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CALIBRATION PROCEDURE AND IMPROVEMENTS IN MULTSED

by

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ABSTRACT

A procedure is presented for calibration of both the water and sediment yields estimated by the MULTSED model. The procedure consists of sequential hydrologic and sediment calibration phases. The hydrologic phase identifies the hydrologic parameter values which produce the "best fit" of the measured hydrograph which has sufficient overland and channel sediment transport capacities to reproduce the measured sediment yield. Once the hydrologic "best fit" is obtained, the sediment calibration phase considers the physical conditions of the watershed and the workings of the MULTSED model in an iteration procedure to estimate the detachment coefficient values which allow the model to match the measured sediment yield.

The calibration procedure is applied to 17 storms events on five small mideastern watersheds with good results in terms of quality of hydrologic fit, reasonableness of calibrated parameter values, and efficiency of computation. The calibration results lead to important conclusions which demonstrate the utility of MULTSED including: guidelines for simulation of ungaged watersheds, selection of detachment coefficients corresponding to different management practices, and calibration of larger watersheds; and the transferability of hydrologic and sediment yield parameters. Additionally, an example demonstrating parameter transferability is presented.

Finally, five errors in the existing MULTSED codes are identified and corrected. Furthermore, three improvements for the current MULTSED codes are suggested. These improvements deal with the number of channel reaches used in the numerical routing procedure and the effects of the sediment size distribution on sediment transport capacity.

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LIST OF SYMBOLS

A	Total surface area subjected to rainfall
A_B	Area reduction factor (i.e., the fraction of bare or unprotected soil in the area)
ADW	The maximum overland flow resistance parameter
A_r	The ratio of the bed layer thickness to the flow depth, i.e., a_r/d
a_r	The bed layer thickness for Einstein's total load relation
a_1	An empirically determined constant describing the erodibility of the soil, i.e., the raindrop splash detachment coefficient
C_a	The reference sediment concentration at the level $y = a_r$ (in weight per unit volume of mixture)
C_g	The ground cover fraction
DOF	The overland flow detachment coefficient
D_n	The sediment size for which n percent of the sediment mixture is finer, e.g., for D_{90}, 90 percent of the sediment mixture is finer
D_{si}	The representative diameter for particles in the ith fraction of the particle size distribution
d	The flow depth
f	The Weisbach resistance coefficient
f'	The Weisbach resistance coefficient corresponding to the grain resistance
f_{min}	The minimum value allowed for f'
g	The acceleration due to gravity
I_1, I_2	The values of Einstein's integrals in his total load relation
i	Rainfall intensity
$i_B q_B$	The bedload for the sediment size represented by fraction i_B
J_1, J_2	The values of Einstein's integrals I_1 and I_2, respectively divided by their constant multipliers
K_g	The overland flow resistance coefficient
K_H	Resaturated hydraulic conductivity

k_s The effective roughness height of the composit bed material (plane bed case)

NDX The number of reaches the channel is divided into for numerical routing

NSP The number of points generated for the simulated hydrograph

n Manning's n for channel flow

Q_{SC_t} Sediment concentration at time t in mg/l

Q_{mt} The measured discharge at time t

Q_{st} The simulated discharge at time t

q_s The suspended load per unit width of flow

R The hydraulic radius

R' The portion of the hydraulic radius that Einstein related to the grain resistance

S The total energy slope

S' The portion of the energy slope corresponding to the grain resistance

S_I The initial soil moisture fraction

S_s The total overland sediment supply

T_c The sediment transport capacity of the overland flow (sum for all sediment sizes)

t Time

u_* The shear velocity of the flow (= $\sqrt{gRS}$)

u_*' The shear velocity corresponding to the flow resistance caused by the individual grains

V The mean flow velocity

VC Canopy cover interception

V_F Nonporous volume of material detached by overland flow

VG Ground cover interception

V_R Nonporous volume of material detached by raindrop splash

V_p The point velocity at a distance y from the boundary

V_s The settling velocity of a sediment particle of size D_s

y	The distance above the bed (or boundary)
z_r	The exponent of the suspended sediment distribution
γ	The specific weight of water
Δ	The apparent roughness diameter
Δt	Time increment
η	Soil porosity
ρ	The density of water
τ_{CR}	The critical shear stress from Shield's diagram
τ'	The effective shear stress acting on the grains (= $\gamma RS'$)
ψ	Average capillary suction

1. INTRODUCTION

1.1 Background

The U.S. Army Construction Engineering Research Laboratory (CERL) has initiated a research project aimed at the maintenance of the environmental quality of the U.S. Army training areas. One key problem faced by Army land managers is deciding when environmental conditions have declined to the point where remedial action is needed. Therefore, one aspect of this project is the identification and implementation of methods which will assist the land managers in this decision making process.

One measure of environmental quality is the magnitude of the erosion-deposition process and the resulting sediment yield. Training activities will affect sediment yield by disturbing the soil and destroying vegetal ground cover. Subsequent heavy storms will cause increased sediment yield. A mathematical computer model which will predict sediment yield can be a useful planning tool. Such a model should reflect the variables which control sediment yield including soil type, vegetal cover, and hydrological factors. If the land manager can relate training activities to changes in model parameters, the model will be useful for evaluation of activities and practices.

In an earlier report (31) several models were identified and two were studied to evaluate their suitability as an evaluation tool. The MULTSED model (Multiple Watershed Storm Water and Sediment Runoff and Simulation Model) (27,28) was selected for further development and implementation. This report also examined the sensitivity and response of MULTSED to artificial storm events.

1.2 Objectives

In order for the model to be used by land managers it must be calibrated for the specific watershed to be simulated. That is, the various parameters used in the model must be assigned values corresponding to local conditions. Some of these parameters are directly related to physical characteristics or properties of the watershed. Others cannot be measured and hence require experience or guidance to evaluate.

It is the objective of this study to develop a procedure and guidelines for calibration of MULTSED. This procedure will vary, depending on the available data and size of the watershed. Emphasis is placed on small watersheds since it is anticipated that most applications will involve this size. In addition, experience with the model has uncovered some errors in the original version and some suggested improvements. These errors and improvements are documented.

1.3 Approach

A formal calibration program was developed to evaluate the hydrologic model parameters based on a best fit criteria between measured and computed runoff hydrographs. This procedure is based on the generalized reduced gradient (GRG) algorithm. Subsequently, the sediment parameters are evaluated. The procedure is summarized and guidelines are presented.

1.4 Scope

The formal calibration procedure was developed using the first component of MULTSED which does not incorporate separate channel routing, and thus channel erosion parameters are not included. However, guidelines for evaluating the channel erosion parameters are included.

Corrections to the model are described and their effect is demonstrated.

1.5 Summary Description of MULTSED

A very brief summary of the essential components of the model is presented here. For a more detailed description see (27,28,31).

MULTSED is a single event, distributed, deterministic simulation model. The model contains two basic components: a hydrologic and hydraulic routing component which computes storm runoff hydrographs and a sediment component which computes sediment concentration hydrographs and sediment yield. These components are summarized below.

1.5.1 Runoff Component

MULTSED utilizes a watershed representation which consists of three types of homogeneous hydrologic units. The first is a two-plane, single channel "open book" subwatershed which is used to simulate the upstream portions of a watershed. A channel unit is used to represent downstream reaches of a river, and single plane units represent areas which produce lateral discharge into the channel units. The number and size of these units for a specific watershed are determined by the user.

Runoff is computed from the subwatershed and single plane units using an analytical solution to the kinematic wave equation. Input is the effective rainfall hyetograph. The flow is routed through the channel units using a numerical kinematic routing scheme.

Rainfall abstractions consist of interception and infiltration. Interception is satisfied during the initial part of the storm. Potential unit interception by canopy and ground cover are utilized together with fraction of the area covered by each. Potential infiltration is determined using the Green and Ampt equation written in an explicit incremental form.

1.5.2 Sediment Component

Sediment yield is determined by comparing potential sediment supply with sediment transport capacity. Actual sediment movement or deposition is determined by the lower value of either the available supply or the transport capacity.

The sediment size distribution is broken into a set of size ranges, each of which is treated independently. The total transport capacity is then the sum of the transport rate for each size. Furthermore, the transport rate for each sediment size consists of bed-load and suspended load rates. The bed-load transport capacity for overland flow is computed using the Meyer-Peter, Müller relationship.

For channel transport capacity, the resistance factor for each sediment size is based on the ratio of sediment diameter to hydraulic radius. Other relationships for computing transport capacity are the same as for overland flow.

The sediment supply is provided by raindrop splash detachment and overland and channel flow detachment. Sediment yield is determined by the smaller of availability or transport capacity and is computed for each sediment size fraction.

Sediment routing is done analytically for subwatershed and plane units, giving total sediment yield. This is then distributed in time in proportion to discharge for input to channel units.

Channel routing is done numerically for each sediment size fraction based on the continuity equation for water and sediment.

2. CALIBRATION PROCEDURE

2.1 Goal of Calibration

The overland erosion process is so complex that an adequate relation to describe it has not been derived. Therefore, modelers have resorted to using empirical relations to describe the overland sediment detachment process. In order to estimate the actual detached sediment supply available for transport, these empirical relations need correction factors known as detachment coefficients. The sediment yield is generally taken as the lesser of the sediment supply and the overland flow sediment transport capacity, which is estimated using modified versions of equations derived to describe sediment transport in open channels. Currently, the primary sources of information regarding the detachment coefficients are rainfall simulator tests on small field plots. While these tests are quite useful for determining the practical range of detachment coefficient values, certain questions exist regarding the appropriateness of using detachment coefficients from small plots in modeling larger watersheds. Therefore, the purpose of this report is to develop a procedure for calibration of both water and sediment yields, and to use this procedure to calibrate detachment coefficient values for storm events on several small watersheds in the mideastern U.S.

2.2 Basic Calibration Procedure

The model of interest in this study is MULTSED developed at Colorado State University by Simons et al. (27,28). The details of this model and its suitability for simulation of water and sediment yield from Army training sites have been discussed by Wenzel and Melching (31), and so only those details relevant to the calibration procedure are discussed here.

Both the overland flow and channel flow sediment transport capacities are a function of the flow rate. Therefore, ideally, it would be desirable to perform the calibration in a stepwise fashion, wherein the "optimal" hydrologic fit is obtained and then the detachment coefficients are optimized based on the transport capacities corresponding to the "best fit" hydrograph. Unfortunately, it was found that the optimal resistance coefficient values for the hydrologic "best fit" were generally too large to allow sufficient flow velocity. Hence, the calculated sediment transport capacities were not large enough to reproduce the measured sediment yield. This high resistance is necessary to reproduce the measured time lag between the rainfall hyetograph and the runoff hydrograph. Thus, when performing the hydrologic calibration it became necessary to artificially reduce the measured time lag between the rainfall hyetograph and the runoff hydrograph in order to obtain reasonable (i.e., "close" to measured) runoff and sediment yield.

MULTSED simulates the hydrograph resulting from a storm event as a function of six hydrologic parameters: resaturated hydraulic conductivity, K_H; average capillary suction, $\bar{\psi}$; potential ground cover and canopy cover interception volumes, VC and VG, respectively; Manning's n for channel flow; and the maximum overland flow resistance coefficient, ADW. The "best" hydrologic fit is determined primarily on the basis of formal optimization of these parameters such that the sum of the squares difference between the measured and simulated hydrographs is minimized, i.e.,

$$\text{MIN} \sum_t (Q_{mt} - Q_{st})^2 \tag{1}$$

where Q_{mt} = the measured discharge at time t,

Q_{st} = the simulated discharge at time t.

It was found that generally the simulated hydrograph which minimized the sum of squares difference provided equally good fits in terms of matching simulated and measured peak discharges and total runoff volumes (generally within 20% for all three fit quality indicators). Upon choosing an initial time shift (i.e., artificial reduction in the measured time lag), Eq. 1 is optimized and the calibrated hydrologic parameters are used to simulate the sediment yield. If the overland and channel sediment transport capacities are sufficient to generate the measured sediment yield, then the detachment coefficients will be calibrated by iterating until the measured total sediment yield is matched. Otherwise, the hydrologic parameters are adjusted or possibly recalibrated until the overland and channel sediment transport capacities are sufficient (more detail on this procedure will be given later), and then the detachment coefficients are calibrated.

2.3 Hydrologic Calibration Model

The complete MULTSED model consists of three components. The first component analytically determines the runoff hydrographs from simple subwatersheds along the hydrologic boundary of the watershed and also from the overland flow planes along the downstream reaches of the stream network by using the method of characteristics solution to the kinematic wave flow routing problem. The sediment transport capacity for both the overland flow and the channel flow is estimated using Einstein's total load relation (8) with the Meyer-Peter, Müller bed load equation (20) substituted for Einstein's bed load relation. The second component merely reorganizes the output from the first component for more efficient use in the third component. The third component routes the water and sediment generated from the subwatersheds and planes in the first component through the channel network using a nonlinear iterative solution to the kinematic wave flow routing problem. Once again, the combined Einstein, Meyer-Peter, Müller relation is used to determine the channel transport capacity. Since the third component uses a numerical solution to the flow and sediment routing, it can account for some natural sediment transport processes which the analytical solution in the first component cannot account for, i.e., the natural suspended sediment setting process and channel bed armoring.

In the analytical method (component 1), the total sediment yield is constrained to a maximum equal to the channel sediment transport capacity. Thus, when using the analytical method to estimate sediment yield from a single subwatershed, if the sediment supply from the planes is in excess of the channel transport capacity it is assumed that this excess is immediately deposited. In the numerical method, a more realistic view of the deposition process is used. If the sediment being transported (i.e., in suspension) exceeds the transport capacity, the sediment routing scheme will predict aggradation (an increase in the loose soil layer; deposition). The amount of potential aggradation (the suspended sediment in excess of the transport capacity) is compared with the feasible aggradation given the flow conditions and the settling velocity of the sediment particles to determine the sediment deposited at each time step. This type of consideration is quite realistic in the routing of fine materials because they will probably not settle out in relatively short reaches of a channel even if the transport capacity is much smaller than the sediment supply.

Armoring of the bed is the natural equilibrium of the bed reached after the fine material is transported away by the flow resulting in the exposure of a thin layer of coarser particles at the bed surface (28, p. 506). This layer of coarser particles is much more difficult for the flow to move and thus it protects the finer sediment below from erosion, hence the name armoring. The numerical routing method accounts for this process as it considers the depth of loose soil and the sediment size distribution within the loose soil layer. The analytical method, however, estimates sediment yield solely as a function of transport capacity, and only by an unrealistic decrease in channel detachment coefficient can the analytical method be brought into agreement with the numerical method.

The numerical method of the third component of MULTSED is more realistic than the analytical method of the first component. Thus, a question arises as to whether the calibration performed here should model the watershed(s) as two planes whose output is generated by component 1 flowing into a channel using component 3 to route the flow, or simply as a single subwatershed using only component 1. For the small watersheds considered here (all less than 16 acres) with heavily vegetated, simple swale channels, the armoring and natural suspended sediment setting processes are not significant since erosion from heavily vegetated channels is negligible and the flow velocity for wide, shallow, heavily vegetated swale channels is low enough that most of the excess supply will settle out-(this has been confirmed by some test runs for these watershed using both modeling approaches). Assuming that the approximations in the analytical method are fairly reasonable for the watersheds considered here, component 1 was used for the calibration. A discussion of calibration for larger watersheds is given in the next chapter.

The generalized reduced gradient (GRG) algorithm (1) was chosen to perform the formal minimization of the sum of squares difference between the measured and simulated hydrographs because it has two important advantages over other optimization techniques. First, it is a very efficient and powerful nonlinear optimization algorithm which converges to the "optimal" solution quite rapidly. Second, it is the only nonlinear optimization algorithm which allows bounds to be placed on the parameters. In previous attempts to develop objective approaches to evaluate and/or calibrate hydrologic models it was necessary to introduce a certain amount of subjectivity as hydrologists interacted with the optimization code in order to keep parameters within their physically meaningful ranges (e.g., see Dawdy and O'Donnell, 7). However, when using GRG, physically meaningful bounds may be placed on the parameters and considered directly in the optimization. Hence, the hydrologic "best" fit simulation based on physically reasonable parameters is obtained totally objectively from GRG. However, it should be remembered that in the procedure reported here the final calibration is generally not determined totally objectively because of the adjustments required to obtain the appropriate sediment transport capacities.

It should be noted that GRG is a nonlinear optimization code and as such it requires a starting point to be assumed, and theoretically the quality of the resulting solution (i.e., whether a local optimum or the global optimum is obtained) is a function of the starting point. It has been found that the sum of squares surface for the difference function between the measured and simulated hydrographs appears to be unimodal (i.e., there are no local optimums). Therefore, GRG tends to converge to the same general solution regardless of the starting point. However, the speed of the convergence is a function of the starting point and so it must be chosen intelligently in order to reduce computer costs.

For this report the GRG code developed by Lasdon et al. (16), as modified for use in the OPT System at the University of Illinois, was used. In order to efficiently use component 1 of MULTSED (MSED1) in conjunction with GRG to optimize the hydrograph fit the entire sediment yield portion of MSED1 was deleted. The remaining hydrologic portion of MSED1 was then set up as a series of subroutines within the collection of subroutines called by GRG. A complete listing of the subroutines called by GRG including the hydrologic portion of MSED1 and details on how to utilize them with GRG for calibration are presented in Appendix A. The hydrologic portion of MSED1 is called by the objective function subroutine, which calculates the sum of squares difference between the measured (input) and simulated (by the hydrologic portion of MSED1) hydrographs. GRG calculates the reduced gradient of the objective function in the vicinity of the current point and from the reduced gradient it determines the direction of greatest improvement of the objective function. GRG then performs a one-dimensional search in this direction and then steps to the best point found in this direction. When the objective function reduced gradient is within a prespecified tolerance of zero a local optimum (in this case probably the global optimum) has been found and GRG terminates. Thus, for each GRG iteration the objective function value must be calculated up to 7 times to determine the reduced gradient. Fortunately, GRG converges to the optimal solution rather quickly and so the computational time is not excessive (this shall be discussed in detail later).

2.4 Initial Hydrograph Response Time

As noted earlier, it was found that the optimal resistance coefficient values for the hydrologic "best fit" were generally too large to allow sufficient flow velocity for the calculated sediment transport capacities to be large enough to reproduce the measured sediment yield. Primarily due to the kinematic wave routing approach's inability to account for the natural attenuation (i.e., backwater effects) which occurs in the actual runoff process, such high resistance becomess necessary to reproduce the measured response time between the rainfall hyetograph and the initial rise of the runoff hydrograph. Thus, in the kinematic wave approximation, the timing of the simulated hydrograph is only a function of the overland and channel flow velocities. To artificially account for natural attenuation, kinematic wave routing schemes must decrease the flow velocities by increasing the overland and channel flow resistance coefficients. While this deviation from reality has provided very reasonable and acceptable results for modeling overland flow (e.g., Woolhiser, 32), it clearly causes problems when modeling sediment yield where higher, more realistic flow velocities are needed to obtain reasonable sediment detachment and sediment transport capacities.

The process of shifting the measured hydrograph to begin earlier serves to remove the effects of natural attenuation in the data. Thus, when fitting the model to the shifted data, the kinematic wave routing approximation is being used to model data which somewhat corresponds to the "no backwater effects" assumption.

From a practical hydrologic viewpoint, the justification for using a time shift on the data is twofold. First, when calibrating runoff events on small watersheds, hydrologists are generally most concerned with reproducing the peak, volume, and general shape of the measured hydrograph, while reproducing the measured time lag between the hyetograph and hydrograph is of secondary importance. This is partially due to the quality of the rainfall data. Generally, rainfall data are obtained by continuously recording rain gages. The hyetograph is then defined by identifying break points on the mass rainfall curve. This process introduces error in determining the break points and the proper intensity occurring at any given time in the storm. Furthermore, there is also the standard question of whether the rainfall at the rain gage is representative of the true areal and temporal rainfall distribution over the entire watershed. Second, from a watershed management standpoint, generally the most important aspects of a model are its ability to reproduce the peak, volume, and shape of the measured hydrograph and the measured sediment yield, rather than the timing with respect to rainfall.

In order to perform the time shift, two modifications were proposed and included in the calibration subroutines. One modification allows the measured hydrograph to be shifted a prespecified number of minutes, and then the "shifted" hydrograph is fitted (this modification is shown in Appendix A). The other modification matches the peak flow times of the measured and simulated hydrographs and then the sum of squares difference between the "shifted" simulated hydrograph and the measured hydrograph is minimized. By using either of these options, the optimization centers around the hydrologic abstractions and their corresponding parameters, while the resistance coefficients remain fairly close to their initial values with only small changes to improve the shape of the simulated hydrograph. Thus, hydrologic calibration can be performed with the resistance coefficients kept in the range of values which allow duplication of the measured sediment yields.

2.5 Suggested Calibration Procedure

The calibration procedure described below was developed based on the experience gained while calibrating the runoff and sediment yield parameters for MSED1 for 17 storm events on five small mideastern watersheds. The general principles and basic concepts described below were used in calibrating all 17 storm events, while the specific procedure outlined was used on only the last 7 storm events calibrated (i.e., the storms on the modified Lawson Creek Tributary number 1 watersheds). The proposed procedure proved to be quite efficient when calibrating these 7 storm events.

2.5.1 Step 1: Estimating the Initial Time Shift

As discussed earlier, two modifications of the calibration subroutines were developed to perform time shifts on the data: one which shifted the data a prespecified number of minutes and one which matched peak discharge times and then calculated the sum of squares difference. It was found that the modification which shifts the data a prespecified number of minutes seemed to be the more practical and reasonable method to use. However, this method requires an appropriate estimate of the initial time shift. Such an estimate may be obtained by one of the following three methods.

1. If previous calibration experience is available, choose a set of optimal parameter values from a previous calibration, which was under similar conditions to the storm event being calibrated. Perform a simulation using MSED1* with the chosen parameter values and the input data for the storm event to be calibrated. Compare the peak discharge, total runoff volume, and overland and channel sediment transport capacities** of the simulation with the measured values. If the transport capacities exceed the measured sediment yield and the peak discharge and total runoff volume are reasonably close to the measured values (generally this should not be a concern unless the difference is very large), the time difference between the measured and simulated peak discharges should be used as the time shift. Otherwise, the overland and channel flow resistance parameters (ADW and n, respectively) should be reduced until the sediment transport capacities exceed the measured sediment yield. Then the measured and simulated hydrographs should be compared to determine the appropriate time shift.

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*Note: Actually MSED1 should be modified so that the overland flow transport capacity is output because the overland areas are the primary erosion sources for small watersheds (See Step 3).

**Note: By setting the detachment coefficient values to their upper bounds the total sediment yield will equal the channel sediment transport capacity.

2. If no previous calibration experience is available for this watershed, choose calibrated parameter values for a similar storm on a similar watershed. Perform a simulation using MSED1 with the chosen parameter values and the input data for the storm event to be calibrated, and use the guidelines for comparison discussed in method 1 to determine the time shift.
3. If no previous calibration experience on this watershed or any similar watershed is available, choose the resaturated hydraulic conductivity, K_H, from the lower portion; the overland flow resistance coefficient, ADW, Manning's n, and the potential ground and canopy cover interception volumes, VG and VC, respectively, from the upper portion; and the average capillary suction, $-\psi$, from the middle of their respective physically reasonable ranges. Perform a simulation using MSED1 with the chosen parameter values and the input data for the storm event to be calibrated, and use the guidelines for comparison discussed in method 1 to determine the time shift.

Methods 1 and 2 should provide a good estimate of the proper time shift because the calibration experience gained in this study showed that the calibrated parameter values for the various storm events tended to remain fairly constant for a specific watershed and consistent when comparing similar watersheds. Method 3 should provide a good estimate of the proper time shift because the calibration results indicated that the portion of the physically reasonable parameter range identified in Method 3 tended to contain the "optimal" parameter value for each of the unknown parameters.

As a final note, for those cases where there is no distinct measured peak discharge but rather a broad flat hydrograph peak, the proper time shift should be determined by plotting both the measured and the simulated hydrographs and comparing the peak regions rather than just the single peak discharge.

2.5.2 Step 2: Formal Calibration and Adjustments

Having determined the proper time shift, the formal calibration of the hydrograph is done using GRG as described in Appendix A. The parameter values used in Step 1 to determine the proper time shift will make good initial values for the calibration using GRG. Perform a simulation using MSED1 and the calibrated parameters.

If the sediment transport capacities exceed the measured sediment yield, the hydrologic "best fit" which allows the appropriate sediment yield has been found and Step 3 should be performed.

If the sediment transport capacities are less than the measured yield, reduce the values of n and/or ADW until the sediment transport capacities exceed the measured sediment yield. It has been found that not only is the sum of squares surface of the difference between the measured and simulated hydrographs unimodal but it is also fairly flat in the optimal region in the n and ADW directions. That is, the quality of the hydrologic fit is fairly insensitive to changes in n and ADW from their calibrated values. Thus, after reducing n and/or ADW, check the quality of the hydrologic fit in terms of peak discharge, total runoff volume, and sum of square difference. It is quite likely that the quality of the hydrologic fit will still be quite good, and if so go to Step 3 without further calibration. If, on the other hand, it is felt that the quality of the hydrologic fit is no longer acceptable, change the time shift to its new value (if necessary) and set the upper bounds on n and ADW to those values necessary to obtain the measured sediment yield.

This calibration procedure should be repeated until a reasonable hydrologic fit is obtained which allows the measured sediment yield to be simulated.

2.5.3 Step 3: Calibration of Detachment Coefficients

Having obtained a "good" hydrologic fit, which has sufficiently large overland and channel sediment transport capacities to reproduce the measured sediment yield, the detachment coefficients may be determined by iteration such that the simulated total sediment yield from MSED1 closely matches the measured yield. Intuitively, it might be expected that a wide variety of combinations of the three detachment coefficients would produce the measured sediment yield, and hence the usefulness of calibration would seem to be reduced because a range of values is the best that can be identified. However, due to the structure of the model and physical considerations, the overland flow and channel flow detachment coefficients may be viewed as insignificant compared to the raindrop splash detachment coefficient.

In the calibration of the detachment coefficient values, it was found that generally sediment yield was not sensitive to the overland flow detachment coefficient (i.e., in 11 of the 17 cases studies). This does not mean that overland flow detachment is unimportant in the true physical sense, but rather this is due to the structure of the model. The total sediment supply, S_S, is estimated in MULTSED as

$$S_S = V_R + V_F \tag{2}$$

where V_R = nonporous volume of material detached by raindrop splash,

V_F = nonporous volume of material detached by overland flow.

In MULTSED V_R is estimated as

$$V_R = a_1 A(1 - \eta) A_B \, i^2 \tag{3}$$

where a_1 = an empirically determined constant describing the erodibility of the soil,

η = soil porosity,

A_B = area reduction factor (i.e., the fraction of bare or unprotected soil in the area),

i = rainfall intensity,

A = total surface area subjected to rainfall,

and V_F is estimated as

$$\begin{aligned} V_F &= DOF * (T_c - V_R) \qquad \text{if } T_c \geq V_R \\ V_F &= 0 \qquad\qquad\qquad\qquad \text{if } T_c < V_R \end{aligned} \tag{4}$$

where T_c = the sediment transport capacity of the overland flow (sum for all sediment sizes),

DOF = the overland flow detachment coefficient.

The total supply is then distributed by size fractions based on the particle size distribution, and then the supply for a given size is compared to the transport capacity for that size. The fraction of the total transport capacity represented by a given size may not be the same as the fraction of the available sediment represented by that size. Thus, generally V_R must be greater than the total transport capacity in order for sufficient sediment supply to be available, and hence DOF becomes unimportant.

From a physical standpoint, for the watersheds of interest to Army land managers, the primary sources of erosion will be the overland flow areas. This is especially true for the watersheds examined in this report. Each of these watersheds is small with highly vegetated, swale channels (especially the Lawson Creek Tributary number 1 channel which is completely grassed throughout its entire length). Therefore, from a physical standpoint, it would be expected that little channel erosion occurs and so the value of the channel detachment coefficient was assumed to be unimportant and set equal to zero.

Thus, in most cases the raindrop splash detachment coefficient, a_1, is the primary erosion controlling parameter requiring calibration. However, for those training sites where gullies are a problem (e.g., Fort Knox) both the raindrop splash and channel flow detachment coefficients need to be examined. A good way to separate the effects of the two sources of sediment might be to use reasonable values of a_1 obtained from calibration of other similar watersheds and then to iterate on the channel flow detachment coefficient until the excess measured sediment is accounted for. (Note: it shall be shown later that detachment coefficient values are transferable between similar watersheds).

3. CALIBRATION EXPERIENCE

3.1 Descriptions of Watersheds Used for Calibration

Runoff and sediment yield data for 17 storm events on five small watersheds, two in Iowa and three in Illinois, were used for calibration. Actually, the two watersheds in Iowa are adjacent to each other, while the three in Illinois are permutations of the same basic watershed. Both of these groups of watersheds are described as groups below.

3.1.1 Lawson Creek Tributary No. 1

This watershed comprises the northwest portion of the Sheffield, Illinois low-level radioactive waste disposal facility. This facility is located 3 miles southwest of Sheffield, Illinois, and its geologic and hydrologic characteristics have been studied by the U.S. Geological Survey from 1975 to the present (9) with monitoring of water and sediment yield beginning in July, 1982. From July, 1982, to late July, 1983, Lawson Creek Tributary number 1 (LCT 1) had an area of 3.25 acres, as denoted by the heavy line in Fig. 1. In late July, 1983, the drainage pattern was altered such that an additional 1.1 acres drained through LCT 1. The modified watershed is referred to as LCT1P, and its boundary is denoted by the dashed line in Fig. 1. The majority of the additional 1.1 acres was bare or nearly bare soil, and so the water and sediment yield for LCT1P show significant increases relative to those for LCT 1. In order to seal off the new sources of high flow and sediment a berm was built across the west end of the watershed on April 10, 1984. The resulting 2.86 acre watershed is referred to as LCT1P2, and its boundary is denoted by the dotted line in Fig. 1.

These permutations on the Lawson Creek Tributary number 1 watershed offer an interesting study in terms of relating detachment coefficients to Army training practices and management practices. LCT1P2 can be viewed as

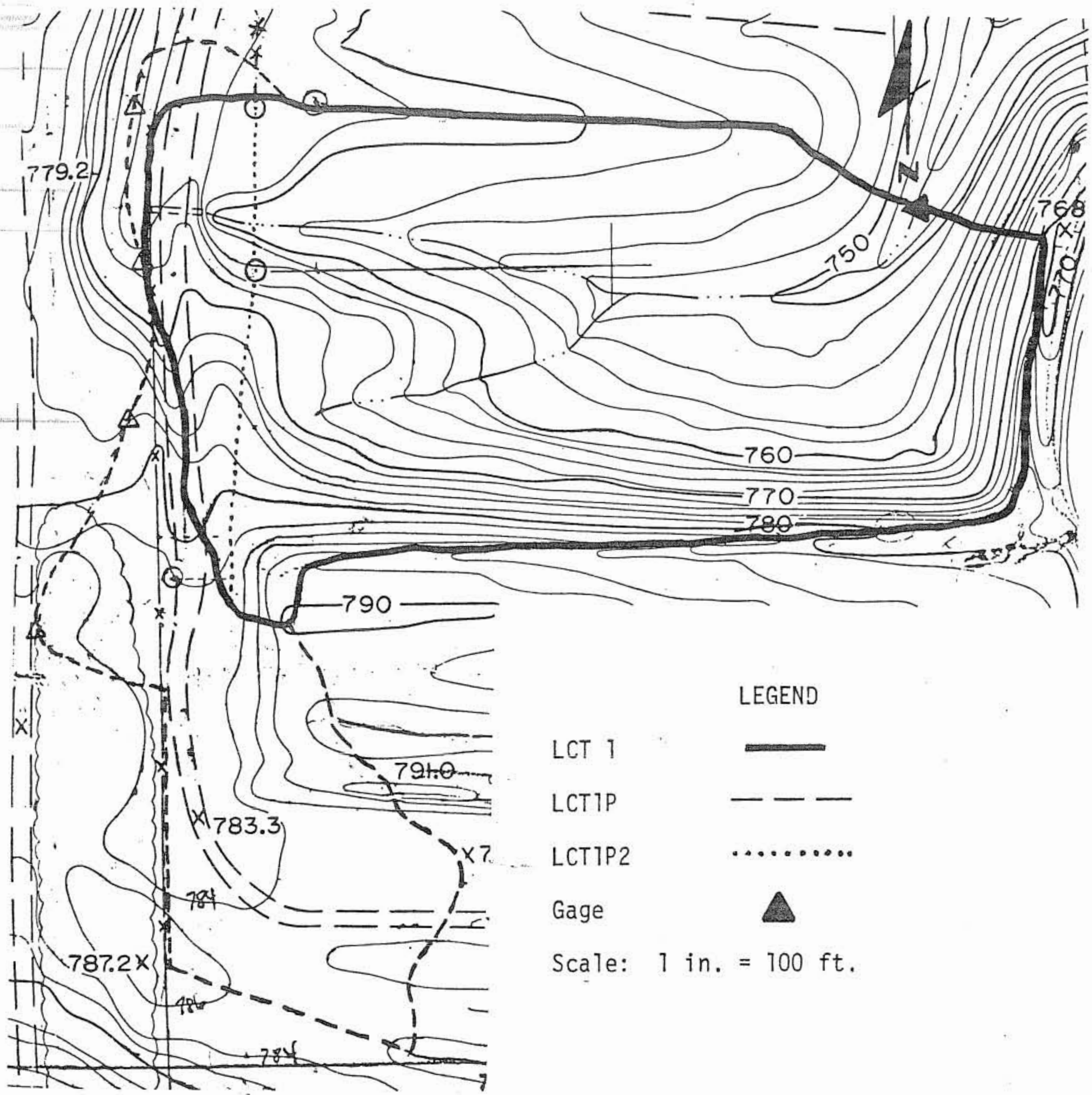

Figure 1. Lawson Creek Tributary Number 1 Watersheds Northwest Corner of the Sheffield, Illinois, Low-level Radioactive Waste Disposal Facility

corresponding to the unaltered state of the training site (watershed). LCT 1 has somewhat more bare soil and greater sediment yield than LCT1P2, hence LCT 1 may be viewed as the training site (watershed) after limited training activity. LCT1P has a good deal of bare soil and large sediment yields, hence LCT1P may be viewed as the training site (watershed) after extensive training.

The soils in this watershed are mainly from the Fayette and Strawn soil associations. The Strawn series soils are deep, strongly sloping to steep, well-drained to moderately well-drained grayish brown silt loams with moderate permeability and moderate available water capacity. The Fayette series soils are gently sloping to very steep, well-drained grayish brown silt loams with moderate permeability and high to very high available water capacity. Based on USDA soil surveys, a reasonable range for the resaturated hydraulic conductivity is 0.1 to 1.0 in./hr. The U.S.G.S. provided data on the soil porosity (0.45) and the initial soil moisture (from tensiometer data) for each storm event, while the final soil moisture fraction was assumed to be 1.0. Actually, the initial soil moisture fraction, S_I, was determined by combining tensiometer data with antecedent rainfall (if any) on the storm date, as shown in Table 1. Data presented by Bouwer (3) indicates a reasonable range of the average capillary suction is -5 to -40 in. for these soils.

The watershed is covered with brome grass, which has an interception potential between 0.01 and 0.05 in. For some of the storms which had significant antecedent rainfall (see Table 1), the interception potential was assumed to be nearly filled, hence the interception potential range was taken as $0.001 \leq VG \leq 0.002$ in. The percentage of vegetal (ground) cover varies both spatially over the watersheds and between seasons. For the summer of 1982, the left side of LCT 1 (looking upstream) had 85% cover and the right side had 60% cover, while in the summer of 1983 the cover percentages

Table 1

Initial Soil Moisture Fraction for Lawson Creek Tributary Number 1 Watersheds

Watershed	Date	S_I, fr. Tensiometer Data	Antecedent Precipitation	S_I Used
LCT1	07/21/82	0.60	--	0.60
LCT1	11/01/82	0.56	0.73 in	0.99
LCT1	06/29/83	0.40	0.31 in	0.80
LCT1P	07/30/83 (1)	0.51	--	0.51
LCT1P	07/30/83 (2)	0.51	2.17 in	0.99
LCT1P	08/26/83	0.44	--	0.44
LCT1P	09/18/83	0.51	0.51 in	0.99
LCT1P2	05/25/84	0.71	0.31 in	0.90
LCT1P2	06/06/84	0.62	0.12 in	0.65
LCT1P2	10/31/84	--	0.45 in	0.99

were 85 and 40 for the left and right sides, respectively. For the summer and fall of 1983, the left side of LCT1P had 70% cover and the right side had 35% cover. For the summer of 1984, the cover conditions for LCT1P2 returned to those for LCT1 in the summer of 1983. In the winter, the percentages on each side for each watershed dropped by about 20%. Due to a lack of sufficient information on the overland flow resistance coefficient, ADW, it was assumed to be unbounded. The channel is heavily grassed, so a relatively high Manning's n value would be expected. Using Cowan's method (6) the range for n was estimated to be 0.05 to 0.10.

Complete rainfall, runoff, and sediment yield data are available for the ten storm events listed in Table 1. The rainfall hyetograph, runoff hydrograph, and total measured sediment yield for each of these storms are presented in Appendix B.

For any given storm event on the watershed only 8 to 10 sediment concentration points are available. While this is an unusually large amount of good quality sediment concentration data, the estimate of the total measured sediment yield can further be enhanced by using a regression equation developed by Gray (9).

$$Q_{SC_t} = 7942.1\ Q_{mt}^{0.33132} \tag{5}$$

where Q_{SC_t} = sediment concentration at time t in mg/l.

This equation was derived by performing a regression analysis on the flow and sediment concentration data, and by using it sediment concentrations corresponding to each point on the hydrograph may be calculated and hence a better estimate of the total sediment yield may be obtained. This equation has a correlation coefficient of 0.823 which, given the relative accuracy of sediment concentration data, makes it a very reasonable representation of the true sediment concentration and the true sediment load. Equation 5 is only valid for LCT 1 and LCT1P, and so the total measured sediment yield for LCT1P2 was determined from the sediment concentration data.

3.1.2 Four Mile Creek Watershed

The Four Mile Creek watershed originates in northwest Tama County, Iowa, near Lincoln. The entire Four Mile Creek basin has been monitored for water, sediment, and nutrient yields by Iowa State University since 1976 (12,13). In this study only two small watersheds in the Four Mile Creek basin are examined. These small watersheds are denoted as ISU-1 and ISU-2 (Iowa State University watersheds number 1 and 2). ISU-1 and ISU-2 are 12.2 and 15.5 acres in area, respectively, and their topography and soils are shown in Fig. 2.

As indicated in Fig. 2, the soils ISU-1 and ISU-2 are Tama silt loam and Colo-Judson silt loam, which are moderately permeable, dark colored soils with gently sloping topography. Based on information provided by Park (21) and Park and Mitchell (22) the porosity of the composite soil is 0.475 and the

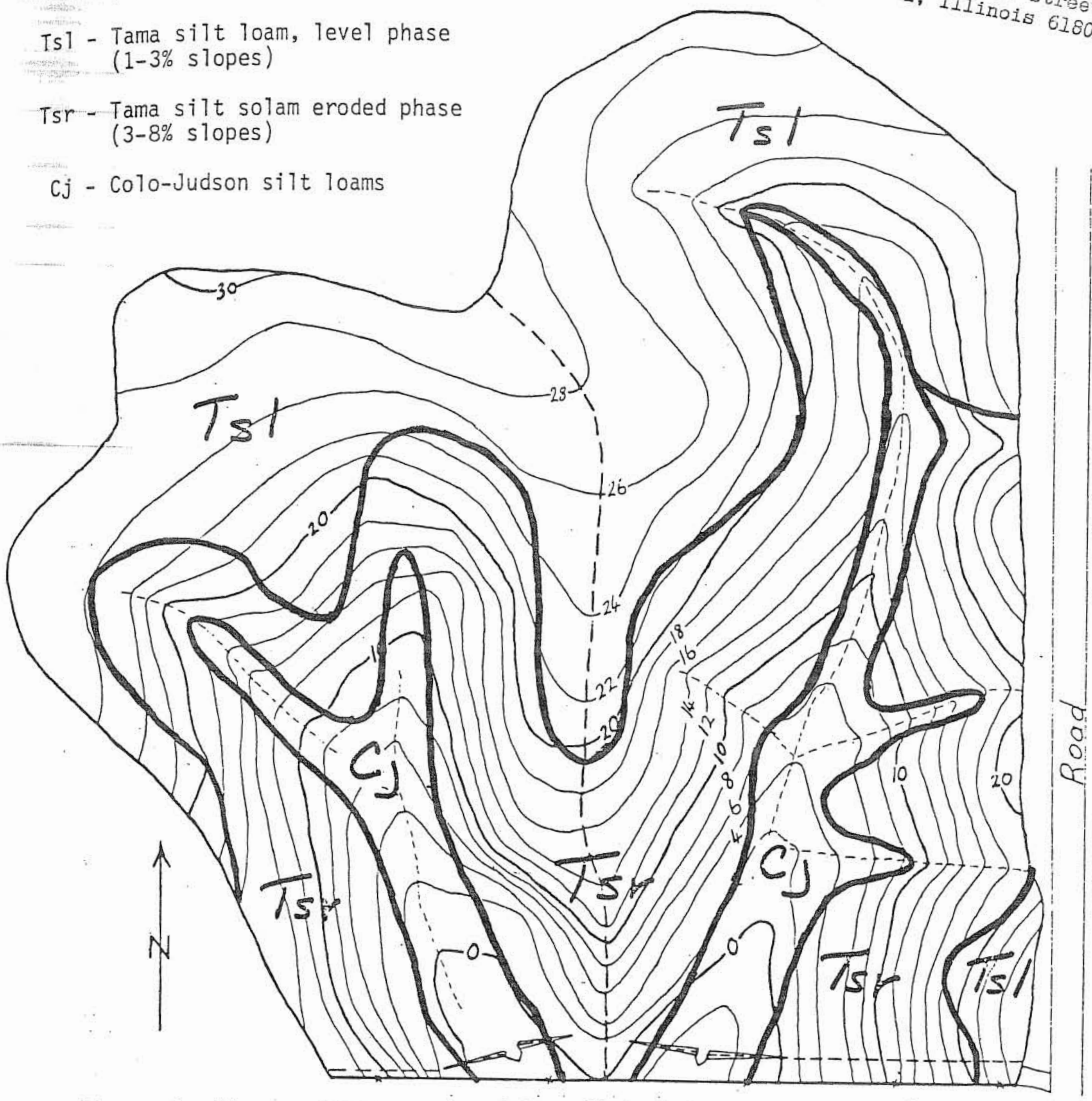

Figure 2. Topography and Soils of Iowa State University Watersheds Numbers 1 and 2 (from Johnson, 13)

reasonable range of values for the resaturated hydraulic conductivity is 0.01 to 0.30 in./hr. The initial soil moisture fraction is taken from the antecedent soil moisture calibrated by Park (21) (see Table 2), and the final soil moisture fraction is assumed to be 1.0. Since these soils are silt loams, the range for the average capillary suction was taken as -5 to -40 in.

Table 2

Initial Soil Moisture Fraction for ISU-1 and ISU-2

Watershed	Date	S_I
ISU-1	04/19/77	0.81
ISU-1	08/15/77	0.81
ISU-1	05/27/78	0.44
ISU-2	08/15/77	0.60
ISU-2	04/18/78	0.83
ISU-2	05/27/78	0.79
ISU-2	05/31/78	0.80

Both ISU-1 and ISU-2 agricultural watersheds which have been used for growing corn (ISU-1 in 1977, ISU-2 in 1978) and soybeans (ISU-1 in 1978, ISU-2 in 1977) on a yearly rotation basis. Each spring the residue from the previous year's crop is plowed and/or disked into the soil along with fertilizer to provide a food base for the new crop and a small amount of erosion protection for the soil. Complete details on the ground and canopy cover conditions for these watersheds are obtainable from the tillage schedule and crop progress photos presented by Johnson (13). Once again the overland flow resistance coefficient was unbounded in the calibration procedure. For these watersheds, the channel is less vegetated than for Lawson Creek tributary number 1, and so from Cowan's method (6), the range of n values of 0.03 to 0.10.

Table 2 lists the dates of the storm events which were calibrated for this report. The storm events are not the same for these adjacent watersheds because it was found that the runoff when soybeans are planted is far less than when corn is planted. Thus, storms which produced significant runoff (peak discharge > 2 cfs) on the watershed planted with corn often produced insignificant runoff (peak discharge < 0.6 cfs) on the neighboring watershed planted with soybeans. When soybeans are planted, a large amount of residue from the previous year's corn crop is tilled into the soil, while when corn is planted a very small amount of residue from the previous year's soybean crop is tilled into the soil. Thus, when soybeans are planted the surface roughness is much greater and hence the detention storage is much greater than when corn is planted. This increased detention storage probably accounts for the difference in runoff magnitude. The MODANSW model (22) is incapable of explicitly dealing with this increased detention storage, and so when Park (21) calibrated these storms for MODANSW the detention storage errors were accounted for in the initial soil moisture, S_I. Hence, the difference in S_I between ISU-1 and ISU-2 for the August 15, 1977 and May 27, 1978 storms. Since MULTSED is also incapable of explicitly accounting for detention storage, it was decided to account for it in the initial soil moisture here as well.

Complete rainfall, runoff, and sediment concentration data are available for the seven storm events on ISU-1 and ISU-2 listed in Table 2. The rainfall hyetograph, runoff hydrograph, and total measured sediment yield for each of these storms are presented in Appendix B. For these watersheds, the total sediment yield was estimated from the sediment concentration data.

3.2 Calibration Results

3.2.1 Hydrologic Fitting

Thirteen of the seventeen storm events calibrated required some time shifting of the hydrographs and/or extra constraints on the resistance coefficients in order to achieve a good hydrologic fit which allows the proper sediment yield. Nevertheless, despite the reduction of hydrologic fit quality brought on by the hydrograph shifting and resistance coefficient constraints, the hydrologic fits obtained were quite good. This is shown in Table 3, where the percent difference between the measured and calibrated hydrographs in terms of the peak discharge and the total runoff volume is given. Also in Table 3, the final calibration objective function is given as a percentage of the total sum of squares of the flow data, this gives some idea of the quality of fit in terms of the hydrograph shape.

Table 3

Quality of the Hydrologic Fit

		Percent Difference* measured versus calibrated		
Watershed	Date	Peak	Volume	TSS
LCT 1	07/21/82	- 9.7	- 2.4	1.8
LCT 1	11/01/82	+ 4.2	- 7.8	2.4
LCT 1	06/29/83	+ 7.1	- 8.0	2.8
LCT1P	07/30/83 (1)	+17.8	- 7.0	2.4
LCT1P	07/30/83 (1)	+22.3	- 6.8	7.0
LCT1P	08/26/83	+33.5	-12.9	6.0
LCT1P	09/18/83	- 7.9	- 5.3	2.1
LCT1P2	05/25/84	+ 8.9	- 5.8	2.2
LCT1P2	06/06/84	+16.0	- 5.8	3.6
LCT1P2	10/31/84	- 1.3	-13.9	2.1
ISU-1	04/19/77	-16.3	+ 3.4	8.0
ISU-1	08/15/77	+ 2.5	-13.5	6.9
ISU-1	05/27/78	-27.0	- 6.3	11.9
ISU-2	08/15/77	-11.7	- 0.2	2.5
ISU-2	04/18/78	+19.3	- 0.7	1.3
ISU-2	05/27/78	+ 5.7	-12.1	3.7
ISU-2	05/31/78	-20.5	+13.4	5.7

*Percent Difference = [(simulated-measured)/measured] * 100

$$TSS = \frac{\sum_t (Q_{mt} - Q_{st})^2}{\sum_t Q_{mt}^2} \tag{6}$$

The "best" fit hydrograph for each of these storm events is plotted along with the measured hydrograph for comparison of the two in Appendix B. To get a feel for the quality of the hydrologic fits obtained, Table 4 is offered for comparison with Table 3. Table 4 displays the fit qualities obtained by Park (21) when he calibrated MODANSW for six of the storm events examined here (note: he calibrated in terms of matching simulated and measured total runoff volume). From the comparison of Tables 3 and 4 it is clear that the fits obtained here are all at least as good as those obtained by Park with most of them better.

Table 4

Quality of Hydrologic Fit Obtained by Park using MODANSW

Watershed	Date	Percent Difference - measured versus calibrated Peak	Volume
ISU-1	04/19/77	-54.0	-0.6
ISU-1	08/15/77	-16.5	-0.2
ISU-1	05/27/78	-17.9	+5.1
ISU-2	08/15/77	-28.5	+1.6
ISU-2	04/18/78	-55.4	+3.5
ISU-2	05/27/78	-32.8	-0.3

The quality of the hydrologic fit could be improved even further by making the adjustment in MULTSED, of not allowing infiltration after the rainfall input has ceased. Ward (29) reports that this adjustment has already been made in the MULTSED version at New Mexico State with great success. Furthermore, it is clear from the comparison of measured and simulated hydrographs in Appendix B that the simulated recession curves decrease much too rapidly, and so this adjustment would improve the fits obtained in this study. An adjustment of this type is not uncommon in hydrologic modeling, and it can be interpreted as accounting for the effects of prompt subsurface flow (i.e., interflow) on the measured hydrograph. This adjustment was not made in the calibration work performed here. Nevertheless, it is felt that the raindrop splash detachment coefficient values calibrated here are quite reasonable since the majority of sediment detachment and transport occurs before the hydrograph reaches the lower part of the recession curve.

Table 5 shows the calibrated values of the hydrologic parameters. All of these values fall within the reasonable range for each respective parameter. It is also encouraging to see that the variance in parameter values from storm to storm is not excessive. Furthermore, a comparison between the similar watersheds, i.e., LCT 1, LCT1P, and LCT1P2; and ISU-1 and ISU-2, shows good consistency in the values of all the parameters. These results indicate that this model can generate realistic runoff events given adequate data about the site conditions. This performance is expected from a good physically based hydrologic model. Finally, the results given in Table 5 support the following important points:

1. Since the parameter values for MULTSED show good consistency between similar watersheds, it is concluded that calibrated hydrologic information for one watershed may be transferred for simulation of similar ungaged watersheds.
2. The calibrated parameter values tended to fall into certain portions of their physically reasonable ranges (i.e., K_H in the lower portion, ADW, n, and interception potential in the upper portion, and $-\psi$ in the middle portion). Thus, for ungaged watersheds for which there are no similar watersheds for parameter transfer, reasonable simulation results

may be obtained choosing parameter values in the appropriate portions of their physically reasonable ranges.

Table 5

Calibrated Hydrologic Parameter Values

Watershed	Date	K_H (in./hr)	$-\psi$ (in.)	VG (in.)	VC (in.)	n	ADW
LCT 1	07/21/82	0.100	5.0	0.010	--	0.090	512.
LCT 1	11/01/82	0.100	20.4	0.050	--	0.091	9000.
LCT 1	06/29/83	0.107	40.0	0.020	--	0.053	1700.
LCT1P	07/30/83 (1)	0.100	16.7	0.050	--	0.061	2300.
LCT1P	07/30/83 (2)	0.100	20.0	0.001	--	0.081	1817.
LCT1P	08/26/83	0.100	20.4	0.050	--	0.086	1900.
LCT1P	09/18/83	0.100	5.0	0.001	--	0.050	2200.
LCT1P2	05/25/84	0.100	16.4	0.001	--	0.100	5363.
LCT1P2	06/06/84	0.118	19.8	0.050	--	0.097	10000.
LCT1P2	10/31/84	0.108	25.0	0.002	--	0.050	60000.
ISU-1	04/19/77	0.183	30.0	0.020	--	0.061	17000.
ISU-1	08/15/77	0.170	30.0	0.000	0.050	0.100	13190.
ISU-1	05/27/78	0.202	29.8	0.020	0.060	0.067	31270.
ISU-2	08/15/77	0.245	32.2	0.020	0.06	0.047	1275.
ISU-2	04/18/78	0.031	36.3	0.020	--	0.100	33078.
ISU-2	05/27/78	0.145	30.0	0.020	0.06	0.080	49711.
ISU-2	05/31/78	0.218	29.9	0.000	0.02	0.035	10795.

Note: K_H = resaturated hydraulic conductivity
$-\psi$ = average capillary suction (expressed as a positive value)
VG = ground cover interception
VC = canopy cover interception
n = Manning's n for channel flow
ADW = the maximum overland flow resistance parameter

3. The fact that n and ADW tended to be in the upper portion of their physically realistic ranges is as expected because these higher resistance values help the kinematic wave approximation artificially simulate natural attenuation of the flow. It is encouraging to see that values within the physically reasonable ranges of n and ADW are capable of accounting for natural attenuation (with some time shifting) because this leads us to

believe that the kinematic wave approximation is acceptable for erosion modeling.

3.2.2 Detachment Coefficient Calibration

As pointed out in Chapter 2, the overland flow detachment coefficient is insignificant due to the structure of the MULTSED model, and for the heavily vegetated, swale channels found in these watersheds it is reasonable to assume the channel erosion and, hence, the channel detachment coefficient, is negligible. Thus, in this study, only the raindrop splash detachment coefficient, a_1, was calibrated and the optimal values of a_1 and the measured and simulated sediment yield for each storm event are shown in Table 6. These

Table 6

Calibrated Values of the Raindrop Splash Detachment Coefficient

Watershed	Date	a_1	Sediment Yield Measured (lbs)	Sediment Yield Simulated (lbs)
LCT 1	07/21/82	0.0140	2190.	2190.
LCT 1	11/01/82	0.0037	2180.	2180.
LCT 1	06/29/82	0.0088	3830.	3840.
LCT1P	07/30/83 (1)	0.0107	13960.	13950.
LCT1P	07/30/83 (2)	0.0114	9970.	10000.
LCT1P	08/26/83	0.0057	11520.	11570.
LCT1P	09/18/83	0.0230	8510.	8510.
LCT1P2	05/25/84	0.0013	512.	520.
LCT1P2	06/86/84	0.0004	180.	180.
LCT1P2	10/31/84	0.0007	35.	35.
ISU-1	04/19/77	0.0088	33120.	31510.
ISU-1	08/15/77	0.0198	8550.	8540.
ISU-1	05/27/78	0.0007	3490.	3480.
ISU-2	08/15/77	0.0196	2280.	2270.
ISU-2	04/18/78	0.0010	1270.	1230.
ISU-2	05/27/78	0.0027	25000.	24900.
ISU-2	05/31/78	0.0009	1940.	2010.

agree quite well with those found by Ward and Seiger (30) for rainfall simulator tests on five different soil types in the Pinon Canyon watershed in Colorado. Ward and Seiger found the mean values of a_1 for these soils ranged from 0.00047 to 0.02433.

By observing the results reported in Table 6 two important inferences may be made:

1. The rainfall detachment coefficients for ISU-1 and ISU-2 seem to be fairly consistent (especially comparing the August 15, 1977 storm event). This leads to the conclusion that these a_1 values may be transferable between similar watersheds for similar storm conditions (this will be examined in more detail later).
2. It is also clear that LCT1P and LCT 1 generally have higher rainfall detachment coefficient values than LCT1P2, with the mean value for LCT1P (the worst case) more than an order of magnitude greater than that for LCT1P2 (the natural case). This comparison points qualitatively toward the type of changes which will need to be made in the values of this coefficient to reflect the watershed degradation caused by training in addition to adjusting the cover percentages.

As a final note, it should be remembered that the results of 17 calibration trials are hardly conclusive, and therefore further calibration and rainfall simulator tests are desirable. It is felt that the calibration procedure described in this report should serve as a good guide to further calibration efforts. Furthermore, the results of these example calibrations should provide a useful foundation for training area simulation until more calibration information and rainfall simulator test results become available.

3.2.3 Overland Flow Resistance

The results of these 17 storm calibrations provides little insight into selecting a value of the overland flow resistance coefficient, ADW, because its value was found to vary greatly between the storms and between the watersheds. Actually, ADW is the maximum overland flow resistance value which would occur if 100% ground cover existed over the watershed. In MULTSED, the actual overland flow resistance coefficient, K_g, is estimated as

$$K_g = 100 + (ADW - 100)\, C_g^2 \tag{7}$$

where C_g = the ground cover fraction.

Perhaps, by considering K_g instead of ADW, a better idea of how to determine the proper overland resistance value can be obtained. Table 7 shows the K_g values for each of the calibrated events. In general, the goal of Army simulation of training sites is to examine the increase in runoff and sediment yield caused by training activities. Thus, if the results for LCT1P2 (whose events produce small sediment yields) are ignored, it is clear that the variance in K_g values is much smaller than that for ADW. Based on Table 7, it seems that when simulating post-training activity conditions, a good initial choice of ADW would be one that results in K_g being between 400 and 1000. Furthermore, LCT1P2 is similar to natural state training area conditions, and from this it appears that value of K_g greater than 2500 is appropriate. These are reasonable "rules of thumb" for now, but more research is needed regarding the proper choice of ADW, both for the post-training activity and the natural state watershed conditions.

Table 7

Calibrated Values of the Overland Flow Resistance Parameter

Watershed	Date	K_g
LCT 1	07/21/82	350.
LCT 1	11/01/82	3078.
LCT 1	06/29/82	432.
LCT1P	07/30/83 (1)	947.
LCT1P	07/30/83 (2)	761.
LCT1P	08/26/83	793.
LCT1P	09/18/83	908.
LCT1P2	05/25/84	2832.
LCT1P2	06/06/84	5240.
LCT1P2	10/31/84	31200.
ISU-1	04/19/77	269.
ISU-1	08/15/77	624.
ISU-1	05/27/78	412.
ISU-2	08/15/77	146.
ISU-2	04/18/78	429.
ISU-2	05/27/78	596.
ISU-2	05/31/78	207.

3.2.4 Efficiency of the Calibration Program

In the course of calibrating the 17 storm events on the 5 watersheds for water and sediment yields the GRG based hydrograph calibration program was used 66 times. The number of objective function evaluations (i.e., hydrograph simulations) necessary to obtain the "optimal" fit ranged from 46 to 292 for these calibration runs with a mean of 129 and a standard deviation of 55. The primary reason for the variance in the number of objective function evaluations is the selection of the starting point for GRG. For comparison, Ibbitt (11) used a version of Rosenbrock's optimization method (24), modified to handle the peculiar fitting problems associated with conceptual catchment models to fit a simple 9 parameter multiple reservoir model (i.e., surface channel, soil moisture, and groundwater storage reservoirs) to synthetic data generated by this same model and then slightly altered. Ibbitt reports that usually a satisfactory fit was achieved in the first few thousand objective function evaluations. While the GRG based calibration is only working with a 6 parameter model as opposed to a 9 parameter model, it is doubtful that an extra three parameters would cause an order of magnitude difference in the number of objective function evaluations needed by GRG. Hence, from this comparison it is clear that the GRG based hydrograph calibration is indeed relatively efficient.

In terms of computer time, all these calibrations were done using the CDC Cyber 175 at the University of Illinois at Urbana-Champaign. For the 66 calibration runs, the execution time ranged from approximately 12 to 130 CP seconds of execution time with a mean of 57 CP seconds and a standard deviation of 33 CP seconds. The execution time for the hydrograph calibration program is primarily a function of the number of objective function evaluations required and of the number of points on the simulated hydrograph. For example, a calibration requiring simulation of a hydrograph 50 min. in duration using 233 objective function evaluations required 68 CP sec., while a calibration requiring simulation of a hydrograph 120 min. in duration using 76 objective function evaluations required 68 CP sec. Figure 3 shows the general nature of the increase of computer time with the number of objective function evaluations and the number of points on the simulated hydrograph. Based on Fig. 3, when calibrating events with long hydrograph durations it would be best to use flow data at 2 min. intervals or greater, even when 1 min. data are available, in order to save computer time.

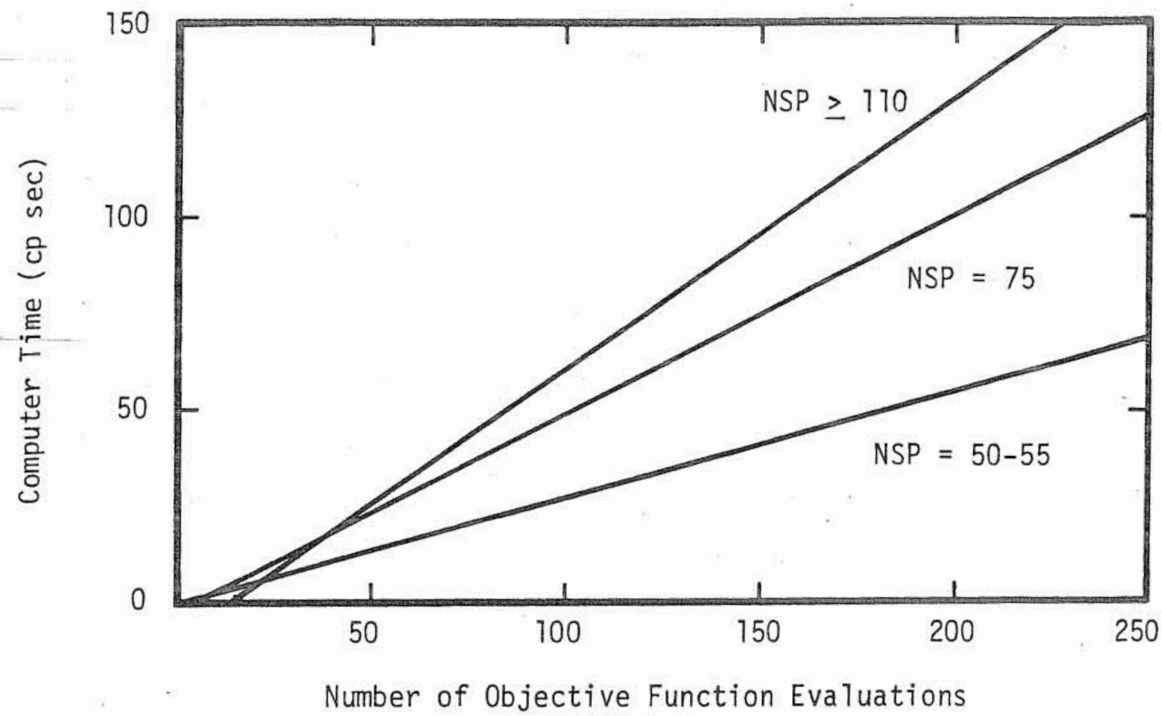

Figure 3. Calibration Program Computer Time as a Function of the Number of Objective Function Evaluations and the Number of Points Generated for the Simulated Hydrograph, NSP

appropriate theoretical and/or empirical relations, which use parameters such as hydraulic conductivity, porosity, capillary suction, flow resistance coefficients, that have physical significance to the field situation. In contrast, regression models and "black box" (input/output) type models typically use parameters which are not derivable from the physical conditions of the watershed but instead the parameters require extensive calibration to be applicable to any particular watershed. Furthermore, these calibrated parameters are only applicable to that watershed in its current condition (i.e., calibration condition). Therefore, the greatest advantage of physically based models is that the component relations are applicable to a wide range of watershed conditions without extensive parameter calibration. Physically based models are very flexible and may be applied to any watershed using parameter values derived from data on the soil and vegetation conditions of the watershed or parameter values transferred from calibration studies of similar watersheds. The vast majority of watersheds do not have runoff and/or sediment yield (especially sediment yield) data available. Therefore, the flexibility and parameter transferability characteristics of physically based models make them an invaluable tool to hydrologists and watershed managers.

The flexibility of physically based hydrologic models and the transferability of parameter values between similar watersheds for these models is well documented and generally accepted. The results of the hydrograph calibration in this study have pointed to the MULTSED hydrologic parameter transferability in that these parameter values remain consistent when comparing calibrated values between similar watersheds. Furthermore, Li et al. (19) demonstrated the accuracy, flexibility, and parameter transferability for the hydrologic portion of MULTSED. Li et al. calibrated parameter values for storm events on ISU-1 (12,13), and then modeled the same storm events over the entire Four Mile Creek basin achieving good results by transferring the calibrated parameter information for use in modeling appropriate parts of the basin.

The flexibility and parameter transferability of the erosion components of physically based overland erosion models is not as easily shown because, as explained earlier, the overland erosion process is so complex that an adequate relation based on physical principles has not been derived. The results of the calibration work performed here seems to point to the conclusion that detachment coefficients are also transferable between similar watersheds because the detachment coefficients also remain consistent when comparing calibrated values between similar watersheds. Thus, in this section the detachment coefficient transferability for MULTSED will be investigated by simulating sediment yield for a larger mideastern watershed by transferring some of the calibration results found earlier.

3.3.1 Watershed for Parameter Transfer Test

The Highland Silver Lake drainage basin is located approximately 30 miles east of St. Louis near Highland, Illinois. This watershed has been monitored by the Illinois State Water Survey for water and sediment yield since 1981. Figure 4 shows a 3188 acre portion of this basin called HSL-1 which was used as the watershed for parameter transfer. HSL-1 is comprised of two subwatersheds whose channels merge to form a larger (main) channel. This main channel continues downstream draining two large planes until it reaches Illinois State Water Survey gaging station number 3 as shown in Fig. 4. Subwatershed number 1 in Fig. 4 also serves as a gaged field site (FS5), and so separate soil and vegetation (and/or land use) data are available for subwatershed number 1 and the rest of HSL-1.

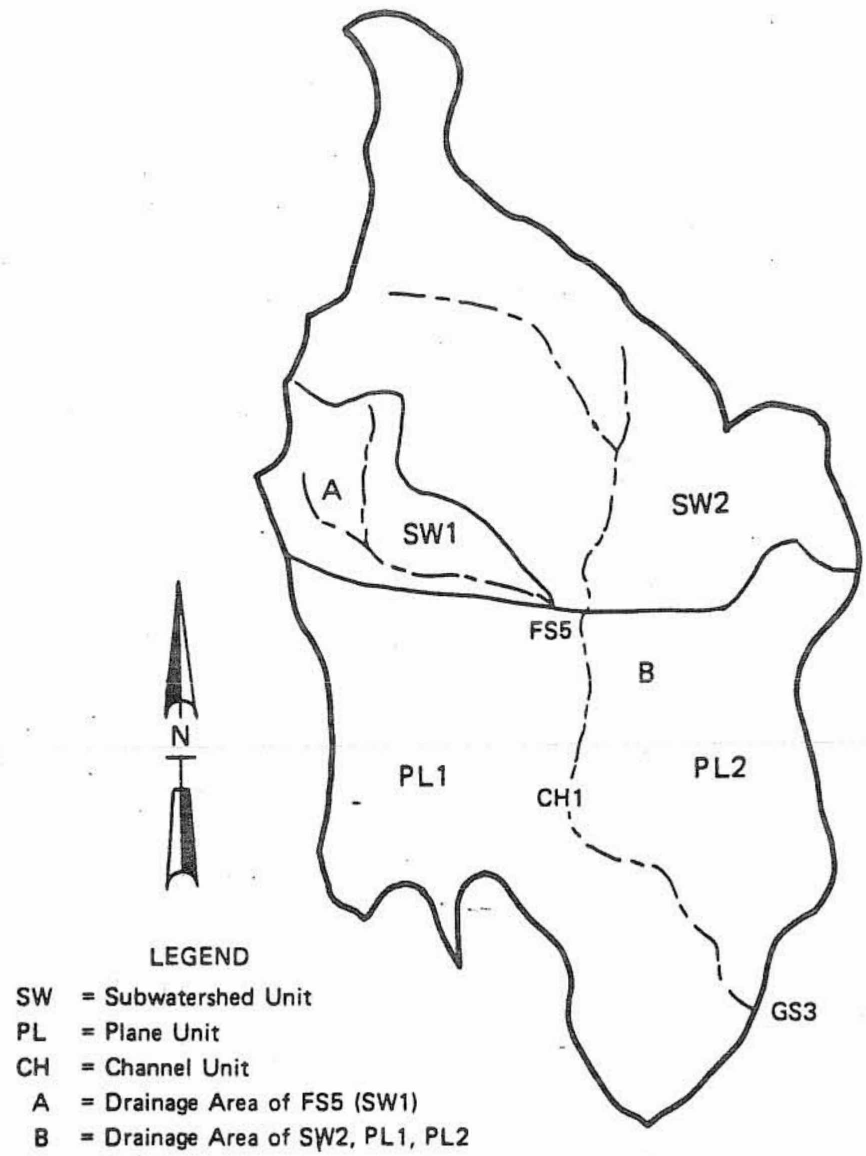

Figure 4. Gaging Station 3 Sub-watershed of Highland Silver Lake, Highland, Illinois (i.e., HSL-1)

The soils in HSL-1 are mainly silt loams and silty clay loams. Four soil types -- Cowden, Darmstadt, Herrick, and Huey -- account for 84.3% of subwatershed number 1 and 82.1% of the remainder of the watershed as shown in Table 8. Cowden series soils are deep, poorly drained, nearly level, dark gray silt loams with low permeability and high available water capacity. Darmstadt series soils are somewhat poorly drained, nearly level to sloping, brownish gray silt loams with low to very low permeability and low available water capacity. Herrick series soils are deep, somewhat poorly drained, nearly level, very dark gray silt loams with moderately low permeability and high available water capacity. Huey series soils are poorly drained, nearly level, gray silt loams and silty clay loams with very low permeability and moderate to low available water capacity.

Table 8 also shows the ranges of resaturated hydraulic conductivity, K_H, for the top layer and for the underlying layers for each of these soils. From this information, 0.03 to 0.35 in/hr would be a reasonable range for K_H throughout the watershed. The final soil moisture fraction was again assumed to be 1.0, but unfortunately no information regarding the value of the initial soil moisture fraction or the soil porosity is available. The MULTSED model estimates infiltration using a modified Green-Ampt approach (27) which combines porosity, average capillary suction, and initial and final soil moisture fractions into a single suction parameter, and so errors in estimating porosity and initial soil moisture fraction may be compensated for in the average capillary suction value. Since these soils are silt loams, the average capillary suction range is -5 to -40 in.

The storm event of September 17, 1982 was simulated. For the summer of 1982 the land use in subwatershed number 1 and the remainder of HSL-1 are shown in Table 9. By September 17 each of these crops were fully mature and so subwatershed number 1 has 42% ground cover and 58% canopy cover and the remainder of HSL-1 has 35% ground cover and 65% canopy cover for this storm event. For these types of cover the ranges of potential interception are 0.01 to 0.05 in. for ground cover and 0.02 to 0.06 in. for canopy cover. Finally, using the "rule of thumb" established earlier, the ranges for ADW were estimated to be 2400-5800 and 3400-7500 for subwatershed number 1 and the remainder of HSL-1, respectively.

Table 8

Highland Silver Lake Watershed: Soil Types and Their Resaturated Hydraulic Conductivities

Soil	SW1 (%)	Remainder of HSL-1 (%)	Top Layer, K_H (in./hr)	Deep Layers, K_H (in./hr)
Cowden	19.0	27.5	0.10-0.32	0.03-0.10
Darmstadt	24.0	27.4	0.03-0.10	< 0.10
Herrick	26.6	14.9	0.32-1.00	0.10-0.32
Huey	14.7	12.3	0.10-0.32	0.03-0.10

Table 9

Highland Silver Lake Watershed: Land Use in the Summer of 1982

Land Use	SW1	Remainder of HSL-1
Soybeans	58%	38%
Wheat	41%	28%
Corn	-	23%
Forrest	-	4%
Miscellaneous Ground Cover	1%	7%

The channels in HSL-1 are lined with earth and fine gravel, highly vegetated, and subjected to an appreciable amount of obstructions from rocks, branches, etc. By comparing photographs of several channel cross sections in HSL-1 to the photographs in Fig. 5.5 (Typical channels showing different n values) of Chow's "Open Channel Hydraulics" (5), it seems a reasonable range of n is between 0.07 and 0.15.

3.3.2 Parameter Transfer for the Storm Event of September 17, 1982

On September 17, 1982, HSL-1 was subjected to 1.40 in. of rainfall over a 190 min. period as shown in the hyetograph in Fig. 5. This storm produced the runoff hydrograph shown in Fig. 5, a total runoff volume of 145.25 acre-ft, (0.0456 in), and a sediment yield of 140,000 lbs (estimated from sediment concentration data).

To test the parameter and information transferability properties of MULTSED, the infiltration, interception, and roughness parameters were varied within the ranges determined from physical conditions until a good reproduction of the measured hydrograph was obtained. The predicted hydrograph for this event is compared to the measured hydrograph in Fig. 5 (the predicted hydrograph has been shifted in time to permit a better comparison). The high quality of the match between the predicted and measured hydrographs is evidenced by the fact that the predicted total runoff volume is only 0.31% less than the measured volume and the predicted peak discharge is only 8.9% less than the measured peak discharge.

The parameter values which lead to this excellent predicted hydrograph are displayed in Table 10. Once again the usefulness of the hydrologic portion of MULTSED is demonstrated by the fact that all the parameters fit within their physically determined ranges and that the porosity data was transferred from LCT 1. Furthermore, it is encouraging to see that the "rule of thumb" for ADW provided an acceptable value for this storm on HSL-1. As previously mentioned, subwatershed number 1 is also a gaged watershed and so the roughness coefficients n and ADW for it were selected to try to produce a

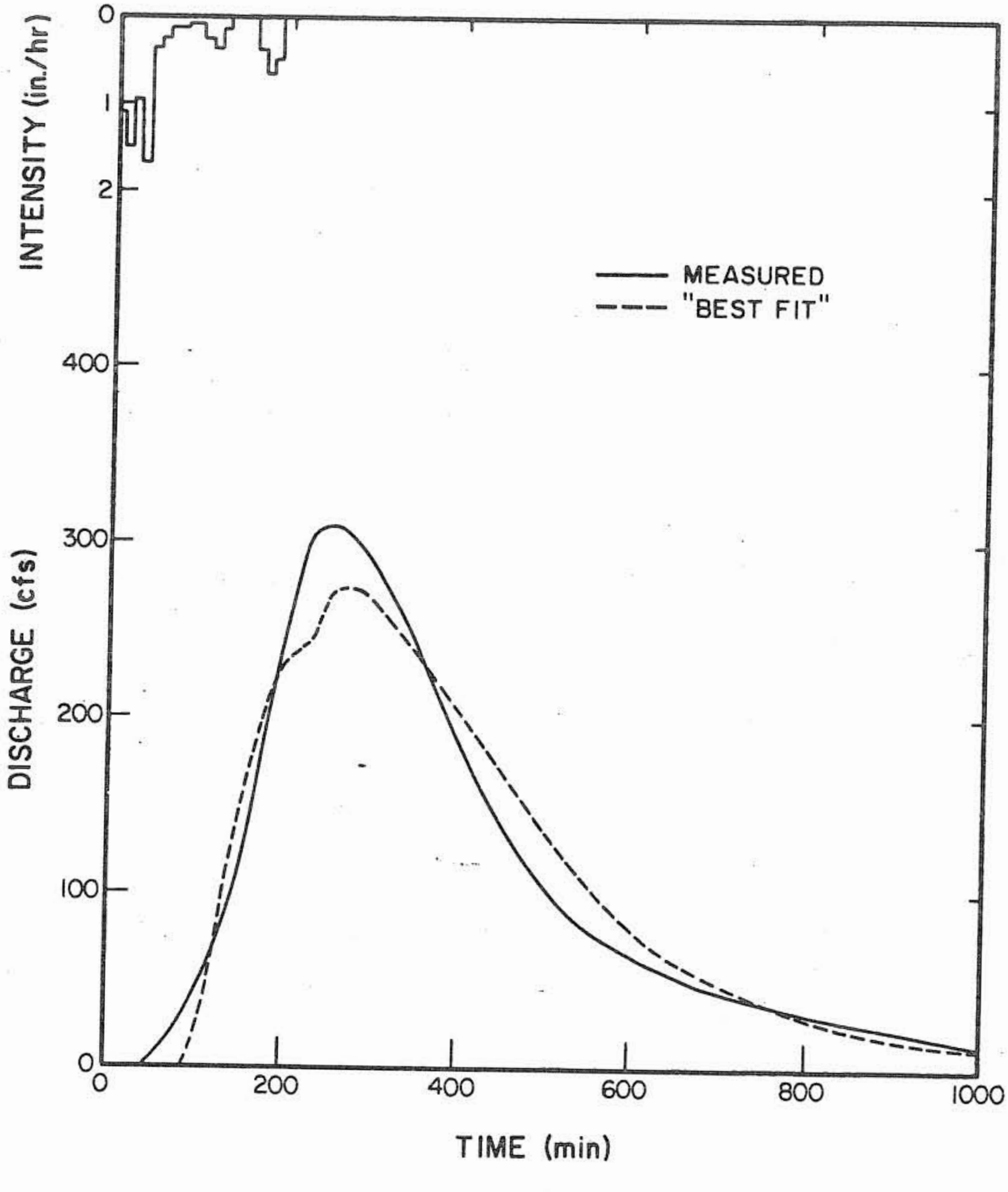

Figure 5 Comparison of Measured and Simulated Hydrographs for the September 17, 1982 Storm on HSL-1

good fit of its measured hydrograph for this storm. Hence, they are a slightly out of their expected ranges.

Table 10

Parameter Values for Good Reproduction of September 17, 1982 Storm Event on HSL-1

Parameter	SW1	Remainder of HSL-1
K_H (in./hr)	0.056	0.056
η	0.45*	0.45*
S_I	0.80	0.80
$-\psi$ (in.)	10.0	10.0
VC (in.)	0.03	0.03
VG (in.)	0.02	0.02
ADW	8000	7500
n	0.12	0.12 (SW2) 0.15 (main chnl)

*transferred from LCT 1.

For the predicted storm event of September 17, 1982 the maximum possible overland flow sediment transport capacity is 454,000 lbs. Thus, an intelligent selection of the raindrop splash detachment coefficient, a_1, will reproduce the measured sediment yield. HSL-1 is primarily an agricultural watershed as are ISU-1 and ISU-2, and so ISU-1 and ISU-2 should be a good source of a_1 values for transfer to HSL-1. The August 15, 1977 storm on ISU-1 and ISU-2 produced unusually high detachment coefficients, while the April 19, 1977 storm on ISU-1 produced an unusually high sediment yield. If these storms are ignored the range of raindrop splash detachment coefficients for ISU-1 and ISU-2 is 0.0007-0.0026 with a mean of 0.0013. Using this mean value of a_1 as an initial guess the predicted sediment yield is 123,600 lbs which is 11.7% less than the measured sediment yield. If the median a_1 value (0.0017) is used as an initial guess the predicted sediment yield is 147,700 lbs which is 5.5% greater than the measured sediment yield.

Based on the results obtained here, if careful consideration is used in choosing the transferred detachment coefficient values, reasonable estimates of sediment yield may be obtained for ungaged watersheds. However, there is a need for more calibration and verification of detachment coefficient transferability. Nevertheless, the results obtained here are enough to inspire optimism in the usefulness of MULTSED.

3.4 Calibration of Larger Watersheds

It is inevitable that it will be necessary to study watersheds which are too large to accurately model as a single subwatershed unit, and hence the multiple subwatershed and plane modeling capabilities of MULTSED must be used. Unfortunately, when a watershed is broken down into a number of units formal optimization of the simulated hydrograph using the GRG based program is no longer possible, and one must resort to iteration. Hence, a good fit is identified by iterating on the parameter values until a reasonable match is obtained between the measured and simulated hydrographs in terms of peak discharge, total runoff volume or both, which also allows the proper sediment yield to be reproduced. Such fits can be quite good such as was found for the September 17, 1982 storm on HSL-1 (Fig. 5), or as was found by Lee and Camacho (17) for the March 18, 1983 storm on HSL-1 (Fig. 6).

The iteration process requires a "good feel" for both the watershed hydrology and the workings of the model to obtain a good fit within a reasonable number of iterations. However, when done carefully, excellent results as in Figs. 5 and 6 may be obtained. From the course of this work two useful guidelines for iteration have been found:

1. If subwatersheds within the boundary of the larger watershed to be calibrated are also gaged (such as Field Site 5 in HSL-1 or ISU-1 and ISU-2 in the Four Mile Creek watershed), these subwatersheds should be

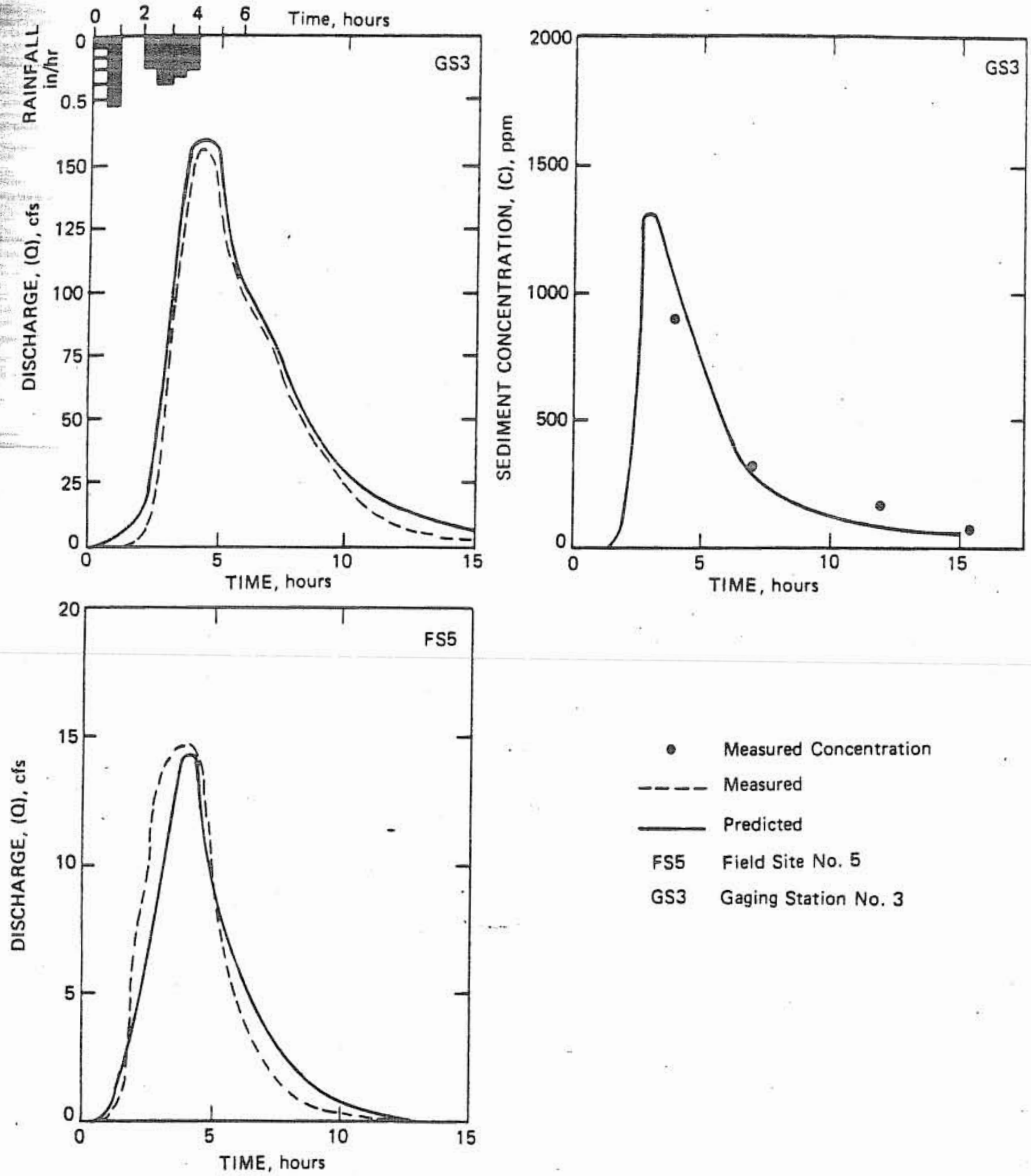

Figure 6. Runoff and Sediment Hydrographs for the March 18, 1983 storm on Highland Silver Lake Watershed, Highland, Illinois (from Lee and Camacho, 17)

formally optimized as described here. Then the calibration information should be transferred, where appropriate, in modeling the entire watershed.

2. When formally calibrating the smaller watersheds in this report it was found that each of the parameters tended to consistently be in a certain portion of its physically reasonable range. These same tendencies also held for HSL-1. Thus, by choosing K_H from the lower portion; ADW, n, VG, and VC from the upper portion; and $-\psi$ from the middle of their respective physically reasonable ranges a good starting point for iteration is obtained.

3.5 Summary

In Chapters 2 and 3 a hydrograph calibration code, which incorporates the GRG algorithm with the hydrologic portion of MULTSED for a single subwatershed unit, has been developed to minimize the sum of squares difference between the measured and simulated hydrographs. The primary advantages of this code are that GRG allows explicit consideration of bounds on the parameters and so the calibration is completely objective and that GRG is very efficient (i.e., very quick) in locating the optimal solution. The efficiency of this code has been demonstrated by the calibration of seventeen storm events on five small mideastern watersheds.

A general procedure for calibrating both the water and sediment yield was also developed. This procedure is not strictly objective, but rather it requires a good deal of judgement and common sense on the part of the user. Due to the nature of the MULTSED model, this procedure generally converges quickly (i.e., in about 2 iterations) to a solution with a good hydrograph fit and sediment transport capacities in excess of the measured sediment yield. The quality of the final "best fit" hydrograph obtained by this procedure has been found to be quite good and the calibrated parameter values for these "best fits" have been found to be quite consistent among similar watersheds. These high quality calibration results have allowed some important conclusions about the usefulness of MULTSED to be drawn, subject to the experience gained in this study.

The flexibility and parameter transferability characteristics of the hydrologic portion of MULTSED have been shown by the very favorable results of the calibration of seventeen storm events on five small watersheds in the mideastern U.S. More importantly, the transferability of information on parameters important to MULTSED's sediment yield prediction has been shown for a large mideastern watershed. Therefore, for any watershed, ranges for the parameters used in MULTSED may be determined from that watershed's physical conditions or by transferring information from similar watersheds. Thus, MULTSED can provide reasonable predictions of water and sediment yield from any storm by using sensitivity analysis over the parameter value ranges for the watershed being studied. This is very important for the evaluation of watershed management strategies.

Finally, it has also been shown that much more information on the proper values of the maximum overland flow resistance coefficient, ADW, and the rain drop splash detachment coefficient, a_1, is needed for the development of rules on how to determine their values based on physical conditions (e.g., relating a_1 to land use and soil type, or relating ADW to ground cover percent and total overland flow resistance, K_g). Thus, calibration of more storm events on more watersheds is recommended to provide this information.

4. RECOMMENDED CHANGES FOR MULTSED

4.1 Errors in Existing MULTSED Codes

As discussed earlier MULTSED is actually a combination of three programs: MSED1 which analytically determines the water and sediment yield from the plane and subwatershed units, MSED2 which reorganizes the output from MSED1 for use as input to MSED3, and MSED3 which numerically routes the water and sediment produced by the planes and subwatersheds through the channel system. In the course of examining these models for calibration use and in comparing the numerical and analytical routing schemes of MSED3 and MSED1, respectively, five errors and/or inconsistencies were detected in the MULTSED programs. These errors are described briefly below and in complete detail in Appendix C, including the modifications necessary to correct the programs. All of these errors have been corrected in the MULTSED programs used in this report's calibration work.

The errors are summarized as follows:

1. In MSED1, the channel sediment transport capacity is calculated as a function of 0.667*wetted perimeter as opposed to simply as a function of the entire wetted perimeter. The factor, which is not justified, of 0.667 causes the transport capacity to be underpredicted.
2. In the channel routing procedure in MSED3, the channel infiltration is incorrectly handled. The resulting error in flow increases with the number of channel reaches used in the routing. Since this number is fixed internally in the program, this error is not easily seen.
3. There is an inconsistency between MSED1 and MSED3 concerning the relationship used for computing the resistance factor as a function of particle size. MSED3 places stricter upper and lower limits on this factor than does MSED1.

4. MSED1 and MSED3 are inconsistent in their use of the Einstein equation for suspended load. Limitations on the Einstein equation are applied in MSED1 which are different from those used in MSED3.
5. In determining the effect of ground cover on raindrop splash detachment MSED1 improperly determines the amount of bare soil, which leads to under-prediction of rainfall detachment at low amounts of ground cover and over-prediction at high amounts.

4.2 Recommended Improvements for MULTSED

In addition to the five corrections to MULTSED described in the previous section, three improvements for MULTSED have been identified. The first improvement deals with the numerical water and sediment routing in MSED3 and an adjustment to improve the quality of the numerically obtained results. The second and third improvements have to do with the estimation of the overland and channel sediment transport capacities. These improvements make the transport capacity estimates more theoretically and/or physically correct, and most important, these improvements will eliminate the transport capacity's dependence on the selection of the largest sizes in the sediment size distribution. All of these improvements have been added to the MULSED codes used for this report.

4.2.1 Convergence of the Numerical Routing

The quality of the solution obtained from a numerical routing technique is a function of the time increment, Δt, the number of reaches the channel is divided into, NDX, and the convergence properties of the numerical method used. From a mathematical viewpoint, it would be desirable to set Δt very small and NDX very large and thus minimize numerical error in the solution to the governing partial differential equations. However, computer time and storage requirements make this impractical and so Δt and NDX must be chosen such that the solution will converge sufficiently close to the "true" solution without having prohibitive computer requirements.

The convergence of the water and sediment yield solutions for MSED3 will be examined for a simple example. ISU-2 was modeled as two plane units by MSED1 and their runoff and sediment yield were routed through the channel using MSED3. The example storm was chosen to be the 5-year return period 60-minute duration storm of uniform intensity. This storm was chosen because it represented a mid-range value of water and sediment yield relative to the other storms previously examined (31). Table 11 shows a comparison of results for the 1% ground cover case with various NDX and Δt values. Table 12 shows the same comparison for 99% ground cover case.

Table 11
Numerical Routing of the Runoff from the Example Storm on the ISU-2 Watershed with 1% Ground Cover

NDX	Δt = 3.0 min		Δt = 0.5 min	
	Total Runoff (in.)	Sediment Yield (lbs)	Total Runoff (in.)	Sediment Yield (lbs)
1	1.8691	162250	1.8867	148160
3	1.9182	143750	1.9229	140910
5	1.9294	121650	1.9290	118080
8	1.9351	113110	1.9319	110060
10	1.9366	103920	1.9325	101210
15	1.9382	95800	1.9331	90530
20	1.9391	94610	1.9332	88550
25	1.9395	94000	1.9333	88040
30	1.9398	93460	1.9333	87560

The total runoff converges to its asymptotic value quite quickly with respect to the number of reaches (NDX) with only 1% difference between the values for NDX = 3 and NDX = 30. This rapid convergence relative to the number of reaches was expected. When developing the numerical routing scheme

Table 12

Numerical Routing of the Runoff from the Example Storm on the ISU-2 Watershed with 99% Ground Cover

NDX	Δt = 3.0 min Total Runoff (in.)	Δt = 3.0 min Sediment Yield (lbs)	Δt = 1.0 min Total Runoff (in.)	Δt = 1.0 min Sediment Yield (lbs)
1	1.7516	8504.	1.7792	8841.
3	1.7944	8972.	1.7917	8837.
5	1.8007	9314.	1.7967	9067.
8	1.8043	9821.	1.7982	9583.
10	1.8049	10450.	1.7970	10054.
15	1.8060	12112.	1.7974	11456.
20	1.8065	13647.	1.7975	11592.
25	1.8067	15064.	1.7976	11631.
30	1.8069	16386.	1.7976	12670.

Li et al. (18) noted the convergence of the numerical scheme is ensured but the accuracy of simulation is dependent on the values of Δt and Δx (channel length/NDX), especially the value of Δt. Generally Li et al. found the numerical scheme was relatively insensitive in regard to Δx given Δt is in a reasonable range and results obtained here confirm this. Table 11 displays results for simulation with Δt's of 3 min and 0.5 min and Table 12 those for Δt's of 3 min and 1 min. From this it can be seen that the total runoff predictions are quite insensitive to both Δt and Δx. Thus, if Δt is chosen as

Note: The sediment yield decreases with NDX in Table 11 because, for the 1% ground cover case, modeling of the suspended sediment settling process using MSED3 is important, and the amount of deposition in the settling process increases asymptotically with the number of reaches. The sediment yield increases with NDX in Table 12 because for the 99% ground cover case, modeling of channel bed armoring using MSED3 is important. Furthermore, as the number of reaches increases the percentage of the channel length subject to armoring decreases and, hence, the sediment yield increases.

a reasonable fraction of the storm duration (this value must be less than the watershed's time of concentration), the hydrologic simulation accuracy should be quite good.

As discussed above the numerical flow routing converges rather quickly to the asymptotic value and is relatively insensitive to the selection of Δt and NDX provided that Δt is chosen as a reasonable fraction of the storm duration. Unfortunately, these same convergence characteristics do not hold true for the sediment routing. Thus, the accuracy of the sediment routing is dependent on the selection NDX and Δt.

By observing Tables 11 and 12, it can be seen for any given Δt the channel must be broken into between 10 and 15 reaches before the sediment yield is within 10% of the asymptotic value (assumed to be that for NDX = 30). On the other hand, for water yield, 3 reaches produced a result within 1% of the asymptotic value. Similarly, by comparing the asymptotic values it can be seen that $\Delta t = 3$ min yields a 7% greater sediment load than $\Delta t = 0.5$ min for the 1% ground cover case and $\Delta t = 3$ min yields a 30% greater sediment load than $\Delta t = 1$ min for the 99% ground cover case.

It would probably not be practical to make every run of MSED3 with $\Delta t = 0.5$ sec and NDX = 30 in an effort to get the most accurate solution possible. Instead, a level of sufficient convergence must be chosen. It is judged that a solution within 10 percent of the "true" solution (i.e., the true solution to the assumed governing differential equation not necessarily the true physical solution) for sediment transport problems would be quite acceptable for decision making. Furthermore, the accuracy of the available sediment data is not likely to be better than ±10 percent, and so a solution convergence within 10 percent is consistent with the quality of the data.

For each of the Δt`s, the solution for NDX equal to 15 is within 10 percent of the asymptotic value. Furthermore, if the asymptotic value for the smaller Δt is viewed as the most accurate solution possible, then the results for the larger Δts with NDX = 15 is within 10 percent of this most accurate solution.

Therefore, selection of NDX equal to 15 for single channel or small number of channels calibration and simulation should prove adequate. For more complicated channel systems storage requirements and computation time may force the use of less reaches, but one should try to keep NDX greater than 10. As far as the value of Δt is concerned, a reasonable fraction of the storm duration should be used, which is less than the watershed's time of concentration.

Currently, in MSED3 NDX has been fixed at 5. Based on the results of the examination of water and sediment yield convergence discussed above, it would seem that more than 5 reaches are necessary to obtain a good sediment yield solution. Therefore, it is recommended that MSED3 be modified to allow the user to specify NDX to obtain acceptable routing accuracy based on the complexity of the channel system.

4.2.2 Transport Capacity Dependence on Two Largest Particle Sizes

Currently in MULTSED the choice of the two largest sizes from the sediment size distribution curve influences the estimated sediment transport capacities in two ways: in the determination of the effective shear stress acting on the particles and in the determination of the bed layer thickness in Einstein's total load equation (8). The fraction of the total amount of erodible sediment represented by the geometric mean of the two largest sizes may be quite small, and letting it play such an important role in the determination of the sediment transport capacity and hence the predicted sediment yield is physically and theoretically erroneous. Furthermore, by arbitrarily choosing the upper cut off point for input of the sediment size distribution to MULTSED, the sediment yield results can be greatly affected. Adjustments must be made to remove this dependence on the choice of the two largest sizes in the sediment size distribution.

4.2.3 Einstein's Total Load Equation

Currently in MULTSED the bed layer thickness, a_r, is taken as two times the geometric mean of the two largest particle sizes. Hence, for the smaller particle sizes a_r is much larger than its theoretical value and so the suspended sediment transport capacity is underestimated. In the following paragraphs a more reasonable estimate of a_r based on Einstein's original derivation will be proposed.

In Einstein's original derivation (8) of the total load equation molecular forces between sediment particles were not introduced to the analysis, and thus according to Einstein the total load relationships are automatically restricted to the larger particles (in general to those coarser than 0.061 mm in diameter). Einstein developed this equation for alluvial streams, and for such streams this restriction had no serious implications because such streams do not contain an appreciable percentage of particles below 0.061 mm in diameter. However, for modeling of small, predominantly silt-sand, watersheds a large percentage of the particles is finer than 0.061 mm in diameter. This leads to some problems when trying to apply Einstein's method.

The primary problem comes in the definition of the thickness of the bed layer for the smaller sediment particles. If Einstein's suggestion that the thickness of the bed layer, a_r, is equal to two times the diameter of the sediment particle, D_s, is used for small sediment particles, the calculated suspended load becomes unrealistically large. In defining the bed layer thickness as $2D_s$ Einstein (8) states:

> "The flow layer at the bed in which the mixing length is so small that suspension becomes impossible has been found to be about 2 grain diameters thick. In reality, the region in which suspension degenerates is not sharply defined. There exists rather a gradual transition to the rest of the flow. It is feasible, nevertheless, to idealize the condition by introducing a sharp division between the bed layer and the bulk of the flow, as is customary in the case of the laminar sublayer."

So, even though his $2D_s$ recommendation is based on some experimental evidence for particles larger than 0.061 mm in diameter there is still a bit of arbitrariness involved in this definition. Thus, it is proposed that the thickness of the bed layer be defined as 0.122 mm (0.0004 ft) for particles less than 0.061 mm in diameter, and $2D_s$ for particles greater than 0.061 mm in diameter.

We know that $2D_s$ is a valid definition of the bed layer thickness for particles greater than 0.061 mm in diameter. Thus it is not correct to represent these particles by two times the largest particle size when we can easily conform to Einstein's original reasoning. The justification for allowing 0.122 mm to represent the bed layer thickness for particles smaller than 0.061 mm in diameter is:

1. This 0.122 mm value of bed layer thickness is approximately the lower bound for which Einstein's relations apply. Thus it provides the best approximation, which has some theoretical justification, of the bed layer thickness for finer sediment particles.
2. Einstein states that, in general, finer particles tend to fill the voids between the larger particles, thus the movement of the finer particles is limited somewhat by the movement of the larger particles. Hence, a larger a_r value may be justified.

3. The very fine silt and clay particles tend to be cohesive and to bond together to form what is equivalent to a larger single particle.

Based on this third point one might think that the diameter in the fall velocity calculations would also need to be altered in order to be consistent with the bed layer estimation. Simons and Senturk (26, p. 552) point out that laboratory studies by several investigators indicated that the concentration distributions for different sizes of sand and even clay follow the form of the suspended sediment equations used by Einstein. Thus, no change in the fall velocity calculations is advocated.

Table 13

Comparison of Transport Capacity Estimates from the Various Einstein Based Methods

Sediment Size (mm)	Percent Finer	MSED1 Functions Left Plane (lbs)	MSED1 Functions Right Plane (lbs)	True Einstein Left Plane (lbs)	True Einstein Right Plane (lbs)	Suggested Einstein Left Plane (lbs)	Suggested Einstein Right Plane (lbs)
0.0002	0.00						
		122.4	375.8	49333.	141434.	633.8	1871.1
0.002	20.2						
		10.8	33.2	983.	2825.	56.0	165.2
0.004	22.0						
		26.2	80.4	1190.	3430.	134.5	397.6
0.008	26.4						
		48.9	150.3	1085.	3157.	244.4	726.0
0.016	34.8						
		300.2	926.0	1797.	5544.	1125.7	3500.8
0.062	91.0						
		17.2	54.5	18.0	68.5	18.0	68.5
0.125	95.4						
		5.8	18.9	5.1	19.0	5.1	19.0
0.25	97.9						
		1.2	3.7	1.1	3.6	1.1	3.6
0.50	99.6						
		0.0	0.0	0.0	0.0	0.0	0.0
1.00	99.9						
TOTAL		533.	1643.	54412.	156482.	2219.1	6752.1

The true test of any proposed method is how reasonably it predicts the sediment transport capacity. Table 13 compares the transport capacities for the left and right planes of LCT 1 for a good fit (not the optimal fit) of the storm event of June 29, 1983. From Table 13 it is clear that using Einstein's proposed bed layer thickness does indeed produce excessively large suspended sediment transport capacities. For the suggested Einstein procedure the fine particle load is much more reasonable, within an order of magnitude of the current MSED1 Einstein relations, and of the measured sediment yield for this event, 3830 lbs.

In addition to changing the value of a_r in MULTSED, the calculation of the exponent of the suspended sediment distribution, z_r, for Einstein's total load equation also should be modified. Appendix D derives the form of Einstein's suspended load relation used in MULTSED. From this derivation it can be seen that the value of z_r should be estimated using the shear velocity corresponding to the flow resistance caused by the individual grains, u_*'. Currently in MULTSED z_r is estimated using the shear velocity corresponding to the total boundary resistance. Thus, z_r is currently being underestimated which leads to an over estimation of the suspended sediment. In MULTSED the effective shear due to the grain resistance is already calculated for use in the Meyer-Peter, Müller bed load equation (20). Hence, it is a simple task to calculate u_*' and determine z_r as recommended by Einstein. This change was made for both the true and suggested Einstein cases shown in Table 13. Since this change leads to a reduction in the estimated sediment transport capacity it is recommended that it should only be made if the a_r change is also adopted (both these changes were made in the MULTSED version used in this report).

In summary, the suggested approach provides sufficient capacity to duplicate the measured sediment yield using the proper detachment coefficient values, and yet the capacity is not so large that it is unreasonable (as a point for comparison, the transport capacity equation used in the ANSWERS model (2) estimates a total capacity of 15235 lbs from the two planes for this storm). Furthermore, the suggested approach is more in line with Einstein's ideas than is the current approach.

4.2.4 Effective Shear Stress

Another effect of the largest sediment sizes in channel flow on the calculated sediment yield is in the calculation of the effective shear stress acting on the grains, τ', which leads to sediment motion. The effective shear stress is calculated as

$$\tau' = \gamma R S' \tag{8}$$

where γ = the specific weight of water,

R = the hydraulic radius,

S' = the energy slope acting on the grains.

The energy slope acting on the grains may be estimated from the Darcy-Weisbach equation as

$$S' = f'V^2/(8gR) \tag{9}$$

where f' = the Weisbach resistance coefficient corresponding to the grain resistance,

V = the mean flow velocity,

g = the acceleration due to gravity.

Hence,

$$\tau' = f'\rho V^2/8 \tag{10}$$

where ρ = the density of water.

Currently in MULTSED the Weisbach f' is calculated as 1.5 times a Colebrook-White type equation for fully turbulent flow

$$f' = 1.5/[1.69 + 2 * \log(2 * R/D_{si})]^2 \tag{11}$$

where D_{si} = the representative diameter for particles in the ith fraction of the sediment size distribution.

Simons et al. (29) reasoned that the resistance acting on a selected particle also depends on the size of the particles surrounding it, hence the resistance factor, f', is not allowed to fall below half the value computed for the largest sizes. Thus, depending on the two largest sizes chosen from the sediment size distribution curve (e.g., Fig. 7) the value of the minimum resistance factor, f_{min}, may be artificially made large or small leading to artificially large or small channel transport capacities as shown in the "current MULTSED" column in Table 14. The percent finer for the largest size column in Table 14 indicates just how arbitrary the selection of the largest

Table 14

Effect of the Two Largest Sediment Sizes on Sediment Yield

				Channel Sediment Transport Capacity		
Two Largest Sizes (mm)		Percent Finer for Largest Size	Geometric Mean, D_{max} (mm)	Current MULTSED (lbs)	Suggested Einstein $k_s = D_{max}$ (lbs)	Suggested Einstein $k_s = 3D_{90}$ (lbs)
0.35	0.25	.990	0.296	4406.	15040	13990
0.50	0.25	.996	0.354	3861.	15400	13990
0.60	0.50	.997	0.548	2852.	15900	13990
0.70	0.50	.998	0.592	2712.	16020	13990
0.80	0.50	.9984	0.633	2598.	16150	13990
0.90	0.50	.9987	0.671	2509.	16380	13990
1.00	0.50	.999	0.707	2442.	16740	13990
2.00	1.00	.9997	1.414	2068.	19660	13990

*June 19, 1983 storm on LCT 1 using best fit hydrologic parameters.

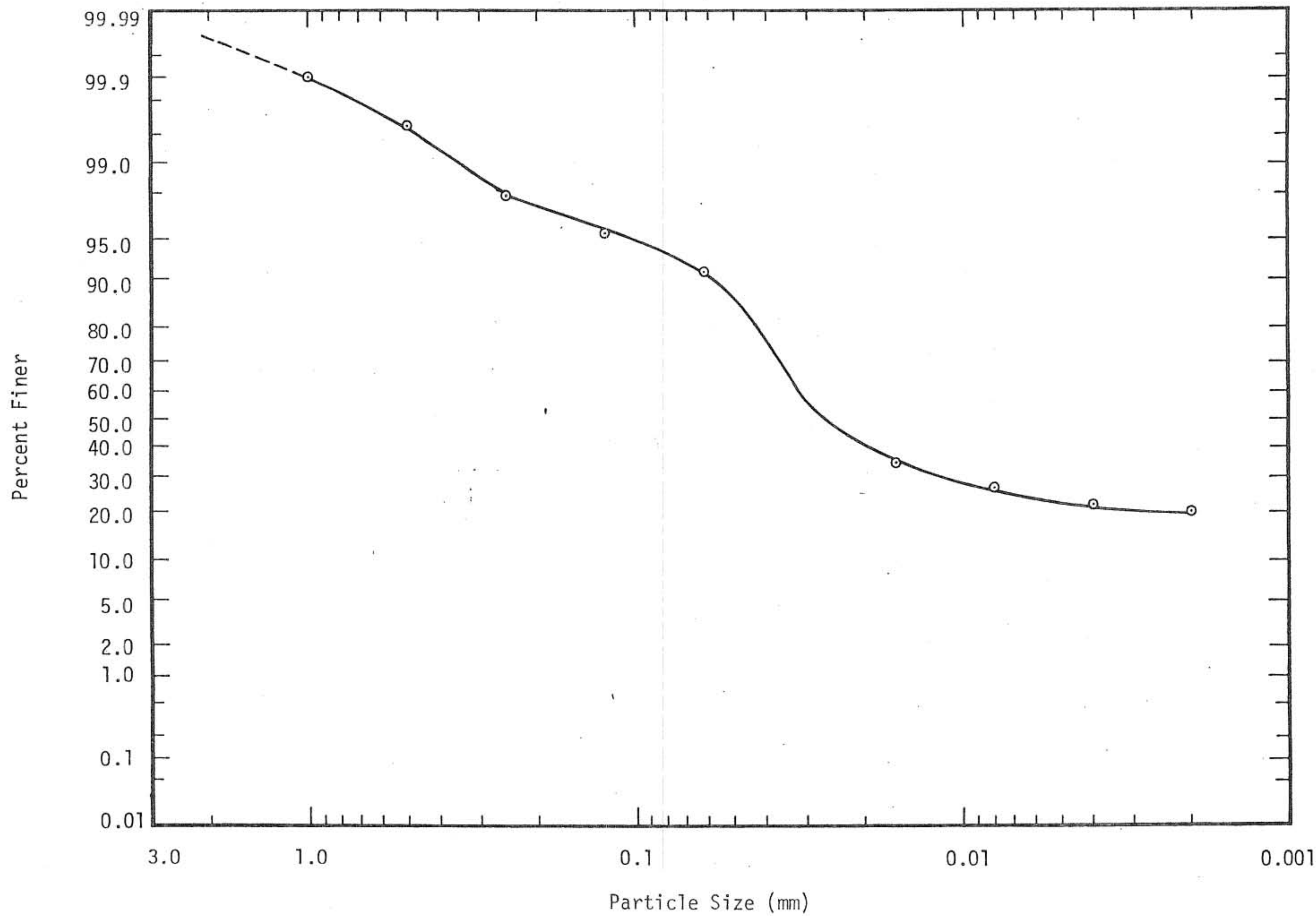

Figure 7. Sediment Size Distribution Curve from Soil Samples for Lawson Creek Tributary Number 1

size from the distribution curve (Fig. 7) may be, and just how great an influence this arbitrary selection may have on the estimated channel sediment transport capacity.

A more reasonable approach would be to relate f_{min} to the effective roughness height, k_s, of the composite bed material. By defining f_{min} as

$$f_{min} = 0.75/[1.69 + 2 * \log(2 * R/k_s)]^2 \qquad (12)$$

(i.e., one half the resistance factor for the effective roughness height for the bed material), the calculation of the effective shear stress is no longer dependent on the largest sizes of the sediment size distribution.

The definition of the effective roughness height, k_s, for a movable plane bed made up of a mixture of sediment sizes has been a widely studied and debated topic. Einstein (8) reported that comparative flume experiments have shown that the representative grain diameter of a sediment mixture is given by that sieve size of which 65 percent of the mixture (by weight) is finer (i.e., D_{65}). However, more recent studies of mixed sediment size beds for both laboratory and field data indicate k_s to be much larger than D_{65}. These studies have sought to determine k_s as a function of a representative particle size from the sediment size distribution such that the velocity distribution equations proposed by Keulegan (15) are obeyed.

$$V_p/u_* = 5.75 \log(y/k_s) + 8.5 \qquad (13)$$

where V_p = the point velocity at a distance y from the boundary,

u_* = the shear velocity of the flow (= $\sqrt{gRS}$)

for fully turbulent flow over hydraulically rough surfaces (i.e., closely packed sand grains), or

$$V/u_* = 5.75 \log(R/k_s) + 6.25 \tag{14}$$

for fully turbulent flow in hydraulically rough rectangular and polygonal channels.

Rijn (23) examined 120 sets of flume (for both fixed and movable bed experiments) and field data with plane bed conditions. He chose to relate D_{90} to k_s and plotted k_s/D_{90} versus the particle mobility number $\tau' - \tau_{CR}$, where τ_{CR} is the critical shear stress from Shield's diagram. He found that the scatter in the data is large and the influence of the particle mobility number cannot be detected, hence fixed bed information should be relevant to movable bed cases. He suggested an average value of $k_s = 3D_{90}$ could be used. Kamphius (14) examined 12 sets of flume data with fixed beds and found k_s/D_{90} to range between 1.5 and 2.5 with $k_s = 2D_{90}$ a reasonable approximation for use. Burkham and Dawdy (4) developed a curve which related the representative particle size, D_n, to the value of C in

$$V/u_* = 5.75 \log(R/D_n) + C \tag{15}$$

If it is desired to maintain the form of Eq. 14, the deviation of C from 6.25 can be accounted for within the logarithmic term. Doing this it was found that $k_s \approx 2.65D_{90}$ or $3.32D_{84}$ based on Burkham and Dawdy's work. Finally, Hey (10) concluded that $k_s = 3.5D_{84}$ was a reasonable approximation based on his analysis of some of the same data used by Burkham and Dawdy (4) and of empirical Colebrook-White type flow resistance equations developed for various channel shapes.

While this review of literature on relating the value of k_s to a representative particle size is far from exhaustive, it does provide some insight into the nature of these relations. For the purpose of this report it was decided to use $k_s = 3D_{90}$ in the calculation of f_{min}. This choice was made because $3D_{90}$ seemed to be a reasonable compromise from among the relations reported. However, further research and literature review is recommended in order to determine a true consensus as to the representative value of k_s. Finally, it should be noted that based on experience gained in the calibration work performed for this report, the final selection of k_s as a function of D_{90} or D_{84} or whatever should not greatly affect the validity of these calibration results unless k_s is chosen to be significantly different from $3D_{90}$.

Table 14 displays the results of using this definition f_{min} ("k_s = 3D90" column) and the corrected Einstein relations to calculate the channel sediment transport capacity for a good hydrologic fit of the June 29, 1983 storm on LCT-1. In Table 14 it can be seen (in the "$k_s = D_{max}$" column) that the suggested Einstein procedure helps reduce some of the variability due to particle size selection, but only when the k_s correction is also incorporated does the sediment yield become independent of the largest sizes. It is clear that using the changes recommended here the channel transport capacity: (1) is no longer a function of the maximum sediment size, and (2) is still a reasonable value.

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APPENDIX A

Computer Subroutines for Formal Hydrograph Calibration

The following pages display the hydrologic portion of MSED1 converted into a series of subroutines and the subroutines necessary to interface the hydrologic portion of MSED1 with GRG for formal hydrograph calibration. The calibration may be performed in the following fashion on the CDC Cyber at the University of Illinois:

1. Convert the program to a binary code:

   /R.FTN,I=file name of program, e.g., CALIB,B=chosen name for the binary file, e.g., BCALIB,L=0

that is

   /R.FTN,I=CALIB,B=BCALIB,L=0

2. Get binary form of GRG

   /GET,BGRG/UN=3PML8R4

3. Run the program

   /R. (rewind all files)

   /P.LOAD(BCALIB,BGRG);EXECUTE

The program will then request the user to input initial values for each of the six parameters to be calibrated, i.e., K_H, $-\psi$, VG, VC, ADW, and n, in that order. The program will also ask the user to input the desired level of detail on the GRG iterations with 0 being little detail and 4 being the greatest detail. Such information is generally of little importance for calibration and so the 0 level should be chosen. Figure A.1 displays an example run of the calibration program.

The calibration program requires four data tapes named TAPE51, TAPE52, TAPE53, and TAPE54 to be in the user's local file space. Examples of each of these data files are presented after the sample output in Fig. A.1.

TAPE51: TAPE1 used in MSED1 with the sediment relation data, lines 13 and 14 (28), removed.

TAPE52: TAPE2 used in MSED1 only with the title input in the first 8 lines at 10 characters per line instead of all in the first line.

For both TAPE51 and TAPE52 all integer variables must be right justified.

TAPE53: contains the measured flow data with line 1 containing the number of flow data points (integer) and the magnitude of the time shift (real) in a free format. The following lines of TAPE53 contain the time from the beginning of the storm event and the discharge at that time, respectively, in a 2F10.0 format.

TAPE54: contains the upper and lower bounds for the parameters. Line 1 contains the number of parameters to be calibrated, i.e., 6. The following lines contain the lower and upper bounds, respectively, for K_H, $-\psi$, VC, VG, ADW, and n (in this order) in a 2F20.10 format.

Finally, it should be noted that in order to properly perform the calibration it was necessary to rescale the values of $-\psi$ and ADW. When the reduced gradient is calculated small steps in each parameter are taken, however, when the scale of a parameter is much greater than the scales for the others its variations may seem to be relatively unimportant and hence it will stay near its initial value and not be calibrated. ADW is on the order of 10^4 and $-\psi$ is on the order of 10^1 while all the others are on the order of 10^{-1} or 10^{-2}. Hence by dividing ADW by 100,000 and $-\psi$ by 10 their scales are on equivalent orders with the other parameters, and the small steps taken by GRG will define realistic gradients. For several calibration runs the final values of $-\psi$ and ADW varied greatly from their initial values, and so the chosen rescaling ratios have served their purpose.

Figure A.1 Sample Run and Results of GRG based Hydrograph Calibration Program (including example data files)

```
/R.
/P.LOAD(BCAL2,BGRG);EXECUTE
GENERALIZED REDUCED GRADIENT ALGORITHM
LAST MODIFIED, JANUARY 1983

WARNING: GRG HAS A BUILT-IN GRADIENT SUBROUTINE NAMED
PARSH, SO THE GRADIENT SUBROUTINE SETUP BY SETP
IS IGNORED. THE GRG STEPSIZE USED FOR X(I) IS
MAX( 1.E-5*X(I), 1.E-5)

STORM EVENT OF  JUNE  6, 1984 ON LAWSON CREEK TRIB NO 1(MOD AREA = 2.8 AC)
MIN
SUM OF SQUARES DIFF: CALCULATED VS. OBSERVED FLOWS
S.T.
.1.LE.WET K.LE.1.
.5.LE.SAVE .LE.4.
.01.LE.VGCOV.LE..05
.01.LE.VCCOV.LE..05
.0036.LE. ADW .LE..1
.05.LE.  N  .LE..1
INPUT INITIAL X VALUES
? 0.15  3.0  0.03  0.04  0.08  0.08
PRINT LEVEL(0 THRU 4)
0 PROVIDES ONLY MINIMAL INFORMATION
4 PROVIDES THE MOST INFORMATION
? 0

KUHN-TUCKER CONDITIONS SATISFIED

THE OBJECTIVE FUNCTION IS 2.861023413831
VAR 1 = .1184509625546
VAR 2 = 1.977516059446
VAR 3 = .05
VAR 4 = .04
VAR 5 = .1
VAR 6 = .0967498253301

199 OBJECTIVE FUNCTION EVALUATIONS
0 CONSTRAINT EVALUATIONS
     1.000      0.000
     2.000      0.000
     3.000      0.000
     4.000      0.000
     5.000      0.000
     6.000      0.000
     7.000      0.000
     8.000      0.000
     9.000      0.000
    10.000      0.000
    11.000       .000
    12.000       .003
```

Figure A.1 (continued)

```
   13.000      .043
   14.000      .244
   15.000      .633
   16.000     1.150
   17.000     1.842
   18.000     2.602
   19.000     3.264
   20.000     3.481
   21.000     3.244
   22.000     2.879
   23.000     2.466
   24.000     2.068
   25.000     1.724
   26.000     1.452
   27.000     1.235
   28.000     1.063
   29.000      .927
   30.000      .816
   31.000      .723
   32.000      .648
   33.000      .584
   34.000      .529
   35.000      .481
   36.000      .441
   37.000      .406
   38.000      .374
   39.000      .347
   40.000      .323
   41.000      .301
   42.000      .281
   43.000      .264
   44.000      .248
   45.000      .234
   46.000      .221
   47.000      .209
   48.000      .198
   49.000      .188
   50.000      .179
 DO YOU WANT ANOTHER RUN?
? NO
 MORE DETAILED OUTPUT IN LOCAL FILE NAMED PRINT
$REVERT.  PDOT
/
```

Figure A.1 (continued)

Typical TAPE51 Data File for Use with the GRG Based Optimization Program

```
Blank Line
 LAWSON CREEK TRIBUTARY NUMBER 1 (MODIFIED); SHEFFIELD, IL. JUNE 6, 1984
SUBWAT 1             2
0.10       0.45      0.65      1.0       16.403
0.10       0.45      0.65      1.0       16.403
0.0        0.0       85.0      0.03
0.0        0.0       40.0      0.03
0.167      201.5
0.0808     81.4
0.0273     440.
     16 70.     0.10           0.0       0.0       0.0       0.0       5363.2
1.20       1.0
3.60       2.00
1.80       3.00
0.60       4.00
0.24       9.00
3.60       10.0
6.00       12.0
4.80       13.0
3.00       14.0
3.60       15.0
3.00       16.0
0.60       20.0
0.30       28.0
0.0545     39.0
0.0857     46.0
0.30       50.0
```

Typical TAPE52 Data File for Use with the GRG Based Optimization Program

```
 STORM EVE
NT OF   JUN
E 6, 1984
 ON LAWSON
 CREEK TRI
B NO 1(MOD
 AREA = 2.
8 AC)
1.00       50.00
        0        1
        1        2        1
```

Figure A.1 (continued)

Typical TAPE53 Data File for Use with the GRG Based Optimization Program

```
34   5.0
17.0          0.118
18.0          0.259
19.0          1.010
20.0          1.260
21.0          1.340
22.0          2.210
23.0          2.900
24.0          2.990
25.0          2.990
26.0          2.900
27.0          2.590
28.0          2.400
29.0          2.120
30.0          1.950
31.0          1.770
32.0          1.600
33.0          1.430
34.0          1.340
35.0          1.180
36.0          1.010
37.0          0.845
38.0          0.770
39.0          0.700
40.0          0.608
41.0          0.525
42.0          0.387
43.0          0.330
44.0          0.330
45.0          0.201
46.0          0.201
47.0          0.155
48.0          0.118
49.0          0.118
50.0          0.089
```

Typical TAPE54 Data File for Use with the GRG Based Optimization Program

```
6
0.10                  1.0
0.5                   4.0
0.01                  0.05
0.01                  0.05
0.0036                0.10
0.05                  0.10
```

Subroutines for Combining MSED1 with GRG for Hydrograph Calibration

```
      SUBROUTINE INIT(TITLE,N,ME,MI,MXMN)
      DIMENSION TITLE(8)
      COMMON/ZZZZST/NOBJ,NCNST,M1,M2
      COMMON/DATA/DTIMTR,FTIMTR,NPL,NWS,ISEG(75),ITYPE(75),IPRINT(75)
     $ ,NUMP
      COMMON/DFLOW/NDATA,TIMED(200),FLOW(200)
      COMMON/BOUND/XL(20),XU(20)
      READ(52,68) (TITLE(I),I=1,8)
 68   FORMAT(A10)
      PRINT 910, (TITLE(I),I=1,8)
 910  FORMAT(8A10)
      NOBJ=0
      NCNST=0
      N= 6
      ME= 0
      MI= 0
      M1=ME
      M2=MI
      READ(54,*) ND
      DO 769 I = 1,ND
 769  READ(54,770) XL(I),XU(I)
 770  FORMAT(2F20.10)
      MXMN="MIN"
      PRINT *, "MIN"
      PRINT *,"SUM OF SQUARES DIFF: CALCULATED VS. OBSERVED FLOWS"
      PRINT *,"S.T."
      PRINT *, XL(1)   ,".LE.WET K.LE.", XU(1)
      PRINT *, XL(2)   ,".LE.SAVE .LE.", XU(2)
      PRINT *, XL(3)   ,".LE.VCCOV.LE.", XU(3)
      PRINT *, XL(4)   ,".LE.VCCOV.LE.", XU(4)
      PRINT *, XL(5)   ,".LE. ADW .LE.",XU(5)
      PRINT *, XL(6)   ,".LE.  N  .LE.", XU(6)
C
      CALL INPUT
C
C  READ IN THE TIME INCREMENT AND THE FINAL TIME FOR THE HYDROGRAPH
C
      READ(52,4002) DTIMTR,FTIMTR
 4002 FORMAT(2F10.0)
C
C  READ THE NUMBER OF PLANES (NPL) AND THE NUMBER OF SMALL
C      WATERSHEDS (NWS)
C
      READ(52,1000) NPL,NWS
 1000 FORMAT(3I10)
C
C  READ IN TYPE ARRAY TO IDENTIFY THE TYPE OF UNITS
C
      NUMP = NPL+NWS
      DO 104 I = 1,NUMP
 104  READ(52,1000) ISEG(I),ITYPE(I),IPRINT(I)
C
C  READ ACTUAL HYDROGRAPH DATA
C
      READ(53,*) NDATA,TIMOFF
      DO 69 I = 1,NDATA
      READ(53,*) TIMED(I),FLOW(I)
 69   TIMED(I) = TIMED(I)-TIMOFF
      RETURN
      END
C
C   CALCULATE THE SUM OF SQUARES DIFFERENCE BETWEEN
C      MEASURED AND SIMULATED HYDROGRAPHS
      SUBROUTINE OBJF(X,F)
      DIMENSION X(20),TIME(200),HYDROG(200)
      COMMON/ZZZZST/NOBJ,NCNST,M1,M2
      COMMON/DFLOW/NDATA,TIMED(200),FLOW(200)
      CALL MSED1(X,TIME,HYDROG)
      K = 1
      SUMSQ = 0.0
      DO 969 I = 1,200
      TP = TIME(I) + 0.5
      IF (TP .LT. TIMED(K))GO TO 969
      DIFF = HYDROG(I)-FLOW(K)
      SUMSQ = SUMSQ + DIFF*DIFF
      K = K+1
      IF (K .GT. NDATA) GO TO 970
 969  CONTINUE
 970  NOBJ=NOBJ+1
      F=SUMSQ/TP
      RETURN
      END
      SUBROUTINE CONST(X,G)
      DIMENSION X(20),G(20)
      COMMON/ZZZZST/NOBJ,NCNST,M1,M2
      NCNST=NCNST+1
      RETURN
      END
      SUBROUTINE BOUNDS(XL,XU)
      DIMENSION XL(20),XU(20)
      COMMON/BOUND/XLOW(20),XUP(20)
      DO 69 I =1,6
      XL(I) = XLOW(I)
 69   XU(I) = XUP(I)
      RETURN
      END
      SUBROUTINE GRAD(X,FGRAD,CGRAD)
      DIMENSION X(20),FGRAD(20),CGRAD(20,20),GG(20),G(20)
      CALL OBJF(X,F)
      DO 10 J=1,  7
      X(J)=X(J)+ .10000E-03
      CALL OBJF(X,FF)
      FGRAD(J)= (FF-F)/ .10000E-03
 10   X(J)=X(J)- .10000E-03
      RETURN
      END
      SUBROUTINE REPORT(X,F)
      DIMENSION X(20),TIME(200),HYDROG(200)
      COMMON/ZZZZST/NOBJ,NCNST,M1,M2
      COMMON/DATA/DTIMTR,FTIMTR,NPL,NWS,ISEG(75),ITYPE(75),IPRINT(
     $ ,NUMP
      PRINT *,NOBJ," OBJECTIVE FUNCTION EVALUATIONS"
      NCNST=NCNST*(M1+M2)
      PRINT *,NCNST," CONSTRAINT EVALUATIONS"
      CALL MSED1(X,TIME,HYDROG)
      NH = INT(FTIMTR/DTIMTR + 0.5)
      DO 69 I = 1,NH
 69   PRINT 70,  TIME(I),HYDROG(I)
 70   FORMAT(2F10.3)
      RETURN
      END
      SUBROUTINE MSED1(X,TIME,HYDROG)
      DIMENSION QDUM(200),TIME(200),HYDROG(200),X(6)

      COMMON/SOIL/WET K(2),POROS(2),SAVE(2),SW(2),SI(2),XN,ADW,C
      COMMON/DATA/DTIMTR,FTIMTR,NPL,NWS,ISEG(75),ITYPE(75),IPRINT(75)
     $ ,NUMP
      COMMON/COVER/GRNCOV(2),CANCOV(2),VG(2),VC(2),FIMP(2),SLOOSE(2)
C
C     --- INITIALIZE VARIABLES.
C
      DO 59 I = 1,2
      WET K(I) = X(1)/60.
      SAVE(I) = X(2)*10.
      VG(I) = X(3)
 59   VC(I) = X(4)
      ADW = X(5)*100000.
      XN = X(6)
      TUP = 0.0
      TIN = 0.0
      TOUT=0.0
      TRVOL=0.0
      TVINTR = 0.0
      TAREA = 0.0
      DO 101 I=1,200
        QDUM(I)=0.0
  101 CONTINUE
C
C
C     --- CONVERT TIMES TO SECONDS
C
      DTIM=DTIMTR*60.
      FTIM=FTIMTR*60.
C
C     --- CALCULATE NUMBER OF INCREMENTS IN HYDROGRAPH.
C
      NUM=IFIX(FTIM/DTIM)+1
C
C
       DO 109 K1=1,NUMP
         DO 110 K2=1,NUM
           QDUM(K2)=0.0
  110    CONTINUE
         T1=0.
         T2=0.
         T3=0.
C
C
         IF (ITYPE(ISEG(K1)).EQ.2) GO TO 12
C
C     --- THIS IS THE ONE PLANE CASE.
C
         CALL ANAWAT(ISEG(K1),DTIM,FTIM,QDUM,T1,T2,T3,QT,NUM)
         GO TO 109
C
C     --- THIS IS THE SUBWATERSHED (2-PLANES ? 1 CHANNEL)
C     --- CASE.
C
 12      CALL ANAWAT(ISEG(K1),DTIM,FTIM,QDUM,T1,T2,T3,QT,NUM)
  109 CONTINUE
      DO 69 I = 1,NUM
      TIME(I) = DTIM*FLOAT(I)/60.
 69   HYDROG(I) = QDUM(I)
      END
      SUBROUTINE ANAWAT(IFILE,DTIM,FTIM,QOUT,TVINTR,TAREA,TRVOL,QT,NUM)
C
C
C     --- PARAMETER DEFINITIONS
C             IFILE  = SUBUNIT NUMBER.
C             DTIM   = TIME INCREMENT FOR HYDROGRAPH.
C             FTIM   = FINAL TIME OF HYDROGRAPH.
C             QOUT   = ARRAY OF THE RESULTING DISCHARGES.
C             TVINTR = TOTAL VOLUME OF INTERCEPTION IN FT**3.
C             TAREA  = TOTAL AREA IN FT**2.
C             TRVOL  = TOTAL VOLUME OF RAINFALL IN FT**3.
C
C
      DIMENSION EXCES(200),EXCEST(200),RAIN(200),OUTTIME(200),RT(200),
     +QLT(200),QLTIME(200),QL(200,2),QOUT(200)
      COMMON/COVER/GRNCOV(2),CANCOV(2),VG(2),VC(2),FIMP(2),SLOOSE(2)
      COMMON/DEPTH/Y(200)
      COMMON/DATA2/IPLANE,RAINOLD(200),RAINT(200),NRAINTR,PLENGTH(3),
     $ SLOPE(3),T,A1,B1,A2,B2
      COMMON/SOIL/WET K(2),POROS(2),SAVE(2),SW(2),SI(2),XN,ADW,C
C
C     --- INITIALIZE VARIABLES.
C
      CHECK=0.0
      TRVOL=0.0
      TAREA = 0.0
      TVINTR = 0.0
      ICHECK = 0
      ERR = 0.0
      QT=0.0
      DO 101 I=1,200
        QL(I,1)=0.0
        QL(I,2)=0.0
        QOUT(I) = 0.0
        QLT(I) = 0.0
        QLTIME(I) = 0.0
      Y(I)=0.0
  101 CONTINUE
      DO 313 I=1,10
  313 CONTINUE
      NR=NRAINTR
C
C     --- CALCULATE VISCOSITY AND CORRECT HYDRAULIC CONDUCTIVITY
C     --- FOR TEMPERATURE.
C
      CALL TEMP(T,VISCO, IPLANE)
C
C     --- CALCULATE TOTAL INCHES OF RAINFALL.
C
      TRINCH=RAINOLD(1)*RAINT(1)
      DO 100 I=2,NRAINTR
        TRINCH=RAINOLD(I)*(RAINT(I)-RAINT(I-1))+TRINCH
  100 CONTINUE
C
C     --- THE FOLLOWING LOOP CALCULATES THE EXCESS OF EACH
```

```
C      --- PLANE AND ROUTS THE EXCESS ON EACH PLANE.
C
       DO 102 I=1,IPLANE
C
C       --- CALCULATE AREA OF PLANE (AREA).
C
        AREA=PLENGTH(I)*PLENGTH(3)
        TAREA=TAREA+AREA
C
C       --- CALCULATE RAINFALL VOLUME.
C
        TRVOL=TRVOL+AREA*TRINCH/12.
C
C       --- INITIALIZE RAIN ARRAY EQUAL TO RAINOLD ARRAY.
C
        NRAIN=NR
        DO 103 J=1,NRAIN
          RAIN(J)=RAINOLD(J)
          RT(J)=RAINT(J)
  103   CONTINUE
        DO 113 J=1,200
          EXCEST(J)=0.0
          EXCES(J)=0.0
  113 CONTINUE
C
C       --- CALCULATE THE INTERCEPTION
C
        CALL INTRCP(ERR,RAIN,RT,NRAIN,VINTR,I)
        TVINTR=TVINTR+VINTR*AREA/12.
        IF(ERR.EQ.0.0) GO TO 10
C
C       --- PRINT KNOWN VARIABLES TO TRACE POSSIBLE ERROR.
C
        WRITE(6,992) IFILE,I
  992   FORMAT(/",TRACE BACK INFORMATION",/,"UNIT NUMBER=",I3,
     +  " I=",I2/,"(NOTE:  I=1 MEANS LEFT PLANE, I=2 MEANS ",
     +  "RIGHT PLANE)")
        ERR=0.0
        GO TO 50
C
C       --- CALCULATE THE INFILTRATION.
C
   10   CALL CUTOFF(ERR,EXCES,EXCEST,NEX,RAIN,RT,NRAIN,
     +  I,FTIM)
        IF(ERR.EQ.0.0.OR.FIMP(I).GT.0.0) GO TO 20
C
C       --- PRINT KNOWN VARIABLES TO TRACE POSSIBLE ERROR.
C
        WRITE(6,992) IFILE,I
        ERR=0.0
C
C       --- FOR THE CASE WHEN THE TOTAL RAINFALL IS COMPLETELY
C       --- INTERCEPTED AND/OR INFILTRATED.
C
   50 IF(IPLANE.EQ.1) RETURN
        ICHECK=ICHECK+1
        IF(ICHECK.EQ.2) RETURN
        DO 104 IT=1,200
          QL(IT,I)=0.0
  104 CONTINUE
        GO TO 102
C
C       --- CONVERT UNITS OF EXCESS RAINFALL IN/MIN TO FT/SEC
C       --- AND UNITS OF TIME FROM MIN. TO SEC.
C
   20 NNEX=NEX-1
        DO 105 J=2,NNEX
      EXCES(J)=(EXCES(J)*(1.-FIMP(I))+RAIN(J-1)*FIMP(I))/720.
        EXCEST(J)=EXCEST(J)*60.
  105 CONTINUE
      EXCES(NEX)=EXCES(NEX)*(1.-FIMP(I))/720.
      EXCEST(NEX)=EXCEST(NEX)*60.
C
C       --- DEFINE B. B IS USED IN THE EQUATION Q=A*Y**B.
C       --- B=3.0 FOR THE CASE OF OVERLAND FLOW.
C
        B=3.0
C
C       --- DEFINE A. A IS USED IN THE EQUATION Q=A*Y**B.
C       --- FOR OVERLAND FLOW A IS A FUNCTION OF THE GROUND
C       --- COVER, SLOPE, AND VISCOSITY OF WATER.
C
        R=100.+(ADW-100.)*(GRNCOV(I)/100.)**2.
        G=32.174
        A=8.*SLOPE(I)*G/(R*VISCO)
C
C       --- CALL THE FORWARD ROUTING PROCEDURE.
C
        CALL FORWARD(A,B,PLENGTH(I),EXCES,EXCEST,NEX,OUTTIME,TSTOP,FTIM
     +,CHECK)
        IF(IPLANE.EQ.2) GO TO 60
        CALL BACK(A,B,PLENGTH(I),DTIM,TSTOP,OUTTIME,EXCEST,EXCES,
     +  QOUT,NEX,CHECK)
      QT=0.0
      DO 201 JJ=2,NUM
        QT=QT+(QOUT(JJ)+QOUT(JJ-1))/2.
  201 CONTINUE
      QT=QT*PLENGTH(3)*DTIM/43560.
        RETURN
   60 CALL BACK(A,B,PLENGTH(I),DTIM,TSTOP,OUTTIME,EXCEST,
     +  EXCES,QL(1,I),NEX,CHECK)
  102 CONTINUE
C
C       --- TO ROUT THE CHANNEL CALL QLAT TO SUM THE LATERAL
C       --- INFLOWS.
C
        NQ=IFIX(FTIM/DTIM)
      CALL QLAT(QL,QLT,QLTIME,DTIM,NQ)
C
      IF(A1.NE.0.0) GO TO 215
C       --- DEFINE B1. B1 IS USED IN THE EQUATION WP=A1*AREA**B1
C       --- FOR A CHANNEL WITH A TRIANGULAR CROSS SECTION B1=0.5.
C
      B1=0.5
C
C       --- DEFINE A1. A1 IS USED IN THE EQUATION WP=A1*AREA**B1
C       --- FOR A CHANNEL WITH TRIANGULAR CROSS SECTION A1 IS
C
      A1=((2./((1./SLOPE(1))+(1./SLOPE(2))))**0.5)*
     +((1.+(1./SLOPE(1)**2))**0.5+(1.+(1./SLOPE(2)**2))**0.5)
C
C     --- DEFINE B2. B2 IS USED IN THE EQUATION T=A2*AREA**B2.
C     --- FOR A CHANNEL WITH TRIANGULAR CROSS SECTION B2=0.5
C
          B2 = 0.5
C
C     --- DEFINE A2. A2 IS USED IN THE EQUATION T=A2*AREA**B2.
C     --- FOR A CHANNEL OF TRIANGULAR CROSS SECTION A2 IS
C
          A2 = SQRT(2./SLOPE(1)+2./SLOPE(2))
  215 CONTINUE
      CALL RESIST(C,XN,A1,B1,A,B,SLOPE(3))
C
C       --- ROUT CHANNEL.
C
        CHECK=1.
      CALL FORWARD(A,B,PLENGTH(3),QLT,QLTIME,NQ,OUTTIME,TSTOP,FTIM
     +,CHECK)
      CALL BACK(A,B,PLENGTH(3),DTIM,TSTOP,OUTTIME,QLTIME,QLT,
     +QOUT,NQ,CHECK)
      QT=0.0
      DO 205 JJ=2,NUM
      QT =QT+(QOUT(JJ-1)+QOUT(JJ))/2.
  205 CONTINUE
      QT=QT*DTIM/43560.
  109 CONTINUE
      RETURN
      END
C
C
C     **********************************************************
C
C
      SUBROUTINE INPUT
C
C       --- THIS SUBROUTINE READS WATERSHED DATA FOR THE
C       --- SUBROUTINE ANAWAT.  DATA IS READ FROM THE FILE
C       --- WITH UNIT NUMBER = 1.
C
C       --- PARAMETER DEFINITIONS.
C            IPLANE = INDICATOR OF WHETHER 1-PLANE OR 2-PLANES
C                     AND 1 CHANNEL IS IN THIS PARTICULAR WATER-
C                     SHED.
C           RAINOLD=ARRAY OF RAINFALL INTENSITIES FOR THE STORM.
C           RAINT  = ARRAY OF FINAL TIMES CORRESPONDING TO THE
C                    RAINFALL INTENSITIES.
C           NRAIN  = NUMBER OF RAINFALL INCREMENTS (INTENSITIES).
C           PLENGTH= ARRAY OF PLANE ? CHANNEL LENGTHS.
C           SLOPE  = ARRAY OF PLANE? CHANNEL SLOPES.
C           T      = TEMPERATURE OF WATER.
C
C
      DIMENSION RAINOLD(200),RAINT(200),PLENGTH(3),SLOPE(3)
     +,P(11),D(11),DPRES(3),PIMP(2)
      COMMON/COVER/GRNCOV(2),CANCOV(2),VG(2),VC(2),FIMP(2),SLOOSE(2)
      COMMON/SOIL/WET K(2),POROS(2),SAVE(2),SW(2),SI(2),XN,ADW,C
      COMMON/VAR1/TITL
      COMMON/DATA2/IPLANE,RAINOLD(200),RAINT(200),NRAINTR,PLENGTH(3),
     & SLOPE(3),T,A1,B1,A2,B2
C
C       --- READ NUMBER OF PLANES.
C
      READ(51,1000)TITL,IPLANE
 1000 FORMAT(//,A10,I10)
C
C       --- FOR EACH PLANE READ HYDRAULIC CONDUCTIVITY,
C       --- SOIL POROSITY, INITIAL SOIL SATURATION, FINAL
C       --- SOIL SATURATION AND AVERAGE SUCTION
C
      DO 100 I=1,2
        READ(51,2000)WET K(I),POROS(I),SI(I),SW(I),SAVE(I)
 2000 FORMAT(6F10.0)
C
C       --- CHANGE HYDRAULIC CONDUCTIVITY TO UNITS OF IN/MIN.
C
        WET K(I)= WET K(I)/60.
  100 CONTINUE
C
C       --- READ IN CANOPY AND GROUND COVER DATA FOR EACH PLANE.
C
      READ(51,3000) (CANCOV(I),VC(I),GRNCOV(I),VG(I),
     + PIMP(I),SLOOSE(I),I=1,2)
      FIMP(1)=PIMP(1)/100.
      FIMP(2)=PIMP(2)/100.
 3000 FORMAT(6F10.0)
C
C       --- READ IN SLOPE AND LENGTH OF EACH PLANE.
C
      READ(51,4000) (SLOPE(I),PLENGTH(I),DPRES(I),I=1,3)
 4000 FORMAT(3F10.0)
      PLENGTH(1)=PLENGTH(1)*(1.-DPRES(1))
      PLENGTH(2)=PLENGTH(2)*(1.-DPRES(2))
C
C
      READ(51,5000)NRAINTR,T,XN,C,A1,B1,A2,B2,ADW
 5000 FORMAT(I8,8F9.2)
C
C       --- READ IN STORM RAINFALL DATA.
C
      DO 200 I=1,NRAINTR
        READ(51,6000) RAINOLD(I),RAINT(I)
 6000 FORMAT(2F10.0)
C
C       --- CONVERT INTENSITY FROM IN/HR TO IN/MIN.
C
        RAINOLD(I)=RAINOLD(I)/60.
  200 CONTINUE
      RETURN
      END
C
C
C     **********************************************************
C
C
      SUBROUTINE TEMP(T,VISCO,IPLANE)
C
C       --- THIS SUBROUTINE CORRECTS THE VISCOSITY AND
C       --- HYDRAULIC CONDUCTIVITY FOR TEMPERATURE VARIATIONS
C       --- FROM THE ASSUMED TEMPERATURE OF 68 DEGREES (F).
C
```

```
C      --- PARAMETER DEFINTIONS.
C            T      = TEMPERATURE IN DEGREES F.
C            VISCO  = KINEMATIC VISCOSITY (FT**2/SEC)
C            IPLANE = NUMBER OF PLANES.
C
C
      COMMON/SOIL/WET K(2),POROS(2),SAVE(2),SW(2),SI(2),XN,ADW,C
      DIMENSION TE(10),V(10)
      DATA TE/32.,40.,50.,60.,68.,80.,90.,100.,120.,140./,
     +V/1.93,1.66,1.41,1.22,1.09,0.930,0.826,0.739,0.609,
     +0.514/
C
C      --- CALCULATE NEW VISCOSITY BY INTERPOLATION.
C
      DO 100 I=1,10
       IF (TE(I).LT.T) GO TO 100
       FAC1=(T-TE(I-1))/(TE(I)-TE(I-1))
       VISCO=V(I-1)+FAC1*(V(I)-V(I-1))
       GO TO 10
  100 CONTINUE
C
C      --- ADJUST THE HYDRAULIC CONDUCTIVITY.
C
   10 FAC2=VISCO/1.09
      DO 101 J=1,IPLANE
       WET K(J)=WET K(J)/FAC2
  101 CONTINUE
      VISCO=VISCO*.00001
      RETURN
      END
C
C      ***************************************************************
C
C
C
      SUBROUTINE INTRCP(ERR,RAIN,RAINT,NRAIN,VINTR,IPL)
C
C      --- THIS SUBROUTINE DETERMINES THE VOLUME OF
C      --- INTERCEPTED RAINFALL.  INTERCEPTION DEPENDS
C      --- ON THE PERCENTAGE OF THE GROUND THAT IS
C      --- COVERED BY (CANCOV) AND GROUND (GRNCOV).  AND
C      --- THEIR RESPECTIVE WATER HOLDING CAPACITIES(VC,VG).
C      --- TOTAL INTERCEPTED VOLUME = VINTR.
C
C      --- PARAMETER DEFINITIONS.
C            ERR    = ERROR INDEX.
C            RAIN   = ARRAY OF RAINFALL INTENSITIES.
C            RAINT  = ARRAY OF FINAL TIMES FOR EACH RAINFALL
C                     INTENSITY.
C            NRAIN  = NUMBER OF RAINFALL INTENSITIES.
C            VINTR  = TOTAL AMOUNT OF RAINFALL INTERCEPTED IN INCHES.
C            IPL    = INDICATOR OF WHICH PLANE THE EXCESS IS
C                     BEING CALCULATED.
C
C
      DIMENSION R OLD(200),RAIN(NRAIN),RAINT(NRAIN),RTOLD(200)
      COMMON/COVER/GRNCOV(2),CANCOV(2),VG(2),VC(2),FIMP(2),SLOOSE(2)
C
C      --- THE R OLD IS AN ARRAY WHICH TEMPORARILY STORES THE
C      --- STORM INTENSITIES. OPERATIONS ARE DONE ON THE R OLD
C      --- ARRAY TO OBTAIN AN ARRAY WHICH EQUALS THE TOTAL
C      --- RAINFALL MINUS THE RAINFALL THAT IS LOST BY
C      --- INTERCEPTION.
C
C      --- INITIALIZE R OLD ARRAY EQUAL TO RAIN ARRAY.
C
      DO 100 I=1,NRAIN
       R OLD(I)= RAIN(I)
       RTOLD(I)=RAINT(I)
  100 CONTINUE
C
C      --- CALCULATE TOTAL INTERCEPTED VOLUME OF RAINFALL.
C
      VGC=GRNCOV(IPL)*VG(IPL)/100.
      VCC=CANCOV(IPL)*VC(IPL)/100.
      VINTR =VGC+VCC
      VRAIN = 0.
C
C      --- THE RAINFALL LOST TO INTERCEPTION IS SUBTRACTED
C      --- FROM THE TOTAL RAINFALL.
C
      DO 101 I=1,NRAIN
       IF(I.EQ.1) GO TO 10
       VRAIN =VRAIN+R OLD(I)*(RAINT(I)-RAINT(I-1))
       GO TO 11
   10 VRAIN = VRAIN+R OLD(1)*RAINT(1)
   11 IF(VRAIN.GT.VINTR) GO TO 12
       RAIN(I) = 0.
  101 CONTINUE
      GO TO 13
   12 DRV =VRAIN-VINTR
      DT=DRV/RAIN(I)
      IF(I.EQ.1) GO TO 14
      RAINT(I-1)=RAINT(I)-DT
      RETURN
   14 RAIN(1)=0.0
      RAINT(1)=RAINT(1)-DT
      GO TO 15
C
C      --- PRINT WARNING IF TOTAL RAINFALL IS LESS THAN
C      --- TOTAL INTERCEPTED VOLUME OF RAINFALL.
C
   13 ERR=1.0
      WRITE(6,1000) VRAIN
 1000 FORMAT(//,"THE ENTIRE VOLUME OF RAINFALL",F10.3,
     +"INCHES.",/,"HAS BEEN ABSORBED BY INTERCEPTION.",/)
      GO TO 16
C
C      --- RESET RAIN ARRAY EQUAL TO R OLD ARRAY.
C
   15 CONTINUE
      NRAIN=NRAIN+1
      DO 102 I=2,NRAIN
       RAIN(I)=R OLD(I-1)
       RAINT(I)=RTOLD(I-1)
  102 CONTINUE
   16 RETURN
      END
C
C
C      ***************************************************************
C
C
      SUBROUTINE CUTOFF(ERR,EXCES,EXCEST,NEX,RAIN,RAINT,NRAIN,
     +IPL,FTIM)
C
C      --- THIS SUBROUTINE CALCULATES THE EXCESS RAINFALL ?
C      --- INFILTRATED RAINFALL BASED ON THE GREEN-AMPT EQUATION.
C      --- THIS IS A CONTINUED INFILTRATION MODEL ( I.E. INFILTRATION
C      --- CONTINUES AFTER THE END OF THE RAINFALL).
C
C
C      --- PARAMETER DEFINITIONS.
C            ERR    = ERROR INDEX.
C            EXCES  = ARRAY CONTIANING EXCESS RAINFALL
C                     INTENSITY VALUES.
C            EXCEST = ARRAY CONTIANING THE FINAL TIMES FOR
C                     EACH EXCESS INTERVAL.
C            NEX    = NUMBER OF EXCESS INTERVALS.
C            RAIN   = ARRAY OF RAINFALL INTENSITIES.
C            RAINT  = ARRAY OF FINAL TIMES FOR EACH RAINFALL
C                     INTENSITY.
C            NRAIN  = NUMBER OF RAINFALL INTERVALS.
C            IPL    = INDICATOR OF WHICH PLANE THE EXCESS
C                     IS BEING CALCULATED.
C            FTIM   = FINAL TIME OF HYDROGRAPH.
C
C
      DIMENSION RAIN(NRAIN),RAINT(NRAIN),EXCES(200),EXCEST(200)
      COMMON/SOIL/WET K(2),POROS(2),SAVE(2),SW(2),SI(2),XN,ADW,C
      COMMON/COVER/GRNCOV(2),CANCOV(2),VG(2),VC(2),FIMP(2),SLOOSE(2)
C
C      --- INITIALIZE VARIABLES.
C
      ITP=0
      FO1 = 0.
      FO2 = 0.
      T = 0.
      FTIMM=FTIM/60.
      EXCES(1) = 0.
      EXCEST(1) = 0.
      GAMMA=SAVE(IPL)*POROS(IPL)*(SW(IPL)-SI(IPL))
C
C      --- CALCULATE NUMBER OF EXCESS INCREMENTS.
C
      NEX=NRAIN+1
C
C      --- THE FOLLOWING LOOP ITERATES EXCESS INCREMENTS.
C
      DO 105 I=1,NRAIN
C
C      --- CALCULATE THE RAINFALL TIME INTERVAL--DTM.
C
       IF(I.EQ.1) GO TO 11
       DTM=RAINT(I)-RAINT(I-1)
       GO TO 12
   11 DTM=RAINT(1)
   12 T=T+DTM
C
C      --- CALCULATE THE POTENTIAL INFILTRATED VOLUME.
C
       DELF = DF(FO1,WET K(IPL),GAMMA,DTM)
C
C      --- COMPUTE THE POTENTIAL AVERAGE INFILTRATION RATE.
C
       FD = DELF/DTM
       R=RAIN(I)
C
C      --- COMPARE THE RAINFALL INTENSITY AND THE AVERAGE
C      --- POTENTIAL INFILTRATION RATE. IF THE RAINFALL
C      --- INTENSITY IS GREATER THAN THE INFILTRAION RATE
C      --- THEN CALCULATE EXCESS. IF THE RAINFALL INTENSITY IS
C      --- LESS THAN OR EQUAL TO THE INFILTRATION RATE THEN
C      --- THE EXCESS IS ZERO.
C
       IF(FD.LE.R) GO TO 10
       FD1S =R
       EXCES(I+1)= 0.0
       EXCEST(I+1) =T
       GO TO 25
   10 ITP=1
       FD1S=FD
       EXCES(I+1)=R-FD1S
       EXCEST(I+1)=T
   25 FO1 = FO1+FD1S*DTM
       FO2=FO1
  105 CONTINUE
      EXCEST(NEX+1)=1.E20
      EXCES(NEX+1)=-WET K(IPL)
      NEX=NEX+1
C
C      --- PRINT WARNING IF THERE IS NO EXCESS.
C
      IF(FIMP(IPL).GT.0.0.OR.ITP.NE.0) RETURN
   17 WRITE(6,10000)
10000 FORMAT(/,"CUTOFF FINDS NO RAINFALL EXCESS.",/,
     +       "NO ROUTING WILL BE ATTEMPTED. CONTROL RETURNED TO ",/,
     +       "ANAWAT.",/)
      ERR=2.0
      RETURN
      END
C
C
C      ***************************************************************
C
C
      FUNCTION DF(F,WK,HEAD,DT)
C
C      --- EXPLICIT APPROXIMATION FOR GREEN-AMPT INFILTRATION
C      --- MODEL DETERMINES THE POTENTIAL INFILTRATION
C      --- VOLUME DURING TIME INCREMENT.
C
C
C      --- PARAMETER DEFINITIONS.
C            F      = ACCUMULATED INFILTRATED VOLUME IN INCHES.
C            WK     = HYDRAULIC CONDUCTIVITY.
C            HEAD   = AV. SUCTION*POROSITY*(FINAL-INITIAL SATURATION)
C            DT     = TIME INCREMENT IN MINUTES.
C
C
```

```
      A=1.
      B=2.*F-WK*DT
      C=2.*WK*(HEAD+F)*DT
      DF=(-B+SQRT(B*B+4.*A*C))/(2.*A)
      RETURN
      END
C
C
C     ************************************************************
C
      SUBROUTINE INTEGRA(T1,T2,ANS,QIN,TIMEIN,N)
C
C     --- SUBROUTINE INTEGRA INTEGRATES THE EXCESS
C     --- RAINFALL (OR INFLOW IN THE CASE OF A CHANNEL)
C     --- HISTOGRAM BETWEEN AN INITIAL TIME (T1)
C     --- AND A FINAL TIME (T2).
C
C
C     --- PARAMETER DEFINITIONS.
C          T1     = INITIAL TIME OF CHARACTERISTIC.
C          T2     = FINAL TIME OF CHARACTERISTIC.
C          ANS    = AREA BETWEEN T1 AND T2 OF IN ARRAY.
C          QIN    = ARRAY BEING INTEGRATED.
C          TIMEIN = ARRAY OF FINAL TIMES CORRESPONDING TO THE
C                   QIN ARRAY.
C          N      = NUMBER OF ELEMENTS IN QIN AND TIMEIN ARRAYS.
C
C
      DIMENSION QIN(200),TIMEIN(200)
C
C     --- INITIALIZE DUMMY VARIABLE WHICH IS USED
C     --- TO STORE INTERMEDIATE ANSWERS.
C
      CUM =0.
C
C     --- FIND INITIAL TIME INCREMENT.
C
      DO 100 I=2,N
      II=I
        IF(T1.LT.TIMEIN(I)) GO TO 55
  100 CONTINUE
   55 INT=II
C
C     --- FIND FINAL TIME INCREMENT.
C
      DO 101 I=INT,N
        IF(T2.GE.TIMEIN(I)) GO TO 101
        IFIN=I
        GO TO 40
  101 CONTINUE
      IFIN=N
C
C     --- FIND AREA INBETWEEN INITIAL AND FINAL
C     --- TIME INCREMENTS.
C
   40 CONTINUE
       DO 102 J=INT,IFIN
       CUMPRE=CUM
       CUM=CUM+(TIMEIN(J)-TIMEIN(J-1))*QIN(J)
      IF(J.EQ.IFIN) CUM=CUMPRE+QIN(J)*(T2-TIMEIN(J-1))
  502 FORMAT(4G15.7,I5)
  102 CONTINUE
C
C     --- CORRECT INTERMEDIATE ANSWER BY SUBTRACTING
C     --- THE AREAS WHICH SHOULD NOT BE INCLUDED.
C
      IF(T1.EQ.0.0) GO TO 80
      CUM=CUM-(T1-TIMEIN(INT-1))*QIN(INT)
  503 FORMAT(G20.10,I5)
   80 CONTINUE
C
C     --- SET VALUE OF FINAL ANSWER.
C
       ANS=CUM
       RETURN
       END
C
C
C     ************************************************************
C
C
       SUBROUTINE FORWARD(A,B,D,QIN,TIMEIN,N,OUTTIME,TSTOP,FTIM
      +,CHECK)
       DIMENSION QIN(200),TIMEIN(200),OUTTIME(200)
       DO 10 K=1,200
          OUTTIME(K)=0.0
   10  CONTINUE
       IFINAL=N-1
       IIFINAL=IFINAL-1
       DO 200 K=1,IIFINAL
          KK=K
          XPRE=0.
          X=0.
          DEPTH=0.
          DX=0.
          DO 100 I=K,IFINAL
             DT=TIMEIN(I+1)-TIMEIN(I)
             IF(QIN(I+1).EQ.0.0) GO TO 50
             IF(I.EQ.IFINAL) GO TO 80
             DEPTH=DEPTH+QIN(I+1)*DT
             DX=(A/QIN(I+1))*(DEPTH**B-(DEPTH-QIN(I+1)*DT)**B)
             XPRE=X
       X=X+DX
       GO TO 60
   50     DX=A*B*(DEPTH**(B-1.))*DT
             XPRE=X
             X=X+DX
   60     IF(X.LT.D) GO TO 100
             X=XPRE
             DEPTH=DEPTH-QIN(I+1)*DT
             IF(QIN(I+1).EQ.0.0) GO TO 70
             DELT=(((D-X)*QIN(I+1)/A+DEPTH**B)**(1./B)-DEPTH)/QIN(I+1)
             OUTTIME(K)=DELT+TIMEIN(I)
             IF(OUTTIME(K).LT.FTIM) GO TO 200
             TSTOP=FTIM
             RETURN
   70     OUTTIME(K)=(D-X)/(A*B*(DEPTH**(B-1.)))+TIMEIN(I)
             IF(OUTTIME(K).LT.FTIM) GO TO 200
             TSTOP=FTIM
             RETURN
   80        XMAX=X-(A*DEPTH**B)/QIN(I+1)
  500 FORMAT(3G20.10,2I5)
C        PRINT 500,DEPTH,QIN(I+1),-3.
             IF(XMAX.LT.D) GO TO 300
             DELT=(((D-X)*QIN(I+1)/A+DEPTH**B)**(1./B)-DEPTH)/QIN(I+1)
             OUTTIME(K)=TIMEIN(I)+DELT
             IF(OUTTIME(K).LT.FTIM) GO TO 200
             TSTOP=FTIM
             RETURN.
  100  CONTINUE
       IF(CHECK.EQ.0.0.AND.QIN(N).LT.0.0) GO TO 200
       IF(DEPTH.EQ.0.0) GO TO 199
       OUTTIME(K)=TIMEIN(IFINAL)+(D-X)/(A*B*(DEPTH**(B-1.)))
       IF(OUTTIME(K).LT.FTIM) GO TO 200
       TSTOP=FTIM
       RETURN
  199 OUTTIME(K)=1.E30
       TSTOP=FTIM
       RETURN
  200 CONTINUE
       IF(CHECK.EQ.1.0) GO TO 310
       IF(QIN(N).EQ.0.0) GO TO 310
       KK=IFINAL
  300 CONTINUE
       CALL STOP(A,B,D,QIN,TIMEIN,N,OUTTIME,TSTOP,FTIM,KK,CHECK)
       RETURN
  310 OUTTIME(IFINAL)=1.E30
       TSTOP=FTIM
       RETURN
       END
       SUBROUTINE STOP(A,B,D,QIN,TIMEIN,N,OUTTIME,TSTOP,FTIM,K,CHECK)
       DIMENSION QIN(200),TIMEIN(200),OUTTIME(200)
 1000 FORMAT(3G20.10)
       IFINAL=N-1
       INT=K-1
       IF(K.GT.1) GO TO 200
       DEPTH=0.0.
       DO 100 I=2,IFINAL
          DEPTH=DEPTH+QIN(I)*(TIMEIN(I)-TIMEIN(I-1))
  100 CONTINUE
       OUTTIME(1)=TIMEIN(IFINAL)-DEPTH/QIN(N)
       TSTOP=OUTTIME(1)
       IF(OUTTIME(1).GT.FTIM) TSTOP=FTIM
       RETURN
  200 CONTINUE
       DTT=(TIMEIN(K)-TIMEIN(INT))/2.
       TIME1=TIMEIN(INT)+DTT
       IIFINAL=IFINAL-1
       IF(CHECK.EQ.1.0) IIFINAL=IFINAL
  300 CONTINUE
       DEPTH=0.
       X=0.
       DO 400 I=INT,IIFINAL
          II=I
          IF(I.NE.INT) GO TO 410
          DT=TIMEIN(K)-TIME1
          GO TO 420
  410 DT=TIMEIN(I+1)-TIMEIN(I)
  420 IF(QIN(I+1).EQ.0.0) GO TO 430
          DEPTH=DEPTH+QIN(I+1)*DT
          DX=(A/QIN(I+1))*(DEPTH**B-(DEPTH-QIN(I+1)*DT)**B)
          X=X+DX
          IF(X.GE.D) GO TO 435
          GO TO 400
  430 DX=A*B*(DEPTH**(B-1.))*DT
          X=X+DX
          IF(X.GE.D) GO TO 435
  400 CONTINUE
       IF(CHECK.EQ.1.0) GO TO 435
       XMAX=X-(A*DEPTH**B)/QIN(N)
       IF(XMAX.LT.D) GO TO 440
       CON=(XMAX-D)/D
       IF(CON.LT.0.05) GO TO 500
  435 DTT=DTT/2.
       TIME1=TIME1+DTT
       IF(CHECK.EQ.0.0) GO TO 300
       DEPTH=DEPTH-QIN(II+1)*DT
       IF(QIN(II+1).EQ.0.0) GO TO 438
       DELT=(((D-X)*QIN(II+1)/A+DEPTH**B)**(1./B)-DEPTH)/QIN(II+1)
       GO TO 439
  438 OUTTIME(K)=(D-X)/(A*B*(DEPTH**(B-1.)))+TIMEIN(II)
       OUTTIME(K)=TIMEIN(II)+DELT
  439 IF(OUTTIME(K).LT.FTIM) GO TO 300
       TSTOP=FTIM
       GO TO 550
  440 DTT=DTT/2.
       TIME1=TIME1-DTT
       GO TO 300
  500 DELT=(((D-X)*QIN(N)/A+DEPTH**B)**(1./B)-DEPTH)/QIN(N)
       OUTTIME(K)=TIMEIN(II+1)+DELT
       IF(II.EQ.INT) OUTTIME(K)=TIME1+DELT
       TSTOP=OUTTIME(K)
       IF(TSTOP.GT.FTIM) TSTOP=FTIM
  550 DUMQ=QIN(K)
       N=N+1
       DO 600 I=K,N
       DUM1=TIMEIN(I)
          TIMEIN(I)=TIME1
          TIME1=DUM1
          DUM2=QIN(I)
          QIN(I)=DUMQ
          DUMQ=DUM2
  600 CONTINUE
       RETURN
       END
            SUBROUTINE BACK (AL,BET,LEN,DTIM,TSTOP,TL,T,Q,QOUT,NQ,CHEC
C
C           THIS SUBROUTINE USES THE SUBDIVIDED SOLUTION DOMAIN
C           AS SUPLLIED BY SUBROUTINE FORWARD TO CALCULATE THE
C           TIME OF ORIGIN OF CHARACTERISTICS CORRESPONDING TO
C           AN ARBITRARILY SELECTED TIME ON THE DOWNSTREAM
C           BOUNDARY.  IN SHORT, BACK CALCULATES CHARACTERISTICS
C           IN THE UPSTREAM DIRECTION.  THIS ALLOWS THE DISCHARGE
C           TO BE KNOWN AT CONVENIENT TIME INTERVALS THEREBY
C           FACILITATING THE FORMATION OF THE LATERAL INFLOW TO
C           THE CHANNEL AND ALLOWING GREATER EASE IN INTERFACING
C           THIS WATER ROUTING SIMULATION WITH OTHER WATERSHED
C           PROCESS MODELS.
C           SUBROUTINE BACK PROCEEDS AS FOLLOWS:
C           IT FIRST DETERMINES THE LOCATION OF THE TIME OF INTEREST
```

```
C          ON THE DOWNSTREAM BOUNDARY WITH RESPECT TO THE
C          CHARATERISTICS SUPPLIED BY SUBROUTINE FORWARD.  NEXT,
C          THE ROUTINE FORMULATES F(TO) AND ITS FIRST TWO
C          DERIVATIVES AS SHOWN IN EQS 3-15 TO 3-17 IN THE
C          ANAWAT REPORT TEXT.  FINALLY, THIS RESULT IS ITERATED
C          UNTIL A SUITABLY ACCURATE ESTIMATE OF THE TIME OF
C          ORIGIN IS CALCULATE USING A SECOND ORDER NEWTONS METHOD.
C
C
C          PARAMETER DEFINITIONS
C            AL     = A IN Q=A*Y**B.
C            BET    = B IN Q=A*Y**B.
C            LEN    = SLOPE LENGTH (FT).
C            DTIM   = TIME INCREMENT FOR HYDROGRAPH (SEC).
C            FTIM   = ENDING TIME OF HYDROGRAPH (SEC).
C            TL     = ARRAY OF FINAL TIMES FOR THE CHARACTERISTIC
C                     LINES FOUND IN FORWARD SUBROUTINE (SEC).
C            T      = TIME ARRAY FOR INFLOW (SEC).
C            Q      = INFLOW ARRAY (FT/SEC OR CFS/FT).
C            QOUT   = OUTFLOW DISCHARGES (CFS/FT OR CFS).
C            NQ     = NUMBER OF INCREMENTS IN INFLOW.
C            TSTOP  = TIME WHEN RUNOFF STOPS.
C
C
          DIMENSION              TL(200)     , T(200)     , Q(200)

     +            CUMQ(200)    , QOUT(200)

          COMMON /DEPTH/         Y(200)
          REAL                   LEN

C          ONE TIME INITIALIZATION OF LOOP PARAMETERS AND TIMES.
C
          EPQ = 1.E - 5
          IF (CHECK.EQ.1.) EPQ = 1.E - 5 * LEN
          NITER = 10
          EP = 0.0001
          TIME = 0.
          B1 = BET - 1.
          B2 = BET - 2.
          B3 = BET - 3.
          Y(1) = 0.0
  501 FORMAT(3G20.10,I5)
C
C          CALCULATE CUMLATIVE INFLOW ARRAY.
C
          TOT = Q(1) * T(1)
          CUMQ(1) = TOT
      TEST=0.0
          DO 100 I = 2,200
             TOT = TOT + Q(I) * (T(I) - T(I - 1))
             CUMQ(I) = TOT
             Y(I) = 0.0
  100 CONTINUE
          I = 1
  110 IF (TL(I).NE.TL(I + 1)) GO TO 120
          I = I + 1
          GO TO 110
C
C          THIS LOOP ITERATES FINAL TIMES FROM 0.0 TO FTIM. FOR
C          EACH FINAL TIME AN INITIAL TIME (TEST) IS CALCULATED.
C
  120 DO 300 J = 2,200
      TPRE=TEST
          TIME = TIME + DTIM
          IF (TIME.GT.TSTOP) GO TO 310
C
C          THIS SECTION IS USED TO CALCULATE THE DISCHARGE FOR
C          ALL TIMES LESS THAN TL(1).  FOR THESE TIMES IT IS NOT
C          NECESSARY GO CALCULATE THE UPSTREAM TIME OF THE CHARACTERI
C          SINCE ALL OF THESE CHARACTERISTICS BEGIN AT T=0.
C
          IF (TIME.GT.TL(1)) GO TO 130
          CALL INTEGRA (0.0,TIME,DEPTH,Q,T,NQ)
          QOUT(J) = AL * DEPTH *  * BET
          Y(J) = DEPTH
          GO TO 300
  130     IK = I
C
C          FIND THE BOUNDS FOR THE CHARACTERISTIC LINE.
C
          DO 140 IJ = IK,200
             IF (TIME.LE.TL(IJ + 1)) GO TO 150
             I = I + 1
  140     CONTINUE
  150     L2 = I
C
C          IF THE LATERAL INFLOW INTENSITY IS EQUAL TO ZERO,
C          IT IS NECESSARY TO SKIP UP TO THE NEXT CHARACTERISTIC.
C
          IF (Q(L2 + 1).NE.0.) GO TO 160
          I = I + 1
          GO TO 150
  160     CALL INDX(TIME,L,NQ,T)
          M = L - L2 - 1
C
C          THE FIRST GUESS OF THE TIME OF ORIGIN TO BE CALCULATED
C          (TEST) IS THE AVERAGE OF THE TIME OF ORIGIN OF
C          THE LOWER BOUNDING CHARACTERISTIC, AND THE SMALLER OF
C          THE TIME ORIGIN OF THE UPPER BOUNDING CHARACTERISTIC
C          AND "TIME".
C
          TUP = T(I + 1)
      TDN=T(I)
      IF(TPRE.GT.TDN) TDN=TPRE
          IF (TUP.GT.TIME) TUP = TIME
          TEST = (TDN + TUP)/2.
C
C          THIS IS AN ANALYTICAL SOLUTION USING A THIRD ORDER
C          NEWTON APPROXIMATION TO SOLVE FOR THE CHARACTERISTIC LINE
C
          DO 281 J1 = 1,NITER
             FF =  - LEN/(AL * BET)
             FTO = FF
             TLAST = TEST
             IF (M.EQ.0) GO TO 210
             C1 = Q(L2 + 1) * T(L2 + 1) - Q(L2 + 1) * TEST
             FTO = FTO + (1./(Q(L2 + 1) * BET)) * (C1 *  * BET)
             FDTO =  - (C1 *  * B1)
             FD2TO = Q(L2 + 1) * B1 * (C1 *  * B2)
             IF (M.EQ.1) GO TO 190
             DO 180 J2 = 2,M
                JJ = L2 + J2
                A =  - Q(JJ) * T(JJ - 1) + CUMQ(JJ - 1) - CUMQ(L2)
     ++ Q(L2
     +          + 1) * T(L2)

                IF (Q(JJ).NE.0.) GO TO 170
                C1 =  - Q(L2 + 1) * TEST + A
                CDT = T(JJ) - T(JJ - 1)
                FTO = FTO + CDT * (C1 *  * B1)
                FDTO = FDTO + B1 * ( - Q(L2 + 1)) * CDT * (C1 *  *
     +B2)
                FD2TO = FD2TO + B1 * B2 * Q(L2 + 1) * Q(L2 + 1) *
     +DT * (
     +          C1 *  * B3)

                GO TO 180
  170           C1 = Q(JJ) * T(JJ) - Q(L2 + 1) * TEST + A
                C2 = Q(JJ) * T(JJ - 1) - Q(L2 + 1) * TEST + A
                FTO = FTO + (1./(BET * Q(JJ))) * ((C1 *  * BET) -
     +C2 *
     +          * BET))

                FDTO = FDTO + ( - Q(L2 + 1)/Q(JJ)) * ((C1 *  * B1)
     +- (C2
     +          *  * B1))

                FD2TO = FD2TO + (Q(L2 + 1) * Q(L2 + 1)/Q(JJ)) * B1
     +* ((C1
     +           *  * B2) - (C2 *  * B2))

  180        CONTINUE
  190        A =  - Q(L) * T(L - 1) + CUMQ(L - 1) - CUMQ(L2) + Q(L2
     + + 1)
     +          * T(L2)

             IF (Q(L).NE.0.) GO TO 200
             C1 = A - Q(L2 + 1) * TEST
             CDT = TIME - T(L - 1)
             FTO = FTO + CDT * (C1 *  * B1)
             FDTO = FDTO + CDT * B1 * ( - Q(L2 + 1)) * (C1 *  * B:
             FD2TO = FD2TO + CDT * B1 * B2 * Q(L2 + 1) * Q(L2 + 1)·
     +* (C1
     +          *  * B3)

             GO TO 220
  200        C1 = Q(L) * TIME - Q(L2 + 1) * TEST + A
             C2 = Q(L) * T(L - 1) - Q(L2 + 1) * TEST + A
             IF (C1.LT.0.0.OR.C2.LT.0.0) GO TO 260
             FTO = FTO + (1./(Q(L) * BET)) * ((C1 *  * BET) - (C2
     +  * BE
     +          T))

             FDTO = FDTO + ( - Q(L2 + 1)/(Q(L))) * ((C1 *  * B1) -
     +(C2 *
     +          * B1))

             FD2TO = FD2TO + ((Q(L2 + 1) * Q(L2 + 1))/Q(L)) * B1 *
     +((C1 *
     +           * B2) - (C2 *  * B2))

             GO TO 220
  210        TEST = TIME - ((LEN/(AL * (Q(L) *  * B1))) *  * (1./BE
     +T))
             GO TO 290
C
C          TEST FOR CONVERGENCE.  IF TEST IS SUCCESSFUL, THE
C          ITERATIONS ARE COMPLETE.  THE PROGRAM THEN PROCEEDS TO
C          THE NEXT TIME INCREMENT.  IF NOT, THE PROGRAM USES
C          THE SOLUTION TO TRUNCATED  TAYLOR)S SERIES TO CALCULATE
C          A NEW TRAIL VALUE OF TEST.
C
  220        IF (ABS(FTO/FF).LE.EP) GO TO 290
             B = (2. * FDTO/FD2TO) - (2. * TEST)
             C = (2./FD2TO) * (FTO - FDTO * TEST + 0.5 * TEST * TE:
     +T * FD
     +          2TO)

             D = B * B - 4. * C
             IF (D.LT.0.) GO TO 230
             DTEST = 0.5 * SQRT(D)
             GO TO 240
C
C          THE NEW ESTIMATE OF TEST MUST FALL INSIDE THE REGION
C          OF THE SOLUTION DOMAIN BOUNDED BY THE CHARACTERISTICS
C          SELECTED ABOVE.  IF IT DOES NOT, THEN AN ESTIMATE MUST
C          BE REPICKED INSIDE THAT REGION.  THIS PROCEDURE MAY
C          RESULT IN THE REJECTION OF THE ESTIMATE PROVIDED BY
C          THE NEWTON)S METHOD.  AND THE SUBSTITUTION OF A NEW
C          NEW AVERAGE VALUE AS THE NEW GUESS OF TEST.
C
  230        TEST = TEST - FTO/FDTO
             IF (TEST.LT.TUP.AND.TEST.GE.TDN) GO TO 280
             GO TO 250
  240        DTEST = 0.5 * (SQRT(B * B - 4. * C))
             IF (ABS(FTO/FF).LE.EP) GO TO 290
             TEST = 0.5 * ( - B) - DTEST
             IF (TEST.LT.TUP.AND.TEST.GT.TDN) GO TO 241
             TEST = 0.5 * ( - B) + DTEST
             IF (TEST.LT.TUP.AND.TEST.GE.TDN) GO TO 280
             TEST = TLAST
             GO TO 230
  241 TESTB=.5*(-B)+DTEST
      IF(TESTB.GT.TUP.OR.TESTB.LT.TDN) GO TO 280
      TESTC=TLAST-FTO/FDTO
      TEST1=ABS(TESTC-TEST)
      TEST2=ABS(TESTC-TESTB)
      IF(TEST1.GT.TEST2) TEST=TESTB
      IF(TEST.LT.TUP.AND.TEST.GT.TDN) GO TO 280
      TEST=TLAST
      GO TO 230
  250        IF (TEST.GE.TUP) GO TO 270
  260        TEST = (TLAST + TDN)/2.
             GO TO 280
  270        TEST = (TLAST + TUP)/2.
  280 CONTINUE
  281    CONTINUE
C
C          THE VALUES OF DEPTH (OF CROSS-SECTIONAL AREA FOR CHANNELS)
```

```
C            AND DISCHARGE ARE NOW CALCULATED. A TEST IS MADE TO DETERM
C            IF THE DISCHARGE IS NEGLIGIBLY SMALL OR IF THE PRESELECTED
C            DURATION OF THE HYDROGRAPH HAS BEEN EXCEEDED. IF SO THE
C            ROUTINE RETURNS TO ANAWAT.
C
  290 CONTINUE
            CALL INTEGRA (TEST,TIME,DEPTH,Q,T,NQ)
              QOUT(J) = AL * DEPTH *  * BET
              Y(J) = DEPTH
              NP = NQ
              IF (CHECK.GT.O.) NP = NQ + 1
              IF (TIME.GE.T(NQ - 1).AND.QOUT(J).LE.EPQ) GO TO 310
  300 CONTINUE
  310 CONTINUE
           RETURN
           END
C
C
C     ***********************************************************
C
C
      SUBROUTINE INDX(TIME,L,NQ,T)
C
C      ---  THIS SUBROUTINE LOCATES WHICH INFLOW TIME INCREMENT (L)
C      ---  CONTIANS A GIVEN TIME (TIME).
C
C      ---  PARAMETER DEFINITIONS.
C             TIME    = TIME OF INTEREST.
C             L       = INDEX OF T ARRAY CONTIANING THE " TIME".
C             NQ      = NUMBER OF INFLOW TIME INCREMENTS.
C             T       = ARRAY OF INFLOW TIME INCREMENTS (SEC).
C
C
      DIMENSION T(200)
      DO 100 I=1,NQ
        L=I
        IF(TIME.LE.T(I)) GO TO 10
  100 CONTINUE
      L=NQ+1
   10 RETURN
      END
C
C
C     ************************************************************
C
C
      SUBROUTINE QLAT(QL,QLT,QLTIME,DTIM,KF)
C
C      ---  THIS SUBROUTINE USED ONLY IN THE 2 PLANES AND
C      ---  1 CHANNEL CASE.  IT TOTALS THE LATERAL INFLOW
C      ---  INTO THE CHANNEL.
C
C
C      ---  PARAMETER DEFINITIONS.
C             QL      = DOUBLE DIMENSION ARRAY CONTAINING THE
C                         OUTFLOWS FROM EACH CHANNEL.
C             QLT     = ARRAY OF THE TOTAL LATERAL INFLOW.
C             QLTIME = ARRAY OF THE TIMES FOR THE TOTAL LATERAL
C                         INFLOW (QLT ARRAY).
C             DTIM    = TIME INCREMENT USED (SEC).
C             KF      = NUMBER OF ELEMENTS IN TIME ARRAY.
C
C
      DIMENSION QL(200,2),QLT(200),QLTIME(200)
C
C      ---  CALUCULATE THE TOTAL AVERAGE INFLOW OVER A GIVEN TIME
C      ---  PERIOD.
C
      QLT(1)=0.0
      QLTIME(1)=0.0
      KFF=KF+1
      DO 105 I=2,KFF
        QLT(I)=(QL(I,1)+QL(I,2)+QL(I-1,1)+QL(I-1,2))/2.
        QLTIME(I)=QLTIME(I-1)+DTIM
  105 CONTINUE
      KFF=KFF+1
      KF=KFF
      QLT(KFF)=0.0
      QLTIME(KFF)=QLTIME(KFF-1)+1.E30
      RETURN
      END
            SUBROUTINE RESIST(C,XN,A1,B1,ALP,BET,SLP)
C
C      ---  THIS SUBROUTINE CALCULATES THE PARAMETERS A AND
C      ---  B IN THE EQUATION Q=A*AREA**B.
C      ---  FOR A CHANNEL A IS A FUNCTION OF THE CHANNEL GEOMETRY (A1),
C      ---  CHANNEL SLOPE (SLOPE(3)), AND THE FLOW RESISTANCE (EXPRESSE
C      ---  AS EITHER MANNING'S N OR CHEZY'S C).
C
C
            IF(C.NE.0.0) GO TO 102
C
C      ---  THIS IS FOR THE MANNINGS RESISTANCE.
C
            BET=(5.-2.*B1)/3.
            ALP=((SLP*2.21)/(XN*XN*A1**(4./3.)))**.5
            RETURN
C
C      ---  THIS IS FOR THE CHEZY RESISTANCE.
C
  102 BET=(3.-B1)/2.
            ALP=(SLP*C*C/A1)**.5
            RETURN
            END
```

APPENDIX B*

Comparison of Measured and Simulated Hydrographs

*Lawson Creek data (LCT) are preliminary and were obtained and supplied by the U.S. Geological Survey, Urbana, Illinois

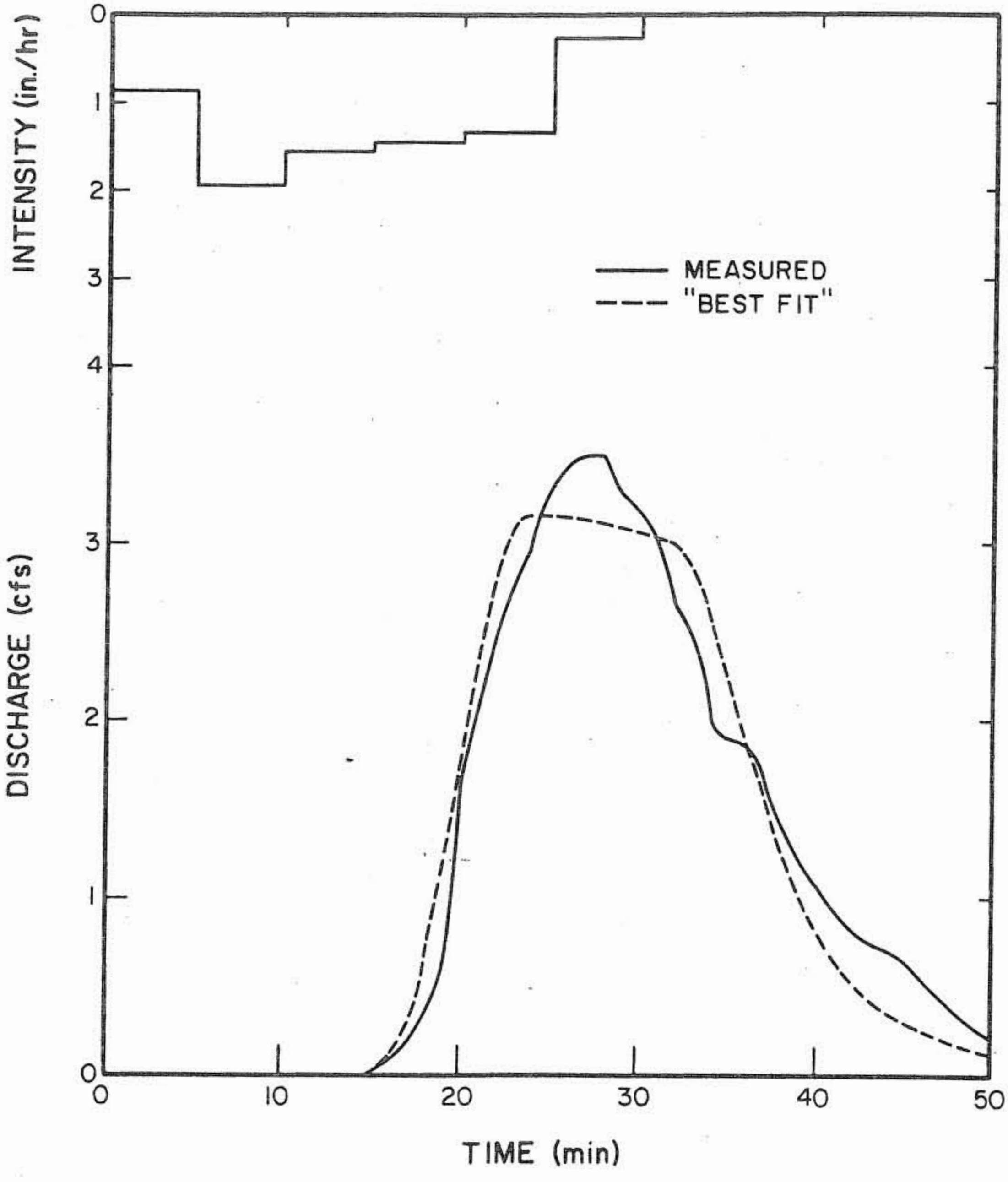

Figure B.1 Comparison of Measured and Simulated Hydrographs for the Storm Event of July 21, 1982 on LCT 1. (Note: Measured Sediment Yield = 2190 lbs)

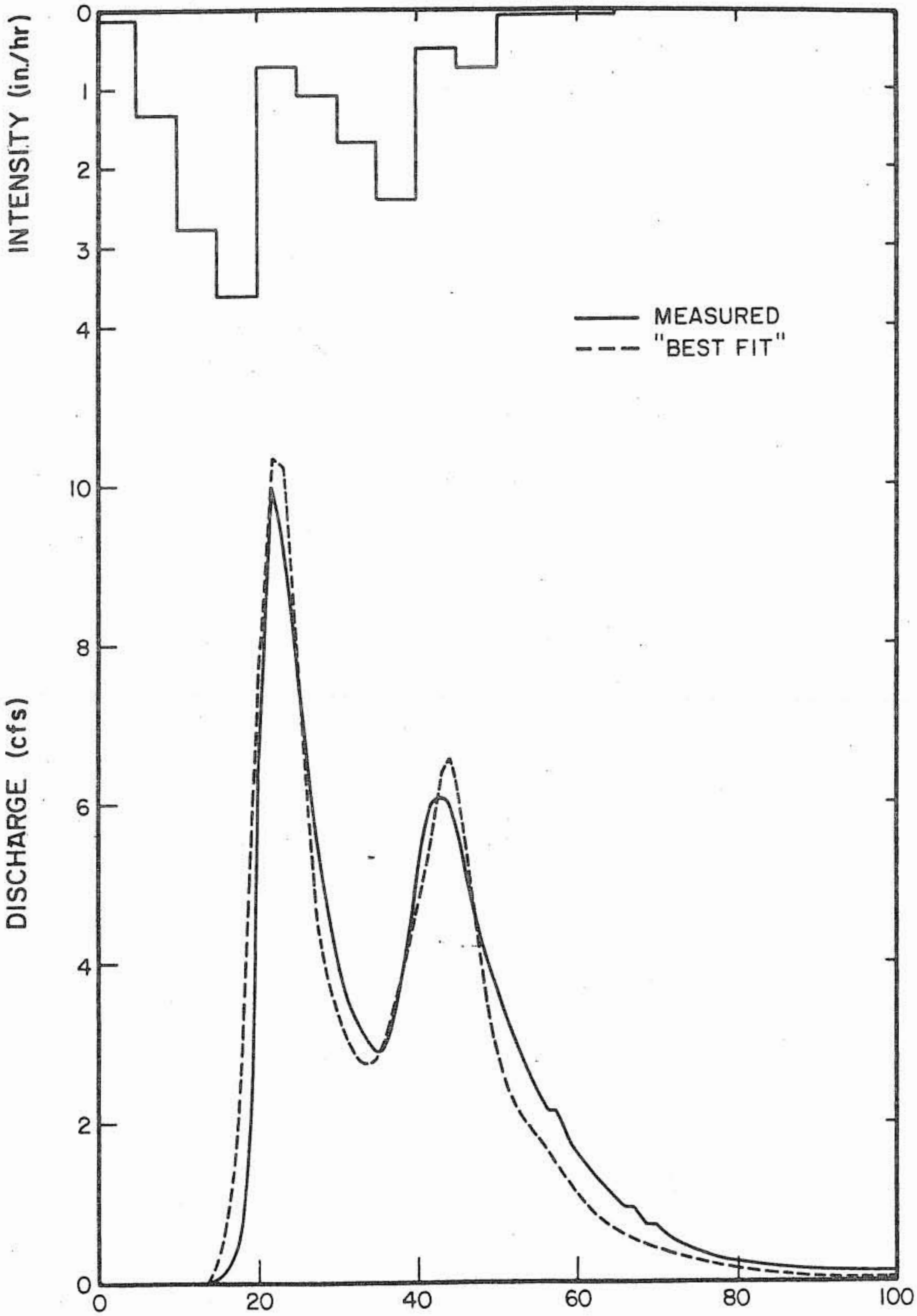

Figure B.2 Comparison of Measured and Simulated Hydrographs for the Storm Event of November 1, 1982 on LCT 1. (Note: Measured Sediment Yield = 2180 lbs)

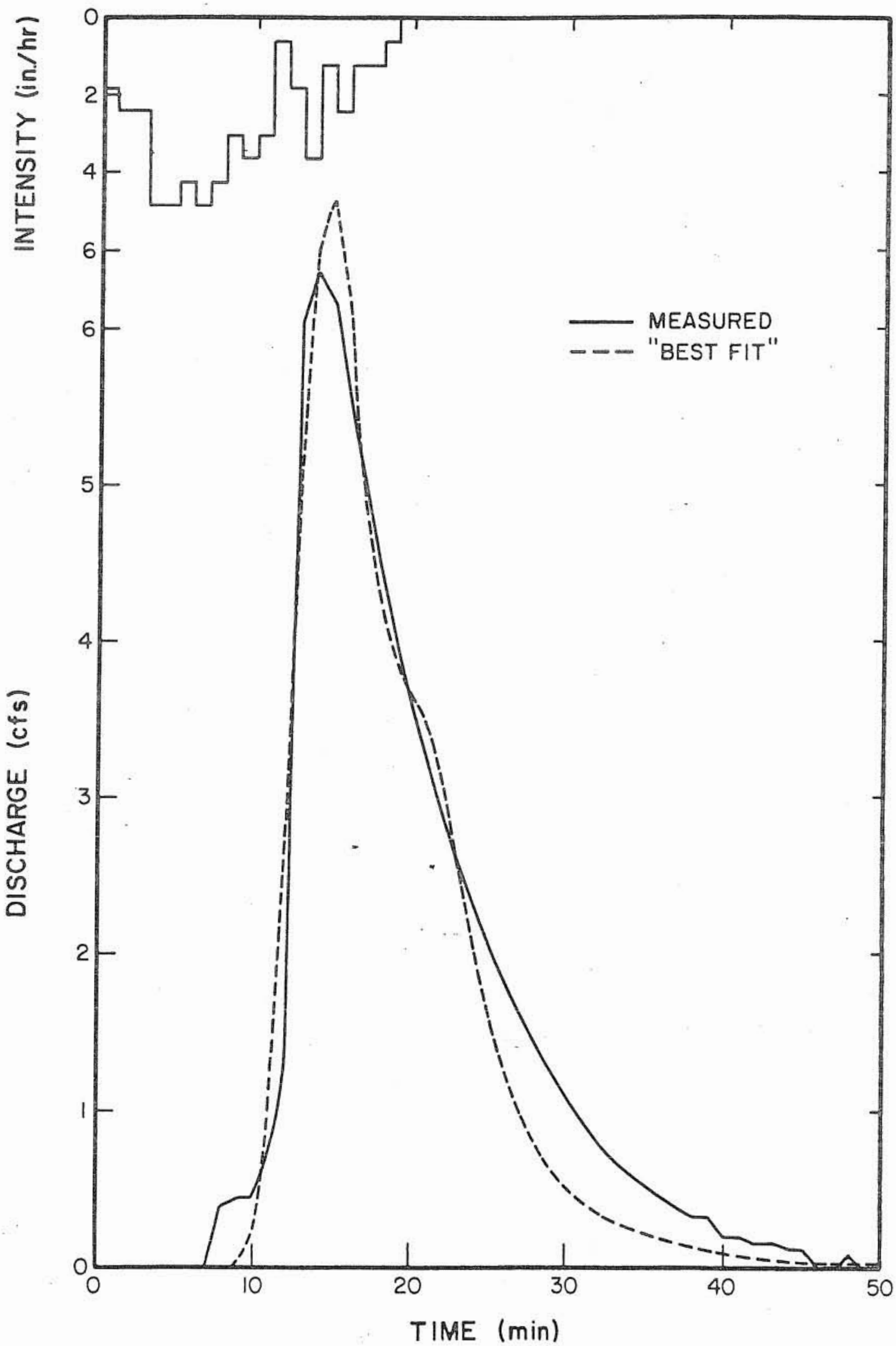

Figure B.3 Comparison of Measured and Simulated Hydrographs for the Storm Event of June 29, 1983 on LCT 1. (Note: Measured Sediment Yield = 3930 lbs)

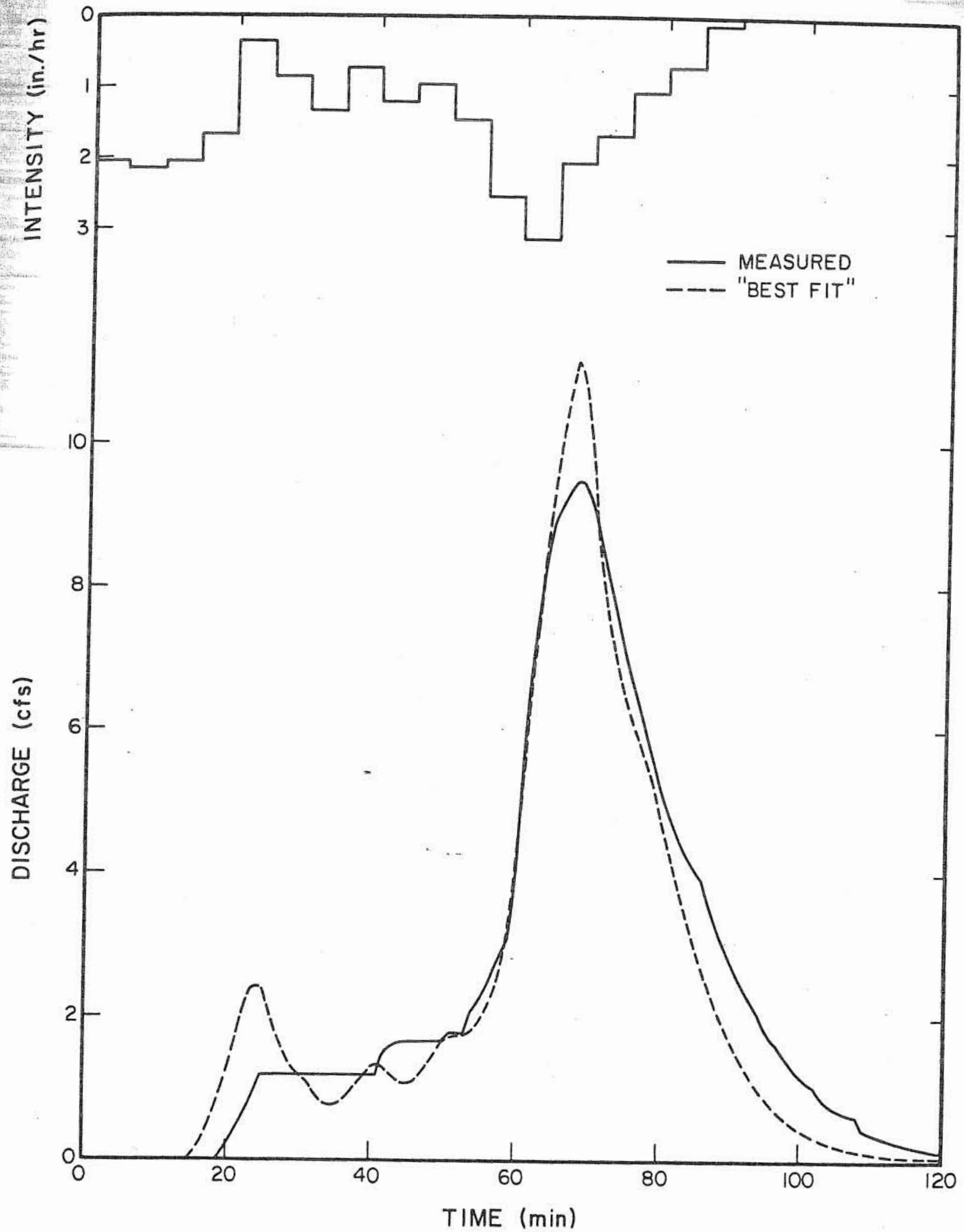

Figure B.4 Comparison of Measured and Simulated Hydrographs for the First Storm Event of July 30, 1983 on LCT1P. (Note: Measured Sediment Yield = 13960 lbs)

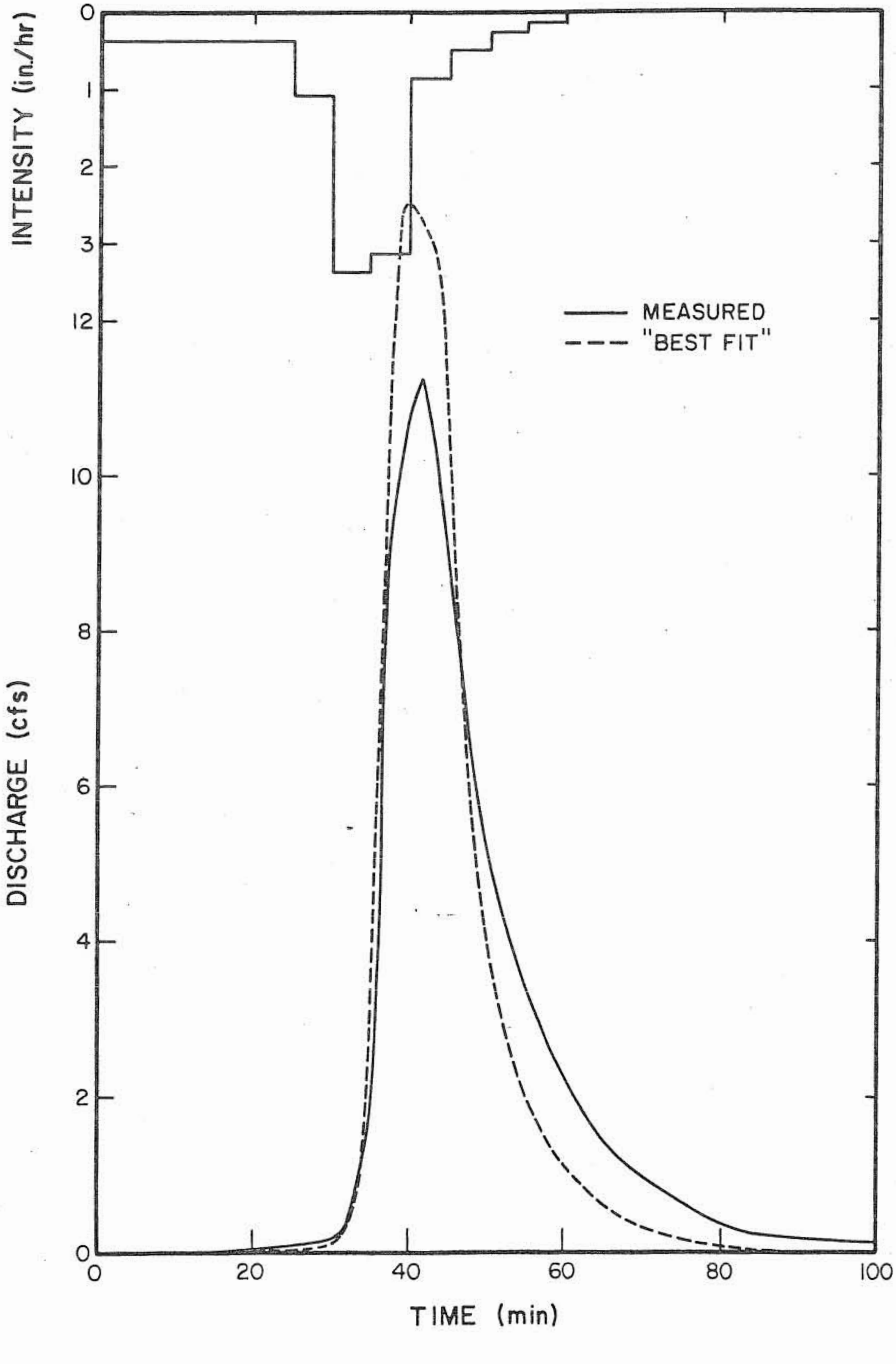

Figure B.5 Comparison of Measured and Simulated Hydrographs for the Second Storm Event of July 30, 1983 on LCT1P. (Note: Measured Sediment Yield = 9970 lbs)

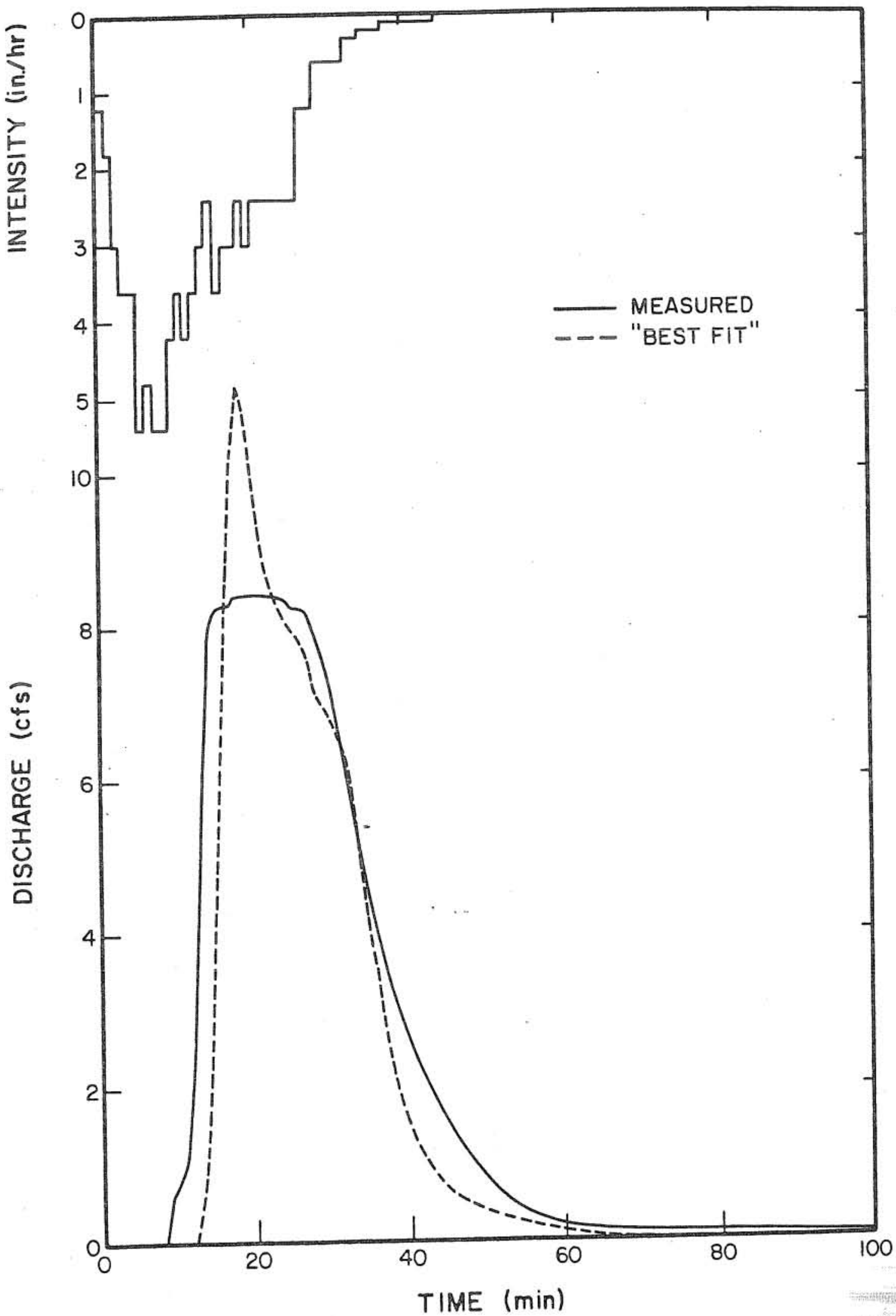

Figure B.6 Comparison of Measured and Simulated Hydrographs for the Storm Event of August 26, 1983 on LCT1P. (Note: Measured Sediment Yield = 11520 lbs)

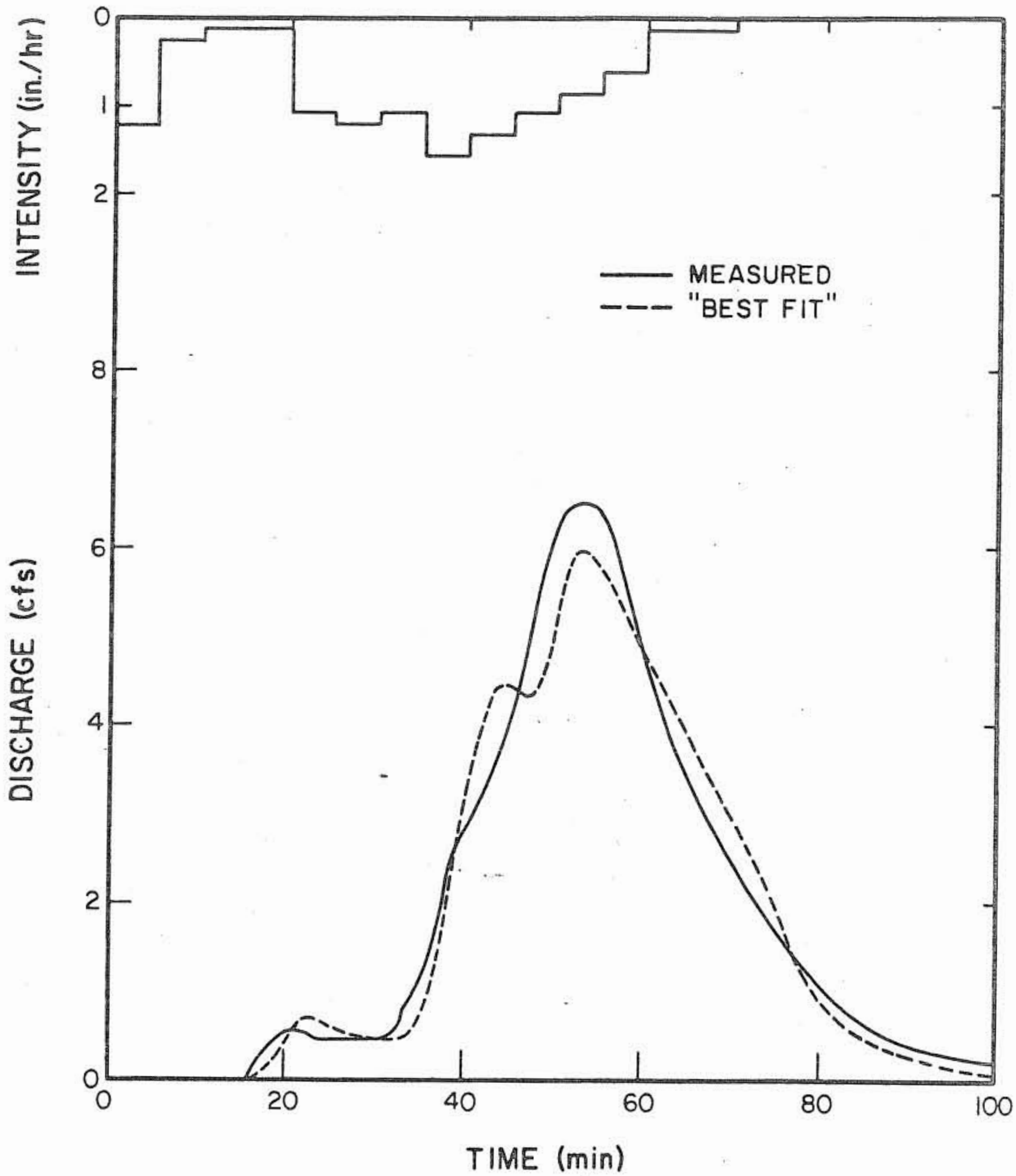

Figure B.7 Comparison of Measured and Simulated Hydrographs for the Storm Event of September 18, 1983 on LCT1P. (Note: Measured Sediment Yield = 8510 lbs)

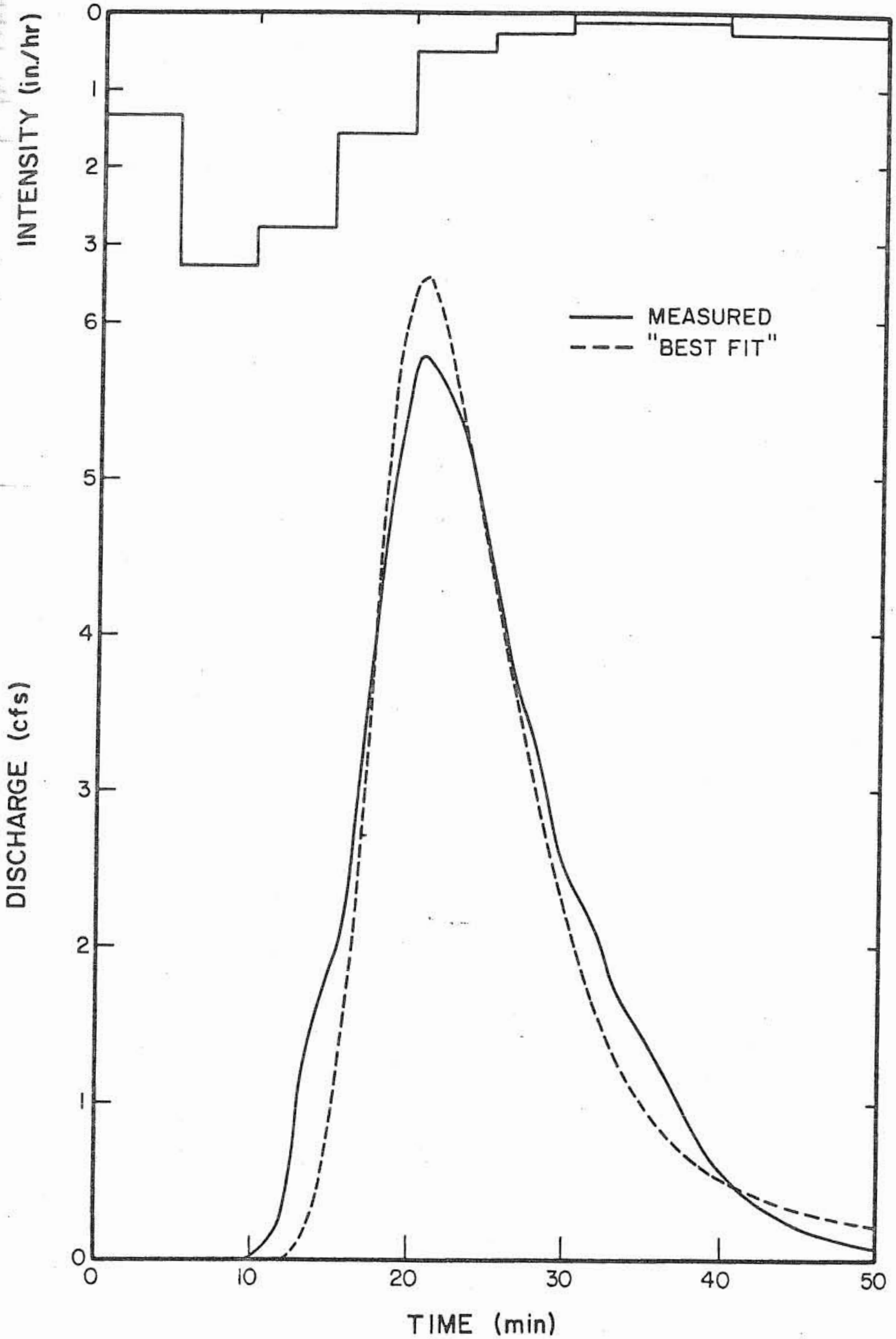

Figure B.8 Comparison of Measured and Simulated Hydrographs for the Storm Event of May 25, 1984 on LCT1P2. (Note: Measured Sediment Yield = 500 lbs)

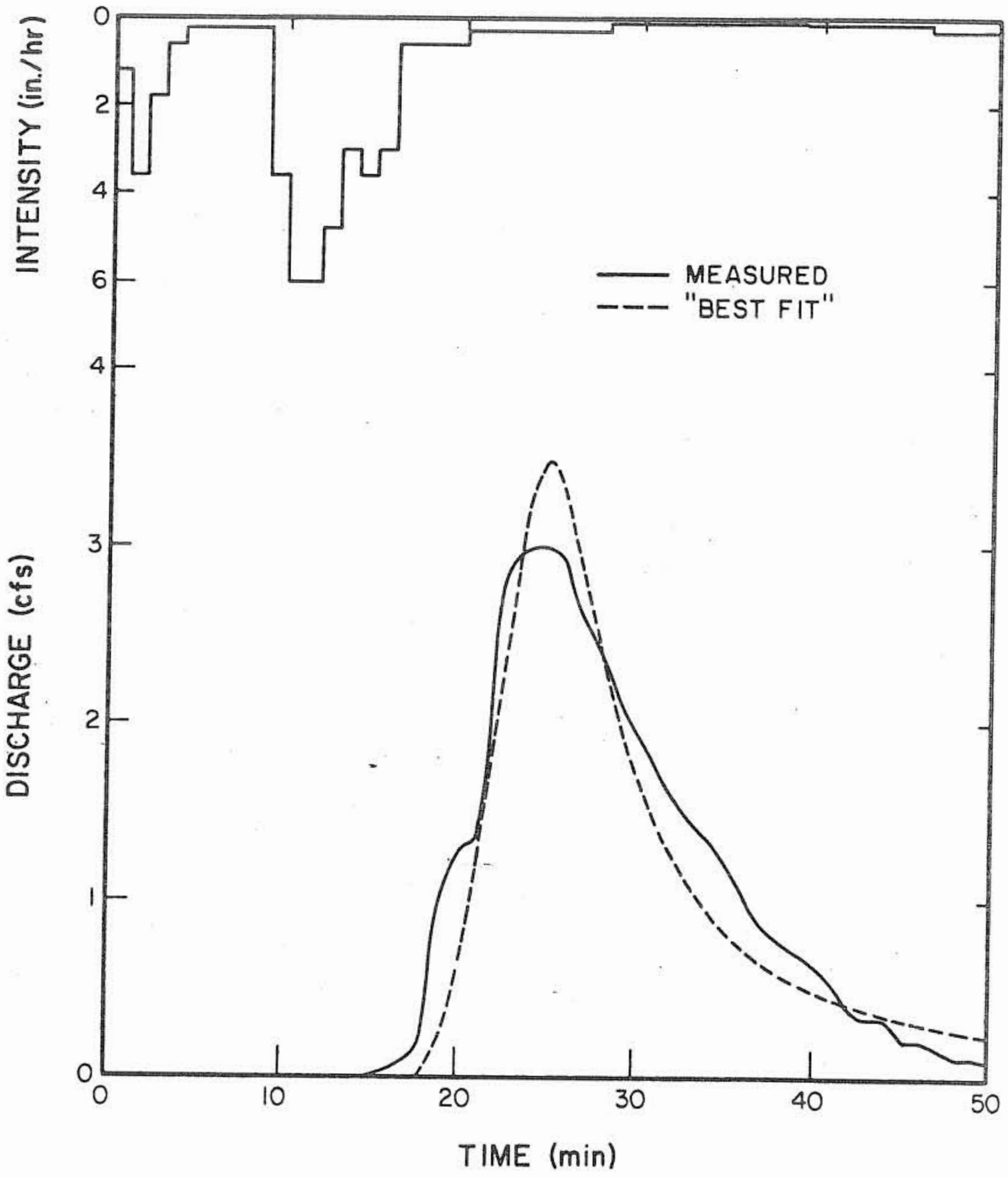

Figure B.9 Comparison of Measured and Simulated Hydrographs for the Storm Event of June 6, 1984 on LCT1P2. (Note: Measured Sediment Yield = 180 lbs)

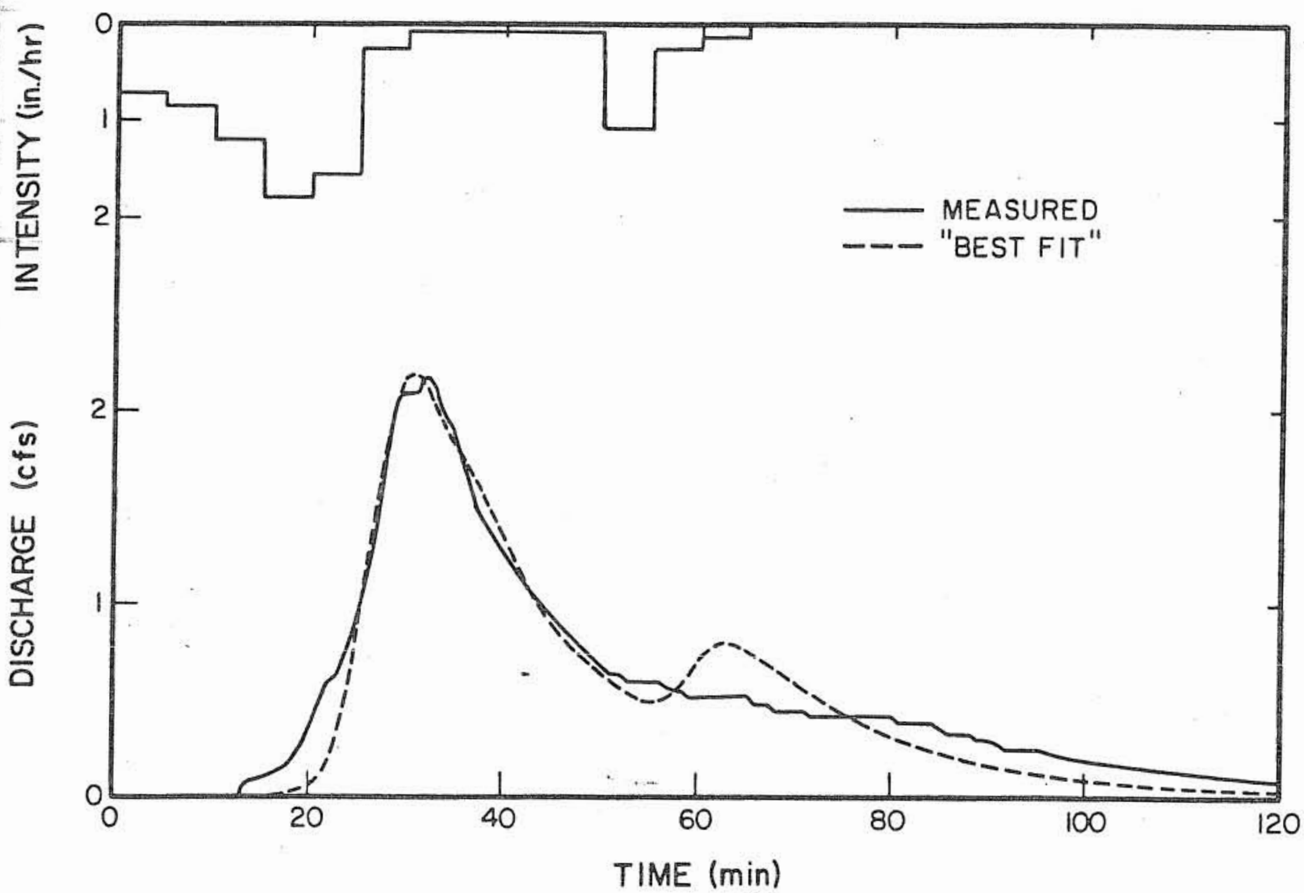

Figure B.10 Comparison of Measured and Simulated Hydrographs for the Storm Event of October 31, 1984 on LCT1P2. (Note: Measured Sediment Yield = 35 lbs)

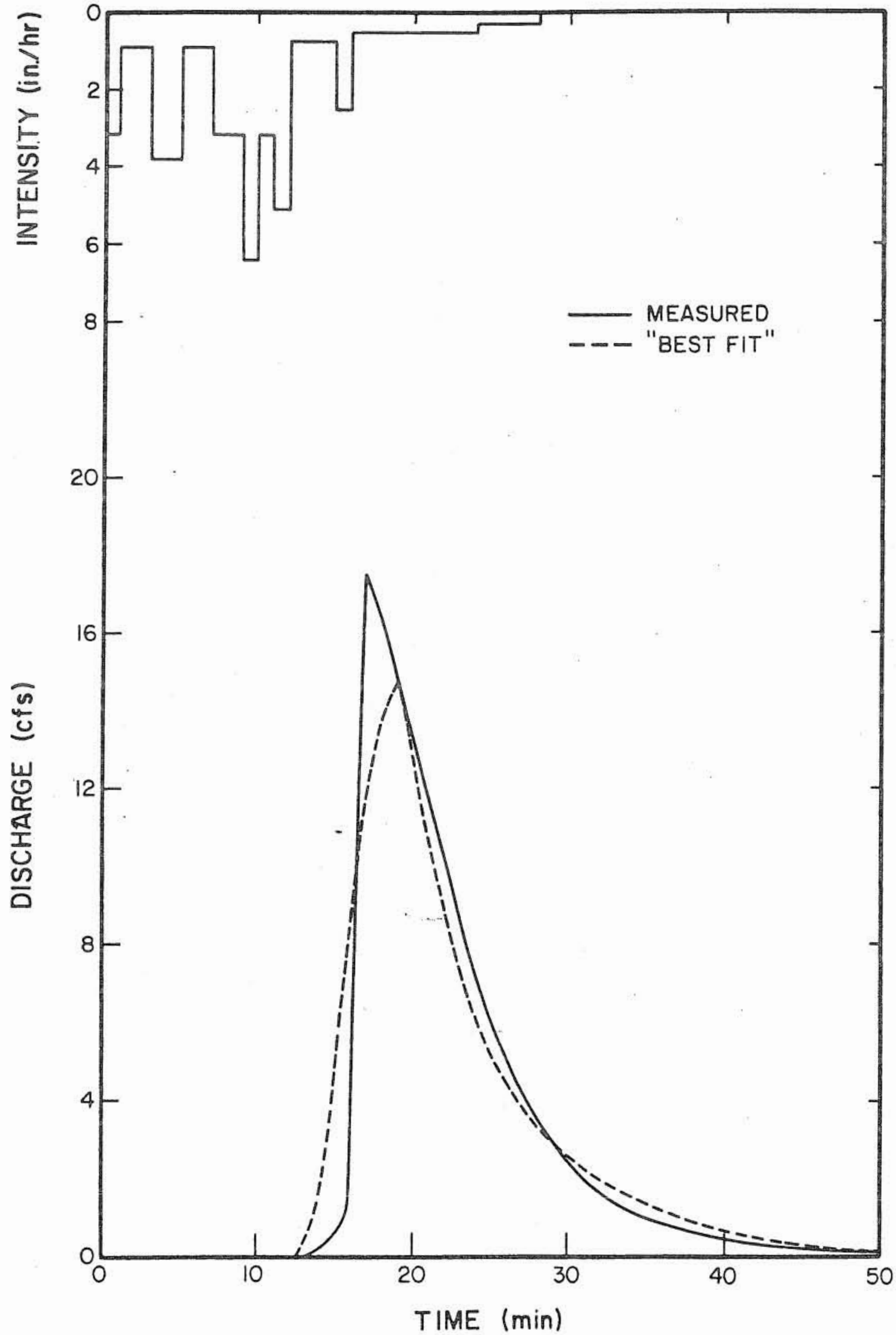

Figure B.11 Comparison of Measured and Simulated Hydrographs for the Storm Event of April 19, 1977 on ISU-1. (Note: Measured Sediment Yield = 33120 lbs)

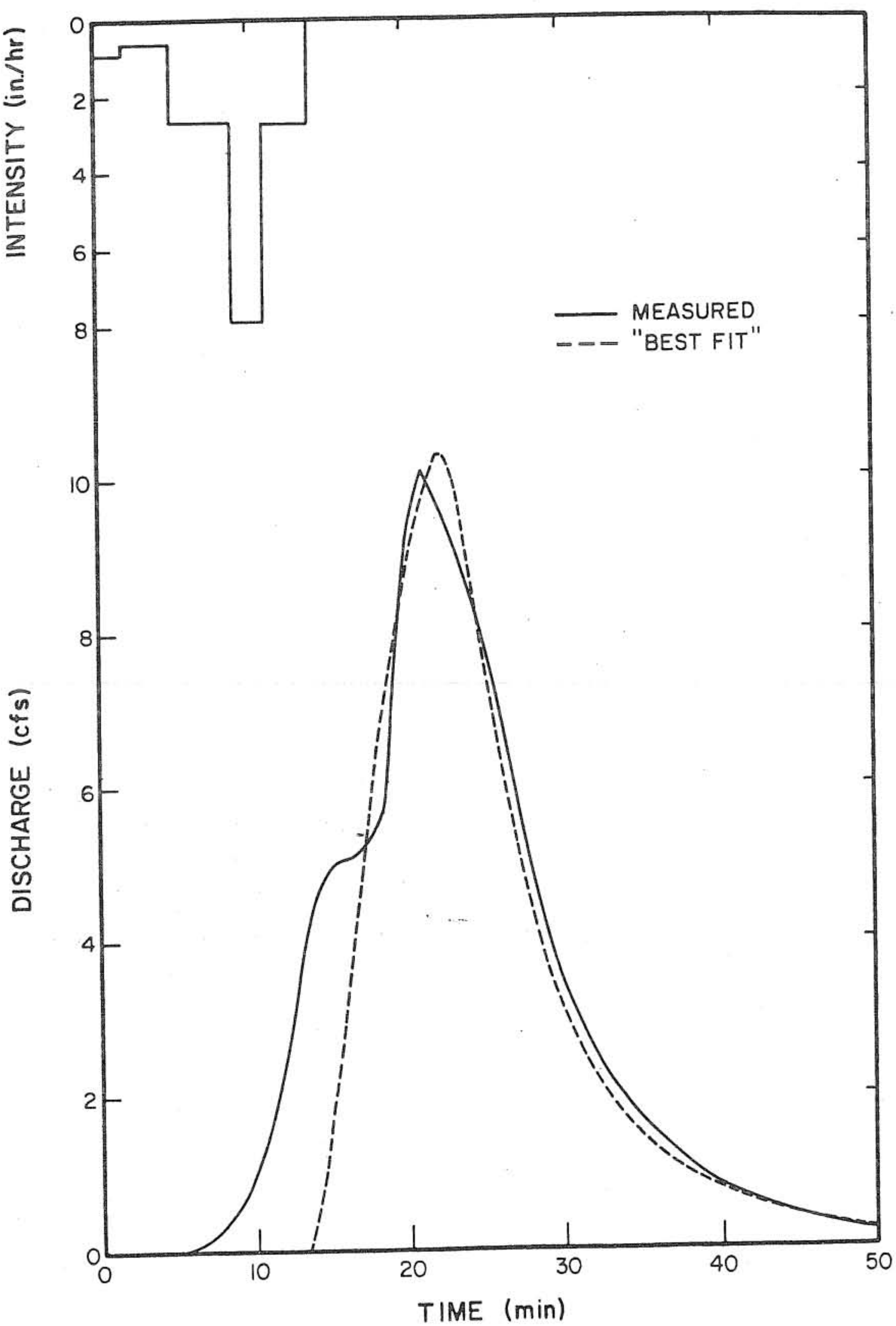

Figure B.12 Comparison of Measured and Simulated Hydrograph for the Storm Event of August 15, 1977 on ISU-1. (Note: Measured Sediment Yield = 8550 lbs)

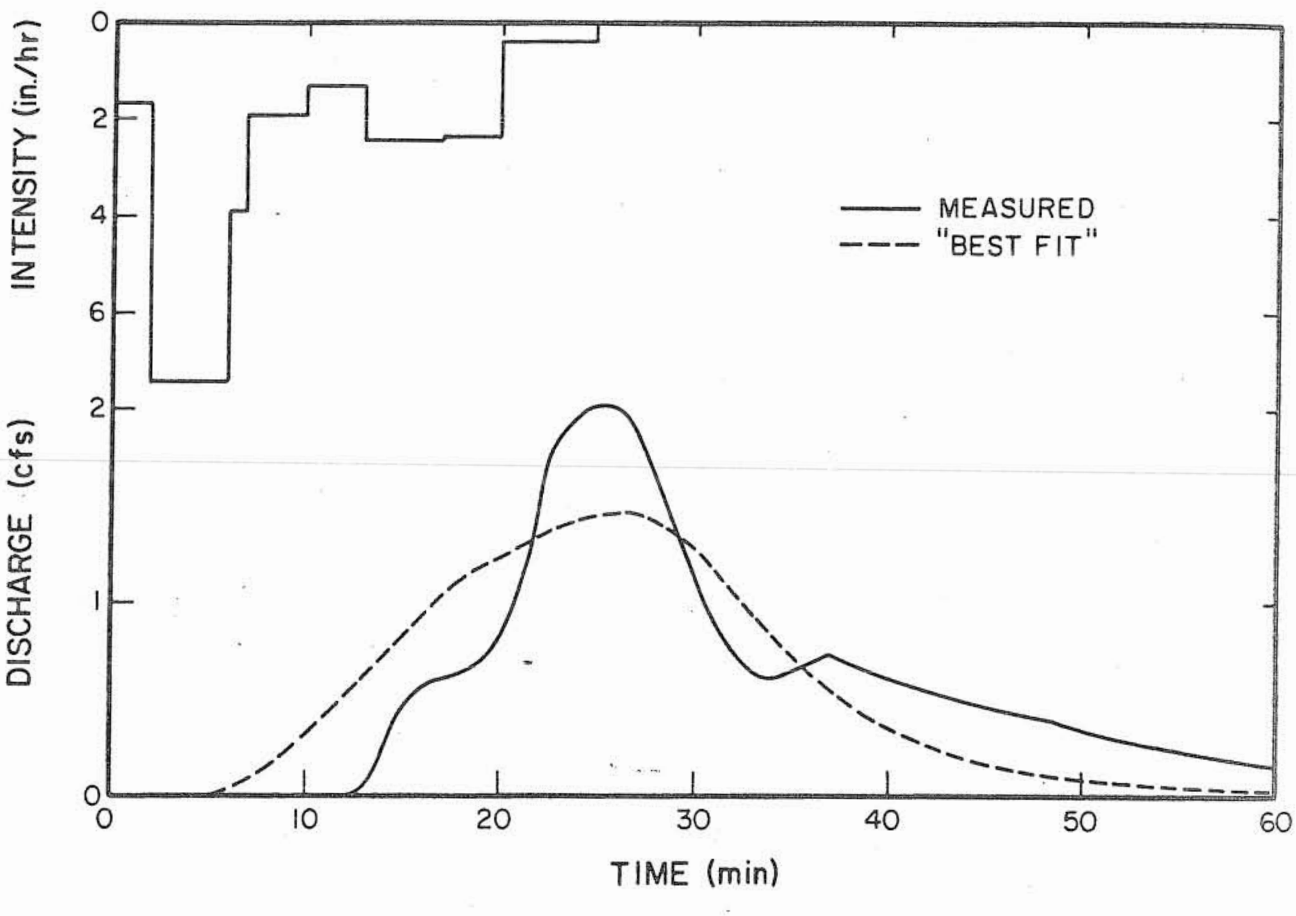

Figure B.13 Comparison of Measured and Simulated Hydrographs for the Storm Event of May 27, 1978 on ISU-1. (Note: Measured Sediment Yield = 2280 lbs)

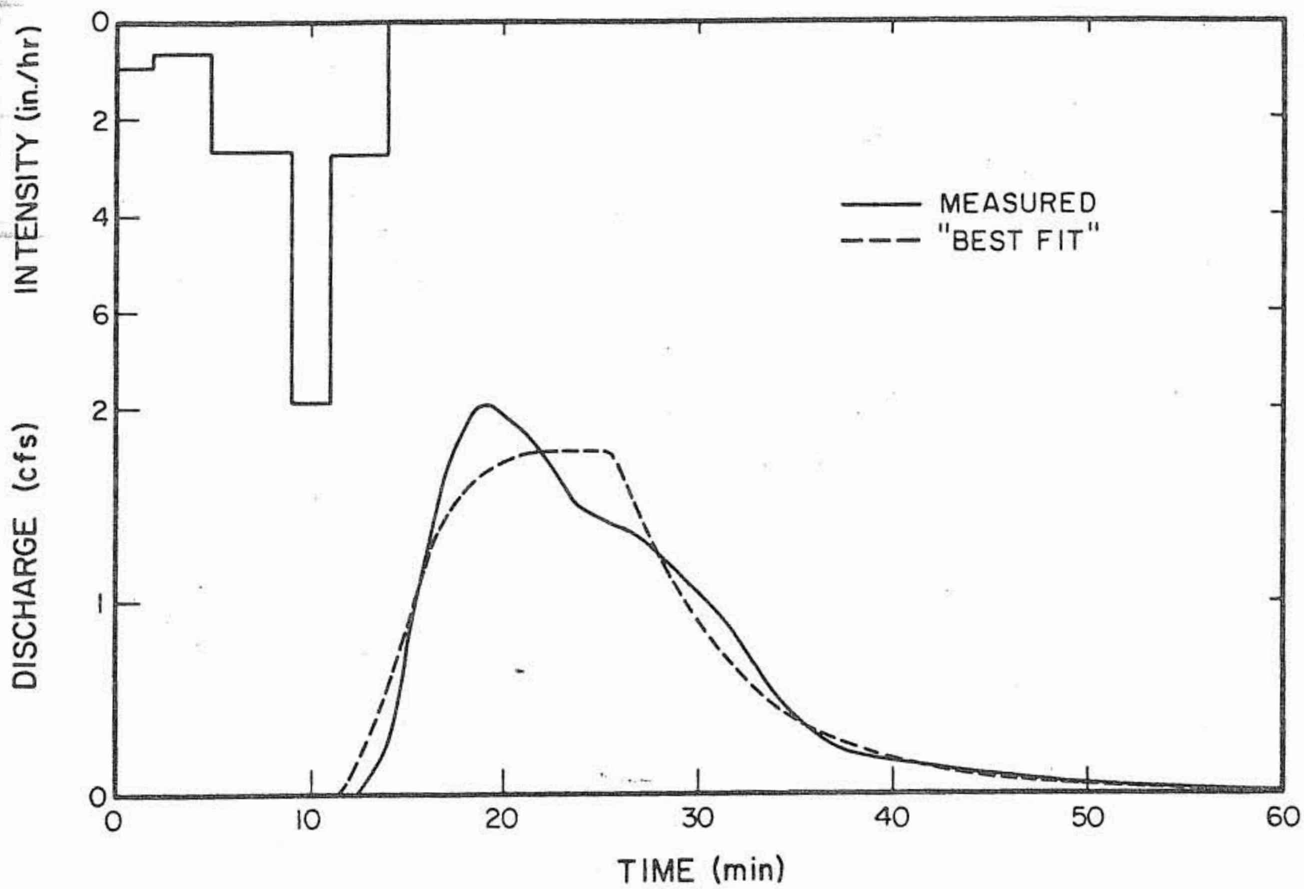

Figure B.14 Comparison of Measured and Simulated Hydrographs for the Storm Event of August 15, 1977 on ISU-2. (Note: Measured Sediment Yield = 3490 lbs)

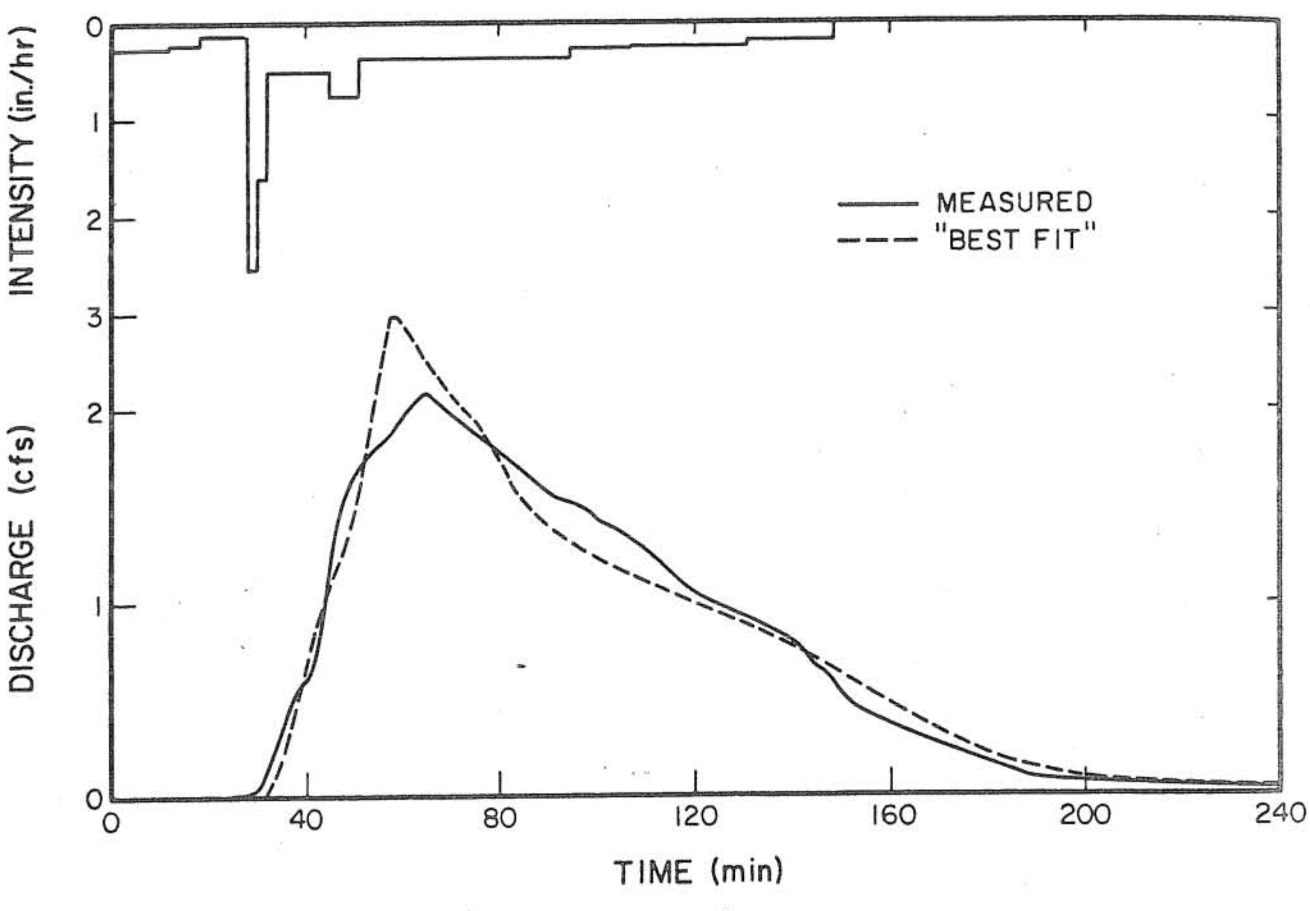

Figure B.15 Comparison of Measured and Simulated Hydrographs for the Storm Event of April 18, 1978 on ISU-2. (Note: Measured Sediment Yield = 1270 lbs)

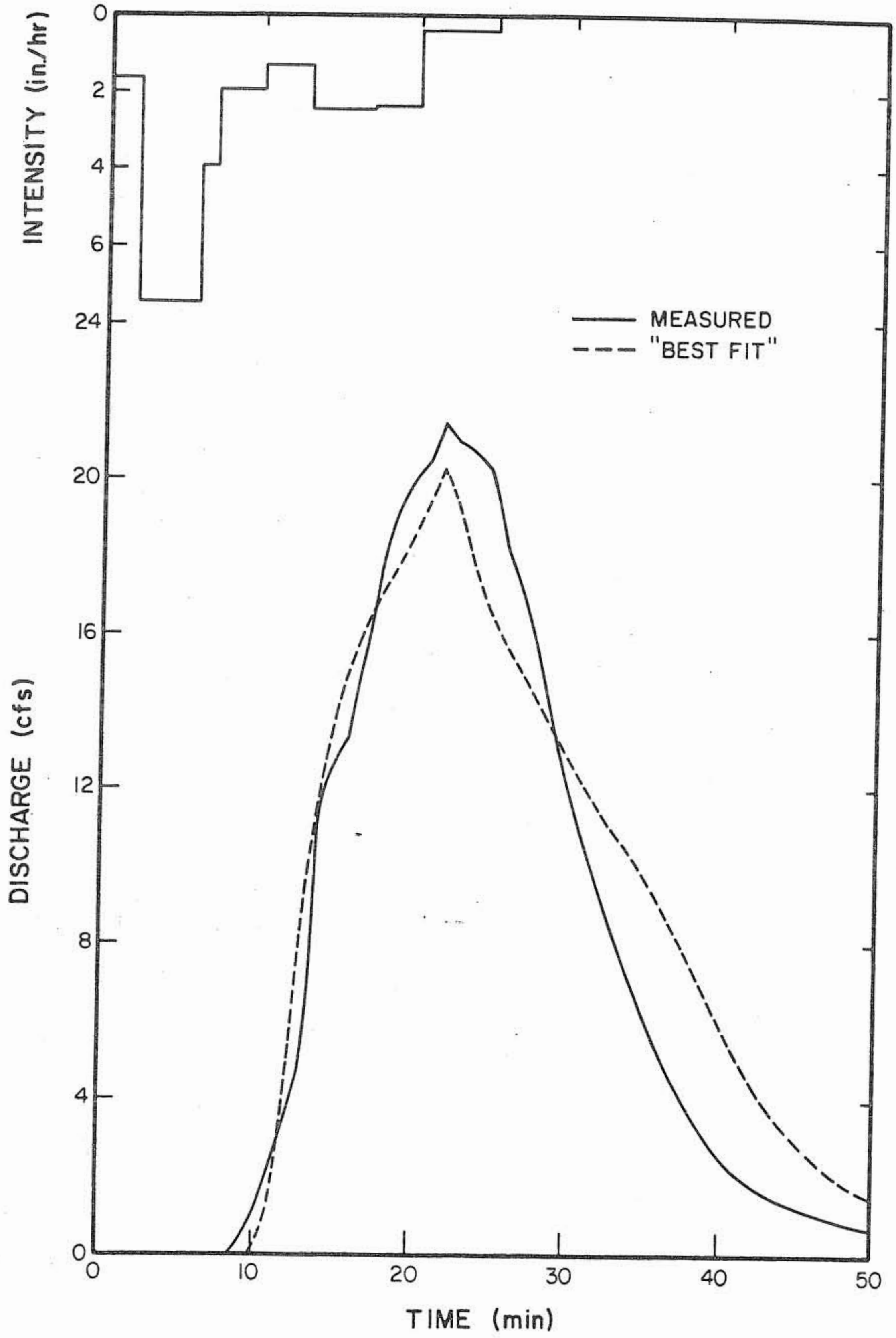

Figure B.16 Comparison of Measured and Simulated Hydrographs for the Storm Event of May 27, 1978 on ISU-2. (Note: Measured Sediment Yield = 25000 lbs)

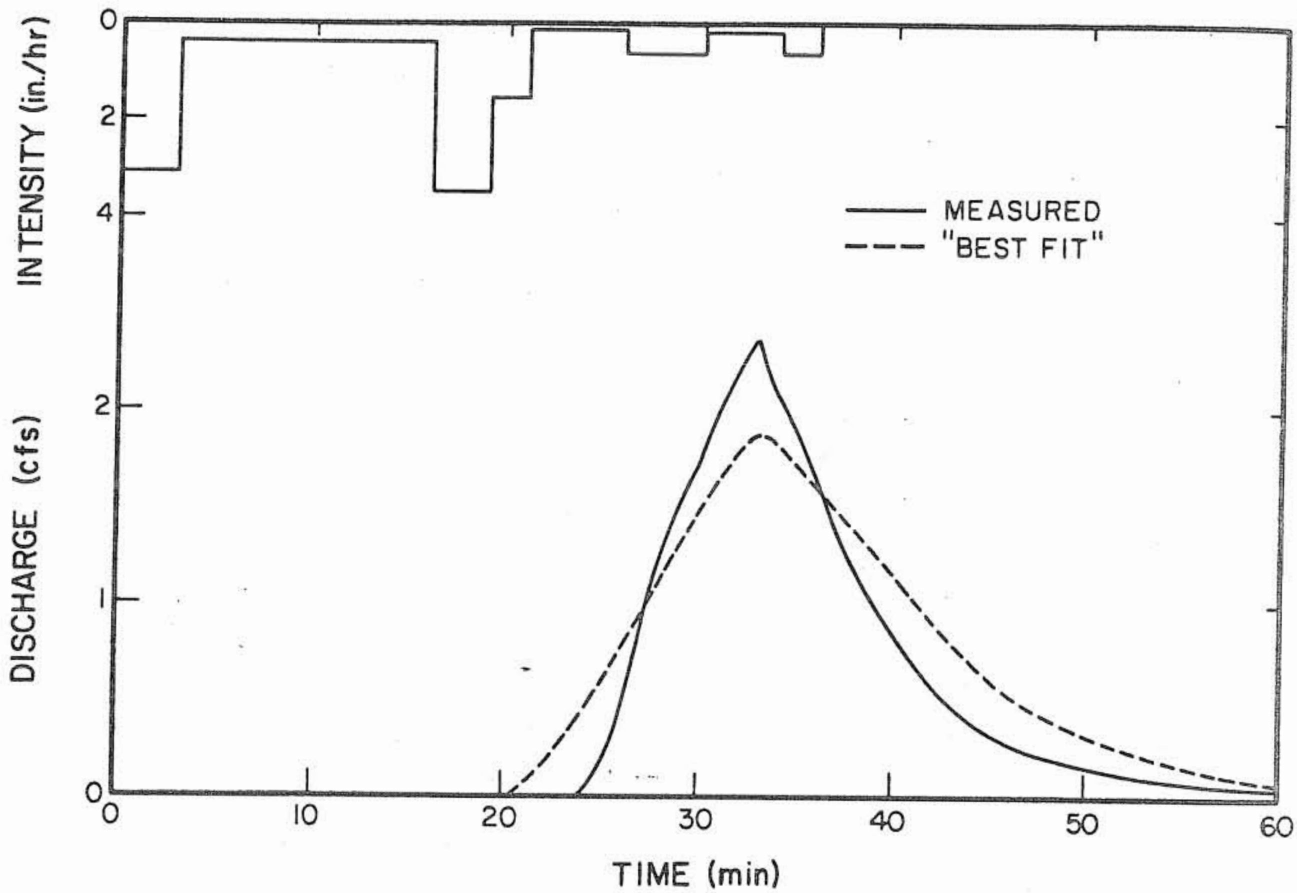

Figure B.17 Comparison of Measured and Simulated Hydrographs for the Storm Event of May 31, 1978 on ISU-2. (Note: Measured Sediment Yield = 1940 lbs)

APPENDIX C

Errors in MULTSED Codes

This appendix contains detailed descriptions of five errors present in existing MULTSED codes (discussed briefly in Chapter 3) and the steps necessary to correct them.

The line numbers referred to below are assigned to each line of the program (including comment statements) by the ICE text editor. Thus, the line numbers are relative to the beginning of the program not the beginning of any of the subroutines.

Error 1

In the analytical model, MSED1, the channel sediment transport capacity was estimated as

Line 1374 SEDQ(ISED)=(1+SUSP)*SEDQ(ISED)*WPER*.667*PS

where SEDQ(ISED) = (Left hand side) the total sediment transport capacity in lbs for sediment of size ISED estimated via the Einstein, Meyer-Peter approach,

= (Right hand side) the bed load in lbs/ft assuming uniform sediment of size ISED estimated by the Meyer-Peter, Müller approach,

SUSP = the constant which via Einstein's formulation relates the suspended load as a function of bed load,

WPER = the wetted perimeter of the cross-section,

PS = the fraction of the total bed sediment of size ISED.

The Einstein, Meyer-Peter approach estimates the total sediment transport capacity in load per unit width of the channel. Thus to get the total load estimate, the Einstein, Meyer-Peter result should be multiplied by the channel top width. In MSED1, however, the hydraulic radius is used instead of the depth and so using the wetted perimeter is correct. Hence, this error can be corrected by simply removing the .667 in Line 1374.

Error 2

In the numerical water routing in MSED3, the DO loop beginning on line 233 and ending at line 301 (statement 300) routes the water through the channel reaches for each of the time steps. Just prior to entering this loop the subroutine UPLAT is called and in that subroutine the lateral inflow from the planes to the channel (QLAT) is determined. The numerical method estimates the channel infiltration for each reach in routine, CHINL, and then accounts for the channel infiltration in the routing scheme by reducing QLAT by an equivalent amount. As the routing continues downstream, QLAT is never reset to the true value (as determined by UPLAT) and so:

for reach 1 QLAT = QLAT(TRUE)

for reach 2 QLAT = QLAT(TRUE) - INFILTRATION IN REACH 1

and so on.

Thus, the more reaches the more water was lost. Figure C.1 illustrates this problem.

By naming the lateral inflow adjusted for infiltration QLATP and then routing QLATP and maintaining the true QLAT for each reach, the correct water yield is obtained. Figure C.1 also shows the corrected values of water yield versus the number of reaches. This result is what would be expected from an unconditionally stable numerical scheme with good convergence as described by Li et al. (18).

The required corrections are as follows:

```
LINE 256    CALL CHINL (K, SIN(K,J), QUP, DTS, A(K,J))
  to        CALL CHINL (K, SIN(K,J), QUP, DTS, A(K,J), QLATP)
LINE 257    500 ALAT = QLAT*DTS
```

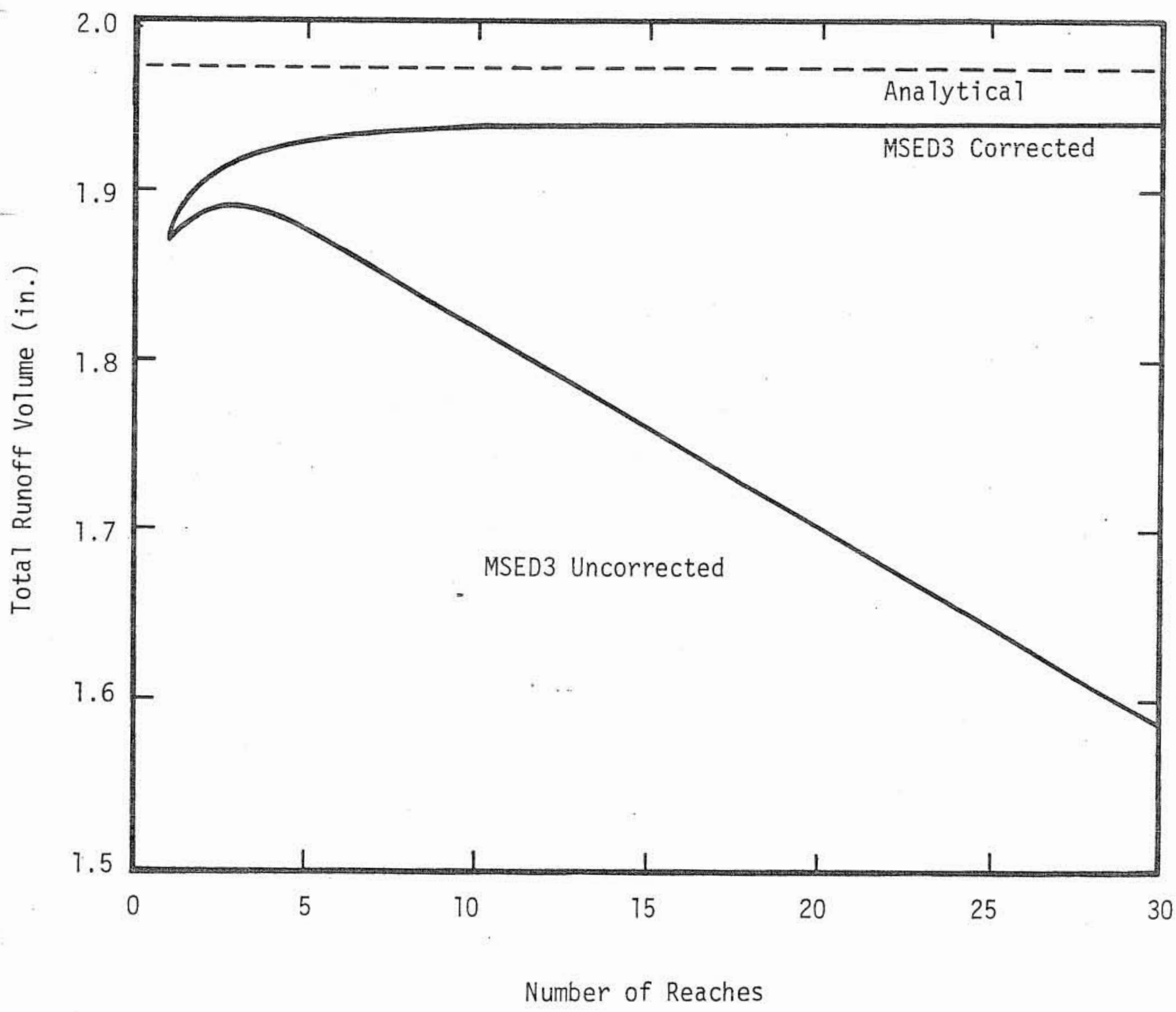

Figure C.1. Demonstration of the Water Routing Error in MSED3 for the Total Runoff Volume from a 5-year Return Period, 60 Minute Duration Uniform Intensity Storm on ISU-2 with 1% Ground Cover

```
  to         500 ALAT = QLATP*DTS

LINE 487     SUBROUTINE CHINL (K, SIN(K,J), QUP, DTS, A(K,J))

  to         SUBROUTINE CHINL (K, SIN(K,J), QUP, DTS, A(K,J), QLATP)

LINE 537     QLAT = QLAT - DELF/(SEGL*DTS)

  to         QLATP = QLAT - DELF/(SEGL*DTS)

LINE 544     QLAT = 0

  to         QLATP = 0
```

finally, insert after line 254 (QCONC = QUP+QLAT*SLEN(K)/NDX)

```
    QLATP = QLAT
```

Error 3

Simons et al. (28) state that, since the resistance due to a selected particle size also depends on the size of the particles around it, the resistance factor is not allowed to fall below half the value computed for the largest size. In addition, the resistance factor is not allowed to fall outside the range 0.1 to 0.01. The numerical model, MSED3, includes this procedure, but the analytical model, MSED1, does not. The necessary modifications of MSED1 are

```
LINE 1323     IF (F .GT. 0.10) F = 0.10

  to          IF (F .GT. FMAX) F = FMAX

LINE 1324     IF (F .LT. 0.005) F = 0.005

  to          IF (F .LT. FMIN) F = FMIN
```

Insert after line 1311 (SUMPS = 0.)

```
    FMAX = 1.5/(1.69+2*ALOG10(2.*HYRAD/DMBI(NSED)))**2
    IF (FMAX .GT. 0.1) FMAX = 0.1
    IF (FMAX .LT. 0.01) FMAX = 0.01
    FMIN = 0.5 * FMAX
```

Error 4

This error involves the determination of Einstein's integrals J_1 and J_2. In MSED1 the following statements occur:

```
LINE 1354          IF (ZR .GT. 5.5 .OR. AR .GT. 0.5) GO TO 107
LINE 1365    107   SUSP = 0.
```

While in MSED3:

```
LINE 709           IF (AR .GT. 0.9) GO TO 125
LINE 716     125   SUSP = 0.
```

By checking the integral evaluations for these alternate boundaries, one can determine which is truly correct. For AR = 0.9, J_1 = 0.005 and J_2 = 0.00037, while ZR = 5.5 and AR = 0.5 have much greater corresponding values of J_1 and J_2. Therefore, MSED1 should be corrected to agree with MSED3.

Error 5

The equation used in MULTSED to estimate rainfall splash detachment is

$$V_r = a_1 \, i^2 \, A(1 - \eta) \, A_b \qquad (C.1)$$

where V_r = the nonporous volume of material detached by raindrop splash,

a_1 = an empirically determined constant describing erodibility of the soil,

i = rainfall intensity,

A = area of the plane,

η = porosity of the soil,

A_b = an area reduction factor which represents the fraction of unprotected or bare soil in the plane.

In MSED1, A_b is found in subroutine PLANE as AR2:

```
LINE 1446   AR1 = 1-CG-FI+CG*FI
LINE 1447   AR2 = 1-AR1-CC+AR1*CC
```

where CG = fraction of ground cover,

FI = fraction of impervious cover,

CC = fraction of canopy cover.

AR1 is then the fraction of the plane area not covered by ground cover or impervious cover. Thus, AR1 represents that portion of the plane area which is subject to overland flow detachment. Hence, AR1 is used later in subroutine PLANE to adjust the overland detachment estimates:

LINE 1485 PS = PSI(ISED)*AR1

While this handling of AR1 is correct, when it is used to find AR2 it is not correct. AR2 is supposed to be the overall fraction of bare soil, and so it should be:

AR2 = 1.-(CG+FI-CG*FI)-CC+CC*(CG*FI)

AR2 = (1-CC)-(1-CC)*(CG+FI-CG*FI)

AR2 = (1-CC)*(1-CG-FI+CG*FI)

AR2 = (1-CC)*AR1 (C.2)

Therefore, by changing 1447 to Eq. C.2 above the program is corrected.

The reason this error was not detected earlier is because the effect of the rainfall splash detachment is masked when overland detachment is estimated. Overland detachment is taken as

$$
\begin{aligned}
V_f &= DOF(T_c - V_r) \qquad && \text{if } V_r < T_c \\
V_f &= 0 && \text{if } V_r \geq T_c
\end{aligned}
\tag{C.3}
$$

where T_c = overland transport capacity,

DOF = overland flow detachment coefficient.

If the overland flow detachment coefficient is fairly large the total sediment load:

$$
\begin{aligned}
V_t &= V_f + V_r \qquad && \text{if } V_r < T_c \\
V_t &= T_c && \text{if } V_r \geq T_c
\end{aligned}
\tag{C.4}
$$

will be a large fraction of the transport capacity regardless of the accuracy of the rainfall splash detachment. Table C.1 shows the effect of the error for varying values of overland flow detachment coefficient. The event simulated is the 5-year return period, 60-minute duration storm of uniform intensity occurring on the ISU-2 watershed with 10% ground cover (a_1 = 0.008). It is quite clear from Table C.1 that the error in the program could have caused the calibrated values of both the overland flow and raindrop splash detachment coefficients to be much greater than their true values.

Table C.1

Significance of Area Reduction Factor Error in MSED1

DOF	Corrected Sed. Yield (lbs)	Uncorrected Sed. Yield (lbs)	% Error	Corrected Sed. Yield (lbs)	Uncorrected Sed. Yield (lbs)	% Error
1.00	62323.	62323.	0.0	87322.	87322.	0.0
0.90	60795.	57097.	6.1	84343.	80029.	5.1
0.80	59266.	51870.	12.5	81364.	72735.	10.6
0.70	57738.	46643.	19.2	78385.	65441.	16.5
0.60	56209.	41417.	26.3	75406.	58148.	22.9
0.50	54681.	36190.	33.8	72427.	50854.	29.8
0.40	53152.	30963.	41.7	69448.	43561.	37.3
0.30	51624.	25737.	50.1	66468.	36267.	45.4
0.20	50095.	20510.	59.1	63489.	28793.	54.6
0.10	48566.	14620.	69.9	60510.	18832.	68.9

APPENDIX D

Einstein's Suspended Load Equation

A derivation of Einstein's (8) suspended load relation is presented below to demonstrate the nature of a modification for MULTSED.

Einstein found the suspended load per unit width of flow, q_s, to be

$$q_s = 11.6\ u_* C_a a_r [2.303 \log_{10} (\frac{30.2\ d}{\Delta})\ I_1 + I_2] \qquad (D.1)$$

where u_* = the shear velocity ($= \sqrt{gRS}$)

g = the gravitational acceleration constant,

R = the flow hydraulic radius,

S = the energy slope of the flow,

C_a = the reference sediment concentration at the level $y = a$ (in weight per unit volume of mixture),

a_r = the thickness of the bed layer (assumed to be $2*D_s$),

D_s = diameter of the sediment size, s, being considered,

d = the flow depth,

Δ = the apparent roughness diameter.

$$I_1 = 0.216 \frac{A_r^{z_r - 1}}{(1-A_r)^{z_r}} \int_{A_r}^{1} (\frac{1-y}{y})^{z_r} dy \quad ,$$

$$I_2 = 0.216 \frac{A_r^{z_r - 1}}{(1-A_r)^{z_r}} \int_{A_r}^{1} (\frac{1-y}{y})^{z_r} \ln (y)\ dy \qquad (D.2)$$

where $A_r = a_r/d$,

y = distance above the bed,

z_r = exponent of the suspended sediment distribution

$= V_s/(0.40\ u_*)$

V_s = settling velocity of a sediment particle of size D_s (determined by Rubey's equation, 25).

If the values in the integrals of I_1 and I_2 are defined as J_1 and J_2, respectively, Eq. C.1 becomes

$$q_s = C_a\ u_* a_r\ \frac{A_r^{z_r - 1}}{(1-A_r)^{z_r}}\ [5.75\ \log_{10}\ (\frac{30.2d}{\Delta})\ J_1\ +\ 2.5\ J_2] \qquad (D.3)$$

Einstein assumed the flow velocity distribution could be described by an equation based on von Karman's similarity theorem with the constants proposed by Kuelegan (15) (the combined form for turbulent flow is)

$$\frac{V}{u_*} = 5.75\ \log_{10}\ (12.27\ \frac{R}{\Delta}) \qquad (D.4)$$

where V = the mean velocity.

If we assume R ≈ d

$$5.75\ \log_{10}\ (30.2\ R/\Delta) = \frac{V}{u_*} + 2.25 \qquad (D.5)$$

Thus in MULTSED the suspended load is estimated as

$$q_s = C_a\ u_*\ a_r\ \frac{A_r^{z_r - 1}}{(1-A_r)^{z_r}}\ [(\frac{V}{u_*} + 2.5)\ J_1\ +\ 2.5\ J_2] \qquad (D.6)$$

The 2.5 is used instead of the 2.25 from theory to account for differences between R and d and for the effects of the channel boundary when defining

V as the mean velocity throughout the cross section. Based on experimental results Einstein found

$$C_a = \frac{i_B\ q_B}{11.6\ u_*'\ a_r} \tag{D.7}$$

where $i_B\ q_B$ = the bedload for the sediment size represented by fraction i_B

u_*' = the shear velocity corresponding to the grain resistance.

Hence, Eq. D.6 becomes

$$q_s = \frac{i_B\ q_B}{11.6}\ \frac{A_r^{\,z_r-1}}{(1-A_r)^{z_r}}\ \frac{u_*}{u_*'}\ [(\frac{V}{u_*} + 2.5)\ J_1 + 2.5\ J_2] \tag{D.8}$$

For practical computation of suspended sediment load Einstein recommended using u_*' in Eq. D.1 and in the calculation of z_r. Therefore, the final form of the suspended load equation becomes

$$q_s = \frac{i_B\ q_B}{11.6}\ \frac{A_r^{\,z_r-1}}{(1-A_r)^{z_r}}\ [(\frac{V}{u_*} + 2.5)\ J_1 + 2.5\ J_2] \tag{D.9}$$

where $z_r = V_s/(0.4\ u_*')$

$u_*' = (gR'S)^{1/2}$

R' = the portion of the hydraulic radius that Einstein related to the grain resistance

Equation D.9 is the form used in MULTSED, however, in MULTSED z_r is calculated using u_* instead of u_*'. This needs to be corrected.

Estimation of u_*'

As discussed above, u_*' represents that portion of the shear which is transmitted to the flow from the roughness of the grainy sand surface. As such, it represents the flow energy expended on the particle grains, and hence it reflects a cause of sediment motion. In Einstein's linear segmentation of the flow resistance (and the corresponding shear) into the portion due to grain resistance and the portion due to bed form resistance, he decided to segment the hydraulic radius into R' and R", respectively. Instead of segmenting the hydraulic radius, the friction slope could be segmented so that S' represents that portion of the friction slope which accounts for the bed resistance. Thus, u_*' becomes

$$u_*' = (gRS')^{1/2} \qquad \text{(D.10)}$$

Consider the Darcy-Weisbach flow resistance equation written to determine the friction slope

$$S = \frac{f}{4R}\,\frac{V^2}{2g} \qquad \text{(D.11)}$$

where f = the Weisbach resistance coefficient.

Thus,

$$S' = \frac{f'}{4R}\,\frac{V^2}{2g}$$

and

$$\tau' = \frac{f'}{8}\,\rho\,V^2 \qquad \text{(D.12)}$$

where f' = the Weisbach resistance coefficient corresponding to the grain resistance.

ρ = the density of water

τ' is already being used in MULTSED to calculate the bed load in the Meyer-Peter, Müller equation. Hence, u_*' can easily be estimated as

$$u_*' = (\tau'/\rho)^{1/2} \tag{D.13}$$