AN INTERACTIVE MODEL OF SUSPENDED SEDIMENT YIELD ON FORESTED WATERSHEDS IN CENTRAL ARIZONA

by

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INTRODUCTION

A prototypical computer simulation model which predicts suspended sediment concentrations in streamflow runoff has been developed to aid watershed management specialists and land use planners estimate the impacts of alternative management practices on suspended sediment yield. The model allows users at remote locations to readily obtain predictions of sediment yields with modest computer equipment and commonly available data. The model, called SED, is structured in an interactive format to facilitate operation by persons not familiar with computer operations. The model is written in ANSI Standard FORTRAN, requires approximately 5,000 words of core, and is currently operative on a DEC-10 computer at the University of Arizona. The prototypical version of SED has been developed to represent southwestern ponderosa pine forest and pinyon-juniper woodland ecosystems in central Arizona; however, the conceptual framework is considered applicable to other ecosystems.

CONCEPTUAL SIMULATION MODEL

Instantaneous suspended sediment concentration in surface runoff from a watershed has been represented by functions of several variables (Anderson, 1949, 1954; Rosa and Tigerman, 1951; Ursic and Dendy, 1963; Hansen, 1966). The time related variable changing most appreciably for a given storm event is discharge. Other variables often included in these representations are expressions of vegetative density, accumulations of organic material, etc. Parameters other than discharge are variable in a longer temporal sense, but are considered constant for a single runoff event. Concentration of suspended sediment is represented by a function of discharge for individual storm events.

Discharge is considered a function of time. With this in mind, a runoff event with a total runoff, Q, flowing for a time T is given as:

$$Q = \int_0^T q(t)\,dt \tag{1}$$

The volume of water, dQ_1, leaving a watershed in time element dt at time t_1 after initiation of surface runoff is given as:

$$dQ_1 = q(t_1)\,dt \tag{2}$$

This expression, multiplied by the instantaneous concentration of sediment, $f(q(t_1))$, at time interval dt, gives the weight of suspended sediment discharged, dW_s, in that interval. This is expressed as:

$$\begin{aligned} dW_s &= f(q)\,dQ \\ &= f(q)q(t)\,dt \end{aligned} \tag{3}$$

The integration of this relationship over the duration of the surface runoff event gives the total weight of suspended sediment carried by water as:

$$W_s = \int_0^T f(q)q(t)\,dt \tag{4}$$

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A surface event hydrograph is composed of both a rising and a receding component. If the crossover from one to the other component occurs at time T_1 after initiation of surface runoff, the weight of suspended sediment produced throughout the event, W_s, is given as:

$$W_s = \int_0^{T_1} f_1(q)q_1(t)dt + \int_{T_1}^{T} f_2(q)q_2(t)dt \qquad (5)$$

where:

$f_1(q)$ = concentration of suspended sediment for rising stage;

$q_1(t)$ = discharge function for rising stage;

$f_2(q)$ = concentration of suspended sediment for receding stage; and

$q_2(t)$ = discharge function for receding stage.

Here, the rising and receding sediment concentration functions are different for a given discharge.

As an approximation to a single surface runoff event, a hydrograph can be assumed to be of a triangular shape (Figure 1). Peak runoff rate, q max, is reached midway through the event, at time T/2. The rising and receding discharge functions are linear in the form:

$$q(t) = bt + c \qquad (6)$$

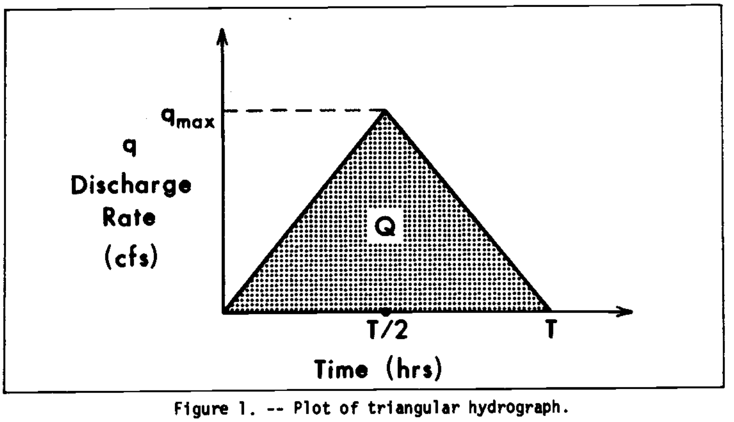

Figure 1. -- Plot of triangular hydrograph.

If the total volume of surface runoff is Q and the duration of the event is T, the discharge function may be written as:

$$Q = \int_0^{T/2} q_1(t)dt + \int_{T/2}^{T} q_2(t)dt \qquad (7)$$

or

$$Q = Q/2 + Q/2 \qquad (8)$$

Equation (8) is apparent by inspection of Figure 1. The discharge function q_1 and q_2 may be obtained either by applying boundary conditions at time t=0, t/2, and t, or through use of trigometric relationships illustrated in Figure 1. Using trigometric relationships results in:

$$Q = \frac{1}{2}Tq_{max} \qquad (9)$$

or, on rearranging:

$$q_{max} = \frac{2Q}{T} \qquad (10)$$

For the rising component of the hydrograph, the following relationships hold:

$$\frac{q_1}{t} = \frac{q_{max}}{T/2} = \frac{\frac{2Q}{T}}{T/2} \qquad (11)$$

or, on rearranging:

$$q_1 = \frac{4Q}{T^2}t, \quad 0 \leq t \leq T/2 \tag{12}$$

Similarily, the descending portion of the curve results in:

$$q_2 = \frac{4Q}{T^2}(T-t), \quad T/2 \leq t \leq T \tag{13}$$

The use of equations (12) and (13) in equation (14) yields a function which predicts the total suspended sediment weight by watershed and runoff event. This is expressed as:

$$W_s = \int_0^{T/2} f_1\left(\frac{4Q}{T^2}t\right)\left(\frac{4Q}{T^2}t\right)dt + \int_{T/2}^{T} f_2\left(\frac{4Q}{T^2}(T-t)\right)\left(\frac{4Q}{T^2}(T-t)\right)dt \tag{14}$$

SED has been written to numerically integrate equation (14) to yield total weight of suspended sediment discharged from a watershed in a surface runoff event of Q area inches, over T hours. The above relationships apply to water release during the summer. Winter release is approximated by a constant value throughout the day. A daily release of Q cubic feet would yield a constant flow, q_c, of:

$$q_c = \frac{Q}{86400} \text{ cfs} \tag{15}$$

Using this constant flow in the suspended sediment function, total daily suspended sediment yield is represented by:

$$W_s = f(q_c)Q \tag{16}$$

Equations for instantaneous suspended sediment concentrations have been developed to represent ponderosa pine forests and pinyon-juniper woodlands in central Arizona (Hansen, 1966). One set of equations for rising and receding components of a hydrograph, respectively, is given as:

$$\log(f_1(q)) = 2.48 - .02L + .66\log(q) - .65\log(q_a) \tag{17}$$

and

$$\log(f_2(q)) = 2.48 - .02L + .47\log(q) - .65\log(q_a) \tag{18}$$

where:

L = percent litter cover;

q_a = average annual streamflow (in inches);

$f_1(q)$ = suspended sediment concentration for the rising portion of the hydrograph (in ppm);

$f_2(q)$ = suspended sediment concentration for the receding portion of the hydrograph (in ppm); and

q = discharge (in cfs).

These relationships resulted from analysis of source data from watersheds ranging from less than 100 to over 2000 acres in size. These watersheds are covered with volcanic material, (primarily basalts, although there are smaller areas of cinders), agglommerates, and tuffs. The heavy clay soils derived from the surface material have a high rock content (Williams et al., 1967).

Relationships similar to the above can be assembled from existing source data from other locations, with resultant equations readily incorporated into SED. The ability to introduce other sediment response functions into the prototypical model has been one of the main design criteria in the development of this simulator. This feature should be useful in predicting suspended sediment concentration in locations other than Arizona. For example, source data from Colorado and Minnesota are currently being analyzed for development of appropriate functions for those locations.

APPLICATION OF MODEL

Perhaps the best way to illustrate the application of SED in simulating concentrations of suspended sediment in surface runoff is through an example. For illustration, a hypothetical 2,500 acre watershed of southwestern ponderosa pine forest is examined to estimate effects of vegetation manipulation on suspended sediment concentration.

Operation of the model begins with a question as to which type of output, daily or instantaneous, is requested (Figure 2). In the hypothetical example, daily values will be used. As such, the question is answered by entering a 'D'. Next, the simulator queries the user as to the nature of the surface runoff event, i.e., summer or winter. A summer event is to be simulated in the example, requiring a

'YES' in response to SUMMER STORM (YES/NO, CR GIVES YES)?[1]

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SED: DO YOU WANT DAILY (D) OR INSTANTANEOUS (I) VALUES ? D
SUMMER STORM (YES/NO, CR GIVES: YES) ?
WATERSHED AREA (ACRES) ? 2500
ENTER "L" TO INPUT LITTER COVER AND STREAMFLOW DATA,
  OR "V" TO INPUT OVERSTORY VOLUME DATA. L
LITTER COVER IN PERCENT (CR GIVES: 60) ? 76
ANNUAL STREAMFLOW IN IN./YR. (CR GIVES: 2.9) ?
DURATION OF RUNOFF IN HOURS (MAX = 24) ? 20
ENTER DAILY STREAMFLOW.

STREAMFLOW IN INCHES (ENTER -1 TO EXIT) ? .1
TOTAL WEIGHT OF SUSPENDED SEDIMENT =    1285. POUNDS.
MAX. SED. CON.=       38. PPM.
MAX. DISCHARGE=       25.1 CFS.

STREAMFLOW IN INCHES (ENTER -1 TO EXIT) ? .25
TOTAL WEIGHT OF SUSPENDED SEDIMENT =    5539. POUNDS.
MAX. SED. CON.=       70. PPM.
MAX. DISCHARGE=       62.8 CFS.

STREAMFLOW IN INCHES (ENTER -1 TO EXIT) ? -1
ANOTHER VEGETATION DENSITY (YES/NO, CR GIVES: NO) ? YES
LITTER COVER IN PERCENT? 44
ENTER DAILY STREAMFLOW.

STREAMFLOW IN INCHES (ENTER -1 TO EXIT) ? .1
TOTAL WEIGHT OF SUSPENDED SEDIMENT =    5609. POUNDS.
MAX. SED. CON.=      167. PPM.
MAX. DISCHARGE=       25.1 CFS.

STREAMFLOW IN INCHES (ENTER -1 TO EXIT) ? .25
TOTAL WEIGHT OF SUSPENDED SEDIMENT =  24181. POUNDS.
MAX. SED. CON.=      306. PPM.
MAX. DISCHARGE=       62.8 CFS.

STREAMFLOW IN INCHES (ENTER -1 TO EXIT) ? -1
ANOTHER VEGETATION DENSITY (YES/NO, CR GIVES: NO) ?
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Figure 2. -- Hypothetical example of SED.

The area of the watershed is requested by WATERSHED AREA (ACRES)? A response of 2500 is given (Figure 2).

The next question posed is which response function is to be used in the prediction of suspended sediment concentration. Two alternative response functions are available; both have about the same "goodness" of fit, as measured by the coefficient of determination. Depending on the input data available, the user selects the appropriate function. For example, it is assumed that percent litter cover and annual streamflow data are available. The choice of using this data set is conveyed to the simulator by a response of 'L' to ENTER 'L' TO INPUT LITTER COVER AND ANNUAL STREAMFLOW DATA, OR 'V' TO INPUT OVERSTORY VOLUME DATA. The values for these two parameters are then requested. First the litter cover value is requested, with a default value of 60 percent offered.[2] In the example, however, a value of 76 percent is considered appropriate; this corresponds to a ponderosa pine forest overstory density of 60 square feet of basal area per acre. Next, average annual streamflow is requested. The default value of 2.9 inches is selected.

Two streamflow discharges will be examined in the example, with the duration of both events held at 20 hours. This value is input in response to DURATION OF RUNOFF EVENT IN HOURS (MAX=24)?

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1. The response of YES may be input to the computer either through depressing the carriage return, CR, key or by typing 'YES'. For the example, the carriage return key was depressed.

2. In many instances, a default value representing the "best" or "most frequent" response to a statement or question is offered to a user in the version of SED. Acceptance of a default value allows a simulation exercise to continue without explicit knowledge of the input requested. It should be noted, however, that the user has the option of overriding any default value offered, if desired.

The simulator requests the daily streamflow in inches. For the example a value of 0.1 is input.

At this point, SED outputs total weight of suspended sediment produced from the watershed in one day (pounds), maximum sediment concentration (ppm), and the maximum discharge (cfs).

Following this, a streamflow of 0.25 is conveyed to the simulator, and outputs representing this example are generated (Figure 2).

These are the only discharges we wish to evaluate; therefore, the question of STREAMFLOW IN INCHES (ENTER -1 to EXIT)? is answered with a '-1'. The simulator then asks if the forest overstory density is to be modified. For the example, we will reduce density by 50 percent. The simulator is informed of our intentions by a 'YES' response to the question of ANOTHER VEGETATION DENSITY? Litter cover is input at 44 percent, corresponding to a basal area of 30 square feet per acre, while the annual streamflow is held constant. The simulation is carried out using the same discharge values as before (i.e., 0.1 and 0.25). As expected, suspended sediment yield increased due to the reduction of the vegetation density.

Computations for the hypothetical example are completed; therefore, the response to the question ANOTHER VEGETATION DENSITY? was NO, causing the program to terminate.

INTERACTIONS WITH OTHER MODELS

While this simulator has been designed to operate alone, it has also been structured to be linked with other simulators, if desired. SED is part of a family of computer models being developed to help watershed management specialists and land use planners estimate impacts of alternative land management practices. This family, called ECOSIM (Ecosystem COmponents SImulation Models), includes three general modules: FLORA for estimating responses of forest overstory, herbaceous understory, and organic material; FAUNA for evaluating animal habitats, carrying capacities, and population dynamics; and WATER for assessing streamflow yield, sedimentation, and chemical quality (Larson et al., 1978). SED is a component of the WATER module, with interfaces to many of the other modules within ECOSIM.

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