AD-A141 281 STREAMFLOW MODELLING(U) FLORIDA UNIV GAINESVILLE SPACE ASTRONOMY LAB M G ANDERSON ET AL. APR 84 DAJA37-81-C-0221 1/2

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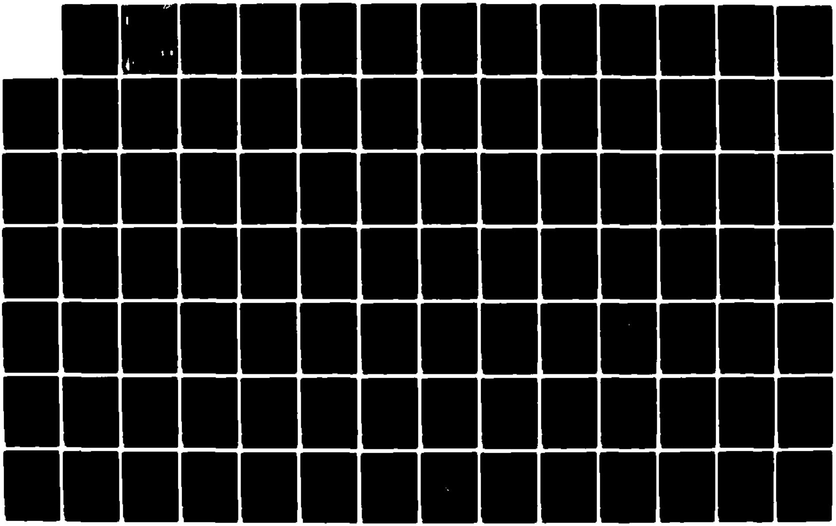

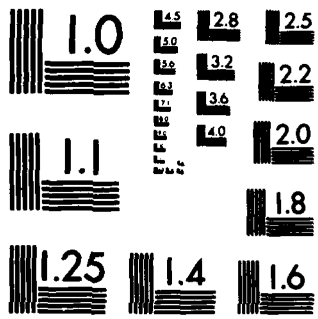

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STREAMFLOW MODELLING

Final Technical Report

by

M.G.Anderson and S.Howes

April 1984

European Research Office
United States Army
London England

CONTRACT NUMBER DAJA37-81-C-0221

Dr. M.G. Anderson

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. AD A141 281
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Streamflow Modelling	5. TYPE OF REPORT & PERIOD COVERED Final Technical Report March 81-April 84
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) M.G. Anderson and S. Howes	8. CONTRACT OR GRANT NUMBER(s) DAJA37-81-C-0221
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Geography University of Bristol Bristol, BS8 1SS, UK	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 611-2A-1T161102-BH57-01
11. CONTROLLING OFFICE NAME AND ADDRESS USARDSG-UK PO Box 65 FPO NY 09510	12. REPORT DATE April 1984
	13. NUMBER OF PAGES 129
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

(To be completed by contractor)

Streamflow forecasting, HYMO, MILHY, sensitivity analysis.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(To be completed by contractor; less than 300 words)

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Abstract

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Predictions from the model developed in this project are shown to be consistently better than MILHY in the two important areas of estimating time to peak discharge and the magnitude of the peak discharge itself. An extensive sensitivity analysis of the model is undertaken and it is shown that it is robust against errors in the input parameters. This is the more encouraging when the model structure developed here is shown to out perform MILHY in selected discharge predictions, in which MILHY is tuned for optimal performance by the selection of curve numbers by back calculation.

Acknowledgements

Discussions with staff at Waterways Experiment Station, Vicksburg, Mississippi, especially Dr E Link and Mr J Collins, have been helpful during the project period. Dr W James of Texas A & M University kindly provided selected data for model testing used in this report. All the computational work was undertaken by Sally Howes at the Geography Department, Bristol University. The drawings were prepared by Simon Godden.

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1. INTRODUCTION

1.1 Background

In a previous report[1] an assessment of currently available hydrological models was made. In that report it was emphasised that the development of relatively sophisticated distributed models could only serve applications that were restricted to a single, or at most a small number of catchments, due to (a) comprehensive calibration requirements and (b) relatively detailed data input needs. This point is emphasised further if we examine the data requirements for the Institute of Hydrology Distributed Model (IHDM) which is typical of distributed sequential models. By contrast, the U.S. Corps of Engineers current use of HYMO (MILHY) has no calibration requirement and a comparatively small data need (see table 1). HYMO however has been shown to be somewhat insensitive to the duration of rainfall elements. Given those general observations it was deemed appropriate to continue the refinement of key sectors within the HYMO procedure to ensure devlopment of a modelling capability that remained within the fully operational sphere, but simultaneously provided an improved resolution and performance.

1.2 Objectives and Scope

The principal objectives of the project were

(i) The establishment of a computer model based on HYMO, which allowed for the more accurate prediction of flood flows than the current version of MILHY. (A prototype structure was available under a previous contract DAJA37-82-C-0092- Anderson 1982).

(ii) The validation and verification of the new model on selected watersheds, with the prerequisite being that <u>no model calibration</u> should be required.

Table 1 **Data requirements of the soil water model**

Soil Profile Hydrologic Characteristics

For each layer:
- soil water content at saturation
- saturated hydraulic conductivity
- suction moisture curve (a maximum of 20 observations)

For each cell:
- initial soil water content

Soil Profile Dimensions

- total number of cells in column
- number of cells in layer 1
- number of cells in layer 2
- thickness of each cell

Surface Conditions

- detention capacity
- maximum evaporation during the day

Precipitation

- rainfall data time increment
- rainfall data for each time increment
- rainfall start time
- rainfall stop time

Program Controls

- iteration time for simulation
- simulation start time
- simulation stop time
- number of profiles for the catchment area

Note: no historical flow data is required.

(iii) A development of the model such that it would be capable of running on a personal computer at acceptable speeds.

(iv) A comparison of MILHY with the "*improved*" version developed under this contract to identify the appropriate elements of the flood forecast which were best predicted by each of the models.

1.3 Background to HYMO

HYMO[2] is a flood hydrograph simulation model whose current data requirements are such that it is suitable for application to the ungauged catchment. Its application to a large catchment, involves a sub-division of the total area into smaller units which are known as sub-catchments, and which are assumed to exhibit similar hydraulic and hydrologic characteristics. Rainfall hyetographs for each sub-catchment are then transformed into runoff hydrographs which are routed down the channel network and are ultimately added to runoff hydrographs produced from each of the other sub-catchments. The final outflow hydrograph represents the response of the catchment as a whole.

HYMO is structured conveniently into subroutines, Figure 1, which allows the present hydrologic procedures to be easily modified or replaced.

Attention is drawn to the currently used procedure which generates the storm hydrograph for each sub-catchment. It is a standard procedure in which the unit hydrograph, derived for each area from its physical characteristics is convolved with incremental runoff. This runoff is derived from the US Soil Conservation Service (SCS) curve number procedure.

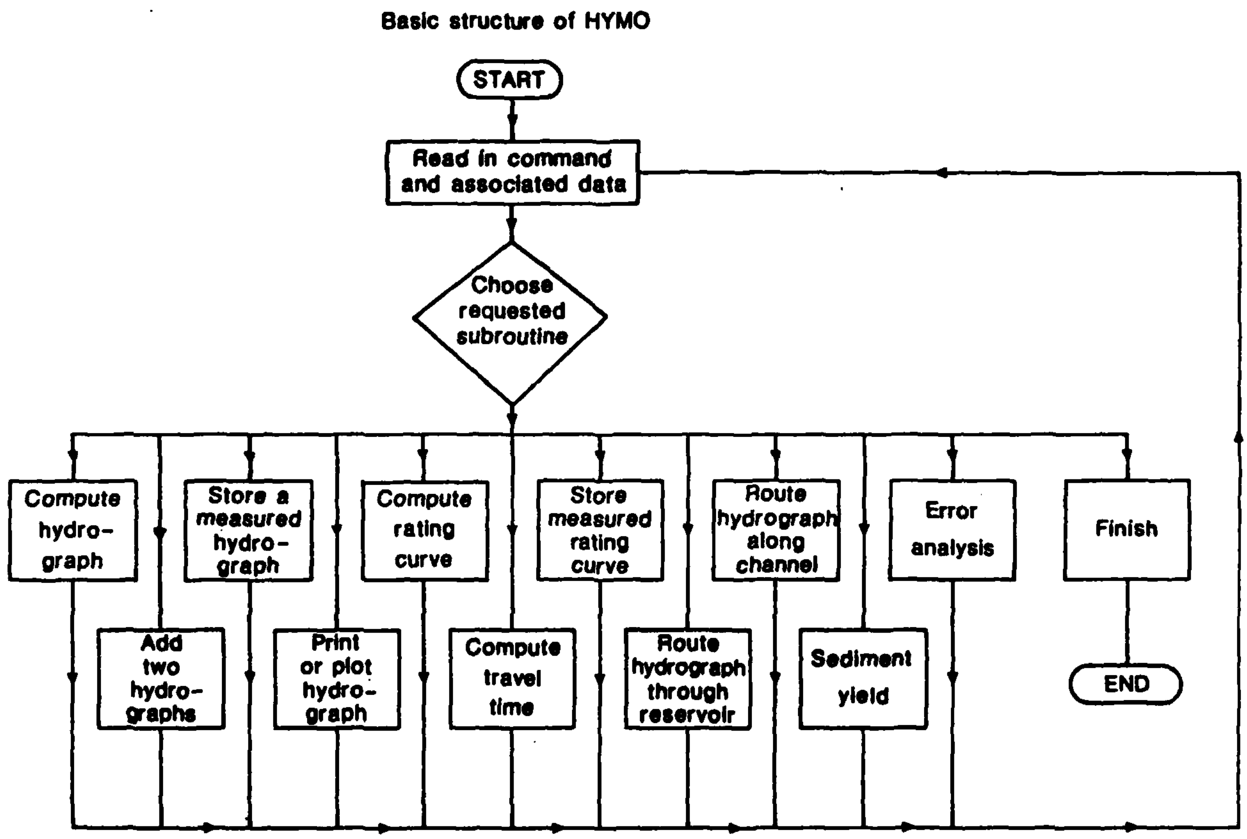


Figure 1: Basic structure of HYMO.

This report develops a critique of this method for deriving incremental runoff, and proposes an alternative to that currently used in HYMO, namely a restructured soil water model. The structure of this model is outlined and is then extended to include the effects of spatial variability.

The development of any model however, must be accompanied by an attempt to establish its suitability and relevance for the particular application. Dawdy and Thompson(3) and Naef(4) both stress that even a simple model will predict an increase in stream flow in response to rainfall, and recession after the storm ceases. It is thus important to define the range of conditions for which the model operates satisfactorily and to establish the degree of confidence which may be placed upon information generated by the model. Consideration is therefore given to the process of validation and verification. Miller et al(5) remark that *failure to fully discuss this aspect of the modelling process* has in the past, lead to a general lack of faith in modelling.

Finally, with reference to two catchments, a number of comparisons are made between the measured hydrographs and predictions made by HYMO with the original SCS CN procedure and HYMO with the soil water model.

From this information, it is possible to begin to define those conditions for which each model may be expected to be the superior.

2. CURRENT PROCEDURE FOR GENERATING INCREMENTAL RUNOFF IN THE HYMO MODEL.

The COMPUTE HYDROGRAPH subroutine in HYMO (Figure 1) contains three sections. Firstly, the unit hydrograph is calculated. The method of computation is developed in Williams and Hann[2]. It requires details of the sub-catchment area, the difference in elevation and the length of the main channel. To successfully predict the unit hydrograph, it is recommended that the sub-catchments be not greater than 25 square miles. The second section derives the incremental runoff volume from precipitation data, and is based upon an empirical relationship, developed by the US Soil Conservation Service (1974). Finally, the runoff and unit hydrograph are convolved to produce the flood hydrograph generated for the sub-catchment, according to the following equation:

$$Q_t = \sum_{t=2}^{n} (r_t \, d_{n-t}) \qquad \text{For } n > 2 \tag{1}$$

Where: n = number of time intervals of hydrograph

Q_t = flood hydrograph discharge at time t

r_t = runoff at time t

d_{n-t} = unit hydrograph discharge at time n-t.

2.1 Soil Conservation Service Curve Number Procedure

The SCS CN procedure for generating incremental runoff is based upon the assertion that for a simple storm, where initial abstraction of rainfall does not occur, rainfall, runoff and storage (rainfall not converted into runoff) are related in the following manner:

$$\frac{P-Q}{S'} = \frac{Q}{P} \tag{2}$$

Where: P = total precipitation

S^1 = potential maximum storage

Q = actual runoff

Solving for Q, a rainfall-runoff relationship, where initial abstraction can be ignored, may be derived.

$$Q = \frac{P^2}{P + S'} \qquad (3)$$

Initial abstraction of precipitation by the processes of interception, infiltration and surface storage does occur and its omission represents a gross over simplification. It is introduced into the relationship by modification of the terms Pand S'. Equation (1) can thus be rewritten:

$$\frac{(P - I_a) - Q}{S} = \frac{Q}{P - I_a} \qquad (4)$$

Where: Ia = initial abstraction

S = S' + Ia

Solving again for Q:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad (5)$$

An empirical relationship between Ia and S was derived by the SCS from data from many small catchments. It is of the nature:

$$I_a = 0.2S \qquad (6)$$

and is presented in Figure 2.

This is then substituted into equation (5):

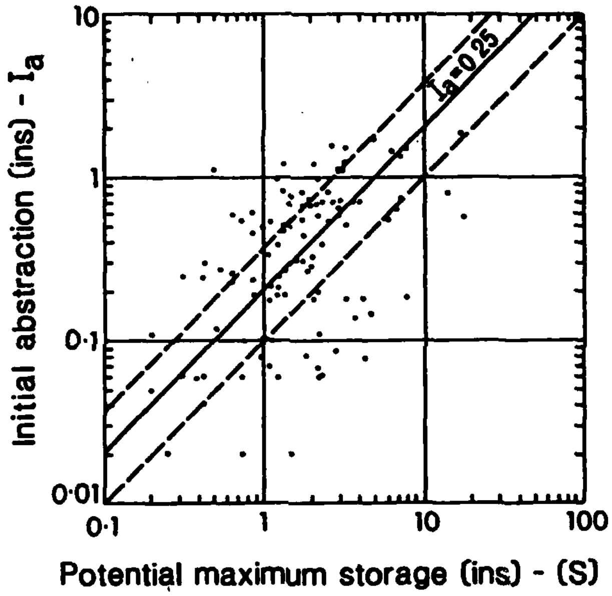


Figure 2: The relationship of initial abstraction (Ia) and storage (S).

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{for } P > 0.2S \tag{7}$$

To apply this relationship, S is transformed by the following expression:

$$S = \frac{1000}{CN} - 10 \tag{8}$$

Where: CN = 0, when S ∞

CN = 100, when S = 0

The value of CN for a catchment is usually derived from field or map surveys and the appropriate USDA tables. It represents the net effect of soil type, land use, hydrologic soil group and the antecedent soil moisture condition. Figure 3 provides a graphical solution.

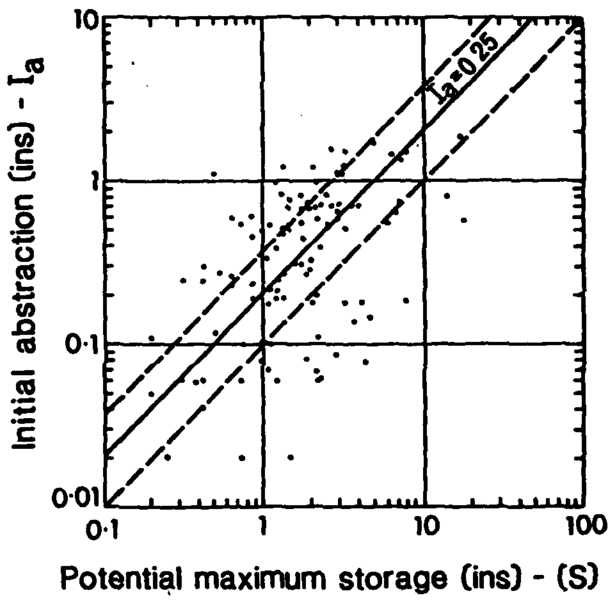
This procedure is simple, quickly and easily applied and requires data usually available for the ungauged catchment. Simplicity of application is however, achieved at the cost of reduced accuracy.

2.2 Critique

Six points can be made in criticism of this method:

(1) Morel-Seytoux and Verdin[6] criticise the theoretical basis of the model. They argue that equation (2) can be justified for long duration storms which experience no initial abstraction. In their opinion however, there is no physical reason for assuming that these ratios will be equal under any other conditions.

(2) These authors also claim that the scatter around the relationship between Ia and S in figure 2 is very great, especially taking into consideration that the points are plotted on a log-log plot.



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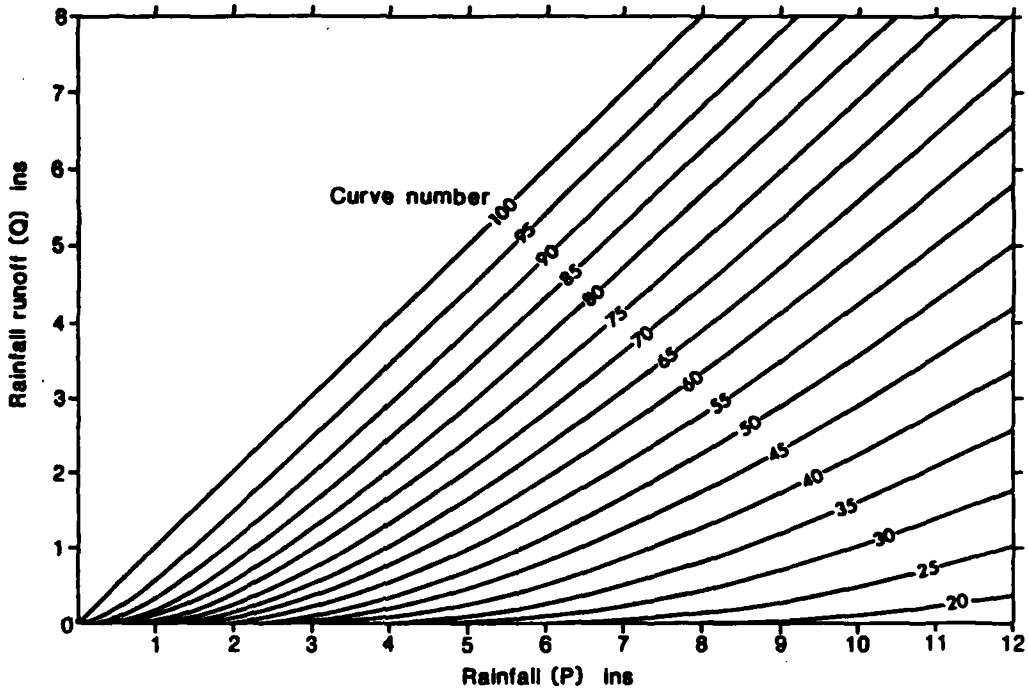


Curves are valid for the case where $I_a = 0.2S$

Figure 3: Graphical solution of the SCS curve number runoff equation (equation 7).

(3) Morel-Seytoux and Verdin[6] suggest that the SCS method can potentially yield misleading excess rainfall, especially when applied to storms not of uniform rainfall intensity. They demonstrate the infiltration behaviour implied by the SCS method to be in direct disagreement with physical infiltration theory by deriving the following equation:

$$I = \frac{S^2 r}{(P-I_a+S)^2} \qquad (9)$$

Where: I = infiltration rate

r = rainfall rate

Here, r appears in the numerator which implies, quite incorrectly, that the infiltration rate varies in direct proportion to rainfall intensity. HYMO divides total precipitation into equal time periods, applying equation (7) to each in turn. As demonstrated by Morel-Seytoux and Verdin, for rainfall of varying intensities the method estimates highly discontinuous and unrealistic infiltration rates. We can illustrate this situation for Sixmile Creek, Arkansas where CN = 85, Figure 4 shows the nature of the infiltration rate for the storm indicated.

(4) Morel-Seytoux and Verdin go on to show that the excess rainfall predicted by the method is also unrealistic. They derive the following equation for rainfall excess (re):

$$r_e = \frac{(P - I_a)\ (P + 2S + I_a)r}{(P - I_a + S)^2} \qquad (10)$$

and suggest that once surface ponding occurs, rainfall excess will be predicted provided that there is some rainfall, regardless of the

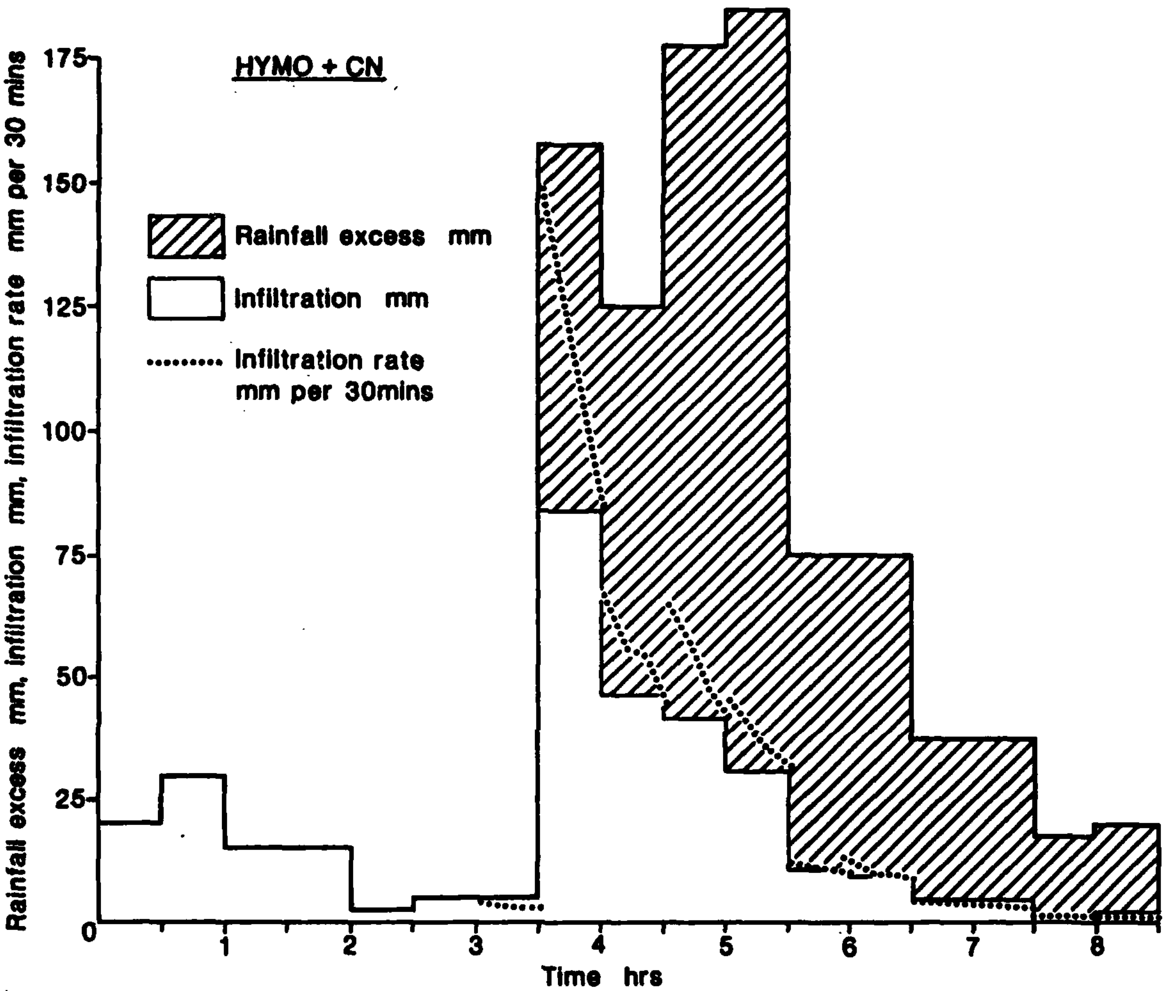


Figure 4: The nature of the infiltration rate predicted by the SCS CN procedure.

relationship of rainfall intensity and the infiltration capacity. Predictions of runoff made for complex storms may therefore require improvements.

(5) Limitations are also imposed by this method, on the choice of antecedant soil moisture conditions which can only be dry, average or wet.

(6) A deterministic sensitivity analysis of HYMO was conducted by Smith[7] and he illustrated that a 10% change in CN produced a 55% change in runoff volume and peak discharge rate. Hawkins[8] also identifies an accurate estimate of CN as the 'weak input link' for this method. For precipitation totals of up to 9 inches, the model is relatively more sensitive to errors in CN than to errors in precipitation.

(7) The CN proceudre in HYMO does not allow for continuous simulation of a number of storms. For each storm, the model is run with different values of CN for the sub-catchment.

(8) Spatial variability in the input parameters cannot be accommodated in such a scheme.

2.3 Outline of Requirements

The requirements of an alternative procedure for predicting runoff may now be suggested. They may be divided into two categories:

1. <u>Those pertaining to the basis and structure of the proposed model</u>

The model should be conceptually based and have firm theoretical foundations. It should represent the processes which operate in the hydrological system and contain parameters which have physical meaning and can be measured in the field. A calibrated model serves a very limited purpose for application to the ungauged catchment.

The application is for the larger scaled, ungauged catchment and hence any model development cannot be realised at the expense of large computational requirements.

The model should be capable of continuous simulation of a series of successive storms, and the intervening periods.

The model should allow the incorporation of spatial variability.

2. Those relating to the manner in which the model operates.

It should be established that the model accurately reproduces, for a sub-catchment area, the runoff and its distribution in time. When it has been convolved with the unit hydrograph, the flood hydrograph should closely approximate the measured hydrograph.

The model should have a wide range of application. It should operate satisfactorily for an extensive number of basin and storm conditions.

The data usually available for the ungauged catchment may be of poor quality. The limitations imposed upon predictions by input data errors must not therefore be substantial.

3. THE SOIL WATER MODEL

3.1 The Mathematical Model

The law governing the flow of water through a rigid, homogenous, isotropic and isothermal porous media, is described by a nonlinear Fokker-Planck equation. This is derived from two equations, Darcy's Law and the principle of continuity.

Darcy's Law states that the flow of water through a porous medium is proportional to the hydraulic gradient and the conductivity:

$$q = - K \nabla \emptyset \tag{11}$$

Where: q = macroscopic vector velocity of water

k = hydraulic conductivity

$\emptyset$ = *gradient of total potential* in 3-dimensional space.

The operator ∇ denotes

$$\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \right)$$

and,

$$\emptyset = \Psi - Z \tag{12}$$

Where: ψ = moisture potential (suction)

Z = gravitational potential, depth from surface where downwards is positive.

Childs and Collis-George (9) confirmed experimentally that Darcy's Law holds for flow in unsaturated soils, but in a modified form, where K and are functions of the soil moisture content (θ).

$$q = -K(\theta) \cdot \nabla \theta \tag{13}$$

$$\emptyset = \Psi(\theta) - z \tag{14}$$

The continuity equation states that the difference between inflow and outflow is equal to the rate of change in storage.

$$\frac{\partial \theta}{\partial t} = -\nabla q \tag{15}$$

Where: t = time

Combining this equation with (11) gives:

$$\frac{\partial \theta}{\partial t} = \nabla \; (K(\theta) \nabla \; \emptyset) \tag{16}$$

Rewriting this in one dimension, for vertical flow, where z is the vertical distance taken downward as positive:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} (K(\theta) \; \frac{\partial \emptyset}{\partial z}) \tag{17}$$

Substituting equation (12) into this gives:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K \; (\theta) \; \frac{\partial}{\partial z} (\Psi(\theta) \; -z) \right] \tag{18}$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(\theta) \right] - \frac{\partial K}{\partial z} \; (\theta) \tag{19}$$

This is equivalent to the Richards equation.

To solve this equation for unsaturated conditions, the hydraulic conductivity function has to be defined.

Values of unsaturated hydraulic conductivity vary with soil moisture content and are very difficult to measure in the field. This data will not usually be available for the ungauged catchment and it is therefore to be numerically derived from the suction-moisture curve using the following relationship which was established by Millington and Quirk[10] and developed by Campbell[11] and Jackson (1972).

$$K_i = K_s \left(\frac{\theta i}{\theta s}\right)^p \frac{\sum_{j=i}^{M} \left[(2_j + 1 - 2_i)\ \Psi_j^{-2}\right]}{\sum_{j=i}^{M} \left[(2_j - 1)\ \psi_j^{-2}\right]} \qquad (20)$$

Where: K_i = hydraulic conductivity at corresponding, moisture content, Θi

Ks = saturated hydraulic conductivity.

s = saturated soil moisture content

ψ = Suction head

M = *number of equal sized increments of moisture content*

p = a constant

Jackson[12] determined that a value of unity for the constant allows a more accurate determination of the K(Θ) over a greater range of soils.

The Richards equation is a non-linear partial differential equation to which exact-solutions are available only for specific initial and boundary conditions. It is necessary to convert the mathematical model into a form which can be solved approximately by digital computer. After Hillel[13], the equations are converted into explicit finite difference equations and solutions are defined at discrete points in space and time.

There are 3 requirements which any numerical technique must fulfil:

(1) The solutions must be stable. Errors must not be amplified as the solution progresses.

(2) The solutions must be convergent, they must approximate the true solution.

(3) The method must be computationally manageable.

The explicit solution fulfils the third criteria, but is usually only conditionally stable. As a check on stability, during the simulation, a mass balance calculation is repeated to identify whether errors are large, (and if so, to identify the point where they become a serious problem):

$$Bal = C\theta - I\theta - CI + CE + CD \qquad (21)$$

Where: Bal = water balance

C = cumulative water content of entire profile

I = initial water content of entire profile

CI = cumulative infiltration

CE = cumulative evaporation

CD = cumulative drainage.

If the value of 'Bal' increases as the simulations proceeds then the size of either the time increments or cell dimensions have to be reduced.

3.2 Basic Structure of the Model

The structure of the soil column is indicated in Figure 5. It is divided into up to 3 layers, each with different hydrologic properties. Each layer is

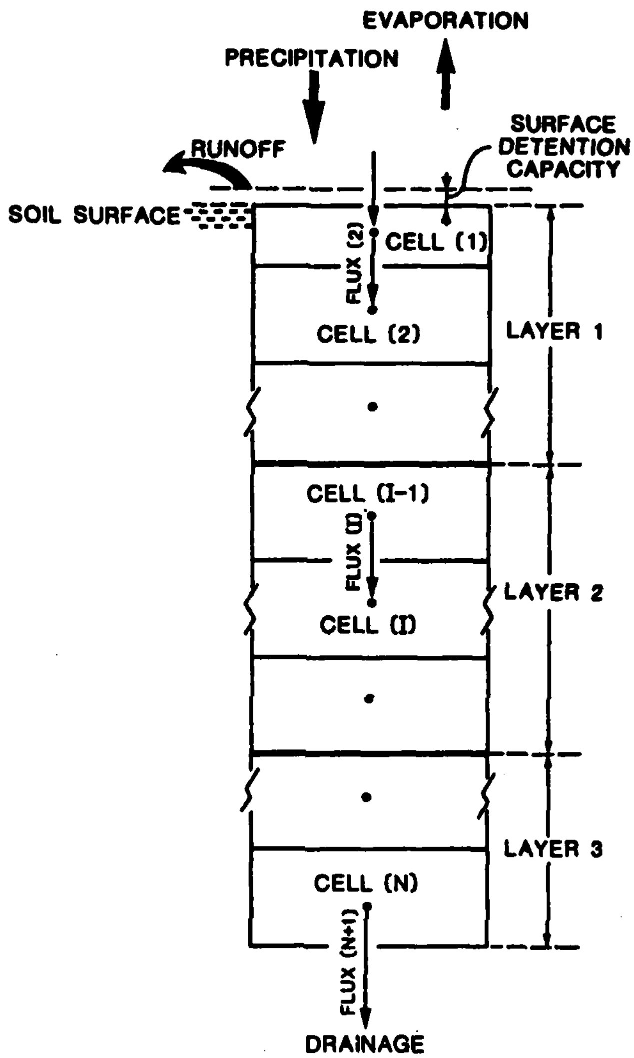


Figure 5: Basic structure of soil water model.

itself divided into cells. Flow between the midpoints of each cell is simulated under both saturated and unsaturated conditions. Detention capacity, expressed as an equivalent depth of water on the soil surface, has to be exceeded by rainfall excess before runoff begins. When precipitation ceases, this store is depleted by infiltration and evaporation. Detention capacity is the only model parameter which is not a measurable characteristic. It is not physically based, but represents the net effect of vegetation interception, litter interception and surface detention. Its value also reflects the antecedent moisture conditions of vegetation and litter.

The model allows dynamic changes in its structure it allows water tables and perched water tables to develop and fluctuate throughout a storm.

3.3 Description of the Program

Figure 6 illustrates the basic structure of the program. It has been written in Fortran 77 so that it is compatible with HYMO, although Sargent[14] comments that use of a special purpose simulation language results in less error and reduced programming time than use of such a strongly typed language. The program is structured into three parts. In the initial section, arrays are dimensioned, variables initialised and the data is read in and checked for inconsistencies; error reports are printed if necessary. The Millington-Quirk method is then used to determine the conductivity functions for each layer. A print-out of the initial conditions, and details of the simulation is output to specified peripherals.

The dynamic section contains the sequence of operations which are performed repeatedly at each time step. An internal clock is set and updated as the simulation proceeds. For each cell, the moisture content,

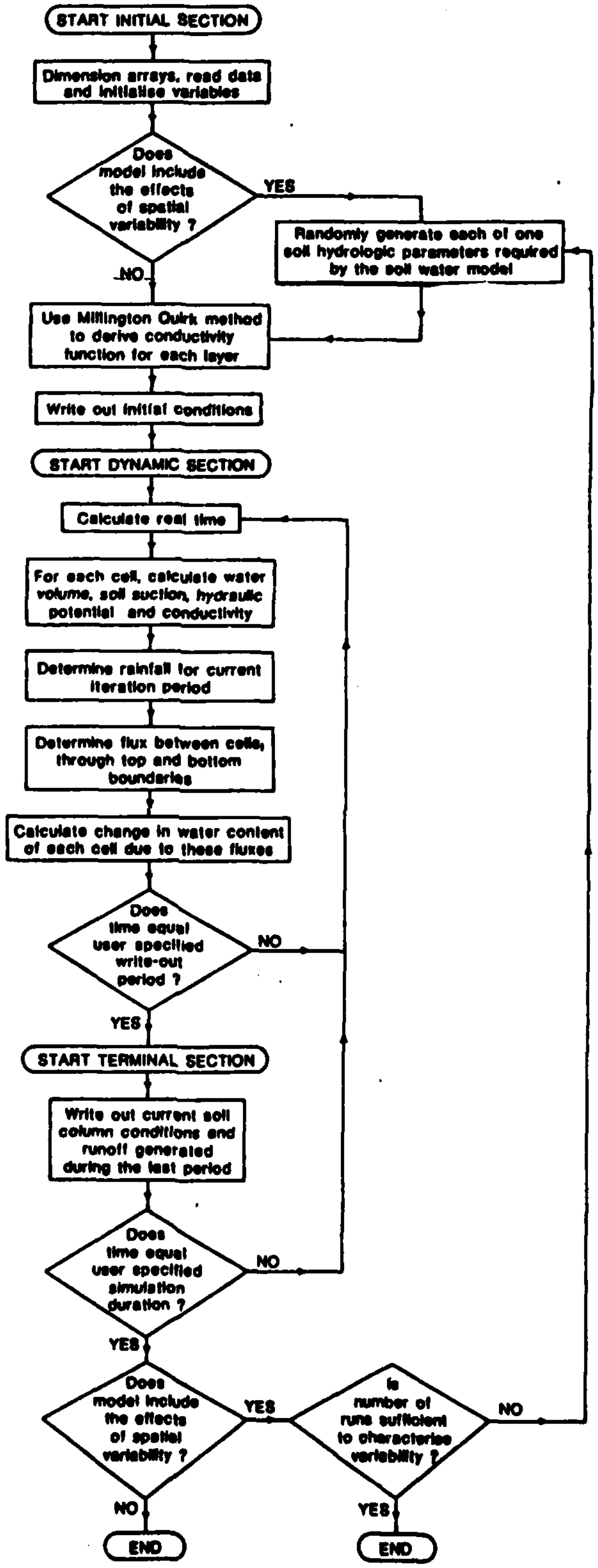


Figure 6: Structure of the soil water model program.

known from the initial conditions or the last time step is then used to derive the values of the following parameters. Water volume is given by:

$$V_i = T_i \theta_i \tag{22}$$

Where: V_i = Water volume of cell i

T_i = Thickness of cell i

Cell i = Moisture content of cell i.

Soil suction is derived from linear interpolation between the known points on the suction-moisture relation; hydraulic conductivity is derived by similar means from the hydraulic conductivity function. The hydraulic potential of each cell is given by equation 14, where z represents the depth from one surface to the midpoint of the cell.

Rainfall for the current time step is derived from the rainfall data input.

The flux into each cell (q_i) is given by Darcys Law in discrete form:

$$q_i = (\phi_{i-1} - \phi_i) \frac{\overline{K}_i}{d_i} \tag{23}$$

Where: d_i = distance between the midpoints of the two cells i and i-1.

and $$\overline{K}_i = \frac{K_{i-1} T_{i-1} + K_i T_i}{T_{i-1} + T_i} \tag{24}$$

The flux out of the bottom cell is assumed to be equal to the hydraulic conductivity of that cell (although other base boundary conditions are of course possible).

The determination of the flux into the top cell is crucial for this application, and deserves closer attention.

Firstly, the infiltration capacity (Ic) is derived from the characteristics of the top cell, i = 1 and is calculated from the following equation.

$$T_c = \frac{.5\ (-\ \phi_1)\ (Ks_{\text{layer 1}} + K_1)}{d_1} \tag{25}$$

Where: Ks layer 1 = Saturation K of layer one.

The precipitation excess (rainfall intensity minus infiltration rate) is then calculated and cumulated throughout the simulation duration. If this is positive, it represents excess water which is stored on the surface.

If it is raining, then evaporation is set to 0. Providing that the rainfall rate is smaller than Ic, and there is no surface detention, the flux into cell 1 equals the rainfall rate. If these conditions are not met, then the flux equals the infiltration capacity. If there is surface detention, and this exceeds the detention capacity, then runoff occurs.

If it is not raining however, runoff is set to 0 and the evaporation rate (e) derived from the following single isothermal equation:

$$e = \frac{e_{max}\ \text{Sin}\ 2\Pi t}{86400} \tag{26}$$

Where: t = time in seconds from 06.00 (sunrise)

e_{max} = maximum midday evaporation rate

(Between 18:00 and 06:00 set to one hundreth of e_{max}.)

If there is water remaining on the surface from the storm, water still moves into cell 1 at a rate equal to the infiltration capacity. The evaporation and infiltration which ocurred during the iteration period is then deducted from the surface detention. If there is no water on the surface, water moves out of cell one at a rate equal to the evaporation rate.

When the fluxes have been determined, the moisture content of each cell, is then recalculated in consideration of these fluxes and is given by:

$$\theta_i = \frac{V_i + (q_i - q_{i-1})}{T_i} \qquad (27)$$

The program then checks the time on its internal clock against the time interval for which a write-out of soil column conditions is required. If the two do not agree, the program returns to the beginning of the dynamic section, if they do, then the program proceeds to the third section, where a write-out of current conditions is performed. Another time check is then performed and the program either loops back to the dynamic section or finishes.

3.4 Assumptions

The following assumptions are made by the model.

1. Darcy's Law is assumed to be appropriate for soil water modelling. The assumptions of this law are fully reviewed by Philip(15) and are briefly outlined below

i) Soil water is assumed to behave as a Newtonian fluid.

ii) The Reynolds number of the flow of soil water is assumed never to exceed 1.

iii) The soil through which flow occurs is assumed to be rigid. Darcy's Law only applies to flow which is relative to the soil particles.

iv) The effects of pressure differences at the soil-air interface are assumed to be negligible.

v) The soil system is assumed to be isothermal.

vi) It is assumed that consideration of the soil at an aggregated level, where measurements of K, ψ, θ and calculations of q refer to a scale larger than the size of the individual por,e is adequate.

2. In simulation of the mathematical model, Hillel[13] draws attention to the fact that simultaneously occurring events are assumed to be independent and that each event is controlled only by the conditions at the start of each time step. Processes (the fluxes) may affect variables describing the system, but their values are not updated until the beginning of the next time step and it does not matter in which order in which they are considered.

3. The soil water model assumes that the effects of the following processes are negligible when considering the flood hydrograph response of the catchment at a large scale.

i) suface crusting

ii) flow through macropores

iii) saturation overland flow

iv) ground water flow

v) return flow

3.5 Data Requirements

Table 1 indicates the data required to drive the soil water model. The soil hydrologic characteristics are parameters which may not be commonly available for the ungauged catchment, but it is suggested that a series of charts and regression equations developed by Brakensiek and Rawls may prove very useful in deriving these parameters and allowing the routine use of the soil water model for the ungauged catchment.

These charts were developed from simulations based upon approximately 5,000 soil data sets in the United States, and represent average soil conditions prior to a particular agronomic practice.

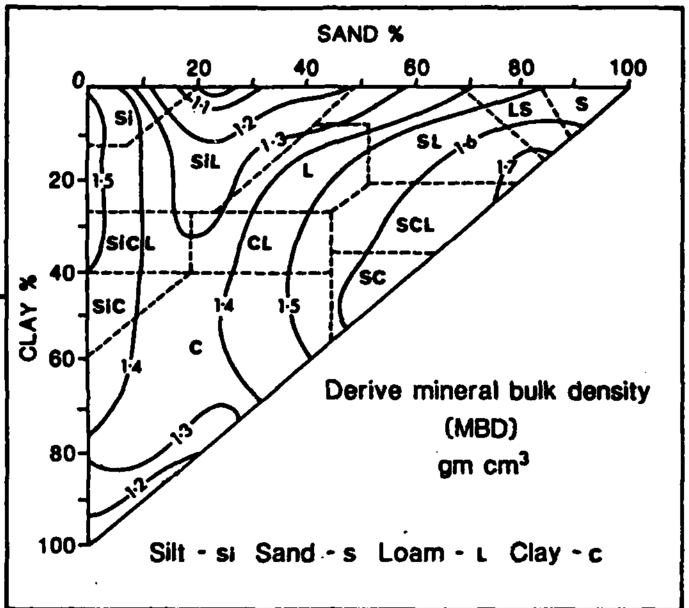
Figure 7 indicates how, with data on only the percent clay, sand and organic matter, moisture contents corresponding to a selection of suction values can be derived. Figure 8 illustrates the two charts from which values of saturated hydraulic conductivity and saturated moisture content can be derived, relating to the soils percent clay and sand.

The suitability of this method for deriving input data for the soil water model is evaluated in the following sections.

3.6 Spatial Variability

One of the major problems in applying the infiltration equation is the spatial variation of the soil's physical, and therefore hydrological properties (Raats (16)). Due to this variability, Zaslavsky (17), Beven (18) and Kiesling et al (19) all stress that it is very difficult to assign values for each parameter which are in some sense meaningful, and representative of a catchment area. Flemming and Smiles (20) remark that soil physicists have now well developed the infiltration theory, for many initial and boundary conditions, but that there remains the challenge to hydrologists to tackle the problem of variability of the infiltration parameters at a scale useful to them. McCuen (8) emphasises that in

% sand
% clay
%org. matter



Evaluates soil bulk density (SBD)

$$SBD = \frac{100}{\dfrac{\%org.\ matter}{0.224} + \dfrac{100 - \%\ org.matter}{MBD}}$$

Table used to derive θ for each given ψ using the regression equation :

$$\theta = a_i + b_i(\%sand) + c_i(\%clay) + d_i(\%org.matter) + e_i(SBD)$$

Matric Potential - Bars	a	b	c	d	e	R^2
-0.20	0.4180	-0.0021	0.0035	0.0232	-0.0859	0.75
-0.33	0.3486	-0.0018	0.0039	0.0228	-0.0738	0.78
-0.60	0.2819	-0.0014	0.0042	0.0216	-0.0612	0.78
-1.0	0.2352	-0.0012	0.0043	0.0202	-0.0517	0.76
-2.0	0.1837	-0.0009	0.0044	0.0181	-0.0407	0.74
-4.0	0.1426	-0.0007	0.0045	0.0160	-0.0315	0.71
-7.0	0.1155	-0.0005	0.0045	0.0143	-0.0253	0.69
-10.0	0.1005	-0.0004	0.0044	0.0133	-0.0218	0.67
-15.0	0.0854	-0.0004	0.0044	0.0122	-0.0182	0.66

Use ψ_b (arithmetic) from table to derive final point for θ-ψ curve

θ-ψ curve

Figure 7: Derivation of suction moisture curve from soil textural information.

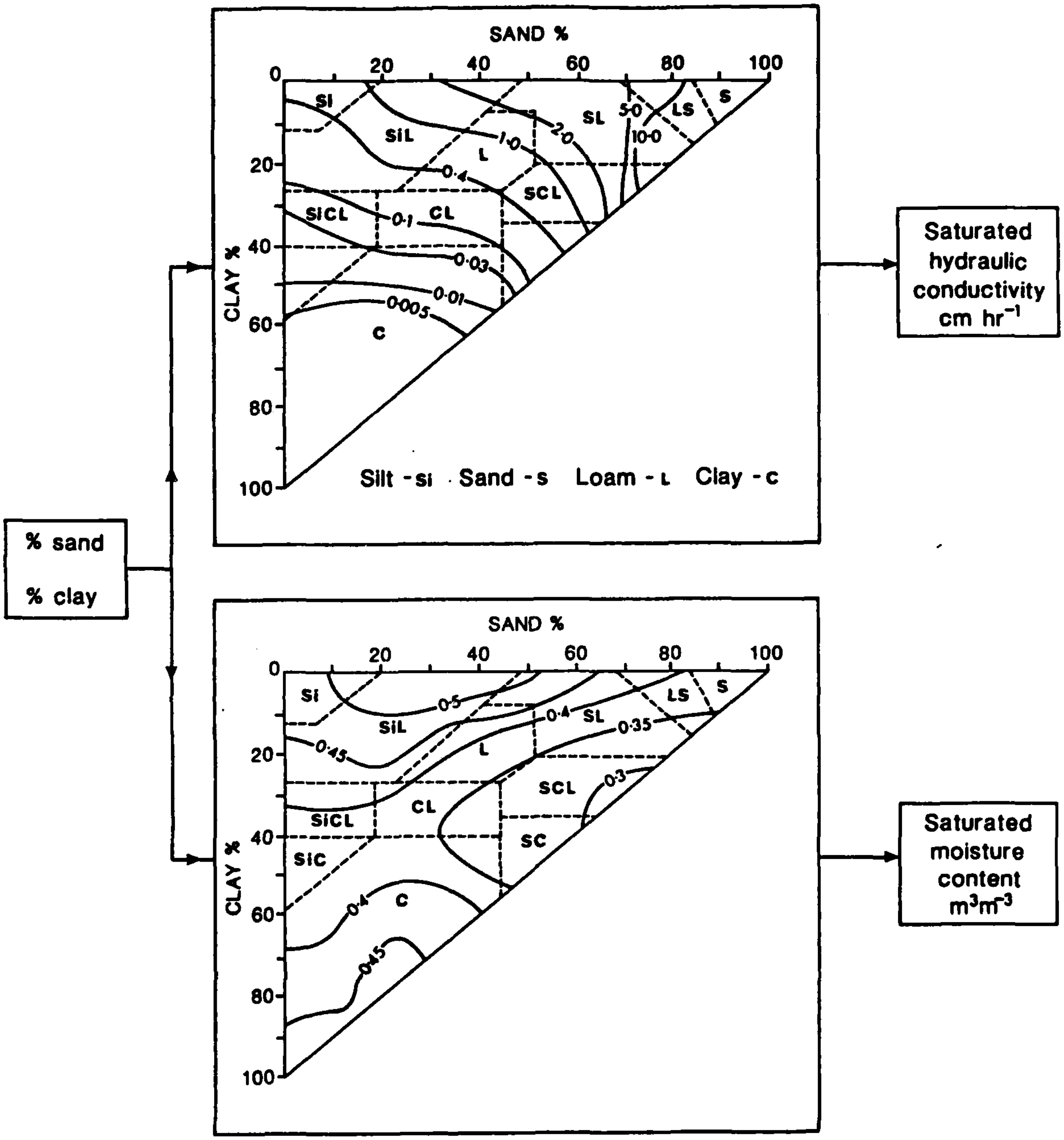


Figure 8: Derivation of saturated hydraulic conductivity and moisture content from soil texture information.

order for a model to respond in a similar manner to that of the real system, it must be formulated to reflect the variability of that system and its response.

Burrough (22) draws attention to the many independent causes of variability of the soil, and also the number of often overlapping scales at which it operates. Russo and Bresler (23) also present evidence for a high degree of variability which exists within a small area. This observed variability may include the actual field variability imposed by the cracks and fissures in the soil, and by the inclusion of different materials. It may also include error associated with the technique adopted to measure a soil property, or as Bouma (24) stresses, it can also be experimental variation associated with the choice of an inappropriate measurement technique for the conditions under consideration.

The evidence of field variability, derived from the literature can be divided into two parts; that relating to the nature of the distribution and that relating to the magnitude of variability.

Evidence for log-normal distributions of hydraulic conductivity is given by Rogowski (25), Nielson et al (26), Coelho (27), Baker (28) and Russo and Breshler (23). Other soil hydrologic properties are shown to be normally distributed. Nielson et al (26) demonstrate that water content displays normality. Rogowski (25) shows that the moisture content at air entry exhibits normality, and Russo and Breshler (23) shows that the moisture content at each suction value in the suction moisture curve is also normal.

Warrick and Nielson (29) provide a summary table which indicates the degree of variability of many soil properties. Of the hydrologic properties, the most variation is associated with saturated hydraulic conductivity, less with the suction moisture curve, and least with saturated soil water content.

This variability leads to a lack of confidence in a deterministic model and thus a probablistic approach is adopted (30). Such a framework is introduced into the soil water model in an attempt to incorporate known spatial variability within a soil type, and to establish its consequences upon the predicted hydrograph.

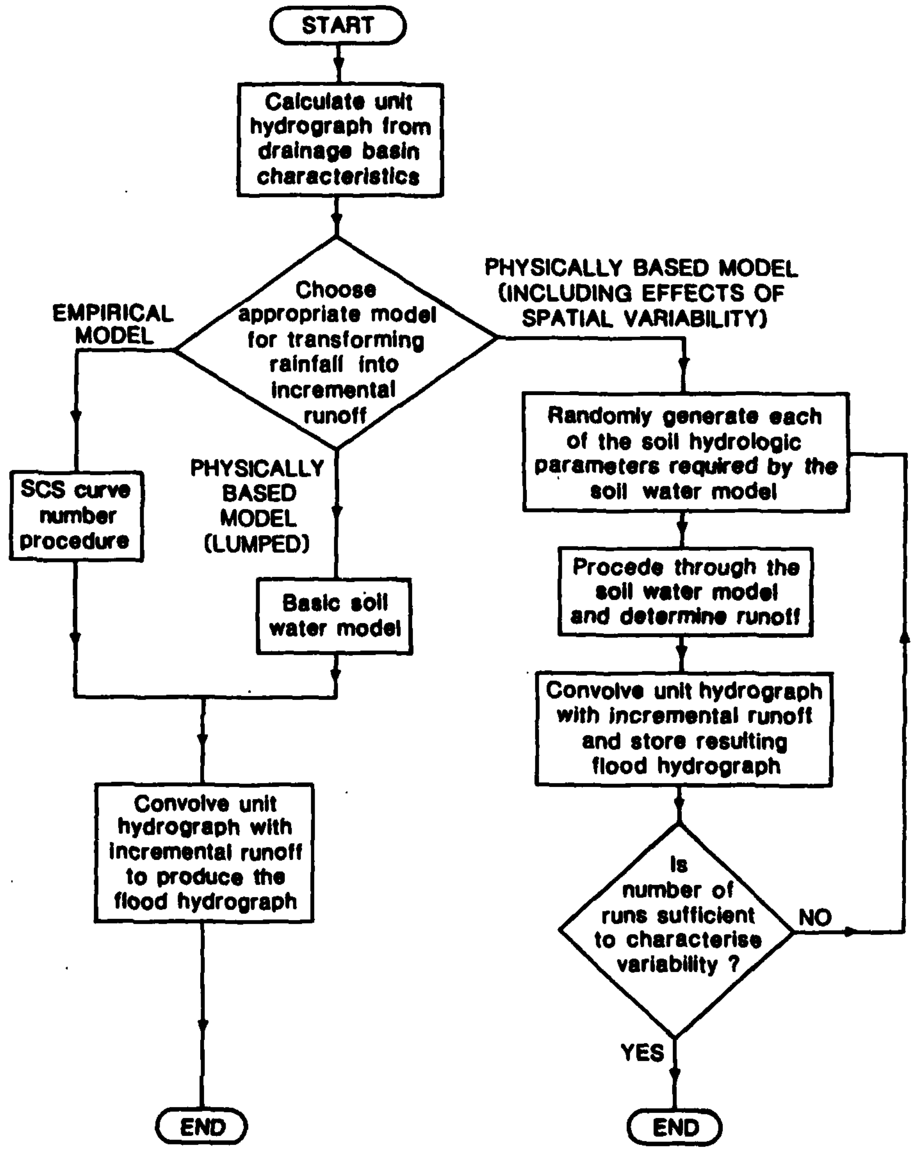
The five soil hydrologic properties necessary to operate the model (table 1), are considered to be independent random variables. It is acknowledged that variability is not without spatial structure (18), but insufficient information concerning the characteristics of this structure is available for incorporation into the model. As Anderson (1) notes, the assumption of independence will provide predictions for the 'worst case' situation; incorporation of spatial autocorrelation would decrease the model output variance.

The program references Fortran Library routines to generate random values for the input parameters from their respective probability density functions, according to a given mean and standard deviation. As neither the normal or log-normal distributions are bounded at the tails, there is a small probability of randomly generated values assuming negative values. Checks are therefore performed on the generated values to ensure physical consistency. For example, the suction moisture curve is prevented from having a positive gradient. The soil water model is then run repeatedly with randomly generated soil water properties, figure 6.

3.7 Incorporation of soil water model into HYMO.

Figure 9 indicates very simply the manner in which both the deterministic and stochastic soil water models have been inserted into the COMPUTE HYDROGRAPH subroutine of HYMO. The basic soil water model merely replaces the CN procedure and the subroutine continues as before. The stochastic model does produce greater than the flood hydrograph. All of these are stored and printed out at present. The probabilistic methodology has so far only been applied to one catchment; no routing in addition to other hydrographs has been performed.

Any one sub-catchment may be represented by more than one soil column. In order to combine the relative contributions of runoff provided by each of the soil types, the complete storm is applied to each of the soil columns, and the incremental runoff produced by each, is weighted according to the percentage area of the catchment occupied by that particular soil type. These relative contributions are then summed to produce the total runoff volume derived from the sub-catchment.



Three alternative procedures for deriving the flood hydrograph

Figure 9: Three alternative procedures for derivation of the flood hydrograph for a sub-catchment.

4. VALIDATION AND VERIFICATION OF SOIL WATER MODEL

Validation and verification together represent a procedure for evaluating and assessing a model's capability and to determine its applicability, accuracy and relevance. It is used specfically to determine the confidence with which information generated from a model may be used. It is very important to apply this procedure within the context of the models intended application, as it is this which sets the appropriate level of detail and precision.

The process of validation and verification is in this study, considered to be a three stage activity which is illustrated in Figure 10. The first stage of design validation, refers to the process of establishing the models 'face validity'. It is basically a subjective procedure aimed at establishing that the assumptions made by the model are reasonable and that the model adequately reflects the essential features and behaviour of the real system which are relevant for the application in mind. If the model is conceptual, then the assumptions made by the model must be seen to conform to basic scientific principles. This process only involves simple assessments, but it should not be overlooked.

The second state, output validation, involves a series of techniques which are designed to ensure that the computer program actually carries out the logical processes expected of it that the hydrological processes act rationally and that it is consistent with the mathematical model. The literature suggests several aspects of the model which it is worth considering.

It is important for example to demonstrate that if the model inputs are held constant, that over several runs of the model, there is no variance of

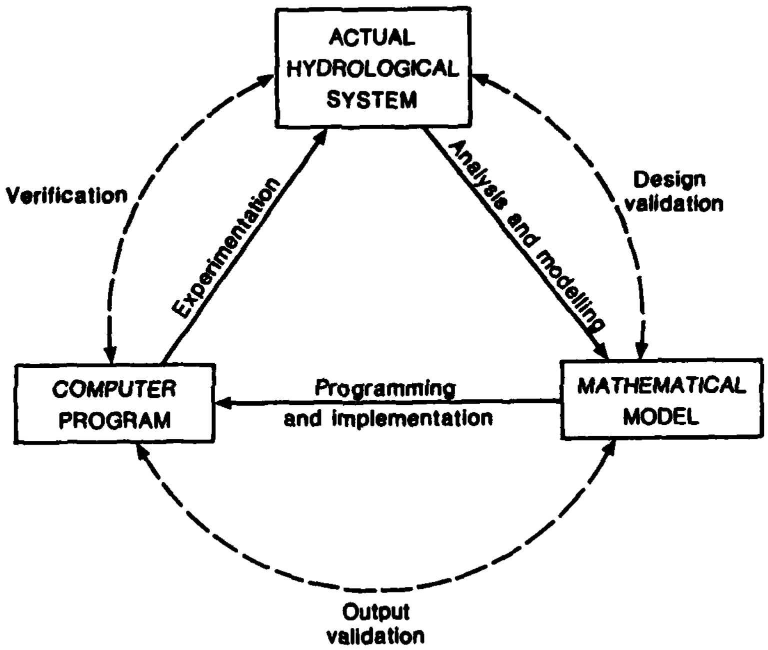


Figure 10: *Three stage process of validation and verification.*

the output. This is reffered to by Hermann[31] as establishing the models internal validity.

Bratley et al[32] suggest that at a basic level, results derived from a short computer simulation be compared to the results of a hand calculation. They also suggest that the parameter values should be stressed to indicate whether or not the model provides sensible output for infrequent events or conditions. There maybe errors in a program which only appear under stress conditions. The period of time for which the model is stable should also be established. Beyond this point, errors may accumulate and predictions become unreasonable. It is also very important to establish whether the model operates satisfactorily for the expected levels of data accuracy. Where the model structure can be questioned and parameters are known only to a given % error, it becomes necessary to apply a sensitivity analysis to establish confidence intervals about information generated by the model.

It is also beneficial to explore the models performance when the assumptions are not met, and to thereby determine the models sensitivity to its central assumptions.

Finally, verification establishes a measure of the extent to which the model and the program implementing it represent an accurate representation of reality. It is achieved by a comparison of predicted and observed values for a wide range of conditions. There will nearly always be some flood event or basin condition where the model produces satisfactory results. Discrepencies must however be small for a wide range of application. Conditions outside the models range of application must also be defined.

4.1 Face Validation

It is necessary to consider the validity of a model within the context of its intended application. It is proposed that the soil water model, incorporated into HYMO constitutes a model suitable for the prediction of the outflow hydrograph of a large scale, ungauged catchment.

The model is conceptual, its parameters are physically based, they are not calibrated, and are consistent with the quantity of data commonly available for the ungauged catchment. Its computer resource requirements are such that it is suitable for application to large scale catchments. It can be modified to include the effects of soil variability and it can also be used as a continuous simulator.

Although the model is conceptual, it is 1-dimensional and only deals with Hortorian, infiltration excess runoff. No attention is paid to other processes which operate in the catchment, in 3-dimensions. These include aturation overland flow, return flow, groundwater flow and pipeflow within the soil. Modelling of these components, and of variable source areas is possible, but application of these complex hydrological models to the ungauged catchment is not feasible due to extensive data and computational needs. The costs incured by these extensive requirements are not always rewarded by more satisfactory predictions. Many comparative studies have indicated that simpler models are preferable. The success of these less complex models is attributed by Naef(4) and Betson and Ardis(33) to the fact that at a large scale, a catchments output are dampened relative to inputs. This application does not require a full understanding or detailed knowledge of all of the processes involved and it is therefore suggested that the soil water model contains the necessary level of detail for flood hydrograph predictions.

4.2 Output Validation: Results

Investigation into the behaviour of the soil water model program has established that:

1) no variance of output is exhibited. If the model inputs are held constant, the soil water model will exactly replicate predictions.

2) the model is stable for periods of time up to 24 hours. Errors in the mass balance do occur, but can be reduced by decreasing the cell size and/or reducing the iteration time step.

3) for three soil types, the relative saturation which develops at 10cm depth after 3 hour precipitation is consistent with the expected behaviour of that soil type for a range of initial soil conditions and storm intensities.(1)

4) fluxes which occur at different depths within three soil types are consistent with those associated with the soil type and initial soil water conditions.(1)

5) the behaviour of infiltration over time is consistent with infiltration theory. There are some problems however with infiltration behaviour when rainfall intensities change very rapidly over short periods of time. This remains the subject of further investigation.

A sensitivity analysis was applied to determine whether the model would be consistent with the quality of data available for the ungauged catchment. This analysis examines the effect of error in input data on the model output by considering the rate of change of the model output with respect to model input.

Jones[34] outlines two possible approaches to sensitivity analysis; deterministic and stochastic. The stochastic methodology is utilised here, as variation in model output relating to a much wider spread of data uncertainty may be evaluated for a given computational effort. Model parameters are randomly selected from probability density functions which represent the relative likelihood of different parameter values, according to a given mean and standard deviation. The standard deviation is a measure of the amount of error associated with the specification of that parameter.

The stochastic methodology was used therefore to quantify the effect of error in the five soil hydrologic properties; detention capacity, the suction moisture curve, saturated soil moisture content, saturated hydraulic conductivity and the initial moisture content, on the predicted flood hydrograph for one subcatchment. The same program adaptations as those which incorporated spatial variability are used.

Flood hydrograph sensitivity is examined under nine different storm conditions (Figure 11). Each of the 5 input parameters are varied individually to evaluate their relative importance and then they are varied simultaneously to determine the effects of interactions. For each set of conditions, with the soil water model is run a number of times. The variation of the flood hydrograph is considered in terms of the co-efficient of variation of its three characteristics; runoff volume, peak discharge rate and time to peak. The co-efficient of variation (CV), is expressed as a percentage, it is dimensionless and therefore allows for comparisons:

(28)

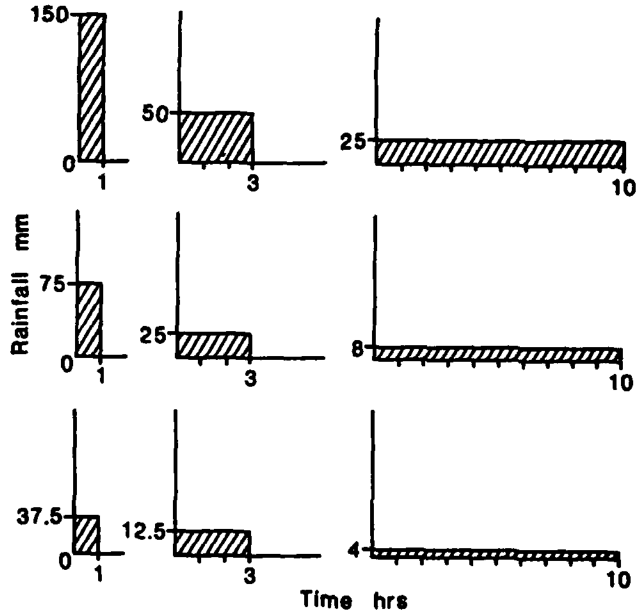


Figure 11: The 9 storms used for the sensitivity analysis.

$$CV = \frac{\sigma}{\bar{x}} \times 100 \quad (29)$$

$$\sigma = \sqrt{\left(\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}\right)} \quad (30)$$

n = sample size.

When each parameter is varied alone, 15 runs was found to be sufficient to represent the variability of the model output. When all 5 are varied simultaneously, 25 runs were required. From the information derived from the analysis, the following comments can be made.

1) The magnitude of the variability of the flood hydrograph is positively related to the magnitude of variation (or error) in the input parameter, but it is also strongly related to the storm characteristics.

Tables 2, 3, 4, 5 and 6 all illustrate that the sensitivity of runoff volume, peak discharge rate and the time to peak to variation in any of the parameters, increases as the storm intensity decreases and storm duration increases. Higher intensity storms, of short duration can therefore be identified as conditions where sensitivity to data error is at a minimum. For example, to attain a CV of 6% or less in runoff volume, for a rainfall intensity of 150mm/hour, occurring over 1 hour, the magnitude of error of detention capacity, the suction moisture curve, saturated hydraulic conductivity and initial moisture content which is allowed is 200%, 100% 3% and 100% respectively. For a rainfall intensity of 12.5mm/hour over 3 hours, the error is reduced to 20%, 100%, .3% and less than 5.7% respectively.

Table 2 **Sensitivity of the flood hydrograph to error in detention capacity**

CV of detention capacity (%)	Total rain (mm)	CV runoff volume (%)			CV peak Q rate (%)			CV time to peak (%)		
		Storm duration (hrs)								
		1	3	10	1	3	10	1	3	10
20	150	.2	1	6	.5	.5	4	0	0	9
	75	1	2	27	1	1	14	0	0	4
	37.5	2	3	120	2	3	108	0	0	60
100	150	2	2	13	2	2	12	0	0	13
	75	6	4	55	5	4	42	0	0	10
	37.5	13	15	111	11	13	112	0	0	106
200	150	5	2	43	5	2	35	0	0	11
	75	10	8	83	10	8	72	0	0	7
	37.5	13	15	125	10	13	121	0	0	100

Note: CV = coefficient of variation (see equation 28). High values of CV denote increased relative error.

Table 3 **Sensitivity of the flood hydrograph to error in the suction moisture curve**

CV of suction moisture curve (%)	Total rain (mm)	CV runoff volume (%)			CV peak Q rate (%)			CV time to peak (%)		
		Storm duration (hrs)								
		1	3	10	1	3	10	1	3	10
6	150	1	0	1	.1	.5	1	0	0	0
	75	1	2	50	.3	1	5	0	0	0
	37.5	0	5	-	.1	13	-	0	0	-
50	150	1	.6	2	.2	.6	2	0	0	0
	75	0	.2	23	.2	1	5	0	0	4
	37.5	0	5	-	1	3	-	0	0	-
100	150	.7	0	2	.2	.5	2	0	0	0
	75	.2	.2	6	.4	1	4	0	0	0
	37.5	0	6	-	1	2	-	0	0	-

Table 4 **Sensitivity of the flood hydrograph to error in saturated hydraulic conductivity (Ks)**

CV of Ks (%)	Total rain (mm)	CV runoff volume (%)			CV peak Q rate (%)			CV time to peak (%)		
		Storm duration (hrs)								
		1	3	10	1	3	10	1	3	10
0.3	150	.5	0	0	.1	.4	1	0	0	0
	75	0	0	0	.2	.4	3	0	0	0
	37.5	0	4	-	.3	2	-	0	0	-
3.0	150	1	2	8	1	2	7	0	0	4
	75	3	8	33	16	7	26	0	0	0
	37.5	4	16	-	4	14	-	0	0	-
50	150	77	69	75	54	70	71	54	59	54
	75	68	100	114	70	97	116	54	90	105
	37.5	100	54	-	97	55	-	83	53	-

Table 5 **Sensitivity of the flood hydrograph to error in initial moisture content (i)**

CV of i (%)	Total rain (mm)	CV runoff volume (%)			CV peak Q rate (%)			CV time to peak (%)		
		Storm duration (hrs)								
		1	3	10	1	3	10	1	3	10
5.7	150	2	5	4	2	4	3	0	0	0
	75	5	11	28	5	9	33	0	0	6
	37.5	13	45	-	13	45	-	0	11	-
57.1	150	6	15	32	7	15	23	0	0	6
	75	10	29	96	11	26	87	0	0	7
	37.5	47	71	-	44	66	-	0	55	-
100	150	6	11	28	6	10	23	0	0	5
	75	7	32	86	17	32	77	0	0	7
	37.5	53	120	-	55	129	-	0	131	-

Table 6 **Difference in mean flood hydrograph produced by increased error in saturated hydraulic conductivity**

CV of input parameter (%)	Total rain (mm)	Mean runoff volume (mm)			Mean peak Q rate (m^3s^{-1})			Mean time to peak (hrs)		
		Storm Duration (hrs)								
		1	3	10	1	3	10	1	3	10
0.0	150	140	135	90	177	159	62	3	4	9
	75	68	60	15	84	72	14	3	4	8
	37.5	30	24	-	37	28	-	3	4	-
0.3	150	140	134	90	177	159	62	3	4	9
	75	68	60	15	84	71	14	3	4	8
	37.5	30	23	-	37	28	-	3	4	-
3.0	150	143	138	90	177	159	63	3	4	9.1
	75	67	60	18	84	72	15	3	4	8
	37.5	29	24	-	37	28	-	3	4	-
50	150	110	90	70	136	106	50	2.4	3.2	6.8
	75	48	35	18	59	41	13	2.4	2.9	3.8
	37.5	18	23	-	21	27	-	1.8	3.6	-

2) Where all of the five parameters are varied individually, over all of the storm conditions, the hydrograph appears to be most sensitive to saturated hydraulic conductivity, then to the initial moisture content and then to detention capacity. The hydrograph displays relatively little sensitivity to variations in the suction moisture curve and finally, no sensitivy at all is displayed to variation of even up to 200% in saturated moisture content. For each storm the magnitude of variation exhibited by runoff volume and peak discharge rate is roughly equivalent. Much less variation is exhibited by the time to peak, except for the case where error in saturated hydraulic conductivity is greater than 3%.

To illustrate these two points, for a rainfall intensity of 25mm/hour, over 3 hours, a CV of 100% in the saturated moisture content causes no variation in the hydrograph. The same degree of variation in the suction moisture curve, detention capacity and initial moisture content causes variation in runoff volume and peak discharge of 1% or less, 4% and 32% respectively. No variation in time to peak occurs. However, only a 50% CV of saturated hydraulic conductivity causes between 97 and 100% of runoff volume and peak discharge, and 90% variation in time to peak.

As the variation of input parameter increases, the mean value of runoff volume, peak discharge rate and time to peak decreases marginally. The largest reduction is experienced for variation in saturated hydraulic conductivity (table 6). Examination of this table suggests that where error in sensitive parameters is great, different predictions of the flood hydrograph are produced. These differences are more marked for lower intensity, longer duration storms.

3) Where all five parameters are varied simultaneously, the relative sensitivity of the model to each of the parameters changes. The flood hydrograph does remain most sensitive to saturated hydraulic conductivity, but the interactions between the parameters has the net effect of reducing the models sensitivity to this parameter. The flood hydrograph is then most sensitive to error in the suction moisture curve, to initial moisture content, to saturated soil moisture content and finally, error in detention capacity produces the least variation.

This information has been derived from table 7. Firstly, to establish a 'base' or 'control' condition from which the relative sensitivity of each parameter can be established, the CV of each of the 5 parameters is kept very low and the degree of flood hydrograph variation for each storm is determined. The CV of each parameter in turn is then increased to 100%, or 50% in the case of saturated hydraulic conductivity, whilst the variation of the other 4 is held constant.

These results have implications for the use of the soil water model for the ungauged catchment. It will be necessary that the Brakensiek and Rawls method provides suitable values of saturated hydraulic conductivity and the suction moisture curve as these are the two parameters to which the model is most sensitive. The lower sensitivity to initial moisture content and detentions capacity however is encouraging for this application.

Variations of all input parameters causes a decrease in the mean values of runoff volume, peak discharge and time to peak. Table 8 details firstly, the mean values of the hydrograph produced where there is no variation of the 5 input parameters. It is then illustrated that a small amount of variation in each causes a reduction of between 5% in the case of high

Table 7 **Flood hydrograph sensitivity to simultaneous variation of all 5 soil hydrologic parameters.**

	Total rain (mm)	CV runoff volume (mm)			CV peak Q rate (%)			CV time to peak (%)		
		Storm duration (hrs)								
		1	3	10	1	3	10	1	3	10
Control	150	3	7	15	3	6	11	0	0	5
Condition	75	7	34	60	6	33	56	0	0	36
	37.5	16	113	-	17	126	-	0	69	-
50% CV	150	35	29	64	35	29	60	33	8	56
for	75	52	44	98	53	42	99	36	36	69
Ks	37.5	57	182	-	58	189	-	54	71	-
100% CV	150	7	24	54	7	43	51	0	0	36
suction	75	16	92	183	16	90	178	0	55	86
Moisture Curve	37.5	53	123	-	55	126	-	0	131	-
100% CN	150	6	22	30	6	20	18	0	0	4
initial moisture	75	14	36	200	15	36	208	0	7	162
content	37.5	49	137	-	49	139	-	0	89	-
100% CV	150	3	6	27	3	27	19	0	0	3
saturated	75	6	35	98	6	33	96	0	0	162
moisture content	37.5	17	126	-	18	125	-	0	69	-
100% CV	150	3	13	36	2	12	29	0	0	10
detention	75	5	38	81	6	36	78	0	7	33
capacity	37.5	17	81	-	16	76	-	0	36	-

Table 8 **Changes in the mean values of the hydrograph caused by simultaneous variation of all 5 soil hydrologic parameters**

	Total rain (mm)	Mean runoff volume (mm)			Mean peak Q rate ($m^3 s^{-1}$)			Mean time to peak (hrs)		
		Storm Duration (hrs)								
		1	3	10	1	3	10	1	3	10
No variation	150	142	137	91	177	159	62	3	4	9
in any	75	69	61	15	84	72	14	3	4	8
parameter	37.5	30	24	-	37	28	-	3	4	-
Small amount	150	135	124	61	167	142	48	3	4	9
of variation	75	58	41	6	74	48	6	3	4	7.8
in all	37.5	23	8	-	27	8	-	3	3.2	-
50% CV	150	124	124	71	155	143	50	2.7	4	2.7
for	75	53	41	6	65	60	12	2.8	3.6	5.8
Ks	37.5	23	6	-	27	6	-	2.4	2.1	-
100% CV for	150	130	84	43	161	8	34	3	4	8
suction	75	53	30	2	66	35	2	3	3.3	5.1
moisture curve	37.5	16	6	-	19	7	-	3	1.6	-
100% CV for	150	130	112	53	159	131	44	3	4	9.8
initial moisture	75	53	48	3	66	56	2	3	4.1	2.6
content	37.5	15	10	-	19	10	-	3	2.7	-
100% CV for	150	135	122	66	167	156	51	3	4	9.9
saturated	75	58	41	3	74	48	4	3	4	2.6
moisture content	37.5	22	7	-	27	8	-	3	3.2	-
100% CV	150	132	119	51	165	137	4	3	4	9.2
for detention	75	58	41	11	71	48	9	3	4.1	8.8
capacity	37.5	20	7	-	24	8	-	3	4.2	-

intensity, short duration storms and 71% in the case of low intensity, long duration storms, for both run off volume and peak discharge rate. The predicted time to peak remains the same, except for lower intensity, longer duration storms, where small reductions in the order of 3% occur.

The variation of each parameter in turn is increased further to 100%, or 50% for saturated hydraulic conductivity, whilst the variation of the other 4 is held low. This indicates that the greatest reduction in mean predicted values occurs in response to variation of saturated hydraulic conductivity. A smaller reduction is caused by variation in the suction moisture curve, and variation of detention capacity and saturated moisture content does not cause any further reduction in runoff volume and peak discharge rate than the case where all 5 exhibit very low variation. Variation in these latter two variables however causes increases in predicted time to peak for some lower intensity, longer duration storms.

4) Anderson(1) demonstrates that for similar basin conditions, the soil water model will produce different predictions to the SCS CN method. For high intensity events, the CN procedure will underpredict the peak discharge rate relative to the soil water model, and for low intensity events, it will overpredict.

It is interesting to note that when all 5 parameters are varied simultaneously, as variation in these increases, predictions for high and low intensity events become closer in terms of mean runoff volume and mean peak discharge to those predicted by the CN procedure. Prediction of mean time to peak however becomes increasingly different.

4.3 Model Verification Results

Discharge and precipitation data for the North Creek catchment, Texas, and the Sixmile Creek catchment in Arkansas, were used to verify HYMO plus the soil water model. Figure 12 indicates the locations of these catchments and figures 13 and 14 supply more detail for each. Information concerning the storms applied to the catchments is given in table 9. The nearest recording precipitation gauges are located 7 miles from North Creek, and 6 miles from Sixmile Creek.

The characteristics of the unit hydrographs derived for each catchment from HYMO, are illustrated in Figure 15 and table 10.

The process of verification involves the comparison of two hydrographs. Consideration is given to runoff volume, peak discharge and the time to peak, but HYMO also offers two quantitive measures of the 'goodness' of fit of two hydrographs. These are provided in the ERRORANALYSIS subroutine (Figure 1). The first measure, the error standard deviation (ESD), compares two hydrographs overall and is given by:

$$ESD = \sqrt{\left(\frac{\sum_{i=1}^{n} (Qm_i - Qc_i)^2}{n} \right)} \qquad (31)$$

Where: n = number of pairs of discharge measurements at equal time intervals.

Qm = measured discharge.

Qc = calculated discharge.

This statistic is evaluated over the duration of the shorter hydrograph. A smaller value of the error standard deviation indicates a closer fit of the predicted to the measured hydrograph.

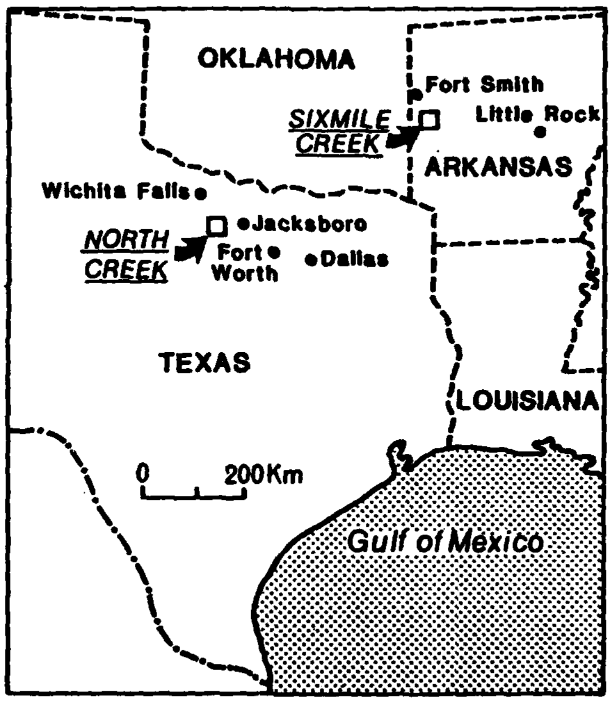


Figure 12: Location of the two study catchments used in model testing.

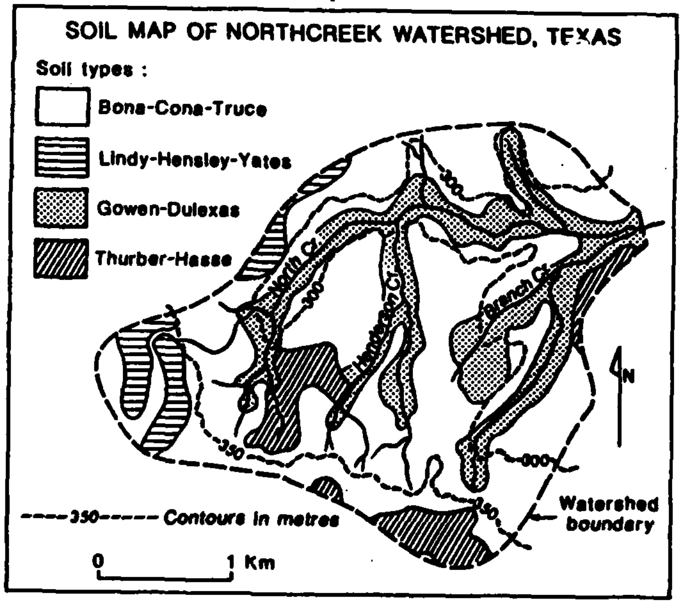


Figure 13: Northcreek catchment, Texas.

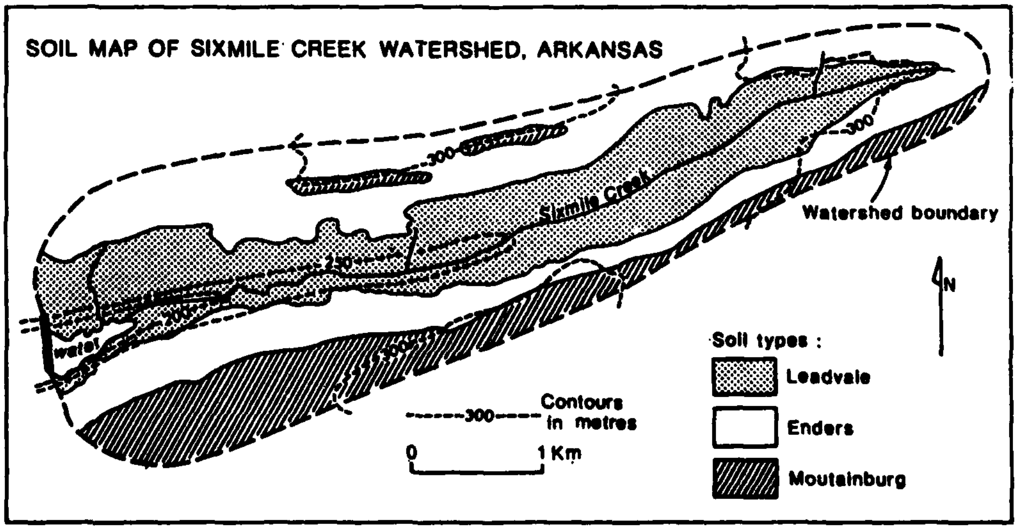


Figure 14: Sixmile Creek catchment, Arkansas.

Table 9 **Storm characteristics**

STORM	date of storm start d-m-yr	time of storm start (hrs)	time increment of rainfall data (hrs)	storm duration (hrs)	total precipitation (mm)
TEXAS					
1	09.10.1962	21.5	.25	8.25	74.5
2	27.07.1962	02.0	.25	9.0	76.7
3	18.09.1965	18.7	.1	1.3	107.2
4	22.04.1966	08.0	.5	7.5	86.1
5	04.05.1969	21.5	.25	7.5	69.8
6	06.05.1969	15.25	.25	8.75	45.2
ARKANSAS					
1	20.03.1955	10.0	.25	8.0	69.6
2	17.11.1957	18.0	.25	16.0	73.7
3	25.06.1958	08.0	.25	14.0	108.5
4	03.11.1959	18.5	.5	8.5	101.6
5	10.12.1960	06.0	.25	17.0	72.6
6	04.05.1961	04.0	.25	6.0	85.6

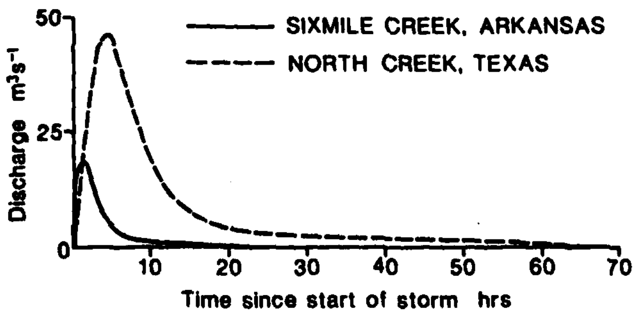


Figure 15: Unit hydrographs for North creek and Sixmile Creek.

Table 10 **Comparison of Catchment Characteristics**
(see figures 13-15)

	Area (sq km)	Difference elevation (m)	Length main channel (km)	Unit peak ($m^3 s^{-1}$)
North Creek	61.6	108.0	5.3	44.4
Sixmile Creek	11	79.0	8.3	18.0

The second measure, the percentage peak discharge error (PDE), quantifies the difference between the two peak discharge rates.

$$PDE = \frac{|Pm - Pc|}{Pm} \times 100 \qquad (32)$$

Where: Pm = measured peak discharge

Pc = calculated peak discharge

Application to the North Creek catchment in Texas will be considered first. The soils of this catchment are represented by three soil columns, the details of which are indicated in table 11. Figure 13 shows that there are four soil types in this catchment area, however, the Cindy-Hensley-Yate group is omitted for two reasons. Firstly, a soil column representing the soil type did not produce any runoff for any of the storms applied to the catchment. Secondly, it occupies only 4% of the total catchment area.

Information concerning the landuse, soil texture and depth of layers within the column were derived from the soils map and accompanying description. The hydrologic characteristics of each column, and for each layer were estimated from the charts in Figures 7 and 8, compiled by Brakensiek and Rawls. The exact % clay and % sand information is not available and therefore, the suction-moisture curve, saturated moisture content and saturated hydraulic conductivity values were determined corresponding to the centroid position of each soil texture group. The initial relative saturation of the soil could be estimated from the rainfall information of the 5 day period, previous to each storm which is available for this catchment. For most of the storms applied to this catchment however, a very high initial relative saturation is required to generate

	BONA-CONA-TRUCE			GOWEN-PULEXAS			THURBER-HASSE		
	LAYER 1	LAYER 2	LAYER 3	LAYER 1	LAYER 2	LAYER 3	LAYER 1	LAYER 2	LAYER 3
Depth (m)	.015	.046	.03	.061	.03	.061	.015	.061	.061
Soil texture	sandy loam	clay	clay	loam	clay loam	sandy clay loam	clay loam	clay	clay
Saturated soil moisture content	.4	.48	.48	.4	.36	.32	.36	.48	.43
Initial relative saturation	>.95	>.95	>.95	>.95	>.95	>.95	>.95	>.95	>.95
Suction moisture curve	See figure 16			See Figure 16			See Figure 16		
Saturated a hydraulic b conductivity c (ms^{-1})	7.2×10^{-6} 2.6×10^{-6} 7.2×10^{-6}	1.67×10^{-7} 1.39×10^{-8} 1.67×10^{-7}	1.67×10^{-7} 1.39×10^{-8} 1.67×10^{-7}	3.67×10^{-6} 6.9×10^{-7} 6.9×10^{-7}	6.39×10^{-7} 1.5×10^{-7} 1.5×10^{-7}	1.19×10^{-6} 4.4×10^{-7} 4.4×10^{-7}	6.39×10^{-7} 1.5×10^{-6} 6.39×10^{-7}	1.67×10^{-7} 1.39×10^{-8} 1.67×10^{-7}	1.67×10^{-7} 1.39×10^{-8} 1.67×10^{-7}
Landuse	Rangeland			Rangeland			Rangeland		
Detention capacity (m)	0.0			0.0			0.0		
% of total basin area	67			23			15		

Table 11 Data for application of the soil water model to the North Creek catchment, Texas

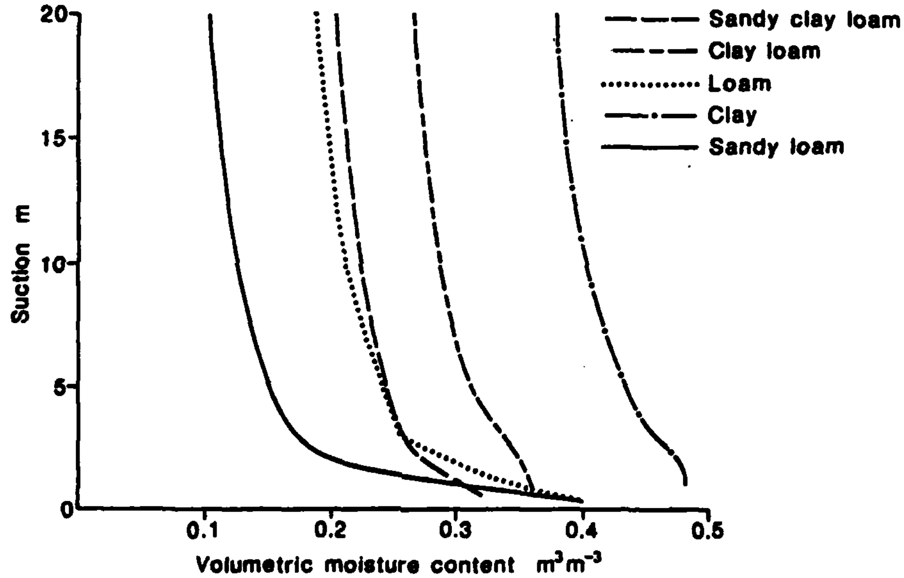


Figure 16: Suction moisture curves for North Creek soils (Figure 13).

sufficient runoff. For the same reason, detention capacity is assumed to be zero.

To establish whether or not the flood hydrograph is sensitive to the data generated by the Brakensiek and Rawls method, a further two sets of soil hydrologic data were generated. One corresponds to the highest % clay for each soil texture group; the other combines the data generated from the highest % clay soil texture group; the other combines the data generated from the highest % clay for the soil occupying the flood plain area, the Gowen-Pulexas, with that generated from the centroid positions for the other two soil types. For all soil texture groups, the organic matter content was estimated at 0.5%.

Thus for each of the 6 storms applied to the catchment, the model was run 6 times; once for each of the three data sets with a model iteration period of 60 seconds and again at 10 seconds. Before comparing these predictions to the measured hydrograph characteristics, the following points can be made concerning figures 17 and 18.

1) For all of the 6 storms, predictions of runoff volume figure 17, is sensitive to the choice of hydrologic parameters and the magnitude of this sensitivity changes according to storm characteristics. An iteration period of 60 seconds for example, and a choice of the soil hydrologic characteristics corresponding to the centroid position of each soil texture group in preference to that corresponding to the highest % clay, results in an increased prediction of runoff volume of 8%, 20%, 7%, 0% 11% and 2% for storms 1 to 6 respectively. For all storms the greatest volume of runoff is predicted by the third choice of soil hydrologic data, which

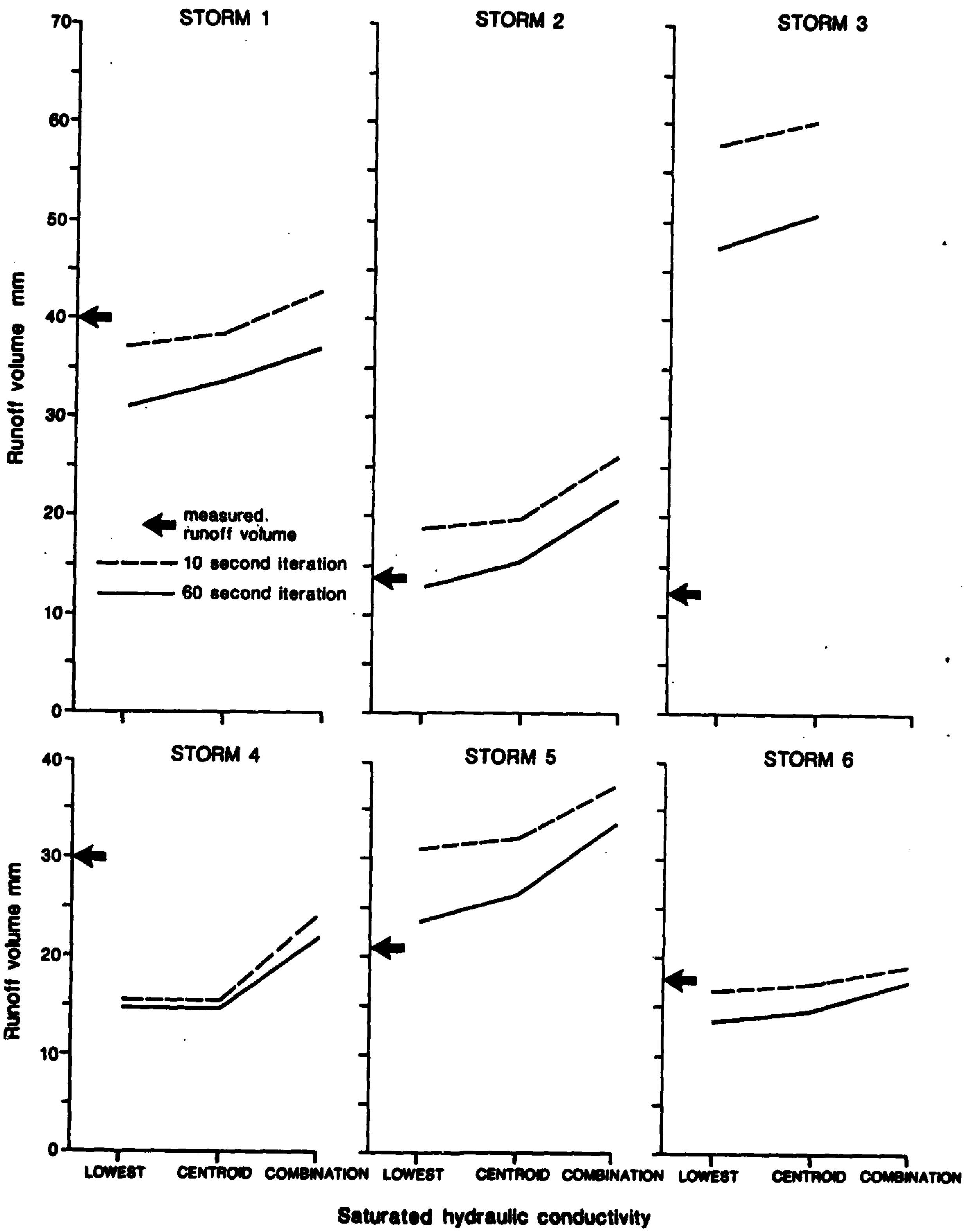


Figure 17: Predicted and measured runoff volume for 6 storms
North Creek.

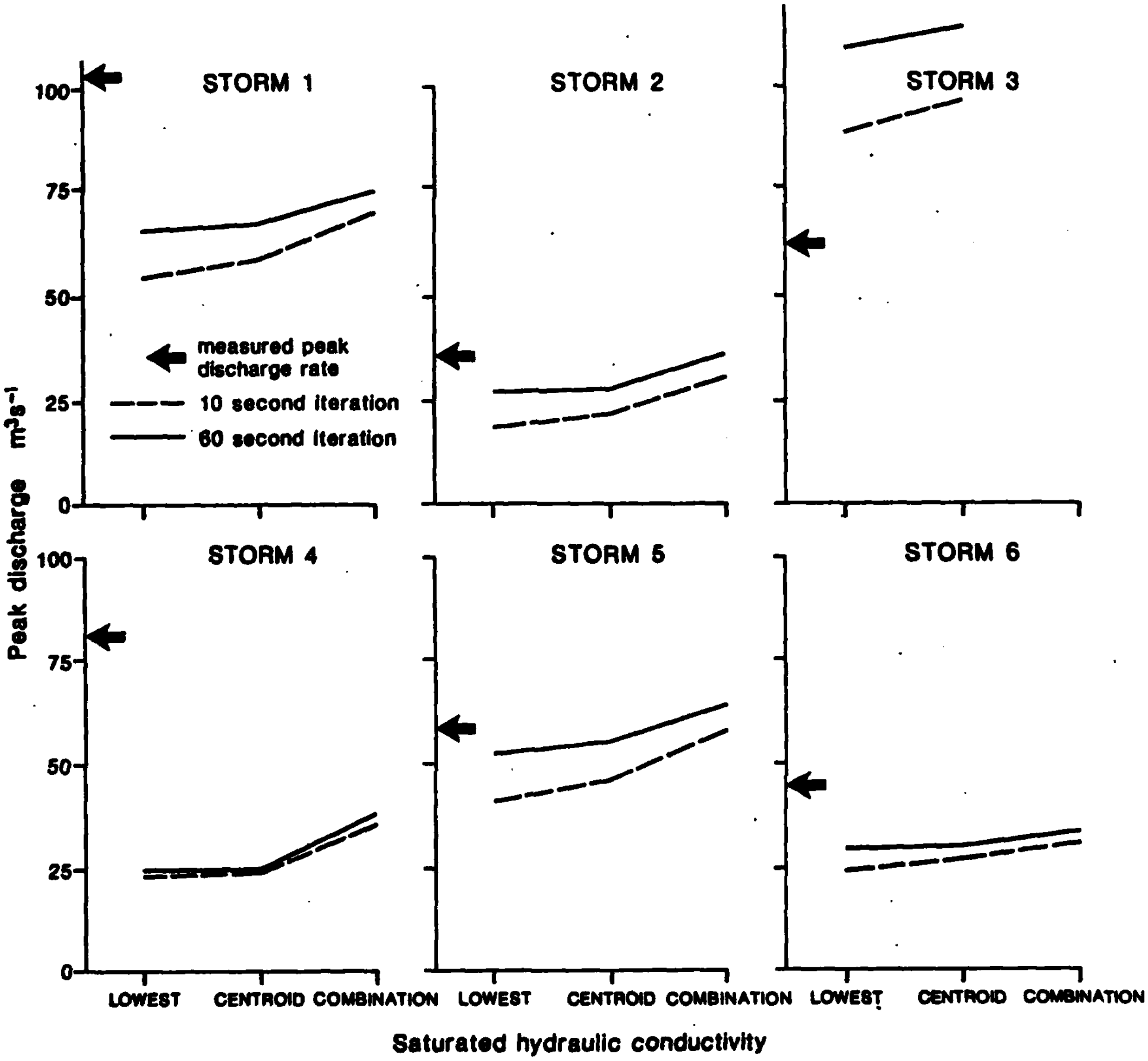


Figure 18: Predicted and measured peak discharge for 6 storms, North Creek.

implicity considers the location and relative contribution of each soil type.

2) The prediction of the peak discharge, figure 18, also displays sensitivity to the choice of input soil hydrologic data. For an iteration period of 60 seconds, a choice of the centroid in preference to the highest % clay, results in an increase of predicted peak discharge rate of 7%, 16%, 9%, 3%, 12% and 12% for storms 1 to 6 respectively.

3) Runoff volume and peak discharge are also sensitive to the choice of iteration period. As this increases from 10 to 60 seconds, greater errors occur in the solution to the infiltration equation which results in a loss of the water content of the soil and as a consequence, in lower predictions of runoff volume.

4) No sensitivity to the choice of data or iteration period is displayed for predictions of the time to peak discharge.

A comparison of the predicted hydrographs to the characteristics of the measured which are indicated on figures 17, 18 and table 12 prompts the following observations.

1. For all storms except number 4, the best estimates of runoff volume, peak discharge rate and the lowest value of the error standard deviation are not produced by the same combination of soil hydrologic data and iteration.

2. Predictions of runoff volume provided by the soil water model, figure 17, are very reasonable for storms 1, 2, 5 and 6. It is underestimated by

Table 12 **Comparison of measured and predicted time to peak discharge, for 6 storms, North Creek, Texas**

Time to Peak discharge (hrs)	Storm					
	1	2	3	4	5	6
Measured	7.25	7.5	3.3	7.0	6.0	5.75
Predicted	8.0	9.25	4.9	10.5	6.0	6.5

19% for storm 4 and overestimated by 375% for storm 3. This latter storm has the shortest duration and highest intensity of the 6 applied to North Creek.

3. The best estimates of peak discharge, figure 19 provided for each storm, attain within 2% of the measured values for storms 2 and 5, and rose to 23% for storm 6, between 35 and 40% for storms 1 and 3 and 54% for storm 4.

4. Figure 20 demonstrates that low values of error standard deviation, are derived for storms 2, 5 and 6. The overall hydrograph of storms 1, 3 and 4 are not so well approximated.

Over the 6 storms for this catchment, the error standard deviation, and % peak discharge error, are not very sensitive to the choice of soil data or iterations period.

5. The time to peak, table 12, is predicted exactly for storm 5, for storms 1 and 6 it is overestimated by an order of 1.6 to 1.75 hours, and for storms 2, 3 and 4, it is poorly estimated.

Overall, the model more closely predicts the hydrographs produced by storms 2, 5 and 6. The predictions for storm 3 however, can be improved. The sensitivity of the model to the input hydrological data allows combinations of higher saturated hydraulic conductivity and reduced initial moisture content to be explored, which will cause the required reduction in runoff volume generated by the model. Table 13 demonstates that by such a fine tuning of model parameters, lower % peak discharge rate errors, and lower error standard deviations can be achieved.

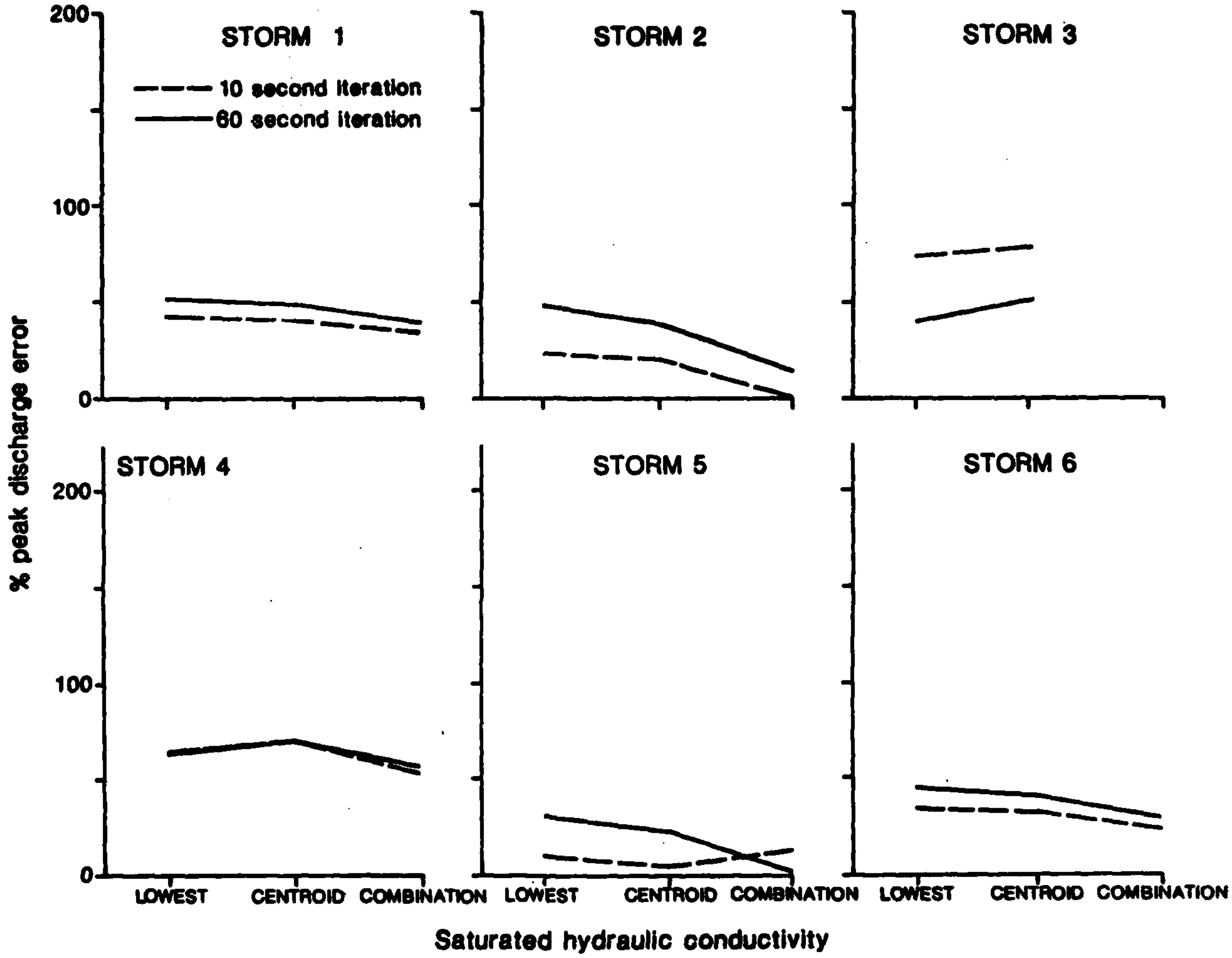


Figure 19: Percentage peak discharge error derived from the soil water model for 6 storms, North Creek.

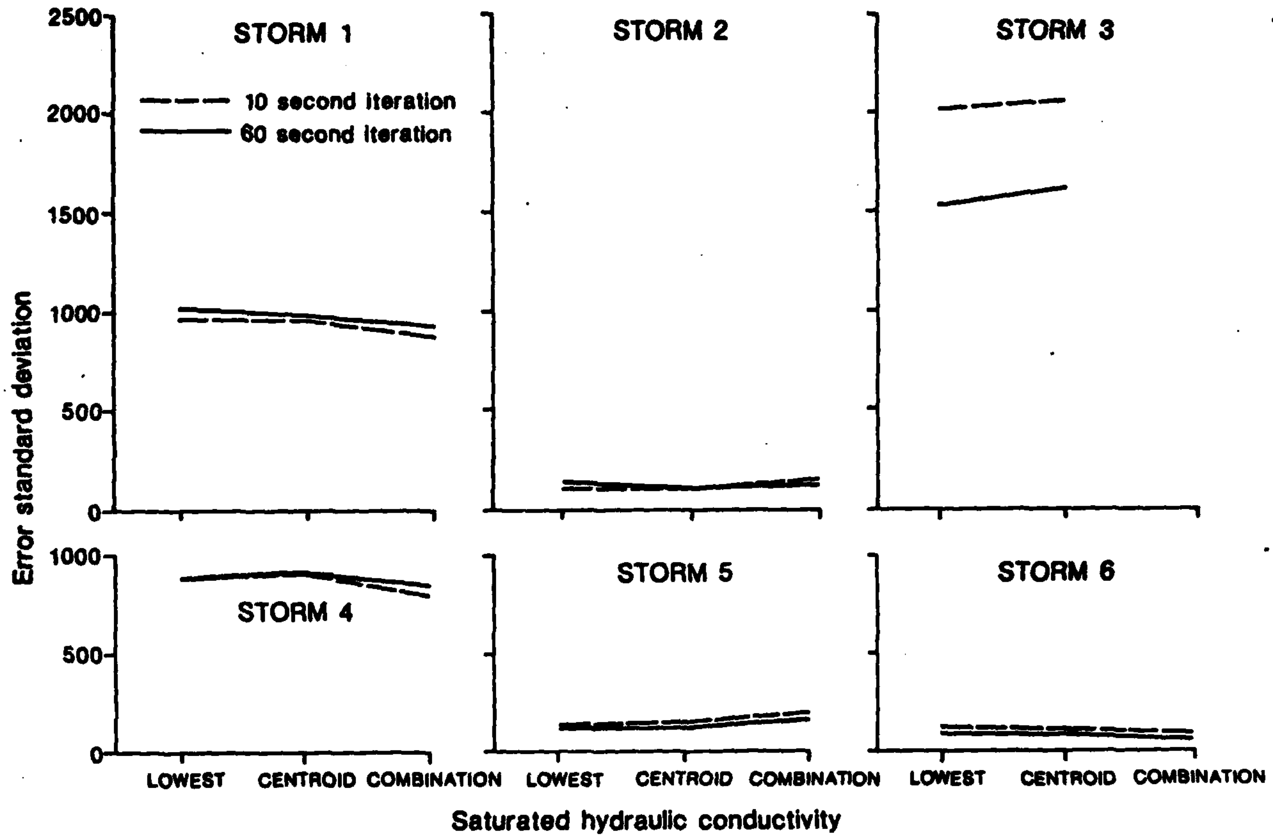


Figure 20: Error standard deviation derived from the soil water model for 6 storms, North Creek.

		SOIL WATER MODEL			Measured
	Iteration Period (seconds)	Lower initial Moisture content	Higher saturated hydraulic conductivity	Lower initial moisture content and higher saturated hydraulic conductivity	
Runoff (mm)	10	43	19	7.5	12.5
	60	32	8.5	4	
Peak discharge ($m^3 s^{-1}$) (% error in brackets)	10	79 (25%)	37 (41%)	12.5 (80%)	63
	60	60 (5%)	16 (75%)	7.5 (88%)	
Time to Peak discharge (hrs)	10	5	4.8	4.9	3.2
	60	4.9	4.7	4.8	
Error standard deviation	10	1420	660	720	-
	60	1030	720	780	

Table 13 **Fine tuning of soil water model parameters to improve hydrograph predictions for storm 3, Texas**

The soils of the Sixmile Creek in Arkansas, are also represented by three soil columns. The details of these are given in Table 14. All of the necessary information was again derived from the map and charts developed by Brakensiek and Rawls. For this catchment however, the exact % clay data is available for each soil texture. Use of these values however, for the deviation of the soil hydrologic data, and application to the catchment, produced no runoff for any of the storms. Those values corresponding to the highest % clay for each soil texture group was therefore used. This data set was used for both 60 and 10 second iteration. For most of the storms, the hydrograph thus produced was sufficiently close to the measured not to warrant the exploration of further data sets.

Prior, however, to a comparison of the predicted and measured, the results displayed is tables 15 though 18 deserves consideration, and the following points can be made:

1) The predictions of runoff volume and peak discharge rate for all storms applied to the Sixmile Creek catchment, illustrated in tables 15 and 16 exhibit sensitivity both to the choice of soil water data, and the iteration period. The soil data derived from the Brakensiek and Rawls charts, corresponding to the given % clay does not generate any runoff, that corresponding to the highest % clay position does. For storms 1, 2, 5 and 6, an increase in the iteration period from 60 seconds to 10 seconds produces an increase in predicted runoff volume of 34% 49%, 55% and 51% and an increase in peak discharge of 20%, 37% and 50% and 43% respectively.

	LEADVALE			ENDERS			MOUNTAINBURG		
	LAYER 1	LAYER 2	LAYER 3	LAYER 1	LAYER 2	LAYER 3	LAYER 1	LAYER 2	LAYER 3
Depth (m)	.015	.046	.076	.018	.069	.018	.01	.03	.01
Soil texture	Silt loam	Silt clay loam	Silty clay	Silt loam	Clay	Clay	Sandy	Sandy clay loam	Sandy clay loam loam
Saturated soil moisture content	.49	.52	.53	.49	.52	.52	.41	.41	.41
Initial relative saturation	>.95	>.95	>.95	>.95	>.95	>.95	>.95	>.95	>.95
Suction moisture curve	See Figure 21			See Figure 21			See Figure 21		
Saturated hydraulic conductivity (ms^{-1})	2.8×10^{-7}	8.3×10^{-7}	1.4×10^{-8}	2.8×10^{-7}	1.4×10^{-8}	1.4×10^{-8}	5.6×10^{-7}	2.8×10^{-6}	2.8×10^{-6}
Landuse	Rangeland			Rangeland			Rangeland		
Detention capacity (m)	0.0			0.0			0.0		
% of total basin area	47			28			25		

Table 14 Data for application of the soil water model to the Sixmile Creek catchment, Arkansas

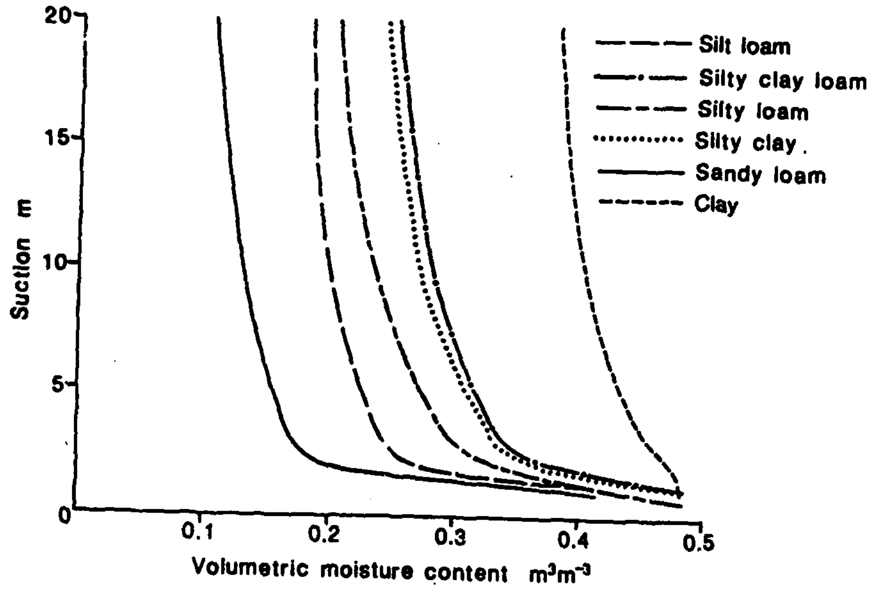


Figure 21: Suction moisture curve for Sixmile Creek soils (Figure 14)

Table 15 **Predicted and measured values of runoff volume (mm) for 6 storms, Sixmile Creek.**

		1	2	3	4	5	6
a) Measured		56.4	50.0	40.6	38.4	50.8	42.7
b) Soil Water Model							
Highest % clay content	60 secs	37.8	36.8	55.9	56.9	27.9	42.2
	10 secs	49.5	53.3	-	-	43.2	63.5
Increased Ks for Moutain burg soil	60 secs				43.9		
	10 secs				68.1		

Table 16 **Predicted and measured values of peak discharge (m^3s^{-1}) for 6 storms, Sixmile Creek**

		1	2	3	4	5	6
a) Measured		46.4	36.8	26.6	29.2	26.9	43.6
b) Soil Water Model							
Highest % clay content	60 secs	23.5 (49%)	23.3 (36%)	26.4 (1%)	33.3 (14%)	13.7 (49%)	25.3 (42%)
	10 secs	28.2 (39%)	31.8 (14%)	-	-	20.5 (23%)	36.3 (17%)
Increased Ks for Mountainburg soil	60 secs				25.3 (13%)		
	10 secs				36.4 (25%)		

% peak discharge errors in brackets.

Table 17 **Predicted and measured time to peak (hrs) for 6 storms, Sixmile Creek**

		1	2	3	4	5	6
a) Measured		4.0	4.75	8.75	6.5	10.5	6.0
b) Soil Water Model							
Highest % clay content	60 secs	4.25	4.5	8.75	6.5	10.75	6.0
	10 secs	4.5	4.75	-	-	10.75	6.0
Increased Ks for Moutainburg soil	60 secs				6.5		
	10 secs				6.5		

Table 18 **Error standard deviation for 6 storms, Sixmile Creek**

		1	2	3	4	5	6
<u>Soil Water Model</u>							
Highest % clay content	60 secs	9151	84	94	133	119	163
	10 secs	140	70	-	-	59	174
Increased Ks for Mountainburg soil	60 secs				95		
	10 secs				190		

2) Table 17 indicates that a very limited degree of sensitivity of the predicted time to peak is exhibited in the case of storms 1 and 2. No variation is found for storms 3, 4, 5 and 6.

In comparison to the measured hydrographs, the predictions made by HYMO incorporating the soil water model, for the Sixmile Creek, are much better overall, than those predicted for the North Creek catchment.

1) For this catchment for storms 1, 2, 3 and 5, the same combination of input parameters and iteration period does produce the best estimate of runoff volume, peak discharge and the lowest error standard deviation. For the remaining two storms, one combination provides the best estimate of peak discharge rate, and another the best estimate of runoff volume and the lowest error standard deviation.

2) Table 15 indicates that predictions of runoff volume are within 15% of the measured for storms 1, 2, 4, 5 and 6, and within 30% for storm 3. These are closer estimates over the range of storms than those derived for Texas.

3) Table 16 also indicates that predictions of peak discharge are also very good, and are within 20% of the measured for 4 storms. The worst estimate of this characteristic is derived for storm 1, where the best prediction which was produced was 39%.

4) Lower error standard deviations are maintained over all storms for this catchment than for the North Creek, table 18.

5) The time to peak discharge, table 17, is exactly predicted for storms 2, 3, 4 and 6. It is only over predicted by .25 hour for the remaining 2 storms.

Having established, the utility of the incorporation of the deterministic soil water model into HYMO, the variability of soil hydrologic properties was incorporated into the model to determine whether or not improvements could be made to the prediction of the hydrograph. This was attempted for storm 1 and applied to the North Creek catchment. The soil hydrologic data which provided the best approximation to the measured hydrograph was taken as the mean value for each input parameter. The respective standard deviations were derived as follows:

(i) suction - moisture curve - estimated, following Anderson[1].

(ii) saturated moisture content - taken from table 19 in Brakensiek and Rawls[35]

(iii) Saturated hydraulic conductivity, initial moisture content and detnetion capacity - taken from Hillel[13]

Twenty repetitions of the model were made for each storm. Figures 22 and 23 illustrate the form of the generated hydrographs for storms 1 and 6, applied to the North Creek catchment. Table 19 illustrates that one mean value provided by the 20 hydrographs provide estimates which are not as close to the measured, as those derived from the solely deterministic model.

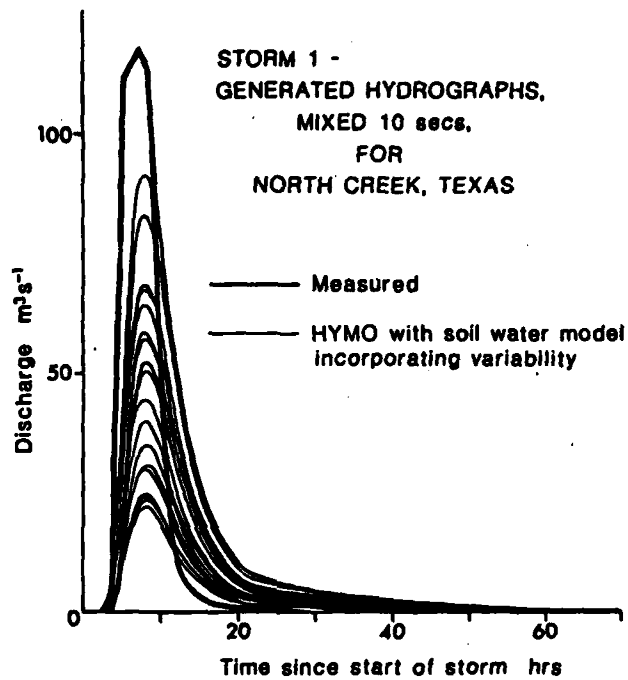


Figure 22: Distribution of hydrographs derived from the application of the stochastic soil water model for storm 1, North Creek.

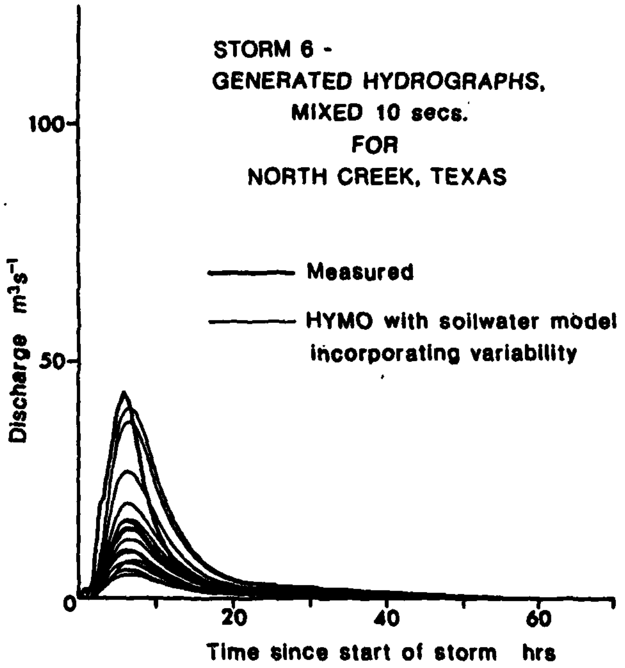


Figure 23: Distribution of hydrographs derived from the application by the stochastic soil water model for storm 6, North Creek.

Table 19 **Comparison of hydrograph predictions derived from the deterministic and stochastic soil water model for storms 1 and 6, North Creek, Texas**

	Measured	Deterministic model	Mean of 20 runs of stochastic model
STORM 1			
Runoff volume (mm)	40	38	27
Peak discharge (M^3S^{-1})	104	76	48
Time to peak discharge (hrs)	7.25	8.0	7.9
Error standard deviation	-	870	1097
% peak discharge error	-	27	54
STORM 6			
Runoff volume (mm)	18	17.5	10.5
Peak discharge rate (M^3S^{-1})	44	33	18
Time to peak discharge (hrs)	5.75	6.5	6.8
Error standard deviation	-	50	302
% peak discharge error	-	25	59

5. COMPARISON OF THE TWO MODELS

Comparison of the hydrographs predicted by HYMO with the SCS CN procedure, HYMO with the soil water model, and the measured hydrograph for a range of experimental frames, will allow specification of the conditions for which each model may represent the superior alternative.

Anderson[1] demonstrates that because the SCS CN procedure predicts a constant runoff volume for a given precipitation volume irrespective of duration, in response to a variety of storms, the soil water model, will predict a much wider range of runoff volume. Figure 24 illustrates that the SCS CN procedure underpredicts the peak discharge rate, relative to the soil water model, for high intensity storms, and underpredicts for low intensity.

In this section, comparisons are made for the 6 storms applied to each catchment. These are indicated in Figures 25, 26, 27 and Tables 20 and 21. The combination of soil hydrologic parameters and iteration period necessary to produce the closest estimates of the soil water model to the measured were used. The value of CN for each storm were those used and provided by Dr James, Texas A and M University, and in most cases they approximate the values which can be derived from back calculation. Hawkins[36] presents the following equation from which the CN value which predicts exactly the total runoff volume, can be derived.

$$CN = \frac{1}{1 + \frac{1}{2}\left(P + 2Q - \sqrt{4Q^2 + 5PQ}\right)} \qquad (33)$$

Attention is drawn to the following points.

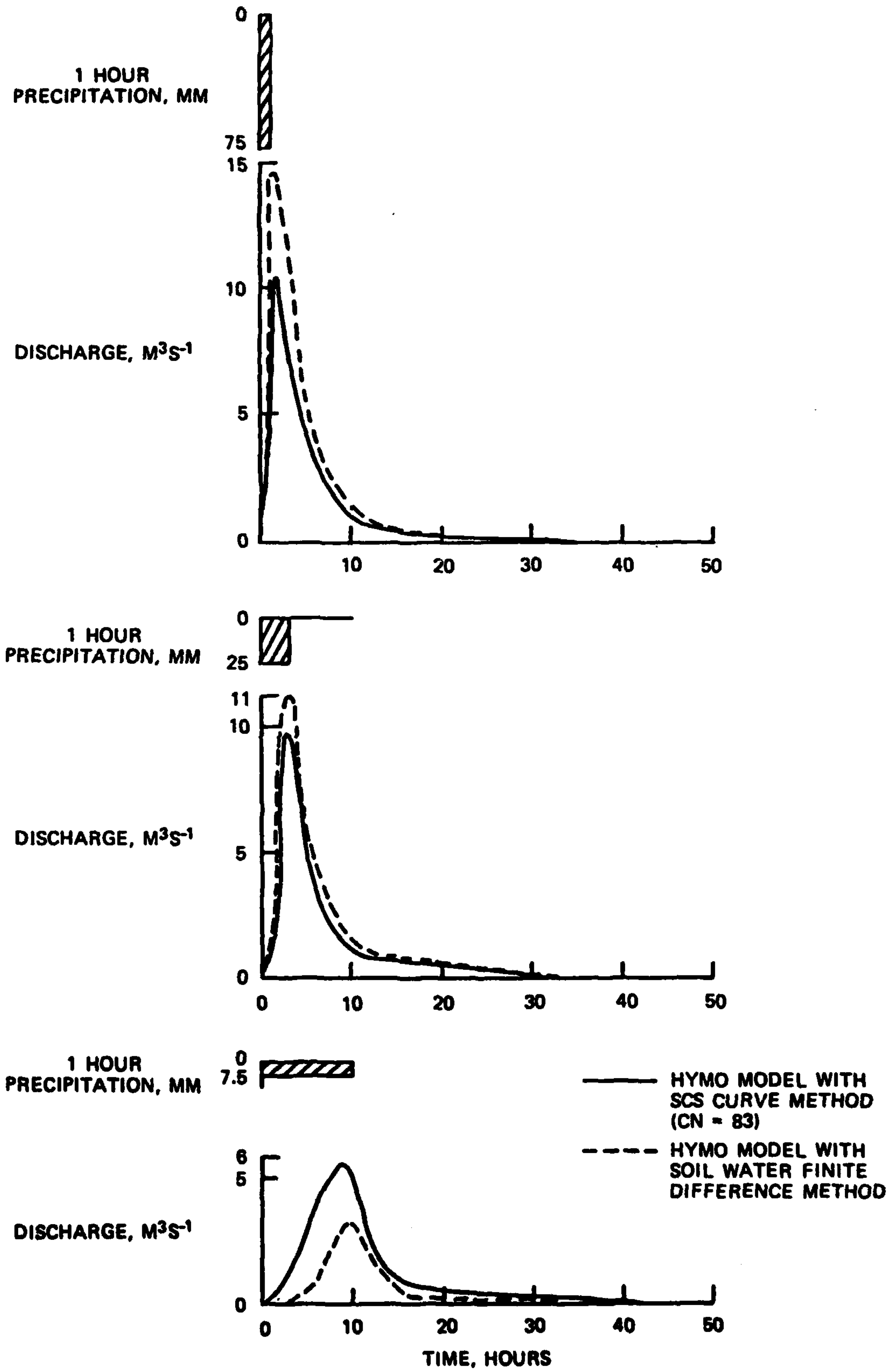


Figure 24: Illustration of rain intensity differences in resulting predictions from CN and soil water models.

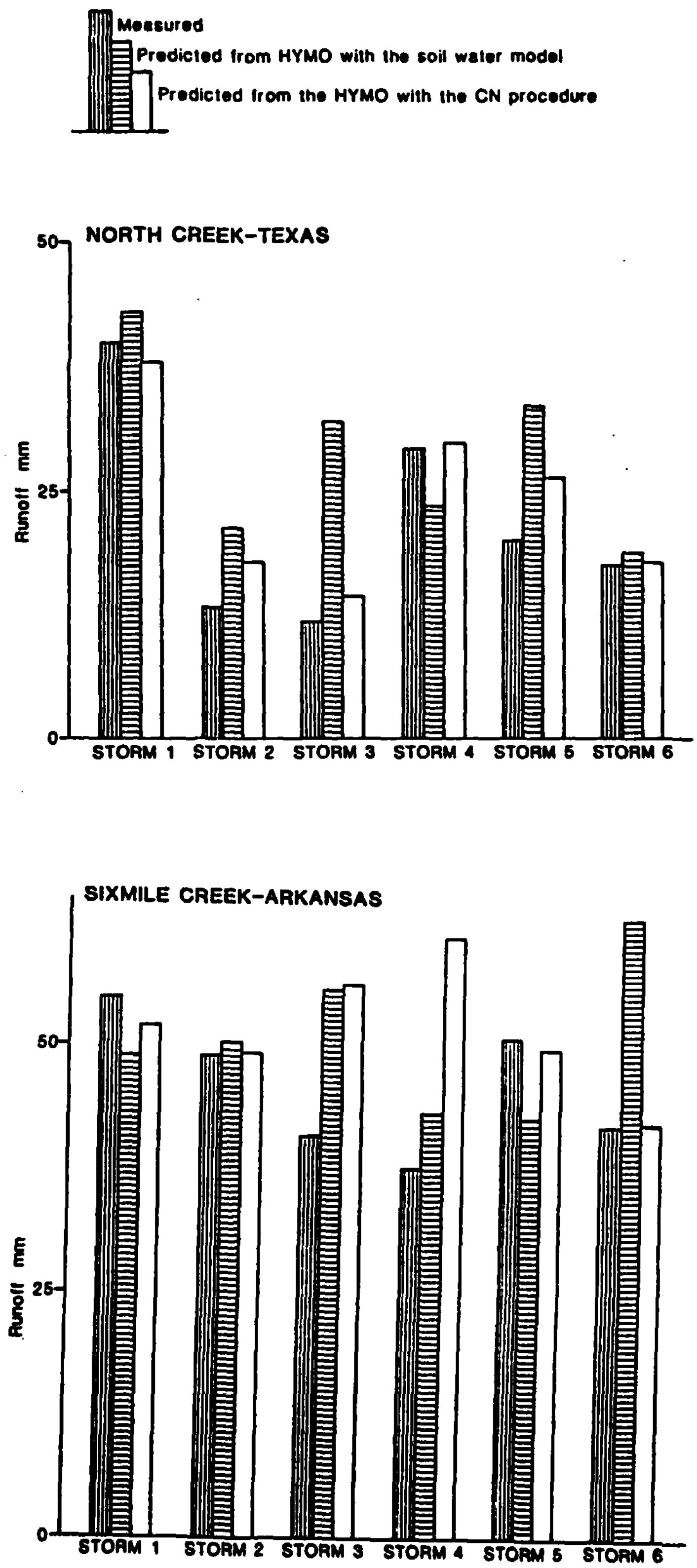


Figure 25: Comparison to measured values of predicted runoff derived from the two models.

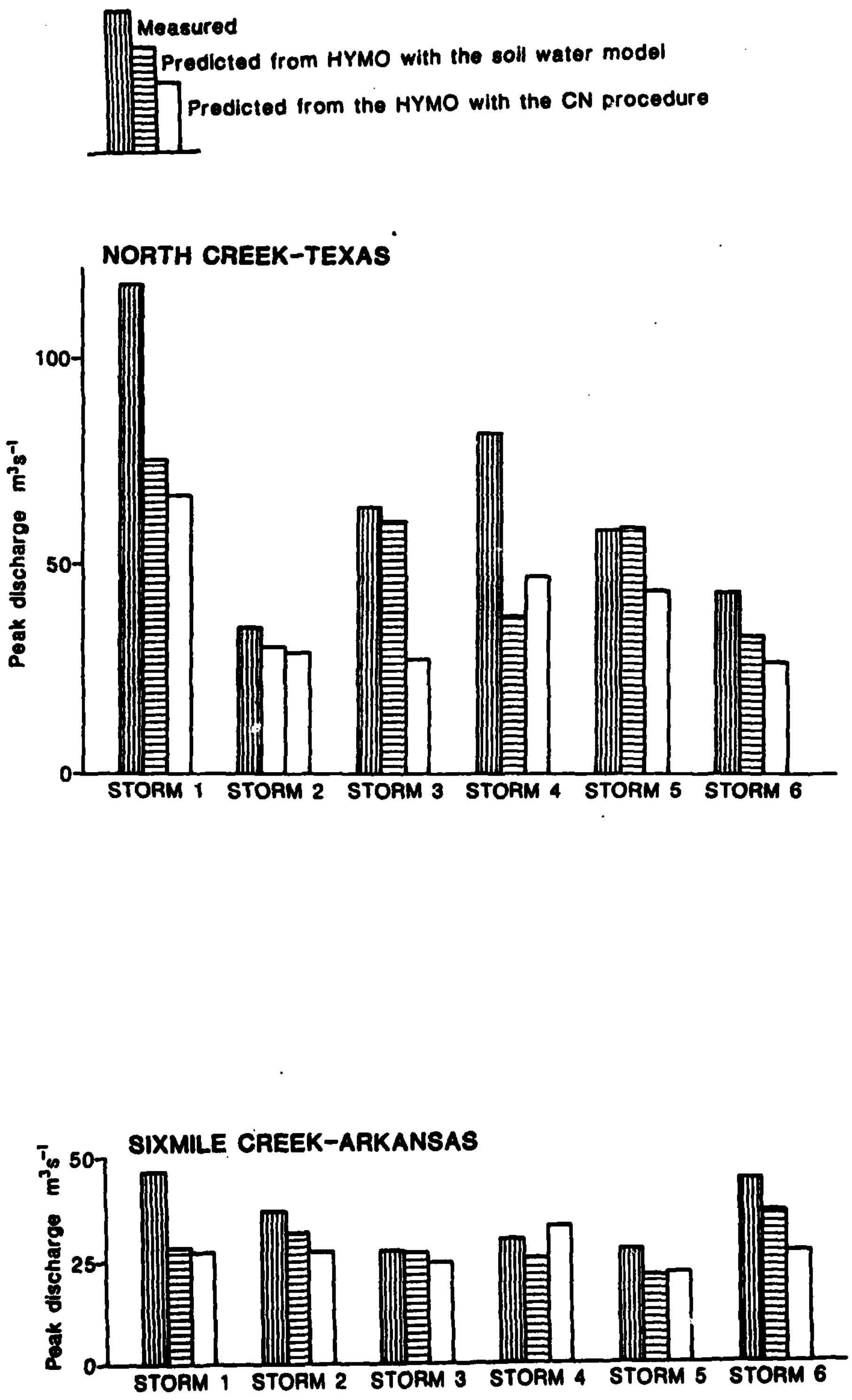


Figure 26: Comparison to measured values of predicted peak discharge derived from both models.

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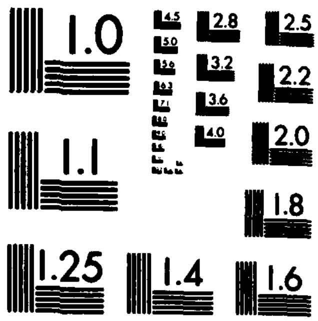

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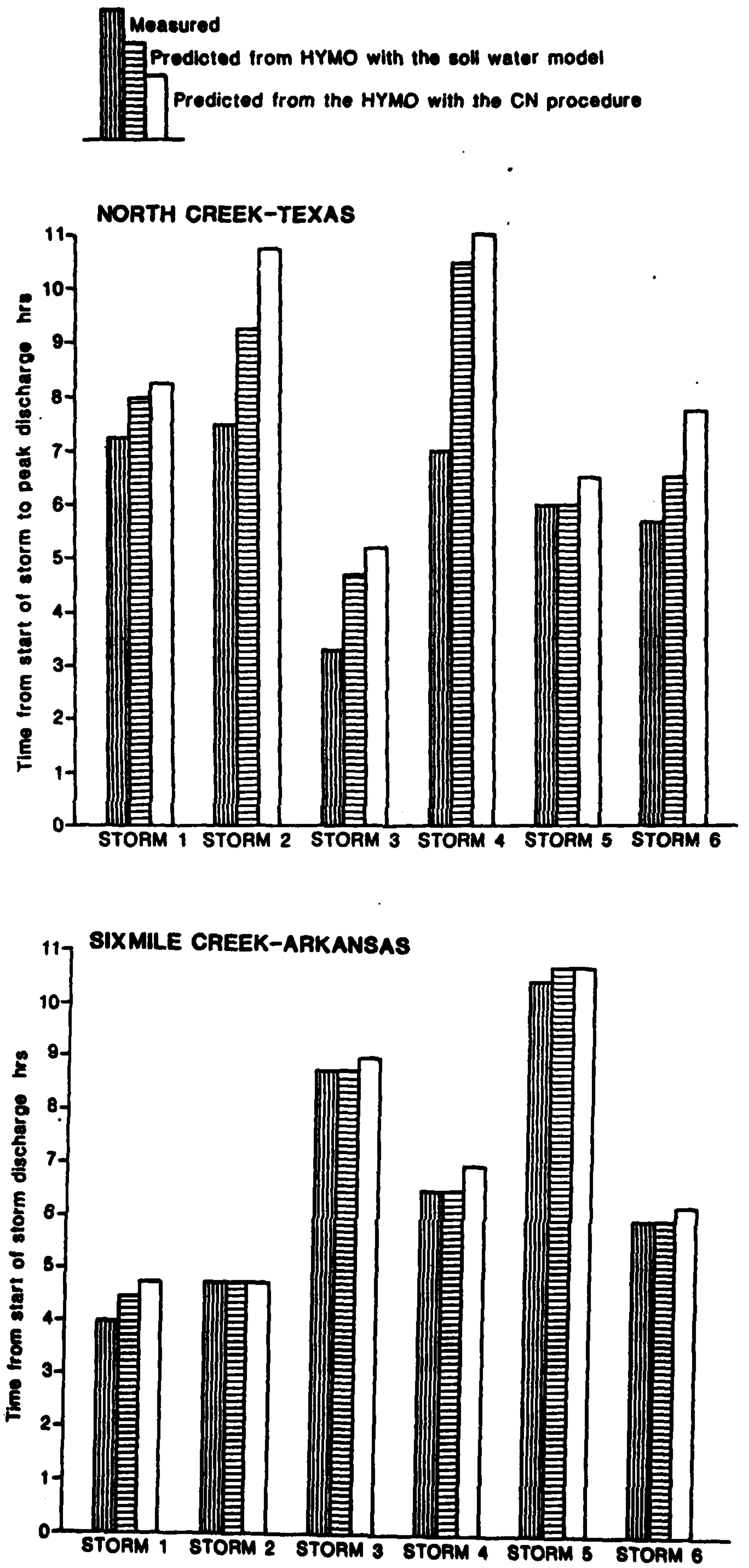


Figure 27: Comparison to measured values of predicted time to peak discharge derived from the two models.

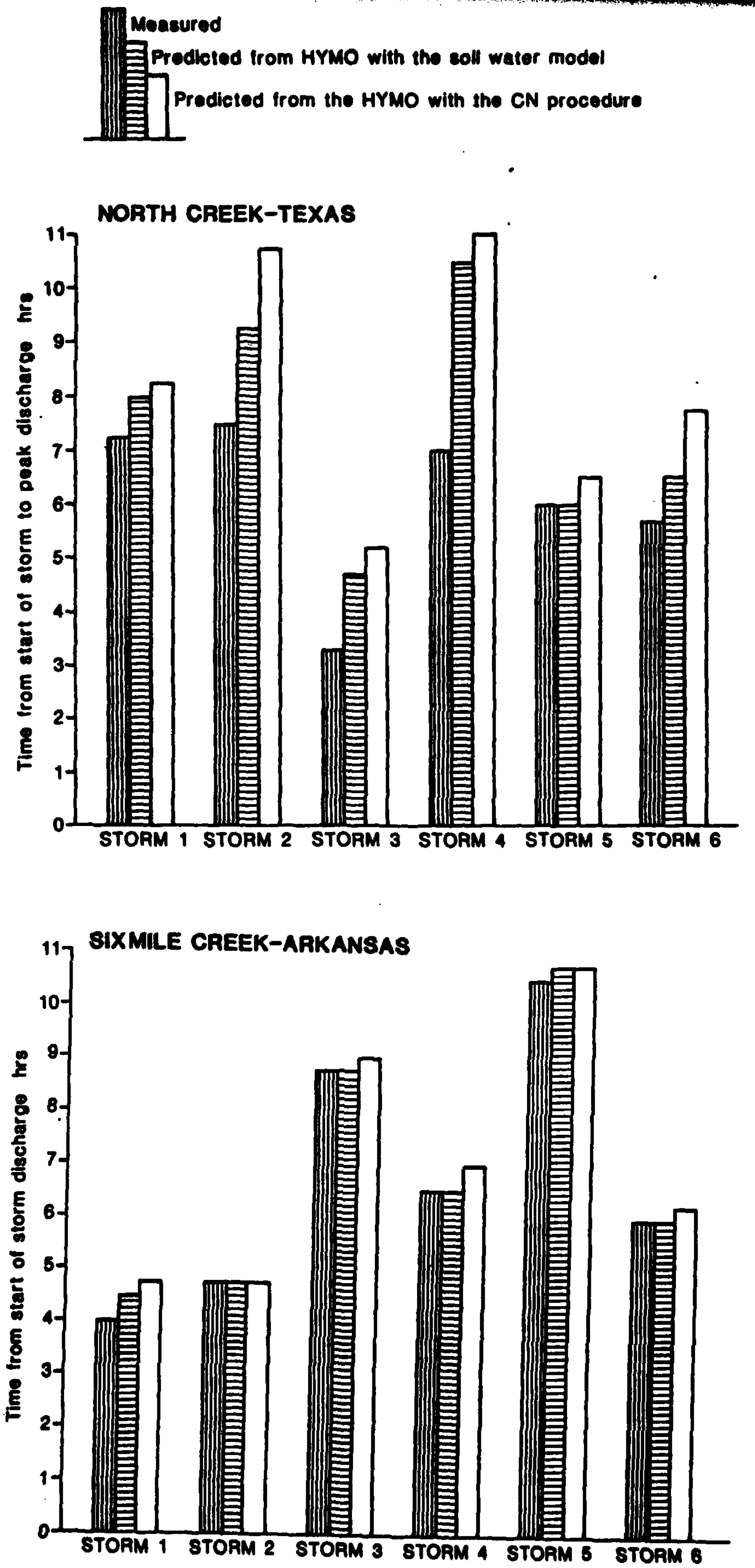


Figure 27: Comparison to measured values of predicted time to peak discharge derived from the two models.

Table 20 **Comparison of % peak discharge error derived from the two models for 12 experimental frames**

	1	2	3	4	5	6
Texas						
HYMO + CN	43	17	57	41	24	37
HYMO + SWM	35	2	5	54	8	23
Arkansas						
HYMO + CN	42	26	9	13	19	41
HYMO + SWM	39	14	1	13	23	17

Table 21 **Comparison of error standard deviation derived from the two models for 12 experimental frames**

	1	2	3	4	5	6
Texas						
HYMO+ CN	979	231	708	666	327	283
HYMO + SWM	886	297	1019	675	318	160
Arkansas						
HYMO + CN	171	78	125	193	60	172
HYMO + SWM	140	70	94	95	59	174

1. Figure 25 indicates that for both catchments, over all storms, with the exception of storms 3 and 4 applied to the Sixmile Creek, that the SCS CN procedure provides the closest estimate of runoff volume, to the measured. Only for storm 4, applied to the Sixmile Creek, does the soil water model represent a significant improvement in runoff prediction.

For storms 1, 2, 3, 5 and 6 on North Creek, and storms 2, 3, 4 and 6 on Sixmile Creek, the soil water model overpredicts the measured runoff volume.

2. Predictions of the peak discharge made by the soil water model are however, closer to the measured values, for nine out of the twelve experimental frames. This is illustrated in Figure 26. Table 20 indicates that reductions in the % peak discharge rate generated by use of the soil water model range from 52% for storm 3, North Creek, to 3% for storm 1, Sixmile Creek. Use of the soil water model for storm 4, North Creek and storm 5, Sixmile Creek, causes increases of 13%, 3% and 4% respectively, neither model produces better estimates of peak discharge for storm 4, Sixmile Creek.

3. Figure 27 indicates that for all storms, on both catchments, predictions made by the soil water model of the time to peak represent improvements to those made by the SCS CN procedure. In 5 cases, this characteristic is predicted exactly.

4. Table 21 shows that the soil water model more closely predicts the overall hydrograph for storms 1, 2, 3, 4 and 5 for the Sixmile Creek; increasing the error standard deviation only by 2 for storm 6. For the North Creek however, it only represents the better model for storms 1, 5

and 6. There are storms on this catchment, where the hydrograph is better simulated by the SCS CN procedure.

Figures 28-39 illustrate the forms of the two predicted and measured hydrograph for each storm applied to the two catchments. For each storm, the following comments can be made.

Storm 1

The measured hydrograph is much more 'peaked' than the predictions derived from both of the models. Neither produce a steep enough gradient for either the falling, or the rising limb. The overall shape of the hydrograph predicted by both models is very similar the model incorporating the CN procedure however, underpredicts the peak discharge rate more than the model incorporating the soil water model. The timing of the peak, predicted by the latter model is slightly more accurate.

Storm 2

The overall shape of this double peaked hydrograph is not well predicted by either model. HYMO with the soil water model supplies the prediction with perhaps the greatest resemblance to the measured.

Storm 3

This high intensity, short duration storm illustrates clearly the difference in predictions made by the two models which were suggested in Figure 24. Inclusion of the soil water model more closely predicts the rising limb of the measured hydrograph.

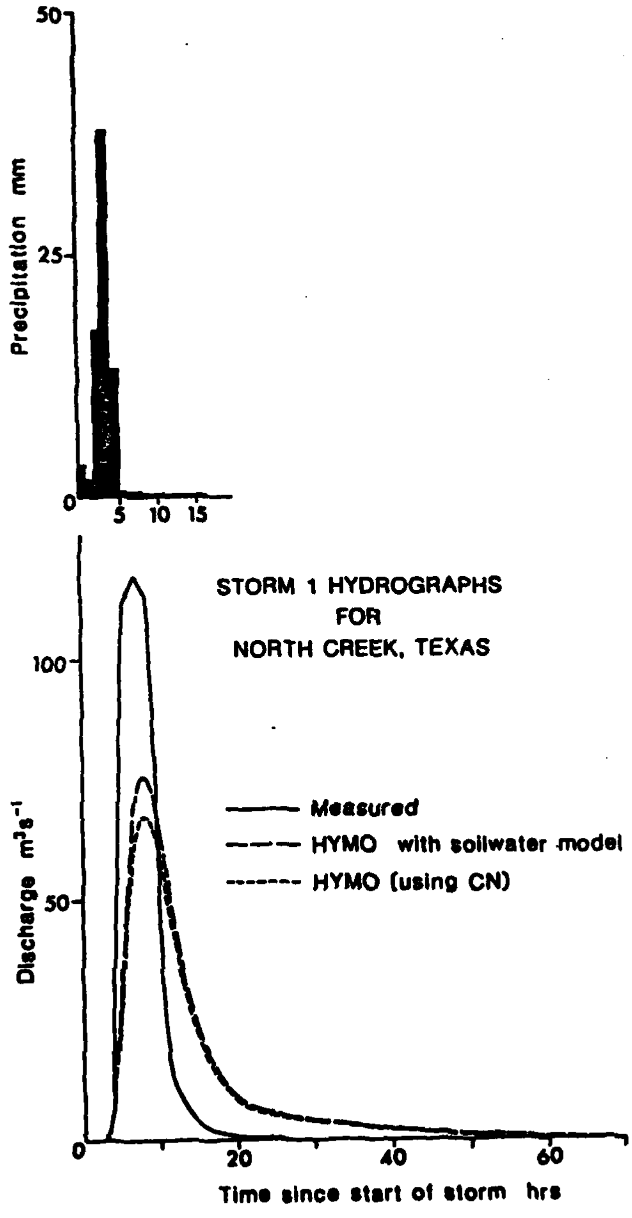


Figure 28: Storm 1, North Creek: comparison of measured hydrograph to those predicted by both models.

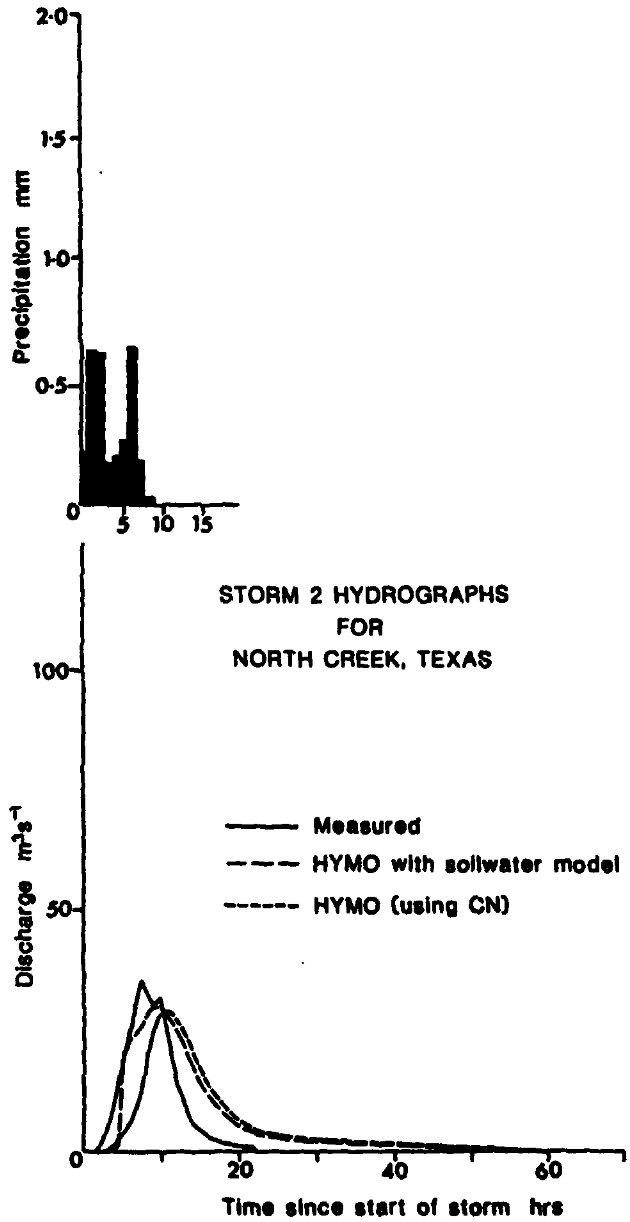


Figure 29: Storm 2, North Creek: comparison of measured hydrographs to those predicted by both models.

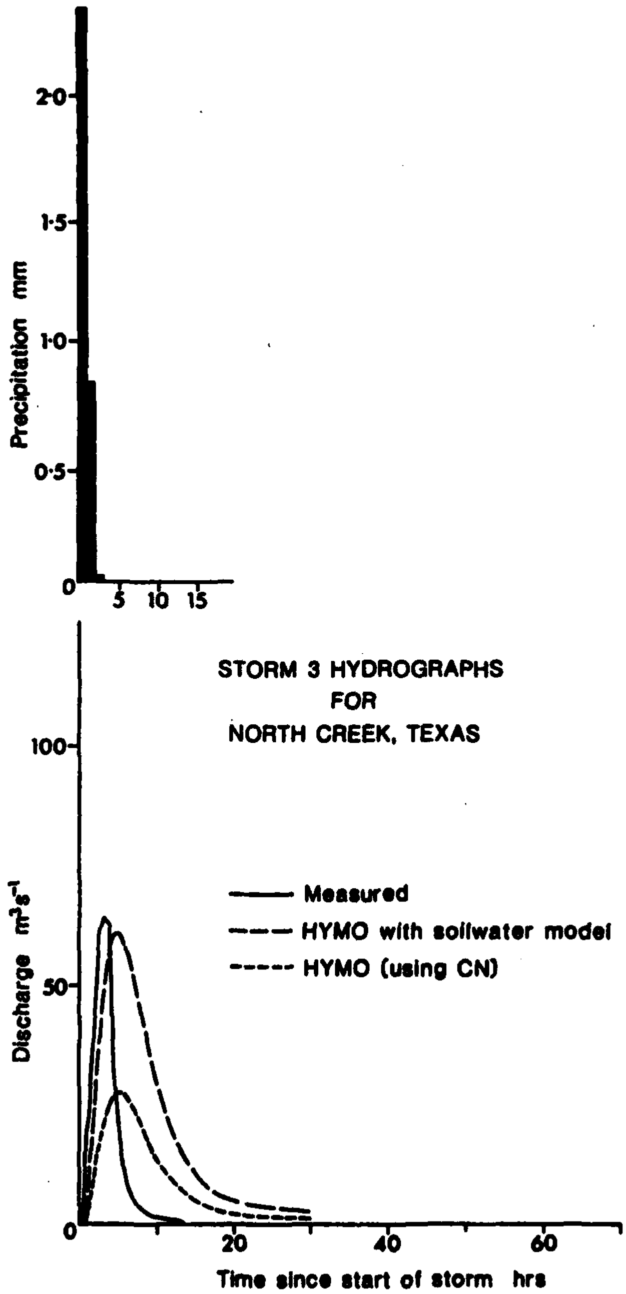


Figure 30: Storm 3, North Creek: comparison of measured hydrograph to those predicted by both models.

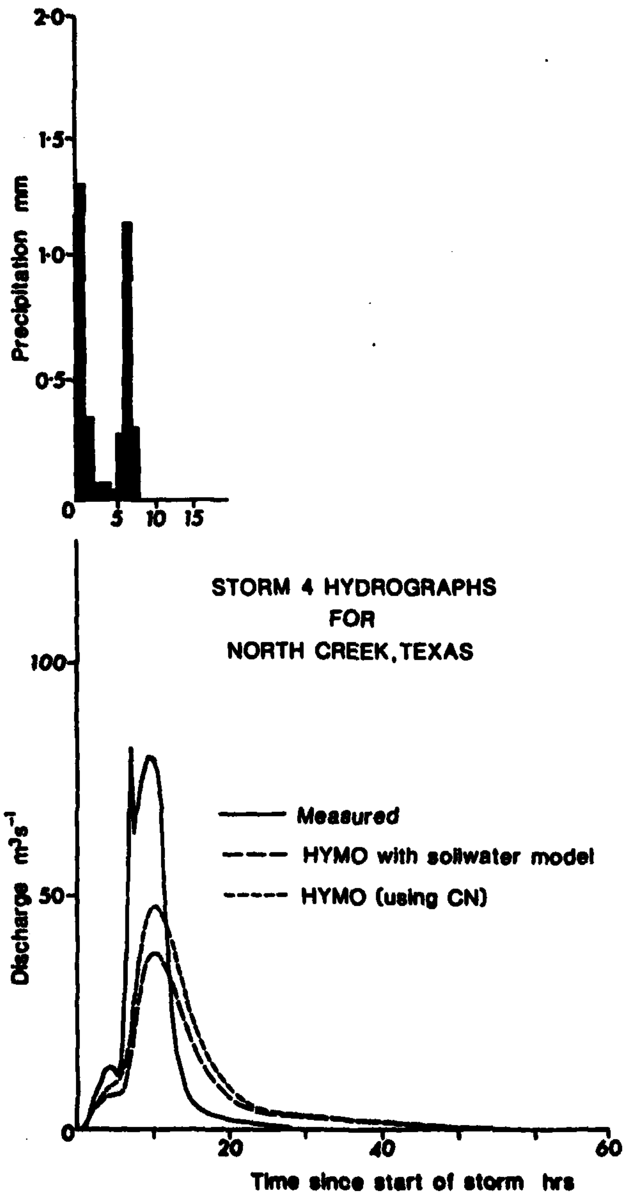


Figure 31: Storm 4, North Creek: comparison of measured hydrograph to those predicted by both models.

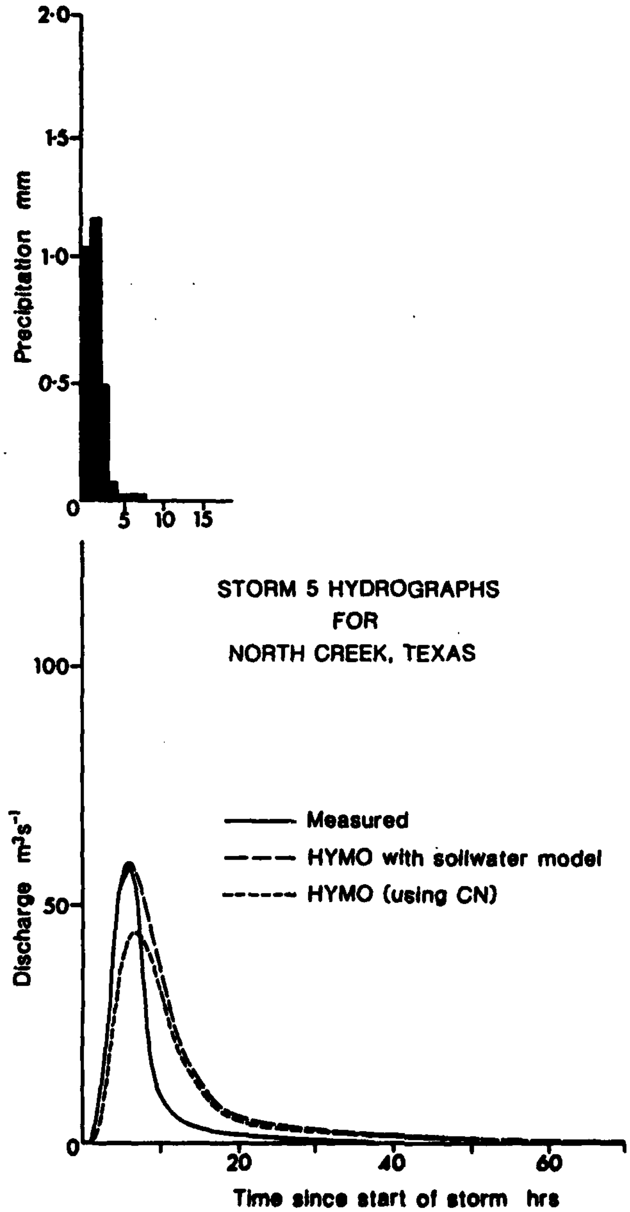


Figure 32: Storm 5, North Creek: comparison of measured hydrograph to those predicted by both models.

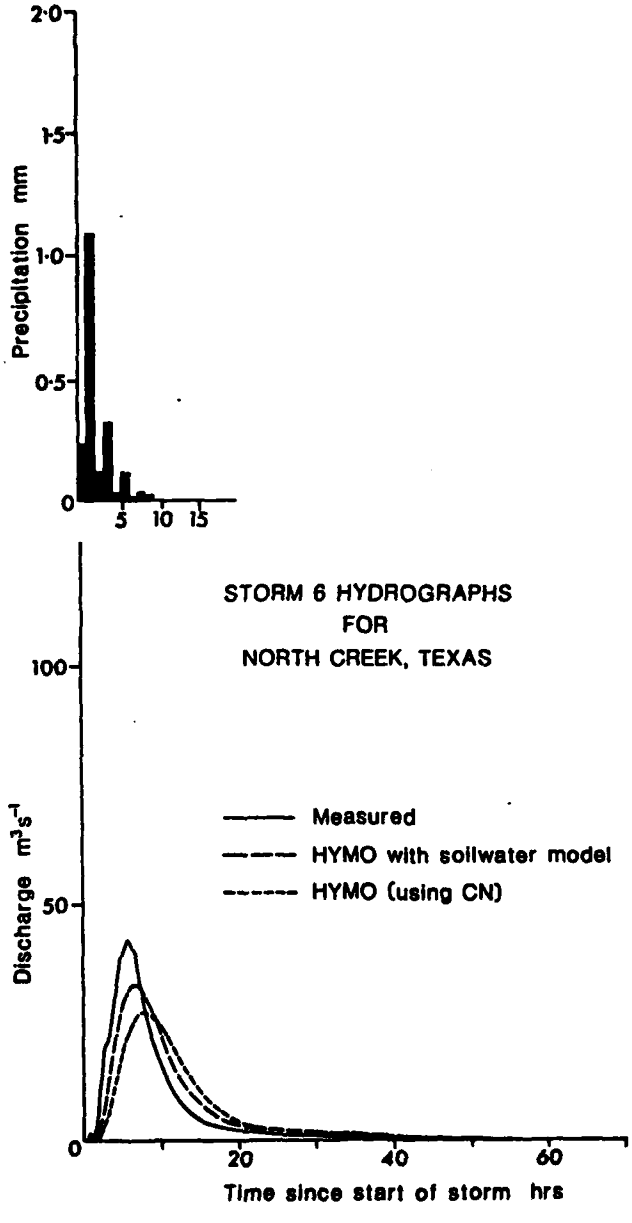


Figure 33: Storm 6, North Creek: comparison of measured hydrograph to those predicted by both models.

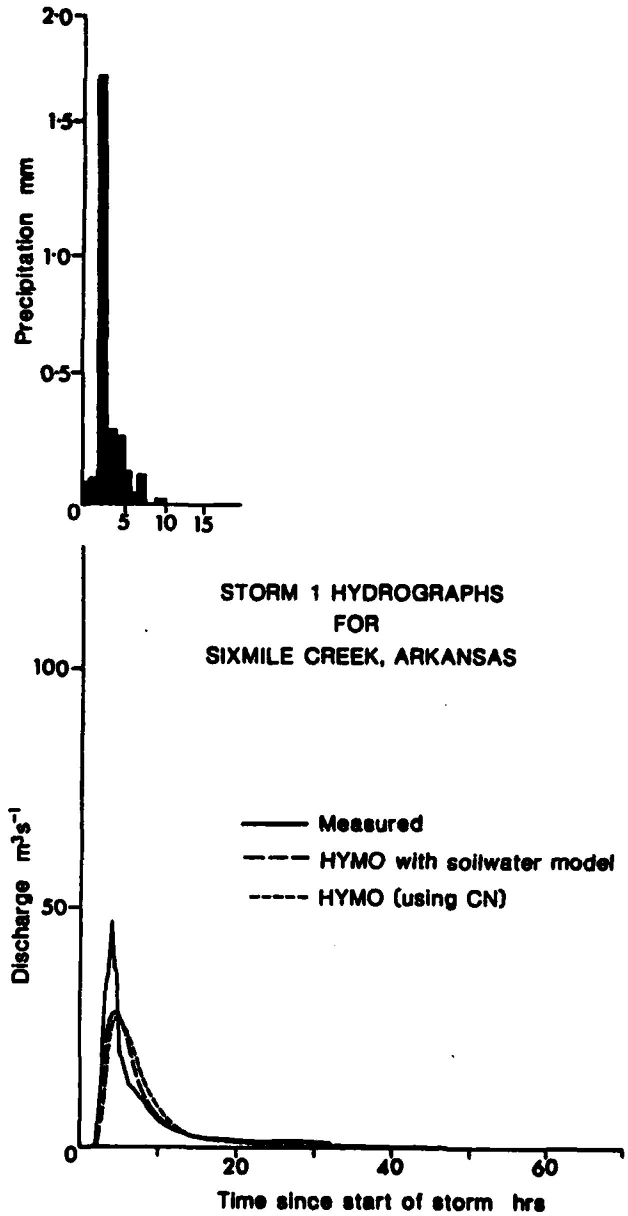


Figure 34: Storm 1, Sixmile Creek: comparison of measured hydrograph to those predicted by both models.

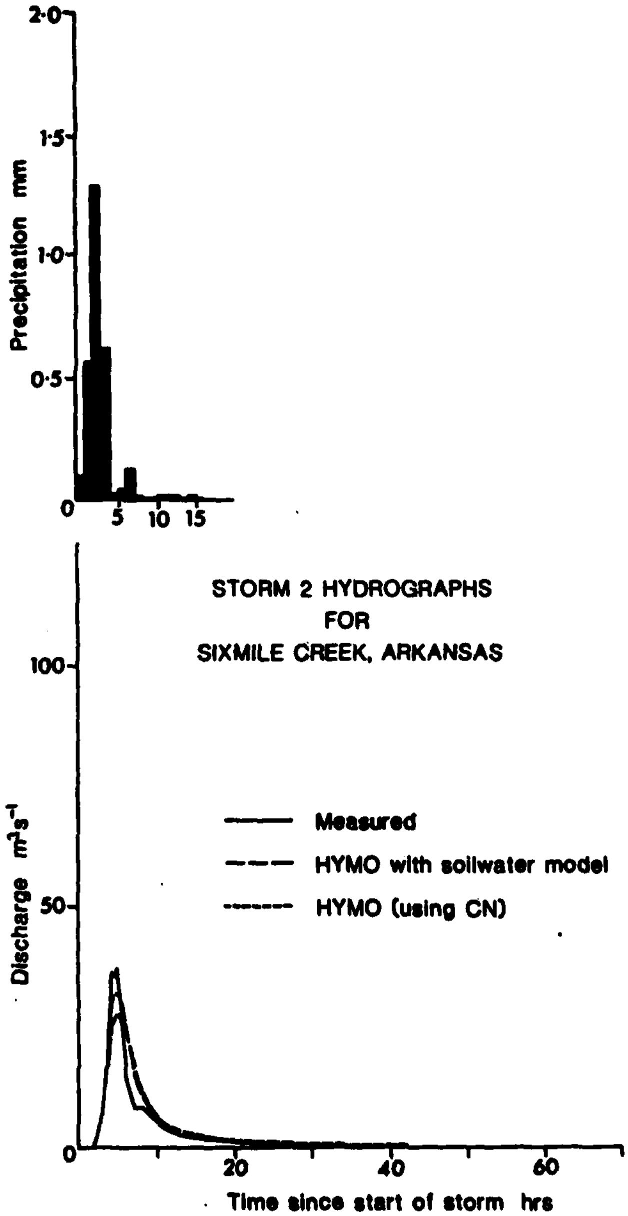


Figure 35: Storm 2, Sixmile Creek: comparison of measured hydrograph to those predicted by both models.

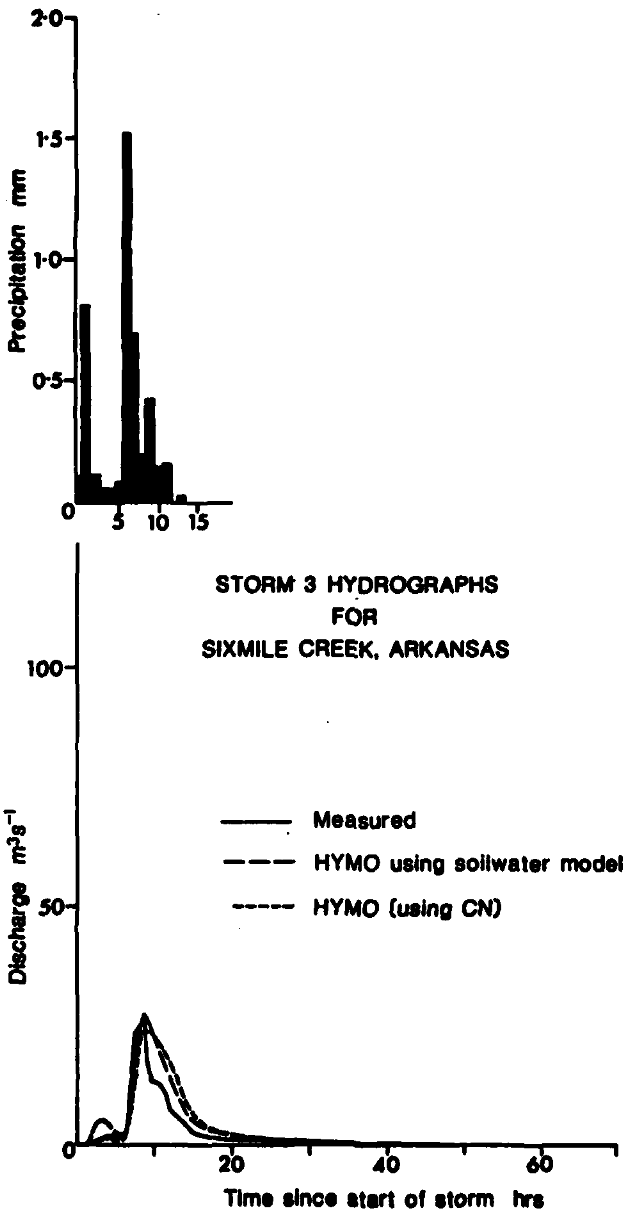


Figure 36: Storm 3, Sixmile Creek: comparison of measured hydrograph to those predicted by both models.

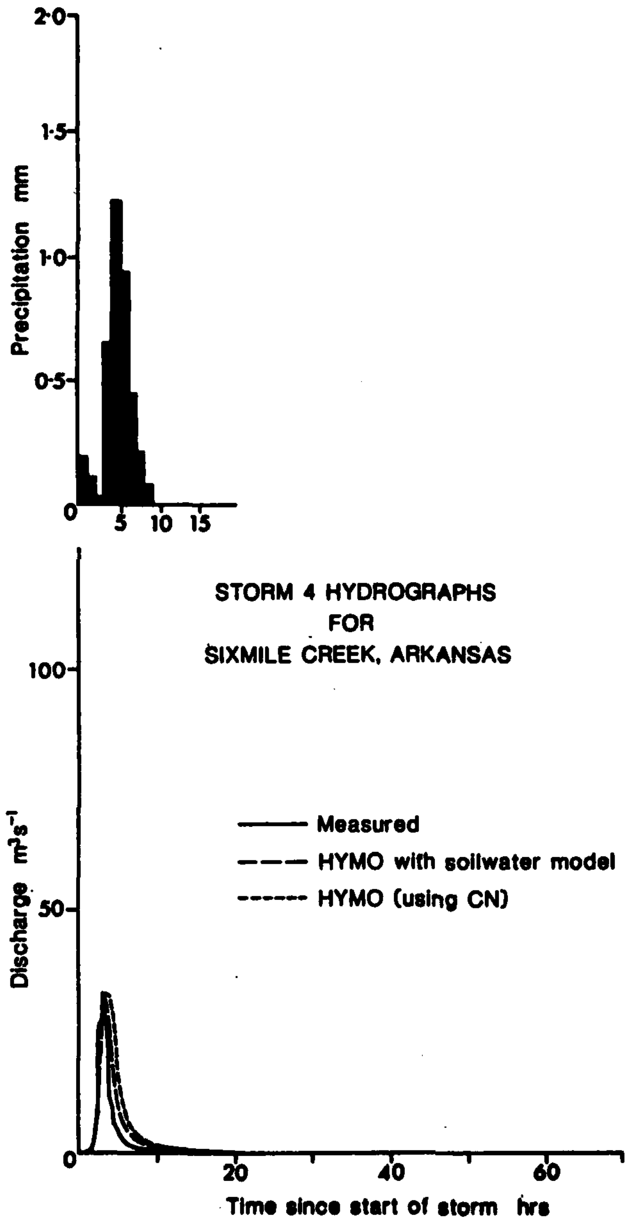


Figure 37: Storm 4, Sixmile Creek: comparison of measured hydrograph to those predicted by both models.

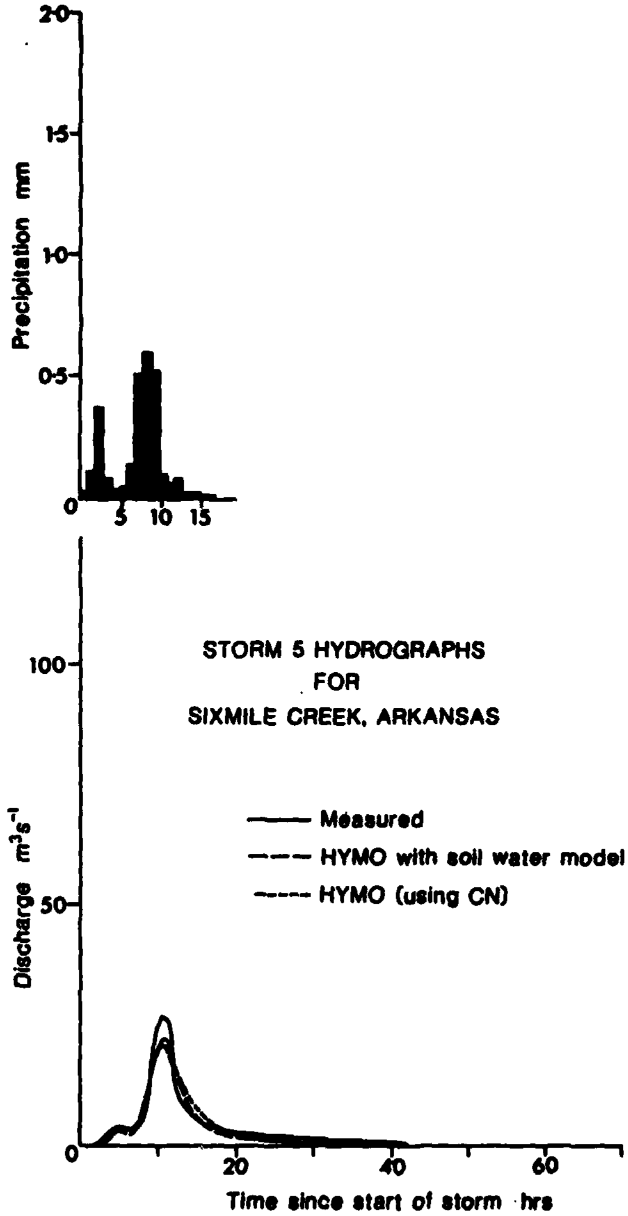


Figure 38: Storm 5, Sixmile Creek: comparison of measured hydrograph to those predicted by both models.

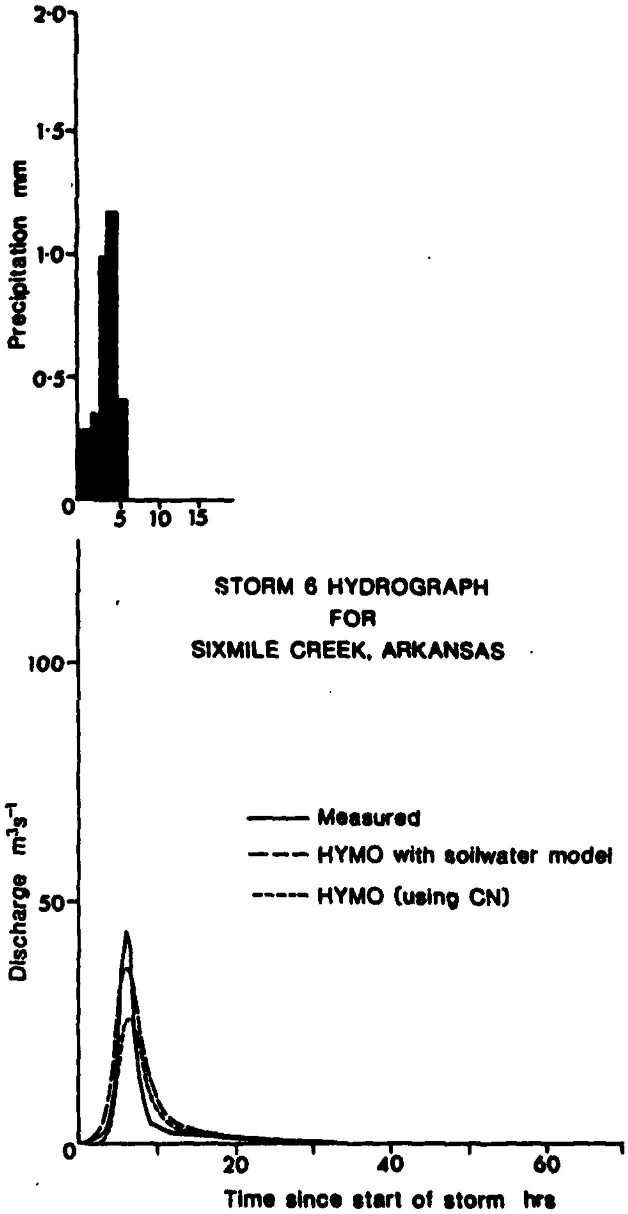


Figure 39: Storm 6, Sixmile Creek: comparison of measured hydrograph to those predicted by both models.

Storm 4

The double peaked nature of this hydrograph is reproduced by both models, but HYMO with the SCS CN model, predicts more accurately the discharge rates for both.

Storm 5

The rising limb and timing of the peak produced by HYMO with the soil water model are superior to those predicted by the SCS CN procedure.

Storm 6

The shape of the hydrograph associated with this storm is again more closely approximated by inclusion of the soil water model. Common to the 5 previous storms applied to North Creek, has been an underestimation of the rate of decrease of the falling limb of the hydrograph. A much better prediction of this characteristic is derived from use of the soil water model for this storm.

In comparison to North Creek, the predictions of hydrographs made by both models for the Sixmile Creek catchment, over all of the 6 storms are of noticably higher quality. Predominantly, closer approximations to the falling limb of the hydrographs are attained.

Storm 1

In response to this storm, very similar hydrographs are produced by both models. The inclusion of the soil water model displays only slightly improved estimates of the timing and magnitude of the peak.

Storm 2

Again, the two models predict similar hydrograph characteristics but a slightly better prediction of the peak discharge rate is derived from the use of the soil water model.

Storm 3

Use of the soil water model for applications to this storm results in a large overestimation of the first, subsidiary peak, but a very close approximation to the second and major peak, in terms of timing and magnitude. An improved prediction of the first peak is gained by application of the SCS CN method, representations of the second, more important peak, is not so good.

Storm 4

Both models overpredict by similar amounts, the peak discharge produced by this storm. They both approximate well to the rising limb, but again, use of the soil water model provides more accurate prediction of the timing of the peak.

Storm 5

The two models predict very similar hydrographs for this double peaked hydrograph.

Storm 6

Improved prediction of the peak discharge attained by application of the soil water model, is gained at the expense of poor estimates of the gradients of the falling and rising limb. These are better estimated by application of the SCS CN procedure.

It has been demonstrated that the hydrograph predicted by the soil water model is sensitive to the choice of soil hydrologic data and iteration period. Different combinations for any one storm have been shown to produce better predictions for certain hydrograph characteristics. This could be considered to be a major disadvantage to the application of this model. Figures 40, 41, 42, 43 and tables 22 and 23 demonstrate however, that similar behavoiur is exhibited by the SCS CN procedure.

1) Figure 40 demonstrates that for all of the storms applied to both catchments, total runoff volume displays a large degree of sensitivity to the value of CN.

The CN values derived from equation 30 for each catchment, for each storm indicated in tables 22 and 23. Figure 40 suggests that for each storm, an estimate of CN greater than this calculated 'best' fit CN produces proportionally greater errors in total runoff volume than an underestimation of a similar magnitude. This asymmetry is not so marked for Arkansas.

It is interesting to compare the magnitude of this sensitivity to that displayed by the runoff volume predicted by the soil water model. For storm 1, applied to the North Creek catchment, the best estimate of runoff volume produced by the soil water model is that derived when the soil hydrologic data corresponds to the centroid positions of the Brakensiek and Rawls charts and when the model iteration period is 10 seconds Figure 18. However even if that combination of data and iteration period were selected which provide the worst estimate of runoff volume; that corresponding to the highest % clay run at 60 second iteration, or the combination of data run at 10 seconds iteration, runoff

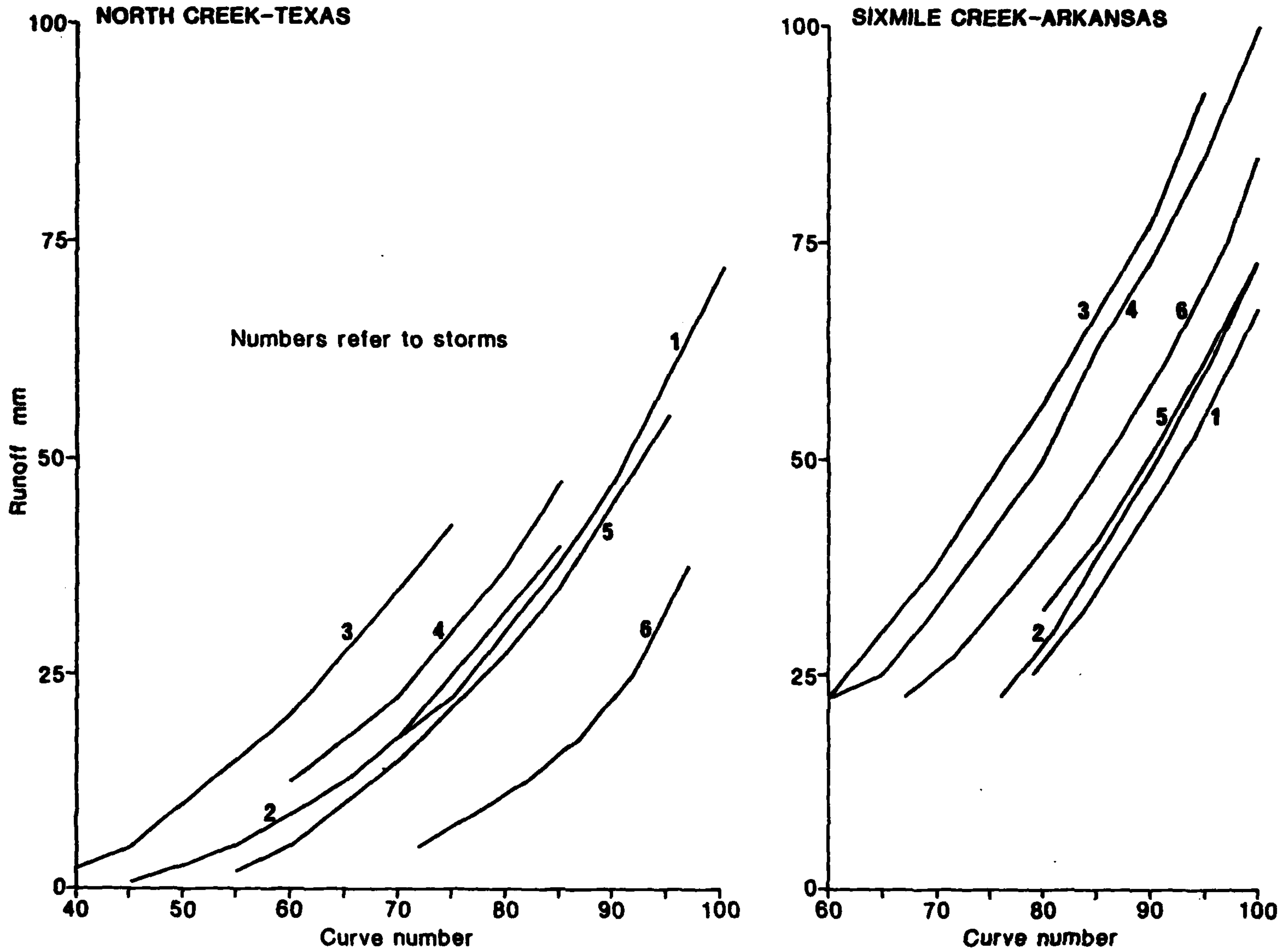


Figure 40: Sensitivity of runoff predictions to the CN value.

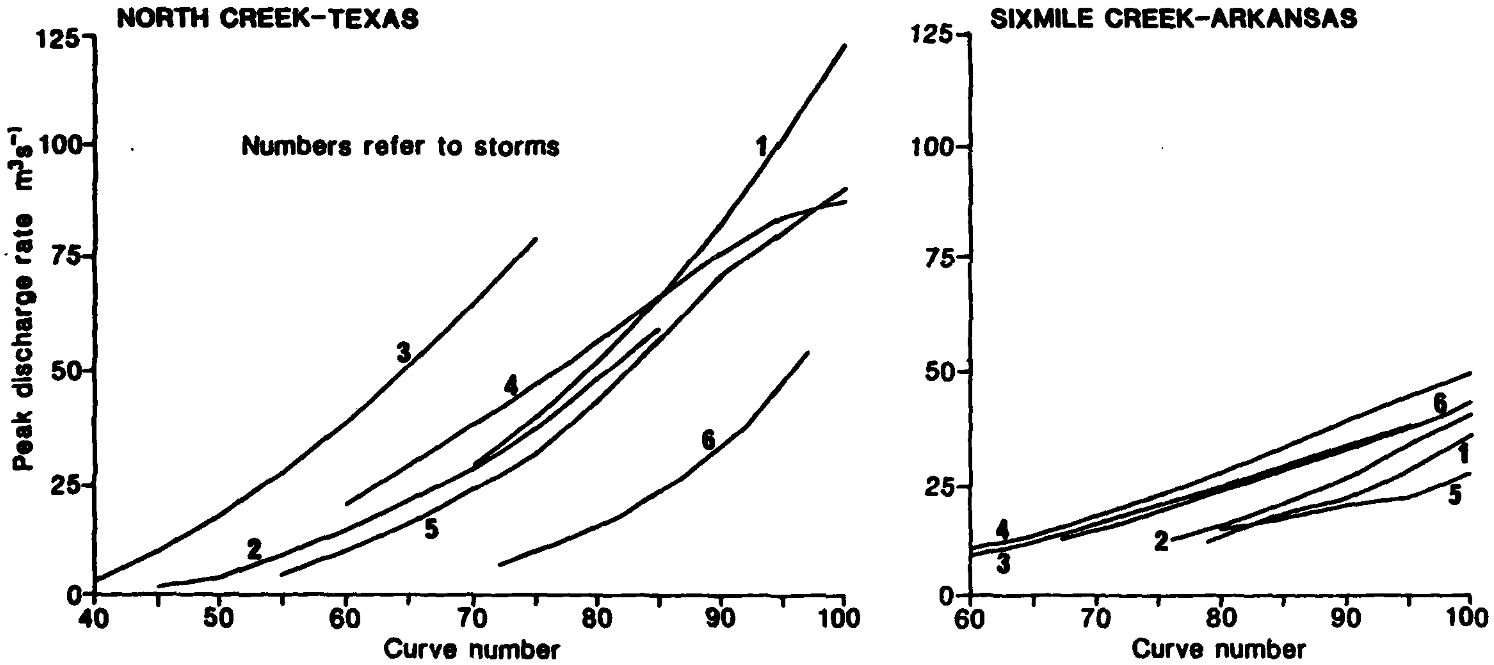


Figure 41: Sensitivity of peak discharge rate to the CN value.

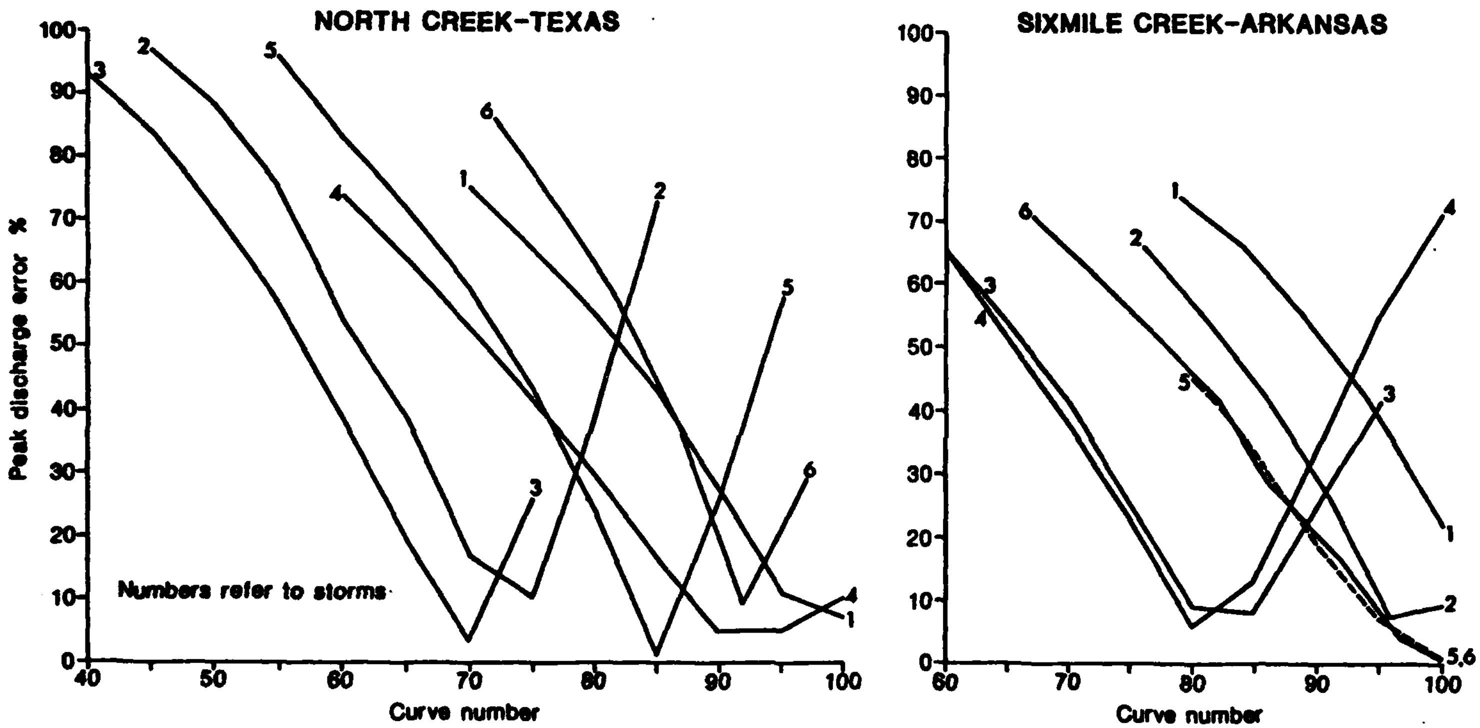


Figure 42: Sensitivity of % peak discharge error to the CN value.

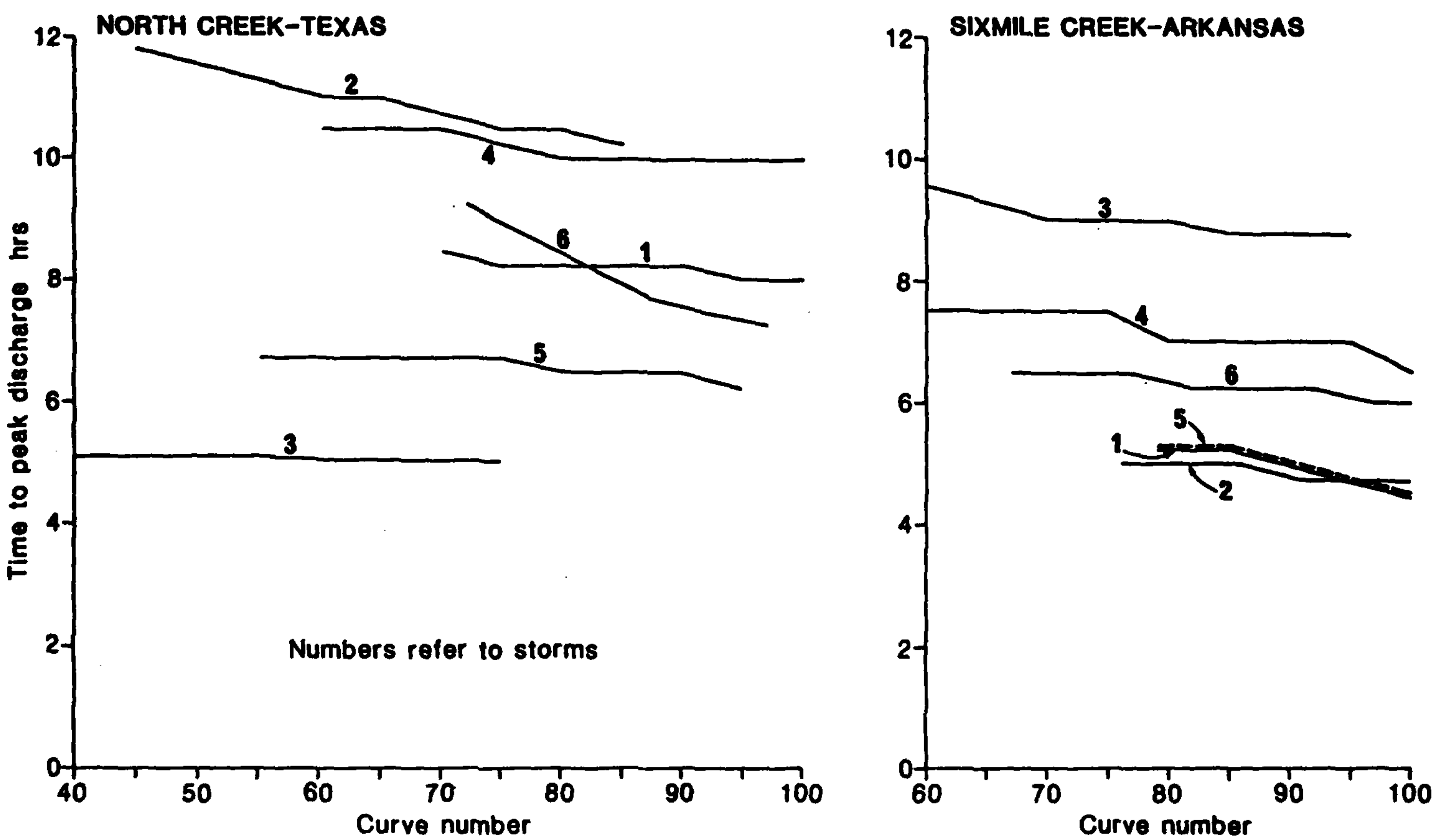


Figure 43: Sensitivity of time to peak discharge to CN value.

Table 22 **Value of CN which provides the best estimate of each hydrograph characteristic for storms 1-6, North Creek.**

Storm	CN derived from back calculation (equation 33)	CN for lowest error standard deviation	CN for lowest % peak discharge error	CN value used in calculation
1	85	90	100	85
2	66	70	75	70
3	61	55	70	55
4	74	80	95	75
5	75	80	85	80
6	87	87	92	87

Table 23 **Value of CN which provides the best estimate of each hydrograph characteristic for storms 1-6, Sixmile Creek.**

Storm	CN derived from back calculation (equation 33)	CN for lowest error standard deviation	CN for lowest % peak discharge error	CN value used in calculation
1	95	99	100	94
2	91	91	96	91
3	72	75	85	80
4	74	72	80	85
5	90	90	100	90
6	82	87	100	82

volume would only have been underpredicted by 19% or overpredicted by 12% relative to the best estimate. In comparison the best estimate of runoff volume for this storm is provided by a CN of 85. A choice of 75 or 95 would have resulted in an underprediction of 41% or overpreidction of 56%.

2) The peak discharge also exhibits sensitivity to the value of CN, figure 41. The predicted peak discharge rates for the North Creek catchment has a much greater sensitivity to CN than is the case for Sixmile Creek.

The value of CN which produces the best predictions of the peak discharge rate (figure 42) is for all 12 experimental frames, larger than that which is necessary for the best estimate of runoff volume. Tables 20 and 21 illustrate the magnitude of this difference. Either side of this CN value, the % peak discharge error increases rapidly.

3) Figure 43 illustrates that time to peak discharge exhibits the least sensitivity to the value of the CN. For the North Creek catchment, the degree of sensitivity may be related to storm characteristics. Storm 3 displays the least sensitivity to CN. This can be identified as the highest intensity, shortest duration storm; 107 mm occurs during 1 hour 20 minutes. Storms 1, 4 and 5 display a 'moderate' degree of sensitivity to CN. Characteristic of all of these storms is that a large proportion of the total rainfall is concentrated into one or two short periods.

Storm 5 for example, has 95% of the total rainfall concentrated into the first 33% of the storm. Finally, storms 2 and 6 display the greatest sensitivity to CN. Storm 2 has rainfall quite evenly distributed throughout its duration. Storm 6 has the lowest total rainfall of the 6 storms applied to this catchment.

The sensitivity of the time to peak predicted for Arkansas, to the CN, can not be so easily related to storm characteristics.

In comparison to this, the time to peak predicted by the soil water model (tables 11 and 14) is not sensitive to the choice of data or iteration period.

4) Figure 44 indicates that for each storm, the error standard deviation forms a minimum where the CN approaches a value equal to or greater than that derived for the best estimate of total runoff volume; but less than that which provides the best estimate of the peak discharge rate. Tables 20 and 21 also emphasised this behaviour. Either side of this value, the error standard deviation increases, but the curves do not appear to be symmetrical. An overestimate of CN causes proportionally higher error standard deviations than a similar underestimate. The gradient of these curves is steeper for the North Creek Catchment, than for Sixmile Creek.

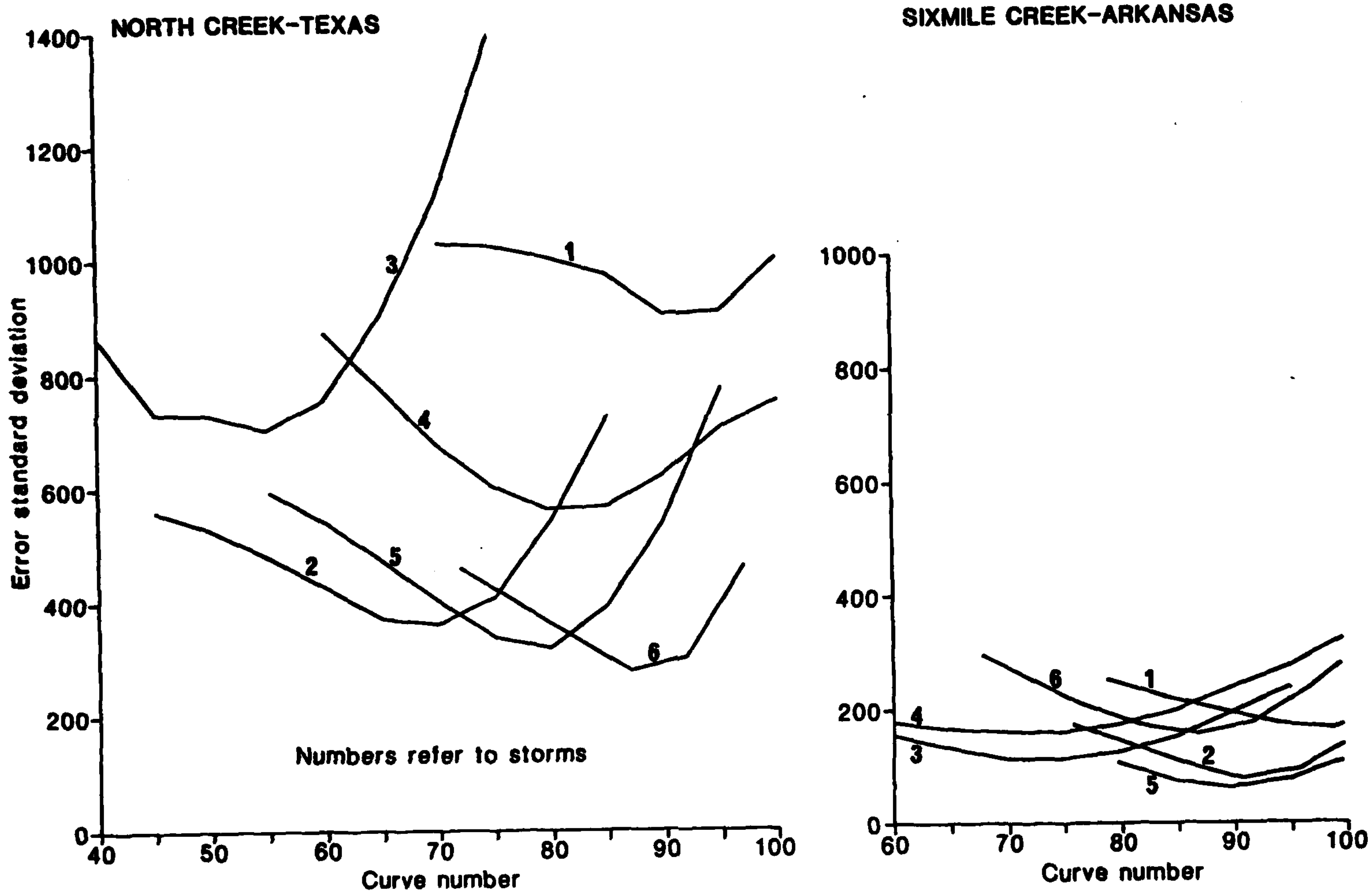


Figure 44: Sensitivity of error standard deviation to CN value.

6. DISCUSSION

6.1 Validation and verification of the soil water model

Face Validation

It is suggested that the soil water model does represent a conceptual model which is of sufficient and suitable complexity for its proposed application. There are many hydrological processes which occur in the catchment which have not been accommodated in the model. There are models available for most of these pocesses, but for the reasons outlined below, it is not appropriate for this application, that they be included.

Firstly, more complex models require data, of a quantity and quality not commonly available for the ungauged catchment. Futher still, many of these model parameters are not physically based, but are calibrated and may not necessarily be independent. Secondly, these models are often associated with computational difficulties and large computer resource requirements. Due to these limitations, the model may be confined solely to the single hillslope element. Thirdly, improvements in predictions derived from these more complex models do not always outweigh the extra effort extended on data collection, programming, implementation or computer resources. This may be especially the case for application at a large scale.

Output Validation

It is further proposed that the program and its implementation is consistent with the mathematical model, and that the processes of runoff and infiltration act rationally over a number of experimental frames. The following three points can be drawn out of the sensitivity analysis.

1. The amount of variation of the model output is related to a number of factors. It has a relationship to the storm characteristics, being positively related to storm duration, and respectively related to precipitation intensity. The model is most sensitive to error in the specification of saturated hydraulic conductivity, than to the suction moisture curve, initial moisture content, saturated moisture content and is least sensitive to error in the estimation of detention capacity. The amount of variation is also related to the particular characteristic of the hydrograph for which predictions are required. Runoff volume and peak discharge rate display greater sensitivty to input parameters and storm conditions, than does the time to peak.

The model is very robust to error in input parameters where rainfall intensity greatly exceeds the infiltration capacity. The model does simulate Hortonian infiltration excess overland flow and thus it would be expected that the model is appropriate for such high intensity events.

As conditions deviate from this, and the storm intensity decreases, the model becomes less appropriate and thus the effect of error in the input parameters increases.

2) When the parameters to which the model is more sensitive, are stressed not only does the magnitude of variation of the mean hydrograph higher but also lower and significantly different mean hydrograph predictions are provided by the model. Comparison to measured data for the North Creek catchment for storms 1 and 6, indicate that this does not improve predictions. This characteristic is especially marked for the lower intensity, longer duration storms.

As variability increases, predictions of runoff volume and peak discharge rate become more similar to that produced by the SCS CN procedure; the time to peak becomes increasingly different.

3. The sensitivity analysis indicates that misleading results concerning the relative sensitivity of the model to input parameters can be derived if independence amongst these parameters is assumed, and they are varied individually. Simultaneous variation alters both the relative sensitivity of each of the 5 input parameters, and the absolute magnitude of the models sensitivity to each.

Model Verification

It has been established that HYMO incorporating the soil water model produces hydrographs which approximate quite well to the measured.

The Brakensiek and Rawls method appears to provide suitable procedure for derivation of soil hydrologic parameters, should these not be available for the catchment.

6.2 Comparison of predictions made by the two models

Anderson[1] and this report have indicated that the two models, HYMO with the SCS CN procedure, and with the soil water model, provide different hydrograph predictions for any one storm.

It is not assumed that because the SCS CN procedure is an empirical model, that it will not provide the more appropriate predictions for certain conditions. At least seven improvements of the soil water model over the SCS CN Procedure can be identified:

1) It is a physically based model, not requiring unreasonable data or computer resources in the context of its application. (See table 1)

2) All of its parameters are measurable, and available, with the use of the Brakensiek and Rawls method, for the ungauged catchment.

3) The necessary data is possibly quicker to assemble than for the CN procedure, where maps of this parameter are not available.

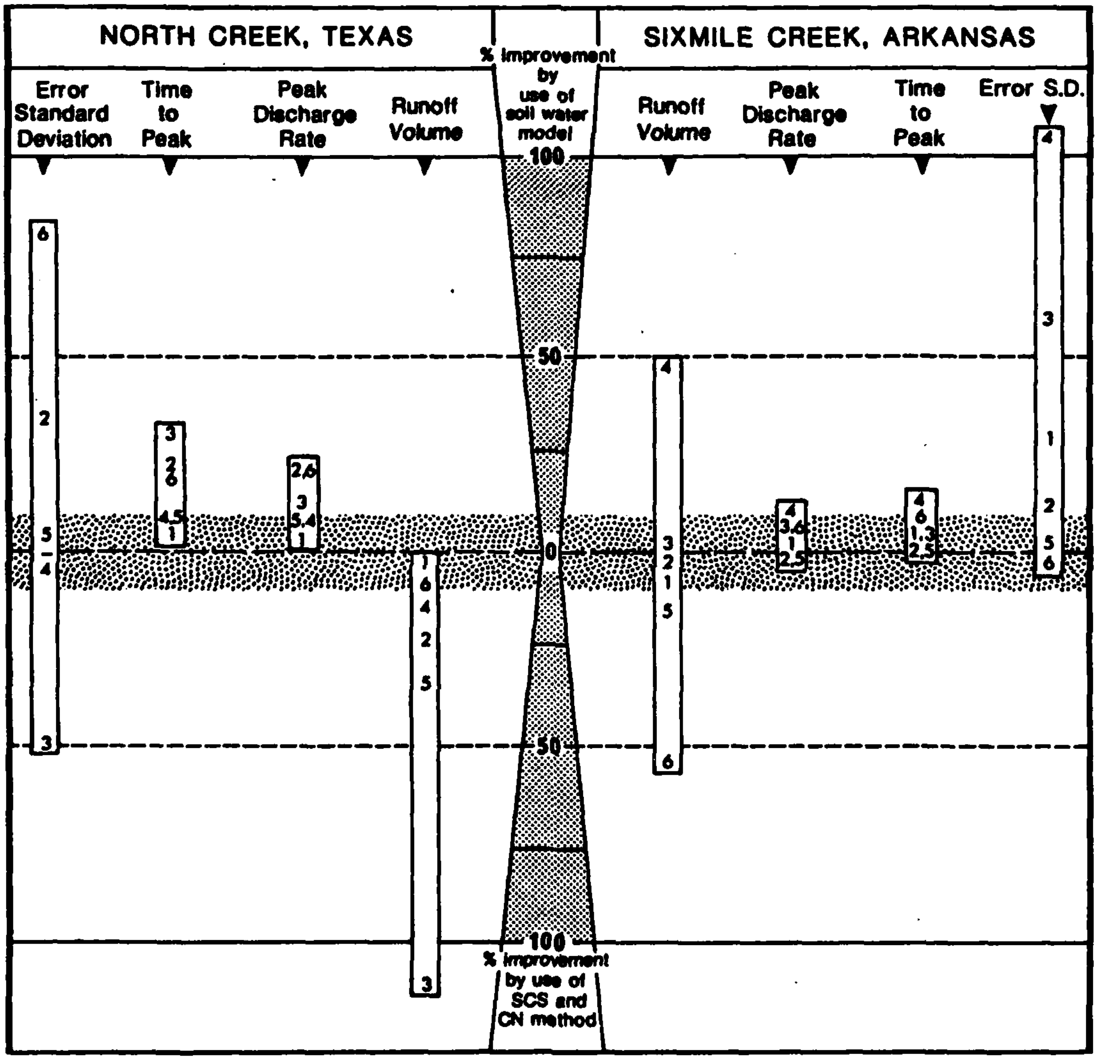
4) It allows for a much wider range of antecedent soil moisture conditions.

5) It can be used to simulate a number of storms, and the intervening periods of soil moisture redistribution.

6) Spatial variability of soil hydrologic characteristics within the sub-catchment can be incorporated into the model.

However, as Klemes[37] stresses, a model, totally unacceptable from the physical point of view, may be highly successful operationally. For the purposes of this application, where concern is with prediction rather than understanding or explanation HYMO with the SCS CN procedure may represent an appropriate model.

Figure 45, summaries the information presented in section 5 of this report. It attempts to establish quantitatively for runoff volume, peak discharge, time to peak and error standard deviation, the choice of model which will produce the better estimate of the particular hydrograph characteristic, for the particular storm and catchment.



Numbers refer to storms used in this report

Figure 45: Percentage improvements in prediction associated with choice of model.

Figure 45 suggests that there are two factors which influence the relative suitably of each model:

1) The particular hydrograph characteristic for which predictions are required.

2) The storm characteristics. Basin characteristics may well be a third factor, its potential influence however, cannot be identified by application to only two catchments.

To predict storm runoff therefore, it appears that the SCS CN procedure provides the better estimate. This is more the case for high intensity, short duration storms (storm 3, North Creek), but possibly not the case where storm precipitation totals are great; storms 3 and 4, Sixmile Creek, have totals exceeding 100mm.

The prediction of peak discharge and its timing are better approximated by the use of the soil water model within HYMO. The choice of this particular model appears to be more critical for application to the North Creek catchment, where greater % improvements are gained by its use. In application to the Sixmile Creek, the percentage improvements derived to negligible for storms 2, 5 and 1; it can be noted that these storms have lower precipitation totals.

The derivation of the lowest error standard deviation, and a closer approximation to the shape of the measured hydrograph, assessed subjectively on the basis of a visual comparison, is gained by use of the soil water model for 5 out of 6 for the Sixmile Creek. The SCS CN procedure appears to provide closer approximations to the double peaked hydrographs associated with storm 4, North Creek, and 5, Sixmile Creek.

In summary, for all hydrographs characteristics, except runoff volume, and over most storm conditions, HYMO with the soil water model provides predictions which are better than or at least as good as those derived from the SCS CN method. However it can be suggested that the reverse is true for predictions of runoff volume and for all characteristics associated with double peaked hydrographs.

The differences in the predictions provided by the two models are maximised when variability of soil hydrologic properties are not included in the soil water.

Comparisons of both models also reveals that both suffer from the same two problems:

1) Predictions made by the models are sensitive to the input data. Predictions of runoff volume and peak discharge rate can be improved by either fine tuning of the soil hydrological parameters model iteration period, or the value of CN. It has been demonstrated that the soil water model exhibits the same, or less sensitivity to the choice of data for each soil texture supplied by the Brakensiek and Rawls method, than the SCS procedure does to a choice of CN which lies + or -10 of the optimum value. Time to peak however displays no sensitivity to the choice of data or iterations period for the soil water model; a degree of sensitivity is exhibited as a response to the choice of CN.

2) The choice of the most suitable model drivers depends upon which aspect of the hydrograph it is required to predict with maximum accuracy; the SCS CN model may be an appropriate model for certain conditions.

6.3 Summary

1) A generalised runoff model has been configured. It is based upon MILHY but includes a physically based infiltration soil water finite difference scheme to generate overland flow, instead of the curve number routine (see figures 5 and 6).

2) The model requires no previous flow data for calibration purposes (see table 1), and is based upon standard soil mapping units only (see figures 7 and 8).

3) An extensive sensitivity analysis was undertaken to examine the effect of data input error upon the resulting discharge predictions (see tables 2-8). Table 8 shows the model to be robust against likely field application error in all five of the input soil hydrologic parameters.

4) A series of tests were undertaken of the modified MILHY model on catchments in Arkansas and Texas. The prediction of peak discharge and time to peak were better undertaken by the model scheme developed here than by the existing MILHY model (see figures 29-39). Moreover, the existing MILHY model was run using near optional or optimal CN values derived by back calculation (see tables 22 and 23) using the measured flow data, whilst the modified MILHY predictions developed in this report were derived from base soil data only. Thus figures 26-37 illustrate the performance of the existing MILHY model under extremely advantageous

conditions - its performance relative to the modified MILHY in standard applications is likely therefore to be worse.

5) There is sufficient justification to undertaken substantial further trials of the model in other catchments. This is already underway under DAJA-45-83-C-0029, with the collaboration of Waterways Experiment Station and U.S.D.A. Beltsville, Maryland.

6) The computer code for the modified MILHY model is being rewritten such that it will run on a Hewlett Packard 9816 personal computer. Completion of this task is expected to be May 1984.

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