two independent equations, therefore, an additional relationship is necessary. The terms, S_{f1} and S_{f2}, can be evaluated from the following equation which is based on the Manning formula:

$$S_f = \frac{V\ |V|\ n^2}{2.22\ R^{4/3}} \qquad \{27\}$$

where

n is the Manning roughness coefficient, and

R is the hydraulic radius.

Substitution of Eqn. {27} into Eqn. {26} results in

$$[K]\ \{(\frac{dt\ g\ n^2}{2.22\ R^{4/3}})\ V^2 + (1 + \frac{dt\ q}{A})\ V\} = \{P\} \qquad \{28\}$$

Then

$$[K]\ \{T\} = \{P\} \qquad \{29\}$$

where

$$T = \begin{Bmatrix} T_1 \\ \\ T_2 \end{Bmatrix} = \begin{Bmatrix} \left(\frac{dt\ g\ n^2}{2.22\ R_1^{4/3}}\right) V_1^2 + \left(1 + \frac{dt\ q}{A_1}\right) V_1 \\ \\ \left(\frac{dt\ g\ n^2}{2.22\ R_2^{4/3}}\right) V_2^2 + \left(1 + \frac{dt\ q}{A_2}\right) V_2 \end{Bmatrix}$$

Solution of Eqn. {29} for T_1 and T_2 allows the quadratic equation to be used in a solution for both V_1 and V_2.

$$V = \frac{-B \pm \sqrt{B^2 - 4\ A\ C}}{2\ A} \qquad \{30\}$$

where

$$A = \frac{dt\ g\ n^2}{2.22\ R^{4/3}}$$

$$B = 1 + \frac{dt\ q}{A}$$

$$C = -T$$

After solutions are obtained for A from Eqn {16} and V from Eqn. {28}, discharge, Q, may be obtained at each node by

$$Q = V A \tag{31}$$

Parabolic Equations

Elimination of the local and convective acceleration terms in Eqn. {19} results in the following equation of momentum.

$$\frac{\partial y}{\partial x} = S - S_f \tag{32}$$

The use of both Eqn. {32} and the continuity equation (Eqn. {3}) is referred to as the parabolic equations approach.

Elimination of the corresponding terms in Eqn. {25} results in the finite element momentum equation below.

$$[K]\ \{S_f\} = S\ \{M\} - \frac{1}{\ell}\ [L]\ \{y\} \tag{33}$$

Substituting Eqn. {27},

$$[K]\ \{(\frac{n^2}{2.22\ R^{4/3}})\ V^2\} = S\ \{M\} - \frac{1}{\ell}\ [L]\ \{y\} \tag{34}$$

$$[K]\ \{V^2\} = \frac{2.22\ R^{4/3}}{n^2}\ S\ \{M\} - \frac{2.22\ R^{4/3}}{n^2}\ [L]\ \{y\} \tag{35}$$

A solution for V_1 and V_2 can then be obtained for the above equation after A_1 and A_2 have been found from Eqn. {16}. Equation {31} provides the values of Q_1 and Q_2.

Kinematic Wave Approximation

Application of the KWA reduces the momentum equation (Eqn. {19}) to the form

$$S = S_f \qquad \{36\}$$

Since friction slope is equated with bed slope, the friction slope in a uniform flow equation, such as the Chezy or Manning equation, can be replaced by the bed slope. The following form of the Manning equation can be used to solve for discharge at the nodes.

$$Q = \frac{1.49}{n} R^{2/3} S^{1/2} A \qquad \{37\}$$

Flow quantities are obtained by solving Eqn. {37} with the pertinent input data and values of A obtained from Eqn. {16} for each node in a flow strip.

Evaluation and Testing of the FESHM

Testing the validity of all models is necessary before the user can properly judge the reliability of model results. This procedure takes on the form of model accuracy in terms of proper mathematical description of the various physical processes being represented, and for those models being driven by numerical methods, an evaluation of convergence and stability.

Errors due to the nature of the numerical approach may be inherent in the solution, yet be completely unperceived by the user. These errors may result from a solution which does not converge to an exact solution due to a time increment which is too large and/or a finite element grid which is too coarse. Another area of concern involving the form of the governing differential equations, is the applicability of the kinematic wave approximation, particularly with respect to the modeling of channel flow.

Validity of Model Approach

To determine the validity of the finite element flow routing technique, several model runs were made. Three distinct cases were evaluated.

Case 1: Overland flow example

Data reported by Crawford and Linsley (1966) were used to evaluate the applicability of the KWA to overland flow on turf and concrete surfaces. The results for a turf surface that were obtained with the complete momentum equation and the KWA are given in Figure 5. The approximation by either approach certainly appears satisfactory, although a variable Manning 'n' defined as a function of depth of flow would likely provide a better fit.

The point to note, however, is the similarity of the two computed hydrographs. These indicate that conditions were met for proper application of the KWA, i.e., gravitational and frictional forces were dominant relative to the gradient and acceleration terms. The Froude (F) and kinematic wave (K) numbers at peak flow conditions were 0.05 and 3600, respectively, well within acceptable limits.

The results for a concrete surface are given in Figure 6. The measured and KWA hydrographs show good agreement. Furthermore, the criteria that define the range of applicability of the KWA were F = 1.4 and K = 87, which indicate that, for extreme overland flow conditions (smooth surface and intense rainfall), the criteria were met.

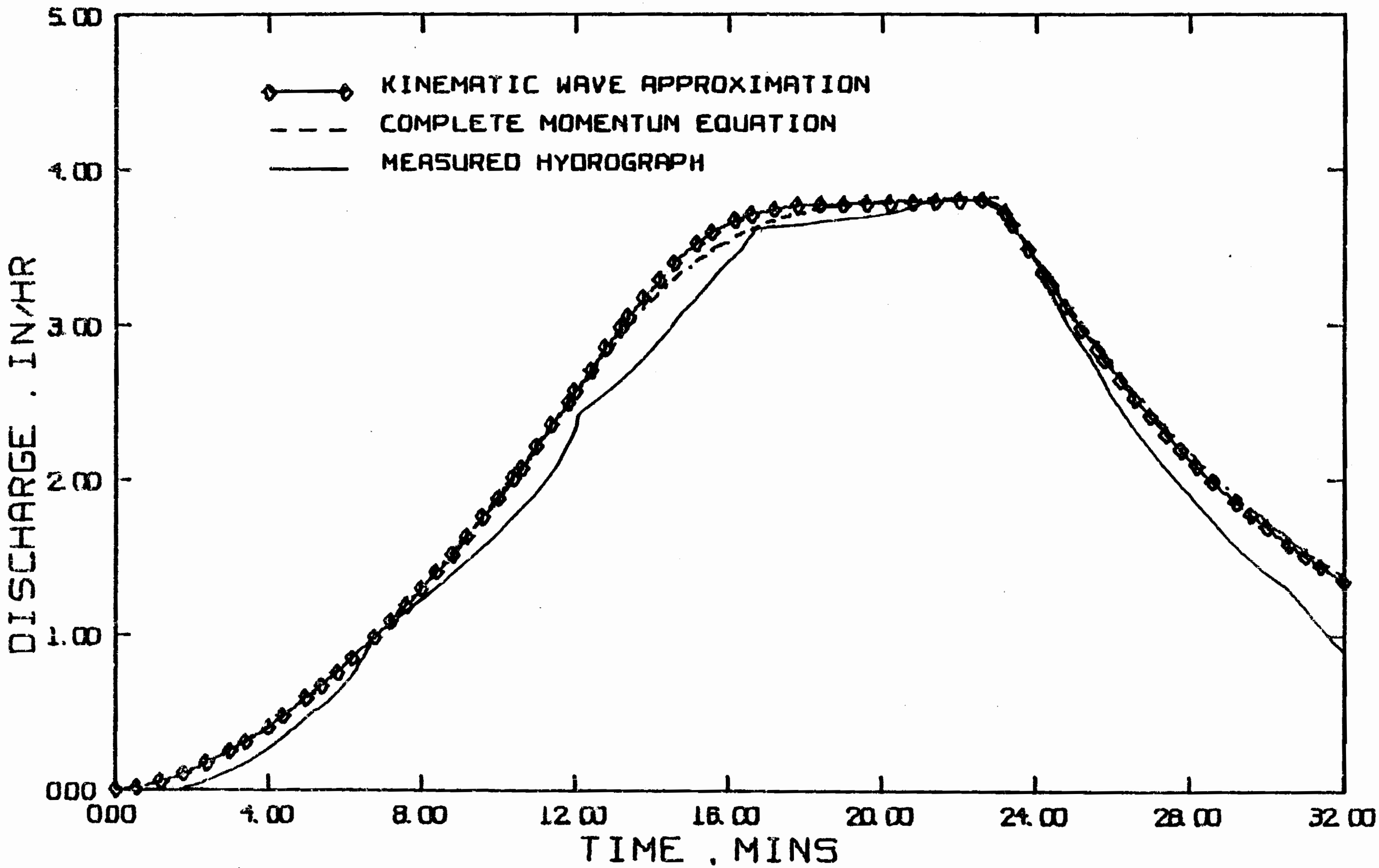


Figure 1. Comparison of simulated and measured flow over a turf surface (length = 72 feet, slope = 0.01, Mannings n = 0.35 and rainfall = 3.81 inches/hour for 23 minutes).

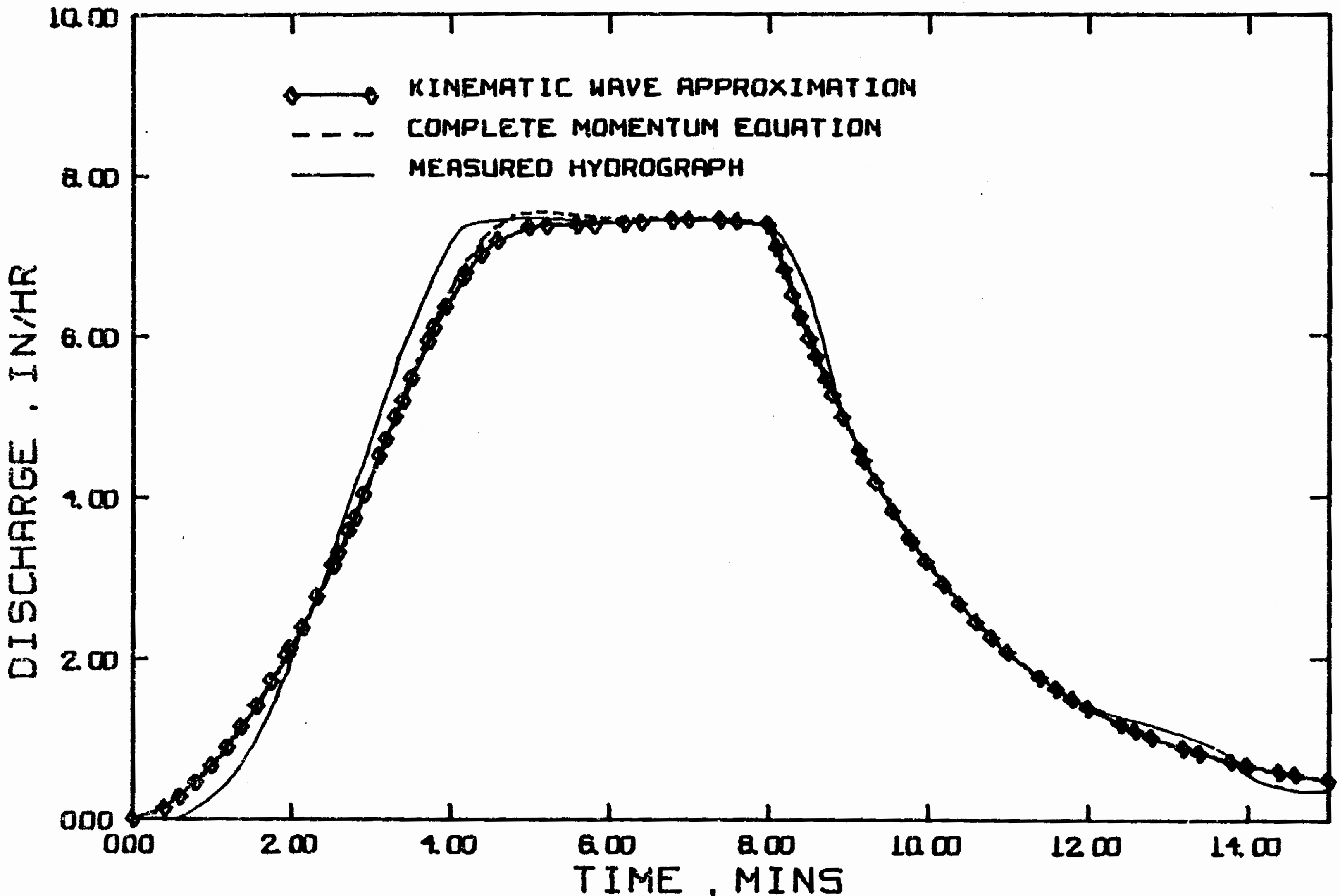


Figure 2. Comparison of simulated and measured flow over a concrete surface (length = 467 feet, slope = 0.02, Manning n = 0.014 and rainfall = 7.44 inches/hour for 8 minutes).

Case 2: River flow example

To further test the validity of the routing technique and the applicability of the KWA to channel routing, data presented by Viessman, et.al. (1972) were used to model a river system.

A 20-foot wide rectangular channel with a bed slope of 0.0015 and Manning roughness coefficient of 0.02 was assumed. Initial flow was assumed to be uniform and at a depth of 6 feet. For the upstream boundary condition the discharge was increased linearly to 2000 cfs for a period of 20 minutes, and for the remaining 40 minutes of simulation, discharge was decreased uniformly until the initial flow conditions were attained. Throughout the routing lateral inflow was zero.

In Figure 7, the results obtained by the finite element model (10 elements and dt = 4 seconds) are compared with the explicit (20 reaches and dt = 2 seconds) and characteristic (20 reaches) solutions obtained by Viessman, et.al. (1972). The finite element and difference solutions are practically identical while the method of characteristics differs slightly.

In order to determine the validity of the KWA under flow conditions such as these, the above data set was used and the results compared with the solutions obtained with the complete momentum equation and the parabolic form of the

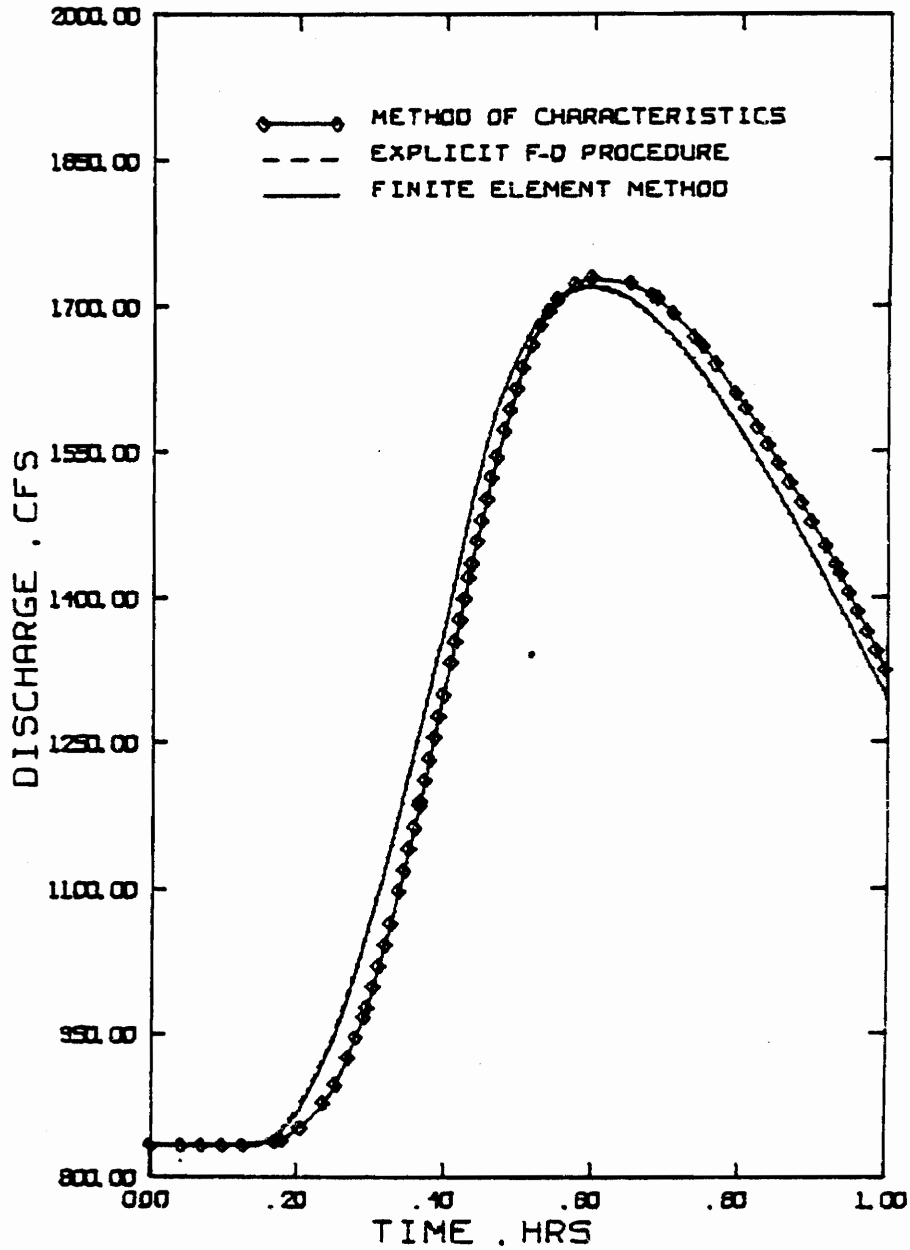


Figure 3. Comparison of hydrographs generated for a river flow example using three numerical solution techniques.

unsteady flow equations (Figure 8). The hydrographs indicate the existence of sizeable errors in the solution by the KWA. The parabolic approach improved the solution considerably, thereby, implying that the terms eliminated from the complete momentum equation (Eqn. (4)) to create the parabolic approximation contribute little individually or collectively for this particular case.

For the peak downstream discharge, F and K were found to be 0.47 and 7, respectively, which indicated that errors should be expected because of the low value of K.

Case 3: Channel flow in small watersheds

Although the method of routing flows on a natural watershed involves the simulation of flow in channels or streams, channel slopes are generally steep enough to allow the application of the KWA for first- or second-order streams. If this assumption is valid for most applications, the computational effort involved in routing can be significantly reduced.

The Crab Creek watershed, Montgomery County, Virginia (see Figure 54) was used to compare hydrographs generated by both the complete momentum equation and the KWA. The input data for this watershed can be found in Tables A10-A12. Figures 9 and 10 show the results of the routing of flows

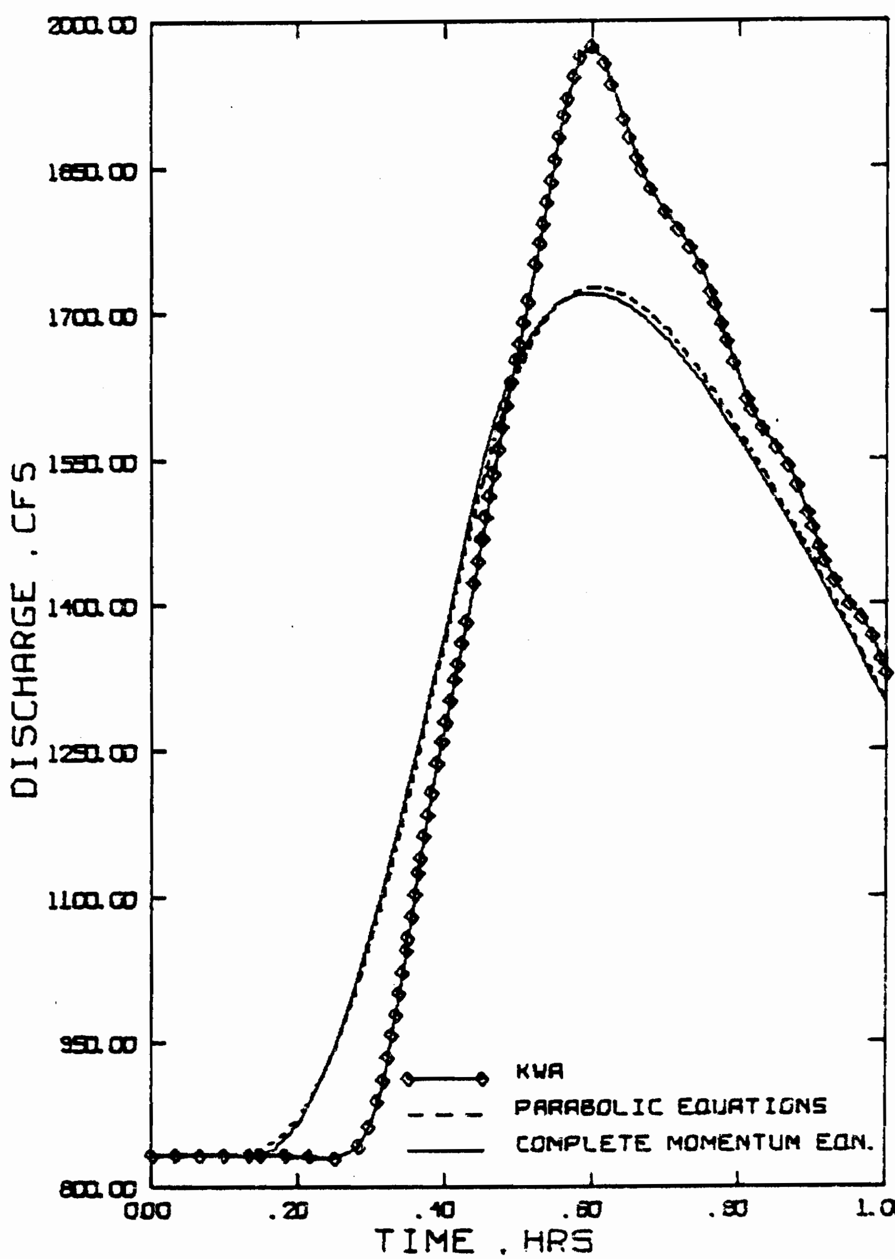


Figure 4. Comparison of hydrographs generated for the river flow example given in Figure 7 with the complete momentum solution, KWA and parabolic approximation.

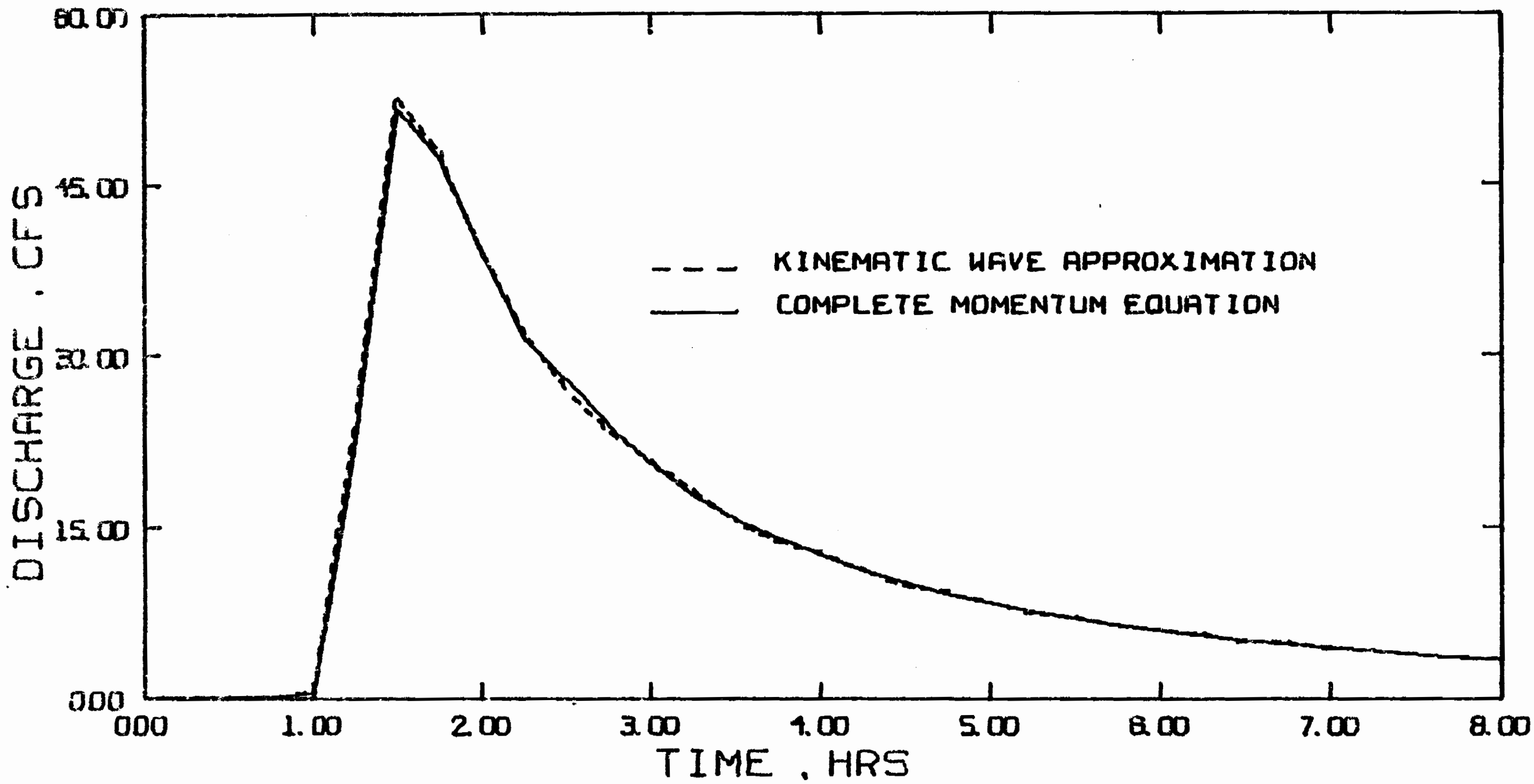


Figure 5. Comparison of channel hydrographs generated for subshed No. 1 of Crab Creek watershed (see Figure 54) using the full momentum solution and the KWA.

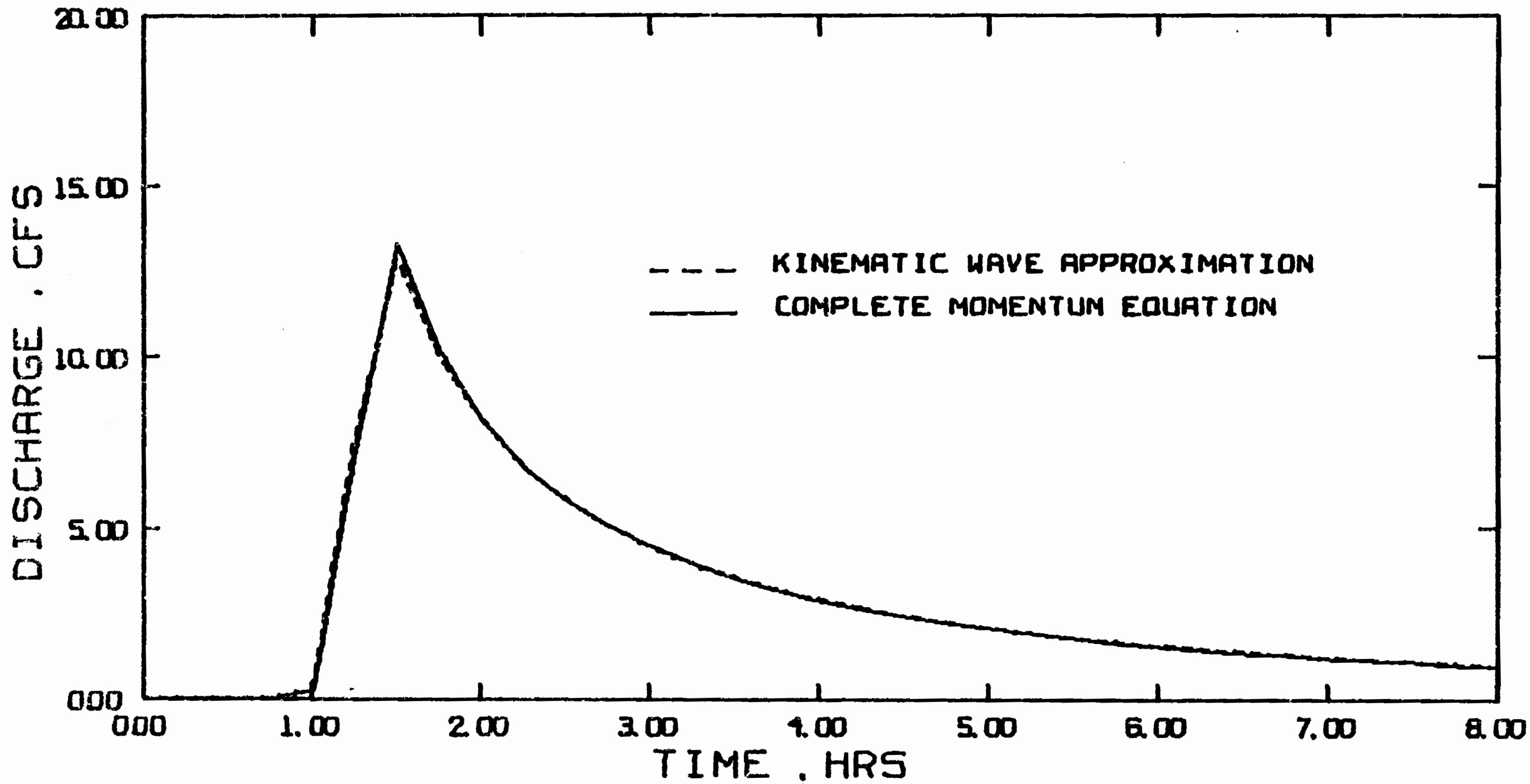


Figure 6. Comparison of channel hydrographs generated for subshed No. 2 of Crab Creek watershed (see Figure 54) using the full momentum solution and the KWA.

under both the KWA and the complete momentum equation, for the channels in subsheds 1 and 2 of Crab Creek watershed, respectively. The peak KWA flows for both examples differed from the complete momentum solutions by 1.9% and 3.2%, respectively. Solution of the Froude and kinematic wave numbers using the total length and average slope of each channel, gave values of F = .59 and K = 374 for the channel in subshed 1 and F = .56 and K = 300 for the channel in subshed 2.

These two subsheds were typical of the majority of the subsheds which appear in Chapter V. The channel slopes in the two examples were among the mildest which were encountered.

Effect of Time Increment on Solution Convergence

Two time integration procedures have been available for use with fixed grid models in the past. These are the explicit and implicit procedures which may take on many forms of varying complexity. A discussion of these two methods and their application to the unsteady flow equations is presented by Liggett and Cunge (1977).

Although the finite element numerical procedure may result in an unconditionally stable solution, the time dependent solutions obtained by an explicit procedure (Eqn.

(16)) may result in an unstable solution. Truncation errors involve a small perturbation of the exact solution which grows, most often exponentially, with time. It becomes obvious, therefore, that the proper selection of the time increment for the numerical solution represents the difference between an accurate or erroneous solution. Proper selection of this parameter to avoid time-consuming convergence testing is no simple task.

Use of the fully explicit procedure as shown in the derivation of the unsteady finite element equations, has been accused by many as being inefficient (e.g., Liggett and Cunge (1977)) and unsuitable for user-type or industrial programs. This is true in view of the fact that time intervals may become excessively small resulting in large computation times.

Implicit time schemes are unconditionally stable and may utilize a larger, and more efficient time increment. The implicit procedure, however, requires an additional boundary condition over the explicit method due to the introduction of an additional term or terms, evaluated at time, t+dt, in the finite element equation. These values are generally obtained from a known downstream hydrograph. This characteristic of implicit time integration schemes presents an immediate problem when a model is desired which will simulate floods on ungaged watersheds. The explicit method has the advantage of being able to solve for the solution "directly" in time. Moreover, use of the explicit method in the model being discussed is not as obvious a handicap when one considers that the time integration need only to be applied to the continuity equation (Eqn. {3}) when the KWA is valid.

Another aspect of the KWA which lessens the inefficiency of using an explicit time integration scheme is better understood by examining a criterion that provides a guide for the selection of the time increment 'dt'. This criterion is referred to as the Courant condition and can be written as

$$dt \leq \frac{dx}{C} \tag{38}$$

where C is the wave speed.

If the complete momentum equation is used, the dynamic wave speed, C_d, applies where

$$C_d = V \pm \sqrt{g\,y} \tag{39}$$

Application of the KWA requires that the dynamic wave speed, C_d, be replaced by the kinematic wave speed, C_k. The value of this parameter, however differs depending upon the resistance equation used.

If the resistance equation is expressed in terms of

$$q = a\,y^m \tag{40}$$

where q is discharge per unit width of the channel, then, for the Manning equation,

$$a = \frac{1.49}{n} S^{1/2}$$

and

$$m = 5/3$$

The kinematic wave speed is given (Henderson (1966)) as

$$C_k = \frac{dq}{dy} = m\,a\,y^{m-1} = m\,V \tag{41}$$

since

$$V = \frac{q}{y} = a\,y^{m-1} \tag{42}$$

Therefore,

$$C_k = 5/3\ V \tag{43}$$

Slightly different results will be obtained when the Chezy resistance equation is applied.

The primary advantage of the above concept is that C_k is always less than C_d provided that conditions are met for the application of the KWA. Thus, when Froude numbers fall below the specified criterion and the KWA can be applied, the insertion of C_k into Eqn. {38} allows the use of a larger time increment.

These criteria are best illustrated by a mathematical example. Consider a flow case with a depth of flow of 2 feet, velocity of 1.5 feet per second, length of flow plane of 100 feet and a slope of 0.05. Solving for F and K gives 0.187 and 71.6, respectively. The KWA, therefore, can be assumed to apply. By Eqn. {43}, C_k = 2.5 and by Eqn. {39}, C_d = 9.52 and the corresponding maximum values of 'dt' for the KWA and dynamic wave approximations were obtained from Eqn. {38} as 40 and 10.5 seconds, respectively. This difference will obviously result in appreciable savings of time and money. The smaller the Froude number, the greater the variance between the computed dynamic and kinematic wave speeds.

Another time increment criterion that must be met to insure stability in the solution when routing flows by the complete momentum equation is the effect of the friction term (S_f). The stablilty of the explicit numerical solution is controlled by the following condition:

$$dt \leq \frac{2.22\ R^{4/3}}{g\ n^2\ |V|} \tag{44}$$

Satisfying this condition on small watersheds may require excessively small time increments because of the small magnitude of the hydraulic radius relative to the flow velocity. This condition exists because channel slopes are generally steeper on small watersheds. This relationship is obvious from the definition of velocity by the Manning equation (Eqn. {37}). The lesser value of 'dt' obtained by the Courant condition (Eqn. {38}) and the friction criterion (Eqn. {44}) must be selected to assure stability when the complete momentum equation is used.

The above criterion illustrates another obvious advantage for the use of the KWA in small watershed flood routing when applicable. The Courant condition is the only time increment criterion that must be satisfied in the application of the KWA.

The differences in computational efficiency are illustrated in Figure 11 where the 5-element concrete surface is shown with the complete momentum and KWA solutions both at dt = 5 seconds compared to the KWA solution at dt = 1 second. Slightly greater divergence is noticeable in the solution by the complete momentum equation at dt = 5 seconds. This situation occurs even though the Froude number for this flow example is approaching the KWA criterion of F = 2.

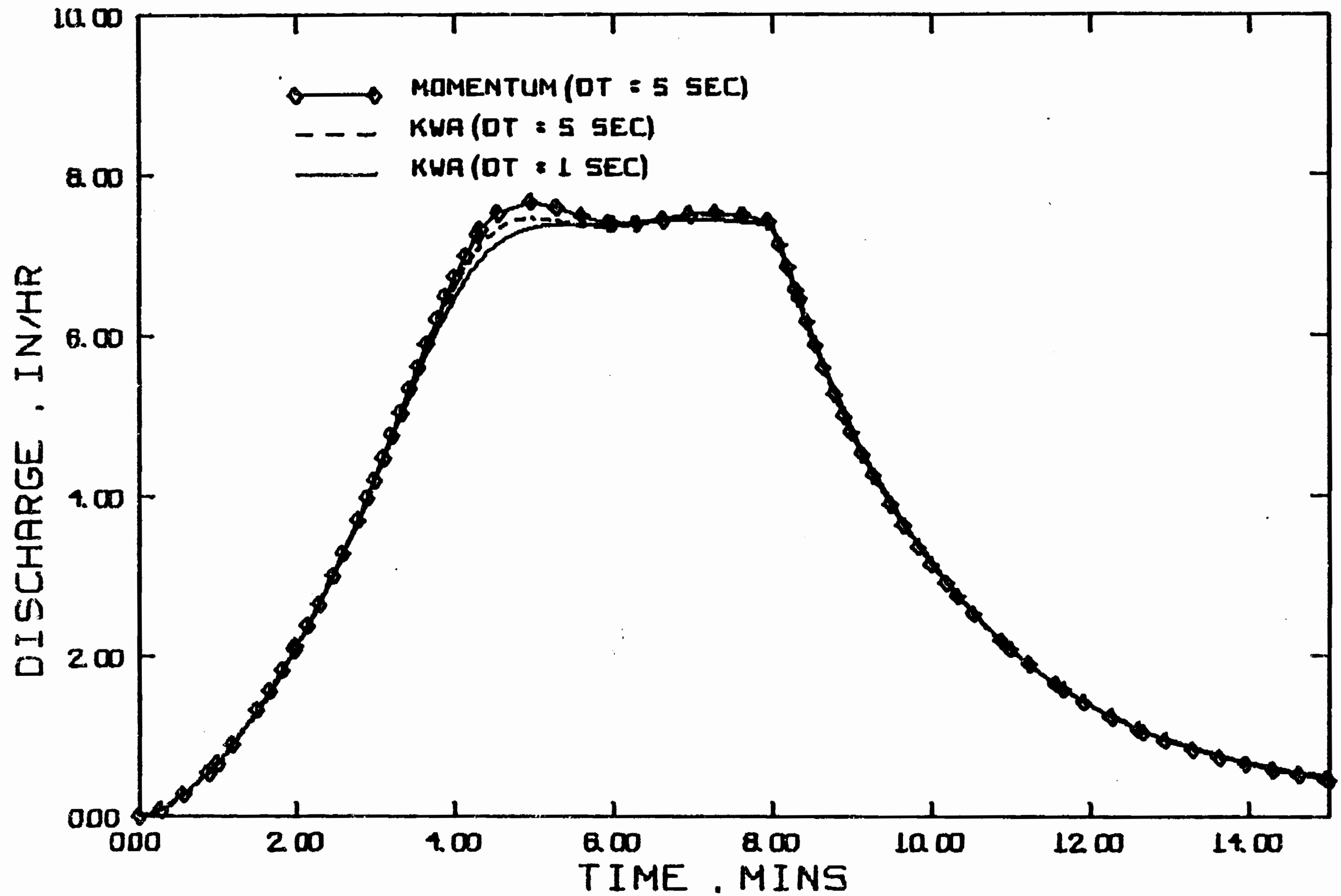


Figure 11. Comparison of time increments needed for a stable solution by the full momentum equation and KWA for a flow situation where the KWA is valid.

Other flow cases involving smaller values of F should result in even greater disparities.

The selection of the correct value of 'dt' is not a straightforward decision. The best choice at any point in time would be that value which is equal to, or slightly less than, the travel time of flow from one element node to the next during that time step. Achieving this, however, is impractical since each element in a flow strip would require a unique 'dt' because of the different flow properties in each which result in different velocities. Furthermore, each element's unique 'dt' would vary as flow properties change during the course of the computations. One danger in computing a new 'dt' as the solution progresses is that, if too large, errors will result from sudden changes in flow patterns where the linear approximation during a large time step is no longer valid.

With these factors considered, it is obvious that small length intervals, such as those encountered on small watersheds, will require small values of 'dt' in order to ensure a stable solution. It is logical, however, that small values of V will enable a longer time increment to be used. This is the case which exists in the overland flow phase of the model. Depth and velocity of flow over the idealized overland flow planes are very small relative to those encountered in the channel, even during extreme flood events. Therefore, the selection of a large time increment for overland flow in conjunction with the smaller time increment selected for channel flow increases the overall efficiency of the numerical procedure.

The best approach appears to be that of assuming a probable maximum velocity of flow for any given element node in a strip and using that value in conjunction with the lengths of the shortest overland flow and channel flow elements to assign a 'dt' to the entire flow strip. This could be done to the extent that the channel and each overland flow strip in a given subshed are routed using different time increments. This finesse is not warranted, however, since flow characteristics will generally not vary enough from one overland flow plane to another in a given watershed.

The approach taken was to select a time increment which is small enough to satisfy the extreme overland flow plane case. Another much smaller time increment must then be chosen for use in channel routing using the same principle. This concept can be extended to the remaining subsheds in the overall watershed. Although variations in other overland flow planes and channels may result in a higher, more efficient, time increment, the procedure that was taken was to use the minimum time increment necessary for a given overland flow strip or channel amd these values were used for routing flows through all overland flow strips and channels, respectively. This greatly simplified the synchronization of the flow routing through the system and minimized errors coordinating the timing of inflows to channels and boundary conditions for downstream channels.

The problem remaining was developing a method by which these time increments may be reliably determined for a given watershed prior to model execution. The selection of the probable maximum velocity for overland and channel flow was done purely from prior experience with this model. More detail will be given about the actual choice of these values in Chapter IV.

An important aspect of the Courant condition is that the maximum allowable value of 'dt', obtained from Eqn. (38), may not give an acceptable convergent solution. For example, Viessman, et.al. (1972) state that for the full explicit scheme, the best results are obtained with a time increment that is approximately 20% of that defined by the Courant condition (Eqn. (38)). This criterion was found to be applicable to the finite element method since the procedures for introducing time integration were identical to the fully explicit method for finite difference techniques.

The use of the Courant condition (Eqn. (38)) to define the value of 'dt' prior to model execution is illustrated with the data for the concrete surface given in Figure 6. The computed velocity at peak discharge for the solution with dt = 1 second was assumed to approach the convergent velocity. The velocity was substituted into Eqn. {43} to define the kinematic wave speed. This value along with dx = 93.4 feet was substituted into Eqn. {38} to give a maximum allowable value for 'dt' of 30.35 seconds. The various hydrographs shown in Figure 12 indicate that considerable error is introduced into the solution at dt = 10 seconds and higher (peak discharge is 6.25% higher than that given by the convergent solution for the former and the latter is completely unstable). The variance in peak discharge for the hydrograph with dt = 5 seconds is 1.52%, thereby indicating that the 20% criterion is, in all probability, necessary for valid hydrograph simulation using the explicit time integration approach.

The effect, however, of a change in time increment on the predicted hydrograph is clearly evident in Figure 12. While the above criterion will lead to a dampening of this influence, it is impossible to predict this effect short of a comparison of runs made with various time increments. Brakensiek (1966) has stated, however, that the non-prismatic nature of natural channels tends to lessen the influence of the time increment size on the resultant hydrograph.

Any value selected by a velocity criterion should not be construed as an absolute maximum quantity in the event that extreme cases are encountered. Therefore, the model con-

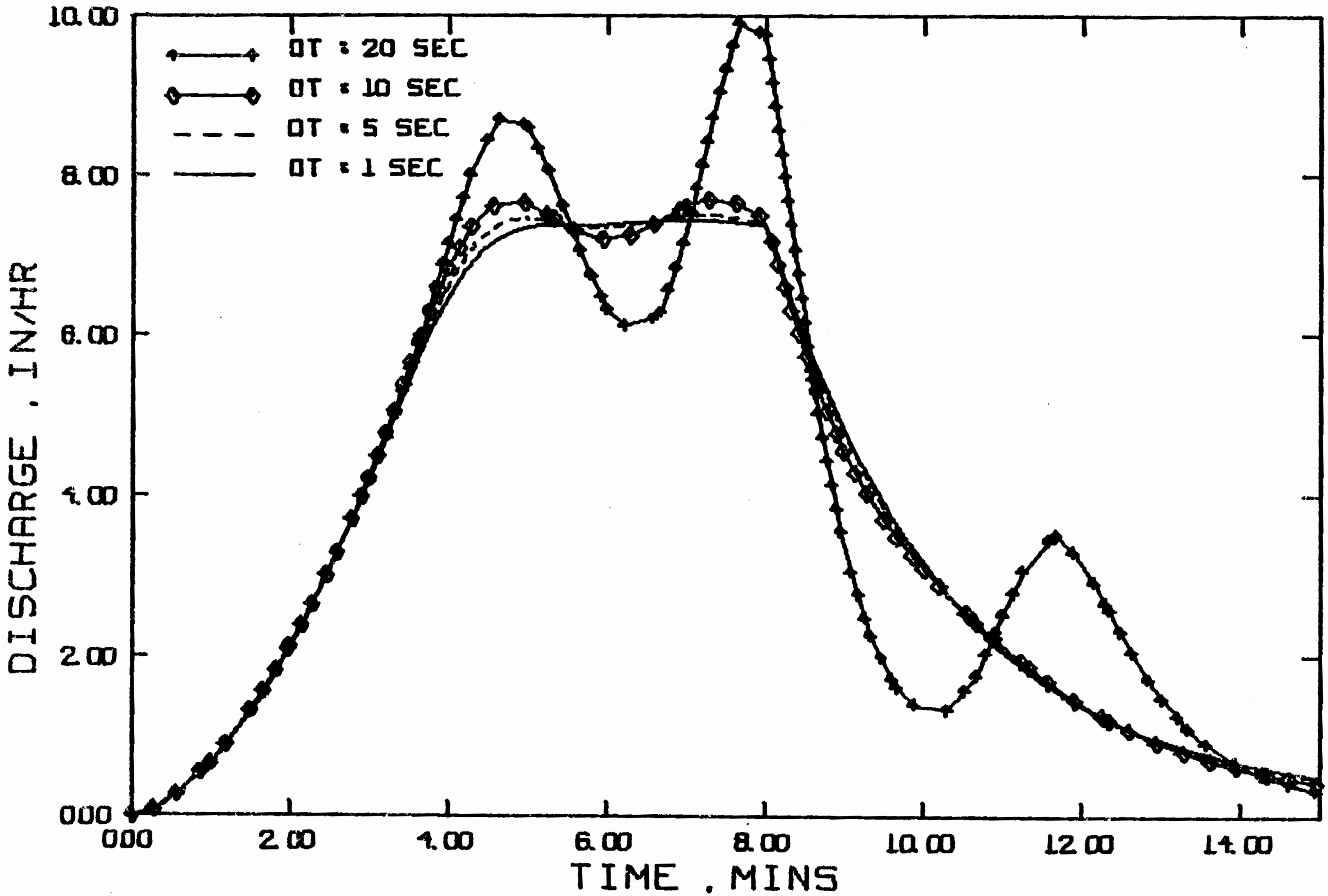


Figure 12. Effect of computation time increment on convergence and stability for a concrete surface.

tains a check to signal the operator when velocities at any given time exceed the prescribed limits set to assure stability. When this occurs the assignment of 'dt' values in the model must be reevaluated.

Effect of Finite Element Mesh on Solution Convergence

The finite element mesh may also affect the convergence of a solution. In some cases a coarse grid will result in a non-convergent solution which will not be improved by using a smaller time increment.

This can be a significant problem when the structuring of the finite element grid results in one or more overland flow strips consisting of a single element. The nature of the discretization generally provides an adequate number of elements in the channel flow regime, however, there may be cases where a channel flow strip also will consist of one element. The problem that arises is determining the minimum number of elements needed in a flow strip to provide a convergent solution.

This problem is illustrated in Figure 13 where the turf surface has been analyzed with different numbers of elements in the flow plane. To maintain similarity of solutions, the ratio, dx/dt, was held constant for each case. It is obvious from the hydrographs that a convergent solution is being

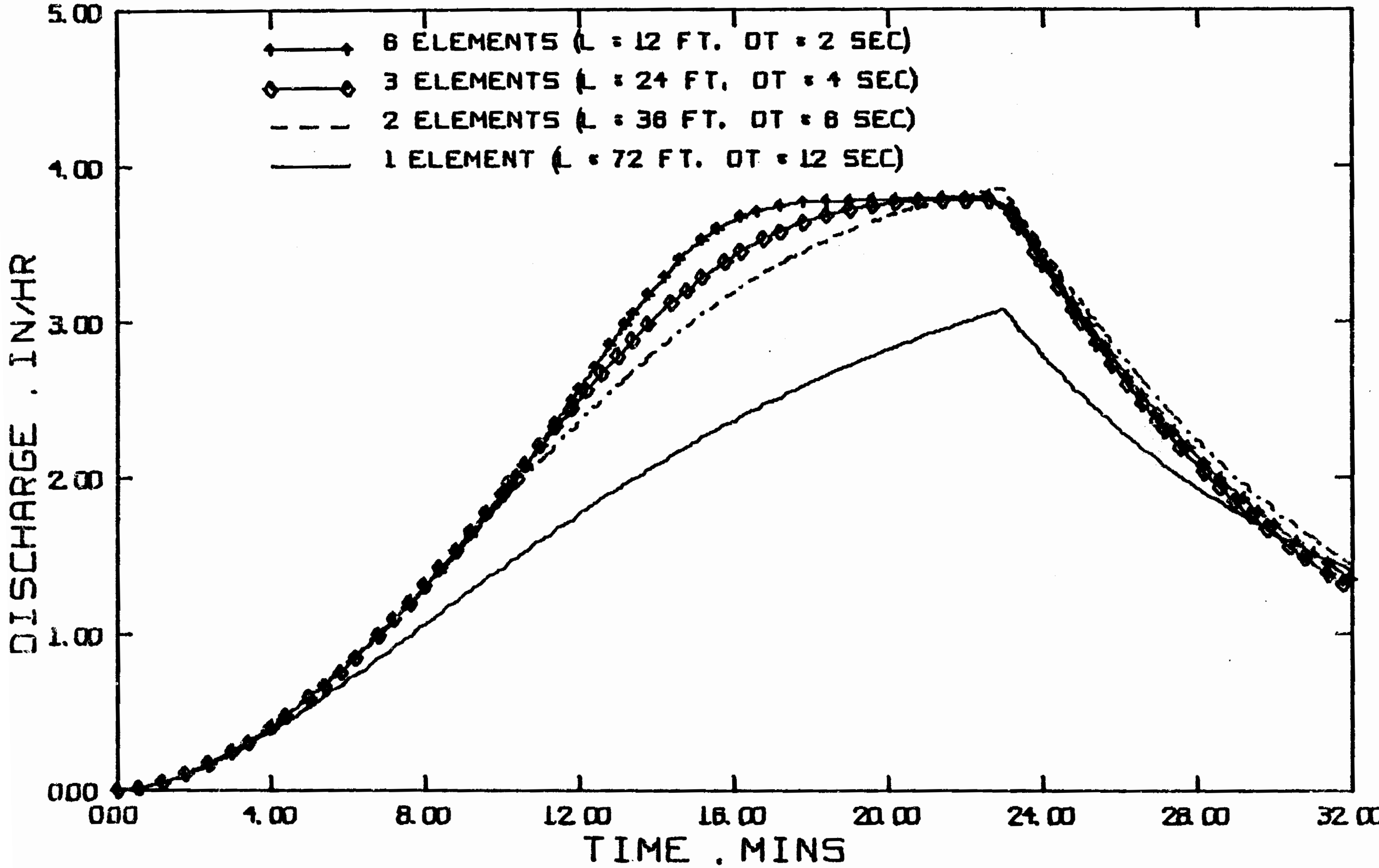


Figure 13. Effect of the finite element grid structure on convergence for a turf surface.

attained as the number of elements is increased.

Assuming that a convergent solution can not be obtained with a minimum of one or two elements, there are two approaches which may be taken. One of these is the internal generation of additional elements within the elements present in the prescribed grid. The immediate drawback to this procedure is the necessity of shortening the time increment to accommodate the reduced element lengths. Additional programming complexity is involved in the assignment of properties to the elements in the newly created finite element mesh, i.e., data preparation is magnified.

An alternative approach without increasing the number of computational steps involves a reformulation of the finite element continuity equation to accommodate a higher-order polynomial in the interpolation function. This approach will result in the use of quadratic or cubic one-dimensional elements in the solution.

This latter approach was selected as the most efficient method for reaching the desired goal since the same number of algebraic equations results for the assemblage from both discretization procedures, i.e., the same number of algebraic equations must be solved in a flow strip consisting of, for example, three linear elements or one cubic element. Some efficiency is lost, however, in the solution by higher-order polynomials since the matrix band width in the assemblage is increased.

The interpolation functions for the quadratic and cubic approximations, along with the linear approximation, are given in Figure 14. The derivations of the matrix terms in Eqn. (16) are performed in the same manner as that of obtaining the matrix values for the linear approximation. These derivations are straightforward, however, the illustration of steps involved is lengthy and will not be presented.

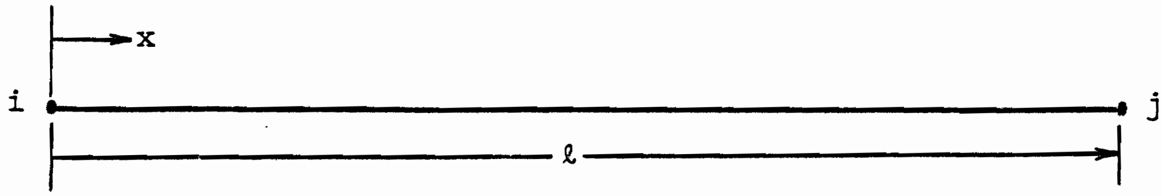
Referring to Eqn. (16), the matrices obtained for the quadratic finite element continuity equation are

$$[K] = \frac{1}{30}\begin{bmatrix} 4 & 2 & -1 \\ 2 & 16 & 2 \\ -1 & 2 & 4 \end{bmatrix}$$

$$[L] = \frac{1}{6}\begin{bmatrix} -3 & 4 & -1 \\ -4 & 0 & 4 \\ 1 & -4 & 3 \end{bmatrix}$$

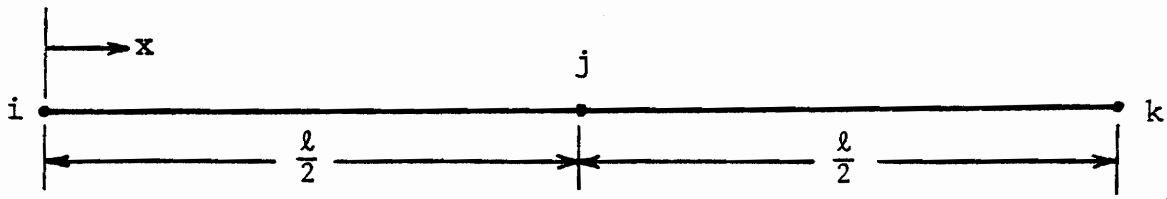
$$\{M\} = \frac{1}{6}\begin{Bmatrix} 1 \\ 4 \\ 1 \end{Bmatrix}$$

$$\{\dot{A}\} = \begin{Bmatrix} \dot{A}_1 \\ \dot{A}_2 \\ \dot{A}_3 \end{Bmatrix}$$



$$N_i = 1 - \frac{x}{\ell} \qquad N_j = \frac{x}{\ell}$$

(a) Linear interpolation functions

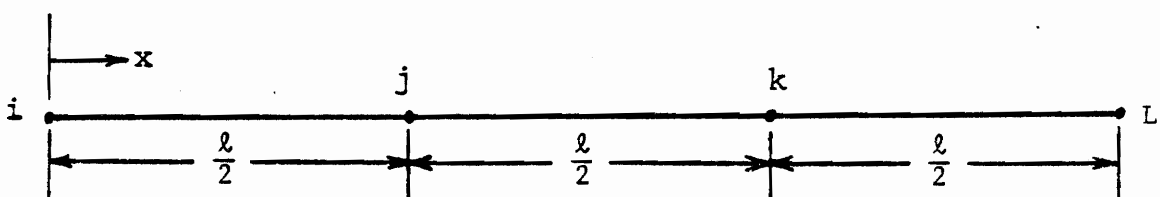


$$N_i = (1 - \frac{2x}{\ell})\ (1 - \frac{x}{\ell})$$

$$N_j = \frac{4x}{\ell}\ (1 - \frac{x}{\ell})$$

$$N_k = \frac{x}{\ell}\ (1 - \frac{2x}{\ell})$$

(b) Quadratic interpolation functions



$$N_i = (1 - \frac{3x}{\ell})\ (1 - \frac{3x}{2\ell})\ (1 - \frac{x}{\ell}) \qquad N_j = \frac{9x}{\ell}\ (1 - \frac{3x}{2\ell})\ (1 - \frac{x}{\ell})$$

$$N_k = -\frac{9x}{2\ell}\ (1 - \frac{3x}{\ell})\ (1 - \frac{x}{\ell}) \qquad N_L = \frac{x}{\ell}\ (1 - \frac{3x}{\ell})\ (1 - \frac{3x}{2\ell})$$

(c) Cubic interpolation functions

Figure 14. Linear, quadratic and cubic interpolation functions for one-dimensional elements.

$$\{Q\} = \begin{Bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{Bmatrix}$$

and those obtained for a cubic approximation are

$$[K] = \frac{1}{1680}\begin{bmatrix} 128 & 99 & -36 & 19 \\ 99 & 648 & -81 & -36 \\ -36 & -81 & 648 & 99 \\ 19 & -36 & 99 & 128 \end{bmatrix}$$

$$[L] = \frac{1}{240}\begin{bmatrix} -120 & 171 & -72 & 21 \\ -171 & 0 & 243 & -72 \\ 72 & -243 & 0 & 171 \\ -21 & 72 & -171 & 120 \end{bmatrix}$$

$$\{M\} = \frac{1}{8}\begin{Bmatrix} 1 \\ 3 \\ 3 \\ 1 \end{Bmatrix}$$

$$\{\dot{A}\} = \begin{Bmatrix} \dot{A}_1 \\ \dot{A}_2 \\ \dot{A}_3 \\ \dot{A}_4 \end{Bmatrix}$$

$$\{Q\} = \begin{Bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \end{Bmatrix}$$

Both the quadratic and cubic approximations were applied to the turf surface and the results are compared in Figure 15 with the linear approximation. It can easily be seen that the quadratic and cubic solutions approximate the corresponding 2- and 3-element linear solutions.

The effect of higher-order interpolation functions on the total response of a natural watershed was examined by using the Pony Mountain Branch watershed, Culpepper County, Virginia. This watershed is described in detail in Chapter V. The discretization of the watershed (see Figure 47) resulted in one element per overland flow strip.

The linear, quadratic and cubic approximations were applied to all overland flow strips and the downstream hydrograph computed and plotted in Figure 16. These results reveal a converging solution as higher-order elements are used.

The above higher-order approximations were only applied to overland flow computations. This same application of

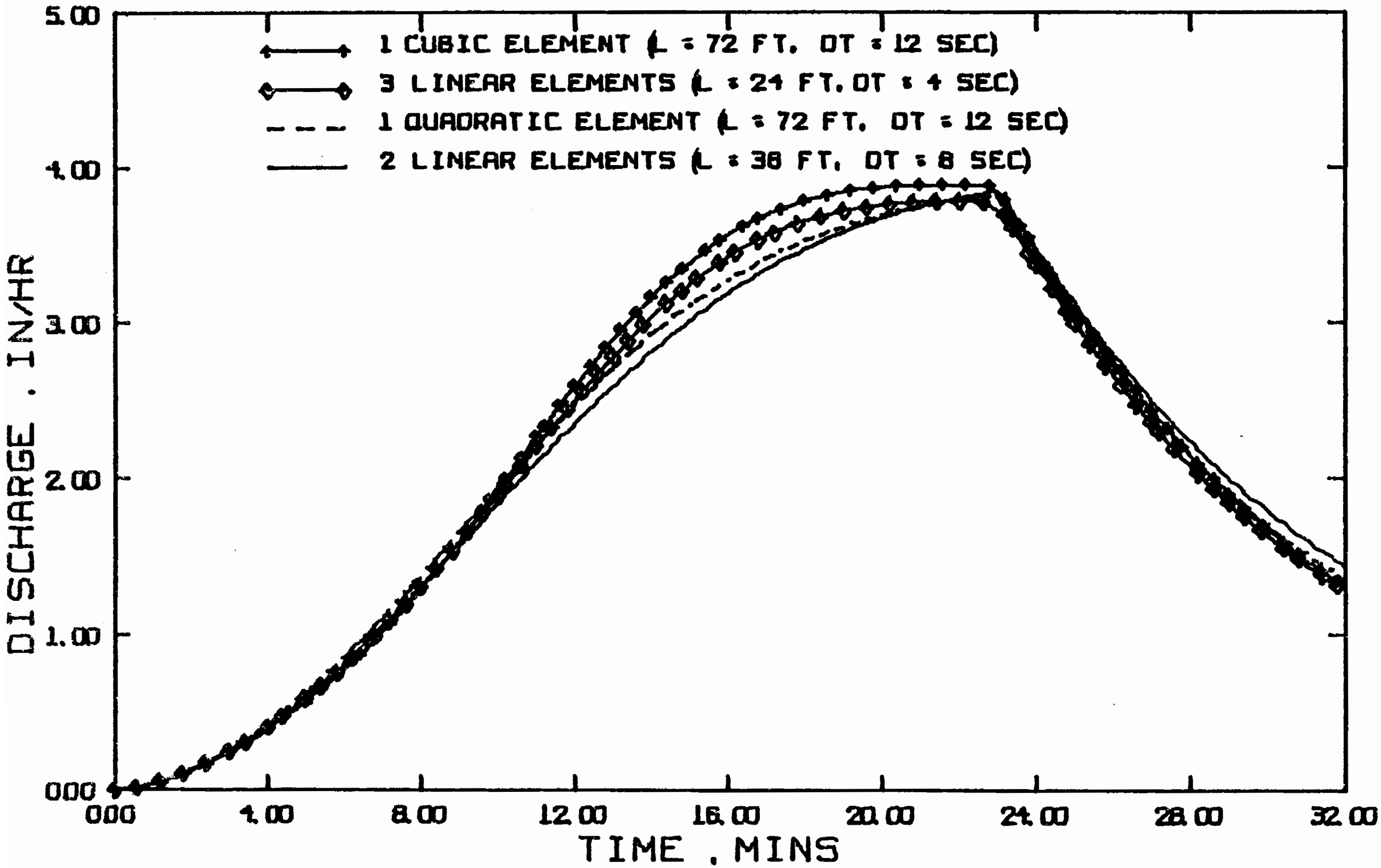


Figure 15. Comparison of solutions obtained by linear elements and by quadratic and cubic elements for a turf surface.

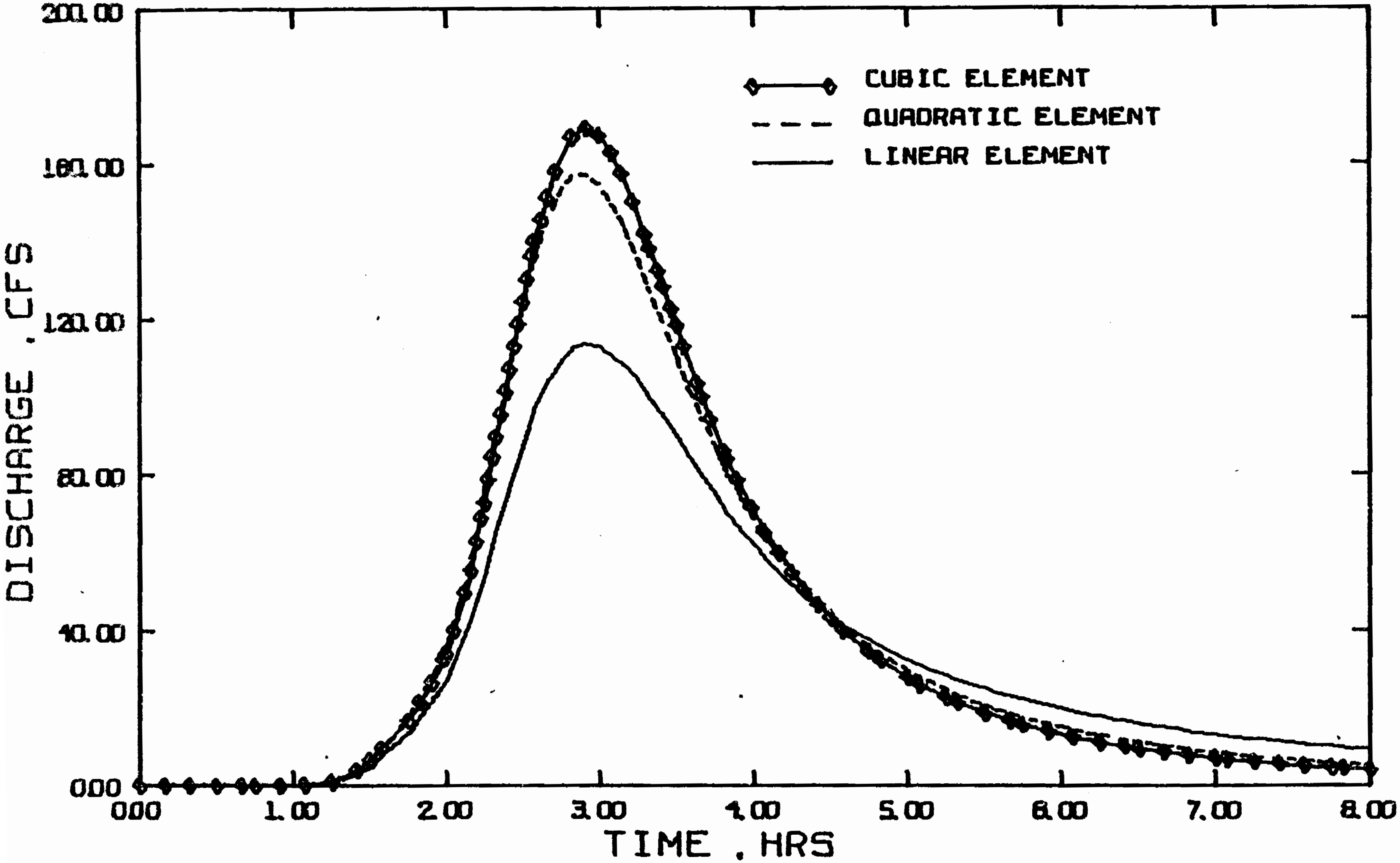


Figure 16. Effect of using higher-order interpolation functions for overland flow elements on convergence, Pony Mountain Branch watershed (Figure 47).

higher-order interpolation functions was extended to include channel flow routing to determine to what extent this additional finesse will improve flow computations. Since all of the subsheds in the Pony Mountain Branch watershed consist of two or more channel elements, with the exception of subshed No. 3, the quadratic approximation was applied only to this subshed. This action was based on the earlier conclusion that a 2-element linear solution will approximate that of a 1-element quadratic solution.

The effects of the two approximations on both subshed No. 3 and the downstream hydrograph are compared in Figure 17. The cubic approximation was retained for the overland flow computations. Improvement in the solution was minimal as it resulted in an increased peak of only 0.9% for subshed No. 3 and a decreased peak of 0.2% for the total watershed.

The magnitude of these improvements for the channel element were less than anticipated because of the improvements which were noted in the above overland flow computations with higher-order elements. Since the mathematical formulation procedure for both overland and channel flow computations is identical, the relative magnitude of the respective velocities is possibly responsible for this inequality.

To evaluate this premise, the turf surface was used (Figure 5). The test procedure was to simply alter flow plane characteristics to create a sequence of higher veloci-

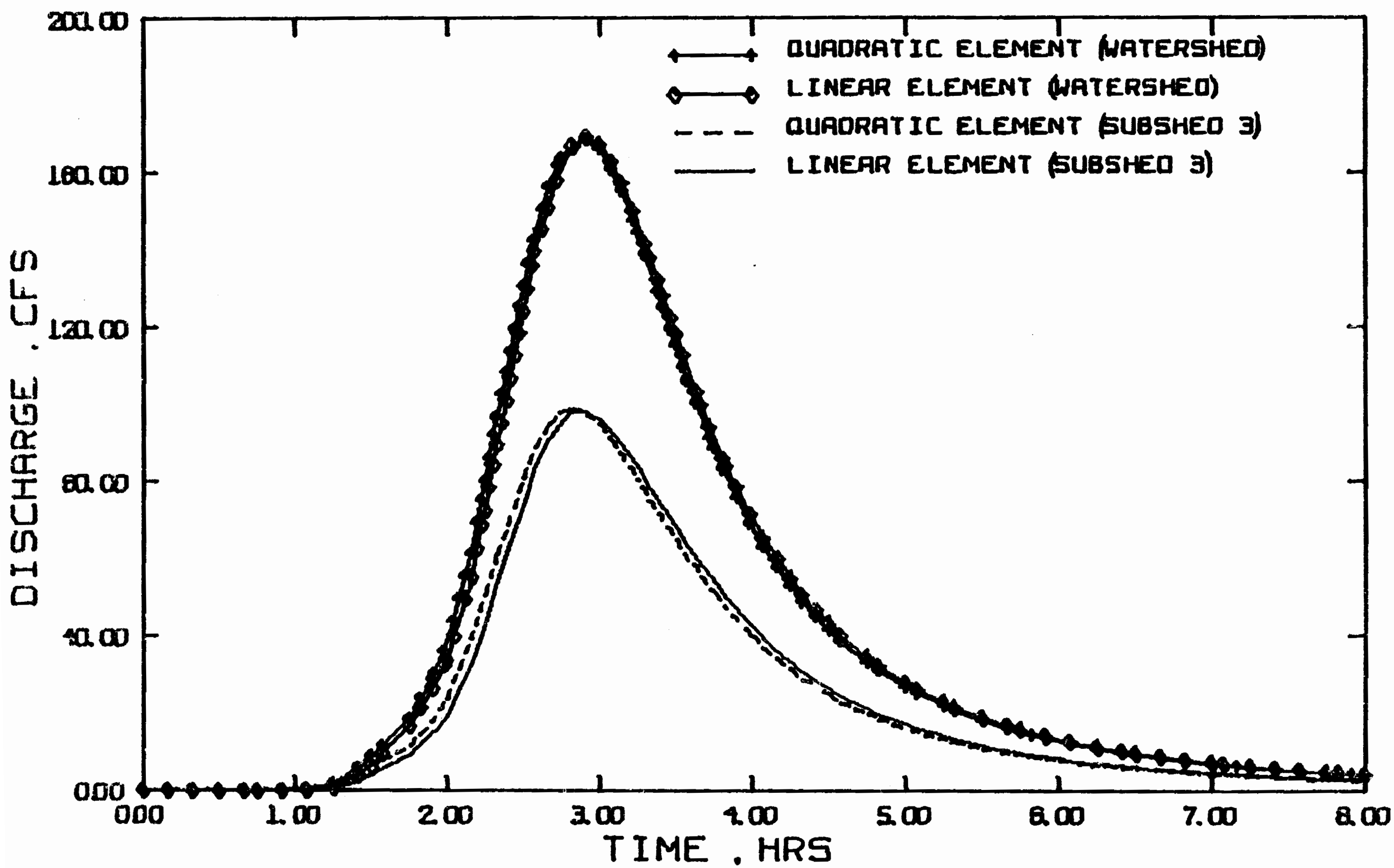


Figure 17. Effect of using a quadratic interpolation function for the channel flow element in subshed No. 3 of Pony Mountain Branch watershed (Figure 47).

ties. This was accomplished by setting the Manning roughness coefficients to 0.175 and 0.035 from the original Manning roughness coefficient of 0.350. This had the resultant effect of increasing the original velocity by factors of 2 and 10 for a given cross-sectional area of flow.

The results of these analyses show that as velocity increases, the magnitude of the error between the linear and higher-order approximations decreases. This is shown in Figure 18 where, for the three velocities, the difference between the linear and quadratic approximations is decreasing as velocity increases. Increasing the velocity from the original flow conditions reduces the error between the compared curves by 17.5% and 67.5%. To compute volume error to peak for the cases of Manning 'n' = 0.35 and 0.175 the hydrographs were extrapolated out to the point where it was estimated that they would attain the constant rainfall intensity rate. This was considered permissible since a continuing period of constant rainfall intensity would have allowed the hydrograph to reach this level.

Based upon the above conclusions, it was decided to design the model to apply the cubic approximation to all overland flow surfaces. Furthermore, for channel flow, the linear approximation was assumed when a channel consisted of two or more elements. For those in which one element existed, the quadratic approximation was utilized. Even

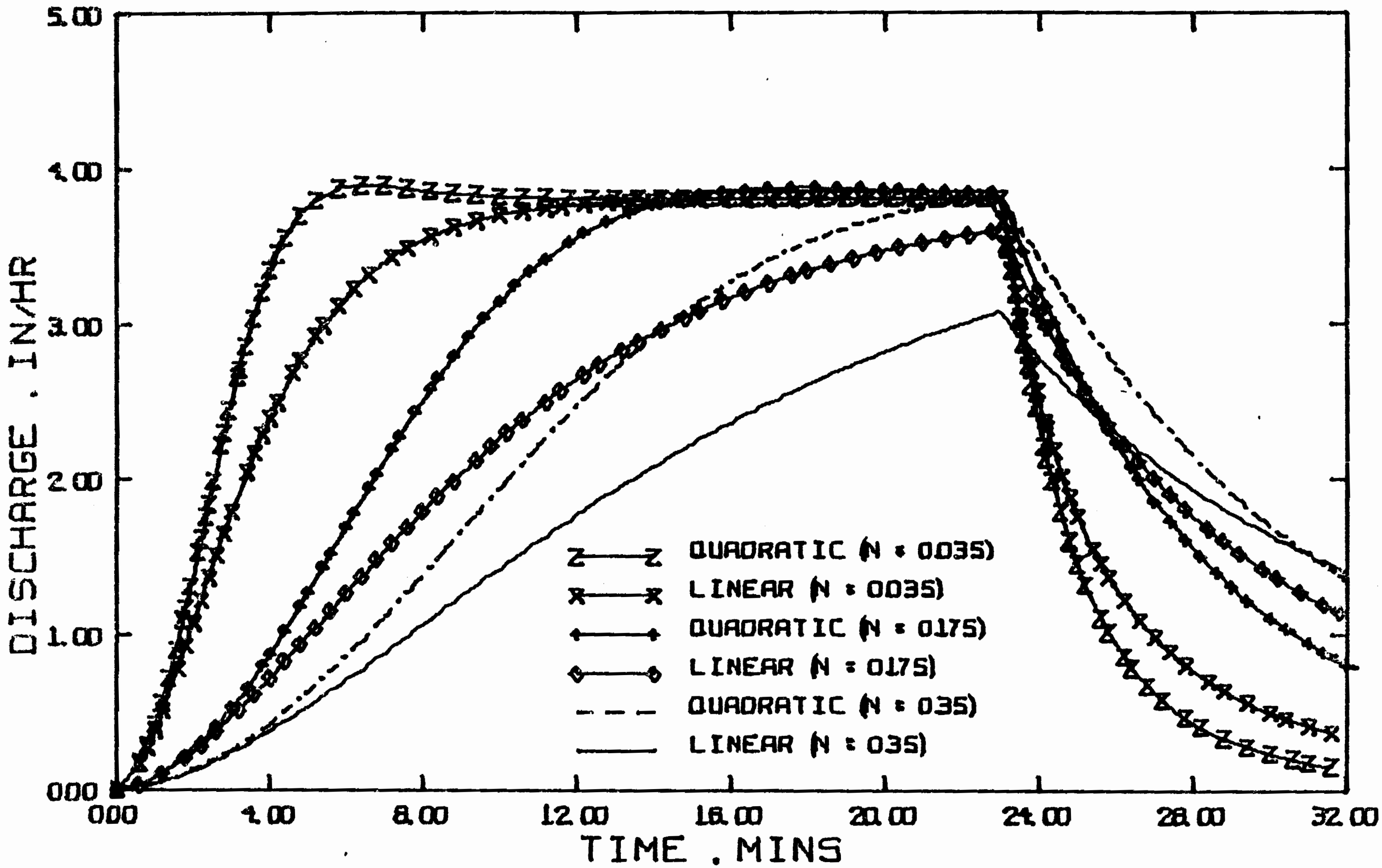


Figure 18. Effect of an increase in flow velocity on the error between solutions obtained by linear and quadratic interpolation functions for a turf surface.

though channel flow velocities are on the order of ten times overland flow velocities, this procedure was adopted to assure reliability in the results. Additional computational effort is negligible.

Another aspect of the finite element grid which was investigated was the potential effect that different element lengths in a flow strip may have on the resultant solution in contrast to that obtained with the use of equal-length elements. This is important since the element grid is designed to represent the physical characteristics of a natural drainage system and line elements with greatly differing length characteristics may result. One of the primary advantages of the finite element method is its ability to handle various element shapes and sizes and to accommodate complex geometry and element properties without appreciably affecting the accuracy of the solution.

The effect of different line element length ratios is illustrated in Figure 19. For this example, the turf surface (Figure 5) was discretized into 2 elements and discharge hydrographs generated with several possible element length configurations. The results indicate that variations are minimal and the finite element method is suited to this type of discretization.

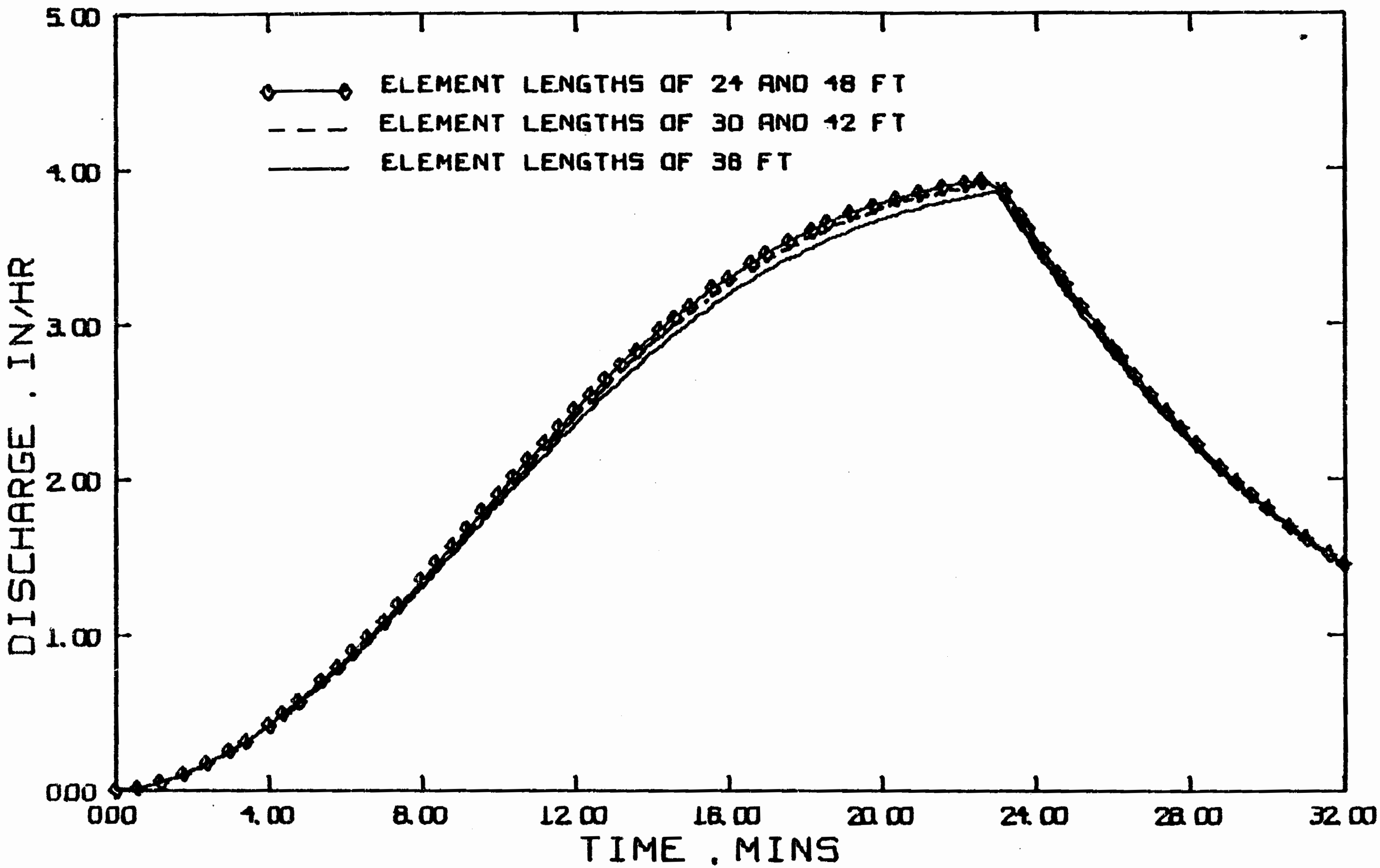


Figure 19. Effect of varying element lengths on the 2-element solution obtained for a turf surface.

CHAPTER IV

THE COMPUTER PROGRAM:

DATA IDENTIFICATION AND PREPARATION

This chapter contains a detailed description of the model for user implementation. Primary emphasis is placed on the I/O data aspects of the FESHM. Three sections follow describing the I/O structure of the model, how data is obtained in building the input data file and a step-by-step illustration of the creation of a typical input data file including watershed and storm event descriptors and program control options.

The Computer Program

The basic program structure was developed following the schematic flow chart given in Figure 20. The program was designed to generate synthetic discharge hydrographs when given a precipitation distribution, HRU and element descriptors and appropriate program control variables. Rainfall excess for each HRU is computed by an iterative solution of Eqn. {2}. Equation {3} is solved for area of flow and discharge is determined from Eqn. {37}.

Program Structure

The computer model was written in the Fortran IV language for use on an IBM 370 model 158 computer. A modular structure was followed to provide a better understanding of program logic, to minimize the effort necessary to make modifications in existing code and to simplify substitutions for existing subroutines. The program is composed of a main and eight subroutines. Each subroutine has been structured to accomplish a specific set of related tasks. A listing of Fortran coding is given in Appendix B which is followed by a description of program variables (Appendix C). This version of the model does not

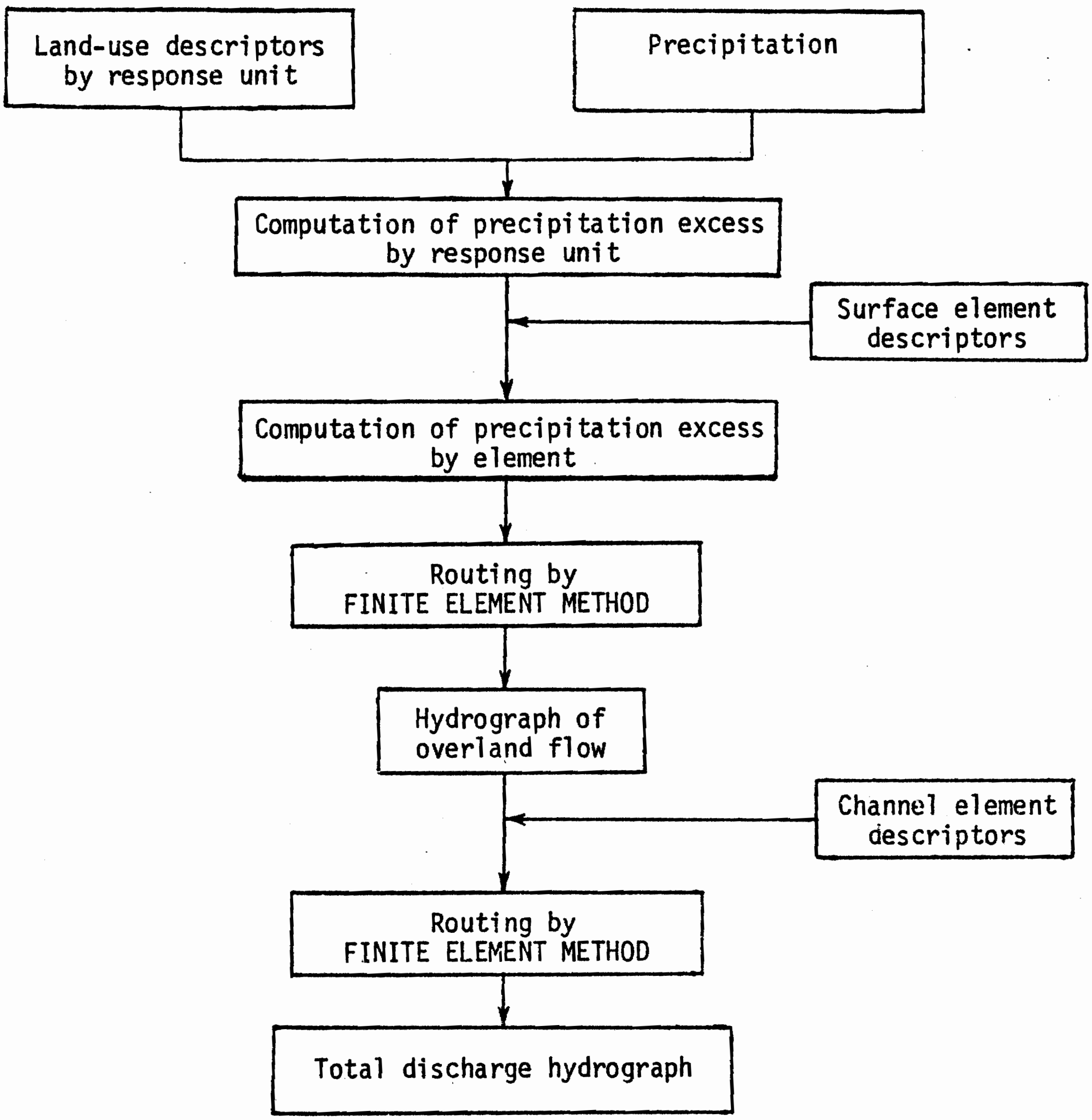


Figure 20. Schematic flow chart of the FESHM.

include a subroutine to solve the full momentum equation nor the coding to generate sediment predictions. These subroutines are being incorporated into the model and will be available at a later date.

MAIN

The MAIN routine performs executive tasks such as initiating the proper access to subroutines.

Subroutine INPUT

All input tasks are handled by this routine.

Subroutine OUTPUT

All output tasks are handled by this routine.

Subroutine EXCESS

The function of this routine is to determine antecedent moisture conditions and initial storage capacity for the soil profile of each HRU. Rainfall excess for each HRU within an element is weighted to create a weighted value that is applicable to the entire element.

Subroutine HOLTAN

The allocation of incoming moisture to rainfall excess and soil water storage is handled by this subroutine. A bookkeeping procedure was used to provide a continuous update of the storage capacity of a given soil profile.

Subroutines for Routing Flow

Subroutines OVERL, CHANG, ROUTE and GELB were structured to perform both overland and channel flow routing. Routing procedures are identical with the exception that a cubic interpolation function is used for overland flow and a quadratic interpolation function is used for those channels which contain only one element.

Rainfall excess generated by HOLTAN and weighted by EXCESS is passed to OVERL where it is converted to excess per unit length of each element. The single-element continuity equation is used to solve the cross-sectional area of flow at the downstream node of each overland flow element and Manning's equation provides the discharge. Thus, all solutions for overland flow are performed by subroutine OVERL.

The discharge hydrograph created at the downstream node of each overland flow strip is retained as input to CHANL where the flows are allocated to the pertinent channel elements and passed to ROUTE. The matrices are then assembled and passed to GELB for a solution of flow areas, however, when the channel consists of only one element this transfer is bypassed and solutions are obtained entirely within

CHANL. Discharges are computed following the procedure outlined for overland flows.

Solution Sequence

Rainfall excess is determined for all HRU's and weighted rainfall excess for all elements in the watershed prior to any routing of flows. The discretization of a watershed into finite elements results in a multi-branched drainage net (tree structure) when the number of subsheds exceeds one. All analyses are performed by subshed. Overland flow routing is performed first for all strips within a subshed, followed by channel routing. The discharge hydrograph at the subshed outlet is retained and the analysis proceeds to the next subshed.

Since routing proceeds from upstream to downstream, the data base must be organized so that the analysis starts at the top of the "tree" and gradually progress to the "trunk", assembling all tributary flows. An example will be given later to illustrate specific details.

Program Features

The major features of this modeling system can be summarized as follows:

1. Incorporation of spatial variability in soil, landuse, topography and rainfall.

2. Grid size is not fixed so that element boundaries can coincide with drainage patterns to maintain the natural geometry of the watershed.

3. A modeling structure sufficiently flexible that different levels of data aggregation are possible without restructuring the computer model.

4. Discharge, velocity, depth and cross-sectional area of flow are determined at all prescribed element nodal points.

5. Rainfall excess is determined for all response units enabling flow contributions from specific HRU's to be identified.

6. Detention storage reservoirs are included.

7. Landuse change can be easily simulated.

Input Structure

Input consists of the following nine data groups: (1) output control parameters, (2) storm event descriptors, (3) assignment of HRU's and flow elements, (4) landuse and HRU descriptors, (5) time increments and order of routing computations, (6) overland flow element descriptors, (7) overland flow flood detention structure properties, (8) channel flow element descriptors and (9) channel flow flood detention structure properties. A detailed description of input variables and formats for each of the above categories is given below. The logic behind the selection of many of the necessary input parameters will be discussed in the next section.

The primary purpose of this section is to describe formatting procedures by referring to the tables listed in Appendix E.

Output Control Options

Stage-discharge relationships are computed at all prescribed element nodes in the finite element structure. The outflow hydrograph generated for the last subshed is normally the only output of interest to the modeler. If the user is interested in flow quantities at all or selected interior nodes, options have been provided to give a listing of the discharge, velocity, area and depth of flow at interior nodes depending on the value of output control codes. Routinely providing output for all interior nodes is expensive, therefore, the time required to create the output control record for selective printing appears justified.

In addition to listing discharge, options also have been provided to list specific information that relates to HRU's, rainfall excess per HRU and weighted rainfall excess per element. The variables that control output listings are described in detail in Table E1.

Storm Event Descriptors

This set of input records defines storm characteristics and assigns the rainfall distributions to the proper element. Spatial variation in rainfall is considered only when the number of raingages exceeds one.

Rainfall data for all raingages are entered at the beginning of execution and stored in matrix PRECIP as shown in Table E2. Note that the data are stacked in the input queue sequentially by raingage. For a given station, eight values are placed per record (or card) until all have been included. Parameters which differ by year are the growth index (GI) term of the Holtan equation and evapotranspiration estimates which must be entered by month for the year being considered. To determine antecedent soil moisture for each HRU, daily rainfall totals for the 30 days prior to the storm event are entered for each raingage.

When the above evapotranspiration and daily rainfall information is unavailable or the user opts not to evaluate antecedent moisture in this manner an estimate may be made of the antecedent moisture capacity for the entire watershed (SMCWS) and applied throughout.

Indexing to Spatially Orient HRU's

This set of records is described in Table E3 and provides indexing to uniquely define and locate a given HRU and information to compute weighted rainfall excess per element. The data provided in the sequence Record No. 2-4 is always entered by element. Ten values of IHRU are entered per card

(Record No. 3) for each element until all are accounted for. For example, when NHRU equals 13, the first card contains 10 values of IHRU and the second contains the remaining 3 values. Column matrix FHRU contains the same number of records as column matrix IHRU.

HRU and Landuse Descriptors

Three data sets are required to describe landuse and HRU properties. The first series of records consists of a set of 'a' values for the Holtan equation for corresponding landuse types. The data are entered eight values per card following the format given for Record No. 1, Table E4. The second series of records contains estimates of potential depression storage for each landuse (Record No. 2, Table E4). These values are used in the moisture accounting routine to account for the water which is stored in land depressions and does not become runoff during succeeding time steps and is available for infiltration and/or evaporation. The third series of records contains values of Manning's 'n' for a given landuse type. These data are also entered eight values per card following the format given for Record No. 3, Table E4.

The last data set in this group describes the properties of each HRU. Included in this definition are those soil properties that determine the water holding capacity of the soil profile, landuse code, slope class and the final rate of infiltration for each HRU. The information for each HRU is entered as separate records (cards) according to the format given for Record No. 4, Table E4.

Computation Time and Index File for Flood Routing

The following input category contains two data files. The first data file gives the computation time increments (dt) for an explicit solution of Eqn. (16) over time. The format for this record is described in Record No. 1, Table E5.

The second data file provides indexing for proper hydraulic routing, since the drainage pattern is approximated with a tree structure when the number of subsheds exceeds one. Specifically, this data set defines the sequence by which subshed computations are performed while defining the type of boundary condition that must be applied at the upstream node of each channel. Two records are required to define boundary conditions. The first record (Record No. 2, Table E5) contains an index code specifying the type of upstream boundary condition. When the upstream boundary flow is not zero (e.g., at the confluence of two channels) a second record (Record No. 3, Table E5) is required which identifies the two channels whose discharges combine to form the upstream boundary condition of the third channel. Record Nos. 2 and 3, Table E5 are omitted when NTSS = 1 (Table E3).

Overland Flow Element Descriptors

Overland and channel flow routing is performed by subshed. This data file, therefore, contains indexing information for identifying the number of unit drainage areas or flow strips within a subshed. It is also necessary to define the number of flow strips on the left side of the channel, facing upstream, and the resultant number of channel elements.

With this indexing information, corresponding element geometric properties are created in a third data set with one card required for each strip since each must consist of one element in this version of the model. Detailed description of these data sets is given in Table E6.

Overland Flow Flood Detention Structure Properties

A sequence of three data sets are required to define the properties of a flood detention structure in a given overland flow element. The sequence must be repeated for each additional structure that is located within the element. A description of this data file is given in Table E7.

Channel Flow Element Properties

One data file is required to enter channel geometry for all elements in a subshed. These data are described in Table E8. A single card is required to enter the data for each element. Note that the top width of the first node of element No. 1 for each channel does not appear in the input stream because flow has been defined from boundary conditions for these nodal points.

Channel Flow Flood Detention Structure Properties

A sequence of three data sets are required to define properties of a flood detention structure in a given channel flow element. A description of this data file is given in Table E9.

Typical Input Data Stacking Order

Due to the flexibility that has been incorporated into the program many variations in the data input stream can occur. A complete stacking order with notations to identify the number of records and special conditions for inclusion of some records is given in Table E10. In the last major section of this chapter a step by step procedure will be presented which illustrates the creation of input data files that are identified in this table.

Output

Several types of output can be obtained depending upon user controlled options specified in Table E1. Appendix G gives a complete output listing for the storm event of 6/24/58, Pony Mountain Branch watershed. All output options are displayed and are discussed categorically below. The first group provides specific information relative to HRU's, the second category provides data describing rainfall excess for HRU's and elements and the third provides displays that relate to flow simulation through the finite element structure.

Hydrologic Response Units

Listings in this category include specific soil hydraulic properties and landuse characteristics, rainfall, rainfall excess per HRU and weighted rainfall excess per element. A listing of specific properties of the HRU's that were identified in the Pony Mountain Branch watershed, Culpepper County, Virginia is given in Appendix G. This table contains the basic properties that were supplied by the user for each HRU. The table also contains values that were determined from internal computer code for exponent 'c' (Holtan's equation), depression storage adjusted for slope class and the maximum soil water storage capacity. These data provide a simple procedure for verifying that user-supplied HRU properties were properly retrieved during execution.

Rainfall Excess

Rainfall excess estimates for each HRU and the weighted rainfall excess by element can be obtained for the duration of a specific storm event. When several rainfall distributions are either known or assumed for a given simulation, a table is generated for each rainfall distribution (raingage). HRU and element rainfall excess tables are listed for each raingage. Only those HRU's and elements located within the areal coverage of the corresponding raingage are listed in the pair of tables given for each raingage.

Simulated Discharge

Listings that can be obtained in this category include physical properties of elements, discharge, cross sectional area, velocity and depth of flow. The user can obtain the above information at all nodes in a given flow strip or at only the downstream node of a flow strip. Since overland flow strips contain one element in this version of the model, this option is trivial for the overland flow aspect. Note that the downstream node of a channel is equivalent to the output from the subshed or subsheds that drain to that point.

The general form of the output when the discharge is requested at the downstream nodal point for overland flow and all nodes for channel flow is illustrated in Appendix G. The last node of the channel in the last subshed represents the total simulated discharge from the watershed.

The flow data displayed in Appendix G often will be used in supporting computer programs that have been designed for a specific analysis. The computer-generated formats for both types of output are given in Table E11. This display shows the location of each data field within a given record, which will allow the user to construct the proper format to retrieve specific information.

The output format for discharge at all nodes is described as Output Option No. 1. This complete format occurs when the number of nodes in a channel is equal to four. For fewer nodes the output columns do not extend across the page but are written by the same format as shown in Appendix G. When the number of nodes exceeds four the above format is repeated in subsequent tables. Note that the position of the calculated discharge for the downstream node depends upon the number of nodes in the given overland flow strip or channel. Flow characteristics are generally printed at the last node of the overland flow strip or by choice at the last node of the channel as described by output option No. 2 when the alternative output format is selected.

Data Accessibility and Preparation

Data preparation is perhaps the most time-consuming and often challenging task with which a modeler is confronted when he attempts to incorporate heterogeneity in soils, landuse and watershed physiographic features. This effort includes both the collection and preparation of data into a usable form and arranging these data into the correct sequence and format to create the data input file for computer simulation.

The discussion of these two broad areas of data preparation continues by using an illustrative example which describes the procedure that was applied to all natural watersheds used in this study. The aspect to be considered below is that of identification and assignment of values to the parameters which must be defined to solve Equations (2), (3) and (37).

Obtaining the Necessary Watershed Data

Pony Mountain Branch watershed (Figure 47) will be used to trace the collection of all necessary data for modeling a natural watershed. The procedures that will be presented for this example were used to create the basic data bases for all watersheds used in this study.

As previously noted, the FESHM was structured primarily as a mechanism capable of including the spatial variability of those factors considered significant to the proper definition of a discharge hydrograph. The major task that confronts the user, therefore, is deciding on the level of discretization, i.e., spatial variability, that must be included to obtain a reliable level of predictability. The problem is complicated because of the general lack of objective criteria to define precisely what detail is essential for most applications.

Since two discretization procedures are involved, data preparation can be categorized into two general areas: (1) rainfall excess and (2) flood routing. The properties of each HRU and each element must be defined and the spatial relationship of each HRU to the finite-sized elements must be identified and the data base for each combined to provide hydraulic continuity.

HRU Descriptors

The first step was to create the HRU map by overlaying soil and landuse maps. The soils map shown in Figure 21 for Pony Mountain Branch Watershed was re-created from a detailed soil survey of the Culpepper County area conducted by the Soil Conservation Service. The landuse map in Figure 22 was developed from a combination of aerial photographs

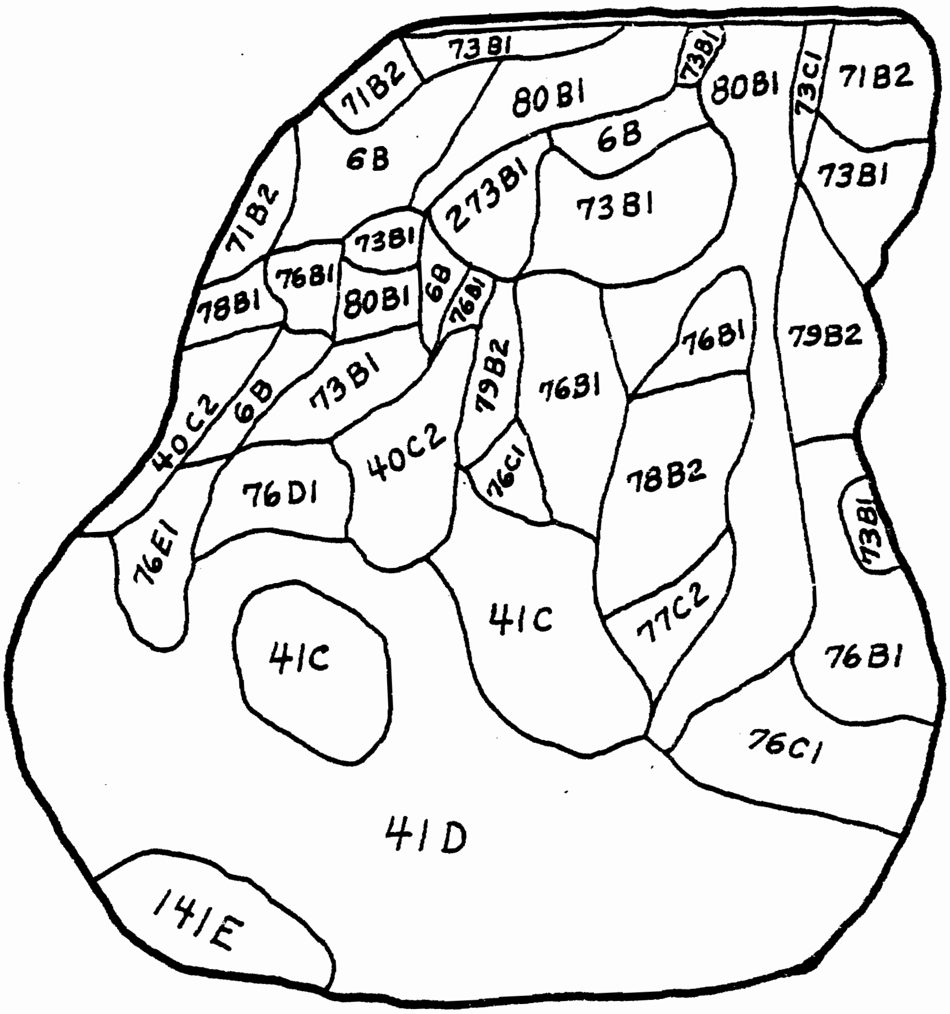


Figure 21. Soil map, Pony Mountain Branch watershed, Culpepper County, Virginia.

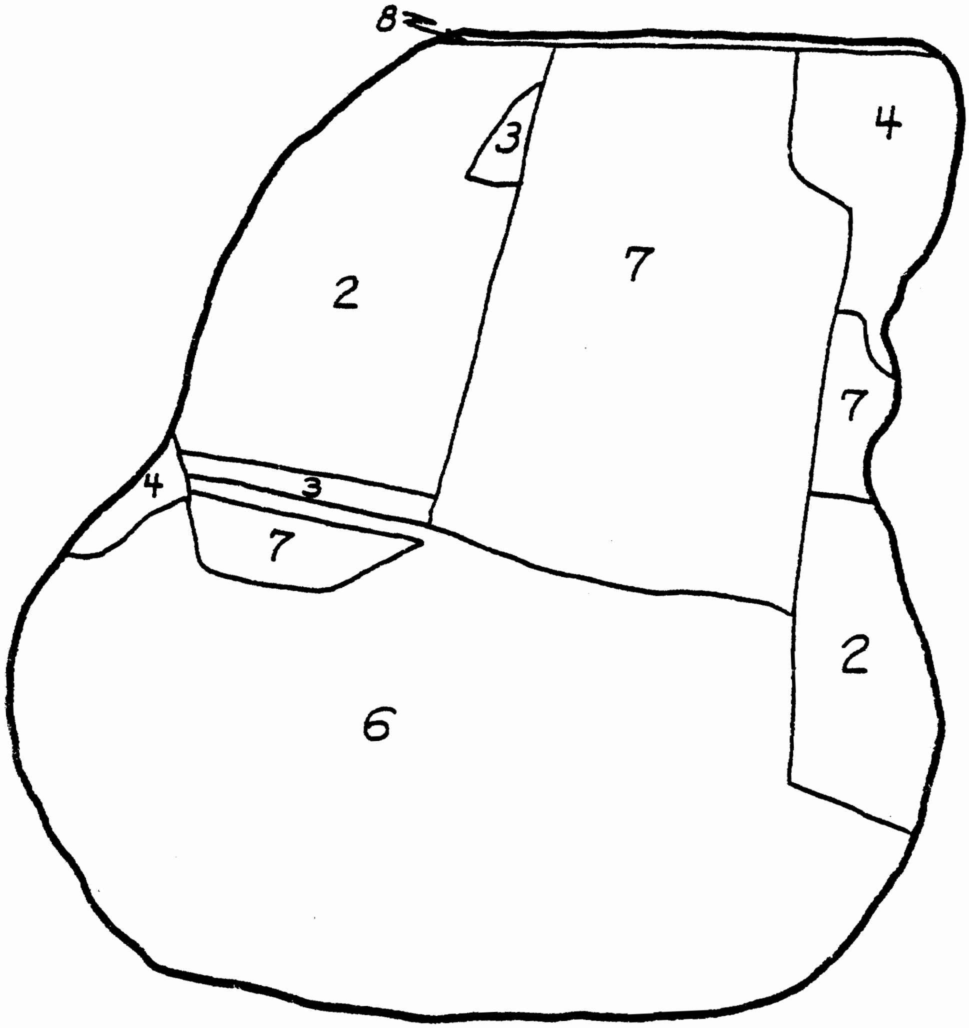


Figure 22. Landuse map, Pony Mountain Branch watershed, Culpepper County, Virginia.

and ground reconnaissance of the watershed area.

The superimposition of the landuse map on the soils map resulted in the HRU grid of Figure 23 which, for this example, contained 47 unique soil mapping unit-landuse combinations. Several characteristics which define an HRU and also correspond to parameters in the Holtan equation (Eqn. (2)) are presented in Table 1. The method by which each is obtained is discussed below.

Soil descriptors:

The soil type, slope class and erosion class combine to identify a soil mapping unit within a given soil series. Surface slope and erodibility are important in the aforementioned discretization into HRU's because these properties can significantly affect topsoil depths. Thus, information necessary to determine rainfall excess consists of the soil textural classification and depth to an impeding layer, which combine to define the maximum water storage capacity. This becomes the zone of hydrologic activity and its description is critical toward obtaining valid rainfall excess estimates.

Soil texture--The soil texture classification provides information necessary for determining total potential storage in a soil profile. England (1970) has provided esti-

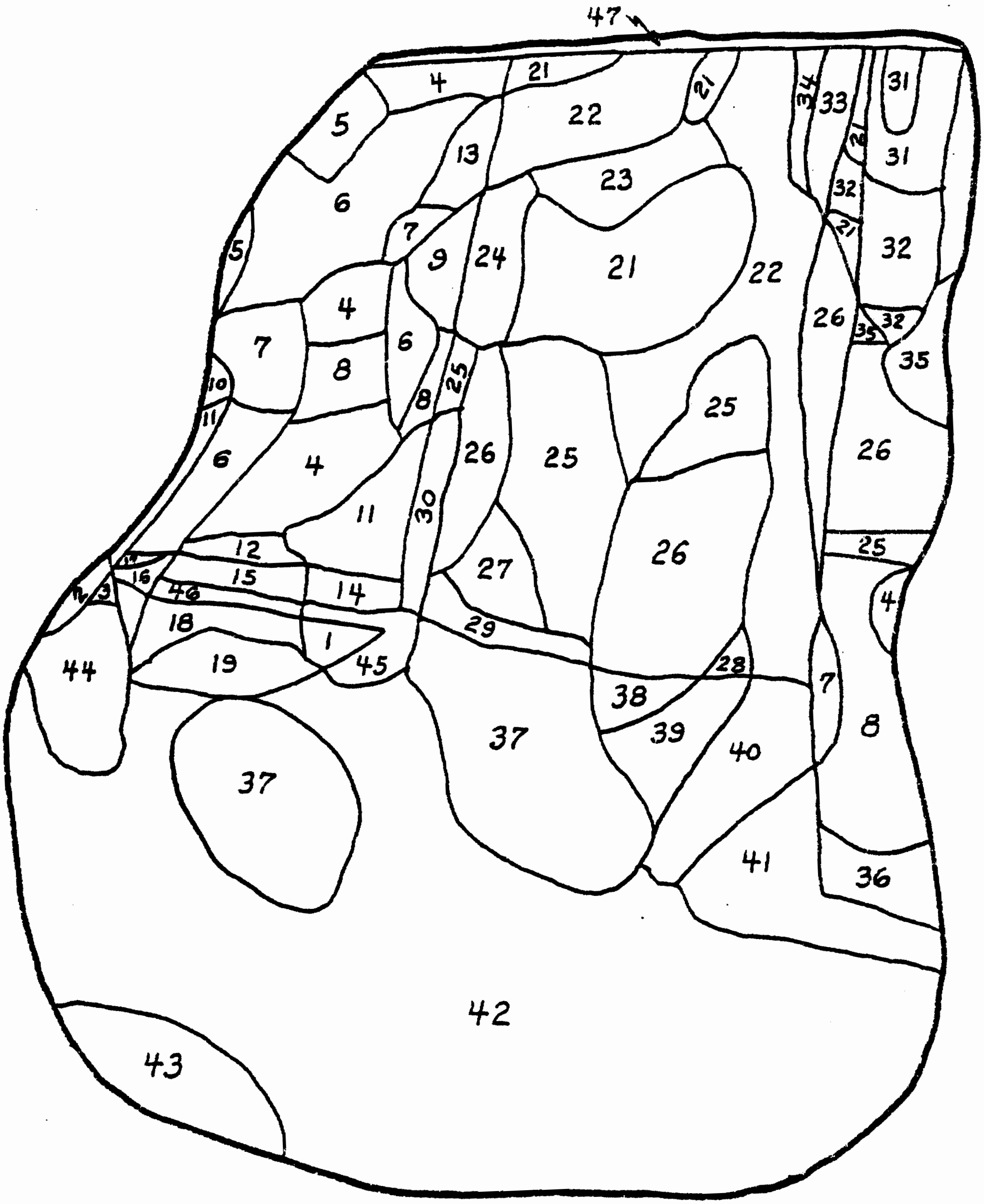


Figure 23. HRU map, Pony Mountain Branch watershed, Culpepper County, Virginia.

Table 1. Summary of characteristics of response units defined in Pony Mountain Branch watershed, Culpepper County, Virginia.

HRU No.	Cover Coeffi-cient	Plant Avail-able Water (in/in)	Gravita-tional Water (in/in)	Final Infil-tration Rate (in/hr)	Depth to Impeding Layer (in)	Map Unit	Soil Type	Landuse
1	0.6	0.11	0.10	0.10	4.0	41D	Stony land	Pasture
2	0.6	0.21	0.10	0.10	7.0	40C2	Montalto silt loam	Pasture
3	0.6	0.21	0.10	0.10	4.0	76E1	Catlett silt loam	Pasture
4	0.2	0.24	0.11	0.05	13.0	73B1	Penn silt loam	Corn
5	0.2	0.24	0.11	0.05	6.0	71B2	Bucks silt loam	Corn
6	0.2	0.24	0.11	0.05	18.0	6B	Manassas silt loam	Corn
7	0.2	0.14	0.05	0.00	17.0	80B1	Croton silt loam	Corn
8	0.2	0.21	0.10	0.10	7.0	76B1	Catlett silt loam	Corn
9	0.2	0.24	0.11	0.05	9.0	273B1	Readington silt loam	Corn
10	0.2	0.24	0.11	0.05	12.0	78B1	Calverton silt loam	Corn
11	0.2	0.21	0.10	0.10	7.0	40C2	Montalto silt loam	Corn
12	0.2	0.21	0.10	0.10	5.0	76D1	Silt loam Catlett	Corn
13	0.7	0.14	0.05	0.00	17.0	80B1	Croton silt loam	Hay
15	0.7	0.21	0.10	0.10	5.0	76D1	Catlett silt loam	Hay
16	0.7	0.21	0.10	0.10	4.0	76E1	Catlett silt loam	Hay
17	0.7	0.24	0.11	0.05	18.0	6B	Manassas silt loam	Hay
18	0.7	0.21	0.10	0.10	5.0	76D1	Catlett silt loam	Idle
19	0.7	0.11	0.10	0.10	4.0	41D	Stony land	Idle
20	0.7	0.21	0.10	0.10	4.0	76E	Catlett silt loam	Idle
21	0.7	0.24	0.11	0.05	13.0	73B1	Penn silt loam	Idle
22	0.7	0.14	0.05	0.0	17.0	80B1	Croton silt loam	Idle
23	0.7	0.24	0.11	0.05	18.0	6B	Manassas silt loam	Idle
24	0.7	0.24	0.11	0.05	9.0	273B1	Readington silt loam	Idle

Table 1. Continued.

HRU No.	Cover Coefficient	Plant Available Water (in/in)	Gravitational Water (in/in)	Final Infiltration Rate (in/hr)	Depth to Impeding Layer (in)	Map Unit	Soil Type	Landuse
25	0.7	0.21	0.10	0.10	7.0	76B1	Catlett silt loam	Idle
26	0.7	0.21	0.10	0.10	12.0	79B2	Kelly silt loam	Idle
27	0.7	0.21	0.10	0.10	6.0	76C1	Catlett silt loam	Idle
28	0.7	0.21	0.10	0.10	12.0	77C2	Brecknock silt loam	Idle
29	0.7	0.11	0.10	0.10	5.0	41C	Stony land	Idle
30	0.7	0.21	0.10	0.10	7.0	40C2	Montalto silt loam	Idle
31	0.6	0.24	0.11	0.05	6.0	71B2	Bucks silt loam	Pasture
32	0.6	0.24	0.11	0.05	13.0	73B1	Penn silt loam	Pasture
33	0.6	0.24	0.11	0.05	10.0	73C1	Penn silt loam	Pasture
34	0.6	0.14	0.05	0.0	17.0	80B1	Croton silt loam	Pasture
35	0.6	0.21	0.10	0.10	12.0	79B2	Kelly silt loam	Pasture
36	0.2	0.21	0.10	0.10	6.0	76C1	Catlett silt loam	Corn
37	1.0	0.11	0.10	0.10	5.0	41C	Stony land	Heavy woods
38	1.0	0.21	0.10	0.10	12.0	79B2	Kelly silt loam	Heavy woods
39	1.0	0.21	0.10	0.10	12.0	77C2	Brecknock silt loam	Heavy woods
40	1.0	0.14	0.05	0.0	17.0	80B1	Croton silt loam	Heavy woods
41	1.0	0.21	0.10	0.10	6.0	76C1	Catlett silt loam	Heavy woods
42	1.0	0.11	0.10	0.10	4.0	41D	Stony land	Heavy woods
43	1.0	0.04	0.04	0.10	3.0	141E	Very rocky land	Heavy woods
44	1.0	0.21	0.10	0.10	4.0	76E1	Catlett silt loam	Heavy woods
45	1.0	0.21	0.10	0.10	7.0	40C2	Montalto silt loam	Heavy woods
46	1.0	0.21	0.10	0.10	5.0	76D1	Catlett silt loam	Heavy woods
47	0.0	-	-	-	-	-	-	Road

mates for gravitational water and plant available water volumes for several textural classes (Table 2). Storage values are given as fractions of the total volume of soil at the depth of the impeding layer. These values also provide an estimate of the exponent 'c' in the Holtan equation (Eqn. {2}) since this parameter is defined as the ratio of the potential plant available water to potential gravitational water.

Soil depth--For the information provided by Table 2 to be usable, an estimate must be made of the actual depth of the soil profile. Soil depth is the most critical parameter in the Holtan infiltration equation and is difficult to estimate in the absence of soil profile descriptions and corresponding soil hydraulic characteristics such as those given in Figure 24.

The procedure normally followed is to locate the soil profile where root penetration from forage crops essentially terminates. This region normally coincides with a significant change in saturated hydraulic conductivity. The depth parameter always includes the 'A' horizon and most often part of the 'B' horizon.

The procedure is illustrated by referring to Figure 24. Common fine roots were found in the B23t horizon at a maximum depth of 26 inches. In Figure 24 note that the satu-

Table 2. Estimates by texture of the water storage capacity in a soil {England (1970)}.

Soil Texture	Gravitational Water (in/in)	Plant Available Water (in/in)	Total Storage (in/in)
Coarse sand	0.177	0.067	0.224
Coarse sandy loam	0.153	0.087	0.245
Sand	0.190	0.133	0.323
Loamy sand	0.269	0.101	0.370
Loamy fine sand	0.272	0.054	0.326
Sandy loam	0.186	0.123	0.309
Fine sandy loam	0.235	0.131	0.366
Very fine sandy loam	0.210	0.117	0.327
Loam	0.144	0.156	0.300
Silty loam	0.114	0.199	0.313
Sandy clay loam	0.134	0.119	0.253
Clay loam	0.130	0.127	0.257
Silty clay loam	0.084	0.149	0.233
Sandy clay	0.116	0.078	0.194
Silty clay	0.091	0.123	0.214
Clay	0.073	0.115	0.188

CECIL GRITTY SANDY LOAM (13,24,P,a)

Location: Brunswick Co., Rocky Run Branch Watershed; located 50' from fence, in pasture, 400 yds. W of county road #656.
Vegetation and land use: Pasture
Topography: Gently sloping
Drainage: Well drained
Parent Material: Granite gneiss and schist
Described and sampled by: K. Russell, J. Williams, J. B. Burford

Horizon	Description
Ap	0 to 7 inches. Dark yellowish brown (10YR 4/4) gritty sandy loam; very friable; moderate medium granular structure; occasional angular quartz rock less than 3" in diameter; many fine roots; strongly acid; abrupt wavy boundary.
B22t	7 to 15 inches. Red (2.5Y 4/6) clay; firm; some ped faces coated with yellowish red (5YR 4/8) clay which apparently is result of root and worm action between horizons; moderate medium subangular blocky structure; thin clay film on most peds; many fine roots; few mica flakes; occasional angular quartz rock less than 1/2" in diameter; strongly acid; clear smooth boundary.
B23t	15 to 26 inches. Red (2.5YR 4/6) heavy clay loam with common fine faint mottles of yellowish red (5YR 4/8), common fine distinct mottles of strong brown (7.5YR 5/6) and brownish yellow (10YR 6/6); friable; moderate medium subangular blocky structure; thin clay film on most peds; common fine roots; common mica flakes; few pockets of gritty clay loam; strongly acid; clear smooth boundary.
B31	26 to 40 inches. Red (2.5YR 4/6) light clay loam with many medium faint mottles of yellowish red (5YR 5/8) and few fine distinct mottles of brownish yellow (10YR 6/6); friable; weak fine and medium subangular blocky structure; thin patchy clay films; many mica flakes, slick and greasy to feel; few pockets of gritty clay loam; strongly acid; clear wavy boundary.
B32	40 to 58 inches. Red (2.5YR 4/6) pockets of light gritty clay loam mixed with highly weathered granite gneiss and schist rock with many medium faint mottles of yellowish red (5YR 5/8) and many medium distinct mottles of brownish yellow (10YR 6/6); friable; many mica flakes; weak coarse granular structure; slick and greasy to the feel; strongly acid; gradual wavy boundary.
C	58 to 66 inches plus. Mottled colors of red (2.5YR 4/6), yellowish red (5YR 5/6), brownish yellow (10YR 6/6), reddish yellow (7.5YR 6/6), and very pale brown (10YR 7/3) gritty loam of highly weathered granite gneiss and schist material.

CECIL GRITTY SANDY LOAM (13,24,P,a)

WEIGHT PERCENT AND VOLUME PERCENT OF WATER RETAINED

IDENTIFICATION 13 24 1 1 DEPTH	TENSIONS (BARS) .1	.3	.6	3.	15.	BD G/CC	TP PCT	K IN/HR
0	14.22	11.72	11.00	8.17	7.74	1.59	40.00	1.31
	22.60	18.63	17.49	12.99	12.30	1.70	35.85	1.32
	FRAGMENT	14.71		SIEVED	8.33ROCK	PERCENT	33.37	
7	28.34	27.08	26.60	23.78	22.56	1.38	47.92	2.01
	39.10	37.37	36.70	32.81	31.13	1.53	42.26	2.44
	FRAGMENT	26.15		SIEVED	29.55ROCK	PERCENT	26.98	
15	30.86	30.05	27.99	25.87	23.43	1.21	54.34	.59
	37.34	36.36	33.86	31.30	28.35	1.35	49.06	.16
	FRAGMENT	32.00		SIEVED	25.70ROCK	PERCENT	10.67	
26	32.59	29.80	29.71	27.55	19.29	1.34	49.43	.27
	43.67	39.93	39.81	36.91	25.84	1.45	45.28	.28
	FRAGMENT	32.78		SIEVED	22.93ROCK	PERCENT	13.76	
40	27.16	23.91	22.79	16.26	14.30	1.45	45.28	.13
	39.38	34.66	33.04	23.57	20.73	1.52	42.64	.07
	FRAGMENT	26.46		SIEVED	13.80ROCK	PERCENT	19.02	
58	35.36	26.08	23.72	16.75	10.34	1.36	48.68	.11
	48.08	35.46	32.25	22.78	14.06	1.44	45.66	.20
	FRAGMENT	28.00		SIEVED	9.77ROCK	PERCENT	14.52	

1=FIST
2=CORE
3=LOOSE

Figure 24. Typical soil profile description and corresponding soil hydraulic characteristics.

rated hydraulic conductivity is significantly less at this horizon. For the example, an A slope with an erosion class 1 would be assigned a depth of 26 inches and an f_c value of 0.16 in/hr. Theoretically, f_c approaches the soil's saturated hydraulic conductivity, although in practice it will be somewhat higher because of entrapped air, etc.

The effects of both erosion and slope on infiltration rates are simulated by varying the topsoil depth since, in general, the depth of topsoil is related to both slope and the severity of erosion. The effect of slope was obtained from soil survey data, which gives the range of topsoil depth for a given soil type. This range represents depths over all slopes existing in the area. For the Cecil gritty sandy loam (Figure 24), the variation was from 15 to 26 inches for slope classes A-C. Soil depths were modified by assigning a 26-inch depth to the A slope, a 20.5-inch depth to the B slope and a 15-inch depth to the C slope.

The depths were further modified for erosion by assuming a 50% reduction in the depth of the 'A' horizon for erosion class 2 and a 75% reduction in the depth of the 'A' horizon for erosion class 3. The topsoil depth for the above example was 7 inches, therefore, the soil depths for this soil type were reduced 3.5 inches when the erosion class was 2 and 5.25 inches when the erosion class was 3.

Final infiltration rate--The final rate of infiltration, f_c, is defined as the rate of infiltration that a soil attains after prolonged wetting. Chow (1964) presents extensive data which relates soil types with a hydrology group. From this information, Table 3 can be used to assign a final rate of infiltration to a particular hydrology group in the absence of laboratory or field measurements such as those in Figure 24.

Landuse descriptors:

Three parameters, Holtan's 'a', potential depression storage and Manning's 'n', must be identified with the landuse map (Figure 22). Eighteen landuse types were defined for this watershed and the remaining experimental watersheds to be applied. These are listed in Table 4 and discussed below.

Holtan's 'a'--The parameter, a, in the Holtan equation (Eqn. {2}) is used in the soil moisture model to index the effect of landuse cover on runoff. The data suggested by Holtan, et. al (1975) were derived from many numerical experiments. Although not a detailed listing, they do provide guidelines for estimating the 'a' factors for other related landuse types. Table 4 shows the estimates of Holtan's 'a' for each landuse.

Table 3. Estimates by hydrology group of the final rate of infiltration {Li (1975)}.

Hydrology Group	Final Rate of Infiltration (in/hr)
A+	0.450
A	0.400
A-	0.350
B+	0.300
B	0.250
B-	0.200
C+	0.150
C	0.100
C-	0.075
D+	0.050
D	0.025
D-	0.0
Impervious	0.0

Table 4. Estimates of Holtan's 'a', potential depression storage Manning's 'n' for selected landuse types.

Landuse Number	Description	Holtan's 'a'	Potential Depression Storage	Manning's 'n'
1	small grain	0.30	0.15	0.10
2	corn	0.20	0.15	0.10
3	hay	0.50	0.30	0.20
4	pasture	0.80	0.40	0.25
5	tobacco	0.20	0.10	0.10
6	woods	1.00	0.50	0.40
7	idle	0.90	0.30	0.30
8	road	0.00	0.05	0.02
9	soybeans	0.40	0.15	0.15
10	cotton	0.40	0.15	0.15
11	sorghum	0.20	0.15	0.10
12	fallowed	0.10	0.80	0.10
13	light woods	0.90	0.50	0.35
14	homestead	0.90	0.40	0.25
15	cemetery	0.90	0.40	0.25
16	buildings	0.80	0.02	0.02
17	pond	0.00	10.00	0.02
18	no-till corn	0.45	0.15	0.25

Depression storage--Many surface depressions exist over land surfaces. These indentations create additional storage of water which will be retained to either infiltrate or evaporate at a later time. The magnitude of this water may vary greatly from one landuse type and/or surface condition to another.

Extensive research on the quantities of depression storage which may exist for a range of landuse types has not been conducted. Several investigators {e.g. Horton (1935), Hicks (1942) and Tholin and Keifer (1960)} give depression storage estimates for several landuse types. From these data a range of magnitude was created from which intermediate values of depression storage were estimated to complete the data in Table 4. These data can be easily changed when more accurate data are available for a given site.

Manning's 'n'--Another parameter that is identified from the landuse map is surface roughness (Manning roughness coefficient). Selecting values of Manning 'n' for surface elements that correlate well with the actual roughness conditions is quite difficult. Since flow in the overland flow planes occurs essentially in small channels, and, even at the smallest scale, in rivulets, this value is little more than a tool by which to calibrate the model. Unlike the two previous landuse parameters, Manning's 'n' is not used for rainfall excess generation but is reserved for the determination of element roughness coefficients by the following procedure.

Since Manning 'n' is defined by the type of landuse, a system of calculating Manning 'n' was devised which would be consistent with changes in landuse. Another primary objective was to be able to define the value of Manning 'n' based upon readily identifiable watershed characteristics that would remain consistent for each watershed instead of an estimating procedure for each element that would involve calibration. Thus, the information on landuse that was also used in the computation of rainfall excess was used for the determination of a Manning roughness coefficient for each element. When the percentage area of each landuse in an element, synonymous with the percentage area of each HRU, is known and a Manning 'n' value assigned to each landuse type, a weighted average can be readily determined for each element.

Information on roughness coefficients for overland flow surfaces is lacking, however, guidelines are provided in the literature {e.g. Petryk and Bosmajian (1975) and Satterlund (1972)}. Table 4 lists the values selected for use with the landuse types in the experimental watersheds.

Element Descriptors

The topographic map in Figure 47 was used to delineate the finite element grid structure shown in the same figure. United States Geological Survey topographic maps can provide the information necessary to define an element grid for a given watershed in the absence of a contour map of finer detail.

Four subsheds were defined in the Pony Mountain Branch watershed, which resulted in four channels to describe the movement of stormwater. The overland flow strips and elements were defined as previously discussed in the earlier section on watershed discretization.

HRU-element relationships:

Prior to defining element characteristics necessary for solving the continuity and momentum equations (Eqns. {3} and {4}), the HRU-element relationships must be defined. This is performed by overlaying the HRU map (Figure 23) and the finite element grid map (Figure 47) and determining the fractional area of each HRU within each element. To provide some continuity of thought, Figure 25 will be used to illustrate how fractional areas were obtained. Element No. 1 of subshed A is depicted in Figure 25 superimposed on a map of HRU's. For this element the procedure was as follows.

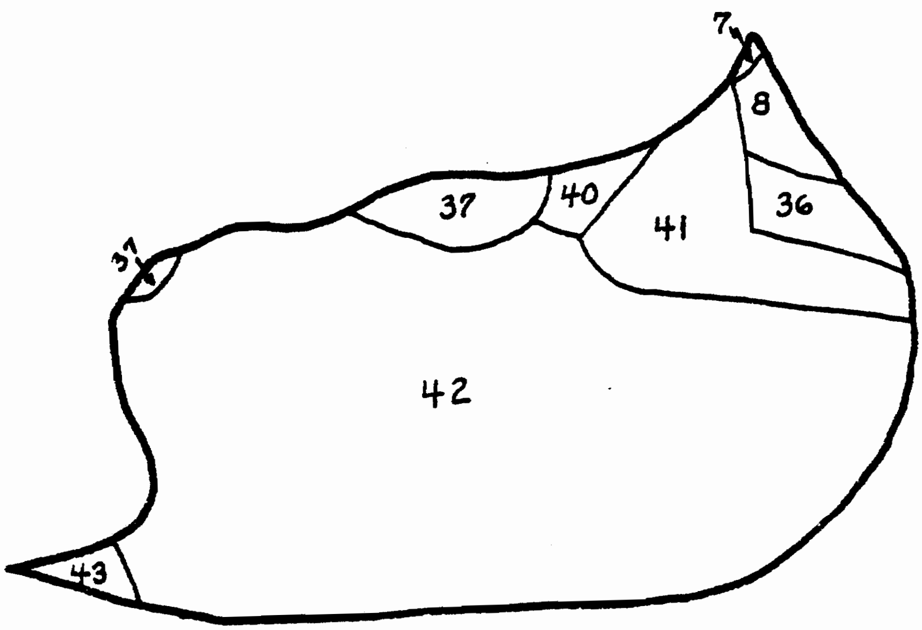


Figure 25. Element No. 1 of subshed No. 1 overlaid on HRU map, Pony Mountain Branch watershed (Figure 47).

The areas for element No. 1 and each HRU within this element were determined with an automatic digitizer. The fractional area of each HRU in the element was determined from a ratio of the HRU area to the element area. Note that when an HRU occurred at different locations within the element, the areas were lumped together. Spatial uniqueness is lost, therefore, at the element level. For example, in element No. 1 (Figure 25), nine HRU's are present, however, the two HRU's identified as No. 37 were lumped together, leaving eight unique HRU's to be defined. It should be apparent that the degree to which spatial uniqueness is maintained in the present model structure is highly dependent upon the finite element structure.

This data base with appropriate soil hydraulic properties provides sufficient information to determine the weighted rainfall excess for each element or the 'q' term in the continuity equation (Eqn. {3}). As was described earlier, the procedure adopted in this model was to weight rainfall excess by HRU for each element. It should be reiterated that these same weights are used to determine a weighted Manning 'n' value for each element from the information provided in Table 4.

Since the parameters describing overland flow and channel flow elements can differ, they are discussed separately below (see Tables 5 and 6).

Table 5. Properties of overland flow elements for Pony Mountain Branch watershed.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
1	960	1570	50.1	190
2	530	1860	9.5	15
3	280	1570	2.9	35
4	270	1870	2.4	10
5	310	1140	3.7	120
6	1320	1840	28.8	90
7	210	1140	3.2	35
8	380	1840	8.3	20
9	290	450	4.9	10
10	260	450	1.9	5
11	270	1180	4.5	55
12	800	1560	19.5	115
13	1170	1560	26.1	65
14	540	1180	9.1	95
15	370	1560	5.6	20
16	520	1560	11.6	10

Table 6. Properties of channel flow elements for Pony Mountain Branch watershed.

Element Number	Length (ft)	Downstream Node Width at 2-Foot Depth (ft)	Relief (ft)	Manninng 'n'
1	1570	11	150	0.08
2	1860	45	50	0.04
3	1140	23	140	0.09
4	1840	45	110	0.05
5	450	115	5	0.05
6	1180	23	155	0.09
7	1560	76	90	0.07
8	1560	115	25	0.05

Overland flow element descriptors:

Length--It was desired to devise a consistent method by which the lengths of overland flow elements can be determined. This can be done easily by locating on a topographic map the primary drainage channel in a surface element and measuring its length from the point where it enters the downstream channel element upstream to the point on the watershed boundary where it would intersect after extrapolating the line to this boundary. This procedure does not, however, produce a length which is representative of the actual overland flow distance in an element. The best selection would be a value which is somewhat less than this total distance. Therefore, this original value is reduced by a factor of two-thirds. There is no theoretical basis for the determination of this factor but it has proven to be suitable in matching lag times between simulated and recorded hydrographs. With this method it should be relatively easy for two users to arrive at the same element length.

Relief--Relief of an overland flow element was determined as the difference between the contour elevations at the upstream and downstream nodal points of the element line described above multiplied by the two-thirds factor. Element slope can then be determined as relief divided by element length.

Top width--This value is simply defined as the width of the flow plane at the downstream node and is equal to the length of the channel element receiving flow from the corresponding surface element.

Area--The area of an overland flow element is obtained by planimetering. This information is obtained when the HRU-element relationships are determined.

Channel flow element descriptors:

Length--Channel element length is measured from the topographic map of the watershed as simply the length of the element between its upstream and downstream nodes.

Relief--Relief of the channel elements is obtained in much the same manner as relief of the surface elements with the exception that there is no reducing factor. A topographic map, however, must be available to provide contour elevations. The slope then can be determined from the relief and length measurements for channel elements.

Top width--This parameter differs greatly from its surface element counterpart in one respect. The node width varies with depth in an attempt to define the channel cross-section. A channel area function, therefore, was included in the model to describe this variation with respect to depth in order to properly compute the hydraulic radius in the Manning equation (Eqn. {37}).

Investigators using flood routing techniques have applied many representative cross-sections in describing the channel. These have included rectangular, triangular and trapezoidal shapes, and, in many cases, a variable function describing an irregular shape.

When modeling extreme flood events, the channel does not represent the sole conveyance of the bulk of the flow through a watershed system, but must be considered in conjunction with out of bank flow occurring over the floodplain. Inclusion of this aspect in a flood routing model requires additional channel description.

Another approach that has been used by modelers has been to route overbank flows as three parallel stream tubes; one for the channel and one each for the left and right floodplains. This allows each section to retain its own resistance characteristics and, therefore, a velocity distribution across the channel can be obtained.

When flow is modeled as one composite quantity, with no distinction made between its channel and floodplain components, a wide range in flow resistance can exist between the channel and floodplain surfaces. The inclusion of floodplain resistance can affect the timing of the rising limb and peak of the hydrograph, especially for storm events with shorter return periods in which there is little overbank flow.

The above observations are all valid and important considerations particularly when dealing with the routing of flows in large streams and rivers. As one models drainage basins of considerably smaller sizes, however, the channel itself has increasingly less influence as a conveyance of flow relative to the floodplain, when storms with large return periods are being considered. The differences between the surface roughness of the channel and floodplain are generally somewhat less in smaller channels than in large rivers.

The approach taken in this study, therefore, was to select a channel cross-section shape which embodies both the channel and floodplain. In doing so, a triangular cross-section was chosen for each node, however, the side slopes are allowed to vary from node to node. At a given node the side slopes can also be different on the left and right hand sides of the channel. These side slopes are primarily dependent upon the inclination of the floodplain. These estimates are best determined from survey profiles and should be fairly representative of the channel section in the element upstream of the given node. If profiles are not available, a detailed topographic map will provide adequate information. It should be kept in mind that the cross-sections should be as representative of the channel through which the flow occurs as possible. While it is true that constrictions may occur in the channel, they are best treated as internal boundary conditions with a depth-discharge, or similar, relationship given for the point in question as mentioned earlier in Chapter III.

Manning's 'n'--As was mentioned above, when considering the routing of channel flow in small watersheds, the variance between the roughness of the channel and that of the floodplain may be minimal. A Manning 'n' was, therefore, selected to be representative of flow resistance in both regimes. Since the FESHM was developed to simulate flood-producing storm events, the floodplain roughness should be given the heavier weighting in this determination.

Selecting roughness coefficients for channel elements involves both judgement and experience, however, helpful information is provided by Chow (1959) to aid in this endeavor. Roughness coefficients for a wide range of flow resistance conditions are given.

Obtaining Data which Pertains to the Storm Event

There are several parameters that are necessary to solve the Holtan equation and are related to the storm event and its period in time.

Rainfall

Measured rainfall data is necessary to simulate a flood event since the model does not contain a routine to generate synthetic rainfall. The rainfall data must be in a form which consists of small equal-time increments of one hour or less to properly match the fluctuations which are present in a discharge hydrograph from small watersheds. Rainfall data of this type may be obtained from several sources, e.g., the National Weather Service.

For small watersheds it is unlikely that the recorded data available from the above sources can be obtained from raingages located within the watershed. This may be important since small variations in rainfall may greatly affect the runoff response from small watersheds.

Antecedent Moisture Conditions

A simplified moisture budget algorithm was developed to determine the antecedent moisture conditions internally for each HRU and storm event. This routine is similar to that used for determining infiltration rates during a storm event. The major difference was the use of a longer computational time increment (1 day). The moisture balance can expressed as follows:

$$\Theta_t = \Theta_{t-1} + P_t - ET_t - DS_t - R_t$$

where

t = time interval in days,

Θ_t = soil moisture content at end of a given day,

Θ_{t-1} = soil moisture content at end of the previous day,

P_t = rainfall during a given day,

ET_t = evapotranspiration losses during a given day,

DS_t = deep seepage losses during a given day, and

R_t = runoff losses during a given day.

The following assumptions were made:

1. Θ_o was set to 50% of field capacity 30 days prior to the storm event to be modeled.
2. For a given day, the total daily rainfall was applied to the soil storage reservoir and then losses (deep seepage and evapotranspiration) were computed to determine the soil moisture status at the end of the day.
3. Depression storage and canopy interception storage losses were ignored in the determi-

nation of antecedent moisture conditions.

4. Water in storage above field capacity was assumed to drain at a rate equal to the soil's saturated hydraulic conductivity (final rate of infiltration).
5. When the 30-day antecedent period spanned a portion of two adjacent months, a weighted evapotranspiration rate was determined and applied uniformly for each day.
6. Evapotranspiration losses were assumed to occur at the potential rate when soil water content was greater than field capacity, while losses were reduced by the ratio of the current soil moisture status to the potential plant available water content when the current soil moisture status was below field capacity.
7. Daily potential evapotranspiration was assumed to be uniformly distributed over the 30-day period.
8. When rainfall occurred, the actual daily evapotranspiration loss was assumed to be one-half of the daily potential evapotranspiration.

Potential Evapotranspiration

Monthly evapotranspiration estimates were obtained by a method described by Liou (1970) which is a function of mean annual lake evaporation and mean number of rainy days per year. Daily potential evapotranspiration rates were calculated and summed to give potential monthly evapotranspiration rates.

Growth Index

The growth index (GI) term was applied to the Holtan equation to characterize the stage of growth of a crop as a function of plant growth at a specific time to that at plant maturity. It is primarily a factor to indicate the capability of a vegetative cover to influence the rate of infiltration.

A method for computing growth indices based on cardinal temperature functions for individual crops is presented by Holtan, et.al. (1975). This approach has been modified so that it is necessary to have only a single monthly GI value for each crop. The monthly values used for the model applications to natural watersheds were derived from a listing of weekly GI values for a climate similar to that of Virginia.

Creating the Data Input File

In an attempt to bring some order to a very confusing topic the input data file for the computer program given in Appendix B is listed in Appendix F. The following discussion will be devoted to how these data were generated. Since the discretization task is non-trivial, considerable discussion will be devoted to how it can best be accomplished. It should be added that the finite element modeling system is a dynamic programming package because it is constantly undergoing change as the understanding of the influence of various spatial inputs on surface flows is improved and better ways of incorporating watershed heterogeneity are developed.

Program Control Options

Since this is an illustrative example, tables that describe the properties of HRU's, rainfall excess per HRU and weighted rainfall excess per element will be obtained by setting NTBLHS and NTBLPE equal to 1 (Table E1). A listing of overland flow and channel flow discharge hydrographs will be obtained every 600 seconds and 300 seconds, respectively. (NOPRIN = 600 and NCPRIN = 300). These data are given in line 1 of Appendix F.

Lines 2 and 3 represent index codes for obtaining discharge hydrographs at various locations in the watershed. Line 2 requests output at the downstream node of the elements in subshed No. 1 only. The third line of Appendix F applies to the stream channel. The option given is a request for a discharge hydrograph to be listed at all nodes of the channel in subshed No. 1 and at the confluence of the channels in subshed Nos. 3 and 4. This is defined by the numeral 2 in the subshed No. 5 position since subshed No. 5 represents the summation of the discharges from subshed Nos. 3 and 4.

Storm Event Descriptors

The second group of data (lines 4-16) given in Appendix F relates to the rainfall distribution that is going to be used in the simulation. Either synthetic rainfall or a recorded distribution can be entered, however, the program does not contain coding to generate a synthetic rainfall distribution at execution time. Rainfall excess computations are based upon rainfall data time intervals, i.e., 15-minute periods, for the duration of the storm event. When break-point data is available, it must be reordered into equal-time intervals for use by the model.

The first record (line 4) gives basic characteristics of the storm, duration of simulation and antecedent conditions.

Rainfall data are routinely collected at this location by two raingages (NGAGES = 2). The duration of the storm event was two hours (NHOURR = 2) and a simulation of discharge was made for three hours (NHOURC = 3). The rainfall data was entered for time increments of 1/4 hour, or 900 seconds (INTPCS = 900). The soil moisture status for the entire watershed at the beginning of the storm event was set to zero (SMCWS =0.0). When SMCWS is set to zero antecedent moisture conditions will be computed internally for each HRU.

The storm event (line 5) began at 5:00 PM (NSTART = 17) June (MONTH = 6) 24th (NDAY = 24), 1958 (NYEAR = 58). Rainfall data for raingage Nos. 1 and 2, by 15-minute time intervals, follows in lines 6 and 7. For convenience in displaying output, the rainfall data are entered for complete hours. For example, if the first non-zero rainfall interval of a storm event begins at 11:30 AM, the storm is assumed to start at 11:00 AM. Zeros are entered for the appropriate time intervals between 11:00 and 11:30 AM. For 15-minute intervals two zero entries would be required. The additional computations required by this procedure are insignificant.

Since a non-uniform rainfall distribution is being assumed by the entry of two rainfall distributions, some method must be provided to assign these distributions to the proper finite elements. Seldom in actual practice will the rainfall distribution be known with certainty at all points within a grid structure such as this example. The procedure that was used to generate the assignment given in line 8 was to construct Thiessen polygons and assign the rainfall distribution represented by the polygon uniformly to those elements within the polygon. Elements falling along the boundary of the polygon were assumed to be within the polygon that contained over 50% of the element area.

This assignment is accomplished in this program by assigning the element represented by matrix NRGAGE the proper raingage number, beginning with the numeral 1 for the first raingage. The numerals for additional raingages are increased sequentially. For example, element 1 was assumed to be under the influence of raingage No. 2 (line 8).

Lines 9 and 10 list the monthly growth index and evapotranspiration estimates, respectively. The 30-day daily rainfall totals for raingage Nos. 1 and 2 are listed in lines 11-16. Each line contains ten data entries.

Indexing Control for HRU's and Flow Elements

The third data group (lines 17-73) results from the discretization of the drainage area into response units and into finite-sized elements. The first record of this group, line 17, provides indexing information to the number of subsheds (NTSS = 4), number of elements (NTELES = 16), number of HRU's (NDHRUS = 47) and the number of landuse types (NLANUS = 17) in the watershed.

Once HRU and element grid maps have been devised, the relative size of each HRU must be assigned to the proper element. This task was accomplished using the procadure described in the previous section. The data obtained from planimetering for all 16 elements was pre-processed into the form given in data group 3 (lines 18-73).

Line 18 represents the number of HRU's (NHRU(1) = 8) located within element No. 1 (see Figure 25). The following line (19) represents the index code for each HRU in that element. This index provides the cross-reference to the table of HRU characteristics in lines 83-129 discussed below.

Line 20 is the fraction of the area covered by corresponding HRU's, line 19, in element No. 1. These factors represent the weighting factor that will be applied to the excess rainfall that is generated for each HRU. The above sequence of data was compiled for the 16 elements defined in Pony Mountain Branch watershed (Figure 47).

Landuse and HRU Descriptors

The fourth data group (lines 74-129) consists of four data matrices defining landuse factors (AFLU), depression storage estimates (DSLU), Manning's roughness coefficient for overland flow (RCLU) and HRU characteristics (LANDU, FAW, FGW, FC, DEPTH and SLOHRU).

The first matrix of data (lines 74-76) consists of a series of values that are used by the Holtan equation (Eqn. (2)) to index the effect of cover conditions on infiltration. Lines 77-79 give estimates of depression storage for each landuse type and the third matrix of data (lines 80-82) in this group represent estimates for Manning's roughness coefficient as a function of landuse.

Note that the list contains more landuse types than were identified in Pony Mountain Branch watershed. This array of landuse need not conform in number to the landuses in a given watershed. The only requirement is that landuse types in the area being investigated are included in the array. An index code provides the proper pointer to these landuse factors for a given HRU.

More importantly, the index code provides a ready mechanism for changing landuse on a given HRU, therefore, eliminating the need to go through the time-consuming task of developing a new HRU map. This option becomes significant for including seasonal variation in landuse in addition to simply simulating "what if" scenarios relative to a pre-arranged order of landuse change.

The characteristics of each HRU are given in six data arrays (lines 83-129) that were organized so that continuity is maintained between each group. The HRU characteristics for Pony Mountain Branch watershed are summarized in Table A1. Referring to this table, FAW was assigned to the second column of data, FGW was assigned to the third column, FC was assigned to the fourth column, DEPTH was assigned to the fifth column and SLOHRU was assigned to the sixth column. The corresponding landuse codes (1-18) were defined in the first column of data and assigned to LANDU.

Computation Time Increments and Indexing for Flow Routing

The first record in the fifth data group (line 130) defines the routing interval for overland flow (DTO = 100) and channel flow (DTC = 5). For all applications DTO must be an integer multiple of DTC. An additional requirement is that the rainfall time increment (INTPCS) be an interger multiple of the overland flow time increment.

Low velocities of flow are common on most overland flow surfaces, while flow velocities in channels are normally much larger over shorter reach lengths and require a shorter routing time increment for accuracy. Some general criteria are given in Chapter III. From these criteria, the best procedure was to select the probable maximum velocity and determine the value of the time increment as previously described. Experience in modeling storm events on these watersheds led to the establishment of V = 0.25 seconds and V = 10.0 seconds as probable maximum velocities for overland flow and channel flow, respectively. By using Eqns. {38} and {43}, the computational time increments can be determined.

For Pony Mountain Branch watershed, the minimum overland flow element length was 210 feet. Substitution of this value and V = 0.25 seconds into the two aforementioned equations gave an overland flow time increment of 100.8 seconds, which was rounded to 100 seconds. Likewise, the time increment for channel flow was determined from the minimum channel element length of 450 feet and V = 10.0 seconds. This gave a time increment of 5.4 seconds which was rounded to 5 seconds. Note that the time increment for overland flow is an integer multiple of the channel flow time increment and that the rainfall time increment (INTPCS = 900) is an integer multiple of the overland flow time increment.

The second record in this data group (lines 131-133) provides indexing for the upstream channel boundary condition for subshed Nos. 1, 2, 3 and 4 (column matrix NODE1). The discharge at the upstream node for all times, t, for subshed Nos. 1, 2 and 4 is zero, therefore, NODE1(1), NODE1(2) and NODE1(4) were set to zero. The discharge at the upstream channel node for subshed No. 3, however, is equal to the sum of the discharge at the downstream nodes of subshed Nos. 1 and 2. NODE1(3), therefore, was set to 1. The outlet of the watershed is located at the confluence of subshed Nos. 3 and 4. To obtain the total discharge hydrograph an imaginary subshed was assumed and NODE1(5) was set to 2. The flows are summed but no routing is generated.

When NODE1 > 0 additional information must be included to identify the subsheds whose channel confluences form the upstream nodal point of a downstream subshed. For this example, the upstream boundary conditions for subshed No. 3 were NCONF1(3) = 1 and NCONF2(3) =2 while the upstream boundary conditions for the imaginary subshed (subshed No. 5) were NCONF1(5) = 3 and NCONF2(5) = 4.

Descriptors for Overland and Channel Flow Elements

The descriptive detail for elements are entered by subsheds as follows: geometry for overland flow elements followed by the geometry for channel elements. A subshed consists of two or more overland flow elements. The data must be entered starting to the left of the drainage channel, facing upstream, with the upper left element and continuing downstream until the data for all elements have been entered. The same procedure is followed for the elements located to the right of the drainage channel for the given subshed.

The first subshed entry given in data group 6 (lines 134-138) is the number of elements within subshed No. 1 (NSTRPS = 4), the number of elements to the left of the stream channel (LHSSPS = 2) and the number of channel elements (NECHAN = 2).

Lines 135-138 contain descriptive data for the overland flow elements. The length of the surface flow path for all elements is placed in column matrix XLEN, relief is placed in column matrix RELIEF, area is placed in column matrix AREA and the top width of the bottom node is placed in column matrix TWIDTH. For element No. 1, Pony Mountain Branch watershed, XLEN(1) = 960, RELIEF(1) = 190, AREA(1) = 50.1 and TWIDTH(2) = 1570. The data for the remaining three elements of subshed No. 1 are given in lines 136-138. The index code NDAMS is used to signify the presence or absence of impoundments. No impoundments were simulated in this watershed, therefore, NDAMS was implied to be 0.

The geometry for channel elements in subshed No. 1 (lines 139 and 140) follow data group 6. For the channel elements in subshed No. 1, XLEN(1) = 1570, RELIEF(1) = 150, RCOEF(1) = 0.08 and TWIDTH(2) = 11.

A triangular cross-sectional shape was assumed to be representive of the natural channel. The channel configuration can be varied by the width (TWIDTH) that is assigned at the 2-foot depth. This depth was chosen for convenience since top width equals area at this depth. For situations where the conveyance system differs greatly from the triangular approximation, an alternative option must be incorporated into the computer program (Appendix B).

The overland and channel flow element properties for the remaining subsheds (Nos. 2-4) were compiled and added to the input stream as shown in lines 141-161.

Simulating Landuse Change

Landuse changes can be rapidly incorporated into an existing data file. For example, assume for the purpose of demonstration that subshed No. 2 will be paved. This landuse change can be incorporated into the input data file (Appendix F) by replacing the existing landuse index code for all elements in subshed No. 2 (element Nos. 5-8) with the value 47 to define the impervious HRU. For example, the landuse codes for element No. 5 {IHRU(5,1) = 37, IHRU(5,2) = 43, IHRU(5,3) = 42} given in line 39, Appendix F would be replaced with the code 47. The corresponding values of FHRU in line 40 would be changed to the value 1.0 to reflect the

100% areal coverage of HRU No. 47 in element No. 5.

Numerous such scenarios can be devised, however, it seems inappropriate to exhaust such combinations in this report. It should be emphasized that this program provides a structure whereby variability within a watershed can be easily incorporated into the streamflow simulation process. Critical to obtaining reliable streamflow predictions, however, are good estimates of rainfall excess at all internal locations (HRU's). Hopefully, through the efforts of research investigators and application of the FESHM to actual field problems, estimating procedures for rainfall excess and mathematical description of interaction between elements can be greatly enhanced.

Simulating the Effect of Flood Detention Structures

Impoundments are often encountered in small agricultural type drainage systems. These may vary from small farm ponds to flood control structures (e.g., a Soil Conservation Service PL-566 structure).

There are two different approaches which may be taken when modeling these influences. The first method discussed is an approximate technique which minimizes user effort. Under this method, structures which are placed in either an overland flow or channel flow element may be simulated.

Simulating Overland Flow Element Flood Detention Structures

For the case of a structure placed in an overland flow element, it is assumed that flow is simulated across the element as usual, however, a portion of the flow is intercepted before entering the channel, the magnitude of which depends upon the size of the drainage area behind the structure. This intercepted flow accummulates to provide an updated account of the volume of water stored behind the structure. At each computational increment of the simulation, the volume is known and the flow which is to be released is calculated and added to that flow from the element which enters the channel.

For example, if a structure were to be placed in element No. 1 of subshed No. 1, the adjustments made to the input data stream to describe this effect would begin by specifying the value of NDAMS (Record No. 2, Table E6) to be 1 in line 135 of Appendix F. It is then necessary, in the records following line 135, to describe the properties of the flood detention structure according to the formats specified in Record Nos. 1, 2 and 3, Table E7.

Simulating Channel Flow Element Flood Detention Structures

For a structure placed in the channel, the approximate method requires that the location of the structure be relegated to the nearest channel node in the prescribed finite element grid. Two subsheds are then defined in place of the single original watershed: one upstream of this node and the other downstream. Thus, routing is performed independently upstream and downstream of the structure. Flow is routed through the structure identically to that routed through the structures placed in overland flow elements. That flow which is released from the structure becomes the upstream boundary condition for the channel in the downstream subshed.

If this type of structure were to be placed at node No. 2 of the channel in subshed No. 1, the value of KDAM (Table E8) would be specified as 1 in line 139, Appendix F. Record Nos. 1, 2 and 3, Table E9 give the formats for the channel element flood detention descriptors which would follow line 139.

Alternative Approach for Flood Detention Structures

A more exact method of simulating flood detention structures is similar to that described above, however, it requires a rediscretization of the watershed to place nodes at the exact structure locations and to route flow through those structures which would have been located in an overland flow element, as channel flow. The magnitude of effort involved in this approach is evident as replanimetering of the watershed would be necessary along with major revisions in the watershed input data file. This realization reiterates the importance of node placement at all existing structures of this type in the original discretized watershed grid.

CHAPTER V

APPLICATIONS AND RESULTS OF THE FESHM

The FESHM was first applied to a hypothetical watershed case for the purpose of evaluating model response under conditions which are not as complex as those encountered in natural watersheds. This type of application provides valuable insight as to how and why certain actions taken by the user produce the results which occur, while eliminating the interactions which generally occur in the modeling of complex physical systems.

The FESHM was also used to simulate discharge from natural experimental watersheds which had extensive historical records. It was important in this respect to model watersheds with complete information and good data resolution for a proper evaluation of the effectiveness of the model.

A Hypothetical Watershed Example

The hypothetical watershed shown in Figure 26 will be used to illustrate the weighting process and sensitivity of several model parameters. The effects of spatial variability on the modeling of streamflows will also be evident and some approaches to optimization will be discussed. The flexibility of the model in simulating the effects of landuse changes and management practices will also be shown.

The model was run with simulated storm data and all pertinent watershed data necessary to drive the model is listed in Tables 7-11. These data are representative of conditions which may exist on a natural watershed. The source and availability of such data was discussed in the previous chapter. In the following comparisons, the hydrograph which results from the original conditions is referred to as the base hydrograph.

Parameter Sensitivity

There are many interacting parameters which have an influence upon the response of the model, however, only those which are least easily identifiable and have the greatest effect will be illustrated. These parameters can be assigned to one of two major groups: those which determine volume of runoff and those which determine the timing

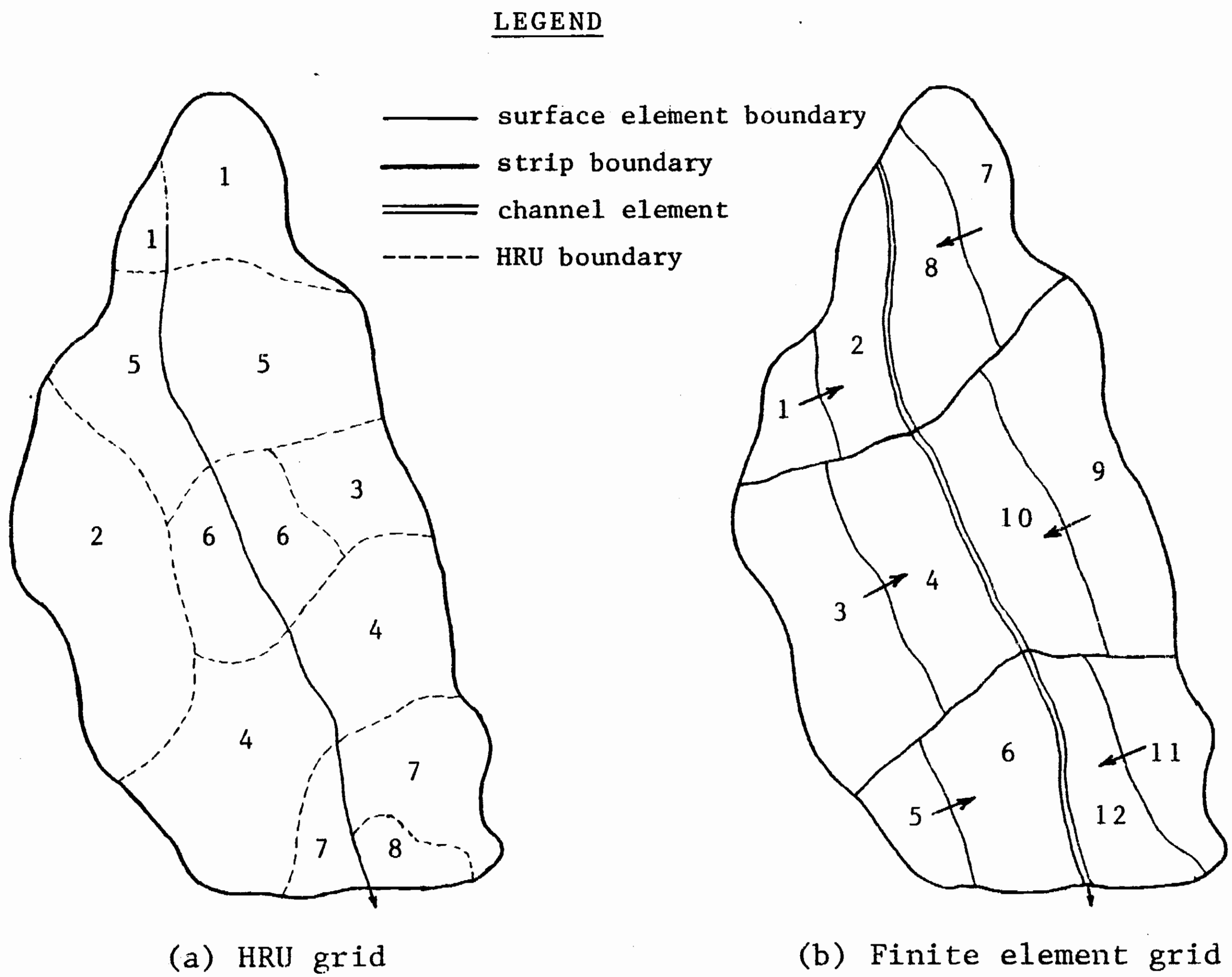


Figure 26. HRU and finite element grids for a hypothetical watershed.

Table 7. Soil mapping unit-landuse combinations to create HRU's in Figure 20a.

HRU Number	Soil Texture	Landuse
1	silty clay loam	woods
2	silty clay loam	woods
3	silt loam	woods
4	loam	pasture
5	loam	row crop
6	loam	row crop
7	sandy loam	residential
8	-	impervious

Table 8. Soil and landuse characteristics for HRU's in Figure 20a.

HRU No.	Plant Available Water (in/in)	Gravitational Water (in/in)	Soil Depth (in)	Final Infiltration Rate (in/hr)	Holtan 'a'	Manning 'n'
1	0.149	0.084	8.0	0.200	1.00	0.40
2	0.149	0.084	10.0	0.200	1.00	0.40
3	0.119	0.114	6.0	0.250	1.00	0.40
4	0.156	0.144	10.0	0.250	0.50	0.30
5	0.156	0.144	5.0	0.250	0.25	0.35
6	0.156	0.144	8.0	0.250	0.25	0.35
7	0.123	0.186	3.0	0.300	0.10	0.25
8	-	-	-	-	-	0.02

Table 9. Properties of the overland flow elements for the hypothetical watershed.

Element Number	Length (ft)	Downstream Node Width (ft)	Slope (ft/ft)	Weighted Manning 'n'
1	1000	1100	0.016	0.388
2	1000	2200	0.010	0.388
3	1000	2650	0.012	0.390
4	1000	2200	0.008	0.353
5	1000	1100	0.008	0.300
6	1000	2200	0.005	0.280
7	750	2200	0.016	0.385
8	750	2200	0.011	0.370
9	750	2900	0.012	0.355
10	750	2200	0.008	0.343
11	750	2050	0.008	0.237
12	750	2200	0.005	0.208

Table 10. Properties of the channel flow elements for the hypothetical watershed.

Element Number	Length (ft)	Channel side slopes at downstream node (%)	Slope (ft/ft)	Manning 'n'
1	2200	11	0.008	0.10
2	2200	15	0.005	0.09
3	2200	11	0.003	0.08

Table 11. Weighting factor for hydrologic response units.

Element Number	Hydrologic Response Unit Numbers 1	2	3	4	5	6	7	8
1	-	0.75	-	-	0.25	-	-	-
2	0.70	0.05	-	-	0.25	-	-	-
3	-	0.90	-	0.10	-	-	-	-
4	-	0.20	-	0.15	0.15	0.50	-	-
5	-	-	-	1.00	-	-	-	-
6	-	-	-	0.60	-	-	0.40	-
7	0.70	-	-	-	0.30	-	-	-
8	0.40	-	-	-	0.60	-	-	-
9	-	-	0.40	0.30	0.30	-	-	-
10	-	-	0.10	0.25	0.25	0.40	-	-
11	-	-	-	0.20	-	-	0.70	0.10
12	-	-	-	0.30	-	-	0.45	0.25

of runoff.

Parameters Determining Runoff Volume

The HRU map shown in Figure 26a is a hypothetical combination of an overlay of maps of soils and landuse. Properties of these HRU's are listed in Tables 7 and 8.

Soil depth--Of the several parameters (Table 8) which must be defined to compute rainfall excess for each HRU by the Holtan equation (Eqn. {2}), soil depth (depth of the control zone) becomes the most critical soil parameter because of its influence on the magnitude of rainfall excess. Simulations of excess rainfall are very sensitive to changes in soil depth because infiltration, as determined by the Holtan equation, is a direct function of the volume of unfilled pore space in a given soil depth. The quantity of rainfall excess will obviously decrease with an increase in soil depth and vice versa, although the magnitude of this change will be tempered by interactions among soil type, cover and rainfall intensity.

The effect of variations in the soil depths of the hypothetical watershed is illustrated in Figure 27 where depths of all soils have been increased and decreased by 3 inches.

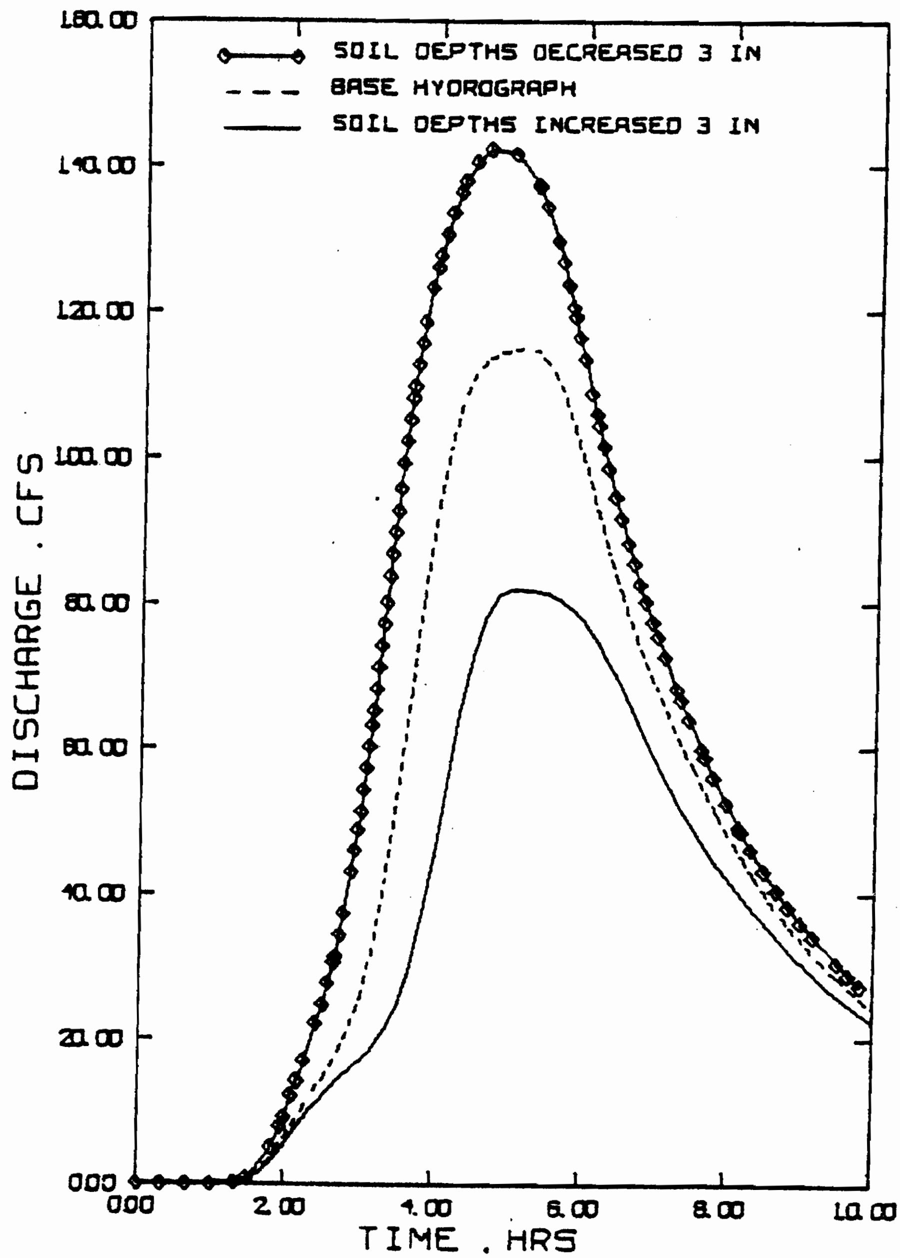


Figure 27. The effect of soil depth on discharge hydrographs generated from a hypothetical watershed.

<u>Antecedent soil moisture</u>--Concurrent with the influence that variations in soil depth has upon the rainfall excess response of the watershed is the proper definition of antecedent moisture conditions, i.e., the amount of pore space in the soil profile which is filled prior to the beginning of rainfall. It is well recognized that the moisture condition existing throughout a watershed prior to a storm event is a significant factor in determining how much water will be available for runoff. The initiation of surface runoff and the resultant volume of flow can be significantly affected. The effect of varying antecedent moisture between dry, average and wet conditions is illustrated in Figure 28. For the base hydrograph, initial moisture content was set to 50% of field capacity.

<u>Holtans 'a'</u>--The parameter 'a' in the Holtan equation (Eqn. (2)) is used in the soil moisture model to index the effect of soil cover on runoff. This value lies between zero for an impervious area and 1.0 for a highly pervious area.

The rate of infiltration is directly influenced by the magnitude of 'a' which may vary greatly for a particular landuse from one season of the year to another depending upon the stage of growth of vegetation. This variation is determined by the GI term in the Holtan equation (Eqn. (2)).

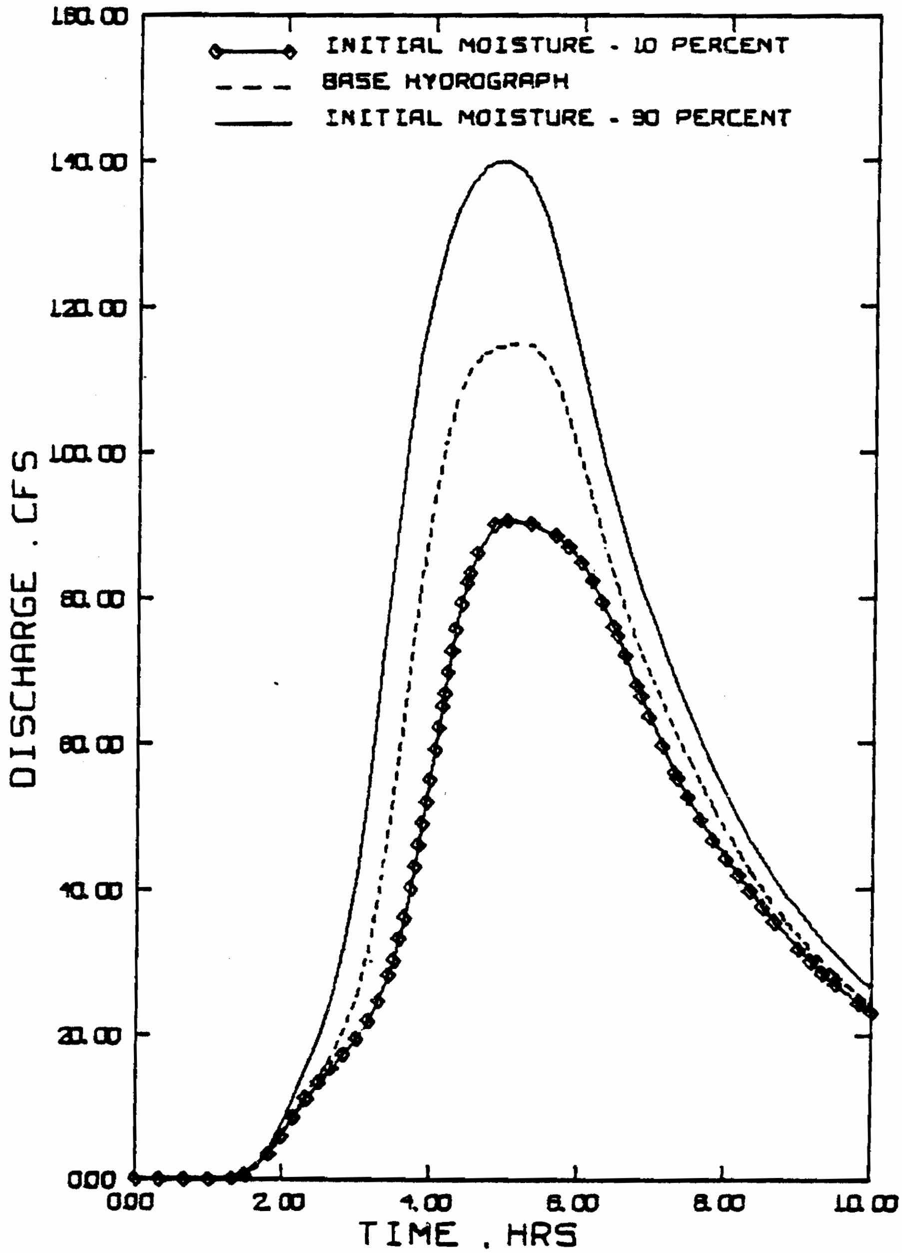


Figure 28. The effect of antecedent moisture conditions on discharge hydrographs generated from a hypothetical watershed.

Accurate rainfall excess predictions, therefore, depend highly upon the assignment of 'a' values to existing landuse types. Figure 29 shows the effect of a plus or minus 20% change in these values upon the downstream hydrograph.

Parameters Determining Runoff Timing

After grid elements have been defined several parameters must be determined for the purpose of correctly routing the excess rainfall throughout the watershed. These are summarized in Tables 9 and 10 for the case of the hypothetical watershed while Table 11 gives the HRU-element weights.

A correct determination of several of these parameters is somewhat vague and requires some degree of judgement by the user. Consequently, these may introduce the greatest errors in the computed hydrograph.

Manning's 'n'--The parameter which presents immediate difficulty is the Manning roughness coefficient. The Manning 'n' values for overland flow elements given in Table 9 are weighted averages of the individual Manning 'n' values for each landuse type in a given element. These resultant element roughness coefficients for the hypothetical watershed were determined from the HRU-element weights given in Table 11 and the Manning 'n' values for the landuse types

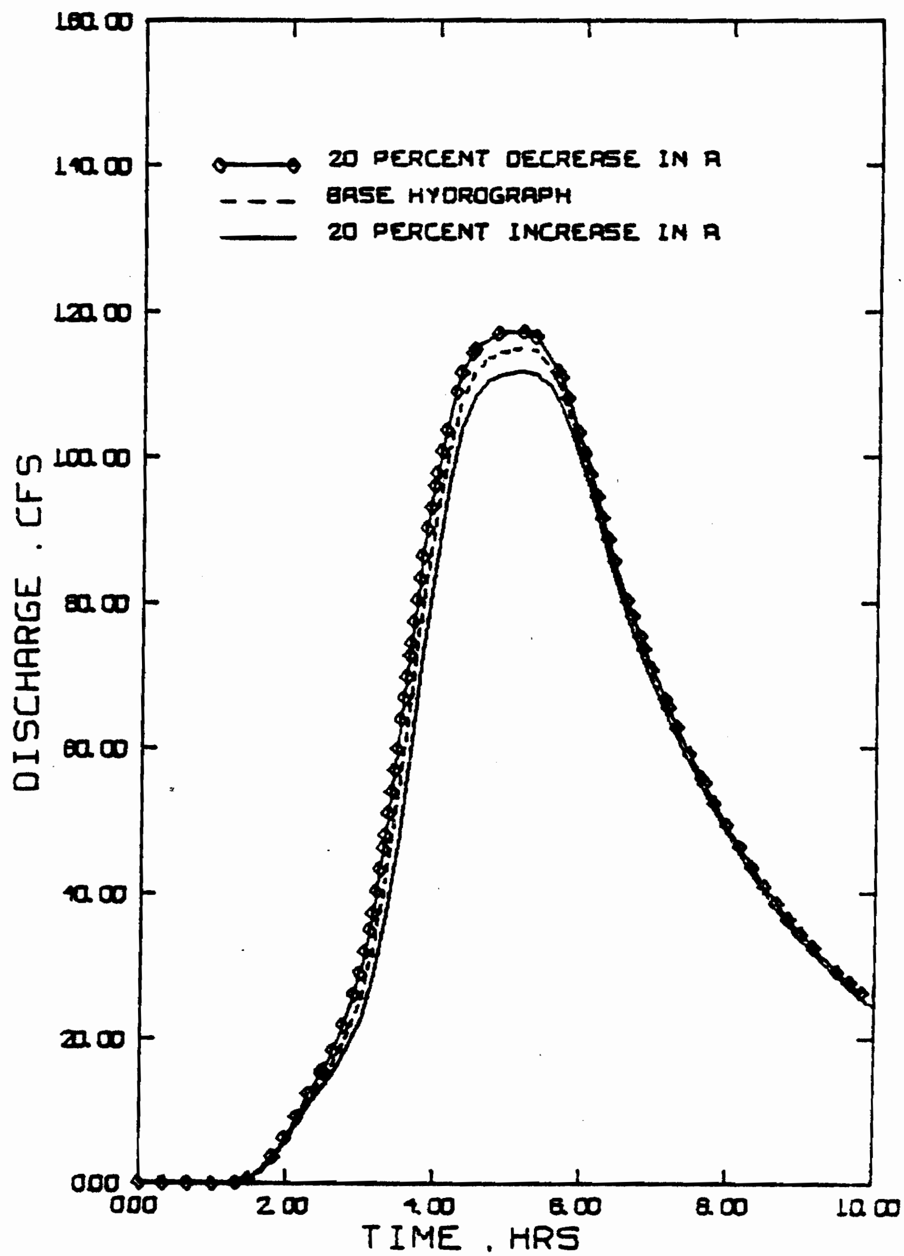


Figure 29. The effect of the vegetative coefficient on discharge hydrographs generated from a hypothetical watershed.

listed in Table 8. Figure 30 shows the effect of increasing and decreasing Manning 'n' for the pervious landuse types by 0.05 and Table 12 lists the resultant Manning 'n' values for each element after these changes were made along with the original values.

The model responds abruptly to changes in channel roughness. The hydrographs generated with channel Manning 'n' values of 0.01 and 0.40 are compared in Figure 31. As expected, rougher flow surfaces dampened flow and delayed peaks.

Element length--The selected length of the flow elements in the grid is important because of the dominant influence of this parameter on the resultant hydrograph. The selection of channel flow element lengths is a fairly simple procedure, however, determining overland flow lengths requires an entirely different concept of flow over the flow plane since it is a highly conceptualized entity. For the hypothetical watershed, overland flow element lengths were increased and decreased 25% to observe this effect. The results of these alterations are illustrated in Figure 32. It is evident that this parameter is a primary factor in determining the lag time and the magnitude of the peak discharge.

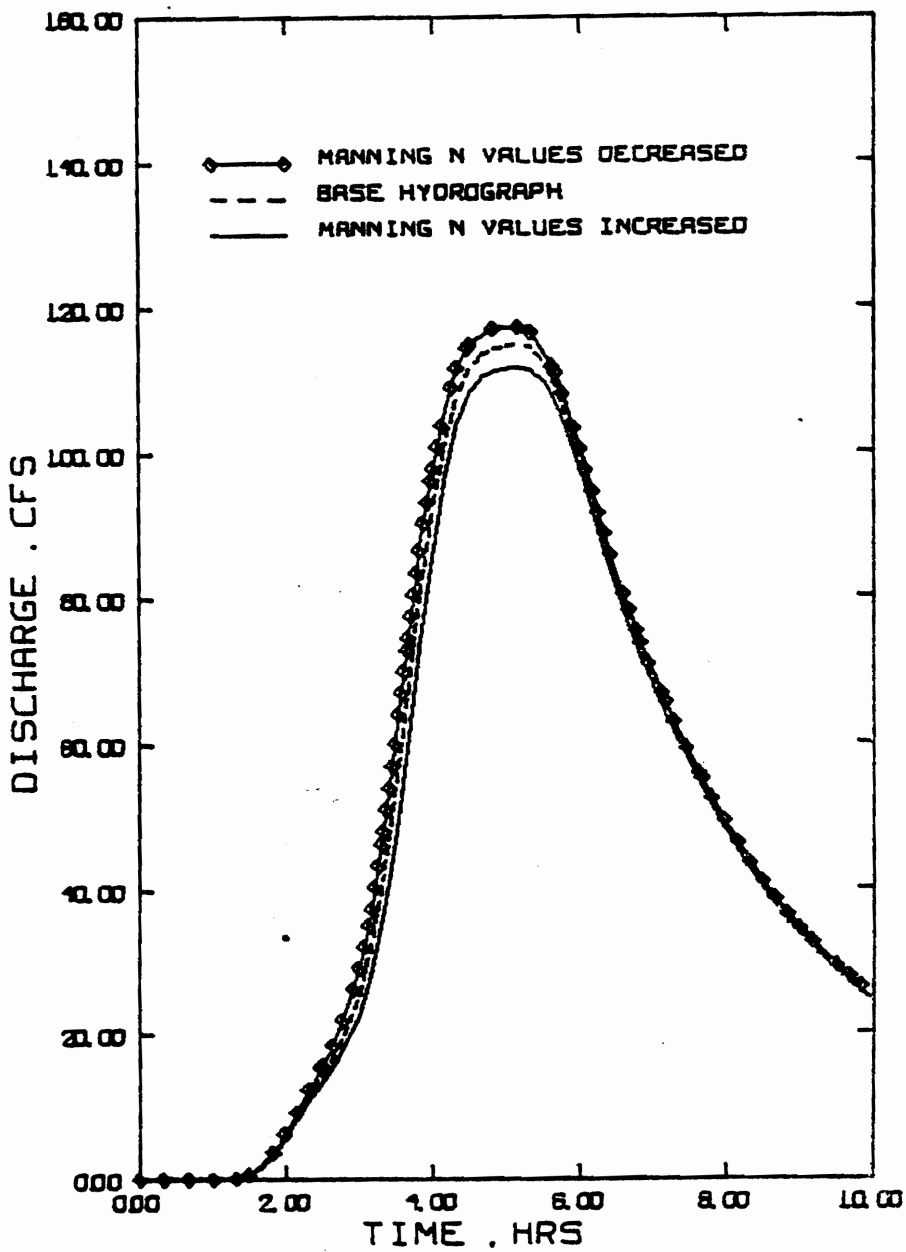


Figure 30. The effect of overland flow surface roughness on discharge hydrographs generated from a hypothetical watershed.

Table 12. Manning's 'n' for overland flow elements with and without landuse changes.

Element Number	Original Value	Plus 0.05	Minus 0.05
1	0.388	0.437	0.337
2	0.388	0.437	0.377
3	0.390	0.440	0.340
4	0.353	0.402	0.302
5	0.300	0.350	0.250
6	0.280	0.330	0.230
7	0.385	0.435	0.335
8	0.370	0.420	0.320
9	0.355	0.405	0.305
10	0.343	0.392	0.292
11	0.237	0.282	0.192
12	0.208	0.245	0.170

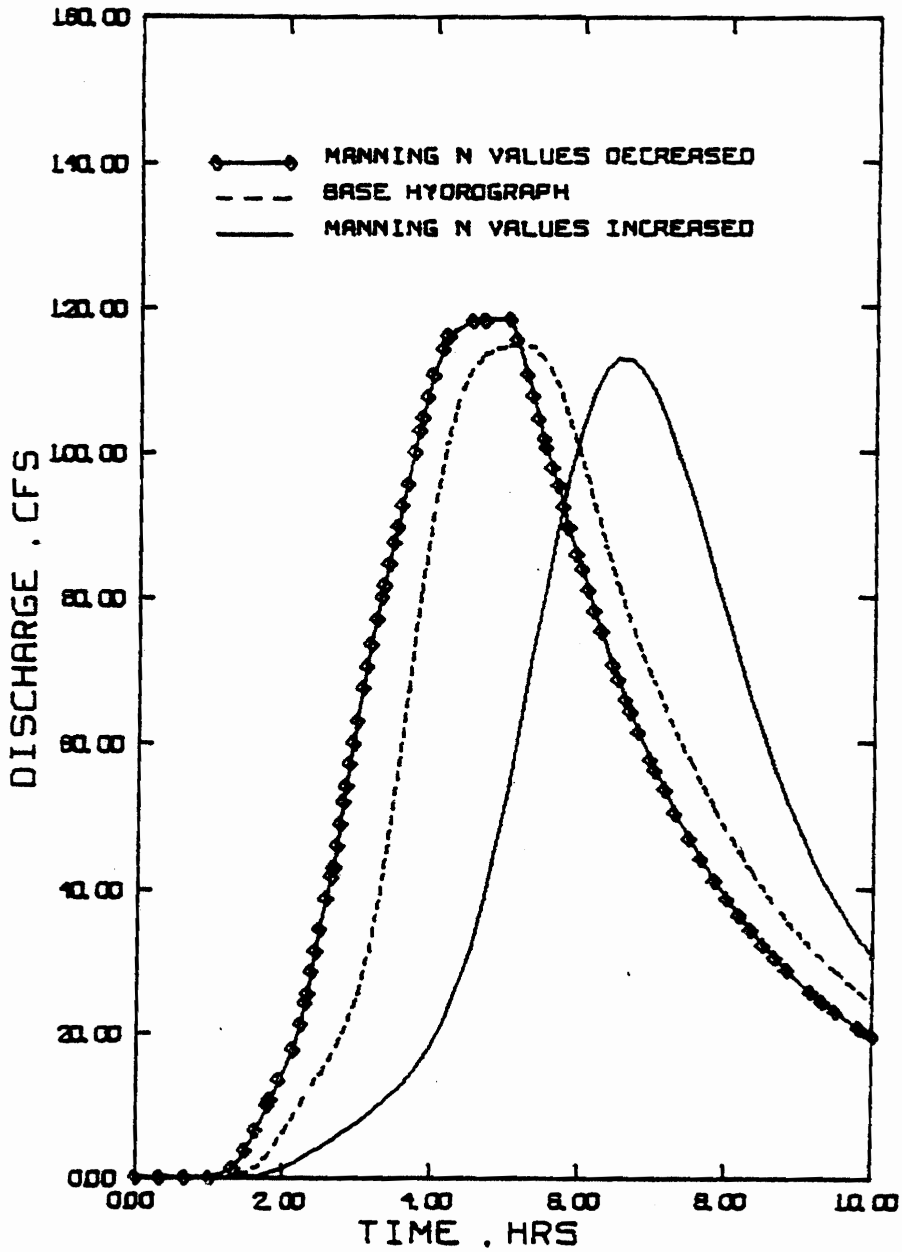


Figure 31. The effect of channel flow roughness conditions on discharge hydrographs generated from a hypothetical watershed.

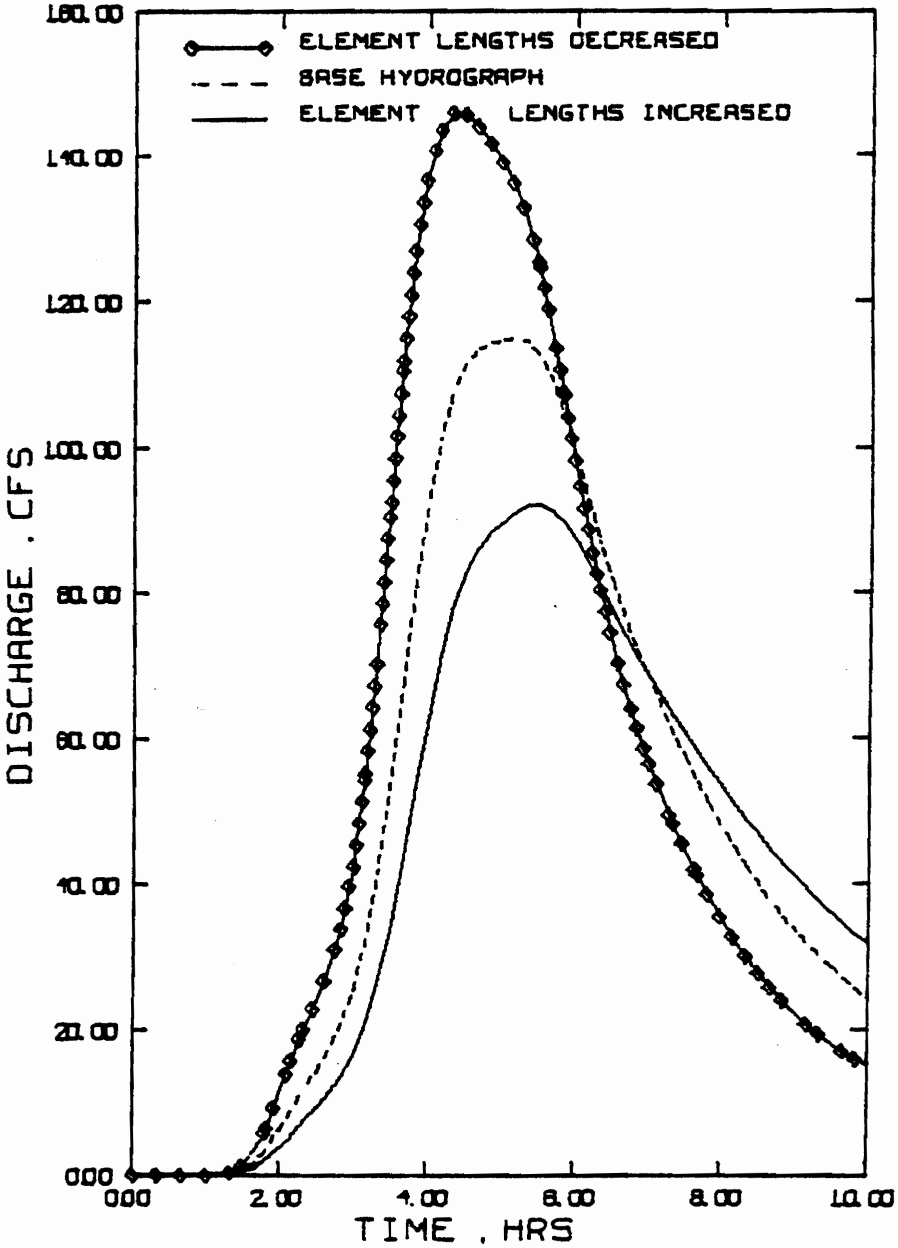


Figure 32. Comparison of discharge hydrographs as overland flow element lengths are varied in a hypothetical watershed.

Channel cross-section--Channel cross-sections which are representative of a channel reach are difficult to define. Proper description is important since this information is necessary in the computation of hydraulic radius, R, in the Manning equation (Eqn. {37}). It is important to have a realization of the kind of impact which results when variations in channel descriptors occur.

A simple triangular-shaped channel was chosen with side slopes given in Table 10. Figure 33 reveals the effect of varying these slopes at node Nos. 2, 3 and 4 from 5.7%, 7.6% and 5.7% to 21.8%, 38.7% and 21.8%. Appreciable differences did not occur despite the wide range of the side slopes used in defining the channel shapes. While the model is fairly insensitive to the applied cross-sections with respect to discharge, other factors, such as velocity and stage, will be very sensitive to these variations.

Effect of Neglecting Spatial Variability

Much of the prior discussion of the model has dealt with the importance of retaining spatial variability, not solely for localizing hydrologic effects, but also for the effect that the lumping of parameters may have upon the downstream hydrograph, particularly when wide variations exist over a watershed. Spatial variation in several of the more impor-

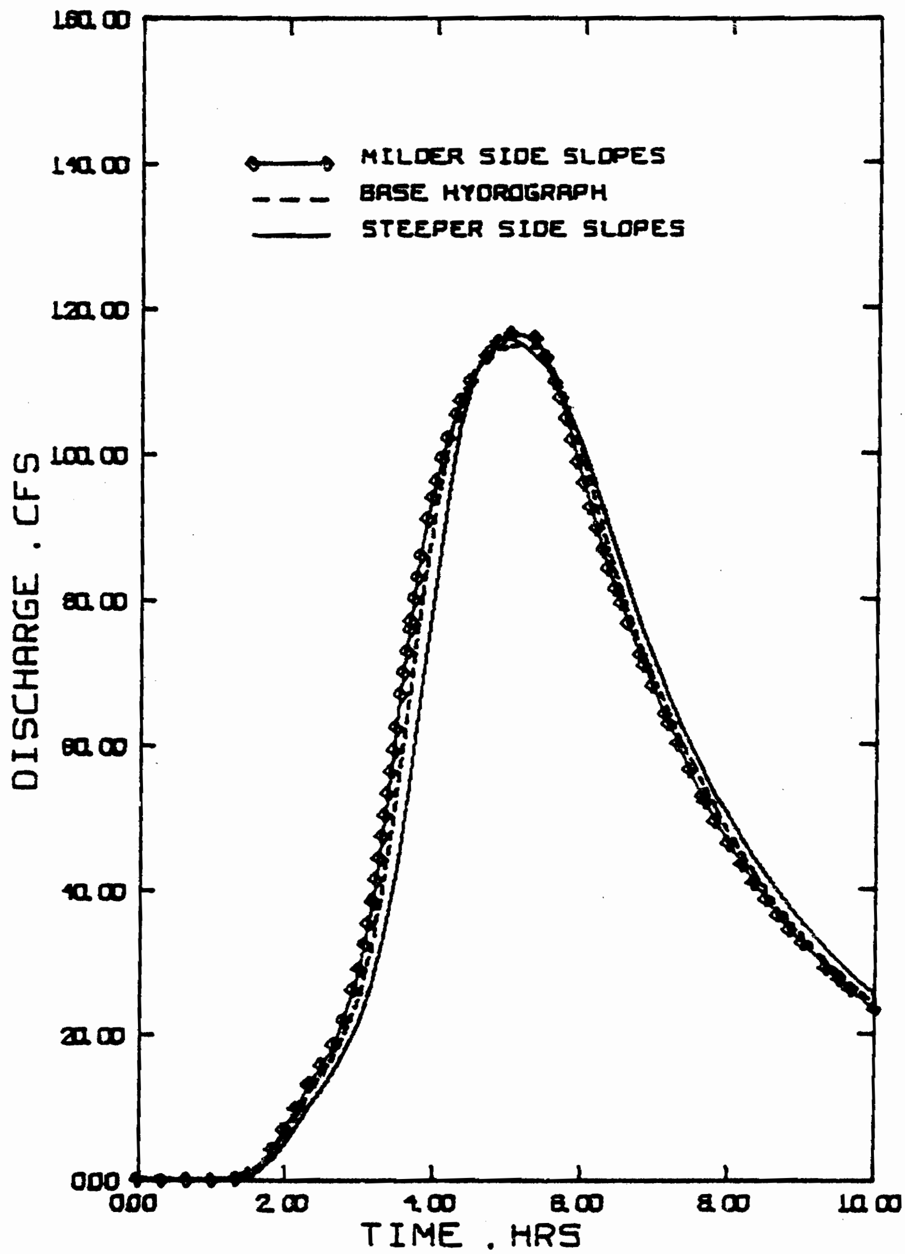


Figure 33. Comparison of discharge hydrographs as side slopes of channel cross-sections are varied in a hypothetical watershed.

tant parameters is considered below by weighting the parameters under consideration and applying these lumped values to the entire watershed.

Rainfall

An attempt was made to retain spatial variability in the rainfall aspect of the model. This is important since it has been well-established that proper representation of the rainfall distribution is significant to minimizing the error between a sequence of recorded and simulated flow {Aitken (1973)}.

The means of accomplishing this is by application of the Thiessen method for determining the linear variation of rainfall between each pair of a series of raingages. When the Thiessen polygons are constructed on a finite element grid it is a simple matter to assign the rainfall rates from a given raingage to the elements which fall within its area of influence. Since the rainfall distribution is varied on an element basis, all HRU's within a given element, therefore, must receive the same rainfall distribution.

Two raingage locations were assumed for the watershed of Figure 26. The Thiessen polygon structure resulted in raingage No. 1 being assigned to element Nos. 1, 2, 4, 7, 8, 9 and 10 while raingage No. 2 was assigned to element Nos. 3, 5, 6, 11 and 12. Table 13 lists the rainfall distribution for raingage Nos. 1 and 2 and the values for the alternative weighting approach. Figure 34 compares the results of these two approaches for the hypothetical watershed and from this it is quite evident that gross errors may result by ignoring the spatial variability in rainfall.

The variations in the rainfall distribution of the two raingages is not untypical of rainfall patterns over small areas during certain periods of the year in many sections of the country.

HRU's

As previously mentioned, spatial variability in hydrologic response units is an important aspect of the model. This allows each flow element to retain its unique hydrologic response to a given input. The effect of the lumping of these response units to create an HRU pattern for each element identical to that of the entire watershed is illustrated in Figure 35. All other watershed parameters remained unchanged while this adjustment resulted in each element containing identical rainfall excess available for runoff. Variations in the lumped versus non-lumped HRU concept are noticeable, however, this disparity can be expected to increase with lower rainfall intensities.

Table 13. Rainfall distributions applied to the hypothetical watershed.

Hour	Unweighted Rainfall (in) Raingage #1	Raingage #2	Weighted Rainfall (in)
1	0.50	0.00	0.293
2	0.75	1.00	0.854
3	1.00	0.50	0.793
4	0.75	0.20	0.522
5	0.50	0.20	0.376
6	0.20	0.00	0.117

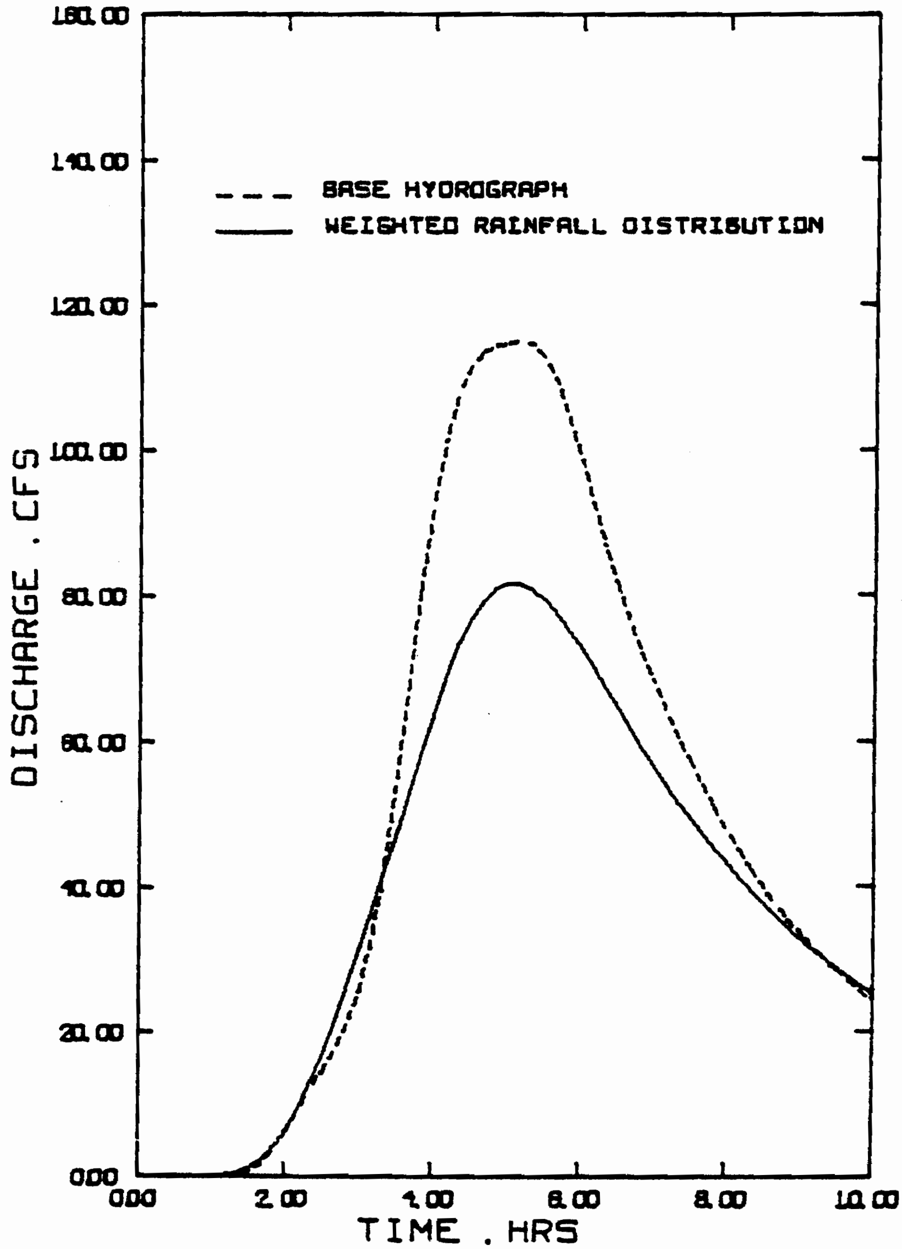


Figure 34. Comparison of discharge hydrographs obtained from weighted and unweighted rainfall distributions in a hypothetical watershed.

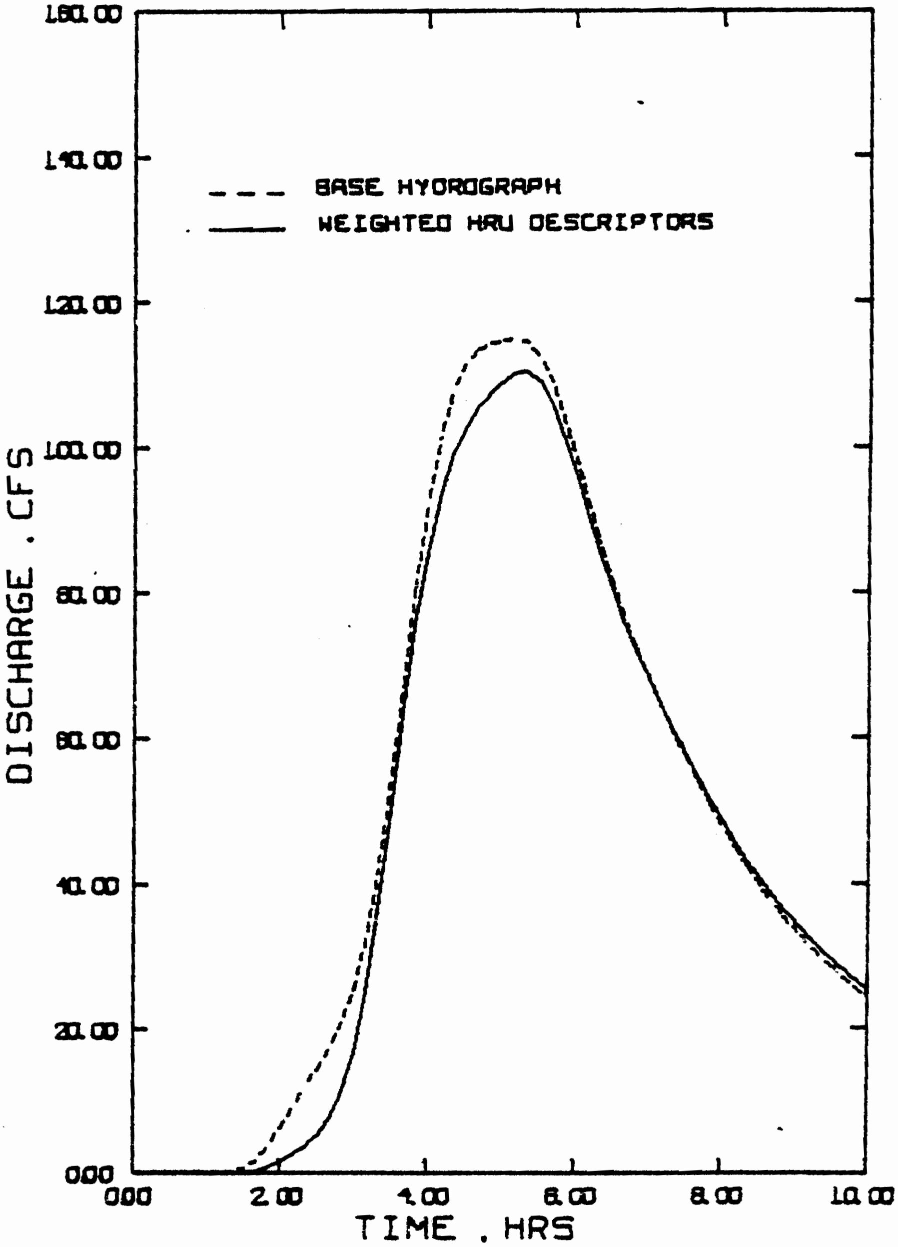


Figure 35. Comparison of discharge hydrographs obtained from weighted and unweighted HRU descriptors in a hypothetical watershed.

Element Roughness

Another important spatially variable parameter is that of resistance to overland flow, or Manning 'n' of surface elements, since this value may vary greatly across a watershed. A weighted average was taken of all current element Manning 'n' values on the watershed and this resultant value of 0.335 was used throughout. Figure 36 reveals the effect of this change on the downstream hydrograph.

Simulating Landuse Changes

It is often beneficial to determine the impact of changing landuse properties in a given element or elements on the discharge hydrograph at some point downstream. Conceptually, this can be easily accomplished with this modeling technique. It must be emphasized, however, that the validity of results at interior nodes must be established from field experiments. The following examples, therefore, serve only to illustrate how landuse changes can be modeled with this procedure, and the simulation results should not be construed as actual occurrences.

Landuse change simulations are not limited to entire areas which are presently designated as HRU's or elements in the data base as is the case in the three examples given below. Any portion of an HRU or element may be altered sub-

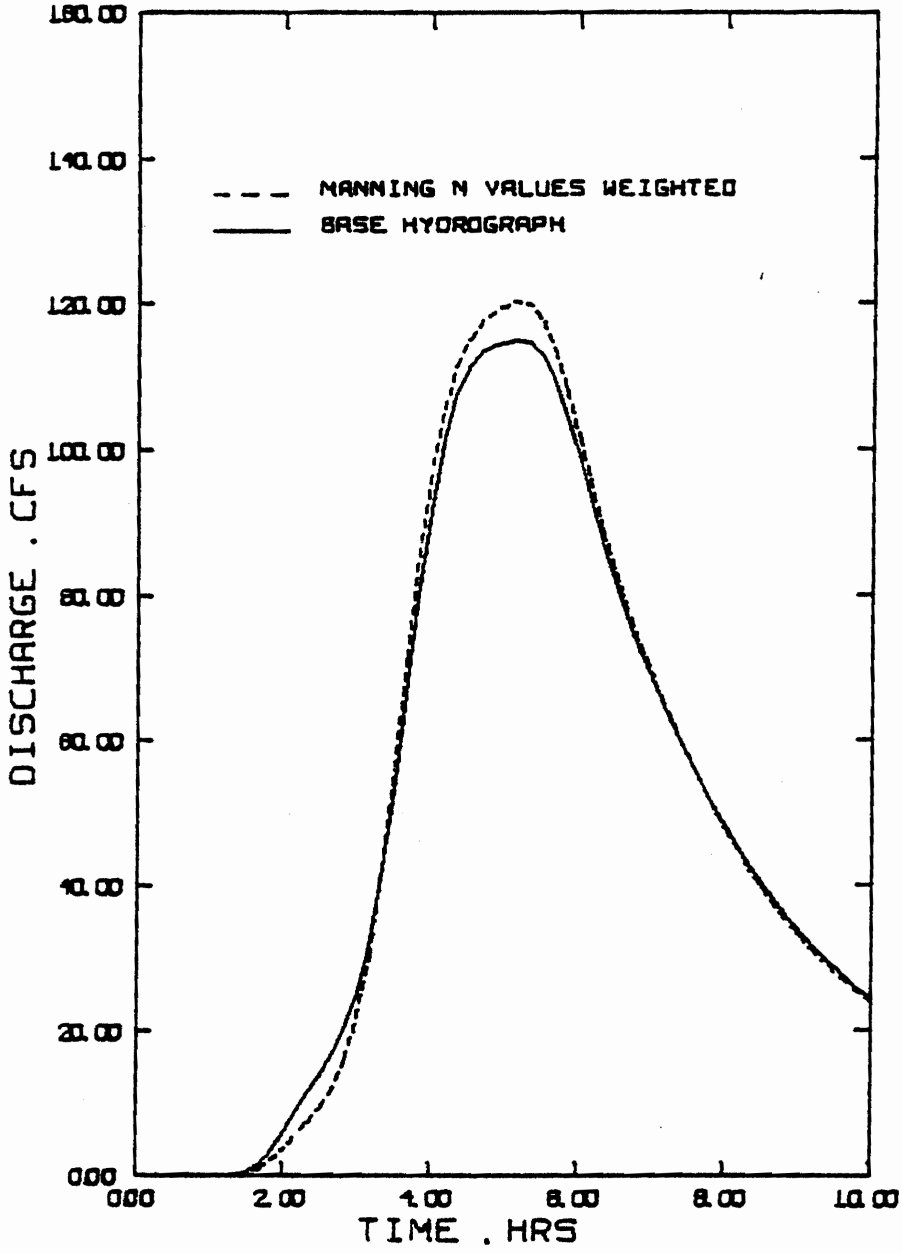


Figure 36. Comparison of discharge hydrographs obtained from weighted and unweighted roughness coefficients for overland flow elements in a hypothetical watershed.

ject to replanimetering of the watershed maps to correct the data base to reflect the proposed landuse change.

Pervious Area to an Impervious Area

To model the effect of the placement of a large impervious area within the watershed (e.g., the construction of a shopping center and adjoining parking lot), element No. 8 was transformed into an element with an impervious landuse. As a result, rainfall excess is equal to rainfall for this element and Manning 'n' is greatly increased. Simulation of these conditions show that the peak flow was increased by 5.1% and the flood wave was passed through the system 1/2 hour sooner (Figure 37). This becomes more impressive when one realizes that an area consisting of less than 8% of the total drainage area was affected.

Agricultural Area to Residential Area

A long-range landuse change is illustrated by changing HRU No. 4 from agricultural (pasture) to residential. To model this change, element Nos. 3, 4, 5, 6, 9, 10, 11 and 12 were redefined in terms of their new landuse properties. This change also has the effect of decreasing infiltration capacity of the affected area and lessening resistance to

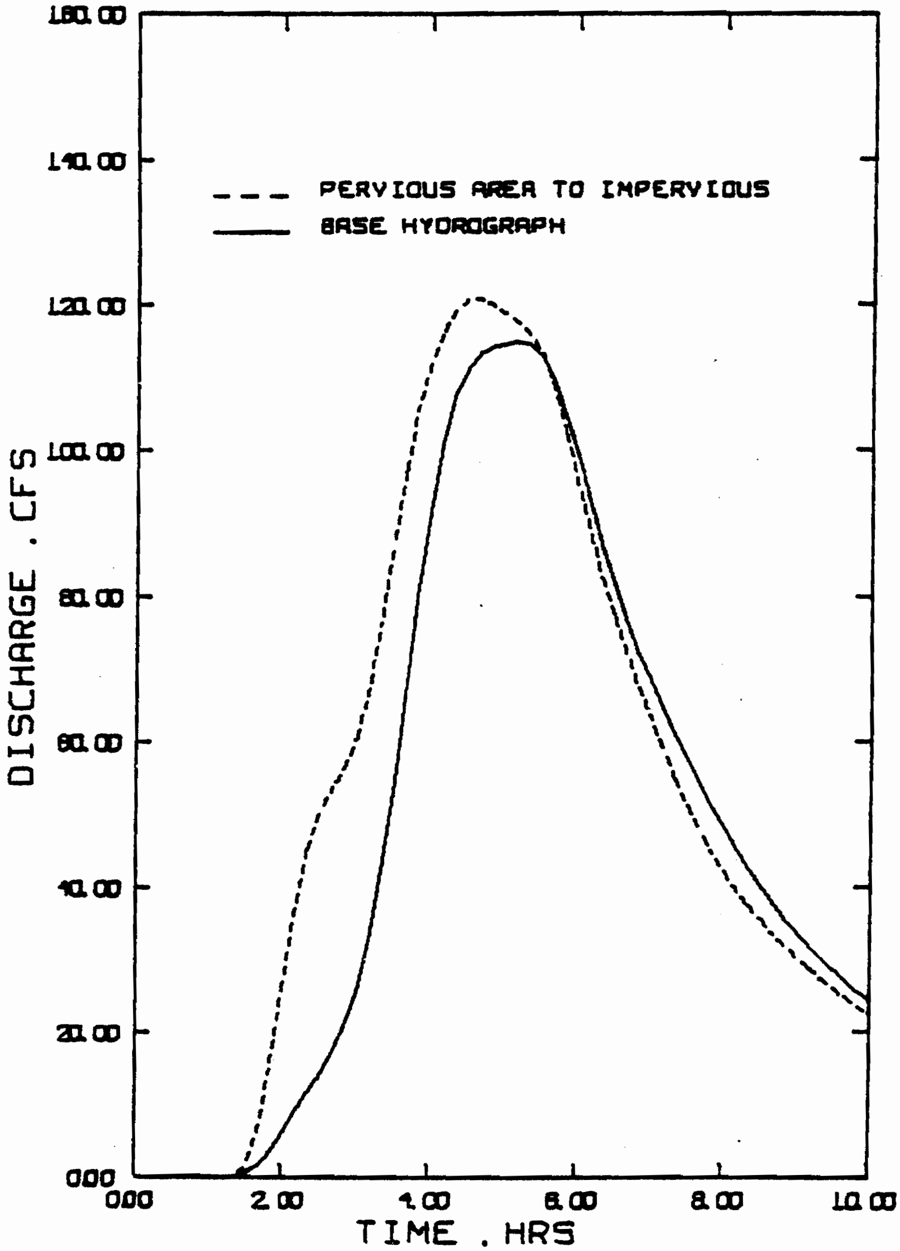


Figure 37. Effect of changing the landuse in element No. 8, Figure 26, to an impervious landuse.

flow. The effect of this change is shown in Figure 38 where hydrographs from present and future landuse conditions are compared. The peak discharge was increased by 10.7% and occurred 1/2 hour sooner.

Conventional Tillage to No-tillage Practice

The effect of agricultural management practices may also be evaluated with the model. HRU Nos. 5 and 6 are currently listed as row crops such as would be the case of a field planted in corn. An agricultural option which has a profound effect upon the hydrologic response of the land area affected is that of no-tillage planting. This practice tends to increase the infiltration capacity of the soil and also to act as an impediment to flow. The Holtan 'a' and Manning 'n' values, therefore, need to be adjusted to reflect this phenomenon. For this case, in HRU Nos. 5 and 6, the 'a' and 'n' values are changed from 0.25 and 0.35 to 0.60 and 0.40, respectively. The area affected by this change consists of 27% of the total watershed area. Figure 39 shows the effect of this practice where the peak discharge decreased by 6.8% and occurred 20 minutes sooner.

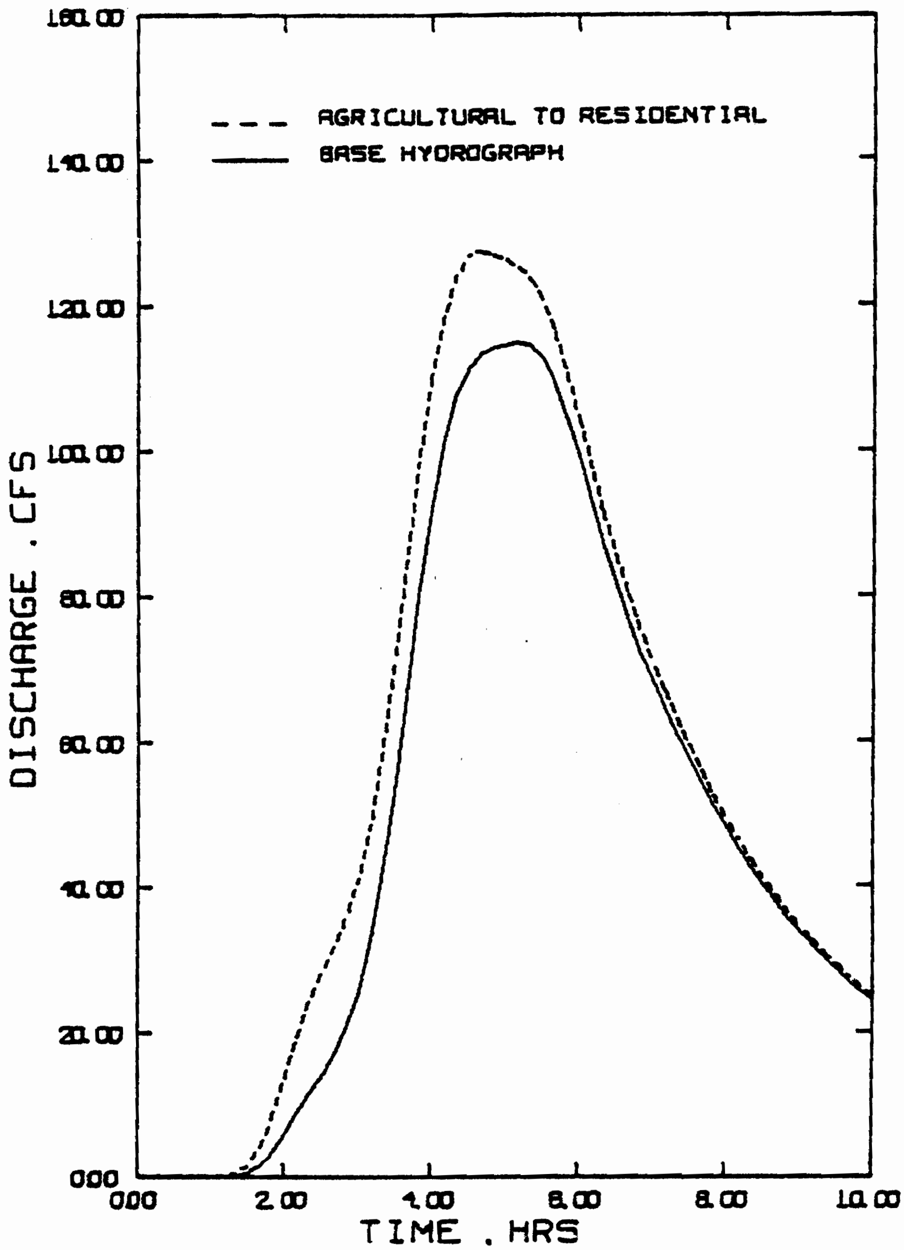


Figure 38. Effect of changing the landuse in HRU No. 4, Figure 26, to a residential landuse.

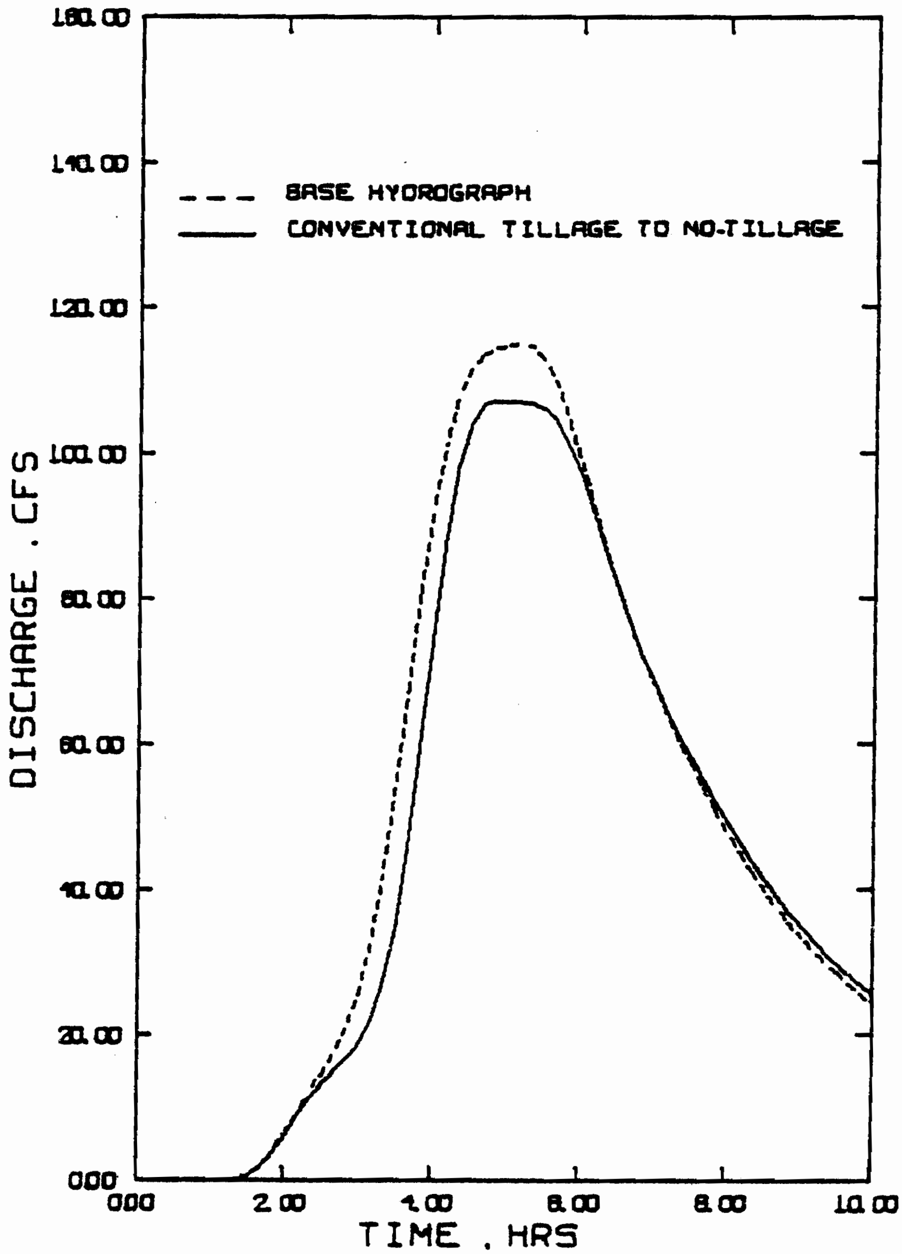


Figure 39. Effect of changing conventional tillage for corn production, Figure 26, to the no-till tillage practice.

Flood Detention Structures

A basic property of the model structure is the capability of simulating point alterations which affect flow as well as those changes which occur over an extended area. This would primarily imply flood control structures but the concept can be expanded to include any structure which impedes flow, such as farm ponds, weirs, etc. A knowledge of the depth-discharge relationship of flow through the structure, however, is necessary and this is easily obtained from design criteria.

Two different approaches are taken in modeling these aspects depending upon whether the structure is to be placed in the overland flow or channel flow regime of the watershed. The technique by which this is accomplished was discussed in Chapter IV which describes the computer model input data requirements.

Overland Flow Structure

One possible use of this capability of the model is that of determining the most advantageous location for a structure by determining the location that minimizes peak flow. To illustrate this procedure, an imaginary flood detention structure, with a drainage area of 90 acres, was placed in strip Nos. 3 and 4. Volume-discharge relationships were estimated for this structure from the operating characteristics of similar structures. The assumption was made that an identical structure could be located anywhere on the watershed and include the same drainage area, although in reality, this would be highly improbable. This, however, is a convenient assumption for the purpose of this illustration and is not a constraint on the application of the model.

The two discharge hydrographs are compared in Figure 40 with the discharge hydrograph from original landuse conditions. It would appear that the prime location for this structure would be strip No. 4. When the structure was located in strip No. 3, the peak discharge was decreased by 12.9%. In contrast, location of the structure in strip No. 4 resulted in a 25.2% decrease in peak discharge. These results from this single storm event example can not be termed conclusive, nevertheless, they do serve to illustrate the nature of the studies which may be performed.

Channel Flow Structure

The effect of a flood detention structure placed in the channel is illustrated by Figure 41. This resulted from the placement of a structure at node No. 2 of the channel where volume-discharge relationships were estimated from the operating characteristics of similar structures.

This particular alteration resulted in a decrease in peak discharge of 61.2%.

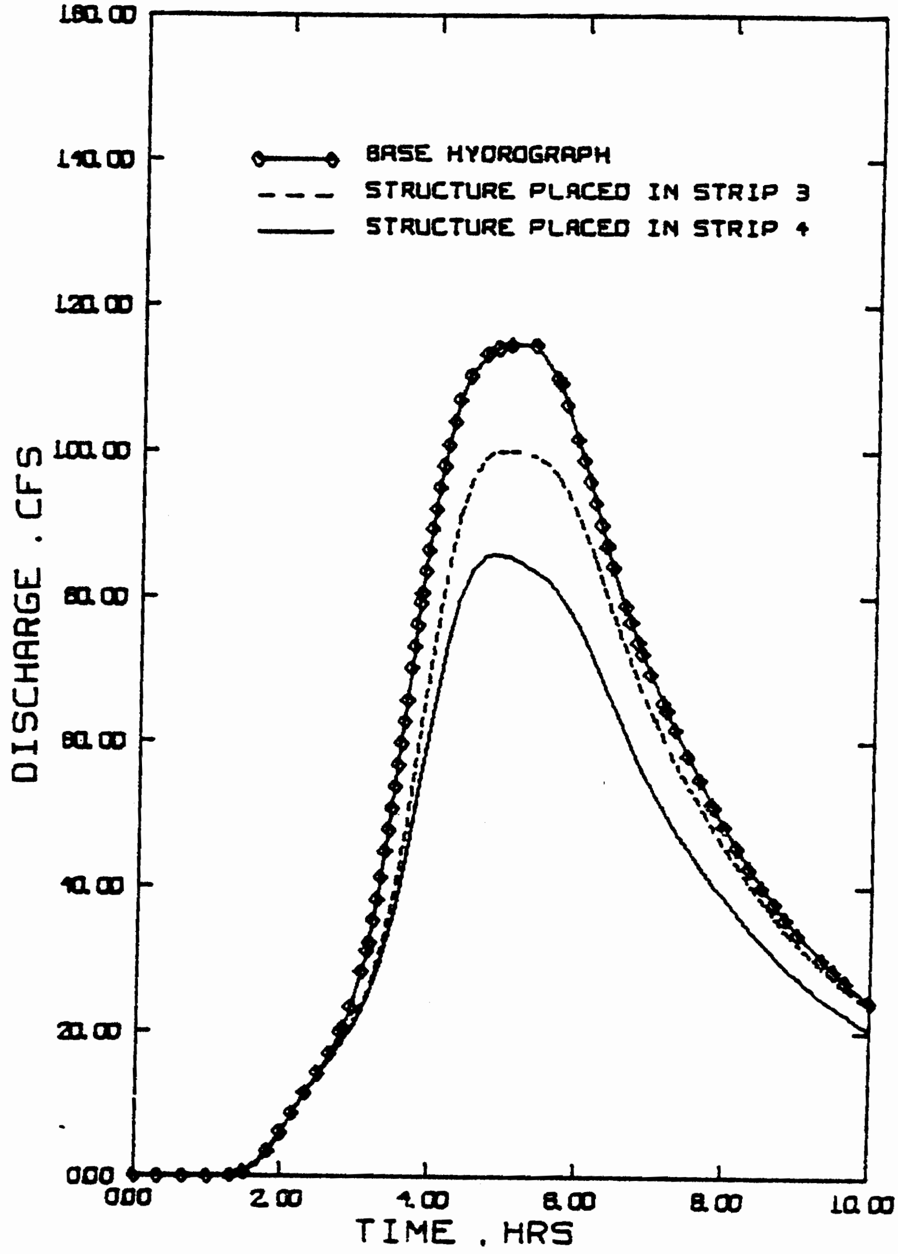


Figure 40. Comparison of two alternative locations, strip Nos. 3 and 4, Figure 26, for the placement of flood detention structures.

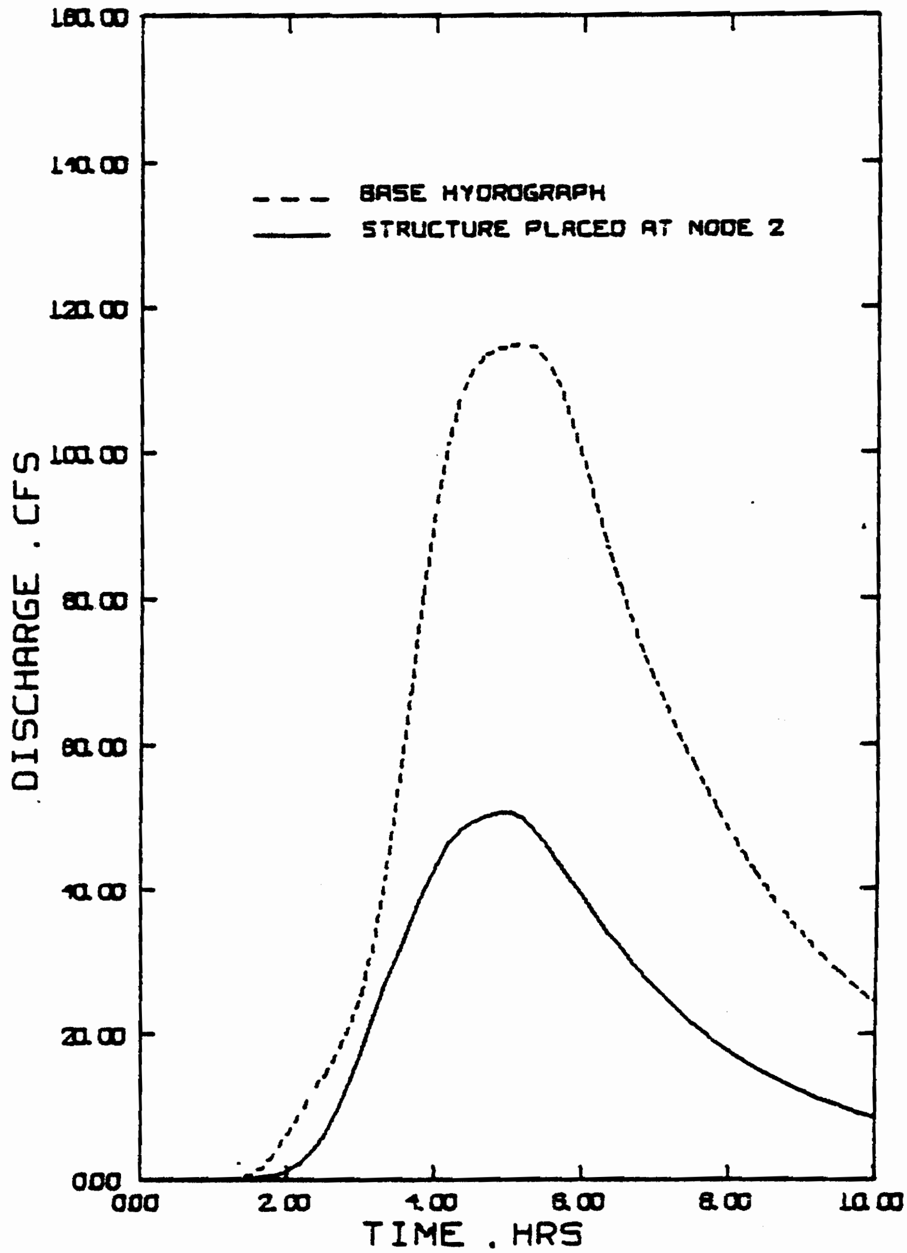


Figure 41. Effect of placing a flood detention structure at channel node No. 2, Figure 26.

Application of the FESHM to Natural Watersheds

To test the effectiveness of the FESHM in simulating stormwater runoff from natural watersheds, six experimental watersheds were selected that had long-term data bases and encompass several physiographic regions within the state of Virginia (Figure 42). A continuous data base was available from these drainage areas as part of Virginia's contribution to Regional Research Projects S-53 and S-108. These areas range in size from 183-1058 acres with complex landuse.

Streamflow measurements were obtained with continuous water level recorders. The control section for each station was a Virginia V-notch weir located in an existing highway culvert {Burford and Lillard (1963)}. At least two continuous recording raingages were located within the boundaries of all watersheds. Detailed soils, landuse and topographic information was available for all areas. Landuse surveys were made on an annual basis. The quality of the measured data was good to excellent for the periods of record.

A brief description of the drainage for each watershed is given in the following discussion. Additional details may be obtained from Wilson, et.al. (1975). For each watershed, a contour map is presented which also shows the finite element grid structure. The descriptive information, or input data base, for HRU's and each watershed element may be

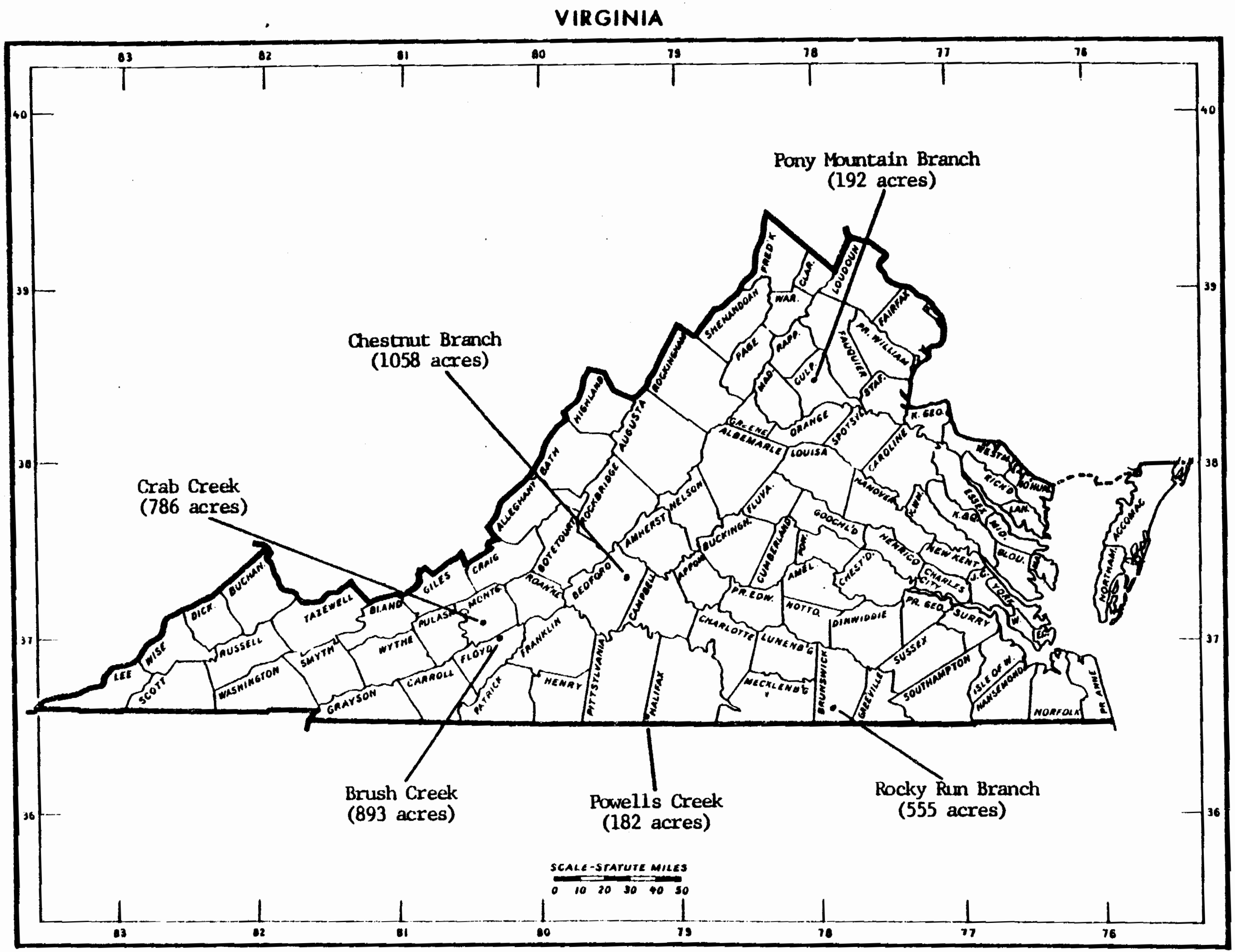


Figure 42. Locations of the six experimental watersheds in Virginia.

found listed in tables in Appendix A.

An ungaged context was assumed in simulating the storm events on these watersheds. Complete data bases were created for all watersheds prior to model execution (Appendix A). No attempts were made to alter a data base for any particular watershed after storm events for a preceding watershed had been simulated. Furthermore, no optimization was performed on any simulations for the purpose of improving individual flow matches, although optimization can be easily performed to obtain excellent agreement between simulated and recorded flows. The simulated hydrographs represent first-run attempts without optimization. The simulation approach, therefore, was performed entirely in the ungaged context.

The two or three largest flood-producing events for the period of record were selected for each watershed (Table 14). The figures presented in the following discussion compare the recorded and FESHM-simulated hydrographs at the watershed outlet. When more than one raingage was used in simulations for a given watershed, the rainfall hyetograph represents the Thiessen weighted rainfall over the entire watershed. This was done only in the interest of plot clarity and does not indicate the manner in which rainfall was applied on the watershed. The rainfall data was entered to the FESHM in 15-minute increments.

Table 14. Rainfall characteristics for selected storm events.

Watershed	Storm Event	Raingage Number	Duration (hr)	Storm Total (in)	Maximum Intensity (in)			Antecedent Rainfall (in)		
					15-min	30-min	60-min	3-day	10-day	30-day
Powells Creek	10/10/59	1	2	1.61	2.52	1.80	1.42	2.50	2.62	4.82
		2	2	0.99	1.12	1.04	0.83	2.55	2.72	5.02
	5/31/62	1	2	2.66	4.00	3.38	2.34	0.01	2.46	3.07
		2	2	2.28	4.37	3.50	2.20	0.02	2.42	2.99
	7/11/65	1	2	3.45	6.64	5.16	3.40	1.31	2.46	5.72
		2	2	3.59	5.70	4.62	3.37	1.37	2.60	6.08
Pony Mountain Branch	6/12/58	1	5	1.75	1.44	1.32	1.03	0.60	1.77	3.30
		2	5	2.16	1.84	1.52	0.99	0.74	2.16	3.50
	6/24/58	1	2	1.36	3.20	2.10	1.31	0.15	1.50	6.45
		2	2	1.36	3.00	2.04	1.31	0.06	1.68	6.09
	9/19/60	1	3	1.57	1.48	1.32	0.84	0.96	3.90	4.85
		2	3	1.74	3.49	1.84	1.08	0.95	4.03	5.06
Rocky Run Branch	7/23/70	1	3	5.38	7.68	6.14	4.46	1.42	1.54	5.17
		2	3	3.37	3.16	2.83	2.43	1.02	1.09	6.02
	10/ 5/72	1	8	7.53	3.30	2.56	2.33	0.33	2.48	4.25

Table 14. Continued.

Watershed	Storm Event	Raingage Number	Duration (hr)	Storm Total (in)	Maximum Intensity (in) 15-min	30-min	60-min	Antecedent Rainfall (in) 3-day	10-day	30-day
Crab Creek	8/21/66	1	2	1.40	3.24	2.40	1.38	0.02	0.23	6.59
		2	2	2.10	3.36	2.64	2.05	0.00	0.25	6.37
		3	2	1.62	2.88	2.37	1.62	0.00	0.21	6.46
		4	2	1.54	2.90	2.34	1.54	0.05	0.22	6.80
	10/24/71	1	3	1.78	0.96	0.88	0.87	1.34	2.21	3.84
		2	3	1.59	1.05	0.96	0.85	1.35	2.27	3.90
		3	3	1.90	1.30	1.13	1.01	1.25	2.15	3.75
		4	3	1.75	1.00	0.97	0.87	1.27	2.11	3.65
	6/16/76	1	4	1.99	1.72	1.68	1.32	2.19	2.19	3.48
		2	4	2.03	1.79	1.75	1.37	2.06	2.06	3.33
		3	4	2.16	2.28	1.83	1.14	1.86	1.86	3.28
		4	4	1.92	1.72	1.68	1.32	2.40	2.40	3.59
Brush Creek	7/22/59	1	2	2.52	7.00	4.52	2.51	1.87	2.69	3.98
		2	2	2.02	5.75	3.44	2.00	1.50	2.13	2.68
	9/30/59	1	5	2.24	1.00	0.86	0.73	4.22	4.22	6.44
		2	5	2.69	1.34	1.21	1.08	4.38	4.38	7.22
	5/27/73	1	2	1.30	2.71	1.71	1.17	1.38	2.77	4.01

Table 14. Continued.

Watershed	Storm Event	Raingage Number	Duration (hr)	Storm Total (in)	Maximum Intensity (in)			Antecedent Rainfall (in)		
					15-min	30-min	60-min	3-day	10-day	30-day
Chestnut Branch	8/23/67	1	2	1.85	3.00	2.50	1.50	3.31	4.77	6.52
		2	2	1.60	2.84	1.88	1.33	2.98	4.71	6.00
		3	2	2.29	3.64	2.79	2.09	2.81	4.21	5.72
	8/ 4/74	1	2	1.79	2.00	1.72	1.47	1.82	4.04	5.29
		2	2	1.89	2.63	2.08	1.54	1.81	4.91	6.27
		3	3	0.99	2.04	1.10	0.83	1.84	4.96	6.75

Powells Creek Watershed

Powells Creek watershed (Figure 43) is located in Halifax County, Virginia, drains 182 acres of land and is characterized by farm use with more than half of the watershed in permanent pasture. The watershed lies in an area of uncertain age with soils developed mostly from a mixture of hornblende, gabbro and acidic rocks such as granite, gneiss and schist. The watershed is located in the Southern Piedmont land resource area and is characterized by a well defined system of drainage ways.

Total relief is 134 feet with 90% of the area having slopes of less than 15%. Two raingages are located in the watershed as shown in Figure 43. Data had been collected for the period 1958-1968.

The results of the simulation for the three largest discharge events that were recorded from the Powells Creek watershed are compared in Figures 44-46. These results are good, particularly when considered in the ungaged context.

With the exception of the first storm, both peak and volume of runoff were overpredicted. The recorded peak for the storm of 7/11/65 appears to be in error judging from the intensity of the rainfall, although this could be expected if errors were present in the rainfall distribution. Such errors would affect the timing of flows, particularly at the channel confluences. The recorded peak flow was sustained

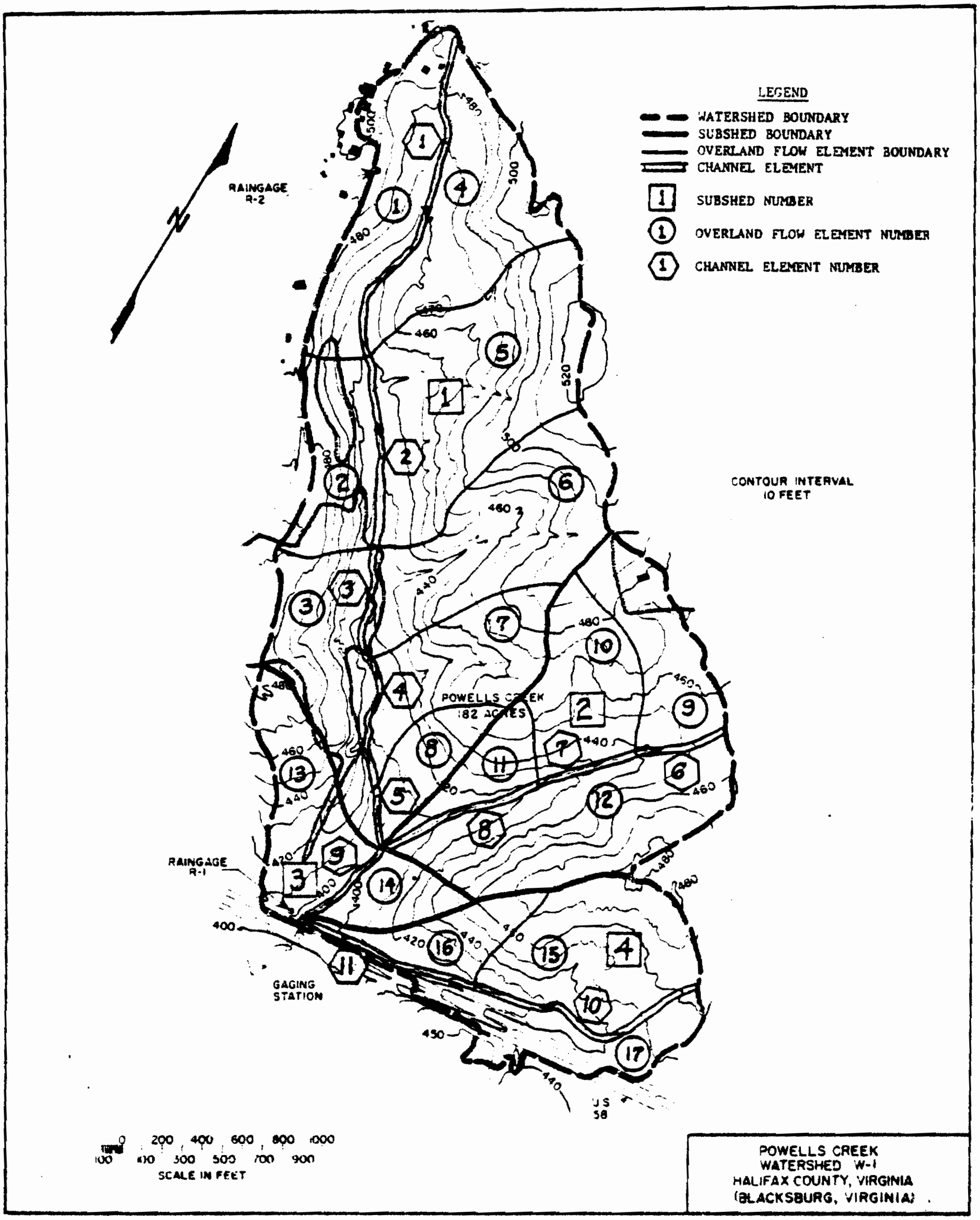


Figure 43. Topographic map and finite element discretization for Powells Creek watershed, Halifax County, VA.

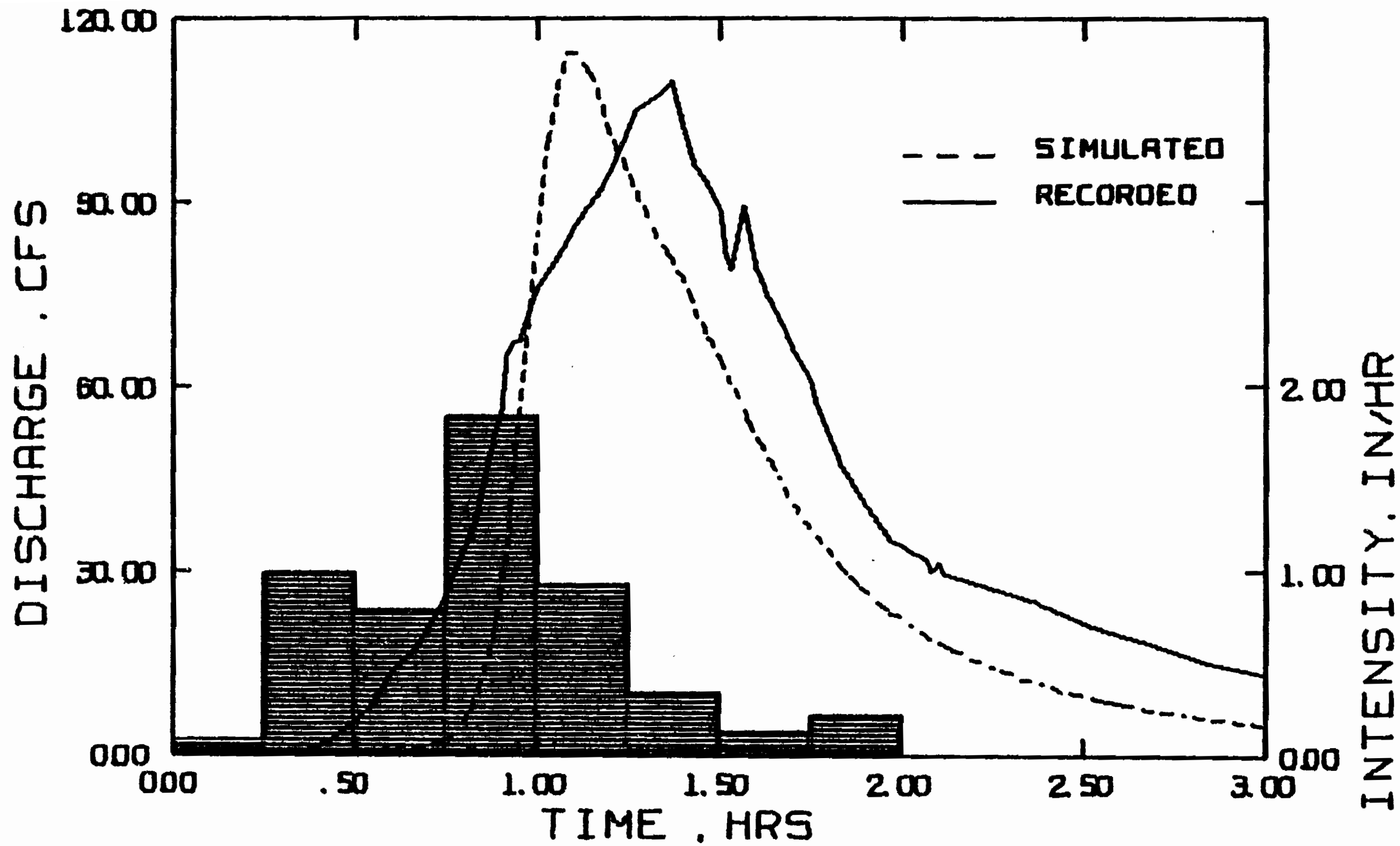


Figure 44. Comparison of recorded and simulated discharge for storm event 10/10/59, Powells Creek watershed, Halifax County, Virginia.

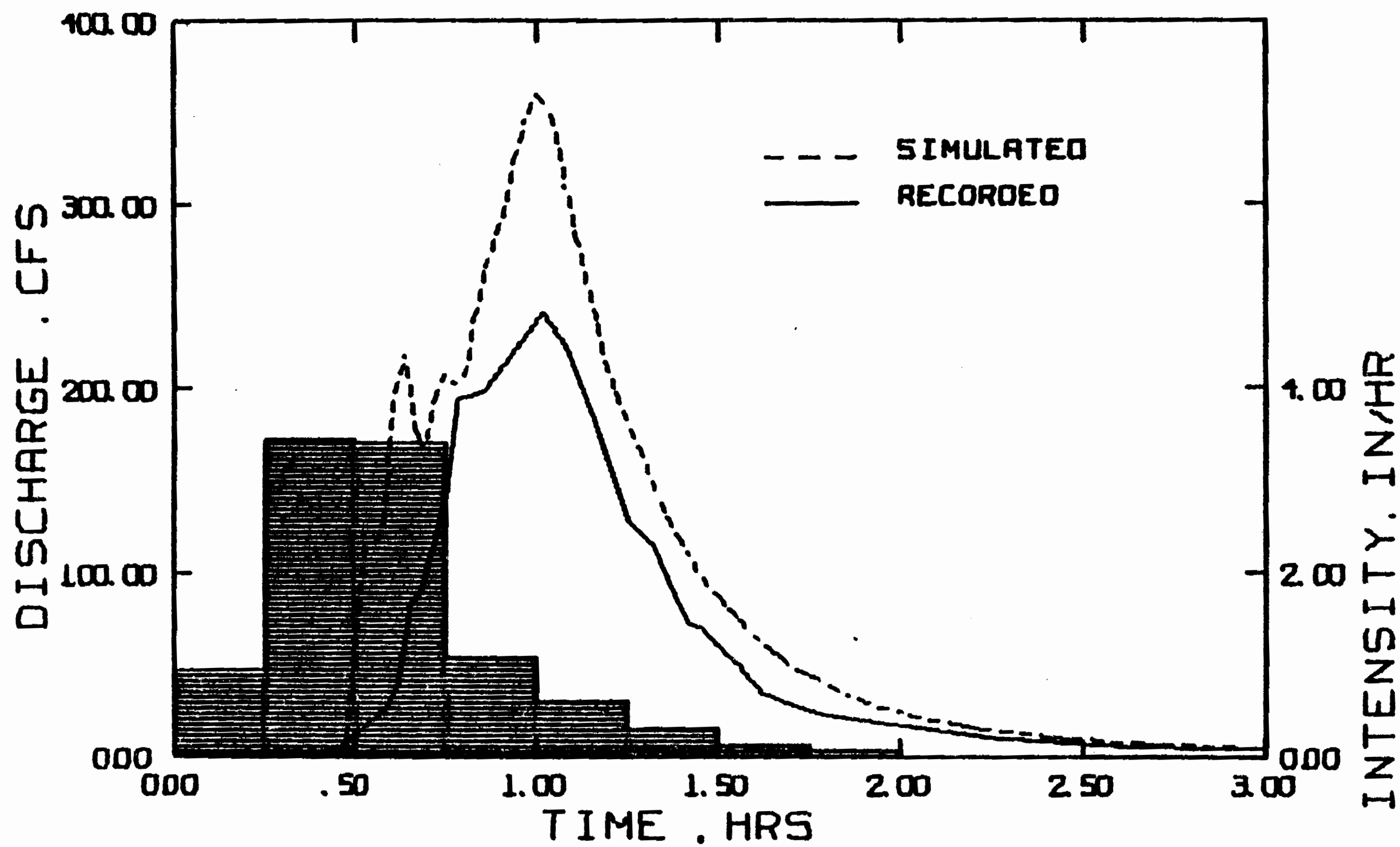


Figure 45. Comparison of recorded and simulated discharge for storm event 5/31/62, Powells Creek watershed, Halifax County, Virginia.

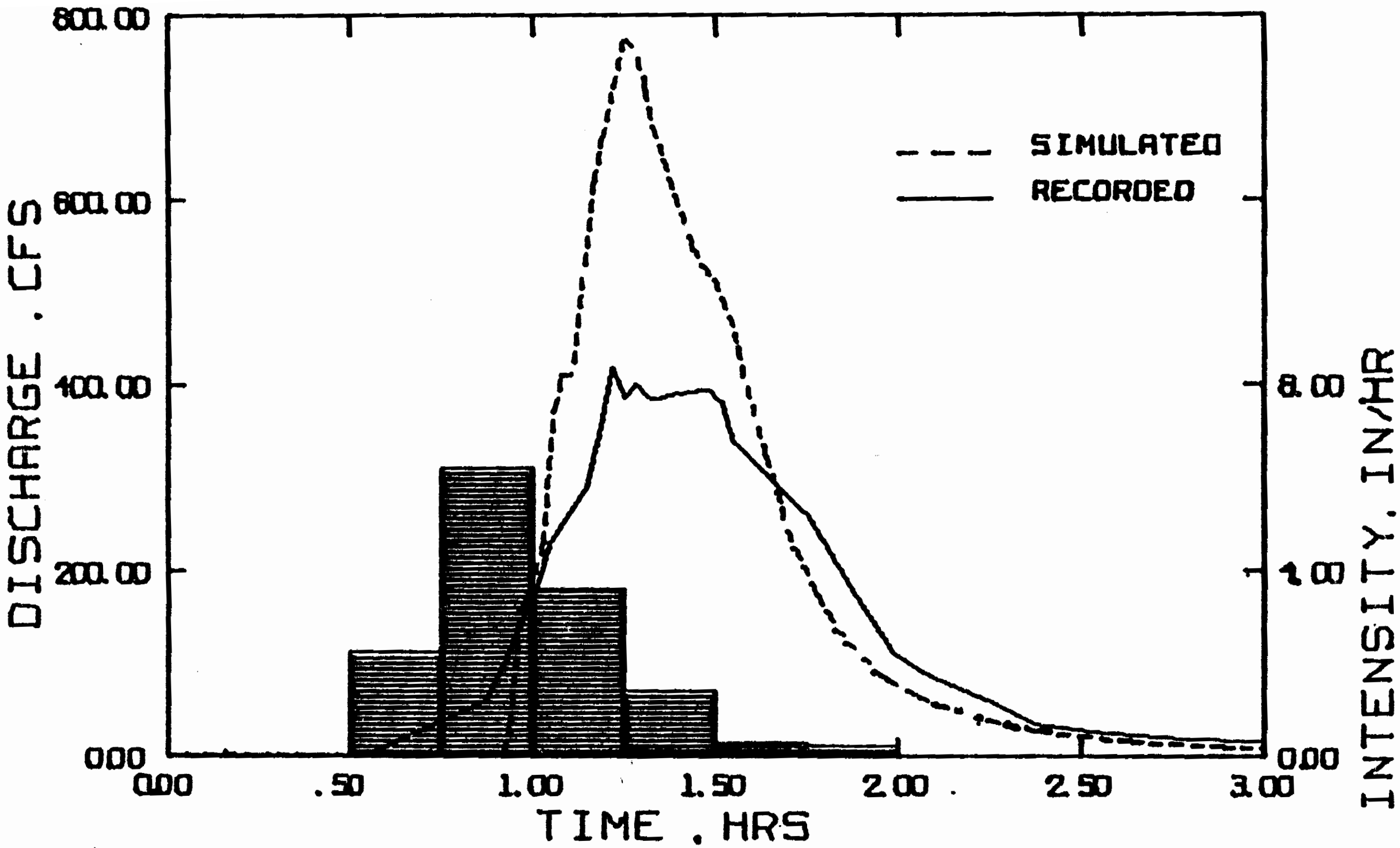


Figure 46. Comparison of recorded and simulated discharge for storm event 7/11/65, Powells Creek watershed, Halifax County, Virginia.

for approximately twenty minutes which is not typical for this watershed, nor is it indicated by the recorded rainfall.

The timing of the peaks appears to be reasonably well in tune although the hydrograph appears to be rising too sharply. This could be due to an underestimation of the floodplain roughness conditions.

Pony Mountain Branch Watershed

Pony Mountain Branch watershed (Figure 47) is located in Culpepper County, Virginia and drains 192 acres of farm land that is dominated by woods and permanent pasture. The watershed lies in the Triassic formation with soils developed mostly from igneous rocks of sills and dikes, diabase, gabbio and shales. The watershed generally represents complex landuse areas in the shallow red shale and sandstone (of Triassic origin) portion of the Northern Piedmont land resource area of Northern Virginia.

Total relief is 457 feet with 35% of the area having slopes in excess of 15%. Two recording raingages are located as shown in Figure 47. Rainfall and streamflow records were collected from 1958-1968.

Simulation results for three contrasting rainfall distributions are presented in Figures 48-50. The comparisons

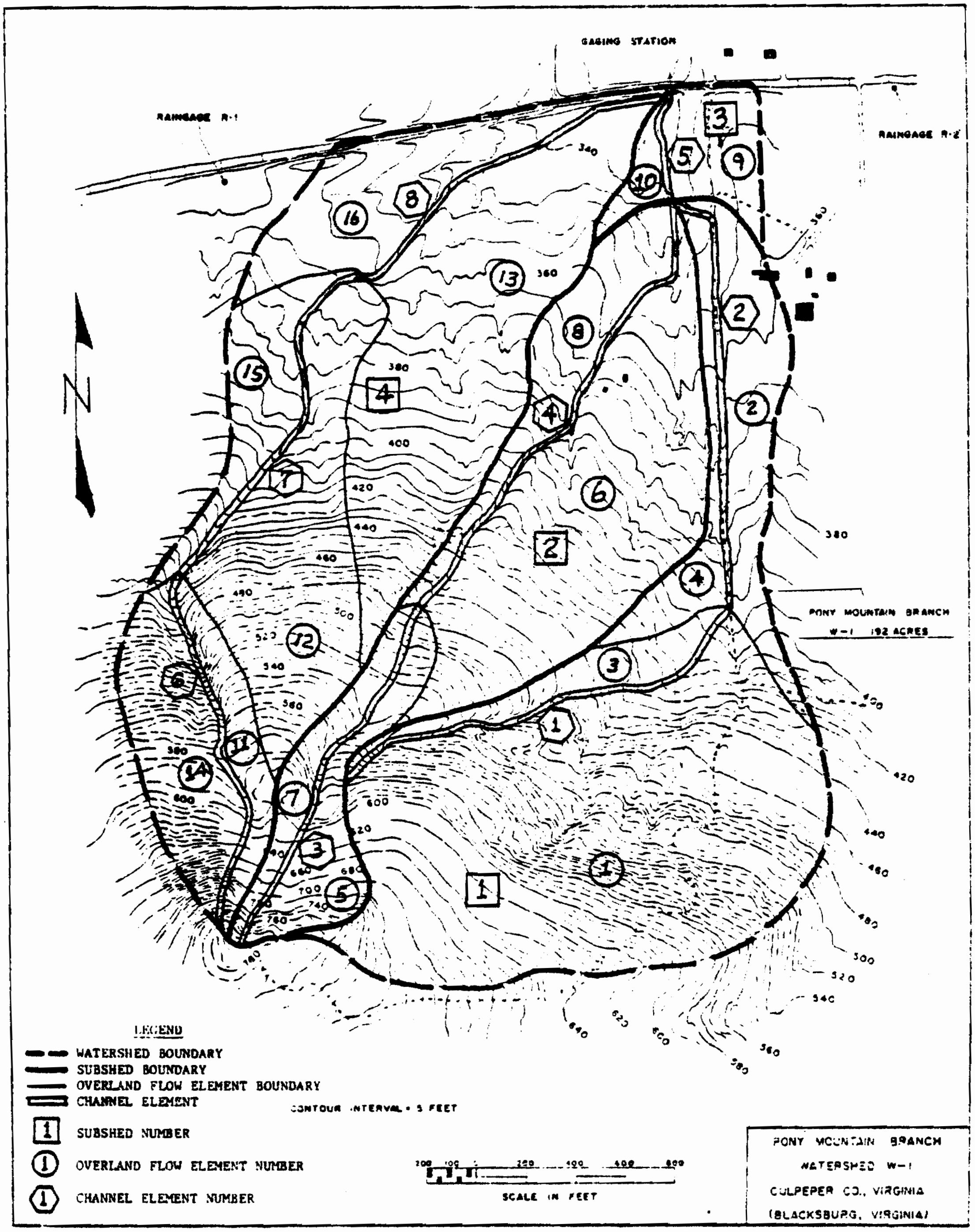


Figure 47. Topographic map and finite element discretization for Pony Mountain Branch watershed, Culpepper County, VA.

are considered to be excellent especially in the absence of any parameter optimization. The storms of 6/12/58 and 6/24/58 were predicted extremely well with respect to both volume and peak discharge.

A multi-peak event is compared in Figure 50. Prediction of the second peak was poor. An examination of the rainfall hyetograph for the second peak indicates that the rainfall measurements at raingages R1 and R2 are not representative of the distribution of the storm over the watershed. There was considerable variability in the rate and magnitude of rainfall recorded at these raingages. Since both R1 and R2 are located near the watershed outlet, the upland mountaneous areas may have received significantly more rain than was recorded in the bottomlands for the second peak. This could explain the poor prediction of the second peak.

Rocky Run Branch Watershed

Rocky Run Branch watershed (Figure 51), Brunswick County, Virginia, has a 555-acre drainage area of which over half is covered by farm woods. The watershed also contains a relatively high proportion of idle land (15-20%).

The watershed area is classified as Precambrian with rock formations of microline, biotite granite and chloritic granodiorite. Soils are developed mostly from a mixture of

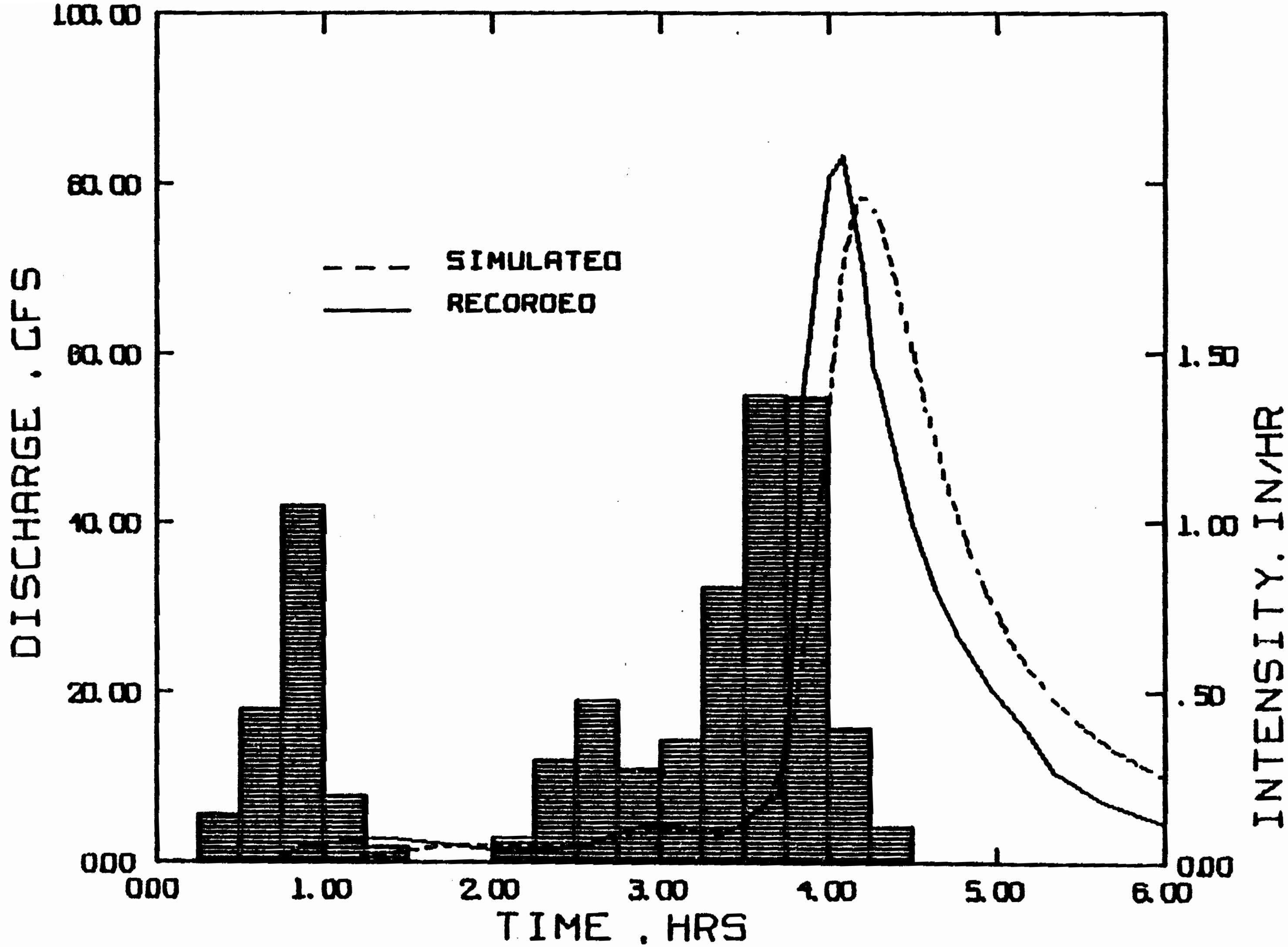


Figure 48. Comparison of recorded and simulated discharge for storm event 6/12/58, Pony Mountain Branch watershed, Culpepper County, Virginia.

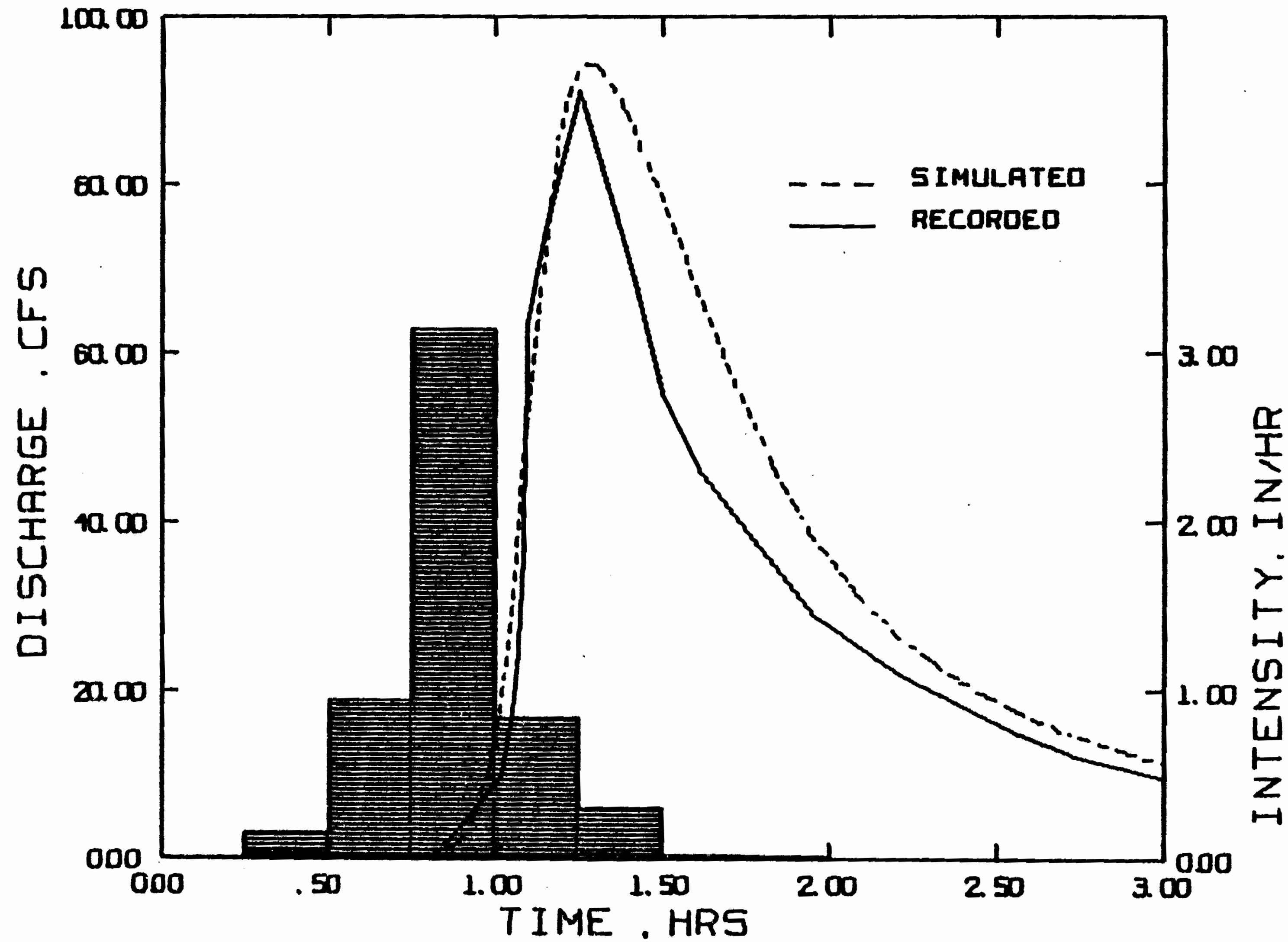


Figure 49. Comparison of recorded and simulated discharge for storm event 6/24/58, Pony Mountain Branch watershed, Culpepper County, Virginia.

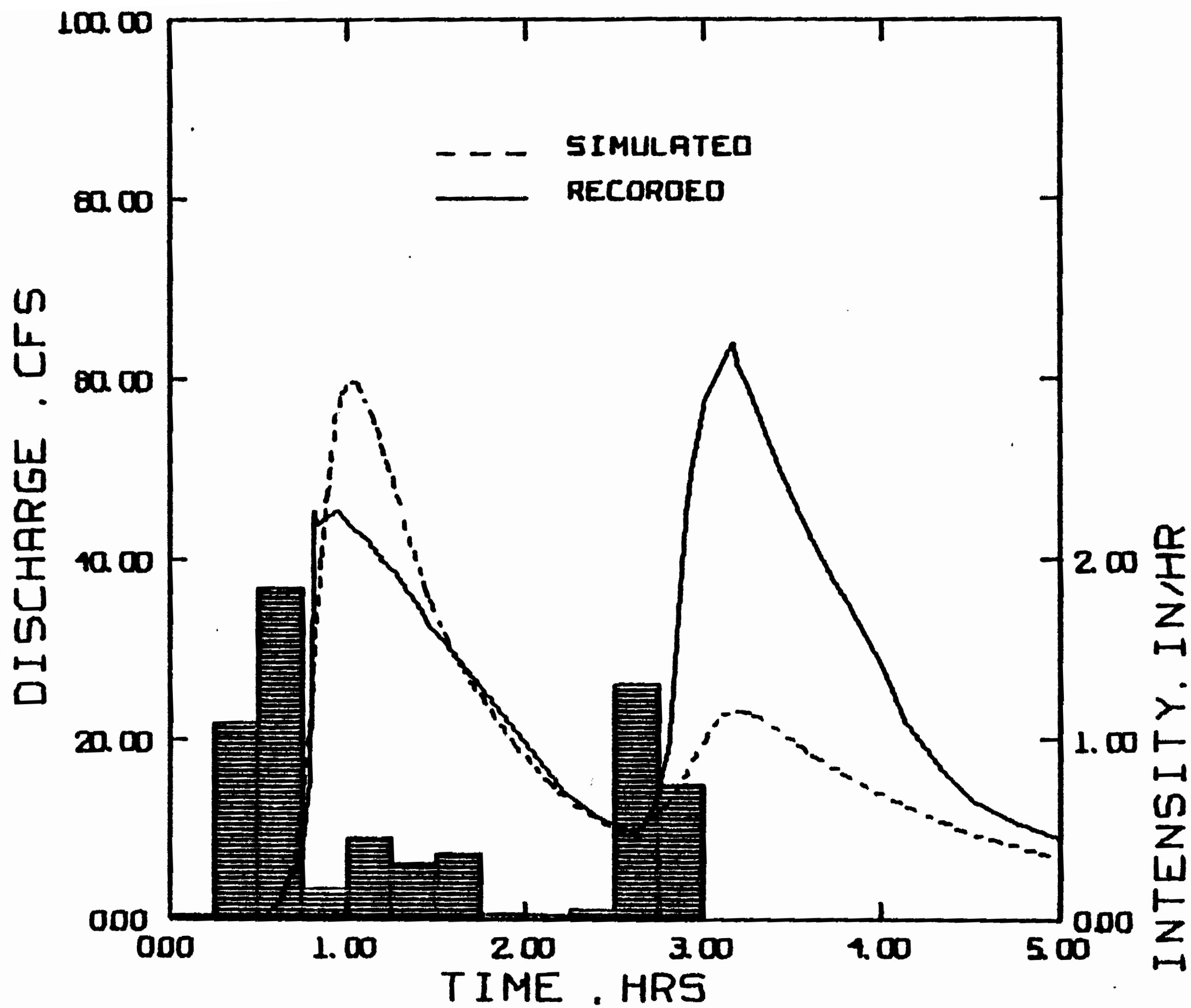


Figure 50. Comparison of recorded and simulated discharge for storm event 9/19/60, Pony Mountain Branch watershed, Culpepper County, Virginia.

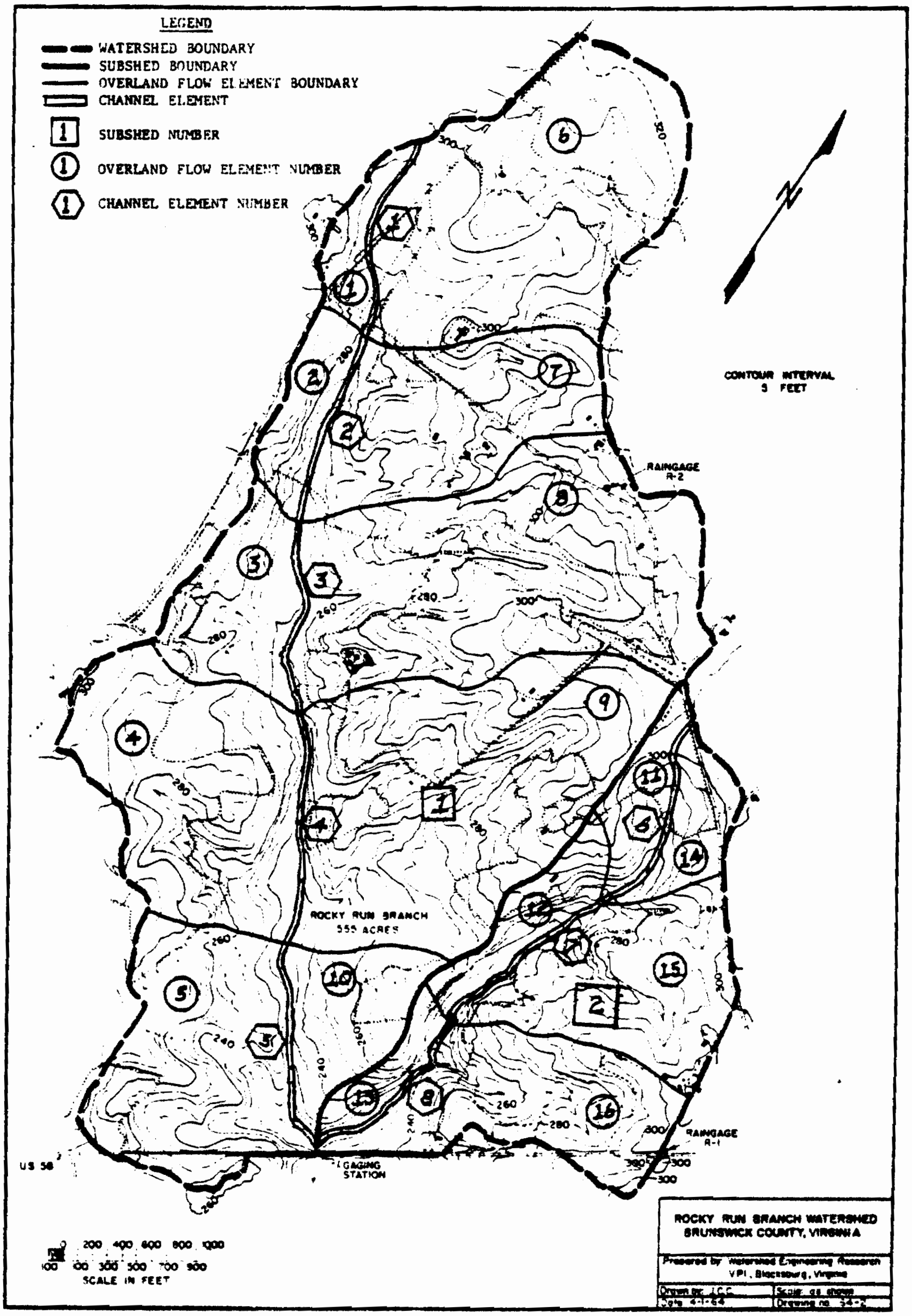


Figure 51. Topographic map and finite element discretization for Rocky Run Branch watershed, Brunswick County, VA.

granite, granite gneiss, schist, and quartz mica schist. The watershed generally represents complex landuse areas in the Southern Piedmont land resource area lying in Southern Virginia, Central North Carolina and Western South Carolina. Land slopes are predominantly mild and total relief of the watershed is only 103 feet. Two recording raingages are located as shown in Figure 51. Rainfall and streamflow data are available from 1958 to the present.

Two of the three largest storm events were simulated for Rocky Run watershed. Equipment failure prevented any comparison between recorded and simulated hydrographs for Hurricane Agnes (6/21/72) which produced the second highest peak for the period of record and resulted in tremendous flooding in Virginia.

The results for the two storms are presented in Figures 52 and 53. Once again results obtained by the FESHM in the ungaged context are termed good.

For the storm of 7/23/70 the simulated hydrograph appears to be falling too rapidly after the peak has passed. One possible explanation for this may be the extreme roughness of the floodplains which are covered with a heavy undergrowth of vines and brush. The channel roughness conditions for the watershed may have been set too low to properly reflect the actual resistance to flow. This also appears to be a problem in the simulation of the 10/5/72

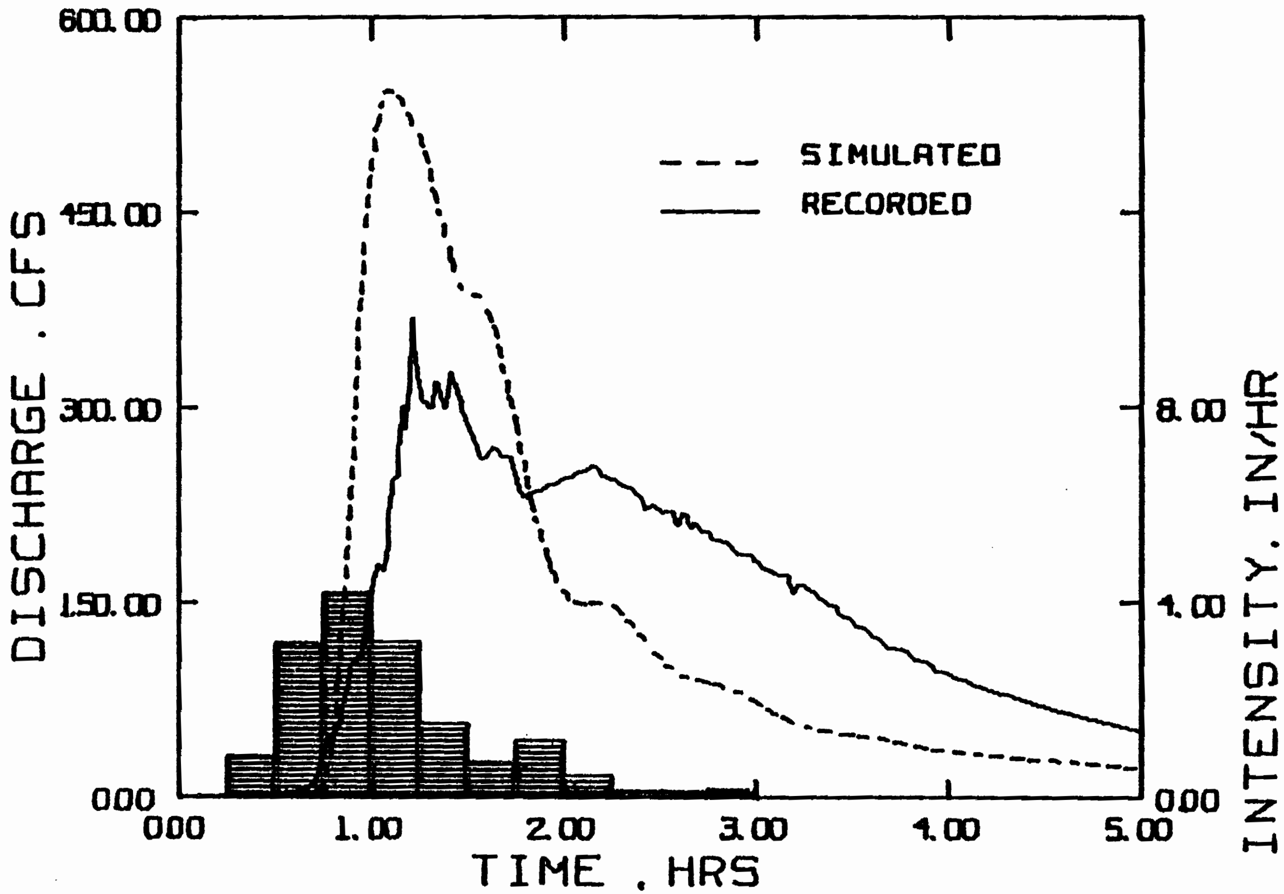


Figure 52. Comparison of recorded and simulated discharge for storm event 7/23/70, Rocky Run Branch watershed, Brunswick County, Virginia.

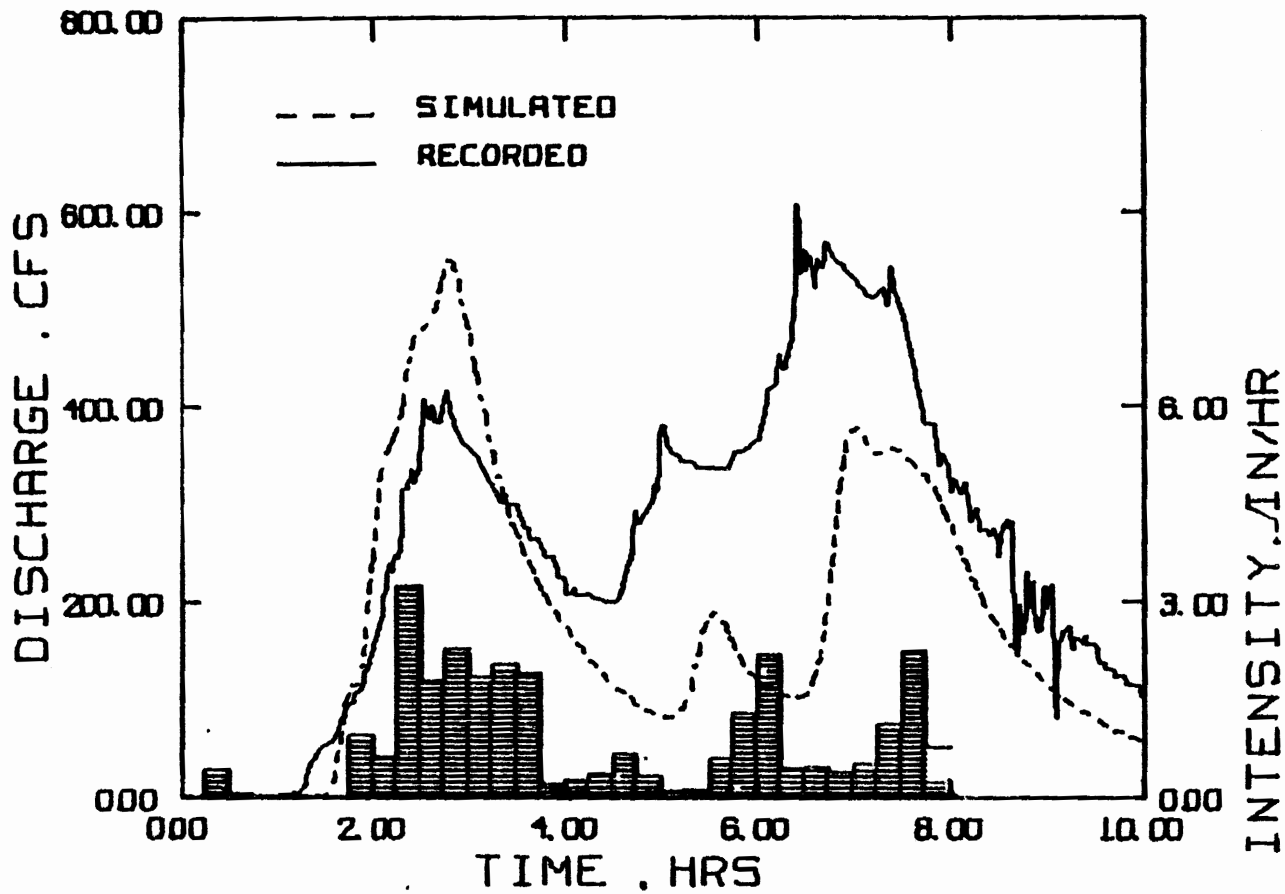


Figure 53. Comparison of recorded and simulated discharge for storm event 10/5/72, Rocky Run Branch watershed, Brunswick County, Virginia.

storm where the flow seems to be passing through the system too quickly.

The flashy and scattered nature of the rainfall occurring in this area can also be a significant factor, as is the case in many humid regions. For example, during a 1-hour period of storm 6/23/70, raingage R1 recorded 4.45 inches while raingage R2 recorded 2.13 inches. Additional raingages located within the watershed would have provided a better measure of spatial variation in rainfall. These variations are critical to obtaining proper timing of flows and subsequent peak discharge estimates.

An investigation of soil storage recovery in the 10/5/72 storm suggests that the final rate of infiltration may be too high. Observation of the rainfall pattern indicates that soils should be close to saturation during the entire storm. This would tend to increase any peaks occurring after the initial peak.

Crab Creek Watershed

Crab Creek watershed (Figure 54) drains 786 acres of primarily agricultural land in Montgomery County, Virginia with only a small portion of the watershed covered by woods (approximately 13%). The watershed lies evenly divided between areas classified as Canadian and Ozarkian with a

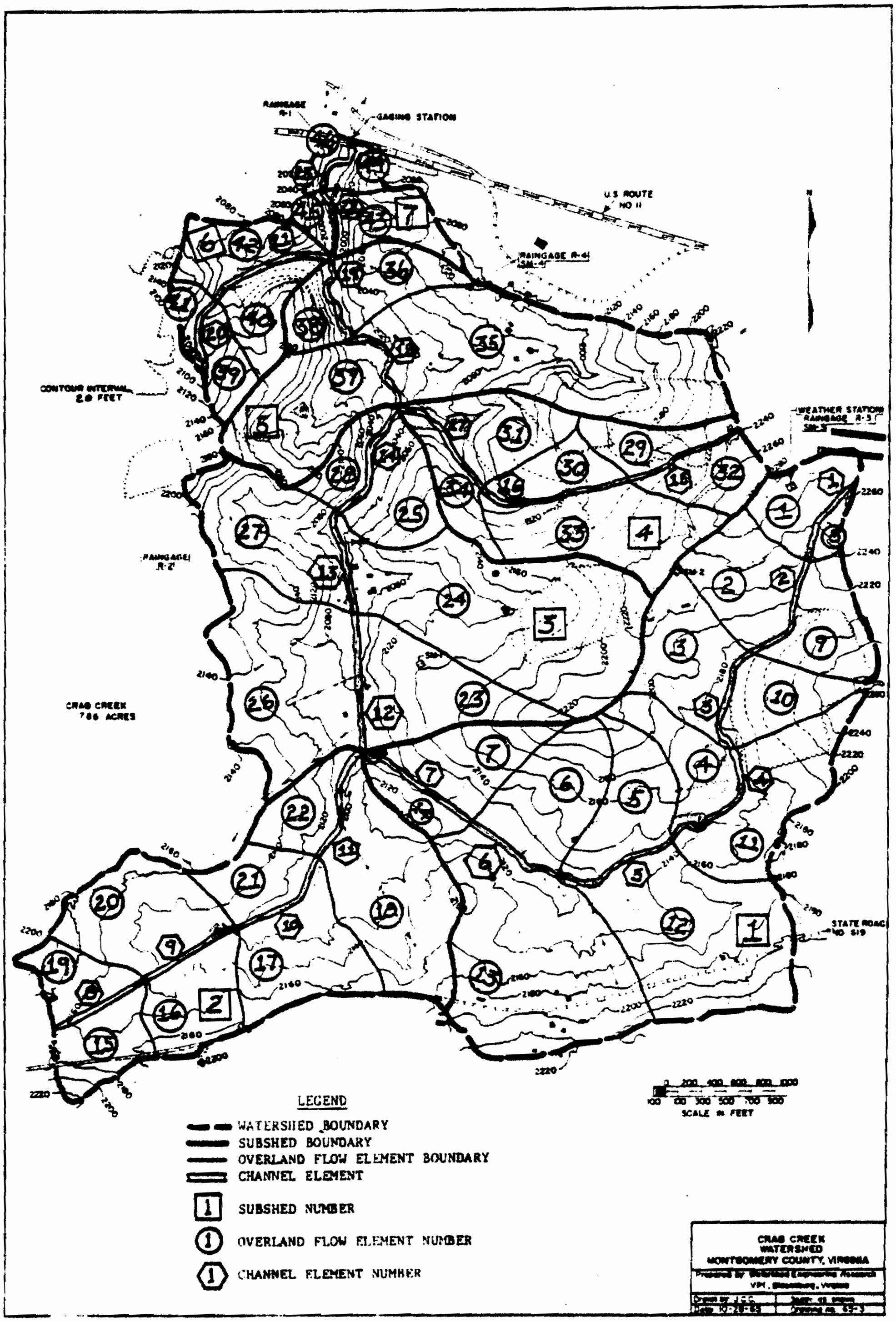


Figure 54. Topographic map and finite element discretization for Crab Creek watershed, Montgomery County, VA.

small portion in the Cambriam formation. Soils are derived from dolomitic and calcic limestones and shales. This area generally represents complex landuse areas in the Southern Appalachian Ridges and Valleys land resource area and the Northern Appalachian Ridges and Valleys land resource area in Tennessee, Virginia, Maryland, and Pennsylvania.

Total relief of the watershed is 311 feet with 22% of the area having slopes in excess of 15%. Erosion is minimal with 83% of the area being classified in erosion class 1. Four raingages have been operating within the watershed boundary since 1964 and are located as shown in Figure 54. Monitoring of this watershed has been conducted since 1957.

The three storm events that produced the highest instantaneous peak discharges were selected for analysis. The recorded flow peaks were very similar despite contrasting storm patterns. Results are considered good for all three applications (Figures 55-57).

Volume and peak predictions were somewhat inconsistent in that, for storm event 8/21/66, they were overpredicted and for the two remaining storms they were underpredicted. One possible explanation for this is that the corn produced in the area is primarily grown by the no-till cultivation practice. This technique can greatly reduce the amount of water available for runoff by increasing infiltration rates, since up to 18% of the watershed may be planted in corn.

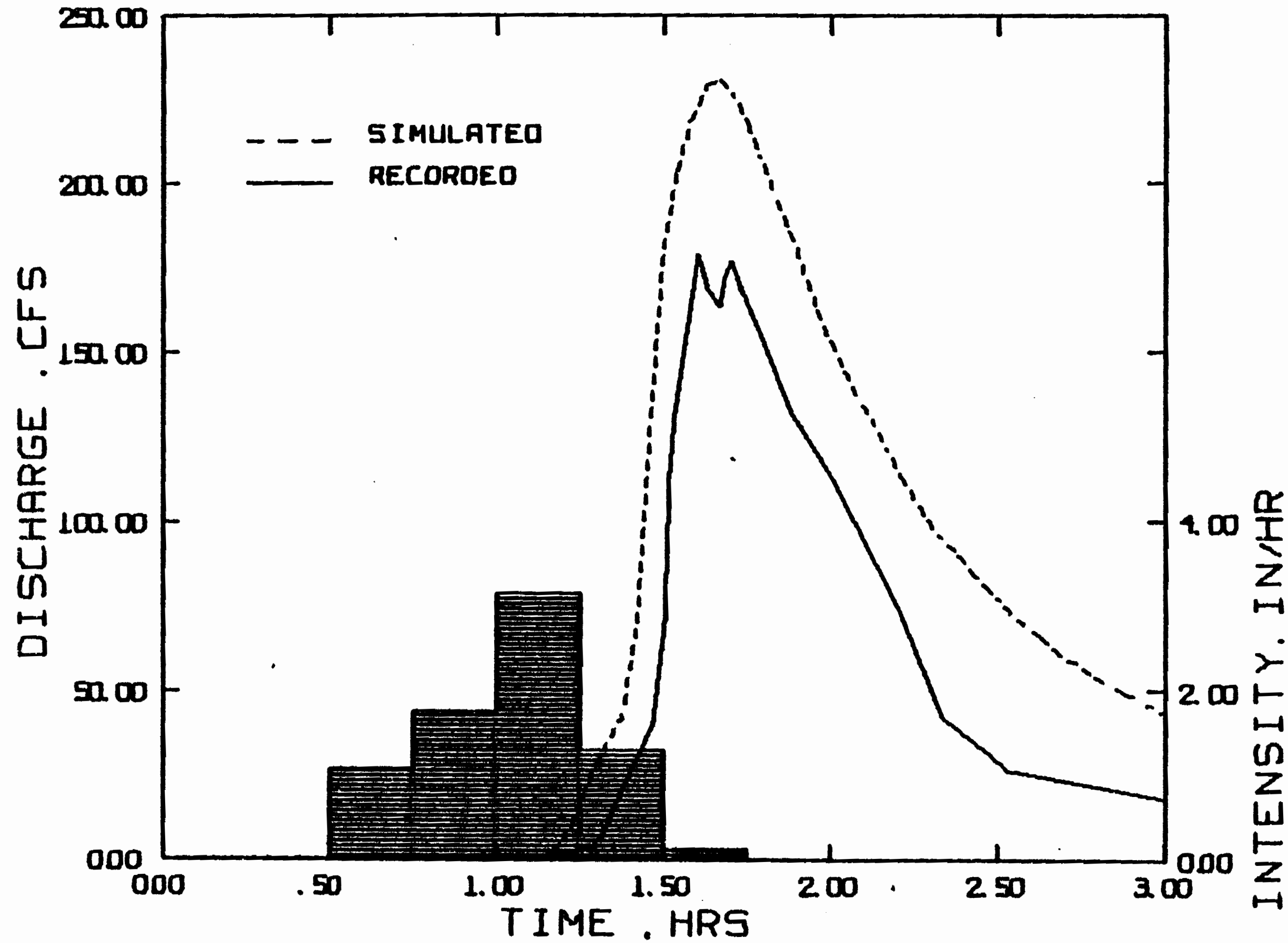


Figure 55. Comparison of recorded and simulated discharge for storm event 8/21/66, Crab Creek watershed, Montgomery County, Virginia.

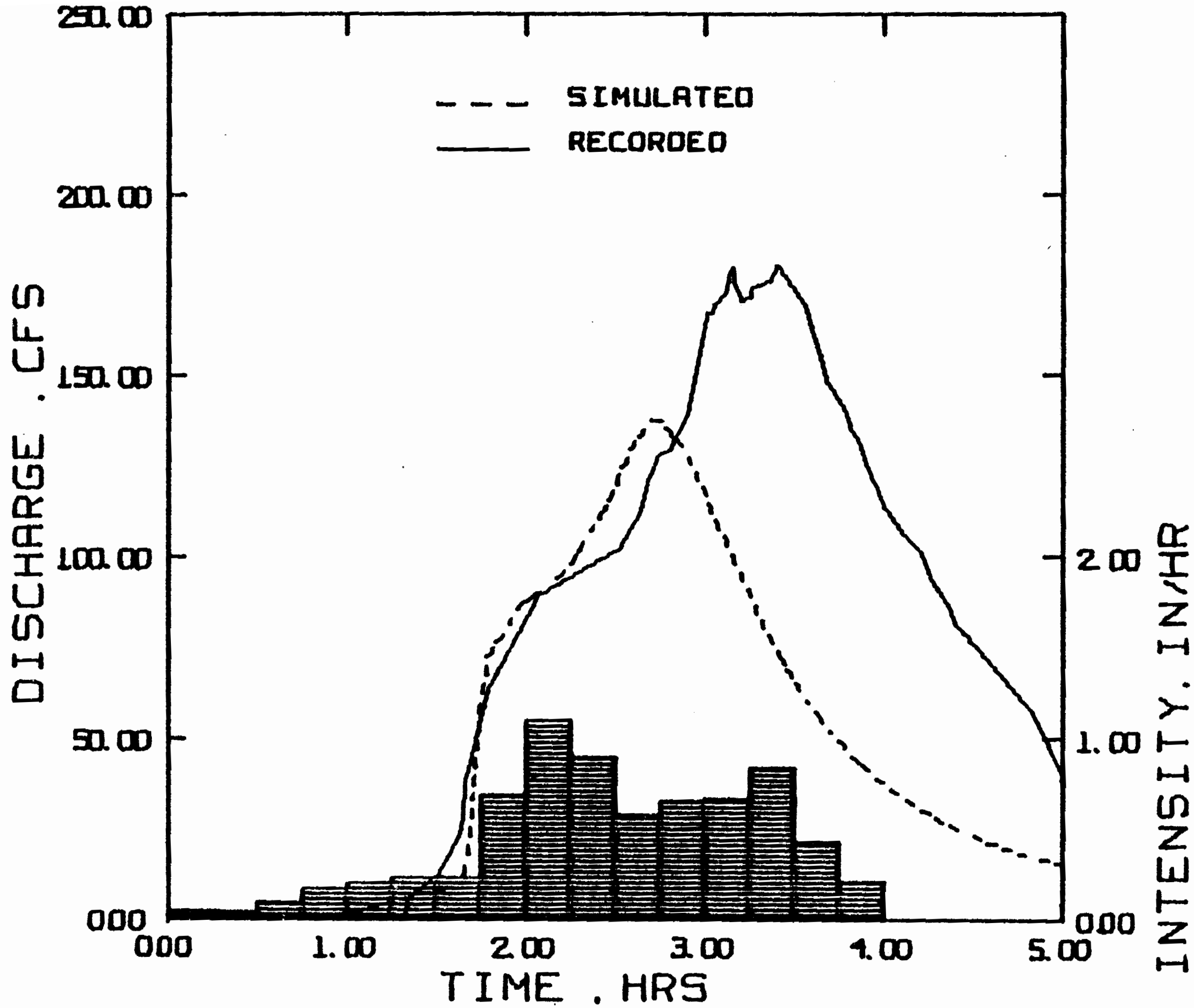


Figure 56. Comparison of recorded and simulated discharge for storm event 10/24/71, Crab Creek watershed, Montgomery County, Virginia.

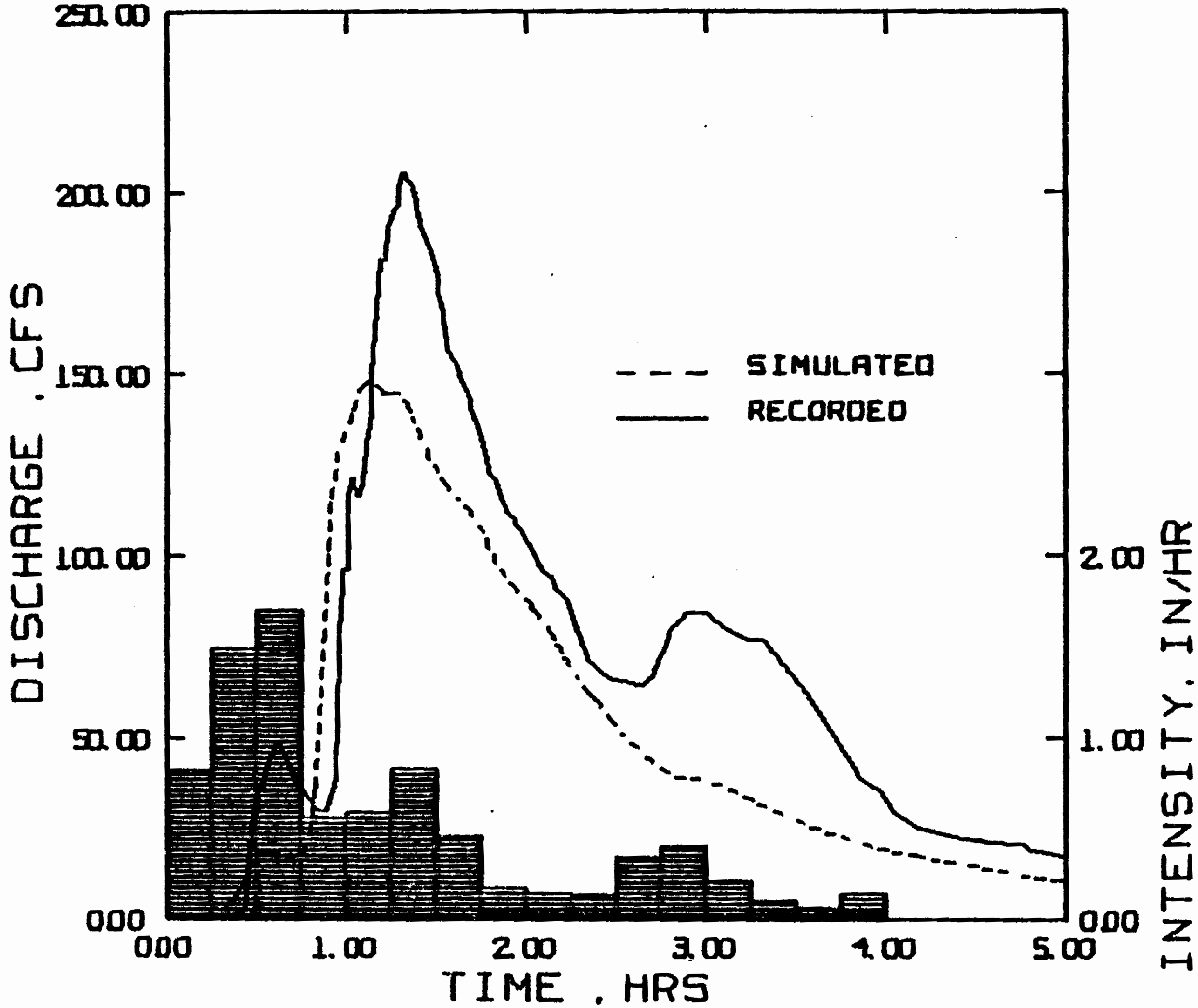


Figure 57. Comparison of recorded and simulated discharge for storm event 6/16/76, Crab Creek watershed, Montgomery County, Virginia.

The August storm occurred at the height of the corn-growing season and the model may not be adequately simulating this aspect.

In addition, the rainfall distribution for the last several hours of the 6/16/76 storm event was lost and was estimated from a raingage located at a distance of some ten miles.

These results were encouraging when compared to simulation studies conducted by Shanholtz, et. al. (1971) on this watershed with the VPI version of the Stanford Watershed Model. This watershed was difficult to model with the lumped-parameter approach because of the diversity in soils, topography and landuse.

Brush Creek Watershed

Brush Creek watershed (Figure 58) is located in Floyd County, Virginia and drains 893 acres of primarily farm land (32% forrested). The watershed lies in an area classified as Precambrian with soils derived from gneisses and igneous rocks. The area generally represents mixed cover conditions in the Blue Ridge land resource area of Virginia, Maryland and North Carolina.

Total watershed relief is 390 feet with 42% of the area having slopes in excess of 15%. Erosion is minimal with 81%

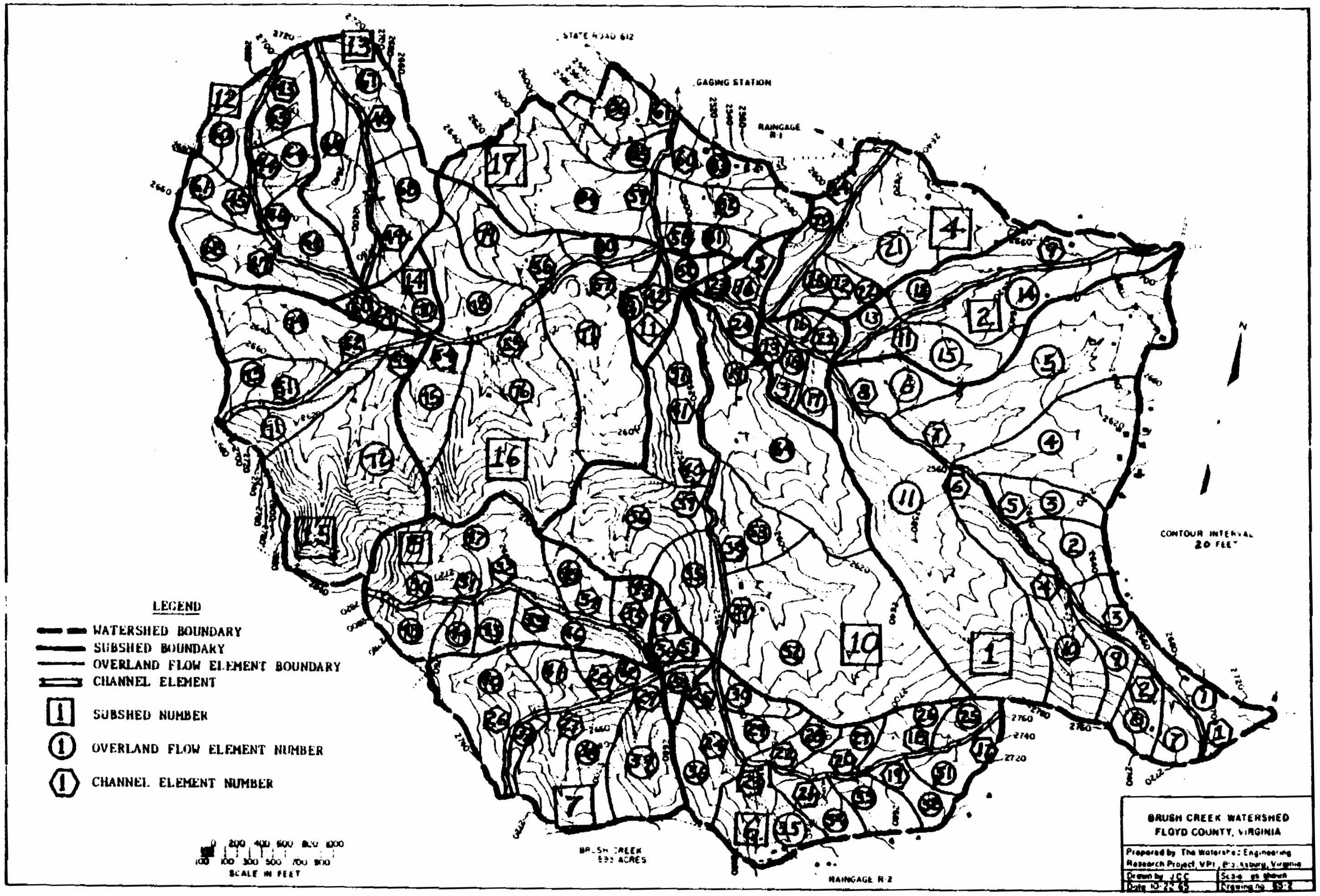


Figure 58. Topographic map and finite element discretization for Brush Creek watershed, Floyd County, VA.

of the watershed area assigned to erosion class 1. Two continuous recording raingages are located in the watershed as shown in Figure 58. Data has been collected from 1957 to the present.

Three storm events were simulated on Brush Creek watershed as shown in Figures 59-61. Fits obtained for events on this watershed were the poorest of those obtained for any of the watersheds in this study.

High base flows are characteristic of this watershed and due to the presence of many springs in the area, the potential exists for high transmission losses due to very porous areas. For the highly intense storm events of 7/22/59 and 5/27/73, the model overpredicted volume and peak of runoff by a considerable margin, although for the former event there appears to be possible data errors in the timing of the rainfall relative to the recorded flow.

The storm of 9/30/59 represents an entirely different type of storm distribution. There appears to be some errors in the magnitude of recorded peaks because of the abruptness of changes in the hydrograph, however, fluctuations in the flow are recreated in the simulation and the predicted volume of runoff is acceptable.

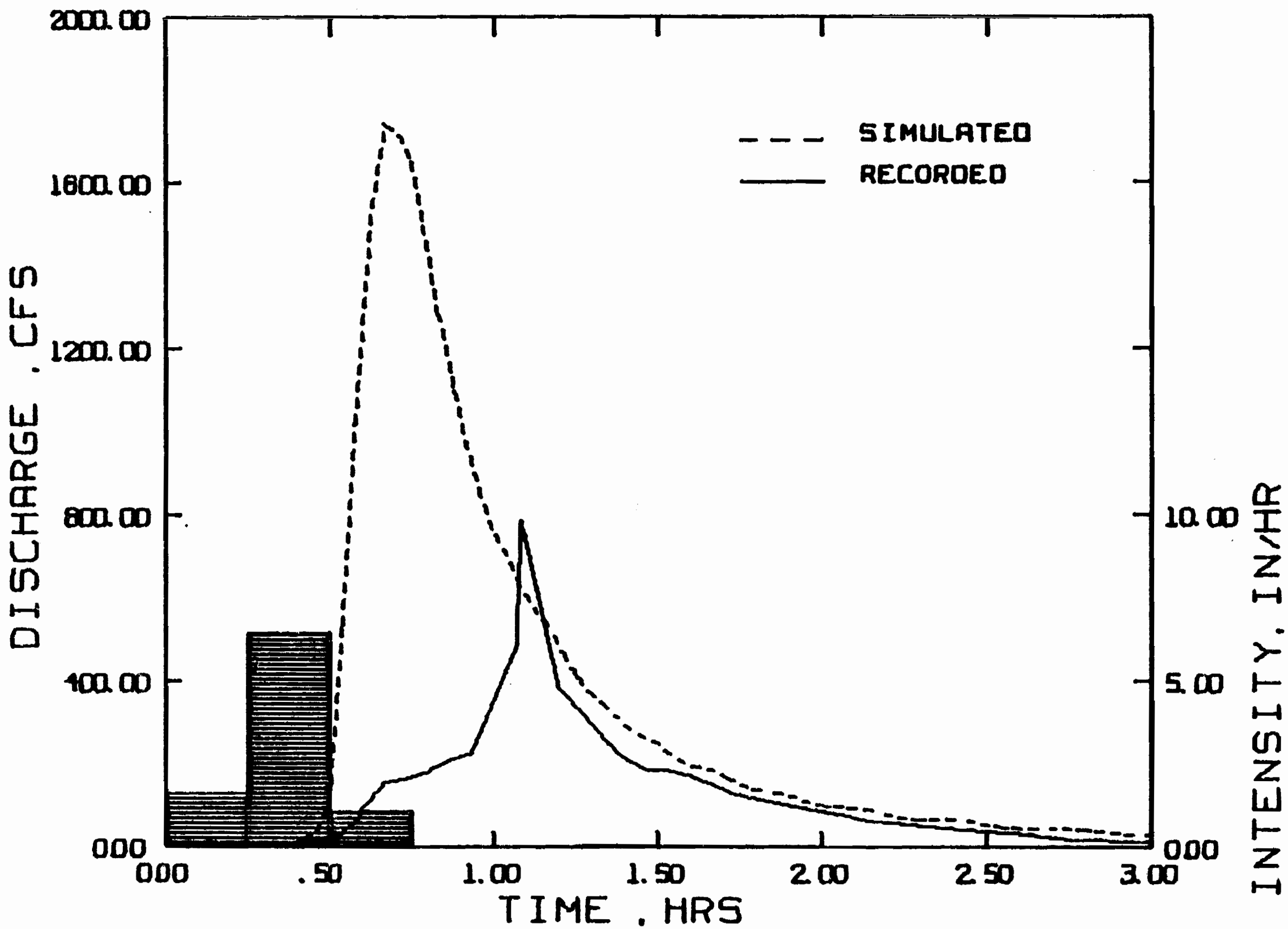


Figure 59. Comparison of recorded and simulated discharge for storm event 7/22/59, Brush Creek watershed, Floyd County, Virginia.

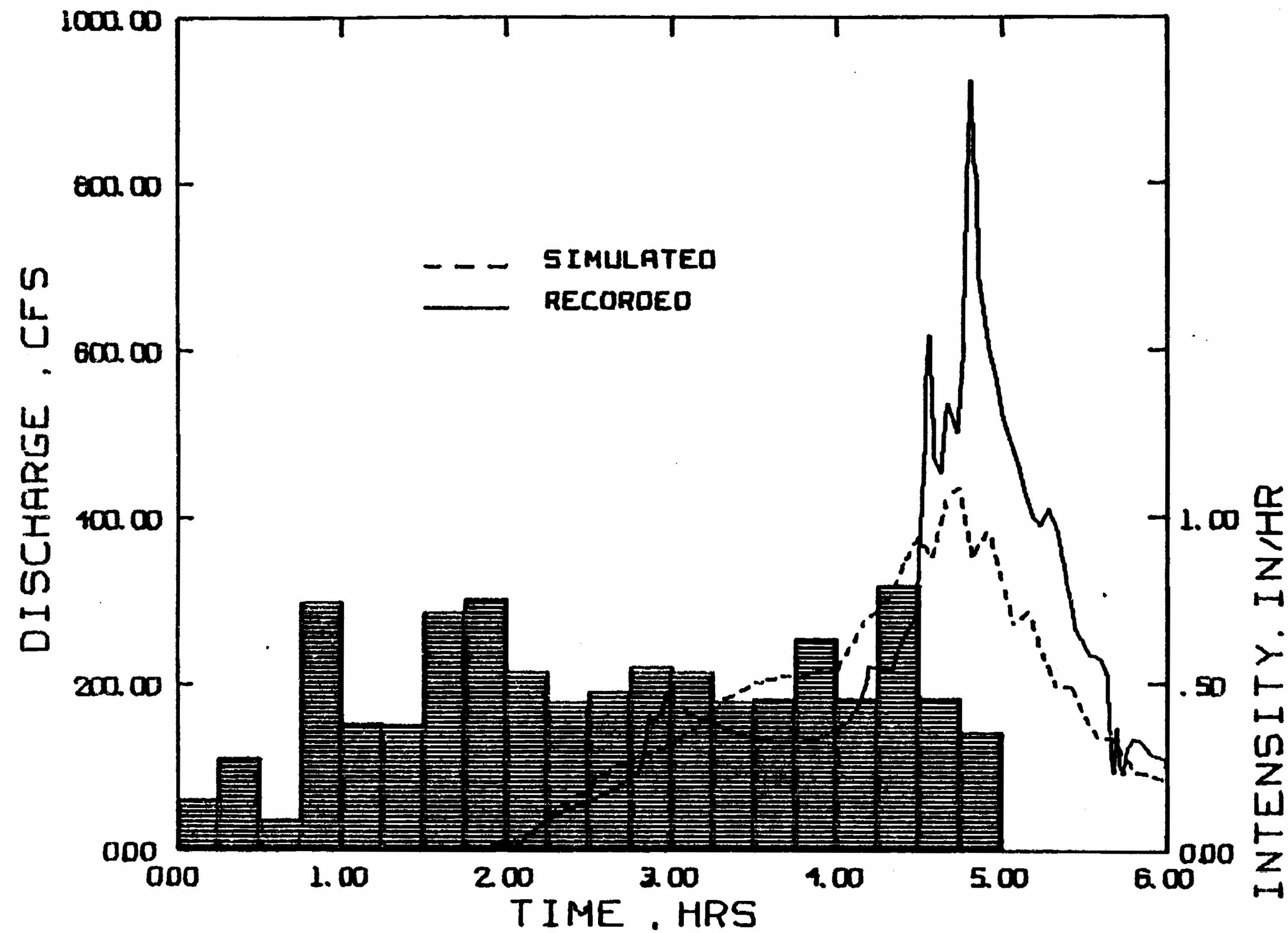


Figure 60. Comparison of recorded and simulated discharge for storm event 9/30/59, Brush Creek watershed, Floyd County, Virginia.

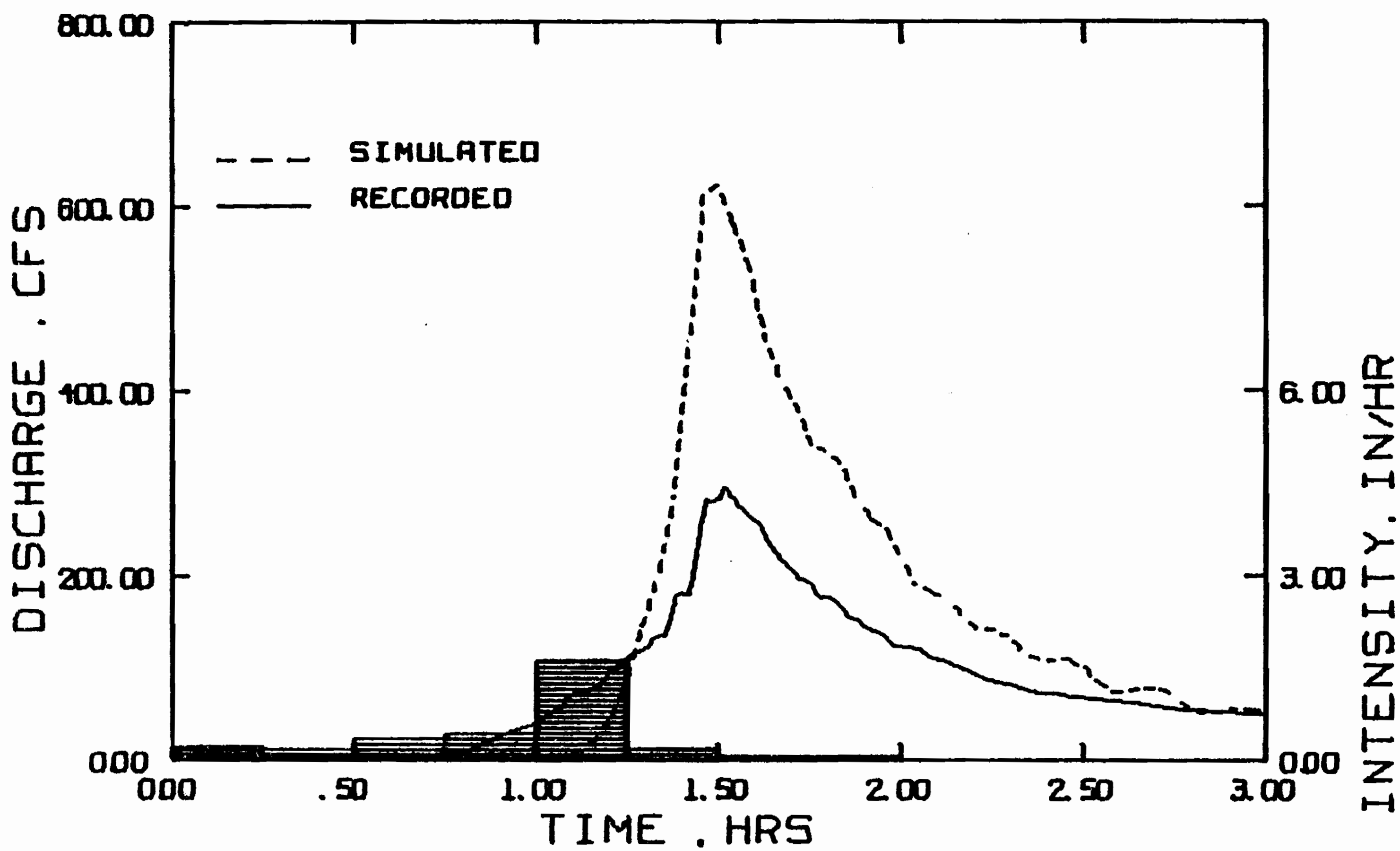


Figure 61. Comparison of recorded and simulated discharge for storm event 5/28/73, Brush Creek watershed, Floyd County, Virginia.

Chestnut Branch Watershed

Chestnut Branch watershed (Figure 62) is located in Bedford County, Virginia and consists of primarily pasture and farm woods while draining 1058 acres. The watershed is located in an area classified as Precambrian with rock formations of mica gneiss, mica schist and intrusive granite gneiss. The area generally represents complex landuse areas of the Northern and Southern Piedmont land resource areas lying east and adjacent to the Blue Ridge land resource area in Virginia, Maryland and North Carolina.

Relief of the watershed is 620 feet with 17% of the area having slopes in excess of 25%. Erosion status is fairly severe with 65% of the watershed being placed in erosion class 2 or higher. There are three raingages located in the watershed as shown in Figure 62. Data collection has been underway on this watershed since 1960.

This watershed was the largest to which the FESHM was applied. Two of the three largest storm events which occurred on this watershed were simulated. Errors in the recorded streamflow data prevented the largest storm from being simulated.

Although peak and volume of flow in both cases were overpredicted, fluctuations in the recorded trace are being produced in the simulated hydrograph with reasonable accuracy (Figures 63 and 64).

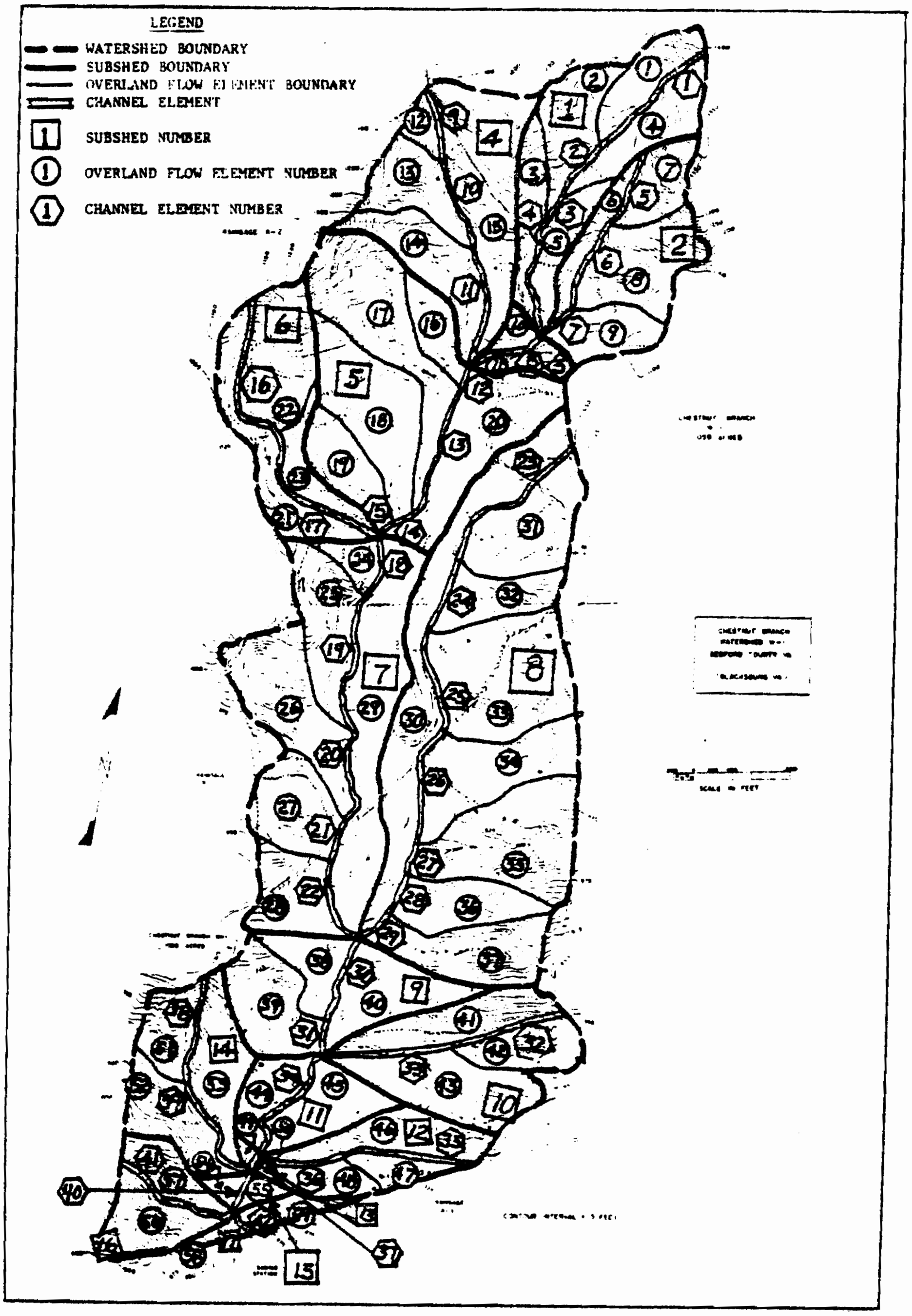


Figure 62. Topographic map and finite element discretization for Chestnut Branch watershed, Bedford County, VA.

Assuming that estimates of soil depth are accurate, the excess volume of runoff may be attributed to the neglect of transmission losses, particularly in the floodplain areas. This watershed has a well-defined system of drainage ways and, consequently, a high drainage density. These floodplain areas are characterized by very deep alluvial soils which may intercept flow before reaching the channel or be lost in transit as out of bank flow. This phenomenon becomes critical as storm events with small return periods are simulated.

Summary of Results for Natural Watersheds

A summary of the recorded and simulated runoff volumes and peak discharge is presented in Table 15. Matches of runoff volume and peak discharges are surprisingly close, particularly when considered in an ungaged context. An underlying assumption of the FESHM simulation technique was that by including spatial variability in those factors that affect the hydrologic response of a watershed, reliable streamflow predictions could be achieved with *a priori* estimate of model parameters.

Parameters describing HRU and element characteristics could be altered to improve yield predictions, however, this manuever was considered purely academic in the context that

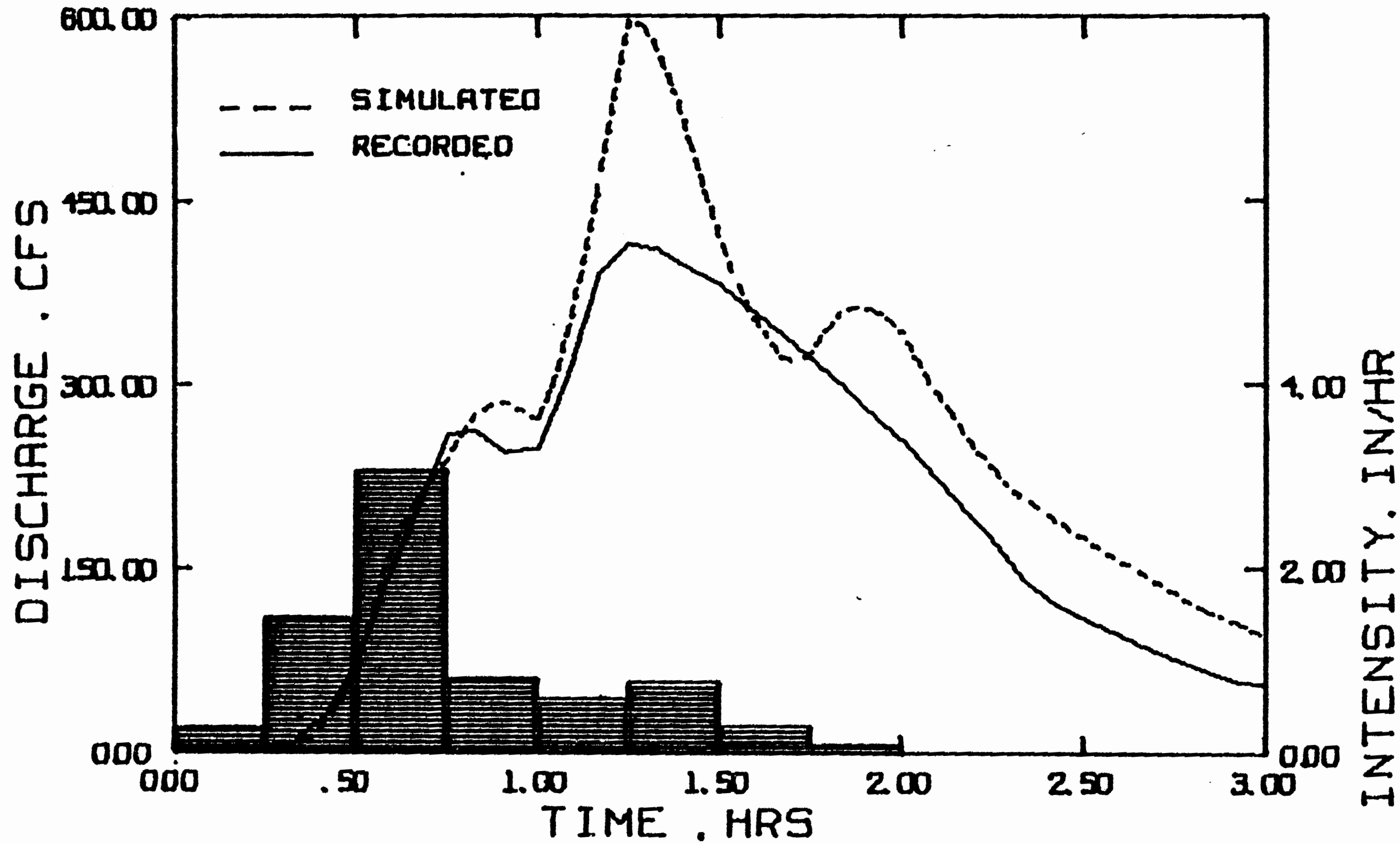


Figure 63. Comparison of recorded and simulated discharge for storm event 8/23/67, Chestnut Branch watershed, Bedford County, Virginia.

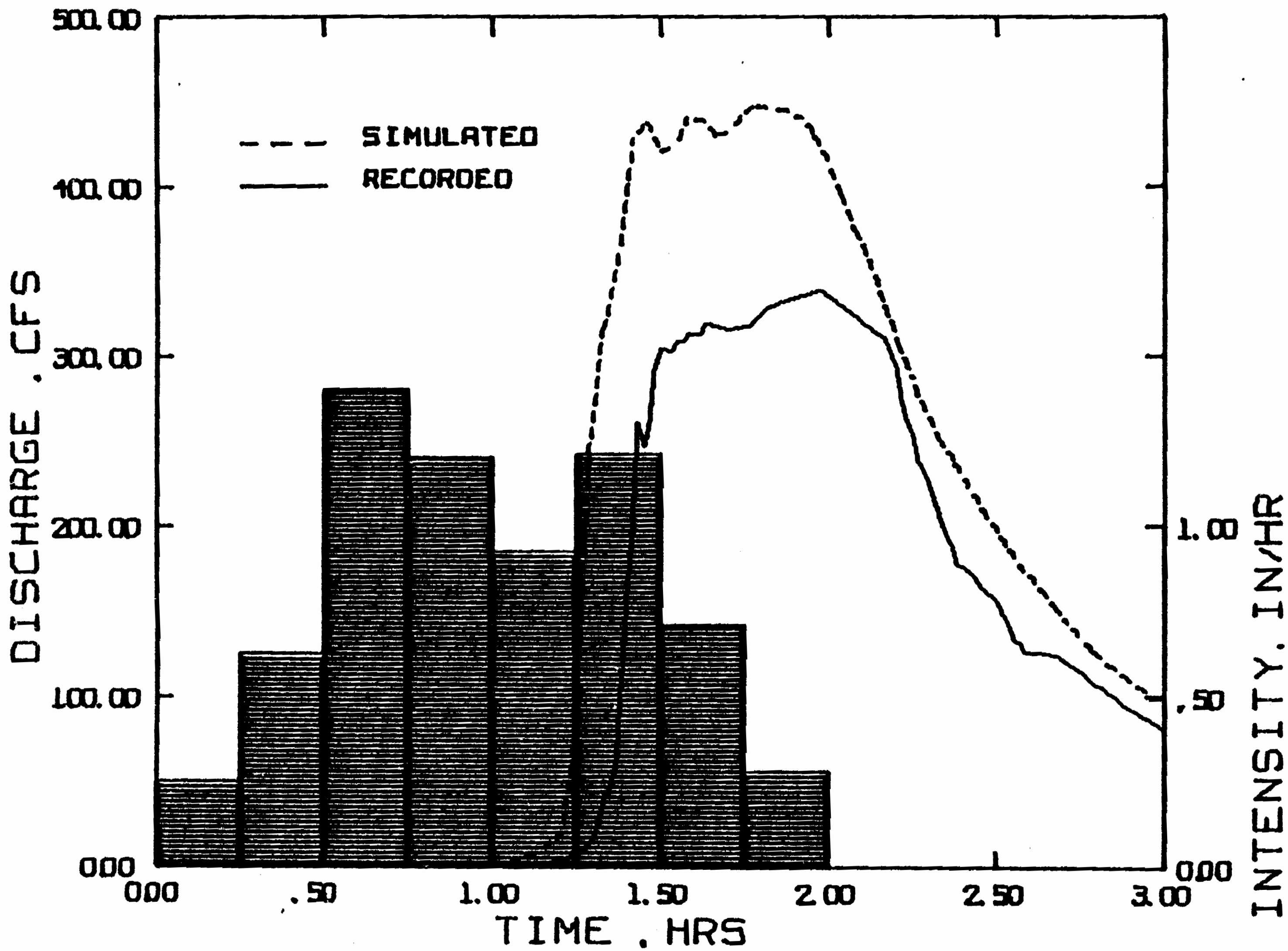


Figure 64. Comparison of recorded and simulated discharge for storm event 8/4/74, Chestnut Branch watershed, Bedford County, Virginia.

Table 15. Comparison of runoff volume and peak flow for simulated and recorded flows.

Watershed	Storm Event	Runoff Volume (in)		Peak Flow (cfs)	
		Recorded	Simulated	Recorded	Simulated
Powells Creek	10/10/59	0.73	0.46	109.88	114.34
	5/31/62	0.92	1.34	241.10	359.71
	7/11/65	2.06	2.38	419.82	775.13
Pony Mountain Branch	6/12/58	0.44	0.46	83.29	78.32
	6/24/58	0.43	0.44	91.26	94.44
	9/19/60	0.73	0.47	45.74	59.95
Rocky Run Branch	7/23/70	1.44	1.13	327.80	544.32
	10/ 5/72	5.79	3.26	609.77	551.00
Crab Creek	8/21/66	0.19	0.26	179.20	231.16
	10/24/71	0.57	0.30	180.54	137.59
	6/16/76	0.49	0.31	205.58	148.34
Brush Creek	7/22/59	0.44	1.08	791.47	1741.56
	9/30/59	1.14	0.86	924.70	434.69
	5/28/73	0.27	0.43	296.38	623.58
Chestnut Branch	8/23/67	0.67	0.63	416.08	595.84
	8/ 4/74	0.43	0.49	339.65	448.43

these flow simulations are being considered. Optimization procedures applied to model parameters, however, could possibly provide important information for determining better estimates of parameter values that could be applied universally to any watershed. This is an important consideration but this effort is beyond the scope of this research effort.

The parameter sensitivity analyses applied to the hypothetical watershed (Fig. 26) revealed that the proper definition of some watershed parameters is crucial to obtaining good matches between simulated and recorded hydrographs. Many interactions between parameters are occurring and may be overlooked by this type of sensitivity study, however, the relative influence of varying a particular parameter can be determined.

There are three major aspects of the hydrograph shape which must be considered in trying to optimize the match between the simulated hydrograph and the recorded trace. These are the volume of runoff, the peak discharge, and the timing of the peak discharge (lag time).

Volume of Runoff

Soil depth is the primary factor that influences the volume of runoff. Concurrent with the selection of the proper soil depth for a given soil type is the final rate of infiltration which determines the rate of storage recovery in the soil profile.

These influences are illustrated in Figures 65 and 66 which show how an adjustment in the magnitudes of the soil depth and final rate of infiltration parameters can improve the fit of the simulated to the recorded hydrograph. In both figures, estimates of soil depth and final rate of infiltration were increased by 40% and 100%.

Peak Discharge

The predicted peak discharge will obviously be affected by the volume of runoff but it is primarily dependent upon the element lengths, particularly those of the overland flow elements. Figure 67 shows how a 10% and 20% increase in this parameter can improve estimates of peak discharge. The coefficients of roughness also will affect peak discharge but its impact is much less than that of element length.

Time to Peak

The time to peak is affected by the selection of roughness coefficients to some degree, however, on small watersheds the timing of peak flows is primarily dependent upon rainfall characteristics. An illustration of this is given

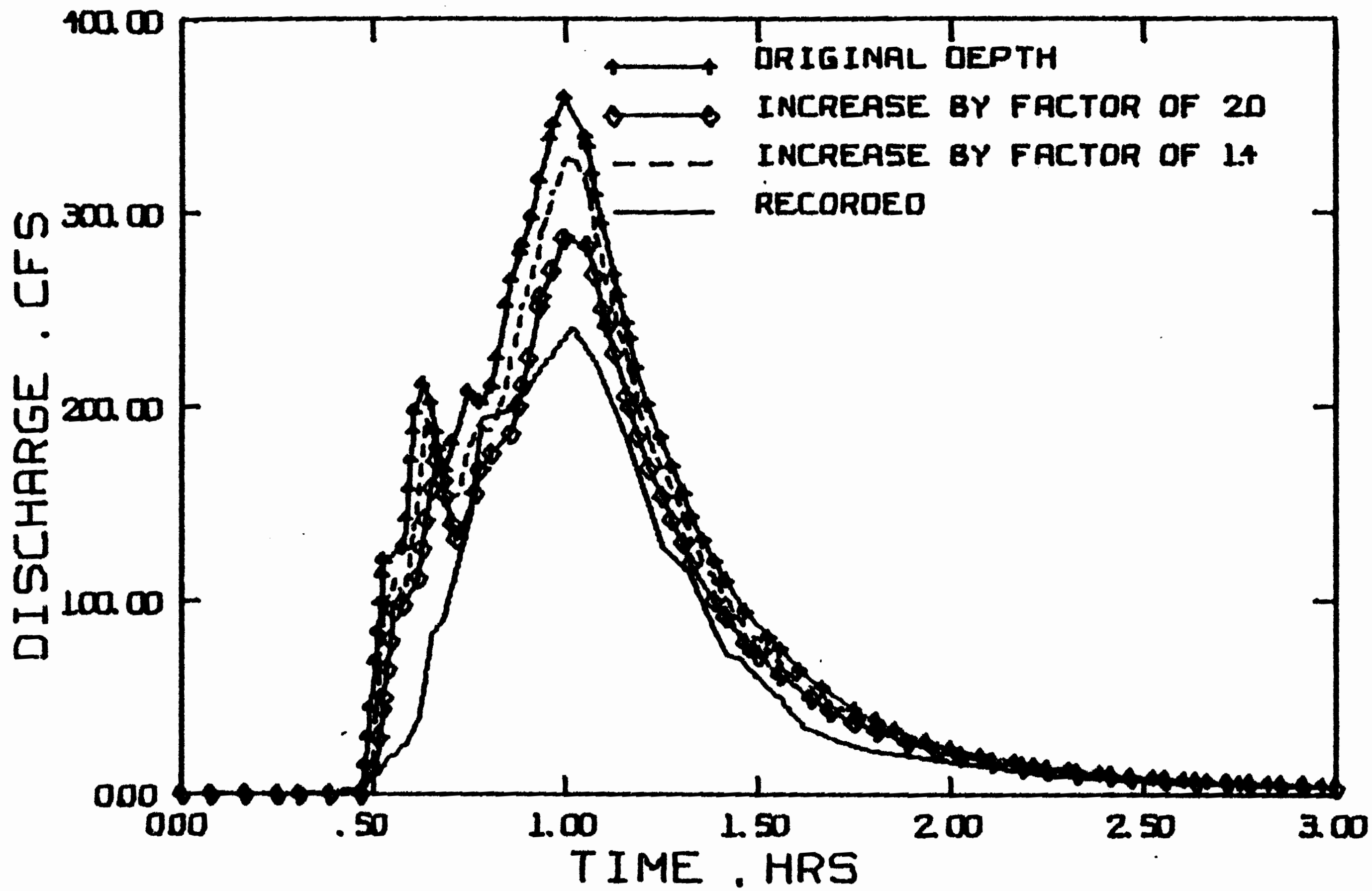


Figure 65. Effect of increasing soil depths in Powells Creek watershed, Halifax County, Virginia, for storm event 5/31/62.

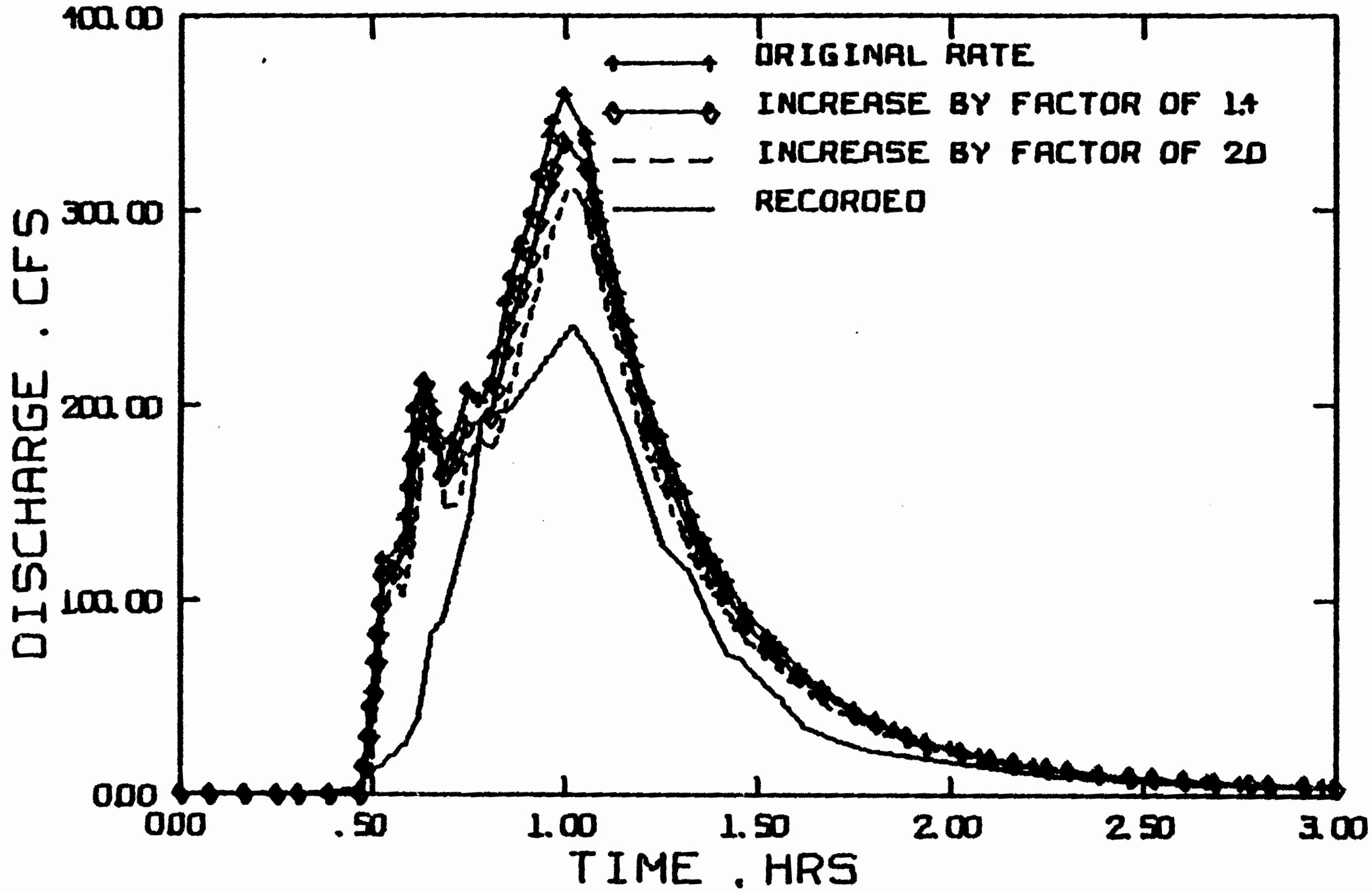


Figure 66. Effect of increasing final rates of infiltration in Powells Creek watershed, Halifax County, Virginia, for storm event 5/31/62.

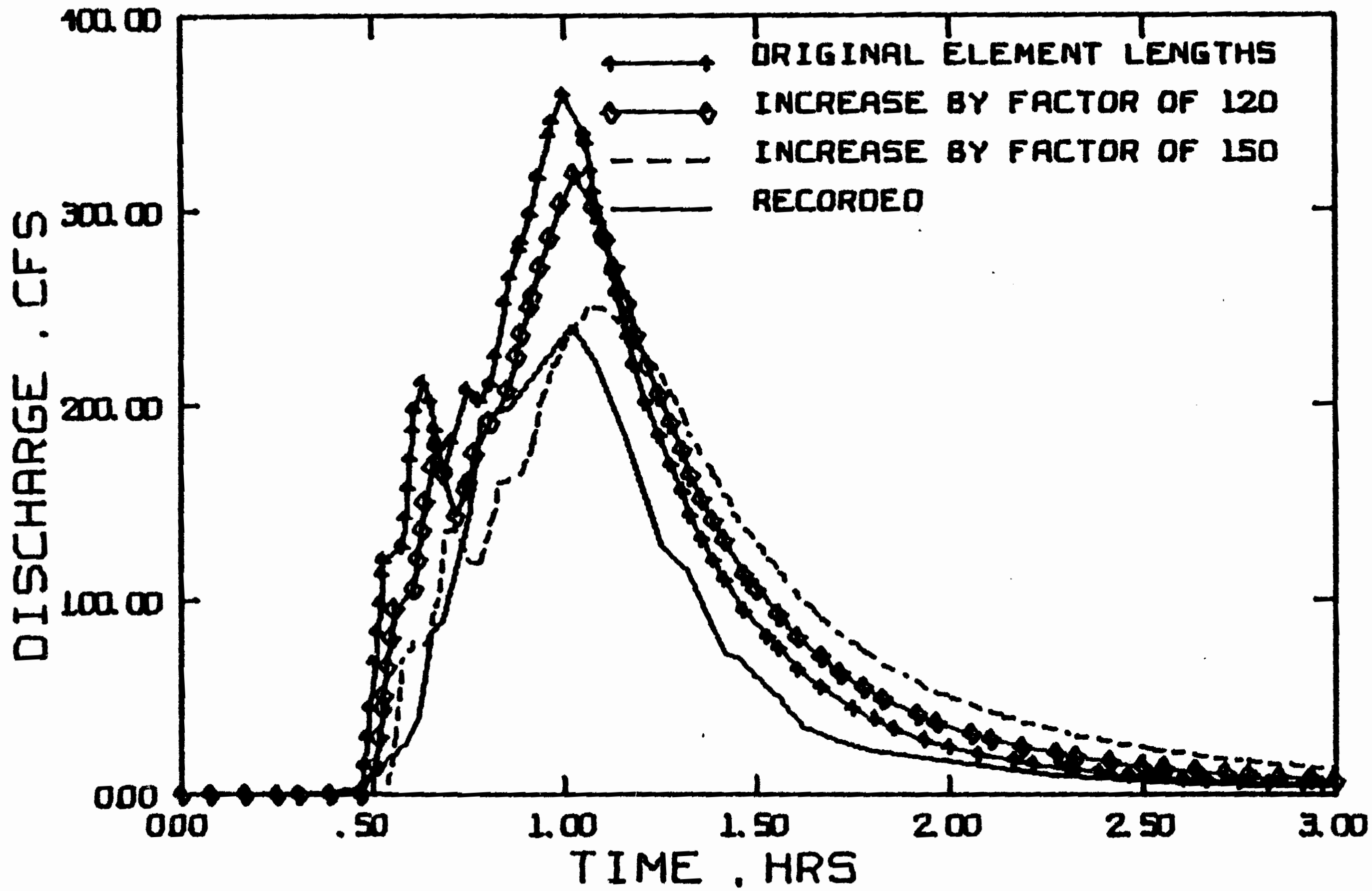


Figure 67. Effect of increasing overland flow element lengths in Powells Creek watershed, Halifax County, Virginia, for storm event 5/31/62.

in Figure 68. In this figure a hydrograph is shown which was determined by shifting the rainfall input for R1 one 15-minute increment backwards in time and is compared with the original simulated and recorded hydrographs. Errors inherent in this aspect of data collection can cause large discrepancies between simulated and recorded flows.

Thus, a major factor in the inability of the FESHM, or any hydrologic simulation model, to match recorded flows may be attributed to errors in data collection. An equipment failure such as a clock which did not keep proper time or two or more raingages that were not synchronized with respect to time may drastically affect the simulated response of the watershed.

Collected hydrologic data which falls in the range of ±5% may be considered of excellent quality, however a variance of even this small amount will adversely affect simulated flows on small watersheds. This point is illustrated in Figure 69 where errors of 5% and 20% are assumed in the quantity measurement of rainfall for each 15-minute increment of the storm. It is easily seen how those errors affect not only the magnitude and timing of flows but also the general hydrograph shape.

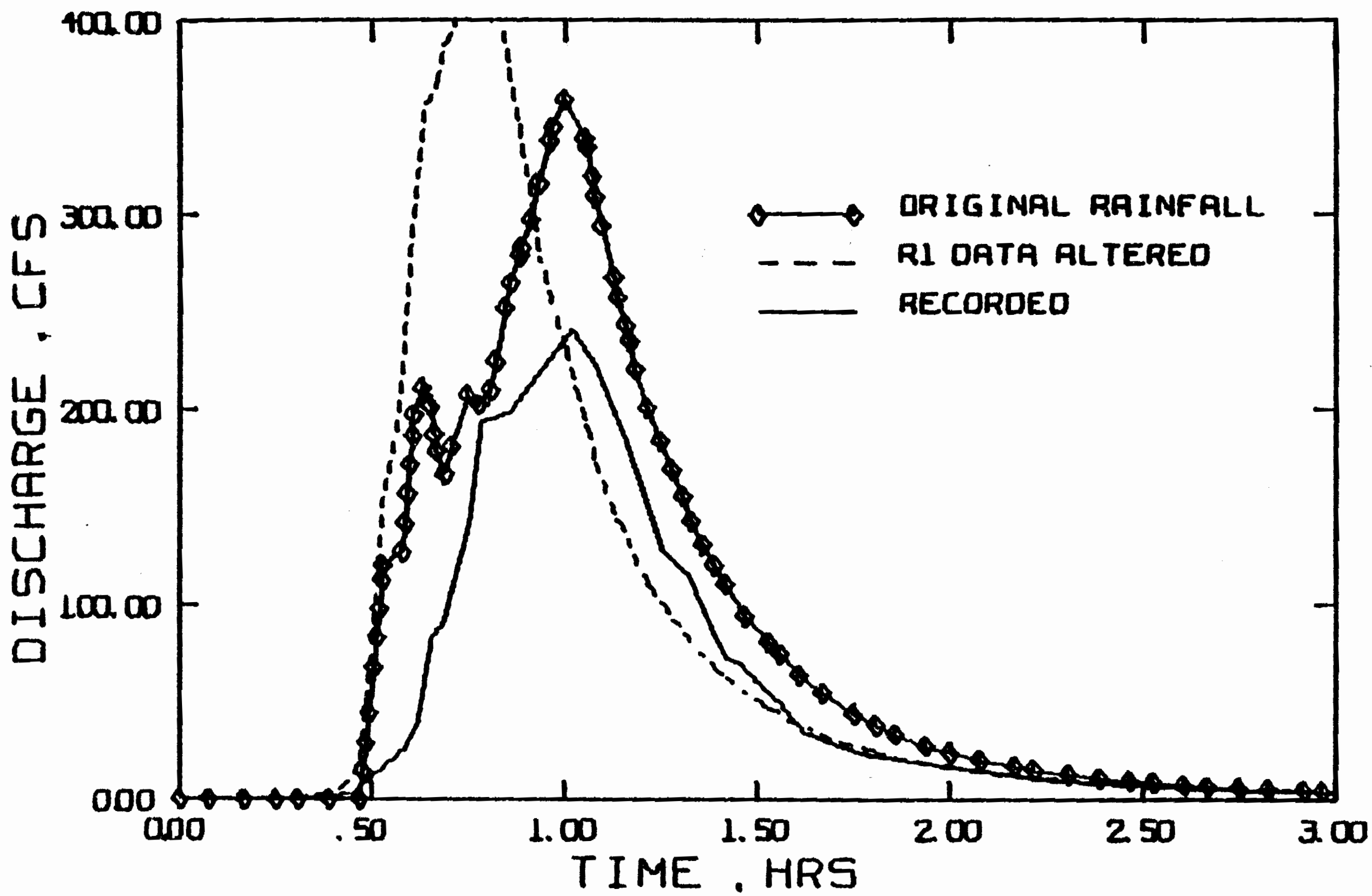


Figure 68. Effect of shifting R1 rainfall sequence for storm event 5/31/62, Powells Creek watershed, Halifax County, Virginia.

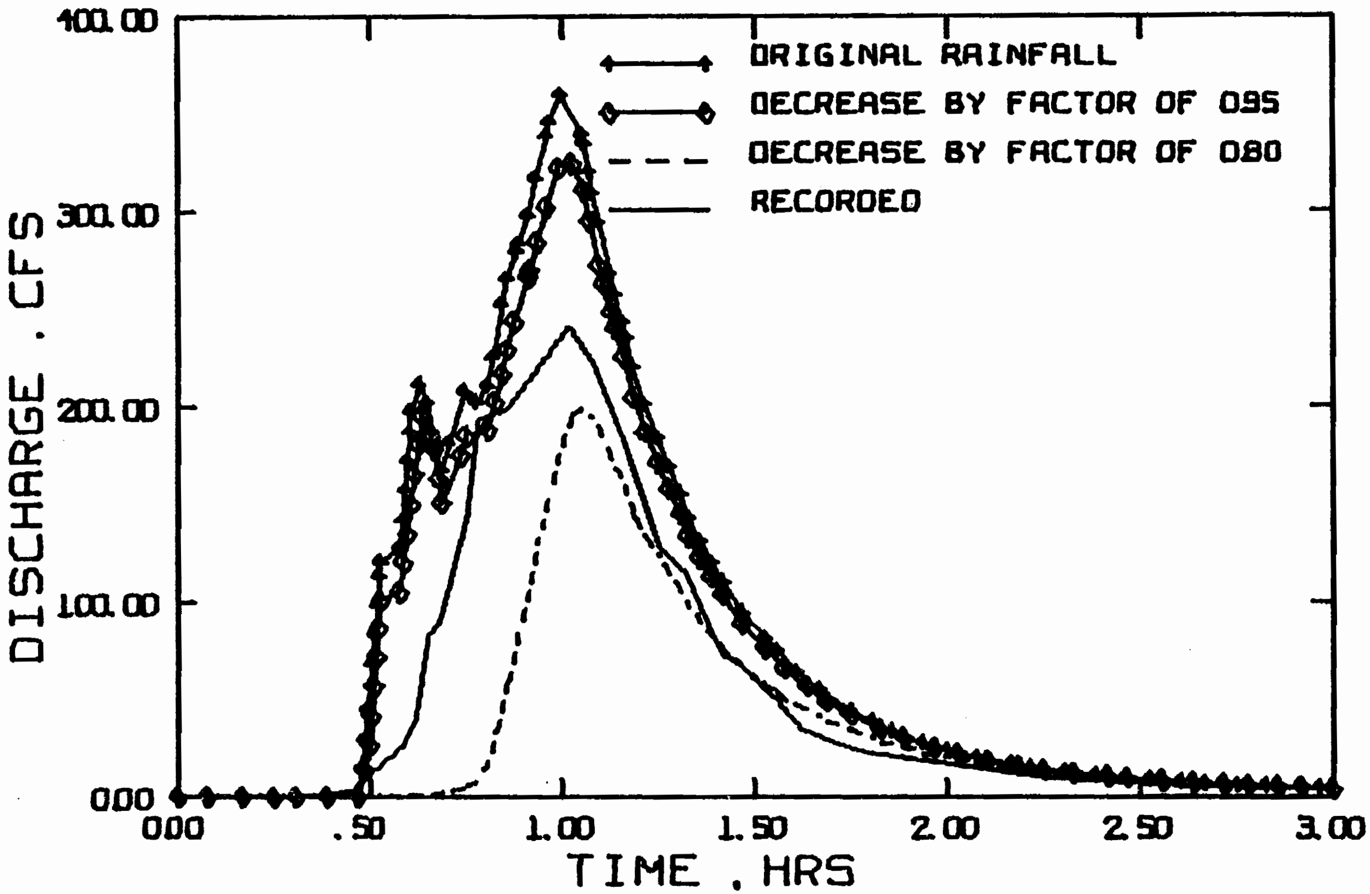


Figure 69. Effect of reducing, by 5% and 20%, the rainfall for storm event 5/31/62, Powells Creek watershed, Halifax County, Virginia.

CHAPTER VI

MODELING OF EROSION AND SEDIMENT TRANSPORT FROM UPLAND WATERSHEDS

One of the most important applications of a spatially responsive hydrologic model is that of simulating the processes of erosion, sediment deposition and sediment transport occurring on a watershed. An effective sediment model is the first step toward successfully predicting many other types of nonpoint pollution encountered in rural areas.

Computer-based modeling of the sediment processes which occur on a watershed represents one approach to solving a problem which has been of concern for several decades. The following discussion provides a review of the factors which need to be considered along with approaches which have been taken in the past. Finally, techniques by which the FESHM may be applied to the simulation of erosion and sediment transport will be illustrated.

Impact of Erosion and Sedimentation

In recent years soil erosion and sedimentation have been recognized as the major water pollutant in rural areas. In general, soil erosion diminishes the fertility and aesthetic quality of the land, while sedimentation degrades the quality of stream waters.

Plant nutrients, viruses, pesticides and some toxic chemicals become adsorbed to soil particles and can be transported to receiving streams by stormwater runoff. Suspended soil particles in a stream can create excessive turbidity which curtails photosynthesis and destroys aquatic plant life. Deposition of sediment on the stream bed may smother out much of the bottom fauna. Sediment buries eggs and larvae, is harmful to shellfish growth and may alter the entire aquatic food chain resulting in sport and commercial fish kill. Damages totalling $500,000,000 occur in the nation's reservoirs and harbors annually due to sedimentation.

The range and extent of sediment damage becomes apparent when one realizes that once erosion has occurred, the soil lost, most always, cannot be returned to its original location. It represents a triple damage threat, which includes erosion at its origin, transport in stream channels and deposition at downstream points in a watershed.

Recent research in the field of sediment transport has narrowed the gap which exists between the information needed and that which is available. There is still, however, a severe lack of procedures to properly integrate the many hydrologic and hydraulic variables which enter into the realm of sediment transport. This is apparent in the general inability to trace or "fingerprint" the movement of sediment through a hydrologic system and/or determine the effects of alternative sediment control measures at local and/or downstream points of interest.

Continuing research in this area is important in light of recent Congressional legislation (PL 92-500) which requires the protection and improvement of the nation's water quality. In an effort to control and regulate nonpoint sources of pollution, Section 208 of this law requires an assessment of the source and amount of sediment by landuse and an evaluation of the integrated effects of a mix of landuse activities on water quality. The development of acceptable alternative control measures is dependent upon an accurate interpretation of sources of sediment and a better understanding of the effect of sediment on downslope, or downstream, locations. Thus, it becomes particularly important to define the source and amount of sediment from various landuse activities at a specific point in a receiving stream. It will be necessary to "fingerprint" sediment for the application of regulatory measures in a just manner.

Sediment as Nonpoint and Point Pollution

A nonpoint source of pollution is defined as a source which is diffuse in nature and discharges polluting substances to the water via widely dispersed pathways in contrast to a point source which originates from discrete, localized operations which generate definable pollutional discharges that are amenable to isolation and treatment.

Technically, sediment can be classified as both a nonpoint and point source of pollution. The two major aspects of watershed sediment are the eroded land and its transport overland to the channels, and scour of the channel bed, banks and floodplain and its transport. Note that the instream transport also includes eroded land from upland areas. After confinement to a conveyance system, sediment becomes essentially a point source. It can be isolated, however, control is usually very difficult.

The primary concern, quantitatively, is determining the nonpoint source contribution to the receiving stream since this material can supply 90-95% of the total sediment load of a stream {Graf(1971), Shen(1971) and Chow(1964)}. The problem is amplified since over 95% of the land area in the United States is classified as rural and nearly all pollution originating from rural land is nonpoint in source.

Upland and Lowland Phases of Erosion and Sediment Transport

The phenomena of sediment transport in a watershed system can be grouped into two distinct classifications which parallel the concepts of overland and channel flow. These groupings are the upland (overland) and the lowland (in-channel) phases.

Upland Phase

There are three subprocesses of soil erosion and transport which can be defined to take place on an upland area. These can all occur concurrently, however, at a specific point in the watershed they will represent varying stages of erosion. These processes, in their order of development, are sheet, rill and gully erosion.

Sheet erosion is conceptualized in terms of a uniform layer of sediment being removed from a sloping land surface. Although no line of demarcation exists to precisely define the point where sheet erosion ends and rill erosion begins, rills are created when runoff concentrates in small, well-defined channels due to small variations in such factors as slope and the erosive resistance of soils.

An advanced stage of rill erosion, resulting from the concentration of a number of rills, is referred to as gully erosion. Gullies are essentially permanent once formed, and although sediment transport in gullies resembles that in channels, the distinguishing characteristic is that gullies exhibit ephemeral flow characteristics. Gullies are less stable than channels unless adequate vegetation has formed to anchor the soil along its banks.

The primary agents that initiate erosion on land surfaces are wind, ice, gravity, snow and rainfall. Except in isolated instances, however, rainfall represents the major threat to land subject to erosion.

Erosion on upland areas of a watershed is dependent upon several factors besides rainfall characteristics. Climatic conditions, such as temperature and humidity, can affect the rate of erosion. Different soil types react differently in their erosive resistance because of such characteristics as soil texture and structure, moisture content, permeability, compactness, infiltration capacity, organic matter content, and chemical and biological factors. Several topographic features, such as slope and slope length, have a profound effect upon erosion.

One of the most important landuse factors that affects the rate of erosion is vegetative cover. Frevert, et.al. (1955) give the following means by which vegetative cover can reduce erosion:

1. Interception of rainfall by absorbing the energy of the raindrops and thus reducing runoff.
2. Retardation of erosion by decreased surface velocity.
3. Physical restraint of soil movement.
4. Improvement of aggregation and porosity of the soil by roots and plant residue.
5. Increased biological activity in the soil.
6. Transpiration, which decreases soil moisture, resulting in increased storage capacity.

The effect of vegetative cover varies greatly with the type of vegetation, season of year, maturity and climate. Alteration of vegetative cover is the primary means by which man can vary the erosive potential of land. EPA (1973) classified landuses according to their effect upon erosion and suggested this grouping to delineate between the various applications of man's use of land.

1. Agriculture: croplands, grasslands, and livestock.
2. Silviculture: forest culture, harvesting, and logging practices.
3. Mining: new, current, and abandoned surface

and subsurface mines, and associated sites and facilities.

4. Construction: land development, highways and roads, and other heavy construction.

From previous discussion it becomes evident that sediment is directly related to precipitation and while sediment discharge is not 'man-made', its impact is directly related to man's activities. An increasing disturbance of the land by man's actions results in an increasing erosion and sedimentation problem.

There are four storm-dependent processes which determine the magnitude and rate of erosion and sediment transport on upland areas. These are generally catagorized as detachment by raindrop splash, transport by raindrop splash, detachment by runoff and transport by runoff.

Raindrop splash can have a devastating effect upon the detachment of soil depending upon such factors as raindrop size and distribution, velocity and angle of impact with the soil. A 30-inch annual rainfall over a square mile of land area contains impact energy equivalent to 10,000 tons of TNT {Shen (1971)}.

Transport of sediment by raindrop splash is seldom significant because of the angle of impact, except on steep slopes. On level land, however, splashed material can travel five feet or more in a horizontal direction {Chow (1964)}.

Soil is detached by runoff primarily by its velocity as it flows over the land surface and transports the majority of the soil which moves in a downslope direction.

Lowland Phase

As mentioned previously, there are two sources by which a stream channel receives sediment for transport; (1) the sediment delivered to the channel from the upland drainage areas and (2) the scour of the channel boundaries.

The major factors which affect the capacity of a stream channel to transport sediment, are flow velocity and depth, viscosity of the water-sediment mixture and particle size distribution of sediments.

The five categories to which sediment is assigned with respect to its mode of transport through a channel are listed as follows:

(1) Bed load - sediment which rolls or slides along the stream bed.

(2) Saltation load - sediment which bounces along the stream bed.

(3) Suspended load - sediment which is held in

suspension by turbulent flow.

(4) Dissolved load - sediment which consists of salts and chemicals in solution.

(5) Washload - very fine particles which are carried along the channel and have no relation to the bed material.

The three major contributors in this group are the bed load, suspended load and washload. Quantitative analysis of sediment and transport is usually limited to these three.

Modeling of Sediment Processes

Early attempts by planning and design agencies to arrive at estimates of sediment-yield required extensive long-term instrumentation at the site, although procedures were developed to extrapolate short-term data for longer periods and extreme flood events. The obvious hazard in a method which relies solely upon historic data is the magnitude of the errors which may be encountered in data collection and extrapolation.

Other early attempts at modeling the sediment phenomenon consisted of equations developed by statistical techniques to define gross erosion or soil loss in terms of influencing watershed factors to which sediment-delivery ratios would be applied to obtain sediment-yield. The most well-known of these are the Musgrave equation {Musgrave (1949)} and the Universal Soil Loss Equation (USLE) {Wischmeier and Smith (1965)}. Several modified forms of these two equations have been developed {e.g. Beer, et.al. (1966); Renfrc (1974); and Williams (1975)}.

Estimates of soil loss obtained by the above equations do not readily give an indication of the amount of deposition and sediment-yield. For the determination of sediment-yield, sediment-delivery ratios have been used which have been based upon estimates of gross erosion. The determination of a sediment-delivery ratio requires prior knowledge of the gross erosion and sediment-yield quantities at a given point. When there is no instrumentation for obtaining these measured values, the sediment-delivery ratio may be estimated from readily determinable watershed factors {Anderson (1957) and Roehl (1962)}.

Predictive equations that involve a direct solution of sediment-yield from identifiable watershed factors have also been developed. Much of the research in the area of sediment transport, until recently, has been limited to stream processes. The data necessary for the solution of sediment transport and deposition in channels is easier to obtain than comparable data for upland drainage. Channel properties are somewhat uniform relative to the properties of the land surface which can vary greatly.

These various sediment transport relationships differ greatly in their predictive capabilities. Errors in excess of 100% have been encountered in their use {Vanoni, et.al. (1960)}. A detailed discussion of formulas that have been developed will not be presented here, however, excellent descriptions are given by Raudkivi (1967) and Graf (1971). Several approaches that consider the watershed as a whole are discussed below.

Ellison (1945) was the first to recognize the four sub-processes of detachment and transport by rainfall and runoff which contribute to the overall upland erosion phenomenon and attempt to analyze them independently. He defined soil erosion as "a process of detachment and transportation of soil particles by erosive agents" including both water and wind. He also stated that these subprocesses were interrelated, but separate, and needed to be studied as such. None of the aforementioned methods for determining sediment-yield were based upon Ellison's (1945) initial suggestions.

Meyer and Wischmeier (1969) presented mathematical submodels to simulate the four components of the upland erosion phenomenon and essentially laid the groundwork for the present direction of sediment modeling. Descriptions of the four subprocesses were obtained but they acknowledged that the interrelationship between the four was inadequate. Soil to be routed was defined as the difference between the quantities of soil detached and transport capacity. A slope was divided into increments whereby the soil was routed downslope through the segments and the remainder was deposited on each segment.

These ideas have been pursued by several recent investigators. A brief discussion follows of several of the comprehensive watershed models that have been developed and highlights and limitations of each are noted.

David and Beer (1975) developed an erosion model and used the Kentucky Watershed Model to obtain estimates of overland flow. Daily recorded streamflow was used in lieu of simulated streamflow to minimize errors in determining channel scour rates.

The four components of the erosion process were each treated separately and the results summed to give the total washload. The washload was added to the estimated scour of channel bed and banks to give the total sediment load of the channel. Sediment was not routed through the channel.

The above model was applied to a small agricultural watershed and results were reported to be favorable for annual, monthly and daily suspended sediment loads. It was also reported that the Kentucky Watershed Model (KWM) and erosion model could not be applied to a large watershed without the necessary segmentation of the watershed into sub-watersheds to reflect the diverse nature of the factors affecting erosion and sedimentation rates.

Onstad and Foster (1975) developed a mathematical procedure to determine sediment-yield for individual storms as a function of the subprocesses of detachment and transport by rainfall and runoff utilizing concepts developed in the Agricultural Chemical Transport Model (ACTMO) {Frere, et.al. (1973)}. They modified the USLE to include both rainfall and runoff energy, to estimate the total soil detached. The USLE was also used to determine transport capacity. An attempt was made to define both rill and interrill components for the purpose of determining the rill and interrill contributions of sediment.

To apply the model, the watershed was defined in terms of its slope segments. The detachment and transport capacity was determined for each segment. Deposition and sediment-yield was calculated for each slope segment by the difference between transport capacity and detached soil load.

Donigian and Crawford (1976) developed the Agricultural Runoff Management (ARM) model to predict pesticide and nutrient transport on agricultural watersheds. Sediment predictions were based on the work of Negev (1967). It was assumed that all soil from upland areas reached the channel and was transported to the watershed outlet. Channel erosion and/or deposition were not considered nor was channel routing of sediment performed. The model contains considerable flexibility for evaluating the effect of vegetative cover, tillage operations and conservation practices on the sediment loss from a watershed.

The entire watershed drainage area was considered to be a homogeneous flow plane and, consequently, the ARM model is limited to watersheds with areas of less than one or two square miles.

Adams and Kirisu (1976) developed a comprehensive hydrologic model to simulate pesticide movement on agricultural watersheds. A necessary part of this effort was the simulation of sediment transport.

A watershed can be subdivided into a maximum of twenty zones, or subplots, each having unique hydrologic properties, although landuse was considered constant throughout the entire watershed. Drainage pattern relationships between subplots were specified for the routing of flow.

No channel component of flow or sediment was included in the model. For most watershed runs, the predictive results were reported to be reasonable although they reported that the accuracy of the sediment predictions was highly sensitive to predictions of runoff volume.

Solomon and Gupta (1977) developed a distributed parameter model for routing flow and sediment on large watersheds based on a system of square grids. Flow routing was performed by the Muskingum routing technique and each of the four erosion subprocesses occurring on upland watersheds were quantified. A channel routing component was also included through which the washload and bed load was routed.

Results obtained after calibration were reported to be acceptable. Comparison of the model results with other simple techniques for predicting sediment load, such as direct measurement and statistical methods, resulted in the conclusion that the distributed parameter model was more accurate. It was also stated that the model is more applicable for evaluating changes in landuse upon the hydrolcgic response of a watershed.

Kuh and Reddell (1977) developed a two-dimensional erosion and transport model. The drainage area was subdivided into square grids. Sediment was routed from each grid to adjacent grids and deposition was determined as the difference between detachment and transport capacity. Soil loss and deposition for each grid was determined which defined critical problem areas.

Results of the model's application on experimental watersheds were very good for long term predictions. A comparison with the USLE revealed that the two-dimensional model performed much better in predicting erosion from individual storms. No erosion or sediment transport through channels was included in the development of the model.

Beasley, et.al. (1977) developed the Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) model, which represented a distributed parameter approach to sediment modeling on agricultural watersheds. The model consists of a hydrologic model interfaced with a model of sediment detachment, transport and deposition, however, the assumption was made that sediment transport by raindrop splash is negligible.

A quasi two-dimensional routing was performed, whereby flow and sediment were routed in two directions from each grid element. Detachment and transport capacity were solved for each element from which sediment-yield to the downstream elements was determined.

No channel erosion was assumed nor was channel routing performed. Both flow and sediment discharges were obtained for short time increments and the spatial detail of the simulation allowed an estimate to be made of critical soil loss and deposition areas of the watershed.

Simulating Erosion and Sediment Transport with a Spatially Responsive Model

A spatially responsive model, e.g., the FESHM, is aptly suited for simulation of erosion and sediment transport for several reasons. The FESHM provides a ready mechanism whereby sediment processes may be simulated on a watershed and analyzed as two distinct transport regimes. The structure of the model provides a base for upland and lowland sediment simulation in the context of overland and channel flow, respectively.

Few of the watershed models which have been developed to date have the capacity to simulate sediment processes occurring in a channel. This becomes a major limitation when it is desired to determine the effects of control measures where they are most easily implemented. As previously mentioned, sediment which is confined to the channel is thereby amenable to control and treatment as a point source. The lowland phase of sediment transport is the site where major damages are incurred in the form of floodplain scour and deposition, channel turbidity and deposition.

Also important in the context of the capability to simulate both upland and lowland phases of erosion and sediment transport is the concept of the flexible grid. A flexible grid structure is considered essential to improving simulations of both upland and lowland phases of erosion. If the necessary data is available, then any point in the watershed can be relegated to either the overland or channel flow regime. For example, if a deposition pond were to be placed in an overland flow strip of the present watershed grid, its effect can be analyzed more closely by a restructuring of the grid at the point in question so that the sediment could be routed to and through the structure by its natural channel conveyance system.

Another advantage of the FESHM is its capability to include spatial variations. The need for sediment models to consider spatial variations in watershed systems has been recognized by several investigators. Glymph (1975) recognized this when he stated, "In each of the methods, the watershed is treated as a lumped system. They deal with the watershed as a whole, rather than with its constituent features, in describing the quantity of sediment expected at a point on the watershed. . . . . .

Greater specificity regarding the sources and properties of sediments and the effectiveness of measures for stabilizing sediment sources requires that our technology treat the watershed as a distributed system. For dealing with water pollution associated with runoff from nonpoint sources, we need technology for sediment-yield predictions that begins with the erosion process and objectively and specifically accounts for deposition of the eroded material as it moves downstream from the point of origin."

Sweeten and Reddell (1976) gave a state-of-the-art overview of nonpoint sources of pollution. It is significant to reiterate their conclusions relative to assumptions and limitations inherent in most of the models presently available for estimating sediment loss. They reported that "The complex land profile is simplified to a uniform, concave or convex slope. Detailed erosion and deposition processes inside the watershed are ignored. The available models are one-dimensional in nature; they do not consider changes in flow direction, land slope and flow velocity which take place on a watershed."

The above statements indicate that the dominant sediment modeling approach has been that of determining the sediment-yield from a watershed at some downstream point by considering the entire watershed to be a homogeneous flow plane. The spatially responsive concept of modeling has just begun to come into prominence as a watershed modeling technique. The aforementioned Congressional legislation has accelerated research efforts in this direction.

A spatially responsive analysis, such as the FESHM, efficiently accounts for the spatiotemporal variations of those factors relevant to the processes of soil loss and sediment transport. The use of this type of model to simulate sediment processes is based on the premise that storm water, soil erosion and sedimentation estimates can be improved with a spatially responsive model.

The data required to drive the FESHM contain much of the information needed to create a sediment data input file. The same vegetative parameters which are used to predict water quantity can be used to determine erosion and sediment transport rates. The most important aspect, however, is quite possibly the fact that the soil mapping descriptors, such as soil texture and erosion class, provide information which is necessary in determining the erodibility of certain soils.

The sediment component also conceptually possesses the ability to simulate sediment processes in the ungaged context. It is expected that, if successful, a model of this type will have the capability of defining the source and amount of sediment from various landuse activities at a specific point in a receiving stream. The movement of sediment through a watershed system may then be traced which will lead to the development of acceptable alternative control implementation and just application of regulatory measures.

Initial attempts at incorporating sediment predictive capability into the FESHM are discussed in the following section. Results are presented below to illustrate the technique. Field validation was not an objective of this study but will be investigated extensively as part of a continuing research effort.

Modaling Erosion and Sediment Transport by the FESHM

The potential use of the FESHM as a predictor of sediment processes occuring on a watershed will be presented by a numerical example utilizing a specific approach. Therefore, the example presented below is nct provided to endorse a particular set of mathematical relationships but is given only to illustrate the potential of the model. The selection of predictive equations to describe erosion and sediment processes is dependent upon the proper definition of runoff and its flow characteristics.

The approach used by Beasley et.al. (1977) for overland flow detachment and transport phases was applied to the overland flow aspect of the FESHM. These relationships are briefly described below.

Detachment by raindrop impact is estimated by the following relationship

$$D_R = 0.027\ C\ K\ A\ I^2 \qquad \{45\}$$

where

D_R is the rainfall impact detachment rate in kg/min,

C is the cropping and management factor (from the USLE),

K is the soil erosivity factor (from the USLE) in tons/acre/EI unit, A is the area increment in sq m, and

I is the rainfall intensity mm/min.

Detachment due to overland flow can be expressed as

$$D_F = 0.018\ C\ K\ A\ S\ q \qquad (46)$$

where

D_F is the overland flow detachment rate in kg/min,

S is the slope, and

q is the flow rate per unit width in sq m/min.

The total soil detached at any given time is

$$D_T = D_R + D_F \qquad (47)$$

where

D_T is the potential soil detached.

Beasley, et.al (1977) assumed soil transport by rainfall splash to be negligible. Soil transport by overland flow was described by the relationships

$$T = 146\ S\ \sqrt{q} \qquad q \leq 0.74 \text{ sq m/min}$$

$$T = 14600\ S\ q^2 \qquad q > 0.74 \text{ sq m/min} \qquad (48)$$

where

T is the potential transport rate of sediment.

For any given time increment, total soil detached is compared to the potential transport rate. If soil detached is greater than the transport capacity, deposition occurs and the remaining sediment is routed through the element. Otherwise, there is no deposition and the total soil detached is transported.

For the channel flow aspect a solution approach used by Chen, et.al. (1976) was adopted since the formulation is readily adaptable to the finite element solution for routing storm water runoff. The equation is referred to as the sediment continuity equation and can be written as

$$\frac{\partial Q_s}{\partial x} + p\,\frac{\partial A_d}{\partial t} + \frac{\partial A_s}{\partial t} - q_s = 0 \qquad (49)$$

where

Q_s is the sediment discharge,

p is the volume of sediment in a unit volume of bed layer, given by the bulk density of the sediment forming the bed divided by the bulk density of the suspended sediment.

A_d is the volume of sediment deposited on the channel bed per unit length of channel,

A_s is the volume of sediment suspended in water per unit length of channel, and

q_s is the lateral sediment inflow.

If, for the purpose of this illustrative example, only washload is routed then, neglecting bed load, Eqn. {49} reduces to

$$\frac{\partial Q_s}{\partial x} + \frac{\partial A_s}{\partial t} - q_s = 0 \qquad \{50\}$$

The basic similarity of Eqn. {50} to Eqn. {3} is evident, therefore, the former can be expressed in its finite element solution form as

$$\ell\ [K]\ \{\dot{A}_s\} + [L]\ \{Q_s\} - \ell\ q_s\ \{M\} = 0 \qquad \{51\}$$

At each time step Q_s may determined by

$$Q_s = V\ A_s \qquad \{52\}$$

where

V is flow velocity.

In Eqn. {51}, the solution procedure is identical to that of Eqn. {14}, where q is known from the solution of the overland flow sediment contribution. Thus, a discharge hydrograph may be obtained for sediment (washload) in the same manner as that for flow.

Application of the FESHM to the Simulation of Erosion and Sediment Transport

A computer submodel was written to solve the finite element form of the sediment continuity equation in conjunction with the FESHM. Equations {45}, {46}, {47} and {48} were inserted into the overland flow component of the model for the description of sediment detachment and transport. Equations {51} and {52} were used to describe sediment transport in the channels.

The sediment erosion and transport model was used to predict washload from Powells Creek watershed (Figure 43) for the storm of 5/31/62. The only data necessary, in addition to those previously used for the simulation of storm water runoff, were the C and K factors for individual landuse and soil types, respectively (Tables 16 and 17).

The simulated discharge hydrograph and sediment graph at the watershed outlet for these conditions is shown in Figure 70. The peak concentration of sediment reached 1087 mg/l, which is reasonable for the type of agriculture in this area.

Simulating the Effect of Land Management on Sediment Yield

The following applications illustrate the use of the FESHM in simulating the effect of land management practice

Table 16. K factors for the soils in Powells Creek watershed, Halifax County, Virginia. {SCS (1973)}.

Soil Type	K-factor
Appling fine sandy loam	0.32
Bremo loam	0.32
Cecil loam	0.32
Enon-Wilkes loam	0.43
Hiwasse loam	0.32
Lloyd loam	0.37
Madison fine sandy loam	0.32
Starr loam	0.00
Turbeville series	0.32
Worsham series	0.00

Table 17. C factors for each landuse in Powells Creek watershed, Halifax County, Virginia (SCS (1973)).

Landuse	C-factors
Corn	0.3380
Homestead	0.0001
Idle	0.0010
Pasture	0.0060
Pond	0.0000
Road	0.0020
Soybeans	0.3380
Tobacco	0.3380
Woods	0.0001

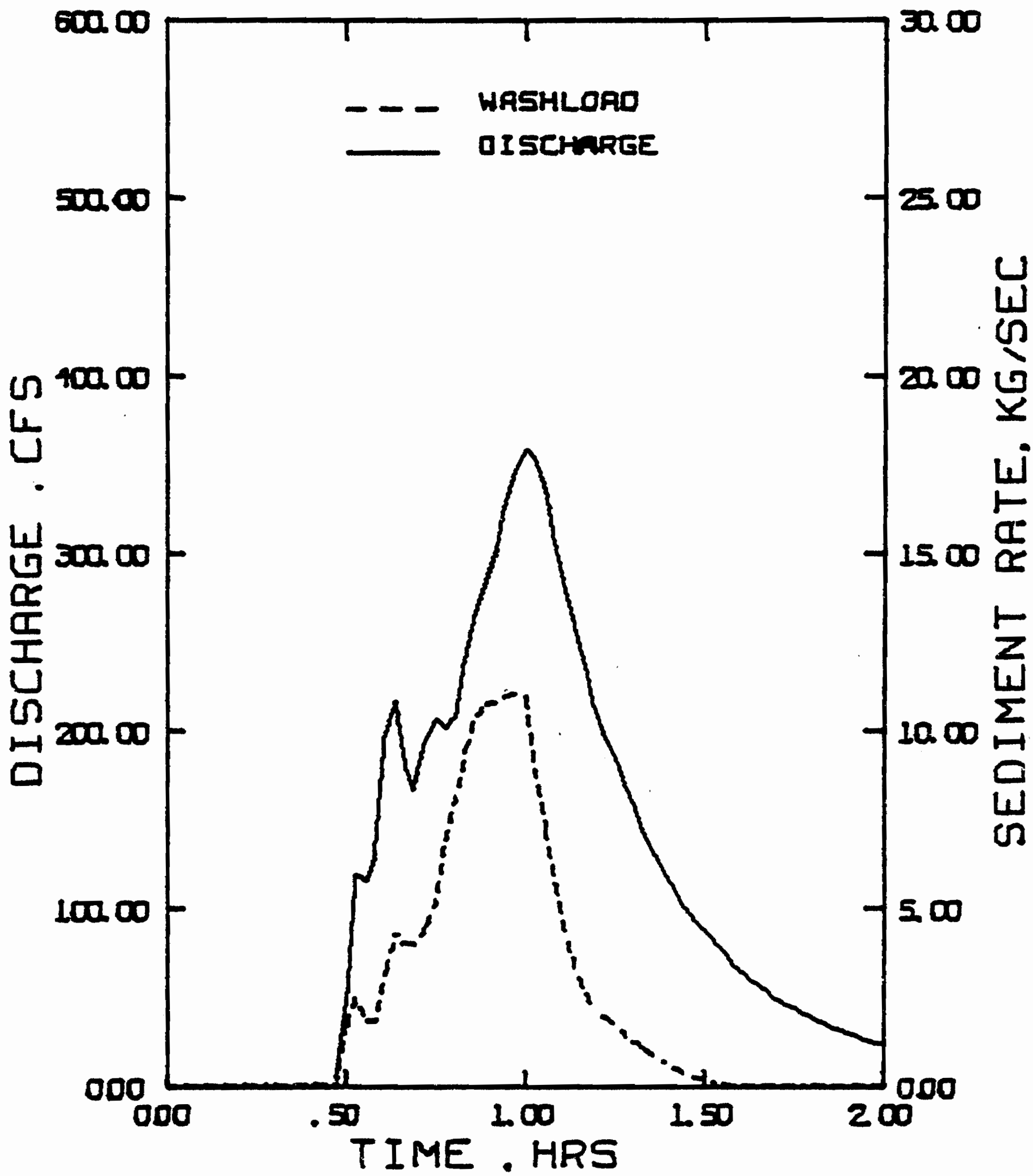


Figure 70. Comparison of simulated washload and stormwater discharge for the landuse conditions on Powells Creek watershed for storm event 5/31/62.

on sediment-yield. Three management practices will be used to illustrate the techniques: (1) no-till versus conventional tillage for corn production, (2) clearing of a wooded area for construction or cultivation and (3) in-stream controls such as a sediment basin or detention pond.

No-till Practice

The effect of converting tillage operations for corn from conventional turn-plow to no-till is illustrated in Figure 71. The appropriate C and K factors were obtained from USDA-SCS Technical Guide (1973) for Virginia.

The simulation shows a drastic reduction in both the concentration and volume of sediment. The reductions were 47% and 44%, respectively. Note that the simulated discharge was also reduced.

Wooded Area to Cultivation or Construction

The effect of clearing a wooded area for a construction project or cultivation was simulated by changing element Nos. 7 and 8 from wooded to fallow. The peak sediment concentration was increased by 129%, while the volume of sediment was increased by 105% (Figure 72). While flow characteristics were only slightly affected in this example, it is

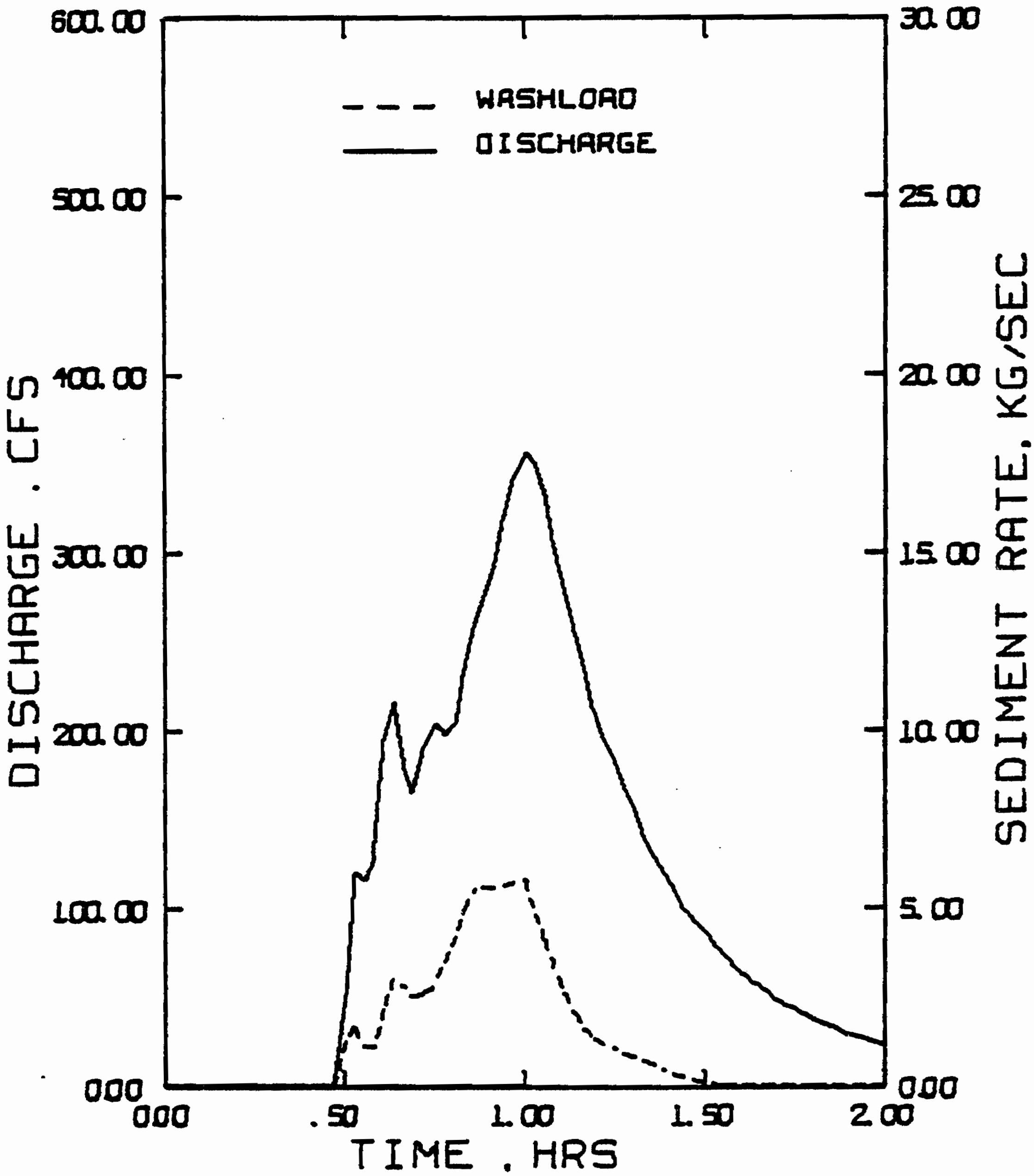


Figure 71. Comparison of simulated washload and stormwater discharge when corn grown with conventional tillage changed to no-till practice, Powells Creek watershed for storm event 5/31/62.

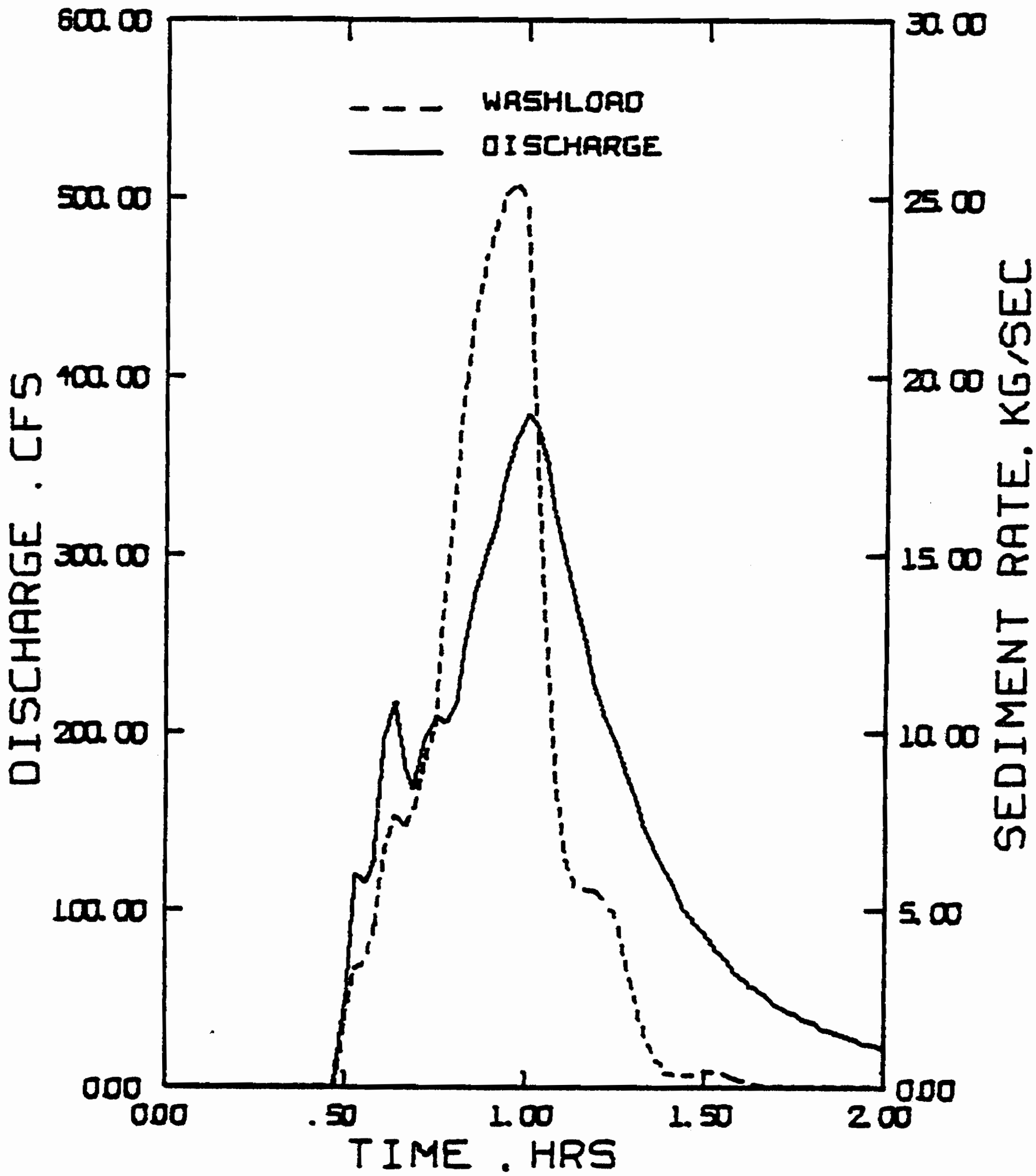


Figure 72. Comparison of simulated washload and stormwater discharge after changing element Nos. 7 and 8 (Figure 43) from wooded to a fallow condition, Powells Creek watershed for storm event 5/31/62.

worthy to note that a relatively small landuse change can have an appreciable impact on the quality of the receiving stream.

In-stream Controls

Another potential application of the FESHM is the evaluation of the effectiveness of in-stream controls for reducing sediment load. Sediment basins, settling ponds, farm ponds and detention basins are all included in this category.

Mathematical relationships based on flow and sediment characteristics can be devised {e.g. Ward, et.al. (1978)} to determine the trap efficiency of a sediment basin or other similar structure and be incorporated into the framework of the FESHM. For the purpose of this illustration, however, a straight 50% reduction in the washload passing through the downstream node of subshed No. 3 was assumed. The effect of this type of control on the sediment load of the stream is shown in Figure 73. The peak sediment concentration was reduced by 34% while the total amount of the sediment was reduced by 37%.

Many more examples of this nature could be illustrated, but, appear academic at this point. A major advantage of a spatially responsive model, however, lies in its ability to

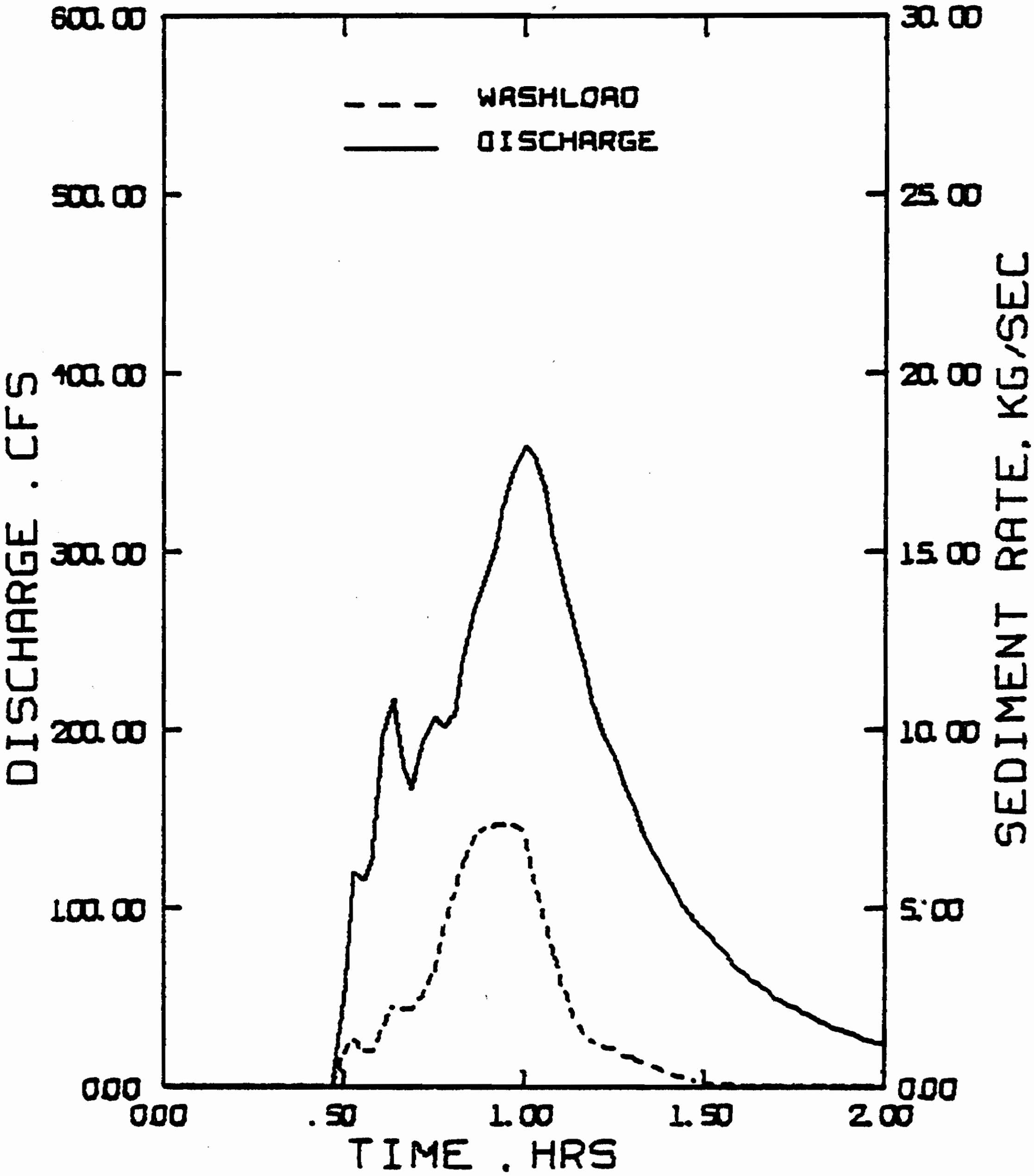


Figure 73. Comparison of simulated washload and stormwater discharge for in-stream control at downstream channel node of subshed No. 3 (Figure 43), Powells Creek watershed for storm event 5/31/62.

provide more comprehensive output information and, therefore, to identify critical influencing areas, whether flow quantity or the detachment and transport of sediment are being simulated. The finite element method is ideally suited for this type of modeling.

Detachment, Deposition and Transport on Overland Flow Planes

The flow simulations for the natural watersheds presented in the above examples were determined with a relatively coarse finite element grid structure. The conceptualized overland flow planes resulting from the definition of overland flow strips for Powells Creek watershed are not adequate to correctly describe the complicated processes of the detachment, deposition and transport of erosion on a micro scale. These strips must be further subdivided into a series of elements to assure that landuse patterns can be properly described so that hydraulic continuity will be maintained between upslope elements with single landuse and all succeeding downslope elements.

Figure 74 illustrates a typical strip crop agricultural practice and the discretization to properly define the elements in the overland flow strip. A series of land slopes is shown to illustrate a recommended farming practice for minimizing soil loss when row crops are grown on hilly ter-

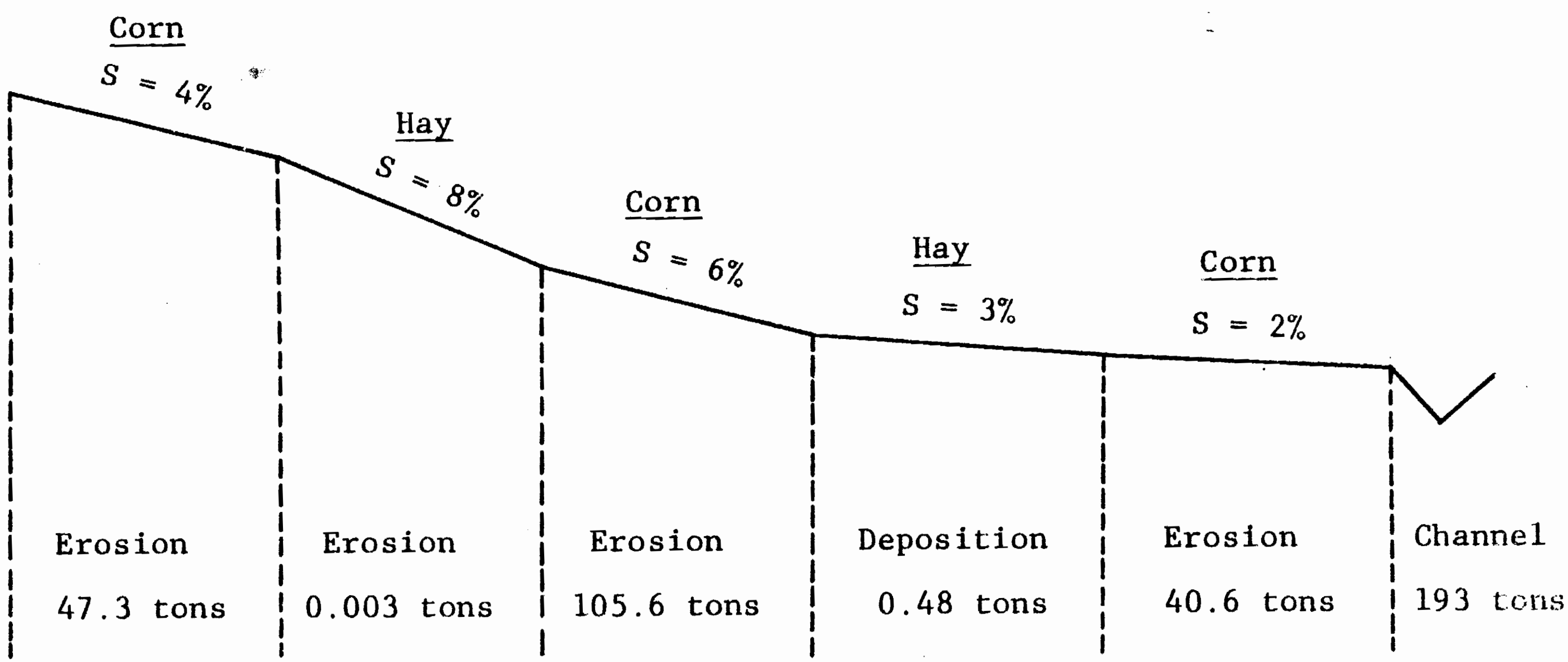


Figure 74. A schematic illustration of the modeling of sediment detachment and transport with the FESHM for a typical strip crop best management practice.

rain.

For the purpose of this illustration, a rectangular flow strip subdivided into equal-sized elements was assumed. A hypothetical storm of one inch per hour for a duration of two hours was assumed. The FESHM with the appropriate data base was used to obtain the results in Figure 74. This plot shows the sequence of erosion and deposition as flow cascaded from one element to the next. A total of 193 tons of soil reached the channel.

An alternative land management practice would be to reverse the cropping pattern in the last two elements. The total sediment entering the stream was reduced to 127 tons due to the settling and filtering effect of the hay field.

Scour and Deposition on Channels and Floodplains

Simulating the effects of deposition in the channel or on the floodplain can be accomplished by the inclusion of the second term in Eqn. {49} which was neglected for the purpose of routing only washload. This approach, however, requires an additional relationship to define sediment discharge as a function of sediment and flow properties., since there is an additional unknown in the equation {Chen, et.al. (1975)}. A_d then becomes the primary unknown in Eqn. {49} for which a solution is necessary.

This approach would be applicable in areas where appreciable floodplain scour and deposition occur. It also provides an alternative method to determine sediment retention in ponds, reservoirs or similar structures which create a significant ponding with a reduction in the velocity of flow.

Modeling Other Types of Nonpoint Pollution

A wide spectrum of potential water quality abaters exists, such as pesticides, nutrients, biodegradable pollution, microbial pollution, thermal pollution, radioactivity, salinity and mineral, heavy metal and acid mine pollution. Many of these pollutants have been modeled by a loading rate approach. The only additional information that is necessary for simulation of these pollutants, in many cases, are flow characteristics and/or information about sediment movement. Because of the simplicity of the technique, many investigators have leaned toward loading rates as the best approach to modeling some nonpoint sources of pollution {Meghji (1973), Bedient (1975) and McElroy (1976)}.

The FESHM, modified for the simulation of sediment, also can easily utilize this loading function approach to define nonpoint pollution. Hydrologic-landuse interactions are sufficiently defined to determine how much of a particular pollutant is available for transport, how easily it can be transported and to what extent it may travel.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The finite element method is readily adaptable to the spatially responsive concept for modeling watershed systems. The incorporation of significant spatiotemporal variation in soils, landuse, topography, land management and climatic conditions can be made with relative ease.

The kinematic wave approximation was found to be applicable to the problem of overland flow routing verifying the results of many investigators, and was also found to be a valid solution technique for most cases of channel flow routing in small watersheds.

When the overland flow plane has less than three elements, large convergence errors will usually be encountered with the use of linear interpolation functions. These problems can be minimized by using cubic interpolation functions for the overland flow strips and quadratic interpolation functions for channel flow segments. An alternative method is to subdivide the flow strips into three or more elements and use linear interpolation functions.

Comparisons between simulated and recorded hydrographs were encouraging, particularly since all simulations were conducted in an ungaged context.

Sensitivity analyses revealed that the model parameters most critical to obtaining reliable flow predictions were soil depth and the length of overland flow elements. Small errors in the magnitude and timing of rainfall data were found to be very crucial to obtaining the proper magnitude and timing of flows on these small watersheds. These types of errors make a valid interpretation of model results difficult.

The FESHM contains sufficient flexibility to simulate the effect of such management practices as in-channel controls, diversion ditches, terraces, etc. and landuse change on the discharge hydrograph.

The simulation of water quality requires a minimum of additional data since most of the necessary data base, such as soils, landuse and topographic information, is required by the FESHM to generate flow characteristics. The effect of management practices on the water quality of the downstream areas may also be simulated.

Because the model is spatially responsive, the data base may be large and excessive amounts of computer memory may be required for internal storage of input data and data generated from computer code. Internal computer storage can be greatly reduced by using direct access to external disk storage. This solution technique requires minimal internal computer memory. When possible, however, it is recommended that all data be stored internally since the time required to access the data base will be much less.

The preparation of spatially variable data sets can be very time-consuming. Once data sets have been prepared for a given area, however, updating can be performed with relative ease. Many data planes, such as soils and topography, will require only minor alterations over time. Landuse and management practice represent dynamic data planes and require considerable effort to be kept current. Although, with the present state-of-the-art, this limits the general attractiveness of the modeling approach, advances in data collection, such as remote sensing and the development of geographic information systems, will tend to lessen this drawback in the future. Also, advances in interactive computer techniques, such as pattern recognition, are making digital modeling more feasible and practical.

The level of data resolution necessary to achieve a given level of model predictability is basically unknown. The refinement suggested by Li (1975) is probably not necessary for simulating water yields from rural areas, however, it was demonstrated that, while the influence of a relatively small area on the total flow response from a large watershed may not be significant, the same area can have a significant impact on water quality.

Recommendations

Objective criteria to relate the level of discretization that is necessary to provide a given level of predictability must be established. The unavailability of such criteria detracts from the general use of spatially responsive and distributed parameter models.

The present model contains no procedure to account for losses of flow in transit due to reinfiltration. As previously discussed, this omission will normally have little impact on the simulation of major flood flows, but can become very important in describing events with short return periods. The losses that can occur in the deep alluvial soils of the floodplain are of primary concern. These losses may need to be taken into account to better predict flow yields and to improve estimates of scour and deposition.

The FESHM is, at present, only capable of event simulation. Certain pollutants may require the inclusion of between-storm periods for continuous simulation. This adds to the complexity and cost of using the model, however, greatly extends its range of application. Continuous modeling will also maintain a continuous accounting of the soil moisture status.

While results obtained from a wide range of watersheds are encouraging and indicate, to some degree, that flows are being simulated properly, a cluster sampling program is necessary to verify flow predictions at internal node points.

Modeling the fate of agricultural nutrients will require an investigation of theoretically-based techniques to describe subsurface flows. These must be compared to simpler, empirical approximations to define the best approach to maximize computational efficiency and minimize errors in simulation.

Considerable effort must be directed towards the development of an efficient procedure for creating spatial data planes. Computer code must be developed to overlay multiple data planes and create pre-defined levels of discretization for determining rainfall excess, flow routing and pollutant loadings.

CHAPTER VIII

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CHAPTER IX

APPENDICES

This chapter contains 7 appendices with detailed data on the structure of the FESHM and it's application. Appendix A contains data on HRU and element properties for selected experimental watersheds. Information relative to the FESHM are given in Appendices B-D. Input-Output requirements for a specific example are given in Appendices E-G.

Appendix A

HRU and Element Properties for the Experimental Watersheds

The following tables list the properties of the HRU's and finite elements which were defined for the six experimental watersheds in Chapter V.

Table A1. HRU properties for Powells Creek watershed, Halifax County, VA.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
1	4	D	0.250	0.160	0.800	0.158	0.113	1.398	0.230	4.00	1.08
2	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	6.00	1.63
3	14	C	0.250	0.240	0.900	0.158	0.113	1.398	0.230	6.00	1.63
4	4	D	0.250	0.160	0.800	0.082	0.267	0.307	0.047	3.00	1.05
5	6	B	0.400	0.400	1.000	0.082	0.267	0.307	0.047	8.00	2.79
6	4	D	0.250	0.160	0.800	0.120	0.190	0.632	0.139	4.00	1.24
7	4	B	0.250	0.320	0.800	0.082	0.267	0.307	0.047	8.00	2.79
8	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
9	4	E	0.250	0.080	0.800	0.105	0.241	0.436	0.390	4.00	1.38
10	4	B	0.250	0.320	0.800	0.120	0.190	0.632	0.139	12.00	3.72
11	4	C	0.250	0.240	0.800	0.120	0.190	0.632	0.139	8.00	2.48
12	4	D	0.250	0.160	0.800	0.105	0.241	0.436	0.390	5.00	1.73
13	4	B	0.250	0.320	0.800	0.087	0.158	0.551	0.380	28.00	6.86
14	4	C	0.250	0.240	0.800	0.105	0.241	0.436	0.390	6.00	2.08
15	9	C	0.150	0.090	0.400	0.120	0.190	0.632	0.139	8.00	2.48
16	7	B	0.300	0.240	0.900	0.120	0.190	0.632	0.139	12.00	3.72
17	7	C	0.300	0.180	0.900	0.120	0.190	0.632	0.139	8.00	2.48
18	7	C	0.300	0.180	0.900	0.105	0.241	0.436	0.390	6.00	2.08
19	7	B	0.300	0.240	0.900	0.105	0.241	0.436	0.390	6.00	2.08
20	2	B	0.100	0.120	0.200	0.158	0.113	1.398	0.230	8.00	2.17
21	2	D	0.100	0.060	0.200	0.120	0.190	0.632	0.139	4.00	1.24
22	2	B	0.100	0.120	0.200	0.082	0.267	0.307	0.047	8.00	2.79
23	2	B	0.100	0.120	0.200	0.120	0.190	0.632	0.139	12.00	3.72
24	4	B	0.250	0.320	0.800	0.087	0.158	0.551	0.380	30.00	7.35
25	4	B	0.250	0.320	0.800	0.105	0.241	0.436	0.390	7.00	2.42
26	4	D	0.250	0.160	0.800	0.105	0.241	0.436	0.390	4.00	1.38
27	2	E	0.100	0.030	0.200	0.158	0.113	1.398	0.230	4.00	1.08
28	2	C	0.100	0.090	0.200	0.105	0.241	0.436	0.390	6.00	2.08
29	2	B	0.100	0.120	0.200	0.131	0.142	0.923	0.110	5.00	1.36
30	14	B	0.250	0.320	0.900	0.158	0.113	1.398	0.230	8.00	2.17
31	7	B	0.300	0.240	0.900	0.158	0.113	1.398	0.230	8.00	2.17
32	7	D	0.300	0.120	0.900	0.131	0.142	0.923	0.110	3.00	0.82
33	7	B	0.300	0.240	0.900	0.131	0.142	0.923	0.110	5.00	1.36
34	6	B	0.400	0.400	1.000	0.087	0.158	0.551	0.380	28.00	6.86
35	6	E	0.400	0.100	1.000	0.131	0.142	0.923	0.110	2.00	0.55
36	6	D	0.400	0.200	1.000	0.131	0.142	0.923	0.110	3.00	0.82
37	6	E	0.400	0.100	1.000	0.158	0.113	1.398	0.230	4.00	1.08
38	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	8.00	2.17
39	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	8.00	2.17

Table A1. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
40	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
41	4	E	0.250	0.080	0.800	0.131	0.142	0.923	0.110	2.00	0.55
42	14	B	0.250	0.320	0.900	0.131	0.142	0.923	0.110	5.00	1.36
43	4	B	0.250	0.320	0.800	0.131	0.142	0.923	0.110	5.00	1.36
44	4	E	0.250	0.080	0.800	0.158	0.113	1.398	0.230	4.00	1.08
45	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	21.00	5.69
46	4	C	0.250	0.240	0.800	0.131	0.142	0.923	0.110	4.00	1.09
47	4	D	0.250	0.160	0.800	0.131	0.142	0.923	0.110	3.00	0.82
48	4	B	0.250	0.320	0.800	0.105	0.241	0.436	0.390	7.00	2.42
49	4	D	0.250	0.160	0.800	0.158	0.113	1.398	0.230	5.30	1.44
50	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
51	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
52	4	D	0.250	0.160	0.800	0.158	0.113	1.398	0.230	4.00	1.08
53	4	C	0.250	0.240	0.800	0.105	0.241	0.436	0.390	6.00	2.08
54	2	D	0.100	0.060	0.200	0.131	0.142	0.923	0.110	3.00	0.82
55	4	B	0.250	0.320	0.800	0.087	0.158	0.551	0.380	30.00	7.35
56	14	B	0.250	0.320	0.900	0.082	0.267	0.307	0.047	8.00	2.79
57	5	B	0.100	0.080	0.200	0.120	0.190	0.632	0.139	12.00	3.72
58	2	B	0.100	0.120	0.200	0.087	0.158	0.551	0.380	30.00	7.35
59	7	B	0.300	0.240	0.900	0.087	0.158	0.551	0.380	28.00	6.86
60	2	B	0.100	0.120	0.200	0.087	0.158	0.551	0.380	28.00	6.86
61	7	E	0.300	0.060	0.900	0.158	0.113	1.398	0.230	4.00	1.08
62	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
63	2	B	0.100	0.120	0.200	0.105	0.241	0.436	0.390	6.00	2.08
64	17	A	0.020	10.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0
65	8	A	0.020	0.050	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A2. Properties of overland flow elements for Powells Creek watershed.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
1	230	1580	12.1	25
2	240	950	8.3	45
3	350	1680	11.4	45
4	350	1580	14.5	30
5	670	950	22.4	55
6	830	640	17.4	45
7	790	740	10.5	40
8	440	300	4.3	45
9	430	260	8.0	20
10	690	520	9.6	45
11	320	880	4.5	35
12	440	1660	17.4	40
13	550	610	9.9	45
14	400	610	3.9	35
15	490	790	15.9	35
16	360	960	5.2	35
17	530	1750	7.1	20

Table A3. Properties of channel flow elements for Powells Creek watershed.

Element Number	Length (ft)	Downstream Node Width at 2-Foot Depth (ft)	Relief (ft)	Manning 'n'
1	1580	76	40	0.06
2	950	76	15	0.06
3	640	28	15	0.07
4	740	28	10	0.08
5	300	45	2	0.07
6	260	45	10	0.08
7	520	45	20	0.08
8	880	45	20	0.07
9	610	45	2	0.05
10	790	45	20	0.05
11	960	45	20	0.05

Table A4. HRU properties for Pony Mountain Branch watershed, Culpepper County, VA.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
1	4	D	0.250	0.160	0.800	0.110	0.100	1.100	0.400	4.00	0.84
2	4	C	0.250	0.240	0.800	0.210	0.100	2.100	0.200	7.00	2.17
3	4	E	0.250	0.060	0.800	0.210	0.100	2.100	0.200	4.00	1.24
4	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.350	13.00	4.55
5	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.350	6.00	2.10
6	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.350	18.00	6.30
7	2	B	0.100	0.120	0.200	0.140	0.050	2.800	0.130	7.00	1.33
8	2	B	0.100	0.120	0.200	0.210	0.100	2.100	0.200	7.00	2.17
9	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.350	9.00	3.15
10	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.350	12.00	4.20
11	2	C	0.100	0.090	0.200	0.210	0.100	2.100	0.200	7.00	2.17
12	2	D	0.100	0.060	0.200	0.210	0.100	2.100	0.200	5.00	1.55
13	3	B	0.200	0.240	0.500	0.140	0.050	2.800	0.130	7.00	1.33
14	3	C	0.200	0.180	0.500	0.210	0.100	2.100	0.200	7.00	2.17
15	3	D	0.200	0.120	0.500	0.210	0.100	2.100	0.200	5.00	1.55
16	3	E	0.200	0.060	0.500	0.210	0.100	2.100	0.200	4.00	1.24
17	3	B	0.200	0.240	0.500	0.240	0.110	2.182	0.350	18.00	6.30
18	7	D	0.300	0.120	0.900	0.210	0.100	2.100	0.200	5.00	1.55
19	7	D	0.300	0.120	0.900	0.110	0.100	1.100	0.400	4.00	0.84
20	7	E	0.300	0.060	0.900	0.210	0.100	2.100	0.200	4.00	1.24
21	7	B	0.300	0.240	0.900	0.240	0.110	2.182	0.350	13.00	4.55
22	7	B	0.300	0.240	0.900	0.140	0.050	2.800	0.130	7.00	1.33
23	7	B	0.300	0.240	0.900	0.240	0.110	2.182	0.350	18.00	6.30
24	7	B	0.300	0.240	0.900	0.240	0.110	2.182	0.350	9.00	3.15
25	7	B	0.300	0.240	0.900	0.210	0.100	2.100	0.200	7.00	2.17
26	7	B	0.300	0.240	0.900	0.210	0.100	2.100	0.200	12.00	3.72
27	7	C	0.300	0.180	0.900	0.210	0.100	2.100	0.200	6.00	1.86
28	7	C	0.300	0.180	0.900	0.210	0.100	2.100	0.200	12.00	3.72
29	7	C	0.300	0.180	0.900	0.110	0.100	1.100	0.200	5.00	1.05
30	7	C	0.300	0.180	0.900	0.210	0.100	2.100	0.200	7.00	2.17
31	4	B	0.250	0.320	0.800	0.240	0.110	2.182	0.350	6.00	2.10
32	4	B	0.250	0.320	0.800	0.240	0.110	2.182	0.350	13.00	4.55
33	4	C	0.250	0.240	0.800	0.240	0.110	2.182	0.350	10.00	3.50
34	4	B	0.250	0.320	0.800	0.140	0.050	2.800	0.130	7.00	1.33
35	4	B	0.250	0.320	0.800	0.210	0.100	2.100	0.200	12.00	3.72
36	2	C	0.100	0.090	0.200	0.210	0.100	2.100	0.200	6.00	1.86
37	6	C	0.400	0.300	1.000	0.110	0.100	1.100	0.400	5.00	1.05
38	6	B	0.400	0.400	1.000	0.210	0.100	2.100	0.200	12.00	3.72
39	6	C	0.400	0.300	1.000	0.210	0.100	2.100	0.200	12.00	3.72

Table A4. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
40	6	B	0.400	0.400	1.000	0.140	0.050	2.800	0.130	7.00	1.33
41	6	C	0.400	0.300	1.000	0.210	0.100	2.100	0.200	6.00	1.86
42	6	D	0.400	0.200	1.000	0.110	0.100	1.100	0.400	4.00	0.84
43	6	E	0.400	0.100	1.000	0.040	0.040	1.000	0.400	3.00	0.24
44	6	E	0.400	0.100	1.000	0.210	0.100	2.100	0.200	4.00	1.24
45	6	C	0.400	0.300	1.000	0.210	0.100	2.100	0.200	7.00	2.17
46	6	D	0.400	0.200	1.000	0.210	0.100	2.100	0.200	5.00	1.55
47	8	A	0.020	0.050	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A5. Properties of overland flow elements for Pony Mountain Branch watershed.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
1	960	1570	50.1	190
2	530	1860	9.5	15
3	280	1570	2.9	35
4	270	1870	2.4	10
5	310	1140	3.7	120
6	1320	1840	28.8	90
7	210	1140	3.2	35
8	380	1840	8.3	20
9	290	450	4.9	10
10	260	450	1.9	5
11	270	1180	4.5	55
12	800	1560	19.5	115
13	1170	1560	26.1	65
14	540	1180	9.1	95
15	370	1560	5.6	20
16	520	1560	11.6	10

Table A6. Properties of channel flow elements for Pony Mountain Branch watershed.

Element Number	Length (ft)	Downstream Node Width at 2-Foot Depth (ft)	Relief (ft)	Manning 'n'
1	1570	11	150	0.08
2	1860	45	50	0.04
3	1140	23	140	0.09
4	1840	45	110	0.05
5	450	115	5	0.05
6	1180	23	155	0.09
7	1560	76	90	0.07
8	1560	115	25	0.05

Table A7. HRU properties for Rocky Run Branch watershed, Brunswick County, VA.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
1	6	B	0.400	0.400	1.000	0.087	0.158	0.551	0.300	21.00	5.14
2	4	B	0.250	0.320	0.800	0.087	0.158	0.551	0.300	21.00	5.14
3	5	B	0.100	0.080	0.200	0.087	0.158	0.551	0.300	21.00	5.14
4	1	B	0.100	0.120	0.300	0.087	0.158	0.551	0.300	21.00	5.14
5	6	B	0.400	0.400	1.000	0.087	0.158	0.551	0.300	22.00	5.39
6	4	B	0.250	0.320	0.800	0.087	0.158	0.551	0.300	22.00	5.39
7	5	B	0.100	0.080	0.200	0.087	0.158	0.551	0.300	22.00	5.39
8	[illegible]	B	0.100	0.120	0.300	0.087	0.158	0.551	0.300	22.00	5.39
9	5	B	0.100	0.080	0.200	0.087	0.158	0.551	0.300	22.00	5.39
10	[illegible]	C	0.400	0.300	1.000	0.087	0.158	0.551	0.300	20.00	4.90
11	4	C	0.250	0.240	0.800	0.087	0.158	0.551	0.300	20.00	4.90
12	1	C	0.100	0.090	0.300	0.087	0.158	0.551	0.300	20.00	4.90
13	6	D	0.400	0.200	1.000	0.087	0.158	0.551	0.300	18.00	4.41
14	4	D	0.250	0.160	0.800	0.087	0.158	0.551	0.300	18.00	4.41
15	5	D	0.100	0.040	0.200	0.087	0.158	0.551	0.300	18.00	4.41
16	1	D	0.100	0.060	0.300	0.087	0.158	0.551	0.300	18.00	4.41
17	6	B	0.400	0.400	1.000	0.087	0.158	0.551	0.300	26.00	6.37
18	4	B	0.250	0.320	0.800	0.087	0.158	0.551	0.300	26.00	6.37
19	5	B	0.100	0.080	0.200	0.087	0.158	0.551	0.300	26.00	6.37
20	4	B	0.250	0.320	0.800	0.087	0.158	0.551	0.250	18.00	4.41
21	6	C	0.400	0.300	1.000	0.087	0.158	0.551	0.300	19.00	4.65
22	4	C	0.250	0.240	0.800	0.087	0.158	0.551	0.300	19.00	4.65
23	5	C	0.100	0.060	0.200	0.087	0.158	0.551	0.300	19.00	4.65
24	1	C	0.100	0.090	0.300	0.087	0.158	0.551	0.300	19.00	4.65
25	6	D	0.400	0.200	1.000	0.087	0.158	0.551	0.300	17.00	4.16
26	4	D	0.250	0.160	0.800	0.087	0.158	0.551	0.300	17.00	4.16
27	6	C	0.400	0.300	1.000	0.127	0.130	0.977	0.200	12.00	3.08
28	4	C	0.250	0.240	0.800	0.127	0.130	0.977	0.200	12.00	3.08
29	4	D	0.250	0.160	0.800	0.127	0.130	0.977	0.200	9.00	2.31
30	6	B	0.400	0.400	1.000	0.087	0.158	0.551	0.300	9.00	2.20
31	4	B	0.250	0.320	0.800	0.087	0.158	0.551	0.300	9.00	2.20
32	6	E	0.400	0.100	1.000	0.087	0.158	0.551	0.300	4.00	0.98
33	4	B	0.250	0.320	0.800	0.127	0.130	0.977	0.200	11.00	2.83
34	6	D	0.400	0.200	1.000	0.127	0.130	0.977	0.200	7.00	1.80
35	6	A	0.400	0.500	1.000	0.131	0.235	0.557	0.025	36.00	13.18
36	5	A	0.100	0.100	0.200	0.131	0.235	0.557	0.025	36.00	13.18
37	6	B	0.400	0.400	1.000	0.131	0.235	0.557	0.025	31.00	11.35
38	4	B	0.250	0.320	0.800	0.131	0.235	0.557	0.025	31.00	11.35
39	5	B	0.100	0.080	0.200	0.131	0.235	0.557	0.025	31.00	11.35

Table A7. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
40	6	B	0.400	0.400	1.000	0.087	0.158	0.551	0.150	25.00	6.12
41	4	B	0.250	0.320	0.800	0.087	0.158	0.551	0.150	25.00	6.12
42	5	B	0.100	0.080	0.200	0.087	0.158	0.551	0.150	25.00	6.12
43	1	B	0.100	0.120	0.300	0.087	0.158	0.551	0.150	25.00	6.12
44	5	B	0.100	0.080	0.200	0.087	0.158	0.551	0.150	25.00	6.12
45	6	C	0.400	0.300	1.000	0.127	0.130	0.977	0.200	9.00	2.31
46	4	C	0.250	0.240	0.800	0.127	0.130	0.977	0.200	9.00	2.31
47	5	C	0.100	0.060	0.200	0.127	0.130	0.977	0.200	9.00	2.31
48	6	B	0.400	0.400	1.000	0.127	0.130	0.977	0.200	15.00	3.85
49	4	B	0.250	0.320	0.800	0.127	0.130	0.977	0.200	15.00	3.85
50	5	B	0.100	0.080	0.200	0.127	0.130	0.977	0.200	15.00	3.85
51	1	B	0.100	0.120	0.300	0.127	0.130	0.977	0.200	15.00	3.85
52	6	C	0.400	0.300	1.000	0.087	0.158	0.551	0.250	16.00	3.92
53	4	C	0.250	0.240	0.800	0.087	0.158	0.551	0.250	16.00	3.92
54	8	A	0.020	0.050	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A8. Properties of overland flow elements for Rocky Run Branch watershed.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
1	250	1100	7.7	15
2	270	1470	17.0	15
3	730	1470	53.8	25
4	930	1470	41.5	35
5	980	1470	35.4	35
6	1810	1100	84.5	25
7	1220	1470	45.2	25
8	1960	1470	76.2	35
9	2010	1470	65.3	45
10	710	1470	8.6	25
11	270	1100	12.1	10
12	470	1350	15.8	30
13	220	1350	6.4	30
14	310	1100	18.1	35
15	980	1350	31.7	35
16	1200	1350	35.7	45

Table A9. Properties of channel flow elements for Rocky Run Branch watershed.

Element Number	Length (ft)	Downstream Node Width at 2-Foot Depth (ft)	Relief (ft)	Manning 'n'
1	1100	115	15	0.10
2	1470	115	20	0.10
3	1470	115	15	0.09
4	1470	115	10	0.08
5	1470	115	10	0.07
6	1100	45	30	0.10
7	1350	76	30	0.09
8	1350	76	15	0.08

Table A10. HRU properties for Crab Creek watershed, Montgomery County, VA.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
1	4	C	0.250	0.240	0.800	0.190	0.160	1.188	0.390	12.50	4.37
2	7	B	0.300	0.240	0.900	0.200	0.110	1.818	0.100	6.00	1.86
3	13	C	0.350	0.300	0.900	0.150	0.080	1.875	0.050	6.00	1.38
4	2	D	0.100	0.060	0.200	0.140	0.160	0.875	0.140	10.00	3.00
5	4	C	0.250	0.240	0.800	0.140	0.160	0.875	0.140	13.00	3.90
6	2	C	0.100	0.090	0.200	0.140	0.160	0.875	0.140	13.00	3.90
7	14	C	0.250	0.240	0.900	0.140	0.120	1.167	0.390	11.50	2.99
8	7	C	0.300	0.180	0.900	0.140	0.120	1.167	0.390	11.50	2.99
9	7	C	0.300	0.180	0.900	0.240	0.100	2.400	0.540	18.00	6.12
10	7	E	0.300	0.060	0.900	0.120	0.090	1.333	0.050	4.00	0.84
11	7	C	0.300	0.180	0.900	0.150	0.190	0.789	0.270	38.00	12.92
12	7	F	0.300	0.0	0.900	0.120	0.090	1.333	0.050	2.00	0.42
13	7	D	0.300	0.120	0.900	0.120	0.090	1.333	0.050	6.00	1.26
14	7	D	0.300	0.120	0.900	0.140	0.160	0.875	0.140	9.00	2.70
15	7	D	0.300	0.120	0.900	0.250	0.130	1.923	0.720	7.00	2.66
16	7	D	0.300	0.120	0.900	0.250	0.130	1.923	0.720	7.00	2.66
17	7	E	0.300	0.060	0.900	0.250	0.130	1.923	0.720	5.00	1.90
18	7	C	0.300	0.180	0.900	0.150	0.080	1.875	0.050	7.00	1.61
19	7	C	0.300	0.180	0.900	0.120	0.090	1.333	0.050	4.00	0.84
20	7	C	0.300	0.180	0.900	0.190	0.160	1.188	0.370	13.50	4.72
21	7	B	0.300	0.240	0.900	0.190	0.160	1.188	0.390	15.50	5.42
22	7	C	0.300	0.180	0.900	0.190	0.160	1.188	0.390	13.50	4.72
23	6	C	0.400	0.300	1.000	0.250	0.130	1.923	0.720	10.00	3.80
24	6	E	0.400	0.100	1.000	0.250	0.130	1.923	0.720	5.00	1.90
25	6	B	0.400	0.400	1.000	0.240	0.100	2.400	0.540	21.00	7.14
26	6	D	0.400	0.200	1.000	0.250	0.130	1.923	0.720	7.00	2.66
27	6	C	0.400	0.300	1.000	0.120	0.090	1.333	0.050	4.00	0.84
28	6	E	0.400	0.100	1.000	0.120	0.090	1.333	0.050	4.00	0.84
29	6	C	0.400	0.300	1.000	0.190	0.160	1.188	0.390	13.50	4.72
30	4	C	0.250	0.240	0.800	0.240	0.100	2.400	0.540	18.00	6.12
31	4	C	0.250	0.240	0.800	0.250	0.130	1.923	0.720	10.00	3.80
32	4	D	0.250	0.160	0.800	0.250	0.130	1.923	0.720	6.00	2.28
33	4	C	0.250	0.240	0.800	0.140	0.160	0.875	0.140	12.00	3.60
34	4	C	0.250	0.240	0.800	0.150	0.190	0.789	0.270	38.00	12.92
35	4	D	0.250	0.160	0.800	0.250	0.130	1.923	0.720	7.00	2.66
36	4	E	0.250	0.080	0.800	0.250	0.130	1.923	0.720	5.00	1.90
37	4	D	0.250	0.160	0.800	0.140	0.160	0.875	0.140	9.00	2.70
38	4	D	0.250	0.160	0.800	0.120	0.090	1.333	0.050	7.00	1.47
39	4	E	0.250	0.080	0.800	0.120	0.090	1.333	0.050	4.00	0.84

Table A10. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
40	6	D	0.400	0.200	1.000	0.250	0.130	1.923	0.720	6.00	2.28
41	6	F	0.400	0.0	1.000	0.250	0.130	1.923	0.720	3.00	1.14
42	3	B	0.200	0.240	0.500	0.140	0.160	0.875	0.140	16.00	4.80
43	3	E	0.200	0.060	0.500	0.250	0.130	1.923	0.720	5.00	1.90
44	3	D	0.200	0.120	0.500	0.120	0.090	1.333	0.050	7.00	1.47
45	7	C	0.300	0.180	0.900	0.250	0.130	1.923	0.720	10.00	3.80
46	7	D	0.300	0.120	0.900	0.250	0.130	1.923	0.720	6.00	2.28
47	7	E	0.300	0.060	0.900	0.250	0.130	1.923	0.720	4.00	1.52
48	4	B	0.250	0.320	0.800	0.140	0.160	0.875	0.140	18.00	5.40
49	4	C	0.250	0.240	0.800	0.140	0.160	0.875	0.140	11.00	3.30
50	4	B	0.250	0.320	0.800	0.190	0.160	1.188	0.390	15.50	5.42
51	4	D	0.250	0.160	0.800	0.190	0.160	1.188	0.390	11.50	4.02
52	4	A	0.250	0.400	0.800	0.200	0.110	1.818	0.010	9.50	2.94
53	4	C	0.250	0.240	0.800	0.190	0.160	1.188	0.390	13.50	4.72
54	4	E	0.250	0.080	0.800	0.190	0.160	1.188	0.390	9.50	3.32
55	4	E	0.250	0.080	0.800	0.140	0.120	1.167	0.390	9.50	2.47
56	4	D	0.250	0.160	0.800	0.190	0.160	1.188	0.390	11.50	4.02
57	4	B	0.250	0.320	0.800	0.140	0.160	0.875	0.140	16.00	4.80
58	4	D	0.250	0.160	0.800	0.140	0.160	0.875	0.140	8.00	2.40
59	6	D	0.400	0.200	1.000	0.190	0.160	1.188	0.390	11.50	4.02
60	6	C	0.400	0.300	1.000	0.190	0.160	1.188	0.390	13.50	4.72
61	6	E	0.400	0.100	1.000	0.190	0.160	1.188	0.390	9.50	3.32
62	6	B	0.400	0.400	1.000	0.190	0.160	1.188	0.390	15.00	5.25
63	6	E	0.400	0.100	1.000	0.240	0.100	2.400	0.540	12.00	4.08
64	4	B	0.250	0.320	0.800	0.150	0.190	0.789	0.260	42.50	14.45
65	4	B	0.250	0.320	0.800	0.140	0.160	0.875	0.140	16.00	4.80
66	7	B	0.300	0.240	0.900	0.150	0.190	0.789	0.260	42.50	14.45
67	7	A	0.300	0.300	0.900	0.200	0.110	1.818	0.010	9.50	2.94
68	3	C	0.200	0.180	0.500	0.140	0.160	0.875	0.140	11.00	3.30
69	3	D	0.200	0.120	0.500	0.140	0.160	0.875	0.140	9.00	2.70
70	3	C	0.200	0.180	0.500	0.150	0.190	0.789	0.260	42.50	14.45
71	3	C	0.200	0.180	0.500	0.140	0.160	0.875	0.140	12.00	3.60
72	3	B	0.200	0.240	0.500	0.190	0.160	1.188	0.390	15.50	5.42
73	4	C	0.250	0.240	0.800	0.140	0.160	0.875	0.140	12.00	3.60
74	6	C	0.400	0.300	1.000	0.140	0.160	0.875	0.140	12.00	3.60
75	6	C	0.400	0.300	1.000	0.150	0.190	0.789	0.260	38.00	12.92
76	6	C	0.400	0.300	1.000	0.140	0.160	0.875	0.140	11.00	3.30
77	6	D	0.400	0.200	1.000	0.140	0.160	0.875	0.140	9.00	2.70
78	6	C	0.400	0.300	1.000	0.140	0.160	0.875	0.140	12.00	3.60

Table A10. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
79	6	B	0.400	0.400	1.000	0.140	0.160	0.875	0.140	16.00	4.80
80	6	D	0.400	0.200	1.000	0.140	0.160	0.875	0.140	9.00	2.70
81	6	A	0.400	0.500	1.000	0.200	0.110	1.818	0.010	9.50	2.94
82	4	C	0.250	0.240	0.800	0.140	0.160	0.875	0.140	11.00	3.30
83	2	A	0.100	0.150	0.200	0.200	0.110	1.818	0.010	9.50	2.94
84	2	D	0.100	0.060	0.200	0.140	0.160	0.875	0.140	9.00	2.70
85	2	C	0.100	0.090	0.200	0.140	0.160	0.875	0.140	11.00	3.30
86	2	B	0.100	0.120	0.200	0.140	0.160	0.875	0.140	16.00	4.80
87	2	B	0.100	0.120	0.200	0.150	0.160	0.938	0.260	42.50	13.17
88	4	D	0.250	0.160	0.800	0.190	0.160	1.188	0.390	10.50	3.67
89	4	D	0.250	0.160	0.800	0.140	0.160	0.875	0.140	9.00	2.70
90	3	B	0.200	0.240	0.500	0.190	0.160	1.188	0.390	15.50	5.42
91	3	D	0.200	0.120	0.500	0.140	0.160	0.875	0.140	9.00	2.70
92	3	C	0.200	0.180	0.500	0.190	0.160	1.188	0.390	13.50	4.72
93	3	D	0.200	0.120	0.500	0.190	0.160	1.188	0.390	10.50	3.67
94	3	B	0.200	0.240	0.500	0.150	0.190	0.789	0.260	42.50	14.45
95	3	C	0.200	0.180	0.500	0.240	0.100	2.400	0.540	18.00	6.12
96	3	C	0.200	0.180	0.500	0.140	0.160	0.875	0.140	12.00	3.60
97	2	C	0.100	0.090	0.200	0.240	0.100	2.400	0.540	18.00	6.12
98	2	B	0.100	0.120	0.200	0.190	0.160	1.188	0.390	15.50	5.42
99	2	C	0.100	0.090	0.200	0.190	0.160	1.188	0.390	13.50	4.72
100	2	C	0.100	0.090	0.200	0.190	0.160	1.188	0.390	13.50	4.72
101	2	B	0.100	0.120	0.200	0.240	0.100	2.400	0.540	21.00	7.14
102	2	A	0.100	0.150	0.200	0.200	0.110	1.818	0.100	11.00	3.41
103	2	D	0.100	0.060	0.200	0.190	0.160	1.188	0.390	10.50	3.67
104	13	B	0.350	0.400	0.900	0.240	0.100	2.400	0.540	21.00	7.14
105	13	B	0.350	0.400	0.900	0.150	0.190	0.789	0.260	42.50	14.45
106	4	B	0.250	0.320	0.800	0.240	0.100	2.400	0.540	21.00	7.14
107	4	C	0.250	0.240	0.800	0.190	0.160	1.188	0.390	8.00	2.80
108	4	C	0.250	0.240	0.800	0.240	0.100	2.400	0.540	18.00	6.12
109	14	C	0.250	0.240	0.900	0.240	0.100	2.400	0.540	18.00	6.12
110	14	C	0.250	0.240	0.900	0.190	0.160	1.188	0.390	13.50	4.72
111	14	B	0.250	0.320	0.900	0.190	0.160	1.188	0.390	15.50	5.42
112	4	C	0.250	0.240	0.800	0.200	0.110	1.818	0.100	4.00	1.24
113	3	B	0.200	0.240	0.500	0.250	0.100	2.500	0.540	21.00	7.35
114	3	C	0.200	0.180	0.500	0.250	0.130	1.923	0.720	10.00	3.80
115	3	B	0.200	0.240	0.500	0.250	0.130	1.923	0.720	14.00	5.32
116	14	B	0.250	0.320	0.900	0.240	0.100	2.400	0.540	21.00	7.14
117	14	C	0.250	0.240	0.900	0.250	0.130	1.923	0.720	10.00	3.80

Table A10. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
118	14	C	0.250	0.240	0.900	0.200	0.110	1.818	0.100	4.00	1.24
119	2	C	0.100	0.090	0.200	0.200	0.110	1.818	0.100	4.00	1.24
120	2	C	0.100	0.090	0.200	0.190	0.160	1.188	0.390	12.50	4.37
121	2	C	0.100	0.090	0.200	0.150	0.190	0.789	0.260	38.00	12.92
122	2	B	0.100	0.120	0.200	0.200	0.100	2.000	0.100	6.00	1.80
123	2	D	0.100	0.060	0.200	0.190	0.160	1.188	0.390	11.50	4.02
124	3	C	0.200	0.180	0.500	0.200	0.110	1.818	0.100	4.00	1.24
125	3	C	0.200	0.180	0.500	0.190	0.160	1.188	0.390	13.50	4.72
126	3	A	0.200	0.300	0.500	0.200	0.110	1.818	0.010	9.50	2.94
127	2	C	0.100	0.090	0.200	0.140	0.160	0.875	0.140	12.00	3.60
128	2	D	0.100	0.060	0.200	0.190	0.160	1.188	0.390	10.50	3.67
129	2	D	0.100	0.060	0.200	0.190	0.160	1.188	0.390	11.50	4.02
130	2	C	0.100	0.090	0.200	0.140	0.160	0.875	0.140	11.00	3.30
131	2	B	0.100	0.120	0.200	0.140	0.160	0.875	0.140	16.00	4.80
132	2	D	0.100	0.060	0.200	0.140	0.160	0.875	0.140	9.00	2.70
133	6	B	0.400	0.400	1.000	0.150	0.190	0.789	0.260	42.50	14.45
134	3	D	0.200	0.120	0.500	0.190	0.160	1.188	0.390	10.50	3.67
135	6	B	0.400	0.400	1.000	0.190	0.160	1.188	0.390	14.50	5.07
136	4	B	0.250	0.320	0.800	0.190	0.160	1.188	0.390	15.50	5.42
137	4	B	0.250	0.320	0.800	0.190	0.160	1.188	0.390	14.50	5.07
138	4	C	0.250	0.240	0.800	0.190	0.160	1.188	0.390	13.50	4.72
139	4	E	0.250	0.080	0.800	0.240	0.100	2.400	0.540	12.00	4.08
140	14	A	0.250	0.400	0.900	0.200	0.110	1.818	0.010	9.50	2.94
141	14	D	0.250	0.160	0.900	0.190	0.160	1.188	0.390	11.50	4.02
142	14	E	0.250	0.080	0.900	0.190	0.160	1.188	0.390	9.50	3.32
143	14	C	0.250	0.240	0.900	0.150	0.190	0.789	0.260	38.00	12.92
144	4	C	0.250	0.240	0.800	0.150	0.080	1.875	0.050	7.00	1.61
145	4	E	0.250	0.080	0.800	0.250	0.130	1.923	0.720	4.00	1.52
146	4	F	0.250	0.0	0.800	0.250	0.130	1.923	0.720	3.00	1.14
147	4	C	0.250	0.240	0.800	0.120	0.090	1.333	0.050	4.00	0.84
148	4	C	0.250	0.240	0.800	0.140	0.120	1.167	0.390	13.50	3.51
149	4	D	0.250	0.160	0.800	0.140	0.120	1.167	0.390	11.50	2.99
150	3	B	0.200	0.240	0.500	0.140	0.160	0.875	0.140	18.00	5.40
151	3	D	0.200	0.120	0.500	0.190	0.160	1.188	0.390	11.50	4.02
152	3	B	0.200	0.240	0.500	0.140	0.160	0.875	0.140	16.00	4.80
153	7	F	0.300	0.0	0.900	0.140	0.160	0.875	0.140	6.00	1.80
154	7	B	0.300	0.240	0.900	0.140	0.160	0.875	0.140	16.00	4.80
155	4	C	0.250	0.240	0.800	0.190	0.160	1.188	0.390	12.50	4.37
156	14	B	0.250	0.320	0.900	0.150	0.190	0.789	0.260	42.50	14.45

Table A10. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
157	14	B	0.250	0.320	0.900	0.250	0.130	1.923	0.720	14.00	5.32
158	14	C	0.250	0.240	0.900	0.240	0.100	2.400	0.540	18.00	6.12
159	2	B	0.100	0.120	0.200	0.240	0.100	2.400	0.540	21.00	7.14
160	4	B	0.250	0.320	0.800	0.250	0.130	1.923	0.720	14.00	5.32
161	2	C	0.100	0.090	0.200	0.140	0.160	0.875	0.140	12.00	3.60
162	17	A	0.020	10.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0
163	8	A	0.020	0.050	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A11. Properties of overland flow elements for Crab Creek watershed.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
1	530	600	11.8	40
2	770	1030	18.7	65
3	700	1030	19.2	40
4	1060	1030	11.7	60
5	840	1030	16.6	55
6	910	1030	21.7	85
7	750	1030	14.7	85
8	330	600	3.2	20
9	540	1030	15.7	35
10	770	1030	12.1	70
11	620	1030	20.4	45
12	1440	1030	38.3	60
13	1170	1030	60.3	65
14	290	1030	4.9	25
15	320	650	8.1	20
16	510	970	14.2	40
17	870	970	21.9	40
18	1130	970	35.5	50
19	320	650	9.0	45
20	780	970	23.8	30
21	430	970	9.9	30
22	420	970	10.9	40
23	1180	1080	15.0	95
24	1700	1080	68.1	110
25	460	1080	13.7	65
26	760	1080	25.4	45
27	710	1080	42.8	70
28	290	1080	6.7	55
29	290	1150	7.6	35
30	340	1150	6.9	25
31	800	1150	14.3	70
32	370	600	11.0	40
33	960	1150	21.9	60
34	490	1150	11.6	55

Table A11. Continued.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
35	1810	870	52.9	135
36	690	870	10.2	75
37	1030	870	25.2	120
38	250	870	6.9	95
39	550	650	6.8	60
40	550	1180	11.1	65
41	240	650	4.3	20
42	460	1180	9.5	45
43	760	600	6.7	65
44	270	600	1.5	65
45	260	600	2.1	80
46	220	600	2.3	25

Table A12. Properties of channel flow elements for Crab Creek watershed.

Element Number	Length (ft)	Downstream Node Width at 2-Foot Depth (ft)	Relief (ft)	Manning 'n'
1	600	76	25	0.0350
2	1030	76	40	0.0350
3	1030	76	25	0.0350
4	1030	76	20	0.0350
5	1030	76	20	0.0350
6	1030	76	25	0.0350
7	1030	76	15	0.0350
8	650	76	20	0.0350
9	970	76	20	0.0350
10	970	76	15	0.0350
11	970	76	15	0.0350
12	1080	76	25	0.0400
13	1080	76	25	0.0400
14	1080	76	35	0.0400
15	600	76	40	0.0500
16	1150	76	60	0.0500
17	1150	76	65	0.0500
18	870	76	15	0.0500
19	870	76	15	0.0500
20	650	76	40	0.0350
21	1180	76	85	0.0350
22	600	45	10	0.0400
23	600	45	5	0.0400

Table A13. HRU properties for Brush Creek watershed, Floyd County, VA.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
1	4	C	0.250	0.240	0.800	0.141	0.093	1.516	0.085	15.30	3.58
2	7	D	0.300	0.120	0.900	0.149	0.151	0.987	0.098	12.00	3.60
3	6	D	0.400	0.200	1.000	0.149	0.151	0.987	0.098	12.00	3.60
4	4	C	0.250	0.240	0.800	0.141	0.093	1.516	0.085	19.50	4.56
5	4	A	0.250	0.400	0.800	0.153	0.090	1.700	0.040	22.00	5.35
6	4	C	0.250	0.240	0.800	0.140	0.160	0.875	0.140	13.00	3.90
7	4	C	0.250	0.240	0.800	0.149	0.151	0.987	0.098	16.00	4.80
8	4	D	0.250	0.160	0.800	0.149	0.151	0.987	0.098	12.00	3.60
9	4	D	0.250	0.160	0.800	0.149	0.151	0.987	0.098	12.00	3.60
10	3	C	0.200	0.180	0.500	0.140	0.160	0.875	0.140	13.00	3.90
11	3	D	0.200	0.120	0.500	0.153	0.090	1.700	0.160	14.10	3.43
12	3	C	0.200	0.180	0.500	0.149	0.151	0.987	0.098	16.00	4.80
13	3	D	0.200	0.120	0.500	0.149	0.151	0.987	0.098	12.00	3.60
14	6	C	0.400	0.300	1.000	0.149	0.151	0.987	0.098	16.00	4.80
15	14	D	0.250	0.160	0.900	0.149	0.151	0.987	0.098	12.00	3.60
16	14	C	0.250	0.240	0.900	0.140	0.160	0.875	0.140	13.00	3.90
17	2	D	0.100	0.060	0.200	0.149	0.151	0.987	0.098	12.00	3.60
18	3	A	0.200	0.300	0.500	0.153	0.090	1.700	0.040	22.00	5.35
19	7	C	0.300	0.180	0.900	0.149	0.151	0.987	0.098	16.00	4.80
20	13	D	0.350	0.200	0.900	0.153	0.090	1.700	0.160	14.10	3.43
21	13	B	0.350	0.400	0.900	0.140	0.160	0.875	0.140	18.00	5.40
22	3	C	0.200	0.180	0.500	0.153	0.090	1.700	0.160	15.60	3.79
23	3	D	0.200	0.120	0.500	0.153	0.090	1.700	0.160	14.10	3.43
24	3	C	0.200	0.180	0.500	0.153	0.090	1.700	0.160	15.60	3.79
25	3	D	0.200	0.120	0.500	0.153	0.090	1.700	0.160	17.50	4.25
26	6	D	0.400	0.200	1.000	0.153	0.090	1.700	0.160	14.10	3.43
27	6	C	0.400	0.300	1.000	0.153	0.090	1.700	0.160	15.60	3.79
28	6	D	0.400	0.200	1.000	0.153	0.090	1.700	0.160	14.10	3.43
29	2	D	0.100	0.060	0.200	0.153	0.090	1.700	0.160	14.10	3.43
30	2	C	0.100	0.090	0.200	0.140	0.160	0.875	0.140	13.00	3.90
31	2	A	0.100	0.150	0.200	0.153	0.090	1.700	0.040	22.00	5.35
32	14	D	0.250	0.160	0.900	0.153	0.090	1.700	0.160	14.10	3.43
33	4	E	0.250	0.080	0.800	0.149	0.151	0.987	0.098	8.00	2.40
34	6	A	0.400	0.500	1.000	0.153	0.090	1.700	0.040	22.00	5.35
35	6	E	0.400	0.100	1.000	0.149	0.151	0.987	0.098	8.00	2.40
36	6	C	0.400	0.300	1.000	0.140	0.160	0.875	0.140	13.00	3.90
37	7	C	0.300	0.180	0.900	0.153	0.090	1.700	0.160	15.60	3.79
38	7	D	0.300	0.120	0.900	0.153	0.090	1.700	0.160	17.50	4.25
39	6	C	0.400	0.300	1.000	0.149	0.151	0.987	0.098	16.00	4.80

Table A13. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
40	6	D	0.400	0.200	1.000	0.149	0.151	0.987	0.098	12.00	3.60
41	2	C	0.100	0.090	0.200	0.149	0.151	0.987	0.098	16.00	4.80
42	14	A	0.250	0.400	0.900	0.153	0.090	1.700	0.040	22.00	5.35
43	14	C	0.250	0.240	0.900	0.149	0.151	0.987	0.098	16.00	4.80
44	4	C	0.250	0.240	0.800	0.153	0.090	1.700	0.160	15.60	3.79
45	4	D	0.250	0.160	0.800	0.106	0.183	0.579	0.117	23.00	6.65
46	13	D	0.350	0.200	0.900	0.149	0.151	0.987	0.098	12.00	3.60
47	13	C	0.350	0.300	0.900	0.149	0.151	0.987	0.098	4.80	1.44
48	13	C	0.350	0.300	0.900	0.149	0.151	0.987	0.098	16.00	4.80
49	13	D	0.350	0.200	0.900	0.149	0.151	0.987	0.098	12.00	3.60
50	7	D	0.300	0.120	0.900	0.149	0.151	0.987	0.098	12.00	3.60
51	7	C	0.300	0.180	0.900	0.149	0.151	0.987	0.098	16.00	4.80
52	7	C	0.300	0.180	0.900	0.140	0.160	0.875	0.140	13.00	3.90
53	14	B	0.250	0.320	0.900	0.149	0.151	0.987	0.098	25.00	7.50
54	2	B	0.100	0.120	0.200	0.149	0.151	0.987	0.098	25.00	7.50
55	4	C	0.250	0.240	0.800	0.153	0.090	1.700	0.160	15.60	3.79
56	4	B	0.250	0.320	0.800	0.149	0.151	0.987	0.098	25.00	7.50
57	4	D	0.250	0.160	0.800	0.153	0.090	1.700	0.160	17.50	4.25
58	3	C	0.200	0.180	0.500	0.141	0.093	1.516	0.085	15.30	3.58
59	6	D	0.400	0.200	1.000	0.153	0.090	1.700	0.160	17.50	4.25
60	6	C	0.400	0.300	1.000	0.141	0.093	1.516	0.085	15.30	3.58
61	6	D	0.400	0.200	1.000	0.141	0.093	1.516	0.085	14.70	3.44
62	6	C	0.400	0.300	1.000	0.153	0.090	1.700	0.160	19.00	4.62
63	7	C	0.300	0.180	0.900	0.141	0.093	1.516	0.085	15.30	3.58
64	7	D	0.300	0.120	0.900	0.141	0.093	1.516	0.085	14.70	3.44
65	7	E	0.300	0.060	0.900	0.141	0.093	1.516	0.085	13.70	3.21
66	7	C	0.300	0.180	0.900	0.153	0.090	1.700	0.160	19.00	4.62
67	6	D	0.400	0.200	1.000	0.141	0.093	1.516	0.085	14.70	3.44
68	6	E	0.400	0.100	1.000	0.141	0.093	1.516	0.085	13.70	3.21
69	6	D	0.400	0.200	1.000	0.141	0.093	1.516	0.085	18.50	4.33
70	6	F	0.400	0.0	1.000	0.141	0.093	1.516	0.085	10.00	2.34
71	6	E	0.400	0.100	1.000	0.106	0.183	0.579	0.117	16.00	4.62
72	6	E	0.400	0.100	1.000	0.141	0.093	1.516	0.085	17.50	4.09
73	6	D	0.400	0.200	1.000	0.106	0.183	0.579	0.117	21.00	6.07
74	6	F	0.400	0.0	1.000	0.141	0.093	1.516	0.085	16.50	3.86
75	6	E	0.400	0.100	1.000	0.141	0.093	1.516	0.085	17.50	4.09
76	6	C	0.400	0.300	1.000	0.153	0.090	1.700	0.160	14.00	3.40
77	4	F	0.250	0.0	0.800	0.141	0.093	1.516	0.085	10.00	2.34
78	4	E	0.250	0.080	0.800	0.141	0.093	1.516	0.085	17.50	4.09

Table A13. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
79	13	C	0.350	0.300	0.900	0.140	0.160	0.875	0.140	13.00	3.90
80	13	D	0.350	0.200	0.900	0.106	0.183	0.579	0.117	21.00	6.07
81	13	C	0.350	0.300	0.900	0.153	0.090	1.700	0.160	15.60	3.79
82	13	E	0.350	0.100	0.900	0.106	0.183	0.579	0.117	16.00	4.62
83	13	A	0.350	0.500	0.900	0.153	0.090	1.700	0.040	22.00	5.35
84	13	C	0.350	0.300	0.900	0.153	0.090	1.700	0.160	19.00	4.62
85	13	F	0.350	0.0	0.900	0.141	0.093	1.516	0.085	10.00	2.34
86	9	D	0.150	0.060	0.400	0.106	0.183	0.579	0.117	21.00	6.07
87	9	E	0.150	0.030	0.400	0.106	0.183	0.579	0.117	16.00	4.62
88	14	C	0.250	0.240	0.900	0.153	0.090	1.700	0.160	19.00	4.62
89	9	D	0.150	0.060	0.400	0.153	0.090	1.700	0.160	17.50	4.25
90	4	E	0.250	0.080	0.800	0.106	0.183	0.579	0.117	16.00	4.62
91	2	E	0.100	0.030	0.200	0.106	0.183	0.579	0.117	16.00	4.62
92	4	D	0.250	0.160	0.800	0.153	0.090	1.700	0.160	17.50	4.25
93	4	D	0.250	0.160	0.800	0.140	0.160	0.875	0.140	10.00	3.00
94	4	C	0.250	0.240	0.800	0.149	0.151	0.987	0.098	16.00	4.80
95	3	C	0.200	0.180	0.500	0.153	0.090	1.700	0.160	19.00	4.62
96	3	C	0.200	0.180	0.500	0.153	0.090	1.700	0.160	14.00	3.40
97	14	C	0.250	0.240	0.900	0.153	0.090	1.700	0.160	14.00	3.40
98	7	E	0.300	0.060	0.900	0.141	0.093	1.516	0.085	17.50	4.09
99	7	E	0.300	0.060	0.900	0.141	0.093	1.516	0.085	17.50	4.09
100	7	D	0.300	0.120	0.900	0.153	0.090	1.700	0.160	17.50	4.25
101	7	C	0.300	0.180	0.900	0.153	0.090	1.700	0.160	14.00	3.40
102	2	C	0.100	0.090	0.200	0.153	0.090	1.700	0.160	19.00	4.62
103	4	C	0.250	0.240	0.800	0.153	0.090	1.700	0.160	19.00	4.62
104	7	E	0.300	0.060	0.900	0.106	0.183	0.579	0.117	16.00	4.62
105	14	D	0.250	0.160	0.900	0.140	0.160	0.875	0.140	10.00	3.00
106	14	C	0.250	0.240	0.900	0.153	0.090	1.700	0.160	15.60	3.79
107	3	D	0.200	0.120	0.500	0.106	0.183	0.579	0.117	21.00	6.07
108	3	C	0.200	0.180	0.500	0.106	0.183	0.579	0.117	26.00	7.51
109	6	B	0.400	0.400	1.000	0.149	0.151	0.987	0.098	20.50	6.15
110	3	C	0.200	0.180	0.500	0.149	0.151	0.987	0.098	16.00	4.80
111	3	B	0.200	0.240	0.500	0.149	0.151	0.987	0.098	20.50	6.15
112	14	B	0.250	0.320	0.900	0.149	0.151	0.987	0.098	20.50	6.15
113	4	B	0.250	0.320	0.800	0.149	0.151	0.987	0.098	20.50	6.15
114	2	B	0.100	0.120	0.200	0.149	0.151	0.987	0.098	20.50	6.15
115	14	B	0.250	0.320	0.900	0.153	0.090	1.700	0.160	20.50	4.98
116	3	B	0.200	0.240	0.500	0.153	0.090	1.700	0.160	20.50	4.98
117	4	B	0.250	0.320	0.800	0.153	0.090	1.700	0.160	20.50	4.98

Table A13. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
118	3	B	0.200	0.240	0.500	0.149	0.151	0.987	0.098	25.00	7.50
119	2	B	0.100	0.120	0.200	0.140	0.160	0.875	0.140	18.00	5.40
120	2	C	0.100	0.090	0.200	0.153	0.090	1.700	0.160	15.60	3.79
121	3	A	0.200	0.300	0.500	0.106	0.183	0.579	0.117	12.00	3.47
122	3	E	0.200	0.060	0.500	0.106	0.183	0.579	0.117	16.00	4.62
123	3	B	0.200	0.240	0.500	0.140	0.160	0.875	0.140	18.00	5.40
124	14	B	0.250	0.320	0.900	0.140	0.160	0.875	0.140	18.00	5.40
125	4	D	0.250	0.160	0.800	0.153	0.090	1.700	0.160	14.10	3.43
126	6	C	0.400	0.300	1.000	0.153	0.090	1.700	0.160	15.60	3.79
127	4	E	0.250	0.080	0.800	0.141	0.093	1.516	0.085	10.30	2.41
128	4	E	0.250	0.080	0.800	0.141	0.093	1.516	0.085	10.30	2.41
129	4	C	0.250	0.240	0.800	0.200	0.110	1.818	0.010	7.00	2.17
130	6	E	0.400	0.100	1.000	0.141	0.093	1.516	0.085	17.50	4.09
131	6	E	0.400	0.100	1.000	0.141	0.093	1.516	0.085	10.30	2.41
132	4	E	0.250	0.080	0.800	0.141	0.093	1.516	0.085	17.50	4.09
133	3	B	0.200	0.240	0.500	0.141	0.093	1.516	0.085	16.40	3.84
134	3	E	0.200	0.060	0.500	0.141	0.093	1.516	0.085	10.30	2.41
135	3	C	0.200	0.180	0.500	0.141	0.093	1.516	0.085	19.50	4.56
136	3	C	0.200	0.180	0.500	0.240	0.110	2.182	0.010	7.00	2.45
137	14	B	0.250	0.320	0.900	0.141	0.093	1.516	0.085	16.40	3.84
138	3	C	0.200	0.180	0.500	0.141	0.093	1.516	0.085	15.30	3.58
139	4	D	0.250	0.160	0.800	0.141	0.093	1.516	0.085	14.80	3.46
140	6	C	0.400	0.300	1.000	0.141	0.093	1.516	0.085	19.50	4.56
141	3	B	0.200	0.240	0.500	0.153	0.090	1.700	0.160	17.10	4.16
142	14	E	0.250	0.080	0.900	0.153	0.183	0.836	0.117	16.00	5.38
143	4	C	0.250	0.240	0.800	0.149	0.151	0.987	0.098	4.80	1.44
144	4	C	0.250	0.240	0.800	0.153	0.090	1.700	0.160	19.00	4.62
145	4	C	0.250	0.240	0.800	0.141	0.093	1.516	0.085	15.30	3.58
146	4	C	0.250	0.240	0.800	0.144	0.156	0.923	0.300	10.00	3.00
147	4	C	0.250	0.240	0.800	0.153	0.090	1.700	0.160	14.00	3.40
148	7	C	0.300	0.180	0.900	0.153	0.090	1.700	0.160	15.60	3.79
149	7	D	0.300	0.120	0.900	0.106	0.183	0.579	0.117	21.00	6.07
150	7	D	0.300	0.120	0.900	0.153	0.090	1.700	0.160	14.10	3.43
151	7	C	0.300	0.180	0.900	0.153	0.090	1.700	0.160	19.00	4.62
152	6	B	0.400	0.400	1.000	0.153	0.090	1.700	0.160	17.10	4.16
153	6	C	0.400	0.300	1.000	0.149	0.151	0.987	0.098	4.80	1.44
154	14	D	0.250	0.160	0.900	0.153	0.090	1.700	0.160	14.10	3.43
155	6	C	0.400	0.300	1.000	0.106	0.183	0.579	0.117	26.00	7.51
156	17	A	0.020	10.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0
157	8	A	0.020	0.050	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A14. Properties of overland flow elements for Brush Creek watershed.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
1	300	1740	12.5	25
2	360	650	6.3	25
3	580	450	6.8	35
4	900	220	18.9	40
5	1600	690	33.3	95
6	440	780	7.3	40
7	310	610	3.6	40
8	350	260	5.3	55
9	410	870	5.1	80
10	800	1320	16.6	105
11	1740	1470	45.9	155
12	300	1730	12.5	45
13	200	740	2.1	35
14	540	1730	13.7	40
15	750	740	9.8	45
16	280	1200	4.4	40
17	340	400	3.5	35
18	320	400	2.9	35
19	170	400	1.7	30
20	280	1600	8.2	35
21	870	890	24.1	75
22	430	710	6.7	25
23	270	820	4.7	35
24	250	820	3.2	45
25	300	560	3.5	55
26	280	670	4.8	40
27	400	570	4.4	40
28	380	460	3.4	40
29	460	440	3.3	45
30	490	420	3.1	45
31	300	800	5.5	20
32	420	430	4.1	25
33	390	320	5.0	25
34	310	450	5.4	35

Table A14. Continued.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
35	580	260	10.9	45
36	380	860	10.9	60
37	280	870	2.0	55
38	640	780	16.3	55
39	770	350	11.9	60
40	610	870	14.5	70
41	380	410	5.4	65
42	270	720	3.5	40
43	300	540	5.8	55
44	280	250	3.0	60
45	300	390	3.1	40
46	200	1340	7.7	55
47	550	1630	22.1	75
48	450	410	5.6	45
49	300	480	3.7	40
50	300	500	2.8	45
51	310	500	3.7	35
52	1330	800	45.8	115
53	430	1500	9.5	55
54	1220	1730	30.0	75
55	360	1300	10.8	65
56	870	500	20.0	75
57	310	2230	15.7	55
58	300	500	2.3	30
59	310	500	4.9	45
60	250	1170	7.1	25
61	540	560	6.7	40
62	580	890	12.9	35
63	550	820	8.3	45
64	520	650	5.8	35
65	290	1150	7.1	35
66	300	2120	14.4	25
67	300	1080	10.2	25
68	380	1040	10.1	40
69	230	540	2.5	25

Table A14. Continued.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
70	300	540	4.8	35
71	260	1270	5.8	25
72	1160	440	37.8	200
73	280	840	9.1	35
74	900	870	18.2	55
75	610	320	8.6	75
76	1180	820	36.0	85
77	1100	1200	25.2	85
78	610	1140	11.5	65
79	730	420	12.2	80
80	200	780	2.8	35
81	560	500	3.9	35
82	840	500	10.6	55
83	620	1000	7.5	40
84	1190	1000	27.0	80
85	800	500	5.8	60
86	480	500	7.8	40

Table A15. Properties of channel flow elements for Brush Creek watershed.

Element Number	Length (ft)	Downstream Node Width at 2-Foot Depth (ft)	Relief (ft)	Manning 'n'
1	610	45	35	0.12
2	260	45	10	0.12
3	870	45	45	0.12
4	650	45	25	0.12
5	450	45	20	0.12
6	220	45	5	0.12
7	690	45	20	0.12
8	780	45	10	0.12
9	1730	45	110	0.12
10	740	45	30	0.12
11	400	76	5	0.09
12	400	76	5	0.09
13	400	76	5	0.09
14	890	45	70	0.12
15	710	45	25	0.12
16	820	76	15	0.09
17	560	45	75	0.12
18	240	45	10	0.12
19	430	45	25	0.12
20	320	45	15	0.12
21	250	45	10	0.12
22	200	45	10	0.12
23	260	45	5	0.12
24	440	45	15	0.12
25	420	45	15	0.12
26	870	45	100	0.12
27	410	45	20	0.12
28	370	45	10	0.12
29	350	45	10	0.12
30	540	45	130	0.12
31	250	45	10	0.12
32	390	45	20	0.12
33	450	45	20	0.12
34	410	45	20	0.12

Table A15. Continued.

Element Number	Length (ft)	Downstream Node Width at 2-Foot Depth (ft)	Relief (ft)	Manning 'n'
35	480	45	20	0.12
36	500	45	20	0.12
37	800	76	15	0.09
38	500	76	10	0.09
39	500	76	10	0.09
40	500	76	5	0.09
41	1730	76	25	0.09
42	500	76	5	0.09
43	820	45	60	0.12
44	350	45	10	0.12
45	300	45	10	0.12
46	260	45	5	0.12
47	890	45	35	0.12
48	1080	45	100	0.12
49	1040	45	40	0.12
50	540	45	15	0.12
51	840	45	80	0.12
52	430	45	20	0.12
53	440	45	15	0.12
54	320	76	10	0.09
55	820	76	20	0.09
56	420	76	10	0.09
57	780	76	15	0.09
58	500	230	2	0.07
59	500	230	5	0.07
60	500	230	5	0.07
61	500	230	2	0.07

Table A16. HRU properties for Chestnut Branch watershed, Bedford County, VA.

HRU No	Landuse No	Slope Class	Manning n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
1	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.230	8.00	2.17
2	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	3.00	0.81
3	3	D	0.200	0.120	0.500	0.158	0.113	1.398	0.230	2.00	0.54
4	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	9.00	2.44
5	3	B	0.200	0.240	0.500	0.131	0.142	0.923	0.110	7.00	1.91
6	3	C	0.200	0.180	0.500	0.131	0.142	0.923	0.110	5.00	1.36
7	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	3.00	0.81
8	4	A	0.250	0.400	0.800	0.153	0.090	1.700	0.230	26.00	6.32
9	4	C	0.250	0.240	0.800	0.105	0.241	0.436	0.390	10.00	3.46
10	4	D	0.250	0.160	0.800	0.131	0.142	0.923	0.110	3.00	0.82
11	4	E	0.250	0.080	0.800	0.105	0.241	0.436	0.390	6.00	2.08
12	4	C	0.250	0.240	0.800	0.105	0.241	0.436	0.390	1.00	0.35
13	4	B	0.250	0.320	0.800	0.105	0.241	0.436	0.390	12.00	4.15
14	4	A	0.250	0.400	0.800	0.153	0.090	1.700	0.040	26.00	6.32
15	4	E	0.250	0.080	0.800	0.131	0.142	0.923	0.110	1.00	0.27
16	4	E	0.250	0.080	0.800	0.105	0.241	0.436	0.390	6.00	2.08
17	4	B	0.250	0.320	0.800	0.131	0.142	0.923	0.110	7.00	1.91
18	4	E	0.250	0.080	0.800	0.082	0.267	0.307	0.047	3.00	1.05
19	4	D	0.250	0.160	0.800	0.158	0.113	1.398	0.230	6.00	1.63
20	4	D	0.250	0.160	0.800	0.082	0.267	0.307	0.047	4.00	1.40
21	4	D	0.250	0.160	0.800	0.158	0.113	1.398	0.230	2.00	0.54
22	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	3.00	0.81
23	4	D	0.250	0.160	0.800	0.105	0.241	0.436	0.390	8.00	2.77
24	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	7.00	1.90
25	16	C	0.020	0.012	0.800	0.131	0.142	0.923	0.110	5.00	1.36
26	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	3.00	0.81
27	6	D	0.400	0.200	1.000	0.158	0.113	1.398	0.230	2.00	0.54
28	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	7.00	1.90
29	6	D	0.400	0.200	1.000	0.131	0.142	0.923	0.110	3.00	0.82
30	6	E	0.400	0.100	1.000	0.158	0.113	1.398	0.230	1.00	0.27
31	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	7.00	1.90
32	6	E	0.400	0.100	1.000	0.131	0.142	0.923	0.110	1.00	0.27
33	2	C	0.100	0.090	0.200	0.149	0.084	1.774	0.120	5.00	1.16
34	2	C	0.100	0.090	0.200	0.158	0.113	1.398	0.230	3.00	0.81
35	2	B	0.100	0.120	0.200	0.131	0.142	0.923	0.110	9.00	2.46
36	2	C	0.100	0.090	0.200	0.131	0.142	0.923	0.110	5.00	1.36
37	2	E	0.100	0.030	0.200	0.131	0.142	0.923	0.110	1.00	0.27
38	7	B	0.300	0.240	0.900	0.158	0.113	1.398	0.230	7.00	1.90
39	7	C	0.300	0.180	0.900	0.131	0.142	0.923	0.110	5.00	1.36

Table A16. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
40	13	C	0.350	0.300	0.900	0.131	0.142	0.923	0.110	5.00	1.36
41	13	E	0.350	0.100	0.900	0.131	0.142	0.923	0.110	1.00	0.27
42	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
43	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
44	3	E	0.200	0.060	0.500	0.131	0.142	0.923	0.110	1.00	0.27
45	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.230	7.00	1.90
46	3	B	0.200	0.240	0.500	0.131	0.142	0.923	0.110	9.00	2.46
47	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	7.00	1.90
48	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	7.00	1.90
49	4	D	0.250	0.160	0.800	0.158	0.113	1.398	0.230	2.00	0.54
50	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	6.00	1.63
51	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	9.00	2.44
52	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
53	4	C	0.250	0.240	0.800	0.131	0.142	0.923	0.110	5.00	1.36
54	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
55	14	B	0.250	0.320	0.900	0.131	0.142	0.923	0.110	9.00	2.46
56	14	C	0.250	0.240	0.900	0.158	0.113	1.398	0.230	7.00	1.90
57	14	C	0.250	0.240	0.900	0.158	0.113	1.398	0.230	9.00	2.44
58	11	B	0.100	0.120	0.200	0.131	0.142	0.923	0.110	9.00	2.46
59	11	B	0.100	0.120	0.200	0.158	0.113	1.398	0.230	8.00	2.17
60	11	C	0.100	0.090	0.200	0.158	0.113	1.398	0.230	7.00	1.90
61	11	C	0.100	0.090	0.200	0.131	0.142	0.923	0.110	5.00	1.36
62	3	B	0.200	0.240	0.500	0.131	0.142	0.923	0.110	9.00	2.46
63	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	6.00	1.63
64	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.230	8.00	2.17
65	14	B	0.250	0.320	0.900	0.158	0.113	1.398	0.230	8.00	2.17
66	16	B	0.020	0.016	0.800	0.158	0.113	1.398	0.230	8.00	2.17
67	6	E	0.400	0.100	1.000	0.131	0.142	0.923	0.110	1.00	0.27
68	6	A	0.400	0.500	1.000	0.153	0.090	1.700	0.230	26.00	6.32
69	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	7.00	1.90
70	6	D	0.400	0.200	1.000	0.127	0.130	0.977	0.120	4.00	1.03
71	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	2.00	0.54
72	6	C	0.400	0.300	1.000	0.082	0.267	0.307	0.047	5.00	1.74
73	6	C	0.400	0.300	1.000	0.082	0.267	0.307	0.047	5.00	1.74
74	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	3.00	0.81
75	6	E	0.400	0.100	1.000	0.105	0.241	0.436	0.390	6.00	2.08
76	6	A	0.400	0.500	1.000	0.153	0.090	1.700	0.040	26.00	6.32
77	6	B	0.400	0.400	1.000	0.105	0.241	0.436	0.390	12.00	4.15
78	3	A	0.200	0.300	0.500	0.153	0.090	1.700	0.230	26.00	6.32

Table A16. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil- tration Rate	Depth of the Soil Profile	Maximum Storage
79	3	D	0.200	0.120	0.500	0.082	0.267	0.307	0.047	4.00	1.40
80	3	C	0.200	0.180	0.500	0.082	0.267	0.307	0.047	5.00	1.74
81	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	3.00	0.81
82	4	D	0.250	0.160	0.800	0.082	0.267	0.307	0.047	4.00	1.40
83	4	C	0.250	0.240	0.800	0.082	0.267	0.307	0.047	5.00	1.74
84	4	C	0.250	0.240	0.800	0.082	0.267	0.307	0.047	5.00	1.74
85	4	B	0.250	0.320	0.800	0.082	0.267	0.307	0.047	6.00	2.09
86	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	7.00	1.90
87	4	D	0.250	0.160	0.800	0.082	0.267	0.307	0.047	4.00	1.40
88	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	3.00	0.81
89	6	B	0.400	0.400	1.000	0.082	0.267	0.307	0.047	8.00	2.79
90	6	B	0.400	0.400	1.000	0.082	0.267	0.307	0.047	6.00	2.09
91	6	D	0.400	0.200	1.000	0.082	0.267	0.307	0.047	4.00	1.40
92	6	D	0.400	0.200	1.000	0.105	0.241	0.436	0.390	8.00	2.77
93	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	7.00	1.90
94	6	D	0.400	0.200	1.000	0.158	0.113	1.398	0.230	2.00	0.54
95	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	7.00	1.90
96	6	D	0.400	0.200	1.000	0.105	0.241	0.436	0.390	5.00	1.73
97	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	8.00	2.17
98	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	3.00	0.81
99	4	D	0.250	0.160	0.800	0.082	0.267	0.307	0.047	4.00	1.40
100	4	C	0.250	0.240	0.800	0.082	0.267	0.307	0.047	5.00	1.74
101	7	B	0.300	0.240	0.900	0.082	0.267	0.307	0.047	8.00	2.79
102	7	D	0.300	0.120	0.900	0.082	0.267	0.307	0.047	6.00	2.09
103	7	C	0.300	0.180	0.900	0.082	0.267	0.307	0.047	5.00	1.74
104	6	B	0.400	0.400	1.000	0.082	0.267	0.307	0.010	13.00	4.54
105	6	C	0.400	0.300	1.000	0.082	0.267	0.307	0.047	5.00	1.74
106	6	D	0.400	0.200	1.000	0.082	0.267	0.307	0.047	6.00	2.09
107	6	B	0.400	0.400	1.000	0.082	0.267	0.307	0.047	6.00	2.09
108	4	B	0.250	0.320	0.800	0.082	0.267	0.307	0.010	10.00	3.49
109	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.120	8.00	2.17
110	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
111	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	3.00	0.81
112	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	3.00	0.81
113	4	B	0.250	0.320	0.800	0.082	0.267	0.307	0.047	8.00	2.79
114	7	A	0.300	0.300	0.900	0.153	0.090	1.700	0.040	26.00	6.32
115	7	D	0.300	0.120	0.900	0.105	0.241	0.436	0.390	5.00	1.73
116	7	C	0.300	0.180	0.900	0.158	0.113	1.398	0.230	6.00	1.63
117	7	A	0.300	0.300	0.900	0.153	0.090	1.700	0.230	26.00	6.32

Table A16. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
118	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	6.00	1.63
119	3	E	0.200	0.060	0.500	0.105	0.241	0.436	0.390	3.00	1.04
120	3	D	0.200	0.120	0.500	0.131	0.142	0.923	0.110	5.00	1.36
121	3	D	0.200	0.120	0.500	0.105	0.241	0.436	0.390	7.00	2.42
122	4	C	0.250	0.240	0.800	0.131	0.142	0.923	0.110	7.00	1.91
123	4	B	0.250	0.320	0.800	0.131	0.142	0.923	0.110	11.00	3.00
124	4	B	0.250	0.320	0.800	0.131	0.142	0.923	0.110	9.00	2.46
125	7	E	0.300	0.060	0.900	0.131	0.142	0.923	0.110	5.00	1.36
126	7	C	0.300	0.180	0.900	0.131	0.142	0.923	0.110	7.00	1.91
127	7	D	0.300	0.120	0.900	0.131	0.142	0.923	0.110	5.00	1.36
128	7	D	0.300	0.120	0.900	0.131	0.142	0.923	0.110	3.00	0.82
129	13	D	0.350	0.200	0.900	0.131	0.142	0.923	0.110	3.00	0.82
130	13	D	0.350	0.200	0.900	0.131	0.142	0.923	0.110	5.00	1.36
131	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	6.00	1.63
132	6	E	0.400	0.100	1.000	0.131	0.142	0.923	0.110	5.00	1.36
133	6	C	0.400	0.300	1.000	0.131	0.142	0.923	0.110	7.00	1.91
134	6	B	0.400	0.400	1.000	0.131	0.142	0.923	0.110	11.00	3.00
135	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	9.00	2.44
136	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	8.00	2.17
137	6	E	0.400	0.100	1.000	0.105	0.241	0.436	0.390	3.00	1.04
138	6	D	0.400	0.200	1.000	0.153	0.090	1.700	0.160	4.00	0.97
139	6	B	0.400	0.400	1.000	0.131	0.142	0.923	0.110	9.00	2.46
140	6	D	0.400	0.200	1.000	0.158	0.113	1.398	0.120	7.00	1.90
141	6	C	0.400	0.300	1.000	0.149	0.084	1.774	0.120	5.00	1.16
142	6	D	0.400	0.200	1.000	0.125	0.170	0.735	0.212	6.00	1.77
143	6	D	0.400	0.200	1.000	0.127	0.130	0.977	0.120	4.00	1.03
144	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	7.00	1.90
145	6	E	0.400	0.100	1.000	0.131	0.142	0.923	0.110	3.00	0.82
146	6	C	0.400	0.300	1.000	0.082	0.267	0.307	0.047	5.00	1.74
147	6	D	0.400	0.200	1.000	0.127	0.130	0.977	0.120	4.00	1.03
148	6	B	0.400	0.400	1.000	0.131	0.142	0.923	0.110	7.00	1.91
149	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.120	7.00	1.90
150	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.120	8.00	2.17
151	3	D	0.200	0.120	0.500	0.127	0.130	0.977	0.120	4.00	1.03
152	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.230	7.00	1.90
153	3	B	0.200	0.240	0.500	0.082	0.267	0.307	0.047	6.00	2.09
154	3	D	0.200	0.120	0.500	0.131	0.142	0.923	0.110	3.00	0.82
155	3	B	0.200	0.240	0.500	0.149	0.084	1.774	0.120	9.00	2.10
156	7	D	0.300	0.120	0.900	0.127	0.130	0.977	0.120	4.00	1.03

Table A16. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
157	7	B	0.300	0.240	0.900	0.158	0.113	1.398	0.230	8.00	2.17
158	7	D	0.300	0.120	0.900	0.105	0.241	0.436	0.390	8.00	2.77
159	3	B	0.200	0.240	0.500	0.153	0.090	1.700	0.230	26.00	6.32
160	3	A	0.200	0.300	0.500	0.153	0.090	1.700	0.040	26.00	6.32
161	3	B	0.200	0.240	0.500	0.082	0.267	0.307	0.010	10.00	3.49
162	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	7.00	1.90
163	3	C	0.200	0.180	0.500	0.082	0.267	0.307	0.047	5.00	1.74
164	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.120	8.00	2.17
165	3	C	0.200	0.180	0.500	0.149	0.084	1.774	0.120	5.00	1.16
166	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	3.00	0.81
167	3	B	0.200	0.240	0.500	0.082	0.267	0.307	0.047	6.00	2.09
168	3	D	0.200	0.120	0.500	0.158	0.113	1.398	0.230	2.00	0.54
169	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.230	5.00	1.35
170	3	C	0.200	0.180	0.500	0.082	0.267	0.307	0.047	5.00	1.74
171	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	3.00	0.81
172	16	D	0.020	0.008	0.800	0.158	0.113	1.398	0.230	2.00	0.54
173	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	7.00	1.90
174	2	C	0.100	0.090	0.200	0.158	0.113	1.398	0.230	7.00	1.90
175	2	B	0.100	0.120	0.200	0.158	0.113	1.398	0.230	7.00	1.90
176	2	A	0.100	0.150	0.200	0.153	0.090	1.700	0.230	26.00	6.32
177	2	B	0.100	0.120	0.200	0.082	0.267	0.307	0.047	6.00	2.09
178	2	D	0.100	0.060	0.200	0.131	0.142	0.923	0.110	3.00	0.82
179	2	D	0.100	0.060	0.200	0.127	0.130	0.977	0.120	4.00	1.03
180	2	E	0.100	0.030	0.200	0.105	0.241	0.436	0.390	3.00	1.04
181	2	B	0.100	0.120	0.200	0.149	0.084	1.774	0.120	8.00	1.86
182	2	B	0.100	0.120	0.200	0.158	0.113	1.398	0.230	8.00	2.17
183	6	B	0.400	0.400	1.000	0.082	0.267	0.307	0.047	6.00	2.09
184	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	8.00	2.17
185	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	7.00	1.90
186	6	D	0.400	0.200	1.000	0.158	0.113	1.398	0.230	6.00	1.63
187	3	B	0.200	0.240	0.500	0.149	0.084	1.774	0.120	6.00	1.40
188	3	B	0.200	0.240	0.500	0.082	0.267	0.307	0.010	13.00	4.54
189	3	D	0.200	0.120	0.500	0.127	0.130	0.977	0.120	4.00	1.03
190	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	7.00	1.90
191	2	C	0.100	0.090	0.200	0.158	0.113	1.398	0.230	3.00	0.81
192	2	B	0.100	0.120	0.200	0.158	0.113	1.398	0.230	7.00	1.90
193	4	C	0.250	0.240	0.800	0.082	0.267	0.307	0.010	9.00	3.14
194	4	B	0.250	0.320	0.800	0.153	0.090	1.700	0.230	26.00	6.32
195	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	3.00	0.81

Table A16. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
196	4	C	0.250	0.240	0.800	0.082	0.267	0.307	0.010	9.00	3.14
197	4	B	0.250	0.320	0.800	0.082	0.267	0.307	0.047	6.00	2.09
198	4	C	0.250	0.240	0.800	0.149	0.084	1.774	0.120	5.00	1.16
199	4	C	0.250	0.240	0.800	0.127	0.130	0.977	0.120	4.00	1.03
200	4	B	0.250	0.320	0.800	0.158	0.113	1.398	0.230	8.00	2.17
201	4	C	0.250	0.240	0.800	0.149	0.084	1.774	0.120	5.00	1.16
202	4	B	0.250	0.320	0.800	0.149	0.084	1.774	0.120	6.00	1.40
203	14	B	0.250	0.320	0.900	0.158	0.113	1.398	0.120	8.00	2.17
204	14	B	0.250	0.320	0.900	0.082	0.267	0.307	0.047	8.00	2.79
205	6	B	0.400	0.400	1.000	0.082	0.267	0.307	0.010	13.00	4.54
206	6	B	0.400	0.400	1.000	0.082	0.267	0.307	0.010	10.00	3.49
207	3	B	0.200	0.240	0.500	0.082	0.267	0.307	0.010	13.00	4.54
208	3	C	0.200	0.180	0.500	0.082	0.267	0.307	0.010	9.00	3.14
209	14	B	0.250	0.320	0.900	0.082	0.267	0.307	0.047	6.00	2.09
210	7	B	0.300	0.240	0.900	0.082	0.267	0.307	0.047	6.00	2.09
211	7	C	0.300	0.180	0.900	0.158	0.113	1.398	0.230	3.00	0.81
212	14	B	0.250	0.320	0.900	0.082	0.267	0.307	0.047	6.00	2.09
213	7	B	0.300	0.240	0.900	0.082	0.267	0.307	0.047	6.00	2.09
214	7	C	0.300	0.180	0.900	0.158	0.113	1.398	0.230	3.00	0.81
215	14	B	0.250	0.320	0.900	0.082	0.267	0.307	0.047	8.00	2.79
216	14	C	0.250	0.240	0.900	0.082	0.267	0.307	0.047	5.00	1.74
217	14	C	0.250	0.240	0.900	0.082	0.267	0.307	0.047	5.00	1.74
218	7	B	0.300	0.240	0.900	0.082	0.267	0.307	0.047	8.00	2.79
219	7	C	0.300	0.180	0.900	0.082	0.267	0.307	0.047	5.00	1.74
220	14	C	0.250	0.240	0.900	0.082	0.267	0.307	0.047	5.00	1.74
221	14	D	0.250	0.160	0.900	0.082	0.267	0.307	0.047	4.00	1.40
222	14	D	0.250	0.160	0.900	0.082	0.267	0.307	0.047	4.00	1.40
223	3	B	0.200	0.240	0.500	0.082	0.267	0.307	0.047	6.00	2.09
224	3	D	0.200	0.120	0.500	0.082	0.267	0.307	0.047	4.00	1.40
225	3	C	0.200	0.180	0.500	0.082	0.267	0.307	0.047	5.00	1.74
226	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	3.00	0.81
227	3	C	0.200	0.180	0.500	0.105	0.241	0.436	0.390	10.00	3.46
228	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	3.00	0.81
229	14	B	0.250	0.320	0.900	0.158	0.113	1.398	0.230	7.00	1.90
230	14	D	0.250	0.160	0.900	0.158	0.113	1.398	0.230	2.00	0.54
231	14	C	0.250	0.240	0.900	0.158	0.113	1.398	0.230	3.00	0.81
232	3	D	0.200	0.120	0.500	0.158	0.113	1.398	0.230	2.00	0.54
233	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	3.00	0.81
234	14	B	0.250	0.320	0.900	0.158	0.113	1.398	0.230	8.00	2.17

Table A16. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
235	13	B	0.350	0.400	0.900	0.082	0.267	0.307	0.047	6.00	2.09
236	13	C	0.350	0.300	0.900	0.158	0.113	1.398	0.230	7.00	1.90
237	6	C	0.400	0.300	1.000	0.082	0.267	0.307	0.010	12.00	4.19
238	6	C	0.400	0.300	1.000	0.082	0.267	0.307	0.010	9.00	3.14
239	5	B	0.100	0.080	0.200	0.082	0.267	0.307	0.047	8.00	2.79
240	2	B	0.100	0.120	0.200	0.082	0.267	0.307	0.047	8.00	2.79
241	3	B	0.200	0.240	0.500	0.082	0.267	0.307	0.047	6.00	2.09
242	6	B	0.400	0.400	1.000	0.125	0.170	0.735	0.212	10.00	2.95
243	6	C	0.400	0.300	1.000	0.125	0.170	0.735	0.212	9.00	2.65
244	6	D	0.400	0.200	1.000	0.082	0.267	0.307	0.047	6.00	2.09
245	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	3.00	0.81
246	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.230	8.00	2.17
247	2	B	0.100	0.120	0.200	0.158	0.113	1.398	0.230	7.00	1.90
248	2	A	0.100	0.150	0.200	0.153	0.090	1.700	0.040	26.00	6.32
249	2	B	0.100	0.120	0.200	0.158	0.113	1.398	0.230	7.00	1.90
250	2	C	0.100	0.090	0.200	0.158	0.113	1.398	0.120	7.00	1.90
251	2	B	0.100	0.120	0.200	0.158	0.113	1.398	0.120	8.00	2.17
252	2	E	0.100	0.030	0.200	0.131	0.142	0.923	0.110	1.00	0.27
253	2	D	0.100	0.060	0.200	0.127	0.130	0.977	0.120	4.00	1.03
254	2	B	0.100	0.120	0.200	0.158	0.113	1.398	0.120	8.00	2.17
255	2	C	0.100	0.090	0.200	0.158	0.113	1.398	0.120	7.00	1.90
256	6	D	0.400	0.200	1.000	0.158	0.113	1.398	0.120	6.00	1.63
257	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.230	7.00	1.90
258	13	A	0.350	0.500	0.900	0.153	0.090	1.700	0.040	26.00	6.32
259	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.120	8.00	2.17
260	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.120	7.00	1.90
261	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.120	7.00	1.90
262	3	E	0.200	0.060	0.500	0.105	0.241	0.436	0.390	6.00	2.08
263	3	D	0.200	0.120	0.500	0.153	0.090	1.700	0.160	4.00	0.97
264	13	D	0.350	0.200	0.900	0.127	0.130	0.977	0.120	4.00	1.03
265	13	E	0.350	0.100	0.900	0.158	0.113	1.398	0.230	1.00	0.27
266	13	D	0.350	0.200	0.900	0.105	0.241	0.436	0.390	5.00	1.73
267	13	C	0.350	0.300	0.900	0.158	0.113	1.398	0.230	3.00	0.81
268	13	C	0.350	0.300	0.900	0.158	0.113	1.398	0.120	5.00	1.35
269	13	E	0.350	0.100	0.900	0.105	0.241	0.436	0.390	6.00	2.08
270	13	D	0.350	0.200	0.900	0.131	0.420	0.312	0.110	3.00	1.65
271	13	E	0.350	0.100	0.900	0.106	0.103	1.029	0.117	13.00	2.72
272	14	D	0.250	0.160	0.900	0.127	0.130	0.977	0.120	4.00	1.03
273	7	E	0.300	0.060	0.900	0.106	0.183	0.579	0.117	9.00	2.60

Table A16. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
274	7	C	0.300	0.180	0.900	0.106	0.183	0.579	0.117	17.00	4.91
275	7	B	0.300	0.240	0.900	0.131	0.142	0.923	0.110	9.00	2.46
276	7	C	0.300	0.180	0.900	0.158	0.113	1.398	0.120	7.00	1.90
277	6	D	0.400	0.200	1.000	0.106	0.183	0.579	0.117	16.00	4.62
278	6	F	0.400	0.0	1.000	0.106	0.183	0.579	0.117	11.00	3.18
279	6	E	0.400	0.100	1.000	0.106	0.183	0.579	0.117	15.00	4.33
280	6	F	0.400	0.0	1.000	0.106	0.183	0.579	0.117	14.00	4.05
281	6	E	0.400	0.100	1.000	0.131	0.142	0.923	0.110	3.00	0.82
282	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.120	7.00	1.90
283	6	D	0.400	0.200	1.000	0.158	0.113	1.398	0.120	7.00	1.90
284	6	E	0.400	0.100	1.000	0.106	0.183	0.579	0.117	13.00	3.76
285	6	F	0.400	0.0	1.000	0.106	0.183	0.579	0.117	14.00	4.05
286	6	E	0.400	0.100	1.000	0.106	0.183	0.579	0.117	15.00	4.33
287	6	D	0.400	0.200	1.000	0.106	0.183	0.579	0.117	13.00	3.76
288	6	D	0.400	0.200	1.000	0.106	0.183	0.579	0.117	13.00	3.76
289	6	B	0.400	0.400	1.000	0.153	0.090	1.700	0.230	24.00	5.83
290	6	F	0.400	0.0	1.000	0.106	0.183	0.579	0.117	14.00	4.05
291	6	E	0.400	0.100	1.000	0.106	0.183	0.579	0.117	12.00	3.47
292	6	D	0.400	0.200	1.000	0.106	0.183	0.579	0.117	16.00	4.62
293	6	C	0.400	0.300	1.000	0.153	0.090	1.700	0.160	5.00	1.21
294	2	D	0.100	0.060	0.200	0.158	0.113	1.398	0.120	6.00	1.63
295	2	C	0.100	0.090	0.200	0.149	0.084	1.774	0.120	5.00	1.16
296	7	C	0.300	0.180	0.900	0.149	0.084	1.774	0.120	5.00	1.16
297	13	D	0.350	0.200	0.900	0.106	0.183	0.579	0.117	16.00	4.62
298	13	E	0.350	0.100	0.900	0.106	0.183	0.579	0.117	15.00	4.33
299	13	B	0.350	0.400	0.900	0.158	0.113	1.398	0.120	8.00	2.17
300	7	C	0.300	0.180	0.900	0.153	0.090	1.700	0.160	5.00	1.21
301	14	D	0.250	0.160	0.900	0.131	0.142	0.923	0.100	3.00	0.82
302	4	B	0.250	0.320	0.800	0.153	0.090	1.700	0.230	24.00	5.83
303	4	C	0.250	0.240	0.800	0.153	0.090	1.700	0.160	5.00	1.21
304	4	D	0.250	0.160	0.800	0.127	0.130	0.977	0.120	4.00	1.03
305	7	D	0.300	0.120	0.900	0.127	0.130	0.977	0.120	4.00	1.03
306	7	D	0.300	0.120	0.900	0.106	0.183	0.579	0.117	16.00	4.62
307	2	D	0.100	0.060	0.200	0.106	0.183	0.579	0.117	16.00	4.62
308	13	D	0.350	0.200	0.900	0.106	0.183	0.579	0.117	16.00	4.62
309	13	F	0.350	0.0	0.900	0.106	0.183	0.579	0.117	14.00	4.05
310	13	E	0.350	0.100	0.900	0.106	0.183	0.579	0.117	15.00	4.33
311	13	E	0.350	0.100	0.900	0.106	0.183	0.579	0.117	12.00	3.47
312	13	C	0.350	0.300	0.900	0.158	0.113	1.398	0.230	6.00	1.63

Table A16. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
313	14	C	0.250	0.240	0.900	0.149	0.084	1.774	0.120	5.00	1.16
314	14	D	0.250	0.160	0.900	0.127	0.130	0.977	0.120	4.00	1.03
315	14	C	0.250	0.240	0.900	0.131	0.142	0.923	0.110	7.00	1.91
316	16	C	0.020	0.012	0.800	0.149	0.084	1.774	0.120	5.00	1.16
317	14	D	0.250	0.160	0.900	0.106	0.183	0.579	0.117	16.00	4.62
318	14	C	0.250	0.240	0.900	0.156	0.113	1.381	0.230	6.00	1.61
319	14	B	0.250	0.320	0.900	0.153	0.090	1.700	0.040	24.00	5.83
320	4	E	0.250	0.080	0.800	0.131	0.142	0.923	0.110	3.00	0.82
321	14	C	0.250	0.240	0.900	0.131	0.142	0.923	0.110	5.00	1.36
322	14	B	0.250	0.320	0.900	0.158	0.113	1.398	0.230	8.00	2.17
323	16	C	0.020	0.012	0.800	0.131	0.142	0.923	0.110	5.00	1.36
324	14	C	0.250	0.240	0.900	0.082	0.267	0.307	0.047	5.00	1.74
325	4	D	0.250	0.160	0.800	0.131	0.142	0.923	0.110	3.00	0.82
326	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.230	8.00	2.17
327	14	E	0.250	0.080	0.900	0.105	0.241	0.436	0.390	1.00	0.35
328	14	C	0.250	0.240	0.900	0.158	0.113	1.398	0.230	3.00	0.81
329	14	C	0.250	0.240	0.900	0.082	0.267	0.307	0.047	5.00	1.74
330	4	D	0.250	0.160	0.800	0.082	0.267	0.307	0.047	6.00	2.09
331	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	10.00	2.71
332	13	D	0.350	0.200	0.900	0.149	0.084	1.774	0.120	6.00	1.40
333	3	C	0.200	0.180	0.500	0.158	0.113	1.398	0.230	9.00	2.44
334	6	C	0.400	0.300	1.000	0.131	0.141	0.929	0.110	5.00	1.36
335	4	C	0.250	0.240	0.800	0.082	0.267	0.307	0.047	5.00	1.74
336	13	B	0.350	0.400	0.900	0.158	0.113	1.398	0.230	8.00	2.17
337	13	C	0.350	0.300	0.900	0.149	0.084	1.774	0.120	5.00	1.16
338	4	D	0.250	0.160	0.800	0.158	0.113	1.398	0.230	2.00	0.54
339	3	D	0.200	0.120	0.500	0.082	0.267	0.307	0.047	4.00	1.40
340	4	B	0.250	0.320	0.800	0.082	0.267	0.307	0.047	8.00	2.79
341	4	B	0.250	0.320	0.800	0.082	0.267	0.307	0.010	13.00	4.54
342	4	D	0.250	0.160	0.800	0.158	0.113	1.398	0.230	8.00	2.17
343	4	B	0.250	0.320	0.800	0.082	0.267	0.307	0.010	13.00	4.54
344	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	5.00	1.35
345	6	B	0.400	0.400	1.000	0.158	0.113	1.398	0.230	7.00	1.90
346	6	B	0.400	0.400	1.000	0.082	0.267	0.307	0.010	10.00	3.49
347	2	B	0.100	0.120	0.200	0.082	0.267	0.307	0.047	6.00	2.09
348	6	C	0.400	0.300	1.000	0.082	0.267	0.307	0.010	9.00	3.14
349	4	C	0.250	0.240	0.800	0.082	0.267	0.307	0.010	12.00	4.19
350	6	C	0.400	0.300	1.000	0.082	0.267	0.307	0.010	9.00	3.14
351	3	D	0.200	0.120	0.500	0.082	0.267	0.307	0.047	6.00	2.09

Table A16. Continued.

HRU No	Landuse No	Slope Class	Mannings n	Depression Storage	Holtans a	Fraction of Avail Water	Fraction of Gravity Water	Exponent c	Final Infil-tration Rate	Depth of the Soil Profile	Maximum Storage
352	6	D	0.400	0.200	1.000	0.127	0.130	0.977	0.120	4.00	1.03
353	3	D	0.200	0.120	0.500	0.105	0.241	0.436	0.390	8.00	2.77
354	3	B	0.200	0.240	0.500	0.149	0.084	1.774	0.120	8.00	1.86
355	7	E	0.300	0.060	0.900	0.131	0.141	0.929	0.110	1.00	0.27
356	13	E	0.350	0.100	0.900	0.105	0.241	0.436	0.390	3.00	1.04
357	13	B	0.350	0.400	0.900	0.131	0.141	0.929	0.110	7.00	1.90
358	14	E	0.250	0.080	0.900	0.158	0.113	1.398	0.230	1.00	0.27
359	13	A	0.350	0.500	0.900	0.153	0.090	1.700	0.230	26.00	6.32
360	3	B	0.200	0.240	0.500	0.158	0.113	1.398	0.230	7.00	1.90
361	13	C	0.350	0.300	0.900	0.082	0.267	0.307	0.047	5.00	1.74
362	17	A	0.020	10.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0
363	8	A	0.020	0.050	0.0	0.0	0.0	0.0	0.0	0.0	0.0
364	2	A	0.100	0.150	0.200	0.149	0.084	1.774	0.120	6.00	1.40
365	2	D	0.100	0.060	0.200	0.127	0.130	0.977	0.120	4.00	1.03
366	2	C	0.100	0.090	0.200	0.082	0.267	0.307	0.047	5.00	1.74
367	2	E	0.100	0.030	0.200	0.105	0.241	0.436	0.390	6.00	2.08
368	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.120	7.00	1.90
369	4	D	0.250	0.160	0.800	0.158	0.113	1.398	0.120	6.00	1.63
370	4	A	0.250	0.400	0.800	0.149	0.084	1.774	0.120	6.00	1.40
371	13	F	0.350	0.0	0.900	0.106	0.183	0.579	0.117	14.00	4.05
372	7	C	0.300	0.180	0.900	0.158	0.113	1.398	0.230	6.00	1.63
373	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	6.00	1.63
374	6	C	0.400	0.300	1.000	0.158	0.113	1.398	0.230	6.00	1.63
375	14	F	0.250	0.0	0.900	0.106	0.183	0.579	0.117	14.00	4.05
376	14	F	0.250	0.0	0.900	0.106	0.183	0.579	0.117	14.00	4.05
377	6	B	0.400	0.400	1.000	0.153	0.090	1.700	0.040	11.00	3.18
378	2	E	0.100	0.030	0.200	0.106	0.183	0.579	0.117	24.00	5.83
379	7	B	0.300	0.240	0.900	0.158	0.113	1.398	0.120	9.00	2.60
380	4	E	0.250	0.080	0.800	0.106	0.183	0.579	0.117	8.00	2.17
381	4	C	0.250	0.240	0.800	0.158	0.113	1.398	0.230	9.00	2.60
382	4	C	0.250	0.240	0.800	0.153	0.090	1.700	0.230	2.00	0.54
383	6	C	0.400	0.300	1.000	0.153	0.090	1.700	0.230	19.00	4.62
384	7	F	0.300	0.0	0.900	0.106	0.183	0.579	0.117	19.00	4.62

Table A17. Properties of overland flow elements for Chestnut Branch watershed.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
1	270	1070	13.9	70
2	730	730	16.0	85
3	490	1640	14.9	80
4	500	1520	16.5	85
5	220	1920	13.1	20
6	210	1870	8.8	20
7	430	370	10.6	135
8	790	1050	24.3	150
9	480	450	12.8	65
10	230	850	4.7	25
11	190	850	5.2	45
12	250	470	5.5	70
13	630	1120	16.2	145
14	970	1280	19.9	200
15	750	2870	38.1	145
16	610	300	10.4	25
17	1460	1490	39.5	105
18	1580	300	31.5	115
19	770	300	13.1	55
20	730	2390	34.4	65
21	280	3120	22.3	50
22	1250	1230	24.5	175
23	260	1890	11.2	20
24	390	780	5.6	45
25	680	1660	23.9	65
26	1360	1180	29.3	65
27	710	460	18.5	65
28	490	1080	17.9	50
29	340	5160	47.3	35
30	280	5820	48.2	15
31	740	1120	25.5	40
32	730	770	13.3	50
33	1000	1290	41.5	65
34	1150	1390	29.5	60

Table A17. Continued.

Element Number	Length (ft)	Downstream Node Width (ft)	Area (acres)	Relief (ft)
35	1190	410	36.3	55
36	1020	480	16.0	70
37	1220	360	24.2	60
38	400	1030	11.2	60
39	920	390	21.8	65
40	750	1420	20.9	55
41	430	2330	23.4	40
42	510	1130	14.4	30
43	770	1200	26.0	45
44	310	1420	13.1	50
45	530	1420	16.1	55
46	340	2060	21.7	40
47	220	1060	5.3	25
48	440	1000	7.9	40
49	100	400	0.6	30
50	100	400	0.4	25
51	520	750	10.5	40
52	400	1620	18.7	25
53	490	2370	20.1	25
54	250	500	2.9	45
55	230	500	1.9	35
56	700	1080	16.8	55
57	260	1080	12.2	45
58	230	500	5.8	35
59	390	500	2.1	45

Table A18. Properties of channel flow elements for Chestnut Branch watershed.

Element Number	Length (ft)	Downstream Node Width at 2-Foot Depth (ft)	Relief (ft)	Manning 'n'
1	1070	57	200	0.12
2	450	57	40	0.12
3	280	57	10	0.12
4	1640	57	55	0.12
5	370	57	95	0.12
6	1050	57	45	0.12
7	450	57	15	0.12
8	850	115	15	0.10
9	470	57	20	0.12
10	1120	57	45	0.12
11	1280	57	30	0.12
12	300	115	5	0.10
13	1490	115	30	0.10
14	300	115	5	0.10
15	300	115	5	0.10
16	1230	57	95	0.12
17	1890	57	55	0.12
18	780	115	15	0.10
19	1660	115	20	0.10
20	1180	115	20	0.10
21	460	115	10	0.10
22	1080	115	10	0.10
23	1120	115	65	0.10
24	770	115	20	0.10
25	1290	115	25	0.10
26	1390	115	25	0.10
27	410	115	5	0.10
28	480	115	5	0.10
29	360	115	5	0.10
30	1030	115	15	0.08
31	390	115	5	0.08
32	1130	57	50	0.10
33	1200	57	40	0.10
34	1420	115	20	0.08

Table A18. Continued.

Element Number	Length (ft)	Downstream Node Width at 2-Foot Depth (ft)	Relief (ft)	Manning 'n'
35	1060	57	60	0.10
36	1000	57	40	0.10
37	400	115	5	0.08
38	750	115	30	0.10
39	1620	115	45	0.10
40	500	115	5	0.07
41	1080	57	60	0.10
42	500	115	5	0.07

Appendix B

Listing of Fortran Program Statements for the FESHM

The following program listing contains all subroutines referred to in Chapter IV with the exception of subroutine GELB which can be obtained from IBM's Scientific Subroutine Program Package.

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      COMMON/BLK1/PRECIP(4,50),STO,AFAC(163),FC(163),REHRU(163,4,80),K   FEM00001
     1IHRU(163),STOMAX(163),CEXP(163),DAILPC(4,30),GINDEX(12),EVP(12)     FEM00002
     2,DEPSTO(163),ACCDP(163),SLOHRU(163)                                 FEM00003
      COMMON/BLK2/REFE(90,60),NRGAGE(80)                                  FEM00004
      COMMON/BLK3/QOUT(20,1100),QCONF(3600,7),WIDINF(20),RCFP(20)         FEM00005
      COMMON/BLK5/RCLU(25),FHRU(90,60),LANDU(163),NHRU(90),IHRU(90,60)    FEM00006
     1,DSLU(25)                                                           FEM00007
      COMMON/BLK6/NODE1(18),NCONF1(18),NCONF2(18)                         FEM00008
      COMMON/BLK9/NOPRIN,SMCWS,NSECR,PCINTH,DTO,DTC,NSECC,NTBLHS,NTBLPE,FEM00009
     1NTELES,NDHRUS,NLANUS,NGAGES,NHOURR,INTPCS,NSTART,MONTH,NDAY,NYEAR,FEM00010
     2NPCINT,INTPCM,NTSS,NSTRPS,NSSHED,NELEM,NZIP,NE,NN,NCPRIN,NHOURC,NDFEM00011
     3AMS,NTSSX,LHSSPS,NECHAN,KDAM                                        FEM00012
      COMMON/BLK10/FAW(163),FGW(163),DEPTH(163),AFLU(25)                  FEM00013
      COMMON/BLK13/NPOVER(40),NPCHAN(40),NPSTRP(40,40)                    FEM00014
      NZIP=1                                                              FEM00015
      CALL INPUT                                                          FEM00016
      CALL EXCESS                                                         FEM00017
      NZIP=8                                                              FEM00018
      CALL OUTPUT(I,K,NTIME,NPRINC,NHEAD)                                 FEM00019
      NELEM=0                                                             FEM00020
      DO 85 NSSHED=1,NTSS                                                 FEM00021
      CALL OVERL                                                          FEM00022
   85 CALL CHANL                                                          FEM00023
      STOP                                                                FEM00024
      END                                                                 FEM00025
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      SUBROUTINE INPUT
      COMMON/BLK1/PRECIP(4,50),STO,AFAC(163),FC(163),REHRU(163,4,80),K
     1IHRU(163),STOMAX(163),CEXP(163),DAILPC(4,30),GINDEX(12),EVP(12)
     2,DEPSTO(163),ACCDP(163),SLOHRU(163)
      COMMON/BLK2/REFE(90,60),NRGAGE(80)
      COMMON/BLK4/XLEN(10),TWIDTH(11),RQ(10),AO(11),QO(11),AA(11),QQ(11)
     1,AREA(10),VV(11),DD(11)
      COMMON/BLK5/RCLU(25),FHRU(90,60),LANDU(163),NHRU(90),IHRU(90,60)
     1,DSLU(25)
      COMMON/BLK6/NODE1(18),NCONF1(18),NCONF2(18)
      COMMON/BLK8/SLOPE(10),RCOEF(10),RELIEF(10)
      COMMON/BLK9/NOPRIN,SMCWS,NSECR,PCINTH,DTO,DTC,NSECC,NTBLHS,NTBLPE,
     1NTELES,NDHRUS,NLANUS,NGAGES,NHOURR,INTPCS,NSTART,MONTH,NDAY,NYEAR,
     2NPCINT,INTPCM,NTSS,NSTRPS,NSSHED,NELEM,NZIP,NE,NN,NCPRIN,NHOURC,ND
     3AMS,NTSSX,LHSSPS,NECHAN,KDAM
      COMMON/BLK10/FAW(163),FGW(163),DEPTH(163),AFLU(25)
      COMMON/BLK11/NESTRP(20)
      COMMON/BLK13/NPOVER(40),NPCHAN(40),NPSTRP(40,40)
      COMMON/BLK14/AREDAM(2,10),XLENDM(2),NLEVLS(2),VOLD(2,10),QQD(2,10)
      GO TO (99,98,97,96,95),NZIP
C***********DATA SET NUMBER 1:  DESCRIPTION OF OUTPUT TABLES***********
C--------IF NTBLHS=1 TABLE LISTING HRU'S AND DESCRIPTIVE CHARACTERISTICS
C           IS PRINTED; IF NTBLHS=0 IT IS NOT
C--------IF NTBLPE=1 TABLE LISTING PRECIPITATION AND PRECIPITATION
C           EXCESS FOR BOTH HRU'S AND ELEMENTS IS PRINTED; IF NTBLPE=0
C           IT IS NOT
C--------NOPRIN = TIME INTERVAL AT WHICH OVERLAND FLOW OUTPUT IS
C           DISPLAYED
C--------NCPRIN = TIME INTERVAL AT WHICH CHANNEI FLOW OUTPUT IS
C           DISPLAYED
99    READ(3,10)NTBLHS,NTBLPE,NOPRIN,NCPRIN
10    FORMAT(2I5,2I10)
C--------NPOVER = PRINT CODE CONTROLLING OVERLAND FLOW OUTPUT FOR
C           A GIVEN SUB-SHED
C             NPOVER=0; NO OUTPUT
C                   =1; OUTPUT FOR BOTTOM NODES OF STRIPS ONLY
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C                    =2; OUTPUT AT ALL NODES OF SELECTED STRIPS          FEM00062
C                        FOR WHICH ADDITIONAL CODES MUST BE READ         FEM00063
      READ(3,100)(NPOVER(K),K=1,40)                                      FEM00064
100   FORMAT(40I2)                                                       FEM00065
C--------NPCHAN = PRINT CODE CONTROLLING CHANNEL FLOW OUTPUT FOR         FEM00066
C            A GIVEN SUB-SHED                                            FEM00067
C              NPCHAN=0; NO OUTPUT                                       FEM00068
C                    =1; OUTPUT FOR BOTTOM NODE OF CHANNEL ONLY          FEM00069
C                    =2; OUTPUT AT ALL NODES OF THE CHANNEL              FEM00070
      READ(3,100)(NPCHAN(K),K=1,40)                                      FEM00071
      GO TO 40                                                           FEM00072
C**********DATA SET NUMBER 2:  DESCRIPTION OF THE STORM EVENT***********FEM00073
C--------NGAGES = NUMBER OF RAIN GAGES IN THE WATERSHED                  FEM00074
C--------NHOURR = NUMBER OF HOURS OF RAINFALL                            FEM00075
C--------INTPCS = TIME INTERVAL OF PRECIPITATION RECORDS                 FEM00076
C--------SMCWS = ANTECEDENT SOIL MOISTURE AS A FRACTION OF               FEM00077
C            FIELD CAPACITY FOR THE ENTIRE WATERSHED                     FEM00078
95    READ(4,7)NGAGES,NHOURR,NHOURC,INTPCS,SMCWS                         FEM00079
7     FORMAT(4I10,F10.2)                                                 FEM00080
C--------NSTART = STARTING TIME OF STORM                                 FEM00081
C--------MONTH = MONTH IN WHICH STORM OCCURS                             FEM00082
C--------NDAY = DAY IN WHICH STORM OCCURS                                FEM00083
C--------NYEAR = YEAR IN WHICH STORM OCCURS                              FEM00084
      READ(4,29)NSTART,MONTH,NDAY,NYEAR                                  FEM00085
29    FORMAT(4I5)                                                        FEM00086
C--------NSECR = NUMBER OF SECONDS OF RAINFALL                           FEM00087
      NSECR=3600*NHOURR                                                  FEM00088
C--------NPCINT = NUMBER OF PRECIPITATION INTERVALS FOR THE STORM        FEM00089
      NPCINT=NSECR/INTPCS                                                FEM00090
C--------INTPCM = PRECIPITATION TIME INTERVAL IN MINUTES                 FEM00091
      INTPCM=INTPCS/60                                                   FEM00092
C--------PCINTH = PRECIPITATION TIME INTERVAL IN HOURS                   FEM00093
      PCINTH=INTPCM/60.0                                                 FEM00094
      NSECC=3600*NHOURC                                                  FEM00095
      DO 12 I=1,NGAGES                                                   FEM00096
C--------PRECIP = PRECIPITATION RECORDS FOR EACH RAIN GAGE AND           FEM00097
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```
C             TIME INTERVAL                                                 FEM00098
12       READ(4,9)(PRECIP(I,JX),JX=1,NPCINT)                                 FEM00099
9        FORMAT(8F10.5)                                                      FEM00100
         IF(NGAGES.EQ.1)GO TO 50                                             FEM00101
C--------NRGAGE = NUMBER OF RAIN GAGE AFFECTING A GIVEN ELEMENT;            FEM00102
C             NOT NECESSARY WHEN NGAGES=1                                    FEM00103
         READ(4,8)(NRGAGE(L),L=1,80)                                         FEM00104
8        FORMAT(80I1)                                                        FEM00105
         GO TO 52                                                            FEM00106
50       DO 53 L=1,80                                                        FEM00107
53       NRGAGE(L)=1                                                         FEM00108
52       READ(4,55)(GINDEX(I),I=1,12)                                        FEM00109
         IF(SMCWS.GT.0.0)GO TO 54                                            FEM00110
         READ(4,55)(EVP(I),I=1,12)                                           FEM00111
55       FORMAT(12F6.2)                                                      FEM00112
         DO 58 J=1,NGAGES                                                    FEM00113
         READ(4,56)(DAILPC(J,I),I=1,30)                                      FEM00114
56       FORMAT(10F8.5)                                                      FEM00115
58       CONTINUE                                                            FEM00116
C*************DATA SET NUMBER 3:  INDEXING CONTROL FOR HRUS*************FEM00117
C--------NTSS = NUMBER OF SUB-SHEDS IN THE WATERSHED                         FEM00118
C--------NTELES = TOTAL NUMBER OF ELEMENTS IN THE WATERSHED                  FEM00119
C--------NDHRUS = NUMBER OF DIFFERENT TYPES OF HRU'S IN THE WATERSHED        FEM00120
C--------NLANUS=NUMBER OF DIFFERENT TYPES OF LAND USES IN THE WATERSHED FEM00121
54       READ(5,1)NTSS,NTELES,NDHRUS,NLANUS                                  FEM00122
1        FORMAT(4I10)                                                        FEM00123
         DO 6 I=1,NTELES                                                     FEM00124
C--------NHRU = NUMBER OF HRU'S IN A GIVEN ELEMENT                           FEM00125
         READ(5,3)NHRU(I)                                                    FEM00126
3        FORMAT(I10)                                                         FEM00127
         N=NHRU(I)                                                           FEM00128
C--------IHRU = IDENTIFYING NUMBER OF AN HRU FOR A GIVEN ELEMENT            FEM00129
         READ(5,4)(IHRU(I,J),J=1,N)                                          FEM00130
4        FORMAT(10I8)                                                        FEM00131
C--------FHRU = AREA OF AN HRU AS A FRACTION OF A GIVEN ELEMENT             FEM00132
6        READ(5,5)(FHRU(I,J),J=1,N)                                          FEM00133
```

```
5     FORMAT(10F8.4)                                                    FEM00134
C***********DATA SET NUMBER 4:  DESCRIPTION OF HRU PROPERTIES**********FEM00135
C--------AFLU = VALUE OF 'A' IN HOLTAN'S EQUATION FOR A GIVEN LAND USE  FEM00136
C           TYPE                                                        FEM00137
      READ(5,33) (AFLU(I),I=1,NLANUS)                                   FEM00138
C--------DSLU = POTENTIAL DEPRESSION STORAGE FOR A GIVEN ELEMENT        FEM00139
      READ(5,33) (DSLU(I),I=1,NLANUS)                                   FEM00140
C--------RCLU = ROUGHNESS COEFFICIENT IN MANNING'S EQUATION FOR A GIVEN FEM00141
C           LAND USE TYPE                                               FEM00142
      READ(5,33) (RCLU(I),I=1,NLANUS)                                   FEM00143
33    FORMAT(8F10.2)                                                    FEM00144
      DO 21 I=1,NDHRUS                                                  FEM00145
C--------LANDU = LAND USE NUMBER FOR A PARTICULAR HRU                   FEM00146
C--------FAW = AVAILABLE WATER POTENTIAL AS A FRACTION OF SOIL PROFILE  FEM00147
C--------FGW = GRAVITY WATER POTENTIAL AS A FRACTION OF SOIL PROFILE    FEM00148
C--------FC = FINAL INFILTRATION RATE                                   FEM00149
C--------DEPTH = DEPTH OF THE 'A' HORIZON                               FEM00150
C--------SLOHRU = SLOPE CLASS FOR EACH HRU                              FEM00151
21    READ(5,22)LANDU(I),FAW(I),FGW(I),FC(I),DEPTH(I),SLOHRU(I)         FEM00152
22    FORMAT(I10,3F10.3,F10.0,9X,A1)                                    FEM00153
C*****DATA SET NUMBER 5:  TIME INCREMENTS AND ORDERING OF CHANNELS*****FEM00154
C--------DTO = TIME INCREMENT FOR OVERLAND FLOW CALCULATIONS IN SECONDS FEM00155
C--------DTC = TIME INCREMENT FOR CHANNEL FLOW CALCULATIONS IN SECONDS  FEM00156
      READ(5,51)DTO,DTC                                                 FEM00157
51    FORMAT(2F10.0)                                                    FEM00158
      IF(NTSS.EQ.1)GO TO 40                                             FEM00159
      NTSSX=NTSS+1                                                      FEM00160
C--------BOUNDARY CONDITION CODE FOR CHANNEL; NOT NECESSARY WHEN NTSS=1 FEM00161
C             NODE1=0; DISCHARGE IS ZERO AT UPSTREAM NODE OF CHANNEL    FEM00162
C                  =1; UPSTREAM NODE OF CHANNEL IS DOWNSTREAM FROM A    FEM00163
C                      STREAM CONFLUENCE                                FEM00164
C                  =2; TOTAL DISCHARGE FROM WATERSHED IS SUM OF         FEM00165
C                      DISCHARGE FROM LAST TWO SUBSHEDS                 FEM00166
      READ(5,25) (NODE1(I),I=1,NTSSX)                                   FEM00167
25    FORMAT(16I5)                                                      FEM00168
      DO 30 I=1,NTSSX                                                   FEM00169
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      IF(NODE1(I).EQ.0)GO TO 30                                         FEM00170
C--------NCONF1 = NUMBER OF FIRST CHANNEL ENTERING CONFLUENCE           FEM00171
C--------NCONF2 = NUMBER OF SECOND CHANNEL ENTERING CONFLUENCE          FEM00172
      READ(5,35)NCONF1(I),NCONF2(I)                                     FEM00173
35    FORMAT(2I5)                                                       FEM00174
30    CONTINUE                                                          FEM00175
      GO TO 40                                                          FEM00176
C********DATA SET NUMBER 6:  OVERLAND FLOW ELEMENT DESCRIPTORS**********FEM00177
C--------NSTRPS = NUMBER OF STRIPS IN A GIVEN OVERLAND FLOW PLANE       FEM00178
C--------LHSSPS = NUMBER OF STRIPS ON LEFT SIDE OF CHANNEL              FEM00179
C--------NECHAN = NUMBER OF CHANNEL ELEMENTS IN THE SUBSHED             FEM00180
98    READ(5,89)NSTRPS,LHSSPS,NECHAN                                    FEM00181
89    FORMAT(3I5)                                                       FEM00182
      GO TO 40                                                          FEM00183
97    DO 70 I=1,NE                                                      FEM00184
C--------XLEN = LENGTH OF THE ELEMENT IN A GIVEN STRIP                  FEM00185
C--------RELIEF = RELIEF OF THE ELEMENT IN A GIVEN STRIP                FEM00186
C--------AREA = AREA, IN ACRES, OF THE ELEMENT IN A GIVEN STRIP         FEM00187
C--------TWIDTH = TOP WIDTH OF THE DOWNSTREAM NODE OF THE ELEMENT IN A  FEM00188
C             GIVEN STRIP                                               FEM00189
C--------NDAMS = NUMBER OF DAMS IN A GIVEN STRIP (SAME VALUE FOR EACH   FEM00190
C             ELEMENT IN THE STRIP)                                     FEM00191
70    READ(5,75)XLEN(I),RELIEF(I),AREA(I),TWIDTH(I+1),NDAMS             FEM00192
75    FORMAT(2F10.0,F10.1,F10.0,I10)                                    FEM00193
      IF(NDAMS.EQ.0)GO TO 120                                           FEM00194
C*****DATA SET NUMBER 7:  O-F FLOOD-DETENTION STRUCTURE PROPERTIES******FEM00195
      DO 110 J=1,NDAMS                                                  FEM00196
C--------AREDAM = AREA, IN ACRES, OF A FLOOD-DETENTION STRUCTURE        FEM00197
C             DRAINAGE AREA LOCATED WITHIN A GIVEN ELEMENT              FEM00198
C--------NLEVLS = NUMBER OF VOLUME-DISCHARGE LEVELS DESCRIBING          FEM00199
C             THE DISCHARGE HYDROGRAPH OF THE FLOOD-DETENTION STRUCTURE FEM00200
      READ(5,111)AREDAM(J,1),NLEVLS(J)                                  FEM00201
111   FORMAT(F10.1,I10)                                                 FEM00202
      NLS=NLEVLS(J)                                                     FEM00203
C--------VOLD = VOLUME, IN ACRE-FEET, OF THE DETENTION POND FOR         FEM00204
C             A GIVEN VOLUME-DISCHARGE LEVEL                            FEM00205
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      READ(5,114) (VOLD(J,K),K=1,NLS)                                   FEM00206
114   FORMAT(8F10.0)                                                    FEM00207
C---------QQD = DISCHARGE FROM THE FLOOD-DETENTION STRUCTURE FOR        FEM00208
C              A GIVEN VOLUME-DISCHARGE LEVEL                           FEM00209
      READ(5,114) (QQD(J,K),K=1,NLS)                                    FEM00210
110   CONTINUE                                                          FEM00211
120   GO TO 40                                                          FEM00212
C*********DATA SET NUMBER 8:  CHANNEL FLOW ELEMENT DESCRIPTORS**********FEM00213
96    DO 90 K=1,NE                                                      FEM00214
C---------XLEN = LENGTH OF THE ELEMENT IN THE CHANNEL                   FEM00215
C---------RELIEF = RELIEF OF THE ELEMENT IN THE CHANNEL                 FEM00216
C---------RCOEF = ROUGHNESS COEFFICIENT OF THE ELEMENT IN THE CHANNEL   FEM00217
C---------TWIDTH = TOP WIDTH OF THE DOWNSTREAM NODE OF THE ELEMENT      FEM00218
C              IN THE CHANNEL FOR A 2-FOOT DEPTH                        FEM00219
      READ(5,71)XLEN(K),RELIEF(K),RCOEF(K),TWIDTH(K+1),KDAM             FEM00220
   71 FORMAT(F10.0,F10.0,F10.4,F10.2,I10)                               FEM00221
      IF(KDAM.EQ.0)GO TO 90                                             FEM00222
C*****DATA SET NUMBER 9:  C-F FLOOD-DETENTION STRUCTURE PROPERTIES******FEM00223
      READ(5,115)NLEVLS(1)                                              FEM00224
115   FORMAT(I10)                                                       FEM00225
      NLS=NLEVLS(1)                                                     FEM00226
      READ(5,114) (VOLD(1,K),K=1,NLS)                                   FEM00227
      READ(5,114) (QQD(1,K),K=1,NLS)                                    FEM00228
90    CONTINUE                                                          FEM00229
40    RETURN                                                            FEM00230
      END                                                               FEM00231
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      SUBROUTINE EXCESS                                                   FEM00232
      COMMON/BLK1/PRECIP(4,50),STO,AFAC(163),FC(163),REHRU(163,4,80),K   FEM00233
     1IHRU(163),STOMAX(163),CEXP(163),DAILPC(4,30),GINDEX(12),EVP(12)    FEM00234
     2,DEPSTO(163),ACCDP(163),SLOHRU(163)                                 FEM00235
      COMMON/BLK2/REFE(90,60),NRGAGE(80)                                  FEM00236
      COMMON/BLK5/RCLU(25),FHRU(90,60),LANDU(163),NHRU(90),IHRU(90,60)   FEM00237
     1,DSLU(25)                                                           FEM00238
      COMMON/BLK6/NODE1(18),NCONF1(18),NCONF2(18)                         FEM00239
      COMMON/BLK9/NOPRIN,SMCWS,NSECR,PCINTH,DTO,DTC,NSECC,NTBLHS,NTBLPE,FEM00240
     1NTELES,NDHRUS,NLANUS,NGAGES,NHOURR,INTPCS,NSTART,MONTH,NDAY,NYEAR,FEM00241
     2NPCINT,INTPCM,NTSS,NSTRPS,NSSHED,NELEM,NZIP,NE,NN,NCPRIN,NHOURC,NDFEM00242
     3AMS,NTSSX,LHSSPS,NECHAN,KDAM                                        FEM00243
      COMMON/BLK10/FAW(163),FGW(163),DEPTH(163),AFLU(25)                  FEM00244
      DIMENSION SLOPCL(6),SLOPCO(6)                                       FEM00245
      DATA SLOPCL/'A','B','C','D','E','F'/                                FEM00246
      DATA SLOPCO/1.00,0.80,0.60,0.40,0.20,0.00/                          FEM00247
      NZIP=5                                                              FEM00248
      CALL INPUT                                                          FEM00249
      NZIP=7                                                              FEM00250
      CALL OUTPUT(I,K,NTIME,NPRINC,NHEAD)                                 FEM00251
      DO 21 I=1,NDHRUS                                                    FEM00252
      ACCDP(I)=0.0                                                        FEM00253
      KIHRU(I)=0                                                          FEM00254
      DO 22 K=1,6                                                         FEM00255
      IF(SLOPCL(K).EQ.SLOHRU(I))GO TO 24                                  FEM00256
   22 CONTINUE                                                            FEM00257
   24 J=LANDU(I)                                                          FEM00258
      AFAC(I)=AFLU(J)                                                     FEM00259
      DEPSTO(I)=SLOPCO(K)*DSLU(J)                                         FEM00260
      IF(AFAC(I).LE.0.0)GO TO 20                                          FEM00261
      CEXP(I)=FAW(I)/FGW(I)                                               FEM00262
      GO TO 23                                                            FEM00263
   20 CEXP(I)=0.0                                                         FEM00264
   23 STOMAX(I)=(FAW(I)+FGW(I))*DEPTH(I)                                  FEM00265
   21 CONTINUE                                                            FEM00266
      IF(NTBLHS.EQ.0)GO TO 60                                             FEM00267
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      NZIP=2                                                            FEM00268
      CALL OUTPUT(I,K,NTIME,NPRINC,NHEAD)                               FEM00269
60    DO 120 I=1,NGAGES                                                 FEM00270
      DO 103 L=1,NTELES                                                 FEM00271
      IF(NRGAGE(L).NE.I)GO TO 103                                       FEM00272
      N=NHRU(L)                                                         FEM00273
      DO 102 M=1,N                                                      FEM00274
      MN=IHRU(L,M)                                                      FEM00275
      KIHRU(MN)=I                                                       FEM00276
102   CONTINUE                                                          FEM00277
103   CONTINUE                                                          FEM00278
55    DO 17 K=1,NDHRUS                                                  FEM00279
      IF(KIHRU(K).NE.I) GO TO 17                                        FEM00280
      IF(AFAC(K).LE.0.0)GO TO 58                                        FEM00281
      SMC=SMCWS                                                         FEM00282
      IF(SMCWS.GT.0.0)GO TO 56                                          FEM00283
      DPAW=FAW(K)*DEPTH(K)                                              FEM00284
      XLEVEL=0.5*DPAW                                                   FEM00285
      STOI=STOMAX(K)-XLEVEL                                             FEM00286
      DO 1 L=1,30                                                       FEM00287
      XLEVEL=XLEVEL+DAILPC(I,L)                                         FEM00288
      IF(XLEVEL.GE.STOMAX(K))XLEVEL=STOMAX(K)                           FEM00289
      IF(XLEVEL.GE.DPAW)GO TO 52                                        FEM00290
      WOUT=0.0                                                          FEM00291
      GO TO 54                                                          FEM00292
52    DEPSEP=24.0*FC(K)                                                 FEM00293
      IF(L.EQ.30)DEPSEP=FLOAT(NSTART-1)*DEPSEP/24.0                     FEM00294
      IF(DEPSEP.GT.(XLEVEL-DPAW))GO TO 53                               FEM00295
      WOUT=DEPSEP                                                       FEM00296
      GO TO 54                                                          FEM00297
53    WOUT=XLEVEL-DPAW                                                  FEM00298
54    ADJLEV=XLEVEL-WOUT                                                FEM00299
      EVPOR=EVP(MONTH)                                                  FEM00300
      IF((NDAY+L).LE.30) EVPOR=EVP(MONTH-1)                             FEM00301
      WOUT=((ADJLEV/DPAW)*EVPOR)/30.0                                   FEM00302
      IF(ADJLEV.GT.DPAW) WOUT=EVPOR/30.0                                FEM00303
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      IF(DAILPC(I,L).GT.0.0) WOUT=WOUT/2.0                               FEM00304
      IF(L.EQ.30) WOUT=FLOAT(NSTART-1)*WOUT/24.0                         FEM00305
      XLEVEL=ADJLEV-WOUT                                                 FEM00306
1     STOI=STOMAX(K)-XLEVEL                                              FEM00307
      SMC=XLEVEL/DPAW                                                    FEM00308
      IF(SMC.LE.0.0) SMC=0.0                                             FEM00309
C     WRITE(6,59) K,SMC                                                  FEM00310
59    FORMAT(I10,F10.3)                                                  FEM00311
      GO TO 57                                                           FEM00312
56    STOI=STOMAX(K)-(SMC*FAW(K)*DEPTH(K))                               FEM00313
      IF(STOI.LT.0.0) STOI=0.0                                           FEM00314
57    STO=STOI                                                           FEM00315
58    DO 12 J=1,NPCINT                                                   FEM00316
      IF(AFAC(K).LE.0.0) GO TO 41                                        FEM00317
      CALL HOLTAN(K,I,J,PCINTH,MONTH)                                    FEM00318
      GO TO 12                                                           FEM00319
41    REHRU(K,I,J)=PRECIP(I,J)                                           FEM00320
      IF(ACCDP(K).GE.DEPSTO(K)) GO TO 12                                 FEM00321
      REHRU(K,I,J)=PRECIP(I,J)-DEPSTO(K)+ACCDP(K)                        FEM00322
      IF(REHRU(K,I,J).LE.0.0) REHRU(K,I,J)=0.0                           FEM00323
      ACCDP(K)=ACCDP(K)+PRECIP(I,J)                                      FEM00324
      IF(ACCDP(K).GT.DEPSTO(K)) ACCDP(K)=DEPSTO(K)                       FEM00325
12    CONTINUE                                                           FEM00326
17    CONTINUE                                                           FEM00327
120   CONTINUE                                                           FEM00328
      DO 14 I=1,NGAGES                                                   FEM00329
      DO 31 M=1,NDHRUS                                                   FEM00330
31    KIHRU(M)=0                                                         FEM00331
      DO 13 L=1,NTELES                                                   FEM00332
      IF(NRGAGE(L).NE.I) GO TO 13                                        FEM00333
      K=NHRU(L)                                                          FEM00334
      DO 101 M=1,K                                                       FEM00335
      MN=IHRU(L,M)                                                       FEM00336
      KIHRU(MN)=I                                                        FEM00337
101   CONTINUE                                                           FEM00338
      IF(NRGAGE(L).NE.I) GO TO 13                                        FEM00339
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      DO 15 J=1,NPCINT                                                  FEM00340
      REFE(L,J)=0.0                                                     FEM00341
      MHRU=NHRU(L)                                                      FEM00342
      DO 16 N=1,MHRU                                                    FEM00343
      K=IHRU(L,N)                                                       FEM00344
      REFE(L,J)=REFE(L,J)+REHRU(K,I,J)*FHRU(L,N)                        FEM00345
   16 CONTINUE                                                          FEM00346
   15 CONTINUE                                                          FEM00347
   13 CONTINUE                                                          FEM00348
      IF(NTBLPE.EQ.0)GO TO 14                                           FEM00349
      NZIP=1                                                            FEM00350
      CALL OUTPUT(I,K,NTIME,NPRINC,NHEAD)                               FEM00351
   14 CONTINUE                                                          FEM00352
      RETURN                                                            FEM00353
      END                                                               FEM00354
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      SUBROUTINE HOLTAN(K,I,J,PCINTH,MONTH)                            FEM00355
      COMMON/BLK1/PRECIP(4,50),STO,AFAC(163),FC(163),REHRU(163,4,80),K FEM00356
     1IHRU(163),STOMAX(163),CEXP(163),DAILPC(4,30),GINDEX(12),EVP(12)  FEM00357
     2,DEPSTO(163),ACCDP(163),SLOHRU(163)                              FEM00358
      COMMON/BLK10/FAW(163),FGW(163),DEPTH(163),AFLU(25)               FEM00359
      RECMAX=FC(K)*PCINTH                                              FEM00360
      STANWT=PRECIP(I,J)+ACCDP(K)                                      FEM00361
      IF(STO.EQ.0.0.AND.FC(K).EQ.0.0)GO TO 9                           FEM00362
      IF(STO.GT.0.0)GO TO 77                                           FEM00363
      XINF=RECMAX                                                      FEM00364
      GO TO 8                                                          FEM00365
77    F1=GINDEX(MONTH)*AFAC(K)*STO**CEXP(K)+FC(K)                      FEM00366
      XP=STO-STANWT                                                    FEM00367
      F2=FC(K)                                                         FEM00368
      IF(XP.GT.0.0)F2=GINDEX(MONTH)*AFAC(K)*XP**CEXP(K)+FC(K)          FEM00369
      FA=(F1+F2)/2.0                                                   FEM00370
      TA=STANWT/FA                                                     FEM00371
      EPS1=0.0                                                         FEM00372
      IF(TA.LE.PCINTH)GO TO 2                                          FEM00373
1     EPS1=EPS1+0.01                                                   FEM00374
      TESTIN=STANWT-EPS1                                               FEM00375
      XXP=STO-TESTIN                                                   FEM00376
      F2=FC(K)                                                         FEM00377
      IF(XXP.GT.0.0)F2=GINDEX(MONTH)*AFAC(K)*XXP**CEXP(K)+FC(K)        FEM00378
      FA=(F1+F2)/2.0                                                   FEM00379
      TA=TESTIN/FA                                                     FEM00380
      IF(TA.GT.PCINTH)GO TO 1                                          FEM00381
      XINF=TESTIN                                                      FEM00382
      GO TO 7                                                          FEM00383
2     CONTINUE                                                         FEM00384
      XINF=STANWT                                                      FEM00385
      IF(XINF.LE.STO)GO TO 7                                           FEM00386
      XINF=STO                                                         FEM00387
      STO=0.0                                                          FEM00388
      GO TO 8                                                          FEM00389
9     XINF=0.0                                                         FEM00390
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      REHRU(K,I,J)=STANWT-DEPSTO(K)                                     FEM00391
      IF(REHRU(K,I,J).LE.0.0) REHRU(K,I,J)=0.0                          FEM00392
      GO TO 75                                                          FEM00393
7     STO=STO-XINF                                                      FEM00394
8     REHRU(K,I,J)=STANWT-(XINF+DEPSTO(K))                              FEM00395
      IF(REHRU(K,I,J).LT.0.0) REHRU(K,I,J)=0.0                          FEM00396
      IF(STO.LT.0.0) STO=0.0                                            FEM00397
      AVM=FAW(K)*DEPTH(K)                                               FEM00398
      GRM=STOMAX(K)-AVM                                                 FEM00399
      WATER=STOMAX(K)-STO                                               FEM00400
      GRWAT=AVM-WATER                                                   FEM00401
      IF(GRWAT.GT.0.0) GO TO 75                                         FEM00402
      IF(PRECIP(I,J).GE.RECMAX) GO TO 75                                FEM00403
      RECOV=RECMAX-PRECIP(I,J)                                          FEM00404
      IF(RECOV.GT.ABS(GRWAT)) RECOV=ABS(GRWAT)                          FEM00405
      STO=STO+RECOV                                                     FEM00406
      IF(STO.GT.GRM) STO=GRM                                            FEM00407
75    REMAIN=STANWT-XINF                                                FEM00408
      IF(REMAIN.LT.DEPSTO(K)) GO TO 70                                  FEM00409
      ACCDP(K)=DEPSTO(K)                                                FEM00410
      GO TO 71                                                          FEM00411
70    ACCDP(K)=REMAIN                                                   FEM00412
71    RETURN                                                            FEM00413
      END                                                               FEM00414
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      SUBROUTINE OUTPUT(I,K,NTIME,NPRINC,NHEAD)                         FEM00415
      COMMON/BLK1/PRECIP(4,50),STO,AFAC(163),FC(163),REHRU(163,4,80),K  FEM00416
     1IHRU(163),STOMAX(163),CEXP(163),DAILPC(4,30),GINDEX(12),EVP(12)   FEM00417
     2,DEPSTO(163),ACCDP(163),SLOHRU(163)                               FEM00418
      COMMON/BLK2/REFE(90,60),NRGAGE(80)                                FEM00419
      COMMON/BLK3/QOUT(20,1100),QCONF(3600,7),WIDINF(20),RCFP(20)       FEM00420
      COMMON/BLK4/XLEN(10),TWIDTH(11),RQ(10),AO(11),QO(11),AA(11),QQ(11)FEM00421
     1,AREA(10),VV(11),DD(11)                                           FEM00422
      COMMON/BLK5/RCLU(25),FHRU(90,60),LANDU(163),NHRU(90),IHRU(90,60)  FEM00423
     1,DSLU(25)                                                         FEM00424
      COMMON/BLK6/NODE1(18),NCONF1(18),NCONF2(18)                       FEM00425
      COMMON/BLK8/SLOPE(10),RCOEF(10),RELIEF(10)                        FEM00426
      COMMON/BLK9/NOPRIN,SMCWS,NSECR,PCINTH,DTO,DTC,NSECC,NTBLHS,NTBLPE,FEM00427
     1NTELES,NDHRUS,NLANUS,NGAGES,NHOURR,INTPCS,NSTART,MONTH,NDAY,NYEAR,FEM00428
     2NPCINT,INTPCM,NTSS,NSTRPS,NSSHED,NELEM,NZIP,NE,NN,NCPRIN,NHOURC,NDFEM00429
     3AMS,NTSSX,LHSSPS,NECHAN,KDAM                                      FEM00430
      COMMON/BLK10/FAW(163),FGW(163),DEPTH(163),AFLU(25)                FEM00431
      COMMON/BLK11/NESTRP(20)                                           FEM00432
      COMMON/BLK13/NPOVER(40),NPCHAN(40),NPSTRP(40,40)                  FEM00433
      DIMENSION NUMBER(24),QP(200,4),AAP(200,4),VVP(200,4),DDP(200,4    FEM00434
     1)                                                                 FEM00435
      GO TO (99,98,97,96,95,94,93,92,83),NZIP                           FEM00436
93    WRITE(6,401) MONTH,NDAY,NYEAR                                     FEM00437
401   FORMAT(1X,'STORM EVENT--',I2,'/',I2,'/',I2)                       FEM00438
      WRITE(6,402) NSTART                                               FEM00439
402   FORMAT(1X,'STARTING TIME--',I2,':00')                             FEM00440
      NPERCT=IFIX(100.0*SMCWS+0.5)                                      FEM00441
      IF(SMCWS.EQ.0.0)GO TO 501                                         FEM00442
      WRITE(6,403) NPERCT                                               FEM00443
403   FORMAT(1X,'INITIAL MOISTURE CONDITION FOR THE WATERSHED--',I3,'% OFEM00444
     1F FIELD CAPACITY')                                                FEM00445
      GO TO 503                                                         FEM00446
501   WRITE(6,502)                                                      FEM00447
502   FORMAT(1X,'INITIAL MOISTURE CONDITION FOR THE WATERSHED-- DETERMINFEM00448
     1ED INTERNALLY FOR EACH HRU')                                      FEM00449
503   GO TO 101                                                         FEM00450
```

```
98    WRITE(6,23)                                                          FEM00451
23    FORMAT('1',46X,'SUMMARY OF HYDROLOGIC RESPONSE UNITS')              FEM00452
      WRITE(6,24)                                                          FEM00453
24    FORMAT(//2X,'HRU',1X,'LANDUSE',1X,'SLOPE',1X,'MANNINGS',1X,'DEPRESFEM00454
     1SION',1X,'HOLTANS',1X,'FRACTION OF',3X,'FRACTION OF',4X,'EXPONENT'FEM00455
     2,4X,'FINAL INFIL-',3X,'DEPTH OF THE',4X,'MAXIMUM'/3X,'NO',4X,'NO',FEM00456
     33X,'CLASS',5X,'N',6X,'STORAGE',5X,'A',4X,'AVAIL WATER',2X,'GRAVITYFEM00457
     4 WATER',7X,'C',7X,'TRATION RATE',5X,'A HCRIZON',5X,'STORAGE'/'  ')FEM00458
      DO 21 I=1,NDHRUS                                                     FEM00459
      J=LANDU(I)                                                           FEM00460
21    WRITE(6,26)I,LANDU(I),SLOHRU(I),RCLU(J),DEPSTO(I),AFAC(I),FAW(I),FFEM00461
     1GW(I),CEXP(I),FC(I),DEPTH(I),STOMAX(I)                               FEM00462
26    FORMAT(I5,I6,5X,A1,F9.3,3F10.3,3X,F10.3,5X,F10.3,4X,F10.3,5X,F10.2FEM00463
     1,2X,F10.2)                                                           FEM00464
      GO TO 101                                                            FEM00465
99    WRITE(6,30)I                                                         FEM00466
30    FORMAT('1',46X,'PRECIPITATION EXCESS FOR RAINGAGE NUMBER',I2)       FEM00467
      WRITE(6,3) INTPCM                                                    FEM00468
3     FORMAT(///34X,'HRU PRECIPITATION EXCESS FOR EACH',1X,I2,'-MINUTE IFEM00469
     1NCREMENT OF THE STORM')                                              FEM00470
      AINT=NPCINT                                                          FEM00471
      NTAB=AINT/24.0+.99                                                   FEM00472
      NUMTAB=1                                                             FEM00473
13    L=0                                                                  FEM00474
      LH=1                                                                 FEM00475
      DO 100 MN=1,NTAB                                                     FEM00476
      WRITE(6,4)                                                           FEM00477
4     FORMAT(//39X,'PRECIPITATION INCREMENTS FROM THE BEGINNING OF THE SFEM00478
     1TORM')                                                               FEM00479
      DO 5 M=1,24                                                          FEM00480
      L=L+1                                                                FEM00481
5     NUMBER(M)=L                                                          FEM00482
      WRITE(6,33) NUMBER                                                   FEM00483
33    FORMAT(4X,24I5)                                                      FEM00484
      WRITE(6,6)                                                           FEM00485
6     FORMAT(/60X,'PRECIPITATION')                                         FEM00486
```

```
      KH=24*MN                                                          FEM00487
      IF(MN.EQ.NTAB) KH=NPCINT                                          FEM00488
      WRITE(6,7) (PRECIP(I,K),K=LH,KH)                                  FEM00489
7     FORMAT(5X,24F5.2)                                                 FEM00490
      IF(NUMTAB.EQ.2)GO TO 19                                           FEM00491
      WRITE(6,8)                                                        FEM00492
8     FORMAT(/1X,'HRU',52X,'PRECIPITATION EXCESS',50X,'HRU')            FEM00493
      DO 10 J=1,NDHRUS                                                  FEM00494
      IF(KIHRU(J).EQ.0) GO TO 10                                        FEM00495
      WRITE(6,9) J,(REHRU(J,I,K),K=LH,KH)                               FEM00496
      WRITE(6,69) J                                                     FEM00497
10    CONTINUE                                                          FEM00498
9     FORMAT(1X,I3,1X,24F5.2)                                           FEM00499
69    FORMAT('+',125X,I3)                                               FEM00500
      GO TO 100                                                         FEM00501
19    WRITE(6,16)                                                       FEM00502
16    FORMAT(/1X,'ELE',52X,'PRECIPITATION EXCESS',50X,'ELE')            FEM00503
      DO 18 J=1,NTELES                                                  FEM00504
      IF(NRGAGE(J).NE.I) GO TO 18                                       FEM00505
      WRITE(6,17) J,(REFE(J,K),K=LH,KH)                                 FEM00506
17    FORMAT(1X,I3,1X,24F5.2)                                           FEM00507
      WRITE(6,68) J                                                     FEM00508
68    FORMAT('+',125X,I3)                                               FEM00509
18    CONTINUE                                                          FEM00510
100   LH=KH+1                                                           FEM00511
      IF(NUMTAB.EQ.2)GO TO 101                                          FEM00512
      WRITE(6,11) INTPCM                                                FEM00513
11    FORMAT(///32X,'ELEMENT PRECIPITATION EXCESS FOR EACH',1X,I2,'-MINUFEM00514
     1TE INCREMENT OF THE STORM')                                       FEM00515
      NUMTAB=2                                                          FEM00516
      GO TO 13                                                          FEM00517
92    NDTO=IFIX(DTO)                                                    FEM00518
      NDTC=IFIX(DTC)                                                    FEM00519
      WRITE(6,410) NDTO                                                 FEM00520
410   FORMAT('1',1X,'ROUTING TIME INCREMENT FOR OVERLAND FLOW--',I4,1X,'FEM00521
     1SECONDS')                                                         FEM00522
```

```
      WRITE(6,411) NDTC                                                 FEM00523
411   FORMAT(1X,'ROUTING TIME INCREMENT FOR CHANNEL FLOW--',I4,1X,'SECONFEM00524
     1DS')                                                              FEM00525
      GO TO 101                                                         FEM00526
94    IF(NTIME.GT.NPRINC) GO TO 97                                      FEM00527
      IF(NHEAD.EQ.1) GO TO 81                                           FEM00528
      WRITE(6,61) NSSHED                                                FEM00529
61    FORMAT('1',41X,'OVERLAND FLOW INFORMATION FOR SUB-SHED NUMBER',I3)FEM00530
      NHEAD=1                                                           FEM00531
81    WRITE(6,91)                                                       FEM00532
91    FORMAT(//6X,'OVERLAND FLOW',10X,'ELEMENT',7X,'ELEMENT',7X,'ELEMENTFEM00533
     1',4X,'ELEMENT',4X,'ELEMENT',5X,'ELEMENT',12X,'NODE',7X,'NODE'/7X,'FEM00534
     2STRIP NUMBER',11X,'NUMBER',5X,'AREA (ACRES)',5X,'LENGTH',5X,'RELIEFEM00535
     3F',5X,'SLOPE',5X,'MANNING N',10X,'NUMBER',5X,'WIDTH')             FEM00536
      DO 70 I=1,NE                                                      FEM00537
      J=I+1                                                             FEM00538
      IF(I.GT.1) GO TO 29                                               FEM00539
      WRITE(6,25) K,I,AREA(I),XLEN(I),RELIEF(I),SLOPE(I),RCOEF(I),J,TWI FEM00540
     1DTH(J)                                                            FEM00541
25    FORMAT(11X,I2,18X,I2,9X,F7.1,8X,F7.1,4X,F6.1,6X,F5.3,7X,F5.3,14X,IFEM00542
     12,5X,F7.1)                                                        FEM00543
      GO TO 70                                                          FEM00544
29    WRITE(6,28)I,AREA(I),XLEN(I),RELIEF(I),SLOPE(I),RCOEF(I),J,TWIDT  FEM00545
     1H(J)                                                              FEM00546
28    FORMAT(31X,I2,9X,F7.1,8X,F7.1,4X,F6.1,6X,F5.3,7X,F5.3,14X,I2,5X,F7FEM00547
     1.1)                                                               FEM00548
70    CONTINUE                                                          FEM00549
97    IF(NPOVER(NSSHED).EQ.1) GO TO 200                                 FEM00550
      GO TO 202                                                         FEM00551
96    IF(NTIME.GT.NPRINC) GO TO 95                                      FEM00552
      WRITE(6,12) NSSHED                                                FEM00553
   12 FORMAT('1',41X,'CHANNEL FLOW INFORMATION FOR SUB-SHED NUMBER',I3) FEM00554
      WRITE(6,60)                                                       FEM00555
60    FORMAT(//15X,'ELEMENT',7X,'ELEMENT',7X,'ELEMENT',7X,'ELEMENT',8X,'FEM00556
     1ELEMENT',12X,'NODE',7X,'NODE TOP WIDTH AT'/16X,'NUMBER',8X,'LENGTHFEM00557
     2',8X,'RELIEF',8X,'SLOPE',8X,'MANNING N',10X,'NUMBER',9X,'2 FT DEPTFEM00558
```

```
      3H')
       DO 90 K=1,NE
       L=K+1
       WRITE(6,80)K,XLEN(K),RELIEF(K),SLOPE(K),RCOEF(K),L,TWIDTH(L)
80     FORMAT(17X,I2,10X,F7.1,7X,F6.1,9X,F5.3,10X,F5.3,14X,I2,13X,F5.1)
90     CONTINUE
95     IF(NPCHAN(NSSHED).EQ.1)GO TO 200
202    IF(NTIME.GT.NPRINC)GO TO 223
       L=1
       LL=2
       LLL=3
       LLLL=4
       NWRITE=4
       IF(NN.GE.4)GO TO 215
       NWRITE=NN
217    GO TO (212,213,214),NWRITE
212    WRITE(6,203)L
203    FORMAT(/20X,'NODE',I3/2X,'TIME',3X,'DISCHARGE',2X,'AREA',2X,'RATE'
      1,2X,'DEPTH')
       GO TO 216
213    WRITE(6,209)L,LL
209    FORMAT(/20X,'NODE',I3,24X,'NODE',I3/2X,'TIME',3X,'DISCHARGE',2X,'A
      1REA',2X,'RATE',2X,'DEPTH',3X,'DISCHARGE',2X,'AREA',2X,'RATE',2X,'D
      2EPTH')
       GO TO 216
214    WRITE(6,210)L,LL,LLL
210    FORMAT(/20X,'NODE',I3,24X,'NODE',I3,24X,'NODE',I3/2X,'TIME',3X,'DI
      1SCHARGE',2X,'AREA',2X,'RATE',2X,'DEPTH',3X,'DISCHARGE',2X,'AREA',2
      2X,'RATE',2X,'DEPTH',3X,'DISCHARGE',2X,'AREA',2X,'RATE',2X,'DEPTH')
       GO TO 216
215    WRITE(6,211)L,LL,LLL,LLLL
211    FORMAT(/20X,'NODE',I3,24X,'NODE',I3,24X,'NODE',I3,24X,'NODE',I3/2X
      1,'TIME',3X,'DISCHARGE',2X,'AREA',2X,'RATE',2X,'DEPTH',3X,'DISCHARG
      2E',2X,'AREA',2X,'RATE',2X,'DEPTH',3X,'DISCHARGE',2X,'AREA',2X,'RAT
      3E',2X,'DEPTH',3X,'DISCHARGE',2X,'AREA',2X,'RATE',2X,'DEPTH')
216    IF(LLLL.GT.4)GO TO 219
```

```
223   HOUR=FLOAT(NTIME)/3600.0
      WRITE(6,218) HOUR,(QQ(I),AA(I),VV(I),DD(I),I=1,NWRITE)
218   FORMAT(1X,F5.2,4(F10.2,F8.2,F6.2,F7.2))
      GO TO 222
219   NPRTS=NSECC/NPRINC
      DO 225 NTI=1,NPRTS
      HOUR=FLOAT(NTI*NPRINC)/3600.0
225   WRITE(6,221) HOUR,(QP(NTI,I),AAP(NTI,I),VVP(NTI,I),DDP(NTI,I),I
     1=M,MMMM)
221   FORMAT(1X,F5.2,4(F10.2,F8.2,F6.2,F7.2))
      IF(NN.GT.LLLL) GO TO 233
      GO TO 101
222   IF(NN.LE.4)GO TO 101
      NNA=NN-4
      TI=NTIME/NPRINC
      DO 224 I=1,NNA
      QP(TI,I)=QQ(I+4)
      AAP(TI,I)=AA(I+4)
      VVP(TI,I)=VV(I+4)
224   DDP(TI,I)=DD(I+4)
      IF(NTIME.LT.NSECC) GO TO 101
233   L=L+4
      LL=LL+4
      LLL=LLL+4
      LLLL=LLLL+4
      M=L-4
      MMMM=LLLL-4
      IF(NN.GE.LLLL) GO TO 215
      NWRITE=NN-MMMM
      MMMM=NWRITE
      GO TO 217
200   IF(NTIME.GT.NPRINC) GO TO 206
      WRITE(6,207)
207   FORMAT(/40X,'FLOW CHARACTERISTICS AT THE LAST NODE OF THE STRIP'/4
     13X,'TIME',3X,'DISCHARGE',4X,'AREA',6X,'RATE',5X,'DEPTH')
206   HOUR=FLOAT(NTIME)/3600.0
```

```
      WRITE(6,208) HOUR,QQ(NN),AA(NN),VV(NN),DD(NN)                     FEM00631
208   FORMAT(37X,5F10.2)                                                FEM00632
      GO TO 101                                                         FEM00633
83    WRITE(6,310) NTSSX                                                FEM00634
310   FORMAT('1',42X,'CHANNEL FLOW FOR IMAGINARY SUB-SHED NUMBER',I3)   FEM00635
      WRITE(6,311)                                                      FEM00636
311   FORMAT(/56X,'TIME',3X,'DISCHARGE')                                FEM00637
      NPRTS=NSECC/NPRINC                                                FEM00638
      DO 312 NTI=1,NPRTS                                                FEM00639
      HOUR=FLOAT(NTI*NPRINC)/3600.0                                     FEM00640
      JT=NTI*NCPRIN/IFIX(DTC)                                           FEM00641
      NPC1=NCONF1(NTSSX)                                                FEM00642
      NPC2=NCONF2(NTSSX)                                                FEM00643
      QQX=QCONF(JT,NPC1)+QCONF(JT,NPC2)                                 FEM00644
312   WRITE(6,313) HOUR,QQX                                             FEM00645
313   FORMAT(50X,2F10.2)                                                FEM00646
101   RETURN                                                            FEM00647
      END                                                               FEM00648
```

```
      SUBROUTINE OVERL                                                  FEM00649
      COMMON/BLK2/REFE(90,60),NRGAGE(80)                                FEM00650
      COMMON/BLK3/QOUT(20,1100),QCONF(3600,7),WIDINF(20),RCFP(20)       FEM00651
      COMMON/BLK4/XLEN(10),TWIDTH(11),RQ(10),AO(11),QO(11),AA(11),QQ(11)FEM00652
     1,AREA(10),VV(11),DD(11)                                           FEM00653
      COMMON/BLK5/RCLU(25),FHRU(90,60),LANDU(163),NHRU(90),IHRU(90,60)  FEM00654
     1,DSLU(25)                                                         FEM00655
      COMMON/BLK8/SLOPE(10),RCOEF(10),RELIEF(10)                        FEM00656
      COMMON/BLK9/NOPRIN,SMCWS,NSECR,PCINTH,DTO,DTC,NSECC,NTBLHS,NTBLPE,FEM00657
     1NTELES,NDHRUS,NLANUS,NGAGES,NHOURR,INTPCS,NSTART,MONTH,NDAY,NYEAR,FEM00658
     2NPCINT,INTPCM,NTSS,NSTRPS,NSSHED,NELEM,NZIP,NE,NN,NCPRIN,NHOURC,NDFEM00659
     3AMS,NTSSX,LHSSPS,NECHAN,KDAM                                      FEM00660
      COMMON/BLK11/NESTRP(20)                                           FEM00661
      COMMON/BLK13/NPOVER(40),NPCHAN(40),NPSTRP(40,40)                  FEM00662
      COMMON/BLK14/AREDAM(2,10),XLENDM(2),NLEVLS(2),VOLD(2,10),QQD(2,10)FEM00663
      DIMENSION HYDRAD(11),TAREAD(2),VOLDAM(2)                          FEM00664
     1,QQDAM(2),DDDAM(2),HRDAM(2),VVDAM(2),QQR(2),REFELE(10),RQ         FEM00665
     2DAM(2),REDAM(2),RC(4),A(16)                                       FEM00666
      NPRINC=NOPRIN                                                     FEM00667
      NZIP=2                                                            FEM00668
      CALL INPUT                                                        FEM00669
      NDT=DTO                                                           FEM00670
      NHEAD=0                                                           FEM00671
      DO 50 K=1,NSTRPS                                                  FEM00672
      NTIME=0                                                           FEM00673
      NE=1                                                              FEM00674
      NN=NE+1                                                           FEM00675
      NZIP=3                                                            FEM00676
      CALL INPUT                                                        FEM00677
      WIDINF(K)=TWIDTH(NN)                                              FEM00678
      DO 70 I=1,NE                                                      FEM00679
      SLOPE(I)=RELIEF(I)/XLEN(I)                                        FEM00680
      RCOEF(I)=0.0                                                      FEM00681
      L=NELEM+I                                                         FEM00682
      MHRU=NHRU(L)                                                      FEM00683
      DO 8 N=1,MHRU                                                     FEM00684
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      J=IHRU(L,N)                                                       FEM00685
      M=LANDU(J)                                                        FEM00686
      RCOEF(I)=RCOEF(I)+(RCLU(M)*FHRU(L,N))                             FEM00687
8     CONTINUE                                                          FEM00688
      RCFP(K)=0.50*RCLU(M)                                              FEM00689
70    CONTINUE                                                          FEM00690
      V1=0.0                                                            FEM00691
      V2=0.0                                                            FEM00692
      V3=0.0                                                            FEM00693
      V4=0.0                                                            FEM00694
      AO1=0.0                                                           FEM00695
      AO2=0.0                                                           FEM00696
      AO3=0.0                                                           FEM00697
      AO4=0.0                                                           FEM00698
      Q1=0.0                                                            FEM00699
      Q2=0.0                                                            FEM00700
      Q3=0.0                                                            FEM00701
      Q4=0.0                                                            FEM00702
      XNEL=XLEN(1)                                                      FEM00703
      RFEOC=RCOEF(1)                                                    FEM00704
      SEPOL=SLOPE(1)                                                    FEM00705
      AAER=AREA(1)                                                      FEM00706
      NTIME=0                                                           FEM00707
      IF(NDAMS.EQ.0)GO TO 2                                             FEM00708
      DO 412 J=1,NDAMS                                                  FEM00709
      VOLDAM(J)=0.0                                                     FEM00710
      TAREAD(1)=0.0                                                     FEM00711
      DO 413 I=1,NE                                                     FEM00712
413   TAREAD(1)=TAREAD(1)+AREDAM(J,I)                                   FEM00713
412   CONTINUE                                                          FEM00714
2     J=NTIME/INTPCS+1                                                  FEM00715
      L=NELEM+1                                                         FEM00716
      REFELE(1)=REFE(L,J)                                               FEM00717
      QR=(REFELE(1)/(FLOAT(INTPCS)*12.0))*((43560.0*AAER)/XNEL)         FEM00718
      GO TO 2000                                                        FEM00719
3     QR=0.0                                                            FEM00720
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```
 2000 A(1)=8.0/105.0                                                      FEM00721
      A(2)=33.0/560.0                                                     FEM00722
      A(3)=-3.0/140.0                                                     FEM00723
      A(4)=19.0/1680.0                                                    FEM00724
      A(5)=33.0/560.0                                                     FEM00725
      A(6)=27.0/70.0                                                      FEM00726
      A(7)=-27.0/560.0                                                    FEM00727
      A(8)=-3.0/140.0                                                     FEM00728
      A(9)=-3.0/140.0                                                     FEM00729
      A(10)=-27.0/560.0                                                   FEM00730
      A(11)=27.0/70.0                                                     FEM00731
      A(12)=33.0/560.0                                                    FEM00732
      A(13)=19.0/1680.0                                                   FEM00733
      A(14)=-3.0/140.0                                                    FEM00734
      A(15)=33.0/560.0                                                    FEM00735
      A(16)=8.0/105.0                                                     FEM00736
      RC(1)=(8.0*AO1)/105.0+(33.0*AO2)/560.0-(3.0*AO3)/140.0+(19.0*AO4)/FEM00737
     11680.0+(NDT/(2.0*XNEL))*Q1-((57.0*NDT)/(80.0*XNEL))*Q2+((3.0*NDT)/FEM00738
     2(10.0*XNEL))*Q3-((7.0*NDT)/(80.0*XNEL))*Q4+(NDT/8.0)*QR             FEM00739
      RC(2)=(33.0*AO1)/560.0+(27.0*AO2)/70.0-(27.0*AO3)/560.0-(3.0*AO4)/FEM00740
     1140.0+((57.0*NDT)/(80.0*XNEL))*Q1-((81.0*NDT)/(80.0*XNEL))*Q3+((3.FEM00741
     20*NDT)/(10.0*XNEL))*Q4+((3.0*NDT)/8.0)*QR                           FEM00742
      RC(3)=-(3.0*AO1)/140.0-(27.0*AO2)/560.0+(27.0*AO3)/70.0+(33.0*AO4)FEM00743
     1/560.0-((3.0*NDT)/(10.0*XNEL))*Q1+((81.0*NDT)/(80.0*XNEL))*Q2-((57FEM00744
     2.0*NDT)/(80.0*XNEL))*Q4+((3.0*NDT)/8.0)*QR                          FEM00745
      RC(4)=(19.0*AO1)/1680.0-(3.0*AO2)/140.0+(33.0*AO3)/560.0+(8.0*AO4)FEM00746
     1/105.0+((7.0*NDT)/(80.0*XNEL))*Q1-((3.0*NDT)/(10.0*XNEL))*Q2+((57.FEM00747
     20*NDT)/(80.0*XNEL))*Q3-(NDT/(2.0*XNEL))*Q4+(NDT/8.0)*QR             FEM00748
      CALL GELB(RC,A,4,1,3,3,5.0E-7,IER)                                  FEM00749
      DO 2002 I=2,4                                                       FEM00750
 2002 IF(RC(I).LE.0.0)RC(I)=0.0                                           FEM00751
      V1=0.0                                                              FEM00752
      RH2=RC(2)/TWIDTH(2)                                                 FEM00753
      V2=(1.49*RH2**.67*SEPOL**.5)/RFEOC                                  FEM00754
      RH3=RC(3)/TWIDTH(2)                                                 FEM00755
      V3=(1.49*RH3**.67*SEPOL**.5)/RFEOC                                  FEM00756
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      RH4=RC(4)/TWIDTH(2)                                               FEM00757
      V4=(1.49*RH4**.67*SEPOL**.5)/RFEOC                                FEM00758
      Q1=0.0                                                            FEM00759
      Q2=V2*RC(2)                                                       FEM00760
      Q3=V3*RC(3)                                                       FEM00761
      Q4=V4*RC(4)                                                       FEM00762
      VV(1)=V1                                                          FEM00763
      VV(2)=V4                                                          FEM00764
      QQ(1)=Q1                                                          FEM00765
      QQ(2)=Q4                                                          FEM00766
      DD(1)=0.0                                                         FEM00767
      DD(2)=RC(4)/TWIDTH(2)                                             FEM00768
      AA(1)=RC(1)                                                       FEM00769
      AA(2)=RC(4)                                                       FEM00770
      NTIME=NTIME+IFIX(DTO)                                             FEM00771
      JT=NTIME/IFIX(DTO)                                                FEM00772
      QOUT(K,JT)=QQ(NN)/TWIDTH(NN)                                      FEM00773
      IF(NDAMS.EQ.0)GO TO 430                                           FEM00774
      DO 426 J=1,NDAMS                                                  FEM00775
      QQDAM(J)=(AREDAM(J,1)/AAER)*QQ(2)                                 FEM00776
      VOLDAM(J)=VOLDAM(J)+QQDAM(J)*NDT                                  FEM00777
      NLS=NLEVLS(J)                                                     FEM00778
      DO 427 L=2,NLS                                                    FEM00779
      IF(VOLDAM(J)-(43560.0*VOLD(J,L)))429,428,427                      FEM00780
  427 CONTINUE                                                          FEM00781
  428 QQR(J)=QQD(J,L)                                                   FEM00782
      GO TO 426                                                         FEM00783
  429 QQR(J)=QQD(J,L)-((QQD(J,L)-QQD(J,L-1))*(((43560.0*VOLD(J,L))-VOLDAFEM00784
     1M(J))/(43560.0*(VOLD(J,L)-VOLD(J,L-1)))))                         FEM00785
  426 CONTINUE                                                          FEM00786
      QQRALL=0.0                                                        FEM00787
      DO 431 J=1,NDAMS                                                  FEM00788
      VOLDAM(J)=VOLDAM(J)-QQR(J)*NDT                                    FEM00789
  431 QQRALL=QQRALL+QQR(J)                                              FEM00790
      QOUT(K,JT)=(1-(TAREAD(1)/AAER))*(QOUT(K,JT))+QQRALL/TWIDTH(NN)    FEM00791
  430 AO1=RC(1)                                                         FEM00792
```

```
      AO2=RC(2)                                                         FEM00793
      AO3=RC(3)                                                         FEM00794
      AO4=RC(4)                                                         FEM00795
      IF(NTIME/NOPRIN*NOPRIN.NE.NTIME)GO TO 177                         FEM00796
      IF(NPOVER(NSSHED).EQ.0)GO TO 177                                  FEM00797
      IF(NPOVER(NSSHED).EQ.1)GO TO 173                                  FEM00798
      IF(NPSTRP(NSSHED,K).EQ.0)GO TO 177                                FEM00799
173   NZIP=6                                                            FEM00800
      CALL OUTPUT(I,K,NTIME,NPRINC,NHEAD)                               FEM00801
177   IF(NTIME.GE.NSECR)GO TO 5000                                      FEM00802
      IF(NTIME/INTPCS*INTPCS.EQ.NTIME)GO TO 2                           FEM00803
      GO TO 2000                                                        FEM00804
5000  IF(NTIME.LT.NSECC)GO TO 3                                         FEM00805
      NELEM=NELEM+NE                                                    FEM00806
50    CONTINUE                                                          FEM00807
      RETURN                                                            FEM00808
      END                                                               FEM00809
```

```
      SUBROUTINE CHANL                                                  FEM00810
      COMMON/BLK3/QOUT(20,1100),QCONF(3600,7),WIDINF(20),RCFP(20)       FEM00811
      COMMON/BLK4/XLEN(10),TWIDTH(11),RQ(10),AO(11),QO(11),AA(11),QQ(11)FEM00812
     1,AREA(10),VV(11),DD(11)                                           FEM00813
      COMMON/BLK6/NODE1(18),NCONF1(18),NCONF2(18)                       FEM00814
      COMMON/BLK8/SLOPE(10),RCOEF(10),RELIEF(10)                        FEM00815
      COMMON/BLK9/NOPRIN,SMCWS,NSECR,PCINTH,DTO,DTC,NSECC,NTBLHS,NTBLPE,FEM00816
     1NTELES,NDHRUS,NLANUS,NGAGES,NHOURR,INTPCS,NSTART,MONTH,NDAY,NYEAR,FEM00817
     2NPCINT,INTPCM,NTSS,NSTRPS,NSSHED,NELEM,NZIP,NE,NN,NCPRIN,NHOURC,NDFEM00818
     3AMS,NTSSX,LHSSPS,NECHAN,KDAM                                      FEM00819
      COMMON/BLK13/NPOVER(40),NPCHAN(40),NPSTRP(40,40)                  FEM00820
      COMMON/BLK14/AREDAM(2,10),XLENDM(2),NLEVLS(2),VOLD(2,10),QQD(2,10)FEM00821
      DIMENSION HYDRAD(11),YY(11),VOLDAM(1),QQR(1)                      FEM00822
      NPRINC=NCPRIN                                                     FEM00823
      NTIME=0                                                           FEM00824
      NE=NECHAN                                                         FEM00825
      NN=NE+1                                                           FEM00826
      NZIP=4                                                            FEM00827
      CALL INPUT                                                        FEM00828
      DT=DTC                                                            FEM00829
      VOLDAM(1)=0.0                                                     FEM00830
      DO 70 I=1,NE                                                      FEM00831
   70 SLOPE(I)=RELIEF(I)/XLEN(I)                                        FEM00832
   34 DO 100 I=1,NN                                                     FEM00833
      AO(I)=0.0                                                         FEM00834
  100 QO(I)=0.0                                                         FEM00835
      V1=0.0                                                            FEM00836
      V2=0.0                                                            FEM00837
      V3=0.0                                                            FEM00838
      AO1=0.0                                                           FEM00839
      AO2=0.0                                                           FEM00840
      AO3=0.0                                                           FEM00841
      Q1=0.0                                                            FEM00842
      Q2=0.0                                                            FEM00843
      Q3=0.0                                                            FEM00844
 1000 IF(NE.GT.1)GO TO 1111                                             FEM00845
```

```
      NDT=IFIX(DTO)                                                     FEM00846
20    JT=NTIME/IFIX(DTO)+1                                              FEM00847
      RQ(1)=QOUT(1,JT)+QOUT(2,JT)                                       FEM00848
30    LT=NTIME/IFIX(DTC)+1                                              FEM00849
      RHS1=(2.0*AO1)/15.0+AO2/15.0-AO3/30.0+(NDT/(2.0*XLEN(1)))*Q1-((2.0FEM00850
     1*NDT)/(3.0*XLEN(1)))*Q2+(NDT/(6.0*XLEN(1)))*Q3+(NDT/6.0)*RQ(1)    FEM00851
      RHS2=AO1/15.0+(8.0/15.0)*AO2+AO3/15.0+((2.0*NDT)/(3.0*XLEN(1)))*Q1FEM00852
     1-((2.0*NDT)/(3.0*XLEN(1)))*Q3+((2.0*NDT)/3.0)*RQ(1)               FEM00853
      RHS3=-AO1/30.0+AO2/15.0+(2.0/15.0)*AO3-(NDT/(6.0*XLEN(1)))*Q1+((2.FEM00854
     10*NDT)/(3.0*XLEN(1)))*Q2-(NDT/(2.0*XLEN(1)))*Q3+(NDT/6.0)*RQ(1)   FEM00855
      A2=(9.0/4.0)*RHS2-(3.0/2.0)*RHS1-(3.0/2.0)*RHS3                   FEM00856
      A3=12.0*RHS2-6.0*RHS1-6.0*A2                                      FEM00857
      A1=15.0*RHS2-8.0*A2-A3                                            FEM00858
      V1=0.0                                                            FEM00859
      Q1=0.0                                                            FEM00860
      D1=SQRT(ABS(A1)/350.0)                                            FEM00861
      IF(NTSS.EQ.1)GO TO 291                                            FEM00862
      IF(NODE1(NSSHED).EQ.0)GO TO 291                                   FEM00863
      NPC1=NCONF1(NSSHED)                                               FEM00864
      NPC2=NCONF2(NSSHED)                                               FEM00865
      Q1=QCONF(LT,NPC1)+QCONF(LT,NPC2)                                  FEM00866
      D1=SQRT((4.0*ABS(A1))/TWIDTH(2))                                  FEM00867
      IF(A1.LE.0.0)GO TO 291                                            FEM00868
      V1=Q1/A1                                                          FEM00869
291   D2=SQRT((4.0*ABS(A2))/TWIDTH(2))                                  FEM00870
      IF(A2.GT.0.0)GO TO 436                                            FEM00871
      D2=0.0                                                            FEM00872
      V2=0.0                                                            FEM00873
      Q2=0.0                                                            FEM00874
      GO TO 437                                                         FEM00875
436   HYDRAD(2)=A2/(2.0*SQRT(D2**2.0+(A2/D2)**2.0))                     FEM00876
      V2=(1.49*HYDRAD(2)**.67*SLOPE(1)**.5)/RCOEF(1)                    FEM00877
      Q2=V2*A2                                                          FEM00878
437   IF(A3.GT.0.0)GO TO 438                                            FEM00879
      D3=0.0                                                            FEM00880
      V3=0.0                                                            FEM00881
```

```
      Q3=0.0                                                            FEM00882
      GO TO 439                                                         FEM00883
438   D3=SQRT((4.0*ABS(A3))/TWIDTH(2))                                  FEM00884
435   HYDRAD(3)=A3/(2.0*SQRT(D3**2.0+(A3/D3)**2.0))                     FEM00885
      V3=(1.49*HYDRAD(3)**.67*SLOPE(1)**.5)/RCOEF(1)                    FEM00886
      Q3=V3*A3                                                          FEM00887
439   VV(1)=V1                                                          FEM00888
      VV(2)=V3                                                          FEM00889
      QQ(1)=Q1                                                          FEM00890
      QQ(2)=Q3                                                          FEM00891
      DD(1)=D1                                                          FEM00892
      DD(2)=D3                                                          FEM00893
      AA(1)=A1                                                          FEM00894
      AA(2)=A3                                                          FEM00895
      AO1=A1                                                            FEM00896
      AO2=A2                                                            FEM00897
      AO3=A3                                                            FEM00898
      GO TO 286                                                         FEM00899
1111  JT=NTIME/IFIX(DTO)+1                                              FEM00900
      CHALEN=0.0                                                        FEM00901
      NLSS=1                                                            FEM00902
      NRSS=LHSSPS+1                                                     FEM00903
      XLSLEN=WIDINF(NLSS)                                               FEM00904
      XRSLEN=WIDINF(NRSS)                                               FEM00905
      DO 105 I=1,NE                                                     FEM00906
      CHALEN=CHALEN+XLEN(I)-.005                                        FEM00907
      IF(CHALEN.GE.XLSLEN)GO TO 2                                       FEM00908
      GO TO 3                                                           FEM00909
2     NLSS=NLSS+1                                                       FEM00910
      XLSLEN=XLSLEN+WIDINF(NLSS)                                        FEM00911
3     IF(CHALEN.GE.XRSLEN)GO TO 4                                       FEM00912
      GO TO 105                                                         FEM00913
4     NRSS=NRSS+1                                                       FEM00914
      XRSLEN=XRSLEN+WIDINF(NRSS)                                        FEM00915
105   RQ(I)=QOUT(NLSS,JT)+QOUT(NRSS,JT)                                 FEM00916
3000  LT=NTIME/IFIX(DTC)+1                                              FEM00917
```

```
      CALL ROUTE(NE,NN,DT)                                              FEM00918
      VV(1)=0.0                                                         FEM00919
      QQ(1)=0.0                                                         FEM00920
      DD(1)=SQRT(ABS(AA(1))/350.0)                                      FEM00921
      IF(AA(1).LT.0.0)DD(1)=-1*DD(1)                                    FEM00922
      IF(NTSS.EQ.1)GO TO 271                                            FEM00923
      IF(NODE1(NSSHED).EQ.3)GO TO 272                                   FEM00924
      IF(NODE1(NSSHED).EQ.0)GO TO 271                                   FEM00925
      NPC1=NCONF1(NSSHED)                                               FEM00926
      NPC2=NCONF2(NSSHED)                                               FEM00927
      QQ(1)=QCONF(LT,NPC1)+QCONF(LT,NPC2)                               FEM00928
      GO TO 273                                                         FEM00929
272   NPC1=NCONF1(NSSHED)                                               FEM00930
      QQ(1)=QCONF(LT,NPC1)                                              FEM00931
273   DD(1)=SQRT((4.0*ABS(AA(1)))/TWIDTH(2))                            FEM00932
      IF(AA(1).LE.0.0)GO TO 277                                         FEM00933
      VV(1)=QQ(1)/AA(1)                                                 FEM00934
      GO TO 271                                                         FEM00935
277   VV(1)=0.0                                                         FEM00936
      DD(1)=-1*DD(1)                                                    FEM00937
271   DO 270 I=2,NN                                                     FEM00938
      DD(I)=SQRT((4.0*ABS(AA(I)))/TWIDTH(I))                            FEM00939
      IF(AA(I).LT.0.0)DD(I)=-1*DD(I)                                    FEM00940
270   CONTINUE                                                          FEM00941
      DO 275 I=2,NN                                                     FEM00942
      IF(AA(I).GT.0.0)GO TO 274                                         FEM00943
      VV(I)=0.0                                                         FEM00944
      QQ(I)=0.0                                                         FEM00945
      GO TO 275                                                         FEM00946
274   HYDRAD(I)=AA(I)/(2.0*SQRT(DD(I)**2.0+(AA(I)/DD(I))*2.0))          FEM00947
      VV(I)=(1.49*SQRT(SLOPE(I-1))*HYDRAD(I)**0.67)/RCOEF(I-1)          FEM00948
278   QQ(I)=VV(I)*AA(I)                                                 FEM00949
275   CONTINUE                                                          FEM00950
286   IF(KDAM.EQ.0)GO TO 289                                            FEM00951
      VOLDAM(1)=VOLDAM(1)+QQ(NN)*DT                                     FEM00952
      NLS=NLEVLS(1)                                                     FEM00953
```

```
      DO 427 L=2,NLS                                                    FEM00954
      IF(VOLDAM(1)-(43560.0*VOLD(1,L)))429,428,427                      FEM00955
427   CONTINUE                                                          FEM00956
428   QQR(1)=QQD(1,L)                                                   FEM00957
      GO TO 426                                                         FEM00958
429   QQR(1)=QQD(1,L)-((QQD(1,L)-QQD(1,L-1))*(((43560.0*VOLD(1,L))-VOLDAFEM00959
     1M(1))/(43560.0*(VOLD(1,L)-VOLD(1,L-1)))))                         FEM00960
426   VOLDAM(1)=VOLDAM(1)-QQR(1)*DT                                     FEM00961
      QCONF(LT,NSSHED)=QQR(1)                                           FEM00962
      GO TO 285                                                         FEM00963
289   QCONF(LT,NSSHED)=QQ(NN)                                           FEM00964
285   NTIME=NTIME+IFIX(DTC)                                             FEM00965
      IF(NTIME/NCPRIN*NCPRIN.NE.NTIME)GO TO 310                         FEM00966
      IF(NPCHAN(NSSHED).EQ.0)GO TO 310                                  FEM00967
      NZIP=4                                                            FEM00968
      CALL OUTPUT(I,K,NTIME,NPRINC,NHEAD)                               FEM00969
  310 DO 320 I=1,NN                                                     FEM00970
      AO(I)=AA(I)                                                       FEM00971
320   QO(I)=QQ(I)                                                       FEM00972
      IF(NTIME.GE.NSECC)GO TO 6000                                      FEM00973
      IF(NTIME/IFIX(DTO)*IFIX(DTO).EQ.NTIME)GO TO 1000                  FEM00974
      IF(NE.EQ.1)GO TO 30                                               FEM00975
      GO TO 3000                                                        FEM00976
6000  IF(NTSS.EQ.1)GO TO 7000                                           FEM00977
      IF(NTSSX.GT.(NSSHED+1))GO TO 7000                                 FEM00978
      IF(NODE1(NTSSX).EQ.0)GO TO 7000                                   FEM00979
      NZIP=9                                                            FEM00980
      CALL OUTPUT(I,K,NTIME,NPRINC,NHEAD)                               FEM00981
7000  RETURN                                                            FEM00982
      END                                                               FEM00983
```

```
      SUBROUTINE ROUTE(NE,NN,DT)                                        FEM00984
      COMMON/BLK4/XLEN(10),TWIDTH(11),RQ(10),AO(11),QO(11),AA(11),QQ(11)FEM00985
     1,AREA(10),VV(11),DD(11)                                           FEM00986
      DIMENSION SE1(2,2),S1(11,2),RE1(2),RE2(2),A1(11,11),A(121),R1(11),FEM00987
     1R2(11),RC(121)                                                    FEM00988
      DO 120 I=1,NN                                                     FEM00989
      R1(I)=0.0                                                         FEM00990
  120 R2(I)=0.0                                                         FEM00991
      DO 125 I=1,NN                                                     FEM00992
      DO 125 J=1,2                                                      FEM00993
  125 S1(I,J)=0.0                                                       FEM00994
      SE1(1,1)=2.0/3.0                                                  FEM00995
      SE1(1,2)=1.0/3.0                                                  FEM00996
      SE1(2,1)=SE1(1,2)                                                 FEM00997
      SE1(2,2)=SE1(1,1)                                                 FEM00998
      M=0                                                               FEM00999
  130 M=M+1                                                             FEM01000
      RE1(1)=(QO(M+1)-QO(M))/(XLEN(M))                                  FEM01001
      RE1(2)=RE1(1)                                                     FEM01002
      RE2(1)=RQ(M)                                                      FEM01003
      RE2(2)=RE2(1)                                                     FEM01004
      R1(M)=R1(M)+RE1(1)                                                FEM01005
      R1(M+1)=R1(M+1)+RE1(2)                                            FEM01006
      R2(M)=R2(M)+RE2(1)                                                FEM01007
      R2(M+1)=R2(M+1)+RE2(2)                                            FEM01008
      S1(M,1)=S1(M,1)+SE1(1,1)                                          FEM01009
      S1(M,2)=S1(M,2)+SE1(1,2)                                          FEM01010
      S1(M+1,1)=S1(M+1,1)+SE1(2,2)                                      FEM01011
      IF(M.LT.NE)GO TO 130                                              FEM01012
      DO 140 I=1,NN                                                     FEM01013
      A1(I,I)=S1(I,1)                                                   FEM01014
      J=I+1                                                             FEM01015
      IF(J.GT.NN)GO TO 145                                              FEM01016
      A1(I,J)=S1(I,2)                                                   FEM01017
      A1(J,I)=A1(I,J)                                                   FEM01018
      NK=J+1                                                            FEM01019
```

```
      IF(NK.GT.NN)GO TO 140                                             FEM01020
      DO 135 L=NK,NN                                                    FEM01021
      A1(I,L)=0.0                                                       FEM01022
  135 A1(L,I)=0.0                                                       FEM01023
  140 CONTINUE                                                          FEM01024
  145 DO 155 I=1,NN                                                     FEM01025
      SUM=0.0                                                           FEM01026
      DO 150 J=1,NN                                                     FEM01027
      C=A1(I,J)*AO(J)/DT                                                FEM01028
  150 SUM=SUM+C                                                         FEM01029
  155 RC(I)=SUM+R2(I)-R1(I)                                             FEM01030
      LL=0                                                              FEM01031
      LC=0                                                              FEM01032
      DO 165 I=1,NN                                                     FEM01033
      LL=LL+1                                                           FEM01034
      LB=2                                                              FEM01035
      IF(I.EQ.1.OR.I.EQ.NN)LB=1                                         FEM01036
      LE=LL+LB                                                          FEM01037
      DO 160 J=LL,LE                                                    FEM01038
      LC=LC+1                                                           FEM01039
  160 A(LC)=A1(I,J)                                                     FEM01040
  165 IF(I.EQ.1)LL=0                                                    FEM01041
      CALL GELB(RC,A,NN,1,1,1,5.0E-7,IER)                               FEM01042
      DO 170 I=1,NN                                                     FEM01043
  170 AA(I)=RC(I)*DT                                                    FEM01044
      RETURN                                                            FEM01045
      END                                                               FEM01046
```

Appendix C

Description of Program Variables

This appendix describes internally generated program variables. A description of input and output variables is given in Appendix E.

Variable	Mode	Dimension	Units	Description
A	R	(121)	-	Column matrix created from values of A1 for solution in subroutine GELB.
A1	R	(11,11)	-	Values of assembled square matrix in the finite element equation.
AAP	R	(200,4)	ft^2	Calculated cross-sectional area of flow at interior nodes of an overland flow strip or channel, which is stored for printing output.
ACCDP	R	(163)	in	Quantity of water in depression storage at end of time interval.
AFAC	R	(163)	-	Values of Holtan's 'a' for each HRU.
ADVLEV	R	-	in	Level of water in soil profile after evapotranspiration during a given antecedent day.
AINT	R	-	-	Equal to NPCINT.
AO	R	(11)	-	Initial cross-sectional area of flow at each node in given strip.
AVM	R	-	in	Plant available water for a given HRU.
CEXP	R	(163)	-	Value of exponent 'c' in Holtan's equation for each HRU.
DDP	R	(200,4)	ft	Calculated depth of flow at interior nodes of an overland flow strip or channel, which is stored for printing output.
DEPSEP	R	-	in	Water lost by deep seepage during a given antecedent day.
DEPSTO	R	(163)	in	Potential depression storage for a given HRU.

Variable	Mode	Dimension	Units	Description
DPAW	R	-	in	Depth of plant available water for a given HRU.
DT	R	-	sec	Routing time increment equal to DTO or DTC.
EPS1	R	-	in	Accumulated soil water removed from storage during iterative solution of Holtan equation.
EVPOR	R	-	in	Total evapotranspiration for 30-day period preceding the storm event.
F1	R	-	in/hr	Infiltration rate at beginning of rainfall time increment.
F2	R	-	in/hr	Infiltration rate at end of rainfall time increment.
FA	R	-	in/hr	Average infiltration rate over rainfall time increment.
GRM	R	-	in	Temporary storage of gravitational soil water content.
GRWAT	R	-	in	Temporary variable used to compute storage recovery from deep seepage over a given time increment.
HYDRAD	R	(11)	ft	Computed hydraulic radius of flow at each nodal point in a given strip.
INTPCM	I	-	min	Time increment of rainfall.
KIHRU	I	(163)	-	Index code which specifies the status of rainfall excess computations for a given HRU.
MHRU	I	-	-	Equal to NHRU for a given element.
NDTC	I	-	-	Equal to DTC.
NDTO	I	-	-	Equal to DTO.

Variable	Mode	Dimension	Units	Description
NE	I	-	-	Number of elements in a given strip.
NELEM	I	-	-	Index counter of the number of elements in the watershed.
NHEAD	I	-	-	Index code which determines format of table headings in output.
NLS	I	-	-	Equal to NLEVLS for a given detention structure.
NN	I	-	-	Number of nodes in a given strip.
NNA	I	-	-	Equal to NN-4.
NPC1	I	-	-	Equal to NCONF1 for a given subshed.
NPC2	I	-	-	Equal to NCONF2 for a given subshed.
NPCINT	I	-	-	Number of rainfall intervals for the storm.
NPERCT	I	-	-	Value of SMCWS expressed as a percentage.
NPRINC	I	-	sec	The time interval of output listings.
NPRTS	I	-	-	Total printing intervals for the simulation.
NSECC	I	-	sec	Duration of simulation.
NSECR	I	-	sec	Duration of rainfall.
NSSHED	I	-	-	Number of subsheds in watershed.
NTAB	I	-	-	Number of tables of rainfall excess which must be printed to cover duration of storm event.

Variable	Mode	Dimension	Units	Description
NTIME	I	-	-	Index counter of elapsed time of simulation.
NTSSX	I	-	-	Number of subsheds, including imaginary subshed, in the watershed.
NUMBER	I	(24)	-	Column matrix to store numerals 1 thru 24. These data used to generate headings in specific output table listings.
NUMTAB	I	-	-	Index code which controls heading of rainfall excess tables.
NWRITE	I	-	-	Index code which controls headings of flow information table.
NZIP	I	-	-	Index code used to control branching to I/O functions.
PCINTH	R	-	hr	Time interval of rainfall.
QCONF	R	(5500,7)	cfs	Discharge at the downstream node of each channel per routing time increment.
QO	R	(11)	cfs	Initial discharge at each nodal point in a strip.
QOUT	R	(20,1100)	cfs	Lateral flow to the channel from each overland flow strip in a subshed per routing time increment.
QQDAM	R	(2)	cfs	Calculated flow to each flood detenture struction.
QP	R	(200,4)	cfs	Calculated discharge at interior nodes of an overland flow strip or channel, which is stored for printing output.
QQR	R	(2)	cfs	Discharge from each flood detention structure.

Variable	Mode	Dimension	Units	Description
QQRALL	R	-	cfs	Accumulated discharge from all flood detention structures located within a given overland flow strip.
QQX	R	-	cfs	Combined discharge from two upstream channels to form discharge in an imaginary channel.
R1	R	(11)	-	Temporary storage variable used in the assembled matrix formulation.
R2	R	(11)	-	Temporary storage variable used in the assembled matrix formulation.
RC	R	(121)	-	Column matrix of the known quantities for solution of the finite element equation.
RE1	R	(2)	ft^2/s	Temporary storage variable used in the assembled matrix formulation.
RE2	R	(2)	ft^2/s	Temporary storage variable used in the assembled matrix formulation.
RECMAX	R	-	in	Maximum possible storage recovery, during rainfall time interval, due to seepage.
RECOV	R	-	in	Actual storage recovery during rainfall time interval due to seepage.
REFE	R	(50,100)	in	Rainfall excess per routing time increment for each element.
REFELE	R	(10)	in	Equal to REFE for the elements in a given strip.
REHRU	R	(153,4,80)	in	Rainfall excess per HRU, rainfall distribution and rainfall time interval.

Variable	Mode	Dimension	Units	Description
REMAIN	R	-	in	Water remaining after infiltration, allocated to depression storage and/or runoff.
RQ	R	(10)	cfs	Lateral flow to each element in a given strip.
S1	R	(11,2)	-	Temporary storage variable used in the assembled matrix formulation.
SE1	R	(2,2)	-	Temporary storage variable used in the assembled matrix formulation.
SLOPCL	R	(6)	-	Slope classes A-F.
SLOPCO	R	(6)	-	Reducing factor for depression storage based on slope class.
SLOPE	R	(10)	ft/ft	Slope of each element in a strip.
SMC	R	-	-	Antecedent soil moisture condition of a given HRU expressed as a fraction of field capacity.
STANWT	R	-	in	Total water available for infiltration at beginning of rainfall time increment.
STO	R	-	in	Current value of unfilled soil water storage for each HRU.
STOI	R	-	in	Initial value of unfilled soil water storage for each HRU.
STOMAX	R	(163)	in	Maximum soil water storage for each HRU.
TA	R	-	hr	Time interval necessary for rainfall in a given time increment to infiltrate.
TAREAD	R	-	ac	Total area of each element which drains into one or more flood detention structures.

Variable	Mode	Dimension	Units	Description
TESTIN	R	-	in	Difference between rainfall and EPS1. Equal to total infiltration when TA x FA ≥ TESTIN.
VOLDAM	R	(2)	ft^3	Accumulated volume of water impounded behind flood detention structure at the end of each simulation interval.
VVP	R	(200,4)	ft/s	Calculated velocity of flow at interior nodes of an overland flow strip or channel, which is stored for printing output.
WATER	R	-	in	Remaining unfilled storage at the end of rainfall time increment.
WOUT	R	-	in	Water lost by evapotranspiration during a given antecedent day.
XINF	R	-	in	Volume of rainfall infiltrated during rainfall time interval.
XLEVEL	R	-	in	Level of water in the soil profile during a given antecedent day.
XP	R	-	in	Unfilled storage after rain for a given time interval is assumed to infiltrate.
XXP	R	-	in	Unfilled storage during successive iteration cycles with the Holtan equation.

Appendix D

Dimensioning of Program Variables

Variable dimensions given in this appendix are identical to the dimensioning given in Appendix B. The following discussion is intended to explain what controls the size of each dimensioned variable so that adjustments can be easily made when it is necessary to increase the size of specific arrays.

Rainfall

Variables PRECIP and REHRU are used to store data that relate to the storm event. PRECIP is a 2-dimensional array, (I,J), where index I equals the number of raingages or different rainfall distributions that are being used in the simulation, and index J equals the number or rainfall data entries. REHRU is a 3-dimensional array (I,J,K) that is used to store rainfall excess computations by HRU. Index I equals the number of HRU's, index J equals the number of raingages, and index K equals the number of rainfall data entries. This array is currently fixed at (163,4,80).

Raingage Assignment

Variable NRGAGE is used to store index codes that assign a specific raingage to a given element. The dimension of NRGAGE must be equal to or greater than the number of elements in the watershed.

HRU Characteristics

Variables ACCDP, AFAC, CEXP, DEPSTO, DEPTH, FAW, FC, FGW, KIHRU, LANDU, REHRU, SLOHRU and STOMAX are used to store data that specifically relate to HRU's. The size of these storage arrays must, therefore, be equal to or greater than the total number of unique HRU's in the watershed. The maximum number of HRU's is limited to 163 in the program given in Appendix B. Note that REHRU is a 3-dimensional array with the first index referring to the number of HRU's.

Landuse Array

Variables RCLU, DSLU, and AFLU are used to store Manning roughness coefficients, potential depression storage estimates and Holtan's 'a' coefficients, respectively, for a given landuse. They must be dimensioned equal to or greater than the number of landuse types within the watershed.

HRU's within Elements

Storage variables FHRU, IHRU, NHRU, and REFE are used to store data that relate to the number of HRU's within each element and weighted rainfall excess per element in the watershed. Variables FHRU and IHRU are 2-dimensional arrays, (I,J), whose indices represent the maximum number of

HRU's per element (I) and the total number of elements in the watershed (J), respectively. The dimension of NHRU is equal to I. Matrix REFE (I,J) is used to store weighted rainfall excess per element. Index J is equal to the number of rainfall entries.

Element Characteristics

Variables AREA, NCONF1, NCONF2, NODE1, RCOEF, REFELE, RELIEF, RQ, SLOPE, and XLEN are used to store data that relate to elements within a given strip. The size of these variables, therefore, must be equal to or larger than the maximum number of elements in a strip or channel. The program is set for a maximum of 10 elements in a flow strip.

Flood Detention Structures

Variables AREDAM, QQDAM, NLEVLS, QQD, QQR, and VOLD are used to store information relating to flood detention structures. The size of each column matrix must be equal to or greater than the maximum number of flood detention structures located within an element. The size of each 2-dimensional array must also be equal to or greater than the maximum number of elements in a strip, i.e., I equals the number of flood detention structures and J equals the number of elements.

Solution Matrix

Variables A, A1, AA, AD, DD, R, HYDRAD, QO, QQ, R1, R2, RC, S1, TWIDTH, and VV are used to store data that relate to the solution of the continuity equation. The size of each array must be greater than or equal to the number of nodal points in a given strip or channel. Since the number of elements in a strip or channel can vary within a given watershed, the size of the above variables must be sufficient to accommodate the strip or channel that contains the most elements. Note that the number of nodal points will be equal to the number of elements plus 1. Storage variables A and R equal the square of the number of nodal points. These arrays are currently dimensioned for 10 elements (11 nodals points) per strip or channel. Note that only the first dimension of matrix S1 (I,J) is equal to the number of nodal points (I), while the second dimension given by J is set to 2 and does not change.

Fixed Arrays

Variables NUMBER, RE1, RE2, S1, and SE1 are fixed because of the analytical procedure that is being used and should not be changed. The exception is the first dimension of matrix S1, which has been previously explained.

Temporary Discharge Arrays

Variables QCONF and QOUT are used to provide temporary storage of discharge from subsheds (QCONF) and strips (QOUT), per routing time increment. The size of matrix QCONF(I,J) is controlled by the number of subsheds (J) and the number of computation increments (I). Dimension I is equal to the accumulated simulation time (seconds) divided by the channel routing interval (DTC). For example, for 20 hours of simulation and DTC = 20 seconds, I must be equal to or greater than 3600. Also, assuming 7 subsheds, QCONF would be dimensioned as (3600,7).

The size of matrix QOUT (I,J) is controlled by the maximum number of strips in a subshed (I) and the number of computation increments (J). Dimension J is equal to the accumulated simulation time divided by the overland flow routing interval (DTO). The computer program is set for 20 strips and 1100 computation increments {QOUT(20,1100)}.

Printing Arrays

Variables NPCHAN and NPOVER are used to index codes that specify output list options. The size of column matrices NPCHAN and NPOVER is set equal to or greater than the number of subsheds.

Nodal Characteristics for Printing

Variables AAP, DDP, VVP, and QP are used for temporary storage of data at interior node points. These data are required when listings have been requested at interior node points. All variables are 2-dimensional arrays, (I,J), where I is equal to or greater than the accumulated simulation time divided by the appropriate printing increment (NOPRIN or NCPRIN), and J is equal to or less than the the maximum number of nodes in a strip or channel minus 4. For example, if the number of nodes equals 11, J would be set to 7.

Subroutine GELB

Subroutine GELB was obtained from an IBM supplied scientific subroutine package. Variables unique to this routine are not defined, however, dimensioning remains constant for all applications.

Appendix F

Description of Input Data Formats

This appendix describes, in detail, the formatting procedures for all input data necessary for operation of the FESHM.

Table E1. Description of output control records.

Record No. 1

1-5	6-10	11-20	21-30
NTBLHS	NTBLPE	NOPRIN	NCPRIN

Record No. 2

1-2	3-4	5-6 -------- 79-80
NPOVER(1)	NPOVER(2)	NOPVER(3) --- NPOVER(40)

Record No. 3

1-2	3-4	5-6 -------- 79-80
NPCHAN(1)	NPCHAN(2)	NPCHAN(3) --- NPCHAN(40)

Variable	Mode	Dimension	Description of Variable
NTBLHS	I	-	Code which specifies whether or not the table describing HRU's and their properties is to be listed. NTBLHS = 0: No table is generated. NTBLHS = 1: Table is generated.
NTBLPE	I	-	Code which specifies whether or not tables listing both HRU precipitation excess and weighted precipitation excess for elements will be listed. NTBLPE = 1: Tables are generated. NTBLPE = 0: No table is generated.

Table E1. Continued..

Variable	Mode	Dimension	Description of Variable
NOPRIN	I	-	Time interval (seconds) at which overland flow output is desired. This value must be equal to, or some integer multiple, of the overland flow routing time increment (DTO).
NCPRIN	I	-	Time interval (seconds) at which channel flow output is desired. This value must be equal to, or some integer multiple, of the channel flow routing time increment (DTC)
NPOVER(I)	I	I≤40	Index which defines the print status for output of overland flow in the Ith subshed. The number of subsheds can vary from 1-40 with the current program configuration. NPOVER(I) = 0: No output for the element in the Ith subshed. NPOVER(I) = 1: Output is generated for the bottom node of each element in the Ith subshed.
NPCHAN(I)	I	I≤40	Index which defines the print status for channel flow output for the Ith subshed. NPCHAN(I) = 0: No output for the channel in the Ith subshed. NPCHAN(I) = 2: Output is generated for all nodes of the channel in the Ith subshed.

Table E2. Description of records related to the storm event.

Record No. 1

1-10	11-20	21-30	31-40	41-50
NGAGES	NHOURR	NHOURC	INTPCS	SMCWS

Record No. 2

1-5	6-10	11-15	16-20
NSTART	MONTH	NDAY	NYEAR

Record No. 3

1-10	11-20	----------------------	71-80
PRECIP(1,1)	PRECIP(1,2)	---------------	PRECIP(1,8)

Record No. 4 (This record is omitted when NGAGES = 1)

1	2	3	---------- 80
NRGAGE(1)	NRGAGE(2)	NRGAGE(3)	--- NRGAGE(80)

Record No. 5

1-6	7-12	----------------------	67-72
GINDEX(1)	GINDEX(2)	-----------------	GINDEX(12)

Record No. 6 (This record is omitted when SMCWS > 0.0)

1-6	7-12	----------------------	67-72
EVP(1)	EVP(2)	--------------------	EVP(12)

Table E2. Continued.

Record No. 7 (This record is omitted when SMCWS > 0.0)

1-8	9-16	----------------	73-80
DAILPC(1,1)	DAILPC(1,2)	----------------	DAILPC(1,10)

Variable	Mode	Dimension	Description of Variable
NGAGES	I	-	Number of rain gages distributed throughout the watershed for the given storm event.
NHOURR	I	-	Duration of storm event in hours.
NHOURC	I	-	Duration of simulation in hours.
INTPCS	I	-	Time interval (seconds) at which precipitation records are entered.
SMCWS	R	-	Antecedent moisture condition for the watershed expressed as a fraction of field capacity for each HRU.
NSTART	I	-	Hour at which precipitation begins (e.g., 0-23).
MONTH	I	-	Month in which storm occurred (e.g., 1-12).
NDAY	I	-	Day in which storm occurred (e.g., 1-31).
NYEAR	I	-	Last two digits of year in which storm occurred (e.g., 00-99).
PRECIP(I,J)	R	NGAGES,NPCINT	Rainfall for the Jth time increment of the Ith raingage.

Table E2. Continued.

Variable	Mode	Dimension	Description of Variable
NRGAGE(I)	I	-	Raingage assigned to the Ith element.
EVP(I)	R	12	Evapotranspiration estimate for the Ith month in the given year in inches per month.
DAILPC(I)	R	NGAGES,30	Daily rainfall for the 30-day period preceding the storm event for the Ith raingage.
GINDEX(I)	R	12	A ratio of plant growth to plant maturity for the Ith month in the given year.

Table E3. Description of indexing control records for HRU's.

Record No. 1

1-10	11-20	21-30	31-40
NTSS	NTELES	NDHRUS	NLANUS

Record No. 2 (for element No. 1)

1-10
NHRU(1)

Record No. 3 (for element No. 1)

1-8	9-16	17-24	-------- 73-80
IHRU(1,1)	IHRU(1,2)	IHRU(1,3)	--- IHRU(1,10)

Record No. 4 (for element No. 1)

1-8	9-16	17-24	--------- 73-80
FHRU(1,1)	FHRU(1,2)	FHRU(1,3)	---- FHRU(1,10)

Variable	Mode	Dimension	Description of Variable
NTSS	I	-	Number of subsheds in the watershed.
NTELES	I	-	Total number of elements in the watershed.
NDHRUS	I	-	Number of different HRU's in the watershed.
NLANUS	I	-	Number of different landuse types in the watershed.
NHRU(I)	I	NTELES	Index giving the number of HRU's within the Ith element.

Table E3. Continued.

Variable	Mode	Dimension	Description of Variable
IHRU(I,J)	I	NTELES,NDHRU	Index code to uniquely identity the Jth HRU in the Ith element and provide a cross-reference to a table of HRU properties.
FHRU(I,J)	R	NTELES,NDHRU	Areal coverage of the Jth HRU in the Ith element as a fraction of the element area.

Table E4. Description of the landuse and HRU descriptor file.

Record No. 1

1-10	11-20	21-30	-------- 71-80
AFLU(1)	AFLU(2)	AFLU(3)	------ AFLU(8)

Record No. 2

1-10	11-20	21-30	-------- 71-80
DSLU(1)	DSLU(2)	DSLU(3)	------ DSLU(8)

Record No. 3

1-10	11-20	21-30	-------- 71-80
RCLU(1)	RCLU(2)	RCLU(3)	------ RCLU(8)

Record No. 4

1-10	11-20	21-30	31-40	41-50	51-60
LANDU(1)	FAW(1)	FGW(1)	FC(1)	DEPTH(1)	SLOHRU(1)

Variable	Mode	Dimension	Description of Variable
AFLU(I)	R	NLANUS	Holtan's 'a' estimate for the Ith landuse type.
DSLU(I)	R	NLANUS	Potential depression storage estimate in inches for the Ith landuse type.
RCLU(I)	R	NLANUS	Manning's 'n' estimate for the Ith landuse type.
LANDU(I)	R	NDHRUS	Index a code that uniquely defines given landuse type and provides a cross-reference to the above properties for the Ith HRU.

Table E4. Continued.

Variable	Mode	Dimension	Description of Variable
FAW(I)	R	NDHRUS	Potential plant available water expressed as a fraction of the volume of a unit of soil (in/in) for the Ith HRU.
FGW(I)	R	NDHRUS	Potential gravitational water expressed as a fraction of the volume of a unit of soil (in/in) for the Ith HRU.
FC(I)	R	NDHRUS	Final infiltration rate in in/hr for the Ith HRU.
DEPTH(I)	R	NDHRUS	Depth of the A horizon in inches for the Ith HRU.
SLOHRU(I)	A	NDHRUS	Slope class of the soil type in the Ith HRU (e.g., A-F).

Table E5. Description of data records for computation time increment and indexing for multiple drainage systems.

Record No. 1

	1-10	11-20
	DTO	DTC

Record No. 2 (The following records are omitted when NTSS =1)

5	10	15 ---------- 80
NODE1(1)	NODE1(2)	NODE1(3) ---- NODE1(16)

Record No. 3 (This record is omitted when NODE1(I) = 0)

5	10
NCONF1(1)	NCONF2(1)

Variable	Mode	Dimension	Description of Variable
DTO	R	-	Time increment for overland flow routing in seconds. Must be equal to, or some integer divisor, of INTPCS.
DTC	R	-	Time increment for channel flow routing in seconds. Must be equal to, or some integer divisor, of DTO.
NODE1(I)	I	NTSS	Index code specifying the boundary condition to be applied at the upstream channel node of the Ith subshed. NODE1(I) = 0: Discharge at upstream boundary is zero. NODE1(I) = 1: Discharge at the upstream boundary is the sum of the discharges at the downstream channel nodes of the two upstream channels.

Table E5. Continued.

Variable	Mode	Dimension	Description of Variable
			NODE1(I) = 2: Subshed NTSS is imaginary. Such is the case when the watershed outlet exists at the confluence of the last two channels of the watershed. The imaginary subshed provides the total watershed discharge as the sum of the discharges from the two upstream channels. NODE1(I) = 3: A subshed has been divided into two subsheds with the flow from the downstream node of the upstream channel being the boundary condition of the upstream node of the downstream channel. This control is provided for the placement of flood-detention structures in a channel.
NCONF1(I)	I	NTSS	The number of the first subshed contributing to the channel confluence at the upstream channel node of the Ith subshed.
NCONF2(I)	I	NTSS	The number of the second subshed contributing to the channel confluence at the upstream channel node of the Ith subshed. NCONF2(I) = 0, when NODE1(I) = 3.

Table E6. Description of input data file to describe the properties of overland flow elements.

Record No. 1

1-5	6-10	11-15
NSTRPS	LHSSPS	NECHAN

Record No. 2

1-10	11-20	21-30	31-40	41-50
XLEN(1)	RELIEF(1)	AREA(1)	TWIDTH(2)	NDAMS

Variable	Mode	Dimension	Description of Variable
NSTRPS	I	-	The total number of overland flow elements within a given subshed.
LHSSPS	I	-	Number of elements on the left side of the channel, facing upstream, in a given subshed.
NECHAN	I	-	Number of elements in the channel of a given subshed.
XLEN(I)	R	1	Length of the overland flow element in feet.
RELIEF(I)	R	1	Relief of the overland flow element in feet.
AREA(I)	R	1	Area of the overland flow element in acres.
TWIDTH(I+1)	R	2	Top width of the downstream node of the overland flow element in feet.
NDAMS	I	-	Index code to specify the status of flood detention structures in the overland flow element.

Table E6. Continued.

Variable	Mode	Dimension	Description of Variable
			NDAMS = 0: No flood detention structure in the element. NDAMS > 0: Flood detention structures must be considered. The value of NDAMS is equivalent to the number of flood detention structures in the element.

Table E7. Description of input variables to describe properties of overland flow flood detention structures.

Record No. 1

1-10	11-20
AREDAM(1,1)	NLEVLS(1)

Record No. 2

1-10	11-20	----------	71-80
VOLD(1,1)	VOLD(1,2)	----------	VOLD(1,8)

Record No. 3

1-10	11-20	----------	71-80
QQD(1,1)	QQD(1,2)	----------	QQD(1,8)

Variable	Mode	Dimension	Description of Variable
AREDAM(I,J)	R	NDAMS,1	Drainage area behind the Ith flood detention structure located within the overland flow element in acres.
NLEVLS(I)	I	NDAMS	Number of volume-discharge levels that were used to define the discharge hydrograph of the Ith flood detention structure in an overland flow element.
VOLD(I,J)	R	NDAMS,NLEVLS	Volume of water in the detention pond of the Ith flood detention structure at the Jth volume-discharge level in acre-feet.
QQD(I,J)	R	NDAMS,NLEVLS	Discharge from the Ith flood detention struture at the Jth volume-discharge level in cfs.

Table E8. Description of input variables to describe the properties of channel elements.

1-10	11-20	21-30	31-40	41-50
XLEN(1)	RELIEF(1)	RCOEF(1)	TWIDTH(2)	KDAM

Variable	Mode	Dimension	Description of Variable
XLEN(I)	R	NE	Length of Ith channel element in feet.
RELIEF(I)	R	NE	Relief of the Ith channel element in feet.
RECOEF(I)	R	NE	Roughness coefficient for the Ith channel element.
TWIDTH(I+1)	R	NN	Top width in feet of a triangular channel cross-section at the downstream node of the Ith element for a 2-foot depth.
KDAM	I	-	Index code to specify the status of flood detention structures in the channel. KDAM = 0: No flood detention structure at the downstream node of the Ith channel element. KDAM = 1: A flood detention structure is located at the downstream node of the Ith channel element.

Table E9. Description of input variables to describe properties of channel flow flood detention structures. structures.

Record No. 1

1-10
NLEVLS(1)

Record No. 2

1-10	11-20	------	71-80
VOLD(1,1)	VOLD(1,2)	------	VOLD(1,8)

Record No. 3

1-10	11-20	------	71-80
QQD(1,1)	QQD(1,2)	------	QQD(1,8)

Variable	Mode	Dimension	Description of Variable
NLEVLS(I)	I	1	Number of volume-discharge levels that were used to define the discharge hydrograph of the flood detention structure.
VOLD(I,J)	R	1,NLEVLS	Volume of water in the detention pond of the flood detention structure at the Jth volume-discharge level in acre-feet.
QQD(I,J)	R	1,NLEVLS	Discharge from the flood detention struture at the Jth volume-discharge level in cfs.

Table E10. Typical input data stacking order.

Order of Data Entry	Description of Data
1	Record No. 1; Table E1. (1 card)
2	Record No. 2; Table E1. (1 card)
3	Record No. 3; Table E1. (1 card)
4	Record No. 1; Table E2. (1 card)
5	Record No. 2; Table E2. (1 card)
6	Record No. 3; Table E2. (Include 1 card per 8 rainfall entries per raingage)
7	Record No. 4; Table E2. (1 card)
8	Record No. 5; Table E2. (1 card)
9	Record No. 6; Table E2. (1 card)
10	Record No. 7; Table E2. (3 cards)
11	Record No. 1; Table E3. (1 card)
12	Record No. 2; Table E3. (1 card)
13	Record No. 3; Table E3. (Include 10 entries per card until NHRU is satisfied)
14	Record No. 4; Table E3. (Include 10 entries per card until NHRU is satisfied)
15	Repeat 12-14 for NTELES cycles.
16	Record No. 1; Table E4. (Include 8 entries per card until a total of NLANUS have been entered)
17	Record No. 2; Table E4. (Include 8 entries per card until a total of NLANUS have been entered)

Table E10. Continued.

18	Record No. 3; Table E4. (Include 8 entries per card until a total of NLANUS values have been entered)
19	Record No. 4; Table E4. (Include NDHRUS cards)
20	Record No. 1; Table E5. (1 card)
21	Record No. 2; Table E5. (Include 16 entries per card until a total of NTSS values have been entered)
22	Record No. 3; Table E5. (Include 1 card for each occurrence of NODE1(1) = 1 where I = 1, NTSS)
23	Record No. 1; Table E6. (1 card)
24	Record No. 2; Table E6. (1 card)
25	Record No. 1; Table E7. (Omit when NDAMS = 0. Otherwise, include up to 8 entries per card)
26	Record No. 2; Table E7. (Omit when NDAMS = 0. Otherwise, include up to 8 entries per card until a total of NLEVLS values have been entered)
27	Record No. 3; Table E7. (Omit when NDAMS = 0. Otherwise, include up to 8 entries per card until a total of NLEVLS have been entered)
28	Repeat 25-27 until NDAMS is satisfied.
29	Repeat 24-28 until NSTRPS is satisfied.
30	Table E8. (Include 1 card for each channel element in the subshed)
31	Record No. 1; Table E9. (Omit when KDAM = 0. Otherwise, include up to 8 entries per card)

Table E10. Continued.

32	Record No. 2; Table E9. (Omit when KDAM = 0. Otherwise, include up to 8 entries per card until a total of NLEVLS have been entered)
33	Record No. 3; Table E9. (Omit when KDAM = 0. Otherwise, include up to 8 entries per card until a total of NLEVLS have been entered)
34	Repeat 30-33 until NECHAN is satisfied.
35	Repeat 23-34 until NTSS is satistied.

Table E11. Description of output formats for simulated discharge hydrographs.

Output Option No. 1

1-6	7-16	17-24	25-30	31-37--	--100-109	110-117	118-123	124-130
HOUR	QQ(1)	AA(1)	VV(1)	DD(1)----	----QQ(4)	AA(4)	VV(4)	DD(4)

Output Option No. 2

38-47	48-57	58-67	68-77	78-87
HOUR	QQ(NN)	AA(NN)	VV(NN)	DD(NN)

Variable	Mode	Dimension	Desciption of Variable
HOUR	I	-	Elapsed time from the beginning of the storm in hours.
QQ(I)	R	NN	Calculated discharge at the nodes of the overland flow or channel element in cfs.
AA(I)	R	NN	Calculated velocity of flow at the nodes of the overland flow or channel element in feet per second.
VV(I)	R	NN	Calculated velocity of flow at the nodes of the overland flow or channel element in feet per second.
DD(I)	R	NN	Calculated depth of flow at the nodes of the overland flow or channel element in feet.

Appendix F

Example Input Data File

The input data file for Pony Mountain Branch watershed and storm event 6/24/58 is listed in this appendix. The output generated by the FESHM using this data file is given in Appendix G.

```
--------------------------------------------------------------------------------------
Line                          Input Data File
 No.
                                     Column
               1         2         3         4         5         6         7         8
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
--------------------------------------------------------------------------------------

   1      1    1       600       300
   2   1 0 0 0
   3   2 0 0 0 1
   4           2         2         3       900      0.00
   5     17    6   24   58
   6     0.00000   0.04000   0.25000   0.80000   0.19000   0.07000   0.00500   0.00500
   7     0.00000   0.04000   0.20000   0.75000   0.27000   0.09000   0.01000   0.00000
   8  2222112222111111
   9    0.30  0.30  0.30  0.45  0.60  0.80  0.90  0.90  0.75  0.40  0.30  0.30
  10    0.71  0.71  1.02  2.40  4.56  5.85  6.50  6.72  4.92  2.91  1.54  0.87
  11   0.00000 0.00000 0.13000 0.00000 0.00000 0.00000 0.50000 0.00000 0.00000 0.00000
  12   0.00000 0.00000 0.00000 0.00000 1.42000 0.00000 0.74000 2.16000 0.00000 0.00000
  13   0.00000 0.00000 0.00000 0.50000 0.00000 0.37000 0.48000 0.00000 0.15000 0.00000
  14   0.00000 0.00000 0.15000 0.00000 0.00000 0.00000 0.50000 0.00000 0.00000 0.00000
  15   0.00000 0.00000 0.00000 0.00000 1.17000 0.00000 0.60000 1.78000 0.18000 0.03000
  16   0.20000 0.00000 0.00000 0.53000 0.00000 0.40000 0.49000 0.00000 0.06000 0.00000
  17           4        16        47        18
  18           8
  19         7       8      36      37      40      41      43      42
  20    0.0012  0.0127  0.0160  0.0352  0.0147  0.0904  0.0237  0.8061
  21           9
  22         4       8      25      41      32      33      35      36      26
  23    0.0382  0.2827  0.0299  0.0096  0.2323  0.0023  0.0766  0.0536  0.2743
  24           5
  25         7      42      39      40      37
  26    0.0102  0.2410  0.0364  0.3495  0.3623
```

Input Data File

Column

Line No.	1234567890 (1)		1234567890 (2)		1234567890 (3)		1234567890 (4)		1234567890 (5)	
27	9									
28	7	8	21	25	40	32	33	35	26	
29	0.1606	0.0656	0.1334	0.0359	0.0606	0.0673	0.0005	0.0085	0.4672	
30	3									
31	37	43	42							
32	0.3090	0.1678	0.5232							
33	15									
34	7	8	19	22	42	26	27	28	29	33
35	37	38	39	40	25					
36	0.0018	0.0072	0.0103	0.1355	0.0303	0.2541	0.0151	0.0774	0.0209	0.0008
37	0.1697	0.0262	0.0643	0.0513	0.1244					
38	3									
39	37	43	42							
40	0.4137	0.1006	0.4830							
41	8									
42	21	37	25	27	29	33	34	22		
43	0.2199	0.0043	0.2439	0.0312	0.0216	0.0061	0.0079	0.4651		
44	4									
45	47	32	33	31						
46	0.0850	0.1698	0.1711	0.5726						
47	4									
48	34	22	33	21						
49	0.2845	0.2263	0.0790	0.4101						
50	5									
51	18	19	44	43	42					
52	0.0182	0.0088	0.1236	0.0702	0.7771					

```
--------------------------------------------------------------------------------------
Line                               Input Data File
 No.
                                       Column
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
--------------------------------------------------------------------------------------

53           19
54         1      46       6       7       8      11      12      14      15      16
55        17      18      19      20      36      37      42      44       4
56    0.2009  0.0312  0.0228  0.0007  0.0348  0.0409  0.0224  0.0219  0.0360  0.0049
57    0.0015  0.0535  0.0648  0.0097  0.0219  0.1560  0.0670  0.0084  0.1412
58           20
59         4       6       7       8       9      11      13      14      21      45
60        23      24      25      26      27      29      30      37      42      22
61    0.0267  0.0353  0.0076  0.0301  0.0354  0.0420  0.0078  0.0039  0.1469  0.0159
62    0.0750  0.1338  0.0837  0.0624  0.0223  0.0120  0.0302  0.0102  0.0064  0.1855
63            4
64         2      44      43      42
65    0.0120  0.2276  0.0537  0.7062
66           11
67         2       3       5      46       7      10      11      16      17      44
68         6
69    0.0511  0.0116  0.0334  0.0103  0.2992  0.0541  0.0881  0.0130  0.0126  0.0103
70    0.4159
71            8
72         4       5      47       7      13      21      22       6
73    0.0957  0.1188  0.1882  0.0090  0.0725  0.0543  0.1164  0.3446
74          0.30      0.20      0.50      0.80      0.20      1.00      0.90      0.00
75          0.40      0.40      0.20      0.10      0.90      0.90      0.90      0.80
76          0.00      0.45
77          0.15      0.15      0.30      0.40      0.10      0.50      0.30      0.05
78          0.15      0.15      0.15      0.80      0.50      0.40      0.40      0.02
```

Input Data File

Line No.	1	2	3	4	5	6	7	8
	1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1234567890
79	10.00	0.15						
80	0.10	0.10	0.20	0.25	0.10	0.40	0.30	0.02
81	0.15	0.15	0.10	0.10	0.35	0.25	0.25	0.02
82	0.02	0.10						
83	4	0.110	0.100	0.400	4.0	D		
84	4	0.210	0.100	0.200	7.0	C		
85	4	0.210	0.100	0.200	4.0	E		
86	2	0.240	0.110	0.350	13.0	B		
87	2	0.240	0.110	0.350	6.0	B		
88	2	0.240	0.110	0.350	18.0	B		
89	2	0.140	0.050	0.130	7.0	B		
90	2	0.210	0.100	0.200	7.0	B		
91	2	0.240	0.110	0.350	9.0	B		
92	2	0.240	0.110	0.350	12.0	B		
93	2	0.210	0.100	0.200	7.0	C		
94	2	0.210	0.100	0.200	5.0	D		
95	3	0.140	0.050	0.130	7.0	B		
96	3	0.210	0.100	0.200	7.0	C		
97	3	0.210	0.100	0.200	5.0	D		
98	3	0.210	0.100	0.200	4.0	E		
99	3	0.240	0.110	0.350	18.0	B		
100	7	0.210	0.100	0.200	5.0	D		
101	7	0.110	0.100	0.400	4.0	D		
102	7	0.210	0.100	0.200	4.0	E		
103	7	0.240	0.110	0.350	13.0	B		
104	7	0.140	0.050	0.130	7.0	B		

Input Data File

Column

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
```

Line No.						
105	7	0.240	0.110	0.350	18.0	B
106	7	0.240	0.110	0.350	9.0	B
107	7	0.210	0.100	0.200	7.0	B
108	7	0.210	0.100	0.200	12.0	B
109	7	0.210	0.100	0.200	6.0	C
110	7	0.210	0.100	0.200	12.0	C
111	7	0.110	0.100	0.200	5.0	C
112	7	0.210	0.100	0.200	7.0	C
113	4	0.240	0.110	0.350	6.0	B
114	4	0.240	0.110	0.350	13.0	B
115	4	0.240	0.110	0.350	10.0	C
116	4	0.140	0.050	0.130	7.0	B
117	4	0.210	0.100	0.200	12.0	B
118	2	0.210	0.100	0.200	6.0	C
119	6	0.110	0.100	0.400	5.0	C
120	6	0.210	0.100	0.200	12.0	B
121	6	0.210	0.100	0.200	12.0	C
122	6	0.140	0.050	0.130	7.0	B
123	6	0.210	0.100	0.200	6.0	C
124	6	0.110	0.100	0.400	4.0	D
125	6	0.040	0.040	0.400	3.0	E
126	6	0.210	0.100	0.200	4.0	E
127	6	0.210	0.100	0.200	7.0	C
128	6	0.210	0.100	0.200	5.0	D
129	8	0.0	0.0	0.0	0.0	A
130	100	5				

```
--------------------------------------------------------------------------------------
Line                                   Input Data File
 No.
                                            Column
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
--------------------------------------------------------------------------------------

131        0    0    1    0    2
132        1    2
133        3    4
134        4    2    2
135           960       190      50.1      1570
136           530        15       9.5      1860
137           280        35       2.9      1570
138           270        10       2.4      1860
139          1570       150     .0800     11.00
140          1860        50     .0400     45.00
141        4    2    2
142           310       120       3.7      1140
143          1320        90      28.8      1840
144           210        35       3.2      1140
145           380        20       8.3      1840
146          1140       140     .0900     23.00
147          1840       110     .0500     45.00
148        2    1    1
149           290        10       4.9       450
150           260         5       1.9       450
151           450         5     .0500    115.00
152        6    3    3
153           270        55       4.5      1180
154           800       115      19.5      1560
155          1170        65      26.1      1560
156           540        95       9.1      1180
```

```
--------------------------------------------------------------------------------------
Line                              Input Data File
 No.
                                       Column
              1         2         3         4         5         6         7         8
     12345678901234567890123456789012345678901234567890123456789012345678901234567890
--------------------------------------------------------------------------------------

157         370        20       5.6      1560
158         520        10      11.6      1560
159        1180       155     .0900     23.00
160        1560        90     .0700     76.00
161        1560        25     .0500    115.00

--------------------------------------------------------------------------------------
```

Appendix G

Example Output Listing

The following pages list the output data generated by the FESHM for storm event 6/24/58, Pony Mountain Branch watershed. Note that the input data file is given in Appendix F.

STORM EVENT--- 6/24/58
STARTING TIME--17:00
INITIAL MOISTURE CONDITION FOR THE WATERSHED-- DETERMINED INTERNALLY FOR EACH HRU

SUMMARY OF HYDROLOGIC RESPONSE UNITS

HRU NO	LANDUSE NO	SLOPE CLASS	MANNINGS N	DEPRESSION STORAGE	HOLTANS A	FRACTION OF AVAIL WATER	FRACTION OF GRAVITY WATER	EXPONENT C	FINAL INFIL-TRATION RATE	DEPTH OF THE A HORIZON	MAXIMUM STORAGE
1	4	D	0.250	0.160	0.800	0.110	0.100	1.100	0.400	4.00	0.84
2	4	C	0.250	0.240	0.800	0.210	0.100	2.100	0.200	7.00	2.17
3	4	E	0.250	0.080	0.800	0.210	0.100	2.100	0.200	4.00	1.24
4	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.350	13.00	1.55
5	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.350	6.00	2.10
6	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.350	18.00	6.30
7	2	B	0.100	0.120	0.200	0.140	0.050	2.800	0.130	7.00	1.33
8	2	D	0.100	0.120	0.200	0.210	0.100	2.100	0.200	7.00	2.17
9	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.35	9.00	3.15
10	2	B	0.100	0.120	0.200	0.240	0.110	2.182	0.35	12.00	4.20
11	2	C	0.100	0.090	0.200	0.210	0.100	2.100	0.200	7.00	2.17
12	2	D	0.100	0.060	0.200	0.210	0.100	2.100	0.200	5.00	1.55
13	3	B	0.200	0.240	0.500	0.140	0.050	2.800	0.130	7.00	1.33
14	3	C	0.200	0.180	0.500	0.210	0.100	2.100	0.200	7.00	2.17
15	3	D	0.200	0.120	0.500	0.210	0.100	2.100	0.200	5.00	1.55
16	3	E	0.200	0.060	0.500	0.210	0.100	2.100	0.200	4.00	1.24
17	3	B	0.200	0.240	0.500	0.240	0.110	2.182	0.350	18.00	6.30
18	7	D	0.300	0.120	0.900	0.210	0.100	2.100	0.200	5.00	1.55
19	7	D	0.300	0.120	0.900	0.110	0.100	1.100	0.400	4.00	0.84
20	7	E	0.300	0.060	0.900	0.210	0.100	2.100	0.200	4.00	1.24
21	7	B	0.300	0.240	0.900	0.240	0.110	2.182	0.350	13.00	4.55
22	7	B	0.300	0.240	0.900	0.140	0.050	2.800	0.130	7.00	1.33
23	7	B	0.300	0.240	0.900	0.240	0.110	2.182	0.350	18.00	6.30
24	7	B	0.300	0.240	0.900	0.240	0.110	2.182	0.350	9.00	3.15
25	7	B	0.300	0.240	0.900	0.210	0.100	2.100	0.200	7.00	2.17
26	7	B	0.300	0.240	0.900	0.210	0.100	2.100	0.200	12.00	3.72
27	7	C	0.300	0.180	0.900	0.210	0.100	2.100	0.200	6.00	1.86
28	7	C	0.300	0.180	0.900	0.210	0.100	2.100	0.200	12.00	3.72
29	7	C	0.300	0.180	0.900	0.110	0.100	1.100	0.200	5.00	1.05
30	7	C	0.300	0.180	0.900	0.210	0.100	2.100	0.200	7.00	2.17
31	4	B	0.250	0.320	0.800	0.240	0.110	2.182	0.350	6.00	2.10
32	4	B	0.250	0.320	0.800	0.240	0.110	2.182	0.350	13.00	4.55
33	4	C	0.250	0.240	0.800	0.240	0.110	2.182	0.350	10.00	3.50
34	4	B	0.250	0.320	0.800	0.140	0.050	2.800	0.130	7.00	1.33
35	4	B	0.250	0.320	0.800	0.210	0.100	2.100	0.200	12.00	3.72
36	2	C	0.100	0.090	0.200	0.210	0.100	2.100	0.200	6.00	1.86
37	6	C	0.400	0.300	1.000	0.110	0.100	1.100	0.400	5.00	1.05
38	6	B	0.400	0.400	1.000	0.210	0.100	2.100	0.200	12.00	3.72
39	6	C	0.400	0.300	1.000	0.210	0.100	2.100	0.200	12.00	3.72
40	6	B	0.400	0.400	1.000	0.140	0.050	2.800	0.130	7.00	1.33
41	6	C	0.400	0.300	1.000	0.210	0.100	2.100	0.200	6.00	1.86
42	6	D	0.400	0.200	1.000	0.110	0.100	1.100	0.400	4.00	0.84
43	6	E	0.400	0.100	1.000	0.040	0.040	1.000	0.400	3.00	0.24
44	6	E	0.400	0.100	1.000	0.210	0.100	2.100	0.200	4.00	1.24
45	6	C	0.400	0.300	1.000	0.210	0.100	2.100	0.200	7.00	2.17
46	6	D	0.400	0.200	1.000	0.210	0.100	2.100	0.200	5.00	1.55
47	8	A	0.020	0.050	0.000	0.000	0.000	0.000	0.000	0.00	0.00

PRECIPITATION EXCESS FOR RAINGAGE NUMBER 1

HRU PRECIPITATION EXCESS FOR EACH 15-MINUTE INCREMENT OF THE STORM

PRECIPITATION INCREMENTS FROM THE BEGINNING OF THE STORM

(Increments 9–24 are printed in the header but have no values.)

PRECIPITATION

	1	2	3	4	5	6	7	8
	0.0	0.04	0.25	0.80	0.19	0.07	0.00	0.00

PRECIPITATION EXCESS

HRU	1	2	3	4	5	6	7	8	HRU
1	0.0	0.0	0.0	0.57	0.06	0.0	0.0	0.0	1
2	0.0	0.0	0.0	0.51	0.08	0.0	0.0	0.0	2
3	0.0	0.0	0.07	0.71	0.12	0.01	0.0	0.0	3
4	0.0	0.0	0.0	0.56	0.04	0.0	0.0	0.0	4
5	0.0	0.0	0.02	0.69	0.09	0.0	0.0	0.0	5
6	0.0	0.0	0.0	0.43	0.0	0.0	0.0	0.0	6
7	0.0	0.0	0.09	0.76	0.16	0.04	0.0	0.0	7
8	0.0	0.0	0.05	0.73	0.12	0.0	0.0	0.0	8
9	0.0	0.0	0.0	0.66	0.07	0.0	0.0	0.0	9
10	0.0	0.0	0.0	0.59	0.05	0.0	0.0	0.0	10
11	0.0	0.0	0.08	0.73	0.12	0.0	0.0	0.0	11
12	0.0	0.0	0.12	0.74	0.13	0.01	0.0	0.0	12
13	0.0	0.0	0.0	0.71	0.15	0.03	0.0	0.0	13
14	0.0	0.0	0.0	0.63	0.10	0.0	0.0	0.0	14
15	0.0	0.0	0.03	0.72	0.12	0.0	0.0	0.0	15
16	0.0	0.0	0.11	0.73	0.12	0.01	0.0	0.0	16
17	0.0	0.0	0.0	0.10	0.0	0.0	0.0	0.0	17
18	0.0	0.0	0.0	0.70	0.10	0.0	0.0	0.0	18
19	0.0	0.0	0.0	0.60	0.06	0.0	0.0	0.0	19
20	0.0	0.0	0.08	0.71	0.12	0.00	0.0	0.0	20
21	0.0	0.0	0.0	0.16	0.0	0.0	0.0	0.0	21
22	0.0	0.0	0.0	0.68	0.14	0.03	0.0	0.0	22
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23
24	0.0	0.0	0.0	0.32	0.02	0.0	0.0	0.0	24
25	0.0	0.0	0.0	0.48	0.08	0.0	0.0	0.0	25
26	0.0	0.0	0.0	0.28	0.01	0.0	0.0	0.0	26
27	0.0	0.0	0.0	0.59	0.09	0.0	0.0	0.0	27
28	0.0	0.0	0.0	0.34	0.01	0.0	0.0	0.0	28
29	0.0	0.0	0.0	0.58	0.08	0.0	0.0	0.0	29
30	0.0	0.0	0.0	0.54	0.08	0.0	0.0	0.0	30
33	0.0	0.0	0.0	0.31	0.0	0.0	0.0	0.0	33
36	0.0	0.0	0.09	0.73	0.13	0.01	0.0	0.0	36
37	0.0	0.0	0.0	0.37	0.05	0.0	0.0	0.0	37
38	0.0	0.0	0.0	0.10	0.0	0.0	0.0	0.0	38
39	0.0	0.0	0.0	0.20	0.0	0.0	0.0	0.0	38
40	0.0	0.0	0.0	0.52	0.14	0.03	0.0	0.0	40
42	0.0	0.0	0.0	0.50	0.06	0.0	0.0	0.0	42
43	0.0	0.0	0.03	0.70	0.09	0.0	0.0	0.0	43
44	0.0	0.0	0.04	0.71	0.11	0.0	0.0	0.0	44
45	0.0	0.0	0.0	0.41	0.08	0.0	0.0	0.0	45
46	0.0	0.0	0.0	0.60	0.10	0.0	0.0	0.0	46
47	0.0	0.0	0.24	0.80	0.19	0.07	0.00	0.00	47

ELEMENT PRECIPITATION EXCESS FOR EACH 15-MINUTE INCREMENT OF THE STORM

PRECIPITATION INCREMENTS FROM THE BEGINNING OF THE STORM

ELE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	ELE
PRECIPITATION																									
	0.0	0.04	0.25	0.80	0.19	0.07	0.00	0.00																	
PRECIPITATION EXCESS																									
5	0.0	0.0	0.01	0.49	0.06	0.0	0.0	0.0																	5
6	0.0	0.0	0.00	0.40	0.05	0.01	0.0	0.0																	6
11	0.0	0.0	0.01	0.54	0.07	0.0	0.0	0.0																	11
12	0.0	0.0	0.01	0.53	0.07	0.00	0.0	0.0																	12
13	0.0	0.0	0.01	0.42	0.06	0.01	0.0	0.0																	13
14	0.0	0.0	0.01	0.56	0.07	0.0	0.0	0.0																	14
15	0.0	0.0	0.04	0.58	0.07	0.01	0.0	0.0																	15
16	0.0	0.0	0.05	0.58	0.08	0.02	0.00	0.00																	16

PRECIPITATION EXCESS FOR RAINGAGE NUMBER 2

HRU PRECIPITATION EXCESS FOR EACH 15-MINUTE INCREMENT OF THE STORM

PRECIPITATION INCREMENTS FROM THE BEGINNING OF THE STORM

PRECIPITATION

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
	0.0	0.04	0.20	0.75	0.27	0.09	0.01	0.0																	

PRECIPITATION EXCESS

HRU	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	HRU
1	0.0	0.0	0.0	0.45	0.11	0.0	0.0	0.0																	4
7	0.0	0.0	0.06	0.71	0.23	0.06	0.0	0.0																	7
8	0.0	0.0	0.0	0.66	0.20	0.02	0.0	0.0																	8
21	0.0	0.0	0.0	0.05	0.0	0.0	0.0	0.0																	21
22	0.0	0.0	0.0	0.66	0.22	0.05	0.0	0.0																	22
25	0.0	0.0	0.0	0.38	0.16	0.0	0.0	0.0																	25
26	0.0	0.0	0.0	0.18	0.06	0.0	0.0	0.0																	26
27	0.0	0.0	0.0	0.48	0.17	0.01	0.0	0.0																	27
29	0.0	0.0	0.0	0.47	0.16	0.0	0.0	0.0																	29
31	0.0	0.0	0.0	0.26	0.14	0.0	0.0	0.0																	31
32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0																	32
33	0.0	0.0	0.0	0.21	0.06	0.0	0.0	0.0																	33
34	0.0	0.0	0.0	0.49	0.22	0.04	0.0	0.0																	34
35	0.0	0.0	0.0	0.13	0.07	0.0	0.0	0.0																	35
36	0.0	0.0	0.03	0.68	0.20	0.03	0.0	0.0																	36
37	0.0	0.0	0.0	0.27	0.12	0.0	0.0	0.0																	37
39	0.0	0.0	0.0	0.12	0.06	0.0	0.0	0.0																	39
40	0.0	0.0	0.0	0.64	0.22	0.05	0.0	0.0																	40
41	0.0	0.0	0.0	0.32	0.16	0.0	0.0	0.0																	41
42	0.0	0.0	0.0	0.39	0.13	0.0	0.0	0.0																	42
43	0.0	0.0	0.0	0.63	0.17	0.0	0.0	0.0																	43
47	0.0	0.04	0.20	0.75	0.27	0.09	0.01	0.0																	47

ELEMENT PRECIPITATION EXCESS FOR EACH 15-MINUTE INCREMENT OF THE STORM

PRECIPITATION INCREMENTS FROM THE BEGINNING OF THE STORM

ELE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	ELE
PRECIPITATION																									
	0.0	0.04	0.20	0.75	0.27	0.09	0.01	0.0																	
PRECIPITATION EXCESS																									
1	0.0	0.0	0.00	0.40	0.14	0.00	0.0	0.0																	1
2	0.0	0.0	0.00	0.31	0.10	0.01	0.0	0.0																	2
3	0.0	0.0	0.00	0.43	0.16	0.02	0.0	0.0																	3
4	0.0	0.0	0.01	0.30	0.10	0.01	0.0	0.0																	4
7	0.0	0.0	0.0	0.36	0.13	0.0	0.0	0.0																	7
8	0.0	0.0	0.0	0.44	0.15	0.02	0.0	0.0																	8
9	0.0	0.00	0.02	0.25	0.11	0.01	0.00	0.0																	9
10	0.0	0.0	0.0	0.33	0.12	0.02	0.0	0.0																	10

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ROUTING TIME INCREMENT FOR OVERLAND FLOW-- 100 SECONDS
ROUTING TIME INCREMENT FOR CHANNEL FLOW--    5 SECONDS
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OVERLAND FLOW INFORMATION FOR SUB-SHED NUMBER 1

OVERLAND FLOW STRIP NUMBER	ELEMENT NUMBER	ELEMENT AREA (ACRES)	ELEMENT LENGTH	ELEMENT RELIEF	ELEMENT SLOPE	ELEMENT MANNING N	NODE NUMBER	NODE WIDTH
1	1	50.1	960.0	190.0	0.198	0.391	2	1570.0

FLOW CHARACTERISTICS AT THE LAST NODE OF THE STRIP

TIME	DISCHARGE	AREA	RATE	DEPTH
0.17	0.0	0.0	0.0	0.0
0.33	0.0	0.0	0.0	0.0
0.50	0.0	0.0	0.0	0.0
0.67	0.00	0.07	0.00	0.00
0.83	2.65	25.01	0.11	0.02
1.00	16.10	73.71	0.22	0.05
1.17	24.56	94.94	0.26	0.06
1.33	28.08	102.85	0.27	0.07
1.50	22.98	91.22	0.25	0.06
1.67	16.69	75.33	0.22	0.05
1.83	11.75	61.05	0.19	0.04
2.00	8.33	49.70	0.17	0.03
2.17	6.04	40.98	0.15	0.03
2.33	4.48	34.29	0.13	0.02
2.50	3.41	29.10	0.12	0.02
2.67	2.65	25.02	0.11	0.02
2.83	2.10	21.76	0.10	0.01
3.00	1.69	19.12	0.09	0.01

OVERLAND FLOW STRIP NUMBER	ELEMENT NUMBER	ELEMENT AREA (ACRES)	ELEMENT LENGTH	ELEMENT RELIEF	ELEMENT SLOPE	ELEMENT MANNING N	NODE NUMBER	NODE WIDTH
2	1	9.5	530.0	15.0	0.028	0.210	2	1860.0

FLOW CHARACTERISTICS AT THE LAST NODE OF THE STRIP

TIME	DISCHARGE	AREA	RATE	DEPTH
0.17	0.0	0.0	0.0	0.0
0.33	0.0	0.0	0.0	0.0
0.50	0.0	0.0	0.0	0.0
0.67	0.00	0.07	0.00	0.00
0.83	0.19	6.90	0.03	0.00
1.00	1.16	20.15	0.06	0.01
1.17	1.60	24.45	0.07	0.01
1.33	1.94	27.48	0.07	0.01
1.50	2.06	28.45	0.07	0.02
1.67	2.04	28.27	0.07	0.02
1.83	1.91	27.19	0.07	0.01
2.00	1.71	25.47	0.07	0.01
2.17	1.49	23.46	0.06	0.01
2.33	1.28	21.38	0.06	0.01
2.50	1.09	19.39	0.06	0.01
2.67	0.92	17.55	0.05	0.01
2.83	0.78	15.89	0.05	0.01
3.00	0.66	14.42	0.05	0.01

OVERLAND FLOW STRIP NUMBER	ELEMENT NUMBER	ELEMENT AREA (ACRES)	ELEMENT LENGTH	ELEMENT RELIEF	ELEMENT SLOPE	ELEMENT MANNING N	NODE NUMBER	NODE WIDTH
3	1	2.9	200.0	35.0	0.125	0.397	2	1570.0

FLOW CHARACTERISTICS AT THE LAST NODE OF THE STRIP

TIME	DISCHARGE	AREA	RATE	DEPTH
0.17	0.0	0.0	0.0	0.0
0.33	0.0	0.0	0.0	0.0
0.50	0.0	0.0	0.0	0.0
0.67	0.00	0.02	0.00	0.00
0.83	0.16	5.34	0.03	0.00
1.00	0.95	15.72	0.06	0.01
1.17	1.48	20.42	0.07	0.01
1.33	1.75	22.63	0.08	0.01
1.50	1.52	20.78	0.07	0.01
1.67	1.13	17.39	0.07	0.01
1.83	0.81	14.21	0.06	0.01
2.00	0.58	11.62	0.05	0.01
2.17	0.42	9.60	0.04	0.01
2.33	0.31	8.04	0.04	0.01
2.50	0.24	6.83	0.03	0.00
2.67	0.18	5.87	0.03	0.00
2.83	0.15	5.10	0.03	0.00
3.00	0.12	4.48	0.03	0.00

OVERLAND FLOW STRIP NUMBER	ELEMENT NUMBER	ELEMENT AREA (ACRES)	ELEMENT LENGTH	ELEMENT RELIEF	ELEMENT SLOPE	ELEMENT MANNING N	NODE NUMBER	NODE WIDTH
4	1	2.4	270.0	10.0	0.037	0.257	2	1860.0

FLOW CHARACTERISTICS AT THE LAST NODE OF THE STRIP

TIME	DISCHARGE	AREA	RATE	DEPTH
0.17	0.0	0.0	0.0	0.0
0.33	0.0	0.0	0.0	0.0
0.50	0.0	0.0	0.0	0.0
0.67	0.00	0.21	0.00	0.00
0.83	0.06	3.54	0.02	0.00
1.00	0.33	9.83	0.03	0.01
1.17	0.46	11.99	0.04	0.01
1.33	0.56	13.61	0.04	0.01
1.50	0.60	14.11	0.04	0.01
1.67	0.57	13.75	0.04	0.01
1.83	0.52	12.90	0.04	0.01
2.00	0.44	11.79	0.04	0.01
2.17	0.37	10.61	0.04	0.01
2.33	0.31	9.48	0.03	0.01
2.50	0.25	8.46	0.03	0.00
2.67	0.21	7.56	0.03	0.00
2.83	0.18	6.77	0.03	0.00
3.00	0.15	6.09	0.02	0.00

CHANNEL FLOW INFORMATION FOR SUB-SHED NUMBER 1

ELEMENT NUMBER	ELEMENT LENGTH	ELEMENT RELIEF	ELEMENT SLOPE	ELEMENT MANNING N	NODE NUMBER	NODE TOP WIDTH AT 2 FT DEPTH
1	1570.0	150.0	0.096	0.080	2	11.0
2	1860.0	50.0	0.027	0.040	3	45.0

		NODE 1				NODE 2				NODE 3		
TIME	DISCHARGE	AREA	RATE	DEPTH	DISCHARGE	AREA	RATE	DEPTH	DISCHARGE	AREA	RATE	DEPTH
0.08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.58	0.0	0.00	0.0	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00
0.67	0.0	0.00	0.0	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.00
0.75	0.0	0.00	0.0	0.00	0.00	0.00	0.03	0.01	0.00	0.00	0.03	0.01
0.83	0.0	0.36	0.0	0.03	0.15	0.16	0.95	0.24	0.0	-0.04	0.0	-0.06
0.92	0.0	1.69	0.0	0.07	1.75	0.82	2.13	0.55	0.0	-0.05	0.0	-0.07
1.00	0.0	3.86	0.0	0.10	7.48	2.19	3.41	0.89	0.76	0.52	1.46	0.22
1.08	0.0	5.28	0.0	0.12	16.67	3.77	4.42	1.17	6.85	2.26	3.03	0.45
1.17	0.0	5.65	0.0	0.13	24.99	4.96	5.03	1.34	17.87	4.28	4.17	0.62
1.25	0.0	5.65	0.0	0.13	30.43	5.68	5.36	1.44	27.45	5.70	4.81	0.71
1.33	0.0	5.24	0.0	0.12	31.66	5.83	5.43	1.46	32.85	6.43	5.11	0.76
1.42	0.0	4.66	0.0	0.12	29.76	5.59	5.32	1.43	33.59	6.52	5.15	0.76
1.50	0.0	4.10	0.0	0.11	26.62	5.18	5.14	1.37	31.64	6.27	5.05	0.75
1.58	0.0	3.56	0.0	0.10	23.14	4.71	4.91	1.31	28.61	5.86	4.88	0.72
1.67	0.0	3.07	0.0	0.09	19.76	4.23	4.67	1.24	25.27	5.39	4.68	0.69
1.75	0.0	2.63	0.0	0.09	16.71	3.78	4.42	1.17	22.02	4.92	4.48	0.66
1.83	0.0	2.26	0.0	0.08	14.07	3.36	4.19	1.11	19.07	4.47	4.27	0.63
1.92	0.0	1.94	0.0	0.07	11.86	2.99	3.96	1.04	16.47	4.05	4.06	0.60
2.00	0.0	1.67	0.0	0.07	10.03	2.67	3.75	0.99	14.24	3.68	3.87	0.57
2.08	0.0	1.45	0.0	0.06	8.52	2.39	3.56	0.93	12.34	3.34	3.69	0.55
2.17	0.0	1.26	0.0	0.06	7.28	2.15	3.38	0.88	10.73	3.05	3.52	0.52
2.25	0.0	1.11	0.0	0.06	6.25	1.94	3.22	0.84	9.37	2.78	3.37	0.50
2.33	0.0	0.97	0.0	0.05	5.40	1.76	3.07	0.80	8.22	2.55	3.22	0.48
2.42	0.0	0.86	0.0	0.05	4.69	1.60	2.93	0.76	7.24	2.34	3.09	0.46
2.50	0.0	0.77	0.0	0.05	4.10	1.46	2.81	0.73	6.40	2.16	2.97	0.44
2.58	0.0	0.69	0.0	0.04	3.60	1.34	2.69	0.70	5.69	1.99	2.85	0.42
2.67	0.0	0.62	0.0	0.04	3.18	1.23	2.58	0.67	5.07	1.85	2.75	0.41
2.75	0.0	0.56	0.0	0.04	2.82	1.13	2.48	0.64	4.54	1.72	2.65	0.39
2.83	0.0	0.51	0.0	0.04	2.51	1.05	2.39	0.62	4.08	1.60	2.55	0.38
2.92	0.0	0.46	0.0	0.04	2.24	0.97	2.31	0.59	3.68	1.49	2.47	0.36
3.00	0.0	0.42	0.0	0.03	2.02	0.90	2.23	0.57	3.32	1.39	2.38	0.35

CHANNEL FLOW FOR IMAGINARY SUB-SHED NUMBER 5

TIME	DISCHARGE
0.08	0.0
0.17	0.0
0.25	0.0
0.33	0.00
0.42	0.00
0.50	0.00
0.58	0.01
0.67	0.02
0.75	0.03
0.83	0.67
0.92	3.29
1.00	14.30
1.08	44.17
1.17	78.41
1.25	93.42
1.33	92.96
1.42	86.30
1.50	78.27
1.58	69.93
1.67	61.59
1.75	53.69
1.83	46.66
1.92	40.69
2.00	35.73
2.08	31.63
2.17	28.21
2.25	25.32
2.33	22.85
2.42	20.72
2.50	18.87
2.58	17.24
2.67	15.82
2.75	14.55
2.83	13.43
2.92	12.43
3.00	11.54

CHAPTER X

VITA

The author was born in La Plata, Maryland on September 4, 1952. He lived in Mechanicsville, Virginia from eleven years of age until graduation from Lee-Davis High School in 1970.

He attended Bluefield College in Bluefield, Virginia and received an Associate of Science degree in Engineering in May, 1972. After graduation he transferred to Virginia Polytechnic Institute and State University where he received a Bachelor of Science degree in Civil Engineering in June, 1974. In the fall of 1974, he began his graduate studies at VPI&SU and completed the requirements for a Master of Science degree in Civil Engineering in November, 1975.

In January of 1976, the author began his studies in the Department of Agricultural Engineering at VPI&SU toward a Ph.D. degree in Environmental Sciences and Engineering.

Burton Blakely Ross

A SPATIALLY RESPONSIVE CATCHMENT MODEL FOR PREDICTING STORMWATER RUNOFF FROM UNGAGED WATERSHEDS

by

Burton Blakeley Ross

(ABSTRACT)

A computer model, the Finite Element Storm Hydrograph Model (FESHM), was developed to integrate spatiotemporal variability in climatic and watershed descriptors into a model structure to determine stormwater runoff from small watersheds. The model consisted of two major components: a rainfall excess generator and a flood routing algorithm.

The Holtan infiltration equation was used as the basis of a soil moisture routine to estimate rainfall excess from a given rainfall distribution. The finite element technique, with Galerkin's residual method, was used to provide a numerical solution of the equations of continuity and momentum for one-dimensional transient flow for routing overland and channel flow through a drainage system.

A spatially responsive modeling concept was assumed. To implement this concept the watershed was discretized into hydrologic response units (HRU's) based on soil mapping units and landuse to improve estimates of rainfall excess. The watershed's topography and drainage patterns were used to define finite elements to improve the accuracy of flow

routing. These two discretization schemes resulted in poor geometric registration. This problem was resolved by a linear weighting of the rainfall excess from each HRU located within a given element as function of the area occupied by the HRU to the total element area. Spatial uniqueness was maintained on a relatively small scale.

Sufficient flexibility was incorporated into the model to allow varying levels of discretization without rebuilding the model structure. Procedures were developed for defining model parameters for application of the model in an ungaged context. The effect of landuse changes on the hydrologic response of a watershed can be, at least, conceptually evaluated with this model structure. A modeling framework also is provided for the prediction of water quality.

A hypothetical watershed was used to conduct a sensitivity analysis of model parameters. Six experimental watersheds located in different physiographic regions of Virginia were used to evaluate the capability of the model to predict stormwater flow for flood-producing events in an ungaged context. Comparison of simulated and recorded hydrographs ranged from good to excellent.