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# ABSTRACT

This research, which developed a distributed parameter model for simulating runoff in ungaged areas, can assist in nonpoint pollution control planning efforts. The sediment detachment and transport component of this finite element storm hydrograph model (FESHM) enables its additional use for simulating erosion processes which result from runoff. Though not dependent on calibration, the FESHM, when applied to field-scale areas, does require extensive information on the field's soils, topography, and cover characteristics.

Application of the FESHM, however, is not limited to field-scale areas. Although most research using the model has been conducted on watersheds of 2 to 1,000 acres, it has performed adequately on watersheds as large as 193 square miles. The FESHM's hydrologic section compares favorably with other watershed models currently in use (ANSWERS, HEC-1, TR-20, and USGS State Equations), in terms of data preparation and execution costs. A sediment washload capability has been demonstrated but presently remains unverified. Work is progressing toward verification.

Key Words: Watershed Model, Land Use Model, Finite Element Model, Hydrologic Model, Water Quality Model, Distributed Parameter Model, Sediment Model, Overland Flow, Spatial Variability, Washload, Stormwater Runoff

# INTRODUCTION

In recent years, eroded soil and resulting sedimentation have been recognized as the major water pollutant of rural areas. In general, soil erosion removes productive soil and plant nutrients from the land surface, resulting in reduced land fertility, gully formation, and a degradation of receiving streams and lakes.

The erosion-sedimentation process is a part of the natural hydrologic system. Man's activity within a watershed, however, has the effect of accelerating the erosion process to the point where the land and water resources may be rapidly degraded. Maintaining these resources for future generations requires that improved land use practices be implemented through a carefully planned sequence. To achieve public acceptance, such practices must be shown to be capable of achieving the stated environmental goals and of being implemented within the constraints of the economy. This implies that cause-effect relationships can be defined and demonstrated in specific situations. The research discussed in this report deals with computer simulation techniques that may be appropriate to this task.

Environmental planning, such as that mandated under section 208 of P.L. 92-500 requires that planning agencies have at their disposal procedures for evaluating alternative actions and selecting those which are most promising. Computer simulation techniques are increasingly important tools for this purpose. It must be stated, however, that the simulation technique used for nonpoint pollution control planning must be based on a reliable model of watershed hydrology.

To meet these needs, a long-range goal of our hydrologic research program in the Department of Agricultural Engineering at Virginia Tech is the development of a distributed parameter 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 mathematical model that can interact with a geographic information system containing soils, topography, and land use data. The modeling system is being 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-operation level to be accessed by farm managers to estimate chemical status and erosion potential of specific field areas as an aid in making management decisions.

The specific emphasis of our hydrologic studies has been to develop a versatile and accurate model to provide a framework for analysis of hydrology-related phenomena such as sediment and chemical transport in a complex watershed. Through a natural progression, our research evolved from lumped parameter models, in which all relevant hydrologic processes were represented as averaged processes, to the distributed parameter model, in which processes are conceived as occurring independently in spatially distinct sections of the watershed. The distributed parameter approach was ultimately selected because of the need to assign a priori estimates of model parameters for most model applications.

The distributed parameter model allows the user to assign these parameter estimates to limited geographic areas within the watershed instead of estimating some average watershed value. By limiting the domain of model parameter estimates to spatially distinct sub-watershed areas, the model parameters have a direct physical meaning rather than a strictly conceptual meaning. The attributes of distributed parameter and lumped models were summarized by Huggins et al. [1977] in their definition of a distributed parameter model as:

> one which incorporates the influences of the spatial variation of controlling parameters, e.g., topography, soil types, vegetation, etc., in a manner internal to its computational algorithms. In contrast, the more commonly employed lumped model approach is one which incorporates, to whatever degree they are not ignored, these effects by an appropriate analysis on a case-by-case basis. In other words, the lumped approach uses some type of averaging technique to generate an "effective" coefficient(s) for characterizing the influence of specific non-uniform distributions of each parameter. The influence of this distribution is then represented by the "lumped" coefficients, and the resulting model is treated as a mathematical transformation of input into output, i.e., a "black box," for the subsequent simulation.

Huggins et al. further state the following principal advantages of the distributed parameter approach:

1. [The distributed parameter analysis has the advantage of] providing a more accurate simulation of natural catchment behavior . . . [by removing] the assumptions and limitations of behaving, at least to some degree, as a linear system [which is] subtly imposed on lumped models.

2. [Lumped parameter models ignore] the influence of geographic placement of spatially varying factors within the catchment boundaries. The magnitude of error associated with such approximations has been demonstrated by Huggins et al. [1973].

3. [It has the] inherent ability to simultaneously model conditions at all points within the watershed. This readily permits the simulation of processes that change both spatially and temporally throughout the catchment. The accuracy with which interacting processes can be modeled is thereby increased. In addition, a great deal more information about the simulated process is available to planners.

4. Distributed models greatly facilitate incorporation of relationships developed from small scale "plot-size" studies to yield predictions on a watershed scale. It is much easier to formulate the individual processes being modeled as independent equations applicable at a point, letting the subsequent model integration process incorporate effects of spatial and temporal variability, than to develop an elaborate weighting function for each process. This approach also directly accounts for process interactions that would otherwise be ignored or require complex modifications of weighting functions.

The purpose of this report is to present a distributed parameter model structure to simulate the hydrologic and water quality impacts of alternative management control practices.

A brief review of techniques for describing spatial variability is followed by a method of modeling sediment processes. The literature review is followed by the hydrology and erosion components of a distributed parameter model, the Finite Element Storm Hydrograph Model (FESHM). Several natural watersheds are used to highlight specific attributes of the modeling concept.

## REVIEW OF TECHNIQUES FOR DEFINING SPATIAL VARIABILITY

The spatial variability of soils, land use, topography, etc., has been recognized for many years as the primary cause of the "noise" observed in runoff predictions. This phenomenon has attracted the interest of hydrologists and others for many years. For example, more than 50 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 land use treatment to be evaluated. Much later, Amerman [1965] utilized unit source areas (areas consisting of single cover and soil type) to subdivide a watershed conceptually into physically homogeneous unit source watersheds.

Betson [1964] examined the unit source concept by applying mathematical models to two small watersheds. He determined that only 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. This concept of contributing and noncontributing areas has since been referred to as Partial Area Hydrology.

The partial area concept represents one of the first attempts to accommodate the heterogeneous factors that contribute to runoff from a natural drainage basin. Ragan [1968] conducted a field investigation of watersheds to determine the partial area contributions to watershed response. His results supported the concept that only a small portion of the watershed contributed directly 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.

Engman and Rogowski [1974] developed a storm hydrograph model that utilized a variable source area to supply surface runoff. The ability of the model to predict runoff response on ungaged watersheds was viewed optimistically because partial source areas could be identified with the model.

England and Onstad [1968] offered a discretization scheme when they suggested that a complex drainage system can be subdivided into an elevational sequence of upland, hillside, and bottom land. Later, England [1970] proposed the use of land capability classes to define these three land form sequences. A major disadvantage with this approach was the need to lump spatially distinct areas, whose only similarity is their position, in the elevational sequence. This approach would be sufficient in a unit source watershed, but in a complex watershed, this level of discretization would be insignificant.

Rogowski [1972] evaluated soil variability criteria and concluded that the smallest area of significance is likely to be a soil series. Kirkby and Chorley [1967], Beckett and Webster [1971], and Nielsen, Biggar, and Erh [1973] conducted studies that confirm the existence of significant spatial variability in the water properties of soils that lead to spatial variability in runoff.

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.

Recently, investigators—including Peck, Luxmoore, and Stolzy [1977] and Warrick, Mullen, and Nielsen [1977]—investigated soil variability in an effort to determine its effect upon water budget components. Peck, Luxmoore, and Stolzy utilized scaling theory to incorporate spatial variability where the scaling factor was assumed to be normally distributed. Warrick, Mullen, and Nielsen attempted to describe spatial behavior of soil hydrologic characteristics with a similar media concept.

Rogowski [1980], utilizing methods of geostatistics from Journel and Huijbregts [1978], attempted to describe hydrologic parameters on a mine spoil. This appears to be a promising technique for quantifying random spatial variability.

Huggins and Monke [1966] presented the underlying concept of a spatially responsive model which could account for partial area hydrology as well as other spatial effects:

> 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.

Li [1975] and Ross [1975] presented a technique for organizing a spatially discretized data base utilizing the concepts of unique hydrologic characteristics assignable by soil series, elevational sequence, and land use. Their system has separate data planes for soils, topography, and land use and interfaces with a distributed parameter model. Soil-mapping unit/land use combinations were suggested as the basis for defining land units that would respond similarly to a given rainfall distribution. This concept was combined with finite element theory to create a distributed parameter model in which hydrologically similar land units could be grouped for computational efficiency. This allows the model to maintain the area's spatial character at different levels of resolution and reduces the computational load to that required for only the minimum number of distinct hydrologic units.

## REVIEW OF MODELS OF SEDIMENT PROCESSES

Early attempts by planning and design agencies to estimate sediment yield involved intensive monitoring and efforts to extrapolate short-term data to predict the recurrence of extreme events. A method which relies solely upon historic data, however, could contain errors inherent in data collection and extrapolation.

Other early attempts used statistical techniques to relate watershed factors to soil erosion. The most familiar of these are the Musgrave equation [Musgrave, 1949] and the Universal Soil Loss Equation (USLE) [Wischmeier and Smith, 1965]. These equations do not account for deposition in transport to the receiving stream, although attempts have been made to modify them to include sedimentation. The USLE has been found to provide adequate estimates of annual soil erosion, but poor estimates of soil erosion from single storms [Wischmeier, 1976]. Sediment and nutrient movement occurring from individual storms may account for the most severe water quality problems. Attempts to describe the hydrologic response from storm events has revealed the need for a better understanding of why watersheds respond the way they do [Decoursey and Meyer, 1976].

Several modified forms of the Musgrave equation and the USLE have been developed to address this problem (see, for example, Beer, Farnham, and Heinemann [1966], Renfro [1975], and Williams [1975]). Estimates of soil loss obtained by these equations do not give an indication of the amount of deposition and sediment yield. Sediment/delivery ratios based upon estimates of gross erosion have been used for the determination of sediment yield. The determination of a sediment/delivery ratio requires prior knowledge of the gross erosion and sediment yield quantities at a given point. Anderson [1957] and Roehl [1962] developed techniques to estimate the sediment/delivery ratio from readily determinable watershed factors.

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

A detailed discussion of formulas that have been developed will not be presented here; however, excellent descriptions are given by Raudkivi [1976] and Graf [1971]. These various sediment transport relationships differ greatly in their predictive capabilities. Errors in excess of 100 percent have been encountered in their use [Vanoni, 1972]. In response to this consideration, attempts have been made to develop more complete simulation models. Several approaches that consider the watershed as a whole are discussed below.

Ellison [1945] was apparently the first to recognize and to attempt to analyze independently the four subprocesses of detachment and transport by rainfall and runoff which contribute to the overall upland erosion phenomenon. 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 was based upon Ellison's 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 the authors recognized that knowledge of the interrelationship among the four was inadequate. Soil to be routed was defined as a function of the quantities of soil detached and transport capacity. A slope was divided into segments to route the soil. Transport capacity was compared to sediment load in each segment and the remainder was deposited. These concepts have been applied by several investigators to develop models describing erosion and sediment transport.

David and Beer [1975] developed an erosion model and used the Kentucky Watershed Model (KWM) [Ross, 1970] to obtain estimates of overland flow. Daily recorded streamflow was used in lieu of simulated streamflow to minimize errors in determining channel scour rates. Each of the four components of the erosion process was 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.

This model was applied to a small agricultural watershed and reasonable accuracy was reported for daily, monthly, and annual suspended sediment loads. Also, David and Beer [1975] stated that the KWM and these erosion models could not be applied to a large watershed without subdividing to reflect the diverse nature of the factors affecting erosion and sedimentation rates.

An event model to predict runoff, sediment, and pesticide transport was developed by Bruce et al. [1975]. The concepts developed by Foster and Meyer [1975] were used to estimate rill and inter-rill erosion. When the transport capacity was less than detached sediment, the rill concentration was reduced to zero before reducing detached inter-rill concentration. Simulated sediment transport results were good; however, these results were calibrated after a separate calibration had been performed on the hydrology component of the model. The authors concluded that refinements were needed to define parameters in terms of measurable physical system quantities.

Onstad and Foster [1975] developed a mathematical procedure to determine sediment yield for individual storms as a function of detachment and transport by rainfall and runoff, utilizing concepts developed in the Agricultural Chemical Transport Model (ACTMO) [Frere, Onstad, and Holtan, 1975]. They modified the USLE to include both rainfall and runoff energy to estimate the total soil detached. An attempt was made to define both rill and inter-rill contributions of sediment.

To apply the model, the watershed was defined in terms of its slope segments. Detachment and transport capacity were determined for each segment. Deposition and sediment yield were 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 lost 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.

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. In the model, a watershed can be subdivided into a maximum of 20 zones, or subplots, each having unique hydrologic properties, although land use 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 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 was quantified. A channel component was also included for routing the washload and bed load.

Simulation results were considered to be acceptable. Comparison with other techniques for predicting sediment load, such as statistical methods, resulted in the conclusion that the distributed parameter model was more accurate. Also, the authors state that the model is more applicable for describing the hydrologic response of a watershed due to a land use change.

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 its adjacent grids, and deposition was determined as the difference between detachment and transport capacity. Soil loss and deposition for each grid were determined to define 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.

For predicting runoff and sediment yield, Simons, Li, and Ward [1977] developed a small basin event model. Detachment is attributed to both raindrop impact and overland flow. Transport capacity functions were structured so as to be responsive to different particle sizes. Beasley, Monke, and Huggins [1977] developed the Areal Nonpoint 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. 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 computed in each element. The sediment transported out of an element was then passed to its next element in the down-slope direction. 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.

DeCoursey and Meyer [1976] suggested that a distributed parameter model fitted to an erosion model such as Smith's [1976] deterministic model provides a system whereby the effect of tillage can be evaluated. They further noted that soil moisture distribution models should be based on models used to predict crop canopy because of the need for a dynamic system. A concept is described by DeCoursey and Meyer for combining hydrologic, infiltration, moisture distribution, and crop growth models with rill/inter-rill erosion models to provide a dynamic simulation to evaluate land management alternatives.

These concepts were incorporated into a dynamic simulation system by DeCoursey, Alonso, and Bolton [1978]. Relationships were assumed to compute soil detachment due to raindrop impact, surface runoff, and transport capacity. Transport equations utilizing sedimentation mechanics were used for routing sediment in the channel. Knisel [1980] developed a field scale model, CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems), to assess nonpoint source pollution and to evaluate various land management practices. Model components included are hydrology, erosion/sediment yield, and chemical transport. A modification of the USLE [Foster and Meyer, 1975] was used to describe inter-rill and rill soil detachment. The Yalin [1963] transport equation was modified to apply to a mixture of particle sizes and densities in overland sediment transport. Erosion and transport of sediment in the channels are also included in the model.

## MODEL STRUCTURE

During the past several years, an attempt has been made to develop a distributed parameter model to provide flow predictions 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. Model documentation and concepts are discussed extensively by Judah [1973]; Judah, Shanholtz, and Contractor [1975]; Li [1975]; Ross [1975, 1978]; Ross et al. [1978]; and Shanholtz, Ross, and Carr [1981]. To provide continuity, a brief discussion of these concepts follows.

### I. Hydrology Component

A computer model, FESHM, was developed to integrate spatiotemporal variability in climatic and watershed descriptors. The model consisted of two major components: a precipitation excess generator and a flood routing algorithm. The first part, a precipitation excess generator, calculates the precipitation excess from each element. The second part routes the excess along overland flow elements and finally down the stream channel elements.

### A. Precipitation Excess

The calculation of rainfall excess depends on the spatial distribution of two watershed characteristics—land use and soil-mapping units. A map of land use patterns is superimposed on a map, defining soils to create a hydrologic response unit map. Each area with a unique land use and soil-mapping unit combination is referred to as a hydrologic response unit (HRU). A given rainfall on the watershed will result in a different amount of precipitation excess from each of the HRU's. The amount of precipitation excess is determined from a soil moisture accounting model that uses the Holtan [1961] equation to describe the infiltration process. This infiltration model has been applied to a wide range of data by Shanholtz and Lillard [1970] and Holtan et al. [1975] with reasonable success. 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:

$$f = GI\, a\, S^c + f_c \tag{1}$$

where:

$f$ = infiltration rate in inches per hour;

$GI$ = seasonal factor to index the effect of seasonal changes in cover on infiltration;

$a$ = coefficient for indexing the effect of cover conditions;

$S$ = unfilled storage space to a restrictive layer, in inches, with the maximum value usually assumed to be the depth of the soil's *A* horizon;

$f_c$ = constant infiltration rate after prolonged wetting, in inches per hour; and

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

### B. Flow Routing

The second part of the FESHM routes precipitation excess to the outlet of the watershed. To accomplish this, the watershed is divided into overland flow and streamflow elements as shown in *Figure 1.* The number of elements to be used depends on the hydraulic and hydrologic heterogeneity of the watershed. The HRU's that occur in each overland flow element are cataloged. The runoff from each HRU, simplified by the precipitation excess subroutine, is weighted by its fractional area in the element. This runoff is then routed through overland flow elements using a finite element approximation of the kinematic wave theory.

The two equations to be solved are the continuity equation and a resistance equation (Mannings). Thus:

$$\partial Q/\partial X + \partial A/\partial t - q = 0 \tag{2}$$

$$Q = 1.49/n \; R^{2/3} \; AS^{0.5} \tag{3}$$

where:

$Q$ = discharge in the overland flow plane or channel;

$q$ = lateral inflow per unit length of flow plane (rainfall excess for the overland flow plane and overland flow output for the channel);

$A$ = cross-sectional area of flow in the channel or overland flow plane;

$x$ = distance in the direction of flow;

$t$ = time;

$R$ = hydraulic radius;

$S$ = bed slope of the flow plane; and

$n$ = Manning's roughness coefficient.

Using the Galerkin technique and linear variation of parameters within an element, the element equations become:

$$\ell \begin{bmatrix}1/3 & 1/6\\ 1/6 & 1/3\end{bmatrix}\begin{Bmatrix}\dot{A}_1\\ \dot{A}_2\end{Bmatrix} + \begin{bmatrix}-1/2 & 1/2\\ -1/2 & 1/2\end{bmatrix}\begin{Bmatrix}Q_1\\ Q_2\end{Bmatrix} - \ell q\begin{Bmatrix}1/2\\ 1/2\end{Bmatrix} = 0 \tag{4}$$

The time differential of the area is replaced by a simple finite difference approximation. Thus:

$$\dot{A}(t) = [A(t+\Delta t) - A(t)]/\Delta t \tag{5}$$

The final element equation is:

$$\ell/\Delta t \begin{bmatrix}1/3 & 1/6\\ 1/6 & 1/3\end{bmatrix}\begin{Bmatrix}A_1\\ A_2\end{Bmatrix}_{t+\Delta t} - \ell/\Delta t \begin{bmatrix}1/3 & 1/6\\ 1/6 & 1/3\end{bmatrix}\begin{Bmatrix}A_1\\ A_2\end{Bmatrix}_t$$

$$+ \begin{bmatrix} -1/2 & 1/2 \\ -1/2 & 1/2 \end{bmatrix} \begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix}_t - \ell q \begin{Bmatrix} 1/2 \\ 1/2 \end{Bmatrix} = 0 \qquad (6)$$

The time increment $\Delta t$ to be used is obtained from numerical stability analysis using the von Neumann technique. The analysis shows that the numerical scheme is unconditionally unstable. However, error amplification is minimal when the following two conditions are met:

$$\Delta t \leqslant k_1 \; A/q \quad \text{and} \quad \Delta t \leqslant k_2 \; \ell/V \qquad (7)$$

Reasonable values for $k_1$ and $k_2$ are 0.1 and 0.15 [Contractor, Ross, and Shanholtz, 1980].

The element equations are assembled into a final stiffness matrix in the standard way described in finite element texts, for example, Desai and Abel [1972].

### II. Sediment Component

Distributed models are aptly suited for simulation of erosion and sediment transport. Sediment processes may be simulated for upland and lowland phases in the context of overland and channel flow, respectively. A flexible grid is used to improve simulations of upland and lowland phases of erosion and sediment transport. When sufficient data are available, any point in the watershed may be assigned to the overland or channel flow regime. For example, assume a watershed discretization exists, and the effect of placing a sediment detention pond in a given element is needed. The element is subdivided at the location in question so that the sediment is routed to and through the structure by its natural channel conveyance system.

Another advantage of distributed models is the capability of including spatial variations. The need for sediment models to consider spatial variations in watershed systems has been recognized by many investigators. For example, Glymph [1975] states:

> 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.

In a state-of-the-art overview of nonpoint sources of pollution, Sweeten and Reddell [1976] state:

> 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.

Soil erosion as related to nonpoint pollution can be considered as two processes—detachment of particles from the soil mass and transport of these particles into streams. The detachment of soil particles may be described by two processes. The first is a function of the kinetic energy of rainfall while the second process involves shear and lift forces generated by overland flow. After investigation of numerous relationships to predict sediment processes, the approach suggested by Beasley, Monke, and Huggins [1977] was selected. A description of the approach follows.

#### A. Upland Phase

Detachment by raindrop impact is estimated by the following relationship:

$$D_R = 0.027 \; C \; K \; A \; I^2 \qquad (8)$$

where:

$D_R$ = rainfall impact detachment rate in kg/min;

$C$ = cropping and management factor (from the USLE);

$K$ = soil erosivity factor (from the USLE) in tons/acre/EI unit;

$A$ = area increment in sq m; and

$I$ = rainfall intensity in mm/min.

Detachment due to overland flow can be expressed as:

$$D_F = 0.018\, C\, K\, A\, S\, q \qquad (9)$$

where:

$D_F$ = overland flow detachment rate in kg/min;

$S$ = slope in m/m; and

$q$ = flow rate per unit width in $m^2$/min.

The total soil detached at any given time is:

$$D_t = D_R + D_F \qquad (10)$$

where:

$D_t$ = potential soil detached.

When a soil particle has been detached, sufficient energy must be available to transport the particle or it will be deposited. After inspecting many transport functions, Beasley, Monke, and Huggins [1977] suggested the relationship shown in *Figure 2.* The two portions of the curve correspond to laminar and turbulent flow. The particle sizes considered in the transport calculation are given in *Table 1.*

Soil transport by rainfall splash was assumed to be negligible. Soil transport by overland flow was described by the relationships:

$$T = 146\, S q^{0.5} \quad \text{when} \quad q \leqslant 0.046 \text{ m}^2/\text{min.}$$

$$T = 14600\, S\, q^2 \quad \text{when} \quad q > 0.046 \text{ m}^2/\text{min.} \qquad (11)$$

where:

$T$ = potential transport rate of sediment.

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

## B. Channel Phase

For the channel sediment routing, an approach used by Chen et al. [1975] was adopted since this formulation is readily adaptable to the finite element technique for routing stormwater runoff. The equation is referred to as the sediment continuity equation and can be written as:

$$\partial Q_s/\partial x + p(\partial A_d/\partial t) + \partial A_s/\partial t - q_s = 0 \qquad (12)$$

where:

$Q_s$ = sediment discharge;

$p$ = volume of sediment in a unit volume of bed layer, given by the bulk density of the suspended sediment;

$A_d$ = area of sediment deposited on the channel bed per unit length of channel;

$A_s$ = area of sediment suspended in water per unit length of channel; and

$q_s$ = lateral sediment inflow.

When bed load is neglected, equation 12 reduces to:

$$\partial Q_s/\partial x + \partial A_s/\partial t - q_s = 0 \qquad (13)$$

Following procedures outlined by Ross et al. [1978], the finite element solution form for equation 13 is:

$$\ell \begin{bmatrix} 1/3 & 1/6 \\ 1/6 & 1/3 \end{bmatrix} \begin{Bmatrix} \dot{A}_s \end{Bmatrix} + \begin{bmatrix} -1/2 & 1/2 \\ -1/2 & 1/2 \end{bmatrix} \begin{Bmatrix} Q_s \end{Bmatrix} - \ell q_s \begin{Bmatrix} 1/2 \\ 1/2 \end{Bmatrix} = 0 \quad (14)$$

The flow resistance equation 3 is replaced by the expression $Q_s = VA_s$, where $V$ is the flow velocity.

The following assumptions are inherent in the erosion component:

1. Sediment detached at one point and deposited at another is re-attached to the soil surface.

2. Detachment of deposited sediment requires the same amount of energy as the original detachment.

3. For each channel segment, rainfall detachment is assumed to be zero and only deposited sediment is available for flow detachment, i.e., the original channel lining is not erodible.

## APPLICATION

The FESHM has been applied to watersheds in geographic regions represented by Georgia, Illinois, Indiana, Mississippi, Ohio, Virginia, and West Virginia. These areas covered a wide range of land use, topography, and climatic conditions. Drainage areas ranged from approximately 2 acres to 193 square miles. The size of the watershed did not limit its utility. The accuracy of simulations, however, most likely was a function of the quality and resolution of data available. Work by Banta [1981] supports this conclusion. A limited set of applications follows to provide insight to the predictability of the FESHM.

### I. Hydrology

#### A. Virginia Watersheds

This model was applied to six experimental watersheds in Virginia, ranging in size from 183 to 1,058 acres. Each was located in a different geographic region. Wilson et al. [1975] and Ross [1978] give descriptive details of each watershed.

Sixteen storm events on these watersheds were simulated by FESHM, and the simulated hydrographs were compared with the observed hydrographs. The simulated hydrographs represented first-run attempts without optimization and are typical of the model's predictability for ungaged areas. The results are summarized in *Table 2.* The mean error in the predicted storm volume was 4.4 percent, with a standard deviation of 49.9 percent. The mean error in the predicted peak discharge was 22.6 percent, with a standard deviation of 50.1 percent. The large standard deviation is due largely to the inclusion of some very small storms on which poor performance is not surprising. Recent work by Banta [1981] tends to confirm this conclusion. The formulation presented tends to simulate best those storms with a runoff return period greater than approximately 20 years.

An example of the simulation results of a storm event on Powells Creek is shown in *Figure 3.* The HRU map is given in *Figure 4,* and the subdivision of the watershed into eight finite elements is shown in *Figure 1.* For this storm, the error in peak discharge was 3.4 percent, and the error in storm volume was 2.1 percent. Despite the satisfactory results of this single simulation run, it would be desirable to know how reliable this result is, i.e., what would be the error if the watershed were subdivided into other eight-element patterns or even into a larger or smaller number of elements? The question was addressed by subdividing the Powells Creek watershed into 24 different eight-element patterns. The simulation results from each of these 24 patterns formed the data base for a frequency distribution. The extreme value distribution *(Figure 5)* was determined to fit the data satisfactorily. The mean error of the distribution is 4.06 percent, with a standard deviation of 5.7 percent. From the distribution, it can be seen that there is a 58.5 percent probability that this model will give results within an error of ±5 percent for this particular case.

### B. Crab Creek and Black Creek Watersheds

The Crab Creek watershed in Virginia and the Black Creek watershed in Indiana were used by Beasley et al. [1980] for a comparative study of the predictability of FESHM and ANSWERS. Data requirements for the two models were nearly identical; however, data reduction techniques varied greatly. The watershed maps and simulation results are shown in *Figures 6-13.* Details of the study may be found in Beasley et al. [1980]. A brief summary and conclusions follow.

> The simulations basically represented the results obtained from using a priori estimates of the initial parameter values with only minor adjustments to infiltration parameters allowed afterward. Adjustments to the ANSWERS data file included slight changes in control depth and steady state and maximum infiltration rates; all of the changes were still within published ranges for the particular parameters. The only change made in the FESHM data file was to the seasonal function (GI) used to modify the cover index, a (equation 1). All three June storms required the same change (25 percent decrease). The other storms required slightly larger decreases or increases to describe the changes in infiltration response which obviously occur throughout the growing season.
>
> The simulations were, in general, reasonable representations of the observed data. The continual underestimation of runoff volume by ANSWERS was due, at least in part, to an overestimation of the parameters controlling the infiltration rate under steady state conditions. Since almost no optimization or "fitting" was ever attempted, these initial simulations provide an insight into the ability of the models to describe the processes occurring within the watersheds. Additional simulations and parameter optimization would certainly have led to better agreement with observed data. However, that was not the objective of this comparison.
>
> The results obtained in this first, non-rigorous examination of ANSWERS and FESHM are quite heartening. Further comparisons of both the hydrology and sediment portions of the models should provide even more information concerning parameter estimation, model applicability and data transferability [Beasley et al., 1980].

### C. Comparison With Other Modeling Procedures

In 1978 the Water Resources Council undertook a pilot test to develop national guidelines for defining peak flood flow frequencies. The pilot test consisted of five independent estimates of peak flow frequency for the 2-year, 10-year, and 100-year flood at 70 sites. Site selection was limited to the central and northwest regions of the United States. Drainage areas varied in size from one to several thousand square miles.

Banta [1981] undertook a study to apply the FESHM to several of these watersheds in an ungaged context. The applicability and practicality of using the FESHM on large basins was studied. Accuracy was based on the closeness of estimates to a true value, and practicality was measured in terms of time and cost effectiveness.

Six watersheds selected by the Work Group on Flood Frequency, Ungaged Watershed Hydrology Committee, of the Water Resources Council were analyzed using FESHM. The six basins ranged in size from 4.2 to 193.5 square miles. Constraints for all simulation studies were set by the Water Resources Council.

The three modeling schemes selected for the pilot study were the USGS State Equations, Soil Conservation Service TR-20, and the Army Corps of Engineers HEC-1. The results generated independently by these methods were compared with results obtained with the FESHM.

The details of this study are given by Banta [1981]. Some relevant conclusions from his study are abstracted in the following statements.

> In general terms the results using the finite element storm hydro-

> graph model show reasonable comparison with frequency analysis flows. Many of the results fall within 95% confidence intervals. . . . The most closely modeled values are those of the 100-year recurrence interval. It is evident from the results that the importance of infiltration decreases with increasing magnitude in recurrence interval. The results of the finite element model are just as good, and in many cases better than those results generated by HEC-1 and TR-20. The finite element method did not perform as well as the USGS State Equations. This is explained by the nature in which the USGS State Equations are derived. The basis for arriving at regional equations is the use of regression analysis of gaged streamflow data, and then relating basin parameters to arrive at a peak discharge that is in good comparison with the observed flow. . . . Problems arose in this project due to uncertainty of soil information. County soil maps were not available for all the basins studied. Two exceptions were Shawnee Creek and Little Scioto River. A more intensive investigation was undertaken in these two basins, and the results show good agreement. . . . Throughout the duration of this project the time to generate and apply input data was considered to be very important [Banta, 1981].

Comparison of the USGS State Equations, HEC-1, TR-20, and FESHM for one watershed in the above study is shown in *Figure 14.* The time required to prepare data bases and execute the models is shown in *Table 3.* The conclusions from this study were that the FESHM provides a reasonable method to simulate watershed hydrologic responses and it easily accommodates watersheds having complex geometry. Most importantly, hydrologic properties associated with land use, soil type, and rainfall patterns are easily accounted for by the FESHM.

### D. Other Applications

Other relevant applications include (1) an evaluation of Best Management Practices for agriculture by Smolen, Younos, and Shanholtz [1981], and (2) the simulation of the hydrologic response from a reclaimed mountain-top removal operation near Beckley, West Virginia [Smolen and Younos, 1980]. For the surface mine application, model verification consisted of a comparison of simulated and observed runoff characteristics using an ungaged context. The model was found to predict runoff volume with acceptable accuracy. Peak runoff rate was generally under-predicted. Use of the model to evaluate the effect of cover management for modification of hydrologic response was demonstrated.

## II. Sediment

The sediment model remains uncalibrated and unverified because of a lack of continuous sediment concentration data for the six Virginia watersheds. Attempts are currently under way to verify the model on watersheds that have such data available. As an example of the FESHM sediment simulation, the storm event of May 31, 1962, on Powells Creek watershed is presented in *Figure 15.* The current land use is compared with an alternative configuration of land use. This example shows that if the land use of element 7 were changed from pasture to fallow land, the sediment washload would increase. If the watershed were to be managed for soil conservation and a particular land use change were suggested, the associated change in sediment erosion and transport could be simulated by the FESHM.

The model presently has the capability of simulating hydrographs and sediment yields (sedi-graphs) for a wide variety of land uses and management practices. Essentially, any land use or management practice for which the change in infiltration capacity, surface roughness, slope, erosivity, and cropping factors are known can be simulated by the FESHM. A series of application examples is presented in the next section.

## EXAMPLES OF FESHM APPLICATION

The natural watershed shown in *Figure 16* will be used to demonstrate how the effect of management alternatives on sediment yield (washload) may be evaluated with a distributed parameter model (FESHM). The first example will be that of changing the tillage practice for corn production from conventional turn-plow to no-tillage. The second example will demonstrate how a small area adjacent to a stream channel can significantly alter the sediment load to the stream system when it is changed from a combination of pasture and woods to a fallow condition. We assumed that the storm event occurred soon after the area was plowed.

The storm of May 31, 1962, Powells Creek watershed, was used to illustrate the procedure for simulation of sediment from a natural watershed. Determination of accuracy was not possible since no observed data existed. Following procedures suggested by Li [1975] and Ross [1975], the land use map *(Figure 17)* and soils map *(Figure 18)* were superimposed to obtain the HRU map shown previously in *Figure 4.* The finite element grid structure *(Figure 16)* was developed following suggestions by Ross et al. [1978].

HRU and flow properties are given in *Tables 4-7.* The appropriate C and K values are given in *Tables 8* and *9* for each land use and soil type, as determined from the soil conservation handbook for Virginia (USDA-SCS, 1973).

### I. Tillage Practice

All areas in corn were changed to no-tillage. The appropriate C and K values were determined and washload simulated with the FESHM. The results are shown in *Figure 19.* The peak concentration of sediment was reduced from 1,087 mg/l to 577 mg/l although only 8 percent of the total watershed was affected.

### II. Changing to Fallow Condition

Elements 7 and 8 *(Figure 16)* were changed to fallow. The effect of changing an area in pasture and woods adjacent to the stream channel to a fallow condition is illustrated in *Figure 20.* The peak sediment concentration was increased from 1,087 mg/l to 2,360 mg/l. The peak sediment concentration and volume were increased by 129 and 109 percent, respectively. Flow characteristics were only slightly changed; however, a significant effect was noted in the washload despite an areal change that represented only 8 percent of the watershed.

### III. Strip Cropping

A typical strip crop agricultural practice is illustrated in *Figure 21.* A series of land slopes is shown to illustrate a recommended farming practice for minimizing soil loss when row crops are grown on hilly terrain. For this illustration, a rectangular flow strip subdivided into equal-sized elements was assumed, along with a hypothetical storm of 1 inch per hour for a duration of two hours. The FESHM with the appropriate data base was used to obtain the results in *Figure 21.* The sequence of erosion and deposition as flow cascades from one element to the next is shown. A total of 193 tons of soil reached the stream channel.

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

## SUMMARY AND CONCLUSIONS

The FESHM has been shown to be an effective approach for simulating storm runoff in ungaged watersheds. Because it is a distributed parameter model, it is not dependent on calibration or calibration data. It does, however, require extensive information on the soils, topographic, and cover characteristics of the watershed. The model has been shown to be appropriate for simulating material transport due to its spatially responsive character. A sediment detachment and transport component has been interfaced to the hydrologic model. The sediment washload simulation capability has been demonstrated, although it remains unverified at this time. Work is progressing toward verification.

The hydrologic section of the FESHM has been shown to compare favorably with other currently accepted watershed models (ANSWERS, HEC-1, TR-20, and USGS regression equations). Although most research with FESHM has been conducted on watersheds ranging in size from 2 to 1,000 acres, it has been shown to perform acceptably on watersheds as large as 193 sq mi. In addition, preparation time and expense were shown to be comparable to other models that are currently used.

To utilize fully the spatially responsive aspect of FESHM, the data base may become large, and considerable amounts of computer memory may be required for internal storage of data arrays 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. Land use and management practices represent dynamic data planes and require considerable effort to be kept current. Although the present state-of-the-art 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. It is probably not necessary to obtain data at the soil series level to simulate water yields from rural areas. It was demonstrated, however, that although the influence of a small area on the flow response of a large watershed may not be significant, the same area can have a significant impact on water quality. Results obtained from a wide range of watersheds are encouraging and indicate generally that flows are being simulated properly. A cluster sampling program must be conducted to verify flow predictions at internal node points.

Objective criteria to relate the level of discretization that is necessary to provide a given level of predictability must be established. When such criteria are developed and verification studies are completed, the FESHM will be an appropriate model for a wide range of planning applications.

## REFERENCES

Adams, R. T. and F. M. Kurisu, 1976. *Simulation of Pesticide Movement on Small Agricultural Watersheds.* Ecological Research Series EPA-600/3-76-066. U.S. Environmental Protection Agency, Washington.

Amerman, C. R., 1965. "The Use of Unit-Source Watershed Data for Runoff Prediction." *Water Resources Research* 1(4):499-507.

Anderson, H. W., 1957. "Relating Sediment Yield to Watershed Variables." *Transactions, American Geophysical Union* 38(6):921-24.

Banta, T. C., 1981. "Comparison of Flood Flows Obtained Using a Finite Element Storm Hydrograph Model with Other Modeling Procedures." M.S. thesis. Virginia Polytechnic Institute and State University, Blacksburg.

Beasley, D. B., E. J. Monke, and L. F. Huggins, 1977. "The Answers Model: A Planning Tool for Watershed Research." Paper No. 77-2532. American Society of Agricultural Engineers, St. Joseph, Michigan.

Beasley, D. B. et al., 1980. "Comparison of Two Distributed Parameter Watershed Models." *Hydrologic Transport Symposium,* pp. 196-205. Publication 4-80. American Society of Agricultural Engineers, St. Joseph, Michigan.

Beckett, P. H. T. and R. Webster, 1971. "Soil Variability: A Review." *Soils Fertility* 34(1):1-15.

Beer, C. E., C. W. Farnham, and H. G. Heinemann, 1966. "Evaluating Sedimentation Prediction Techniques in Western Iowa." *Transactions, American Society of Civil Engineers* 9(6):828-33.

Bernard, M., 1937. "Giving Areal Significance to Hydrologic Research on Small Areas." *Headwaters Control and Use,* pp. 50-75. Report of the Upstream Engineering Conference at Washington, D.C. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C.

Betson, R. P., 1964. "What is Watershed Runoff?" *Journal of Geophysical Research* 69(8):1541-52.

Betson, R. P. and J. B. Marius, 1969. "Source Areas of Storm Runoff." *Water Resources Research* 5(3):574-82.

Bruce, R. R. et al., 1975. "A Model for Runoff of Pesticides from Small Upland Watersheds." *Journal of Environmental Quality* 4(4):541-48.

Chen, Y. H. et al., 1975. "Transport of Material by Unsteady Flow." *Unsteady Flow in Open Channels, Volume 1,* pp. 313-65. Fort Collins, Colorado: Water Resources Publications.

Contractor, D. N., B. B. Ross, and V. O. Shanholtz, 1980. "A Finite Element Watershed Model to Predict Storm Hydrographs, Sediment Erosion, and Transport." *Proceedings of the Third International Conference on Finite Elements in Water Resources,* pp. 6.24-6.34. University of Mississippi, May 19-23, 1980.

DeCoursey, D. G., C. V. Alonso, and G. C. Bolton, 1978. "Erosion Simulation for Land Use Management." Paper No. 78-2082. American Society of Agricultural Engineers, St. Joseph, Michigan.

DeCoursey, D. G. and L. D. Meyer, 1976. "Philosophy of Erosion Simulation for Land-Use Management." *Soil Erosion: Prediction and Control,* G. R. Foster, editor, pp. 193-200. Special Publication No. 21. Soil Conservation Society of America, Ankeny, Iowa.

Desai, C. S. and J. F. Abel, 1972. *Introduction to the Finite Element Method.* New York: Van Nostrand Reinhold Company.

Donigian, A. S., Jr. and N. H. Crawford, 1976. *Modeling Pesticide and Nutrients on Agricultural Lands.* EPA-600/2076-043. U.S. Environmental Protection Agency, Washington.

Ellison, W. D., 1945. "Soil Erosion Studies—Part I." *Journal of Agricultural Engineering* 28(4):145-46.

England, C. B., 1970. *Land Capability: A Hydrologic Response Unit in Agricultural Watersheds.* ARS-41-172. U.S. Department of Agriculture, Washington.

England, C. B. and C. A. Onstad, 1968. "Isolation and Characterization of Hydrologic Response Units Within Agricultural Watersheds." *Water Resources Research* 4(1):73-77.

Engman, E. T. and A. S. Rogowski, 1974. "A Partial Area Model for Storm Flow Synthesis." *Water Resources Research* 10(3):464-72.

Foster, G. R. and L. D. Meyer, 1975. "Mathematical Simulation of Upland Erosion by Fundamental Erosion Mechanics." *Present and Prospective Technology for Predicting Sediment Yields and Sources,* pp. 190-207. U.S. Department of Agriculture, Washington.

Foster, G. R., I. D. Meyer, and C. A. Onstad, 1977. "An Erosion Equation Derived from Basic Erosion Principles." *Transactions, American Society of Agricultural Engineers* 20:678-82.

Frere, M. H., C. A. Onstad and H. N. Holtan, 1975. *ACTMO, An Agricultural Chemical Transport Model.* ARS-H-3. U.S. Department of Agriculture, Washington.

Glymph, L. M., 1975. "Evolving Emphases in Sediment-Yield Predictions." *Proceedings of the Sediment-Yield Workshop, November 1972,* pp. 1-4. ARS-S-40. USDA Sedimentation Laboratory, Oxford, Mississippi.

Graf, W. H., 1971. *Hydraulics of Sediment Transport.* New York: McGraw-Hill Book Co., Inc.

Hewlett, J. D. and C. A. Troendle, 1975. "Nonpoint and Diffused Water Sources: A Variable Source Area Problem." *Watershed Management,* pp. 21-46. New York: American Society of Civil Engineers.

Holtan, H. N., 1961. *A Concept for Infiltration Estimates in Watershed Engineering.* ARS-41-45. Agricultural Research Service, U.S. Department of Agriculture, Washington.

Holtan, H. N. et al., 1975. *USDAHL-74 Revised Model of Watershed Hydrology.* Technical Bulletin No. 1518. Agricultural Research Service, U.S. Department of Agriculture, Washington.

Huggins, L. F. and E. J. Monke, 1966. *The Mathematical Simulation of Small Watersheds.* Technical Report 1. Indiana Water Resources Research Center, Purdue University, West Lafayette.

Huggins, L. F. et al., 1973. *Simulation of the Hydrology of Ungaged Watersheds.* Technical Report 38. Indiana Water Resources Research Center, Purdue University, West Lafayette.

Huggins, L. F. et al., 1977. "Modeling." *Modeling the Environmental Impact of Land Use on Water Quality,* James Morrison, editor, pp. 177-203. EPA-905/9-77-007-B. U.S. Environmental Protection Agency, Washington, D.C.

Journel, A. G. and C. H. J. Huijbregts, 1978. *Mining Geostatistics.* New York: Academic Press, Inc.

Judah, O. M., 1973. "Simulation of Runoff Hydrographs from Natural Watersheds by Finite Element Method." Ph.D. dissertation. Virginia Polytechnic Institute and State University, Blacksburg.

Judah, O. M., V. O. Shanholtz, and D. N. Contractor, 1975. "Finite Element Simulation of Flood Hydrographs." *Transactions, American Society of Agricultural Engineers* 18(3):518-22.

Kirkby, M. J. and R. J. Chorley, 1967. "Throughflow, Overland Flow and Erosion." *Bulletin of the International Association of Scientific Hydrology* 12(3):5-21.

Knisel, W. G., editor, 1980. *CREAMS: A Field-Scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems.* Conservation Research Report No. 26. U.S. Department of Agriculture, Washington.

Kuh, H. C. and D. L. Reddell, 1977. *Two-Dimensional Model of Watershed Erosion.* Technical Report 80. Texas Water Resources Research Institute, Texas A&M University, College Station.

Li, E. A., 1975. "A Model to Define Hydrologic Response Units Based on Characteristics of the Soil-Vegetative Complex Within a Drainage Basin." M.S. thesis. Virginia Polytechnic Institute and State University, Blacksburg.

Lowdermilk, W. C., 1929. "Further Studies of Factors Affecting Surficial Runoff and Erosion." *Proceedings of the International Congress of Forestry Experiment Station,* pp. 606-28. Stockholm, Sweden.

Meyer, L. D. and W. H. Wischmeier, 1969. "Mathematical Simulation of the Process of Soil Erosion by Water." *Transactions, American Society of Agricultural Engineers* 12(6):754-58, 762.

Musgrave, G. W., 1949. "The Quantitative Evaluation of Factors in Water Erosion." *Journal of Soil and Water Conservation* 2(3):133-38.

Negev, M. A., 1967. *Sediment Model on a Digital Computer.* Technical Report No. 76. Department of Civil Engineering, Stanford University, Stanford, California.

Nielsen, D. R., J. W. Biggar, and K. T. Erh, 1973. "Spatial Variability of Field-Measured Soil-Water Properties." *Hilgardia* 42(7):215-60.

Onstad, C. A. and G. R. Foster, 1975. "Erosion Modeling on a Watershed." *Transactions, American Society of Agricultural Engineers* 18(2): 288-92.

Peck, A. J., R. J. Luxmoore, and J. L. Stolzy, 1977. "Effects of Spatial Variability of Soil Hydrologic Properties in Water Budget Modeling." *Water Resources Research* 13(2):348-54.

Ragan, R. M., 1968. "An Experimental Investigation of Partial Area Contributions." *Symposium on Hydrological Aspects of Utilization of Water,* pp. 241-51. Publication No. 76. International Association of Scientific Hydrology, Bern, Switzerland.

Raudkivi, A. J., 1976. *Boundary Hydraulics.* New York: Pergamon Press.

Renfro, G. W., 1975. "Use of Erosion Equations and Sediment-Delivery Ratios for Predicting Sediment Yield." *Proceedings of the Sediment-Yield Workshop, November 1972,* pp. 33-45. ARS-S-40. USDA Sedimentation Laboratory, Oxford, Mississippi.

Roehl, J. W., 1962. "Sediment Source Areas, Delivery Ratios and Influencing Morphological Factors." *Symposium of Bari,* W. H. Ward, editor, pp. 202-13. Publication No. 59. International Association of Scientific Hydrology, Gentbrugge, Belgium.

Rogowski, A. S., 1972. "Watershed Physics: Soil Variability Criteria." *Water Resources Research* 8(4):1015-23.

———, 1980. "Hydrologic Parameter Distribution on a Mine Spoil." *ASCE Watershed Management Symposium, Irrigation and Drainage Division, Boise, Idaho, July 21-27.* American Society of Civil Engineers, New York.

Ross, G. A., 1970. *The Stanford Watershed Model: The Correlation of Parameter Values Selected by a Computerized Procedure With Measurable Physical Characteristics of the Watershed.* Research Report No. 35. Kentucky Water Resources Research Institute, University of Kentucky, Lexington.

Ross, B. B., 1975. "A Finite Element Model to Determine the Effect of Land Use Changes on Flood Hydrographs." M.S. thesis. Virginia Polytechnic Institute and State University, Blacksburg.

———, 1978. "A Spatially Responsive Catchment Model for Predicting Stormwater Runoff from Ungaged Watersheds." Ph.D. dissertation. Virginia Polytechnic Institute and State University, Blacksburg.

Ross, B. B. et al., 1978. *A Model for Evaluating the Effect of Land Uses on Flood Flows.* Bulletin 85. Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, Blacksburg.

Shanholtz, V. O., B. B. Ross, and J. C. Carr, 1981. "Effect of Spatial Variability on the Simulation of Overland and Channel Flow." *Transactions, American Society of Agricultural Engineers* 24(1):124-38.

Shanholtz, V. O. and J. H. Lillard, 1970. *A Soil Water Model for Two Contrasting Tillage Systems.* Bulletin 38. Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, Blacksburg.

Simons, D. B., R. M. Li, and T. J. Ward, 1977. "A Simple Procedure for Estimating On-Site Soil Erosion." *Proceedings of the International Symposium on Urban Hydrology, Hydraulics and Sediment Control, July 18-21, 1977,* pp. 95-102. University of Kentucky, Lexington.

Smith, R. E., 1976. "Simulating Erosion Dynamics With a Deterministic Distributed Watershed Model." *Proceedings of the Third Federal Interagency Sedimentation Conference,* pp. 163-73. U.S. Water Resources Council, Washington.

Smolen, M. D. and T. M. Younos, 1980. "Simulation of Surface Mine Hydrology With the Finite Element Storm Hydrograph Model." *Proceedings of the Symposium on Surface Mining Hydrology, Sedimentology, and Reclamation,* pp. 41-46. University of Kentucky, Lexington.

Smolen, M. D., T. M. Younos, and V. O. Shanholtz, 1981. "Evaluation of Agricultural BMP Alternatives With the Finite Element Storm Hydrograph Model." Paper No. 81-2004. American Society of Agricultural Engineers, St. Joseph, Michigan.

Solomon, S. I. and S. K. Gupta, 1977. "Distributed Numerical Model for Estimating Runoff and Sediment Discharge of Ungaged Rivers." *Water Resources Research* 13(3):613-36.

Sweeten, J. M. and D. L. Reddell, 1976. "Nonpoint Sources: State-of-the-Art Overview." Paper No. 76-2563. American Society of Agricultural Engineers, St. Joseph, Michigan.

U.S. Department of Agriculture, Soil Conservation Service, 1973. *Conservation Treatment Alternatives for Cropland, Section III-B.* Washington.

Vanoni, V. A., 1974. "Task Committee on Preparation of Manual on Sedimentation, Sediment Engineering." *Journal of the Hydraulics Division, American Society of Civil Engineers* 98(HY12):2087-99.

Warrick, A. W., G. J. Mullen, and D. R. Nielsen, 1977. "Scaling Field-Measured Soil Hydraulic Properties Using a Similar Media Concept." *Water Resources Research* 13(2):355-62.

Williams, J. R., 1975. "Sediment-Yield Prediction With Universal Equation Using Runoff Energy Factor." *Proceedings of the Sediment-Yield Workshop, November 1972,* pp. 244-52. ARS-S-40. USDA Sedimentation Laboratory, Oxford, Mississippi.

Wilson, T. V. et al., 1975. *Hydrologic Data Summaries for Small Watersheds in the Southern Region.* Report of Cooperative Research Under Southern Regional Project S-53. Bulletin 199, South Carolina Agricultural Experiment Station, Clemson.

Wischmeier, W. H., 1976. "Use and Misuse of the Universal Soil Loss Equation." *Journal of Soil and Water Conservation* 31(10):5-9.

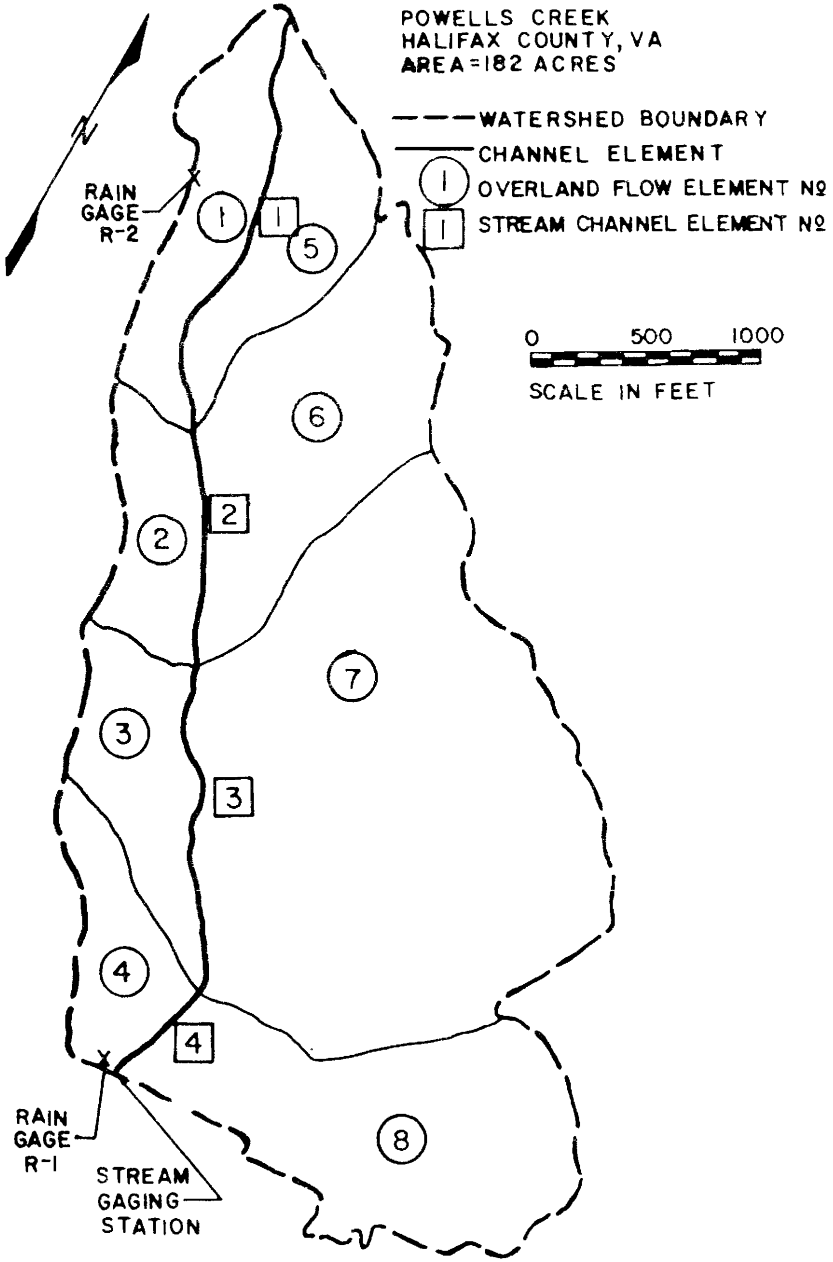
Wischmeier, W. H. and D. D. Smith, 1965. *Predicting Rainfall Erosion Losses from Cropland East of the Rocky Mountains.* Agricultural Handbook 282. U.S. Department of Agriculture, Washington.

Yalin, Y. S., 1963. "An Expression for Bedload Transportation." *Journal of the Hydraulics Division, American Society of Civil Engineers* 89(HY3):221-50.

# FIGURES

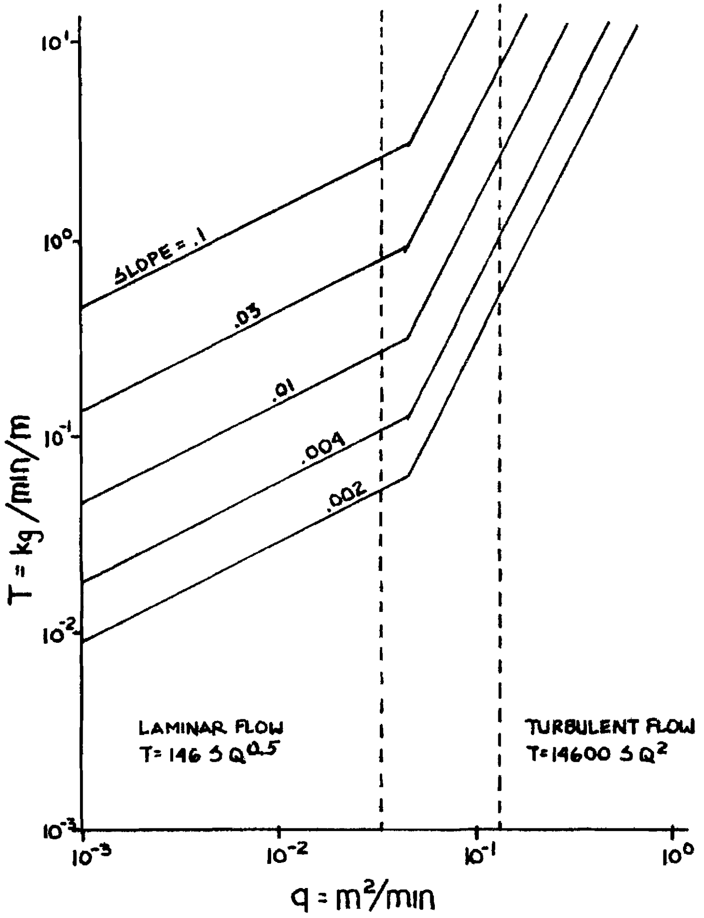
## FIGURE 1

Finite Element Map



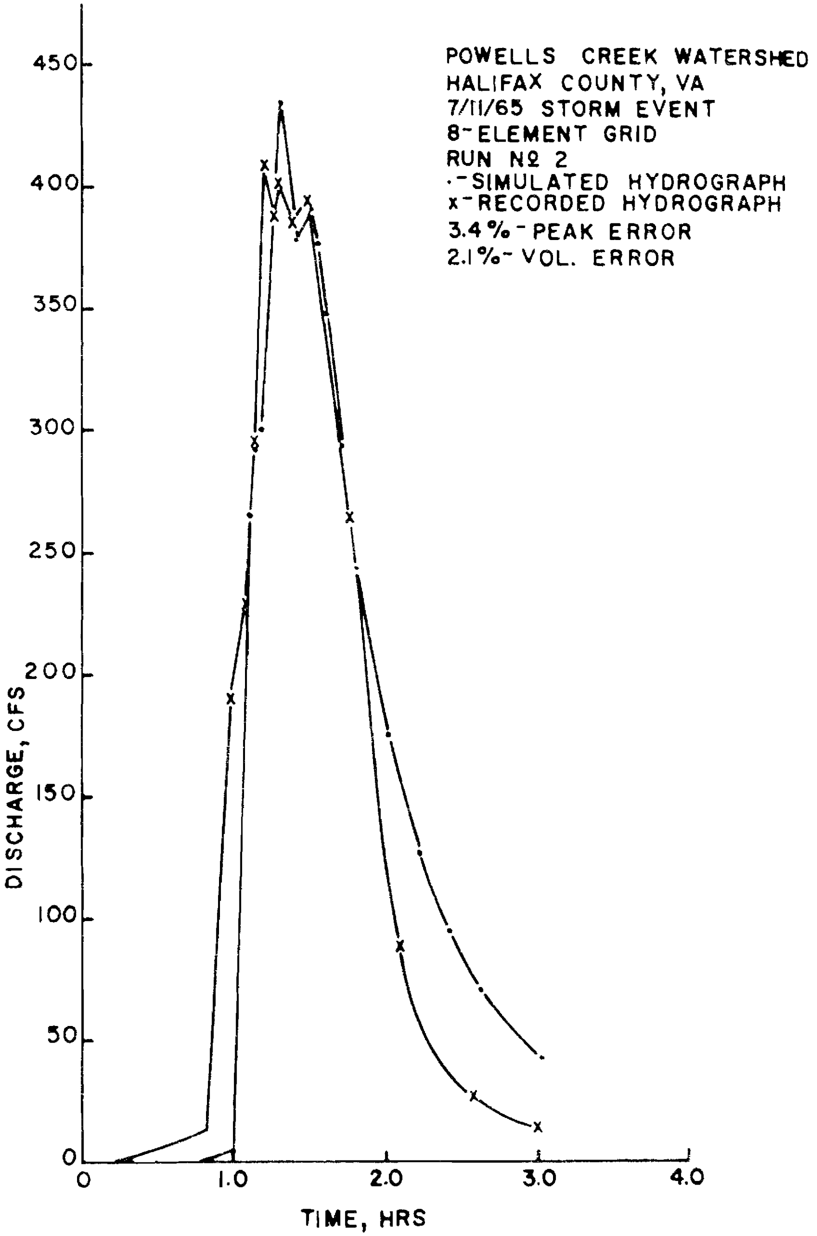
## FIGURE 2

Transport Relationship Used in ANSWERS Model



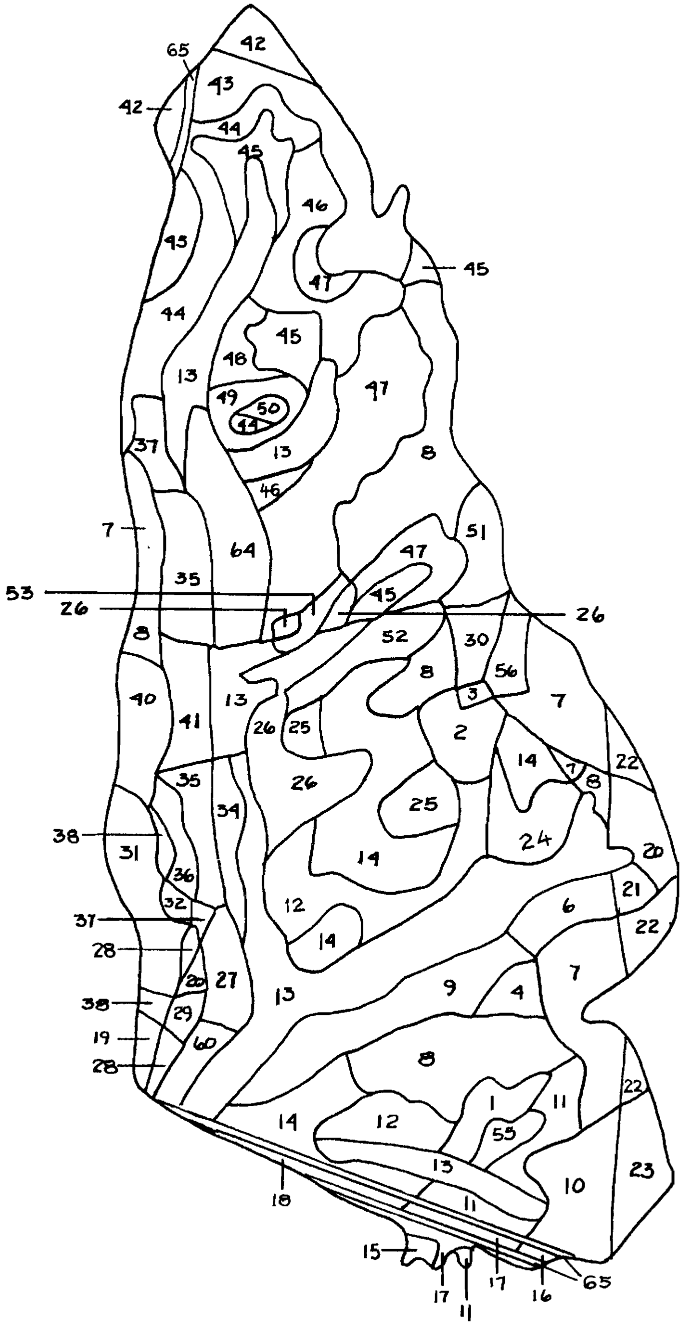
## FIGURE 3

Comparison of Simulated and Recorded Hydrographs, Powells Creek

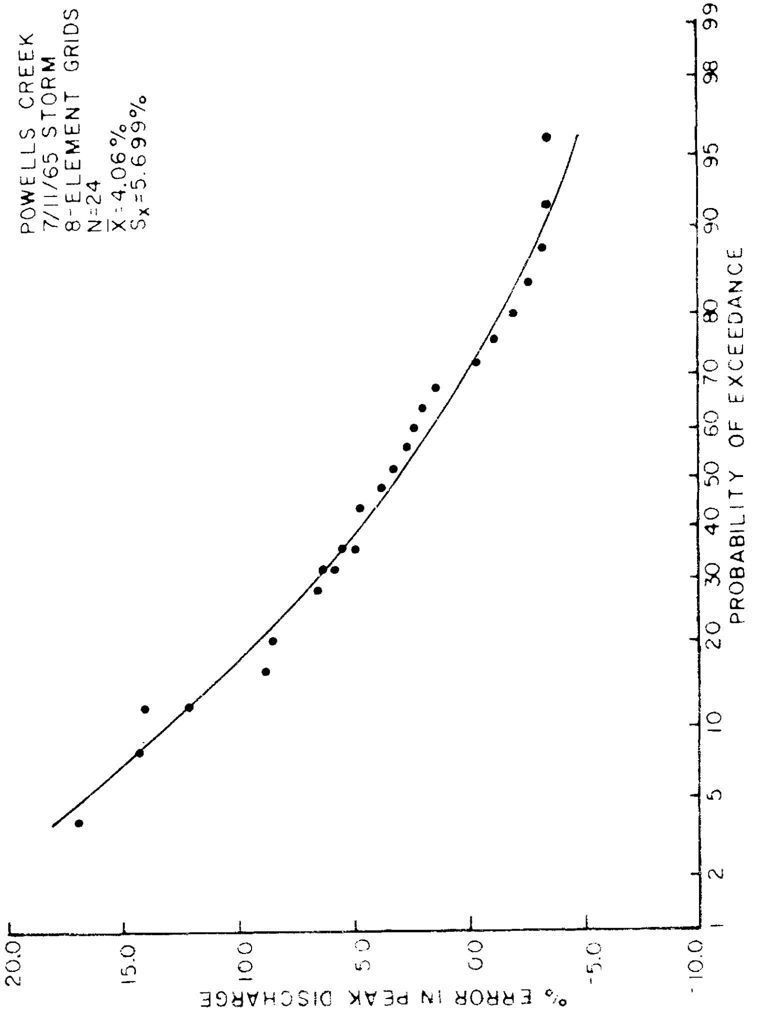


## FIGURE 4

HRU Map for Powells Creek Watershed



## FIGURE 5
Probability Distribution of Errors



## FIGURE 6
Black Creek Watershed, Indiana

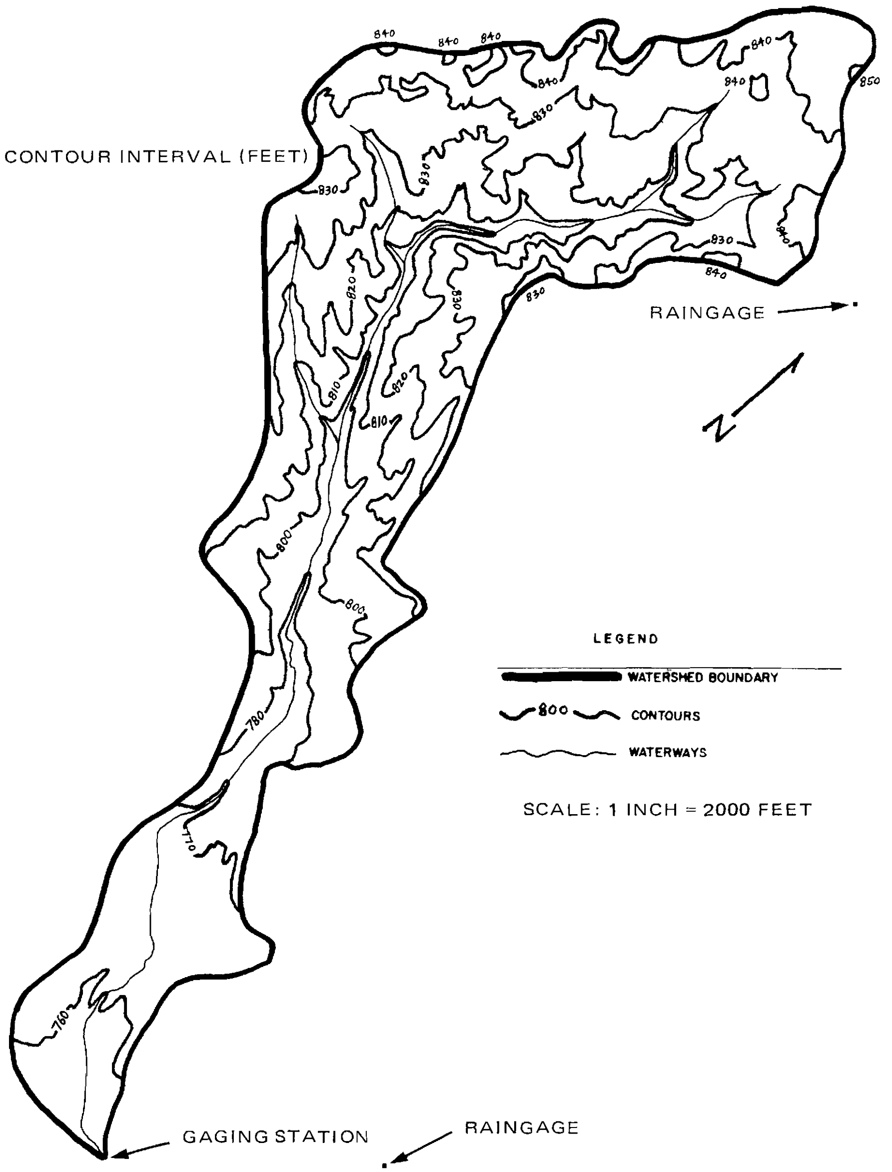


FIGURE 7

Comparison of Simulated and Recorded Flows for Black Creek Watershed for Storm 9/17/77

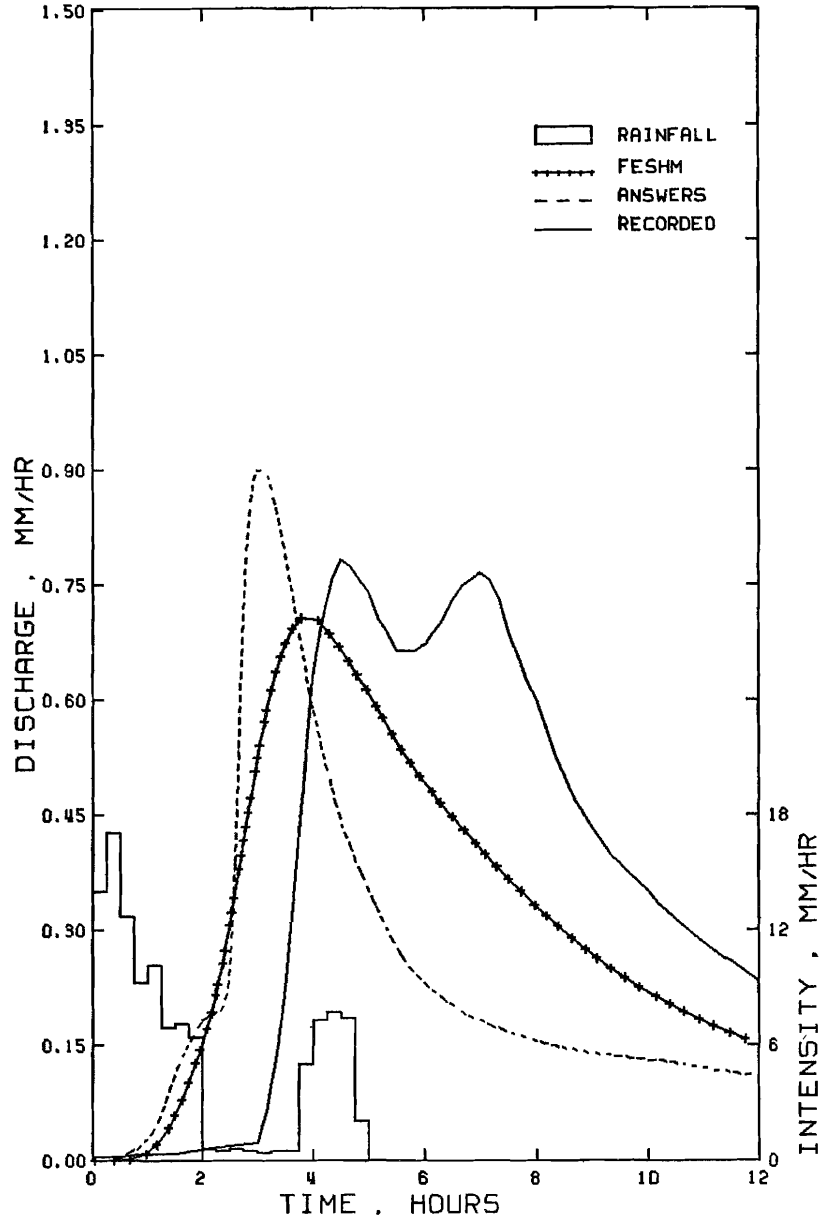
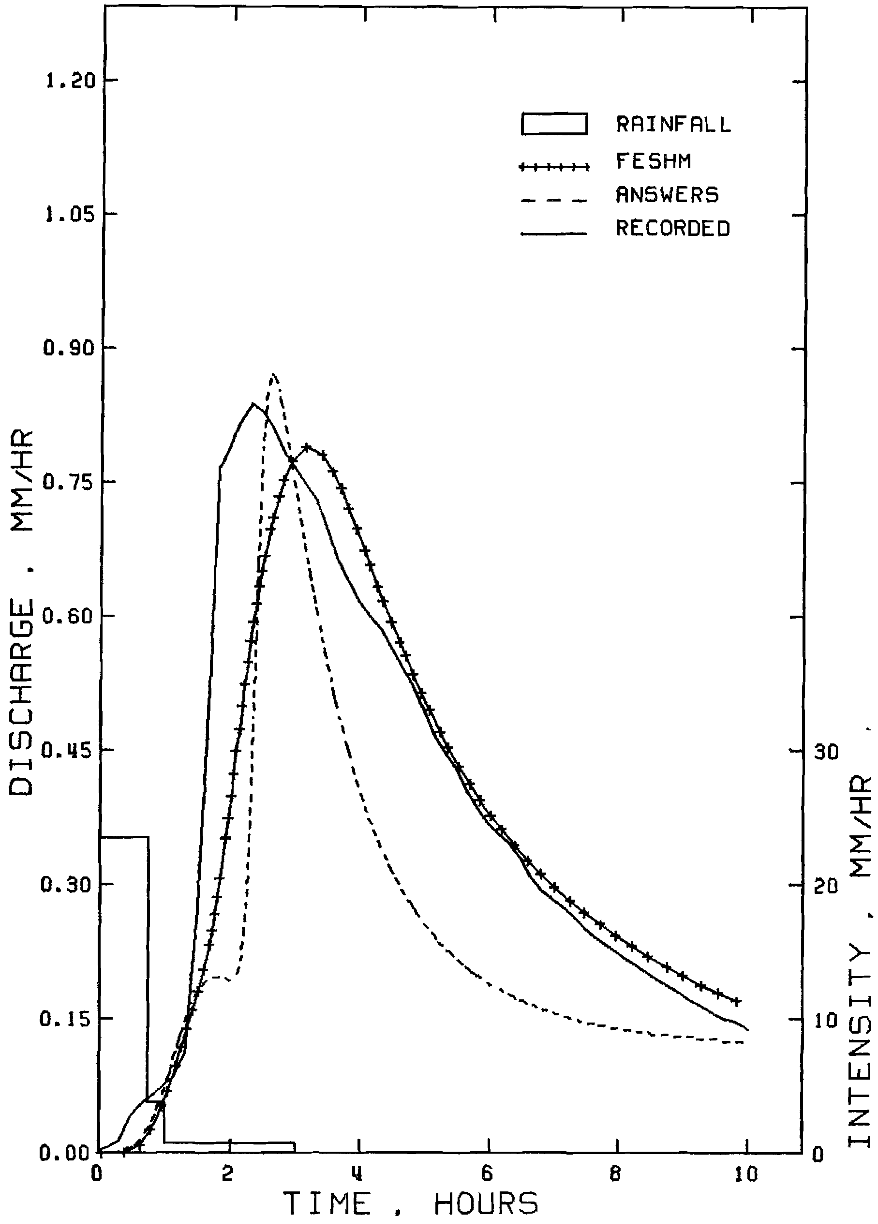


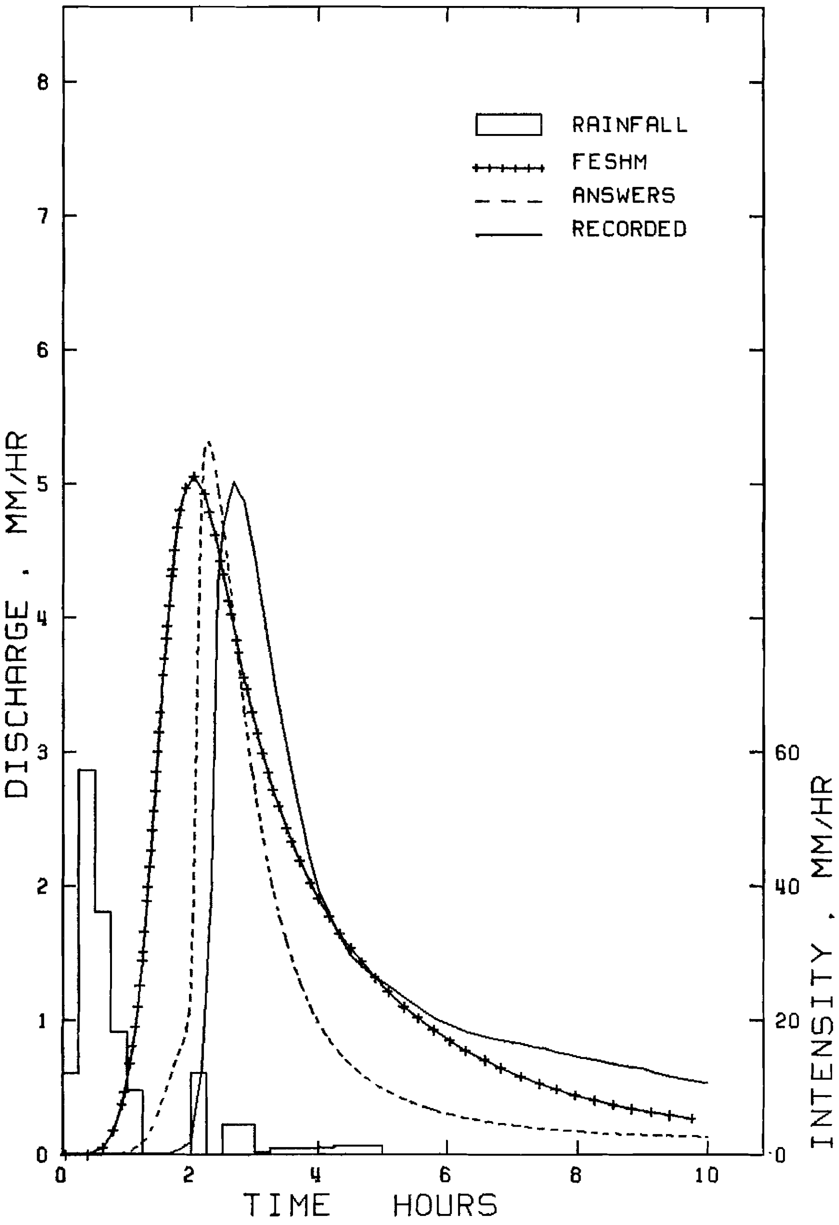
FIGURE 8

Comparison of Simulated and Recorded Flows for Black Creek Watershed for Storm 6/24/75



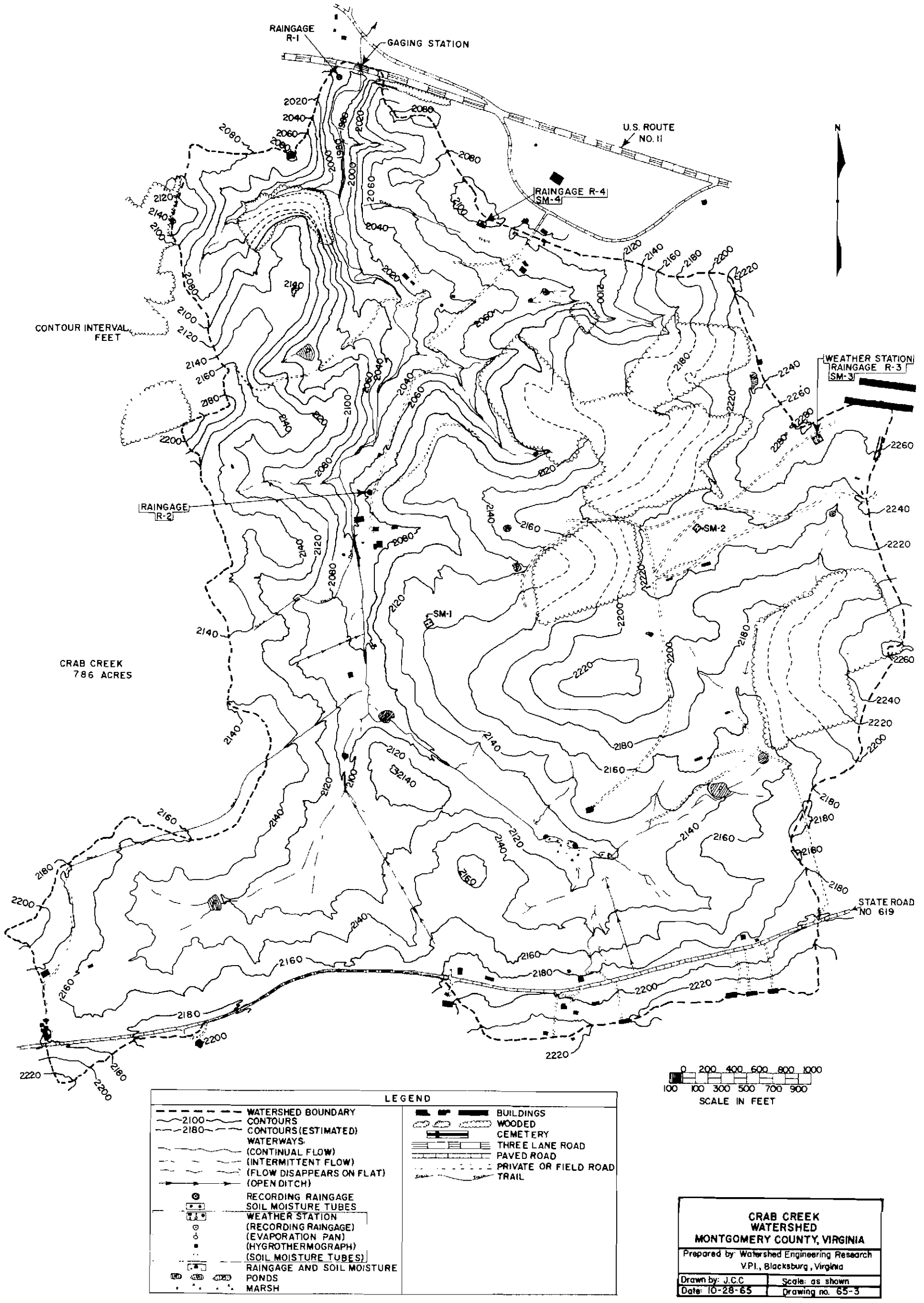
## FIGURE 9

Comparison of Simulated and Recorded Flows for Black Creek Watershed for Storm 6/30/77



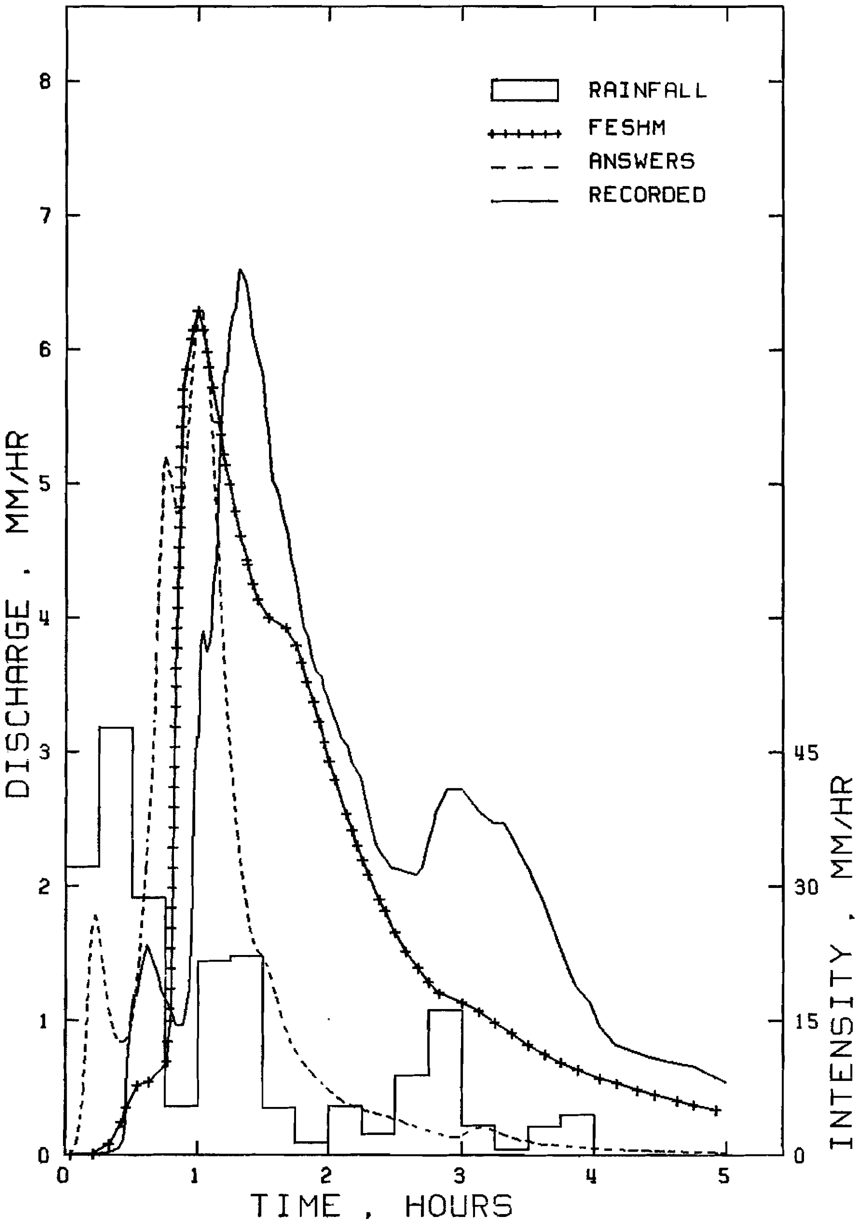
## FIGURE 10

Crab Creek Watershed, Virginia



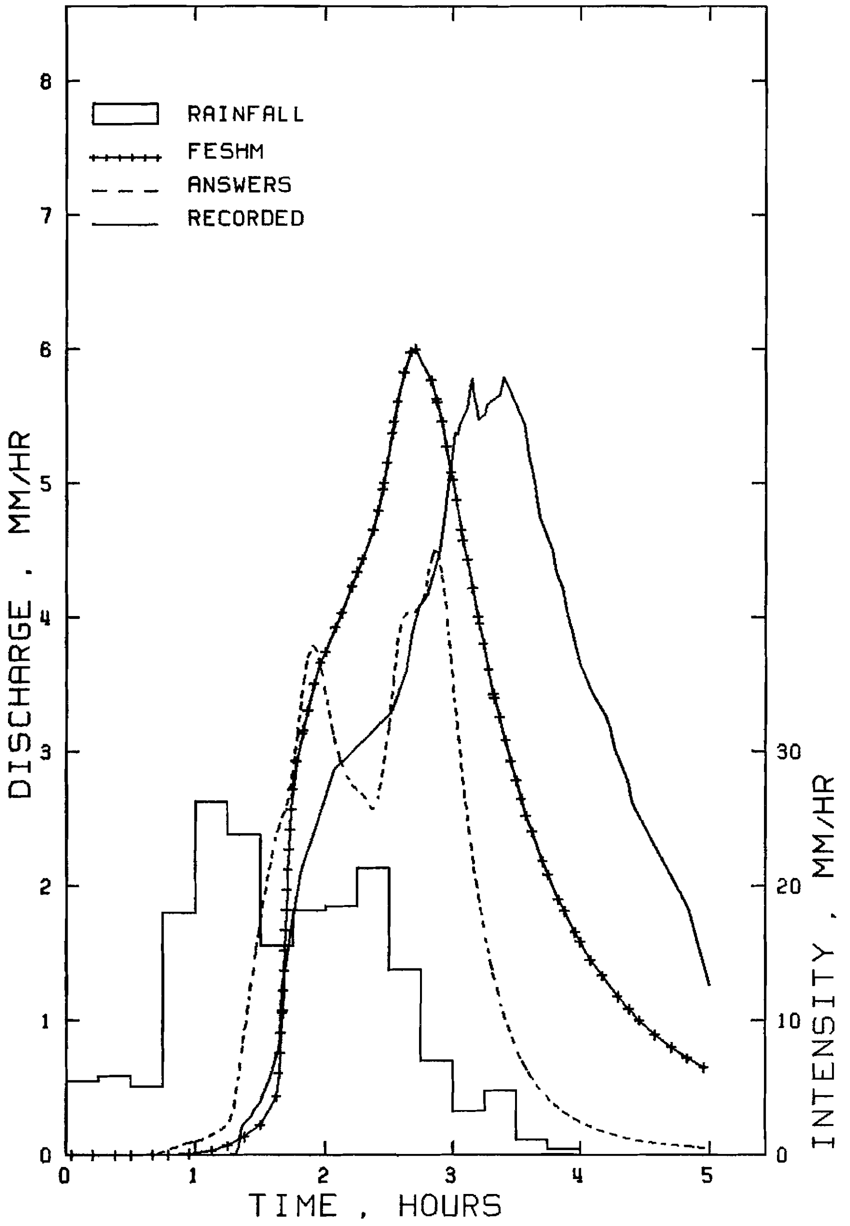
## FIGURE 11

Comparison of Simulated and Recorded Flows for Crab Creek Watershed for Storm 6/16/76



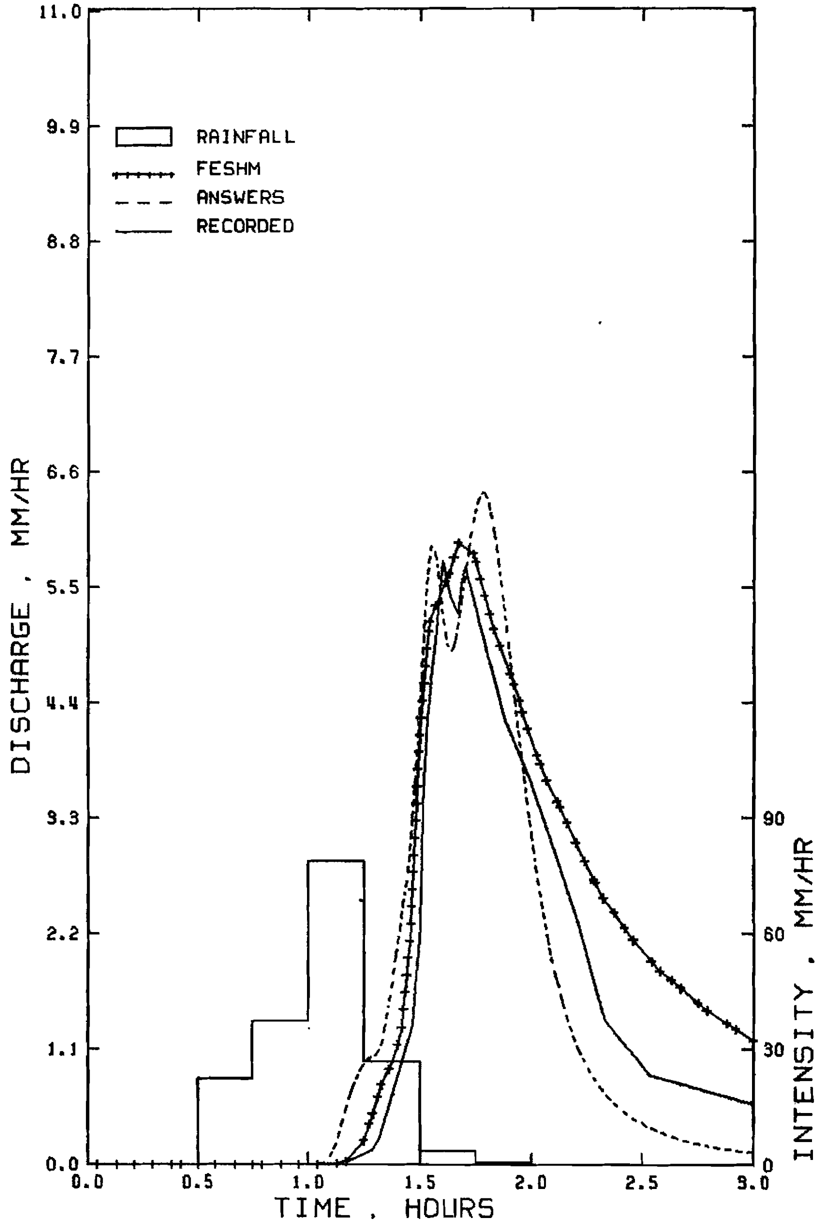
## FIGURE 12

Comparison of Simulated and Recorded Flows for Crab Creek Watershed for Storm 10/25/71



## FIGURE 13

Comparison of Simulated and Recorded Flows for Crab Creek Watershed for Storm 8/21/66



## FIGURE 14

Simulated Versus Frequency Analysis, Shawnee Creek, Ohio [Banta, 1981]