THE WEPP WATERSHED MODEL: II. SENSITIVITY ANALYSIS AND DISCRETIZATION ON SMALL WATERSHEDS

C. Baffaut, M. A. Nearing, J. C. Ascough II, B. Liu

ABSTRACT. *The Water Erosion Prediction Project (WEPP) watershed scale model was developed by the USDA for purposes of erosion assessment and conservation planning. The purpose of this study was to verify that the watershed model behaves rationally and consistently over a range of discretization structures and channel parameter inputs for applications to small watersheds. Effects of watershed discretization were evaluated for selected events within a one-year continuous simulation by comparing results for two watersheds under various discretization schemes. Impacts of channel input parameters were assessed by comparing the value of a linear sensitivity coefficient for user-specified parameters. Hillslope length, Manning's coefficients, and channel slope were found to be key parameters in the prediction of watershed sediment yields. Erodibility and critical shear stress were found to be important for events where channel scour was active, and the results were sensitive to the hydraulic conductivity for events with small runoff and small sediment contributions from hillslopes. Improvements in the WEPP model are suggested where limitations were observed.*

Keywords. *WEPP, Sensitivity analysis, Discretization, Runoff, Erosion, Modeling, Hydrology.*

The Water Erosion Prediction Project (WEPP) model is a continuous simulation model for predicting erosion and deposition due to surface runoff from rainfall, irrigation, and snowmelt. It is based on fundamental hydrological and erosion processes (Flanagan and Nearing, 1995). The watershed version of the model is described in part I of this series (Ascough et al., 1997).

The first important questions a user faces when trying to model a watershed are: "What channels should be represented in the model?" and "How many hillslope profiles should be used to characterize an area?" The process of identifying the channels and the hillslopes which represent the watershed components is called the watershed discretization. For permanent channels such as terrace channels or grassed waterways, it may be intuitive to model all of them. For a larger watershed, however, the representation of all channels adds to the cost of data preparation and required computer time and may not increase accuracy. The problem is more difficult for impermanent channels or flow paths than for permanent channels. Which one should be represented? Is there a threshold size below which flow should be considered overland flow? Where does a channel start? Depending on which channels are represented, the hillslope profiles, the direction of flow on the hillslopes, and the way they feed the channels (laterally or at the inlet) vary. The level of discretization greatly influences the data requirement and the required computer time, increasing them with the number of hillslopes and channels used.

Other questions that a user quickly faces are: "What values should be assigned to each channel parameter?" and "What parameters are the most important to estimate accurately?" The wide range of conditions that WEPP can represent requires a large number of parameters to characterize the various hillslopes and channels. Previous studies discussed the parameter sensitivity analysis and uncertainty propagation for the hillslope version of WEPP. A sensitivity analysis of the hillslope input parameters was performed for cropped land on a single event basis (Nearing et al., 1990), wherein a linear sensitivity coefficient was chosen to quantify and compare the sensitivity of the model results to input parameter variations. Deer-Ascough (1995) conducted a comprehensive sensitivity and uncertainty analysis of the hillslope model, which included a sensitivity analysis of the input parameters, first order error analysis, and Monte Carlo simulations. Chaves and Nearing (1991) used the Point Estimate Method (Herr, 1987) to assess the uncertainty of WEPP results under cropping conditions. Expected output values and their variance were calculated in terms of the mean and variance of the input values, and the correlation coefficient between input variables.

Another sensitivity analysis was performed by Tiscareno-Lopez et al. (1993, 1994) for rangeland conditions. His methodology, based on a Monte Carlo simulation and the calculation of sensitivity indices, gave a measure of the variation of results due to input uncertainty and assessed the sensitivity of the model to hillslope parameters (Tiscareno-Lopez et al., 1993) and channel parameters (Tiscareno-Lopez et al., 1994). Sensitivity indices were calculated from the regression coefficients of the linear regression equation obtained when several parameters were varied simultaneously and independently.

Article was submitted for publication in March 1996; reviewed and approved for publication by the Soil & Water Div. of ASAE in April 1997.

The authors are **Claire Baffaut**, Scientist, **Mark Nearing**, ***ASAE Member Engineer,*** Scientist, and **Bao-Yuan Liu**, Scientist, National Soil Erosion Research Laboratory, USDA-ARS, Purdue University, West Lafayette, Ind.; and **Jim Ascough II**, ***ASAE Member Engineer,*** Agricultural Engineer, Great Plains Systems Research Unit, USDA-ARS, Fort Collins, Colo.. **Corresponding author:** Mark A. Nearing, NSERL, USDA-ARS-MWA, Purdue University, 1196 Soil Bldg., West Lafayette, IN 47907-1196; tel.: (765) 494-8697; fax: (765) 494-5948; e-mail: <nearing@ecn.purdue.edu>.

Tiscareno-Lopez used the single event watershed model and applied it on a small watershed under semi-arid rangeland conditions. Soil erodibility parameters, precipitation characteristics, soil composition, and vegetation (litter and biomass) were considered. The channel topography and the watershed discretization were not investigated.

No study has tested the WEPP watershed model using a wide range of channel parameters. This is an important step to confirm the basic reliability of the watershed version of WEPP. The simulation results need to be within expected values for all possible input parameters. Additionally, the variations of the results need to be consistent with the variations of the input parameters (McCuen and Snyder, 1986). This step in model testing also reveals the channel parameters to which the model is most sensitive. Also, for the watershed version, it is important to know the impact which the level of discretization has on the results. Because of the decreased time in data preparation and computer run-time for lower levels of discretization, users may be tempted to choose a coarse level. It is important to evaluate the sensitivity of the results to the amount of detail in the data and to estimate the level of discretization which is appropriate.

The objectives of this study were: (1) to investigate some of the more important aspects of watershed discretization effects on the model response; and (2) to perform a sensitivity analysis for channel parameters which are user-defined. The study was directed toward small watersheds, i.e., of approximately 1 ha in size. Considerable work has been conducted with WEPP on the hillslope scale, but relatively little has been conducted on the watershed scale. Even though WEPP is designed for use on areal sizes ranging from small hillslopes to larger watersheds, the smaller watershed size was targeted because: (1) it is considered the next step in the model evaluation process in moving from the slope to watershed scale of application; and (2) WEPP is designed with intended use primarily for application at smaller scales.

METHODS

DISCRETIZATION

Two series of tests were designed to evaluate the response of the model to increasing levels of discretization. The first test series used a 200 m wide × 50 m long hillslope drained laterally by a 200 m long channel (fig. 1). The channel and hillslope were then divided in 2, 4, and 8 parts. The purpose of the test was to determine the effect of the number of channels and hillslopes used with the same basic watershed geometry and size. The channel was assumed to be triangular with a constant 4% slope and to have conditions of normal (rather than critical) depth for the flow at the outlet. The Rational equation option was used to estimate peak flows for all tests. The hillslopes had a 9% slope. Simulation conditions include a Miami soil and a conventional alfalfa scenario for both hillslopes and channels, and a one year climate file constructed with the CLIGEN weather generator (Nicks et al. 1995) at the station of Greensboro, Alabama. CLIGEN uses statistically summarized weather data from a particular weather station or sequence. The CLIGEN input data from Greensboro were derived from National Weather Service records. The total and bare soil Manning's coefficient values were respectively assumed to be 0.04 and 0.015.

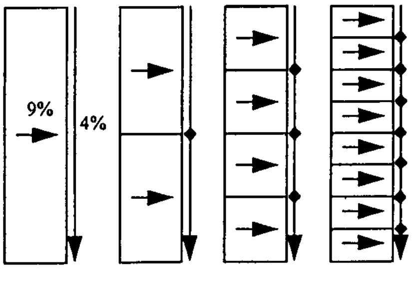

Figure 1–Watershed discretization used in test series #1. Rectangles represent hillslope element, and the arrows in the boxes represent direction of flow on the hillslope. Arrows outside of boxes represent channels.

The second series of tests used a 1 ha (100 × 100 m) area (fig. 2), drained by a channel network of increasing complexity. At the first level, one channel divided the area into two identical hillslopes. This area was then divided into up to 15 different hillslopes drained by nine channel elements. Soil and management characteristics remained constant for all tests: a conventional alfalfa scenario and a Miami soil for both hillslopes and channels. Channels elements were all triangular with a uniform 4% slope. Hillslopes had a 9% uniform slope. The climatic data and Manning's coefficient values were the same as in the previously described tests.

Yearly values of soil loss and peak flow discharge rates were compared for the different test cases. In addition, discretization impact was assessed using predicted soil loss and peak flow discharge rates for the generated events of 9 January, 1 March, 4 May, 2 August, 12 October, and 23 December. These six events were selected because they caused significant erosion on the watershed and they were representative of different seasons and management phases. Among these, 1 March and 12 October had the lowest maximum intensities (table 1). May 4 and 23 December were high intensity events that followed one or more days of rainfall. August 2 was the highest intensity event and the conditions were relatively dry, i.e., rainfall had not

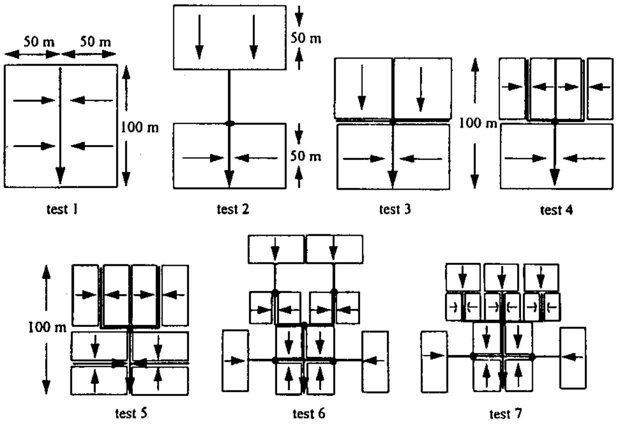

Figure 2–Structure of the watersheds used in test series #2. Rectangles represent hillslope element, and the arrows in the boxes represent direction of flow on the hillslope. Arrows outside of boxes represent channels.

Table 1. Characteristics of the six selected rainfall events as generated by CLIGEN for Greensboro, Ala.

Date	Precipitation (mm)	Duration (h)	Time to Peak (h)	Max. Intensity (mm/h)
9 January	44.9	1.67	1.40	193
1 March	29.7	1.23	0.02	52
4 May	53.8	3.89	0.47	181
2 August	31.3	1.90	0.00	254
12 October	43.0	4.37	0.35	87
23 December	90.0	7.96	0.24	208

occurred in the previous two weeks. The 9 January storm characterized a strong winter event.

In terms of quantitative comparison, we used here the criteria which has been implicitly assumed by the WEPP developers of ±10% as an acceptable level of error (Lane and Nearing, 1989). Since treatments for the simulations result in unique values rather than sample distributions, it is not possible to perform statistical comparisons of means, such as l-tests or Duncan tests.

THE CHANNEL PARAMETERS

The third and last series of tests were designed to evaluate the sensitivity of the model response to changes in the channel parameters on small watersheds. A square, 1 ha area divided into four hillslopes and drained by three channel elements was used (fig. 3). Channel parameter values were modified individually over a wide range of possible values, with all other input parameters remaining constant. All hillslope parameters remained constant so as not to modify the flow and sediment input to the channels. We thus studied the parameters which affected channel erosion, runoff, and sediment routing: channel slope, channel bank slope or side-slope, channel critical shear stress, channel erodibility, channel hydraulic conductivity, and channel total and bare soil Manning's coefficients. Parameters that are internally updated by WEPP on a daily basis (such as soil moisture content, canopy and residue cover, soil consolidation, and surface sealing state) were not included in this study. The management conditions (conventional alfalfa scenario) also remained constant in this study. The goal of this experiment was to investigate whether trends in model response to parameter variations were in agreement with what was expected, and determine to which parameters the model was particularly sensitive.

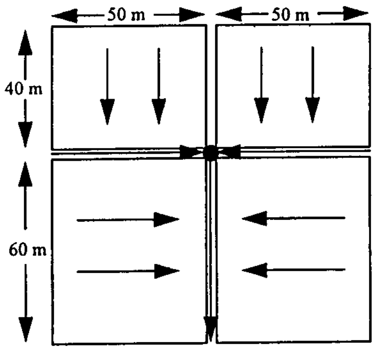

Figure 3–Structure of the watershed used for the channel parameter sensitivity analysis. Rectangles represent hillslope element, and the arrows in the boxes represent direction of flow on the hillslope. Arrows outside of boxes represent channels.

WEPP allows the user to define the type and shape of the watershed outlet structure, if one is present. This option was intended primarily for use in gauged watersheds where the collection flume may cause some effect on the outflow from the channel. In these studies we considered that the channel ended in hydraulically normal flow with no constrictions or backflow caused by flumes or other structures, and that the characteristics of the channel outlet were the same as for the entire channel.

To quantify the impact of the output variation over a range of values of an input parameter, a relative sensitivity index (McCuen and Snyder, 1986) was calculated:

$$S = \frac{\dfrac{O_2 - O_1}{O_{\overline{12}}}}{\dfrac{I_2 - I_1}{I_{\overline{12}}}} \qquad (1)$$

where I_1 and I_2 are the minimum and maximum value of input used respectively, $I_{\overline{12}}$ is the average value of I_1 and I_2, O_1 and O_2 are the associated outputs for the two input values, and $O_{\overline{12}}$ is the average of O_1 and O_2. S represents a normalized change in output to a normalized change in input. Because it is independent of the magnitude of the input and the output, its value can be used to compare the sensitivity of the model to different variables.

The use of this sensitivity index does not account for interactions between variables. Several model error and sensitivity studies have been conducted on the WEPP hillslope model. These may assume independence of variables (e.g., Nearing et al., 1990) or inter-dependence of variables (e.g., Chaves and Nearing, 1990). This study is limited in scope to the broad assumption of parameter independence and no linkage between hillslope and channel parameters. In other words, the assumptions are strong, and the study represents a first step rather than comprehensive study of the model. Sensitivity indices were evaluated for annual average values of response and for the six events discussed previously.

In most cases, the sensitivity index was calculated between the minimum and maximum input value of the parameter, i.e., a global analysis was conducted. In some instances, the response was not gradual because different processes were active depending on the level of the parameter value. For example, there may be deposition in the channel at low erodibility values, sediment transport only for intermediate erodibility, and soil detachment for the higher erodibility. In those cases, plots of the response function versus input variables were constructed in order to assess how the sensitivity of the model varied over the range of the input values.

RESULTS AND DISCUSSION

LEVEL OF DISCRETIZATION — TEST 1

As the discretization level increased, there was a trend toward increasing peak flow rate. The soil loss at the outlet of the watershed for the two events of 2 August and 12 October (table 2) in the 8-channel case gave estimates of both peak flow discharge rate and sediment yield which exceeded the

Table 2. Simulated peak runoffrates and sediment loads for the six rainfall events in Test Series No. 1

	9 January		1 March		4 May		2 August		12 October		23 December	
	Peak Flow (m^3/s)	Sed. Yield (kg)	Peak Flow (m^{3}s)	Sed. Yield (kg)	Peak Flow (m^3/s)	Sed. Yield (tonnes)	Peak Flow (m^3/s)	Sed. Yield (kg)	Peak Flow (m^3/s)	Sed. Yield (kg)	Peak Flow (m^3/s)	Sed. Yield (kg)
1 chant	0.168	867	0.058	144	0.182	29.1	0.111	1459	0.017	71.1	0.352	1147
2 chant	0.168	867	0.058	145	0.185	29.9	0.118	1545	0.019	76.1	0.352	1143
4 chan.	0.168	868	0.058	145	0.187	30.2	0.125	1641	0.020	81.8	0.352	1142
8 chant	0.168	870	0.058	146	0.188	30.5	0.140*	1848*	0.024*	97.6*	0.352	1143

* These data exceed 110% of the average response for each case.

† These data were less than 90% of the average response for each case.

±10% criteria. Peak flow rates and outlet sediment yields remained essentially constant for the other four events.

The increases of peak flow discharge rates and soil loss with the increase of the number of channel elements for the 2 August and 12 October events were not expected, since the total channel length remained constant and the lateral hillslope contribution was the same in each case. However, the results can be explained by the way the channel runoff is currently calculated in the WEPP model. For each channel element, the excess rain is calculated as a function of the rain characteristics, the soil characteristics, and the moisture condition. The runoff volumes from upstream elements are then added. Finally, recession infiltration (infiltration losses after rainfall stops) is calculated as a function of the time of equilibrium of the channel element, the runoff volume, and the rainfall duration. As runoff losses were calculated for channel elements in the upstream part of the watershed, the time of equilibrium was smaller, causing a decrease in calculated recession infiltration losses. For this reason, the runoff volumes and consequently the peak flow discharge rates and sediment loads increased as the channel was divided in smaller segments. The phenomenon was important when recession infiltration losses in the channels were high (2 August and 12 October events), and may be particularly important in arid or semi-arid conditions where channel infiltration rates are relatively high. The calculations made by WEPP for channels are analogous to those used to predict recession infiltration of overland flow on hillslopes. We recommend revision of the recession infiltration equations for channels to better account for the case where the watershed is more finely discretized with shorter channel segments.

LEVEL OF DISCRETIZATION — TEST 2

Loads and peak flow discharge rates from the six rainfall events described previously are presented in table 3. Generally, we observed a trend toward a decrease of the sediment load as the discretization level increased, except on 12 October where it remained constant and 2 August where it increased (table 3). There was a lesser trend for the case of peak discharge flow rates, but some differences in peak flows for the 4 May and 2 August events exceeded the 10% criteria.

Table 3. Simulated peak runoff rates and sediment loads for the six rainfall events in Test Series No. 2

	9 January		1 March		4 May		2 August		12 October		23 December	
	Peak Flow (m^3/s)	Sed. Yield (kg)	Peak Flow (m^{3}s)	Sed. Yield (kg)	Peak Flow (m^3/s)	Sed. Yield (tonnes)	Peak Flow (m^3/s)	Sed. Yield (kg)	Peak Flow (m^3/s)	Sed. Yield (kg)	Peak Flow (m^3/s)	Sed. Yield (kg)
Test 1	0.182	824	0.054	156	0.203	34.6*	0.162†	2170†	0.028	108	0.329	1064
Test 2	0.182	856	0.054	168*	0.204	41.8*	0.162†	2581	0.028	111	0.328	1169*
Test 3	0.183	820	0.054	153	0.206	34.0*	0.163†	2126†	0.028	108	0.331	1044
Test 4	0.203*	790	0.053	149	0.270*	30.1	0.224*	2521	0.031	109	0.337	1004
Test 5	0.161	754	0.051	146	0.167†	20.8†	0.199	2734	0.032	110	0.356	948
Test 6	0.161	758	0.051	145	0.168†	26.0†	0.198	3313*	0.032	109	0.356	993
Test 7	0.166	735	0.051	142	0.173†	24.6†	0.208	3275*	0.033	110	0.357	877†

* These data exceed 110% of the average response for each case.

† These data were less than 90% of the average response for each case.

For all events, the sediment loads at the outlet of the watershed followed the same trend as the hillslope contribution (data not shown). For the events of 9 January, 1 March, 4 May, and 23 December, the hillslope contribution to the channels decreased as the level of discretization increased. A higher level of discretization implies shorter hillslope lengths, which correspond to a decrease of the hillslope contribution because of a decrease in rill erosion (Nearing et al., 1990). On 12 October the hillslope contribution remained constant, and on 2 August it increased with the level of discretization (data not shown). The increase of the hillslope contribution on 2 August corresponds to an increase of the runoff from the hillslopes caused by the decrease of the recession infiltration, similar to the case of channels as discussed above for test series no. 1. This phenomenon is particularly noticeable for short and intense rain events, for which flow discharge continues after the rain has stopped, such as the 2 August event. Overall, the hillslope length is a dominant factor in determining watershed discretization.

The appropriate hillslope length for use in the model corresponds to the length beyond which water enters a channel. The length used should be representative of the geomorphology of the landscape. Field observation will provide the correct information on slope length. One might also refer to county soil maps to obtain guidance on hillslope length for a given area, keeping in mind that the USLE slope lengths identified in soil mapping units are shorter than the slope lengths required by WEPP. This is because WEPP simulates deposition on hillslopes as well as detachment while the USLE provides an estimate of soil loss only. While the WEPP slope length is the distance from the top of the slope to the point where the runoff enters a channel, the USLE length is defined as "the distance from the point of origin of overland flow to the point where the slope gradient decreases enough that deposition begins, or the runoff water enters a well defined channel" (Wischmeier and Smith, 1978). Further work needs to be conducted in evaluating complex watersheds where data is available to better define the appropriate hillslope lengths for a given application. In the meantime, the user needs to be cognizant of the issue and make informed estimates of appropriate hillslope lengths when using the model.

One additional point should be kept in mind regarding hillslope length and watershed discretization. Studies of the hillslope model have indicated that when slope length exceeds approximately 100 m WEPP tends to overpredict erosion (Nearing and Nicks, 1997). This limitation could place some significant restrictions on the sizes of watersheds to which WEPP may easily be applied with accurate results.

In addition to the length of the hillslope, the position of the hillslopes relative to the channel was also important. In the first three tests of series no. 2, hillslopes had all the same length and their total width was the same, yet flow discharge and sediment yield varied. The hillslope contribution in runoff and sediment was therefore identical; the only difference was the number of channels and the configuration of the watershed (hillslopes feeding the channel laterally or at its inlet). The third test of series no. 2 was different from the first one only by the number of channels and the total channel length. In this comparison, the differences in results were minor. In the second test of series no. 2, hillslopes were feeding a channel at its inlet instead of laterally as in the first test. As a result, although runoff volume and peak flow discharge rates at the outlet were identical, the outlet sediment loads were higher for test case 2 compared to test case 1 of series no. 2. The reason is that runoff and detachment rates in the first half of the channel were higher when hillslopes fed the channel at its inlet. The same phenomenon was observed in comparing test cases 5 and 6. The user needs to be aware of this result in setting up the watershed configuration to best describe the case at hand.

CHANNEL PARAMETER SENSITIVITY

Sensitivity to Slope Parameters. The influence of the channel slope was determined between slope values of 0.9% and 10%. Channels had constant uniform slope and the slope of the outlet structure (discussed above) was given the same value as the channel slope. As expected, outlet yields increased with increasing slope values (fig. 4, table 4). In these analyses, the friction slopes were calculated by WEPP using the approximated solutions of the spatially varied flow equation that were developed for the CREAMS model (Knisel, 1980; Ascough et al., 1997). These approximation equations have been derived for different sets of conditions relating the flow rate, the Manning's coefficient, the depth of flow and the bed slope. For slopes less than 1% these equations gave unstable results, and consequently large variations of outlet sediment yields were observed. We therefore recommend that the bed slope rather than the friction slope be used when slopes are below 1% (which is an option with the WEPP model), unless backwater effects are important.

Table 4. Sensitivity values for the annual average and six selected storm sediment yields

	Annual Sediment Yield Sensitivity	Event Sediment Yield Sensitivity					
		9 Jan.	1 Mar.	4 May	2 Aug.	12 Oct.	2 Dec.
Slope*	0.133	0.210	0.482	0.097	0.383	0.350	0.563
Side slope	–0.029	–0.081	–0.177	–0.082	–0.056	–0.064	–0.259
n total	–0.162	–0.770	–1.260	–0.095	–0.297	–0.430	–0.250
n bare soil	0.332	1.090	1.740	0.290	0.671	1.340	1.510
Crit. shear stress	–0.045	–0.193	–0.558	0	0	–0.495	–0.725
Erodibility	0.042	0.356	0.525	0	0	0.221	0.740
Hyd. coed.	–0.013	–0.001	–0.008	0	–0.522	–1.000	–0.004

* Refer to figures 4-10 for ranges of input values considered.

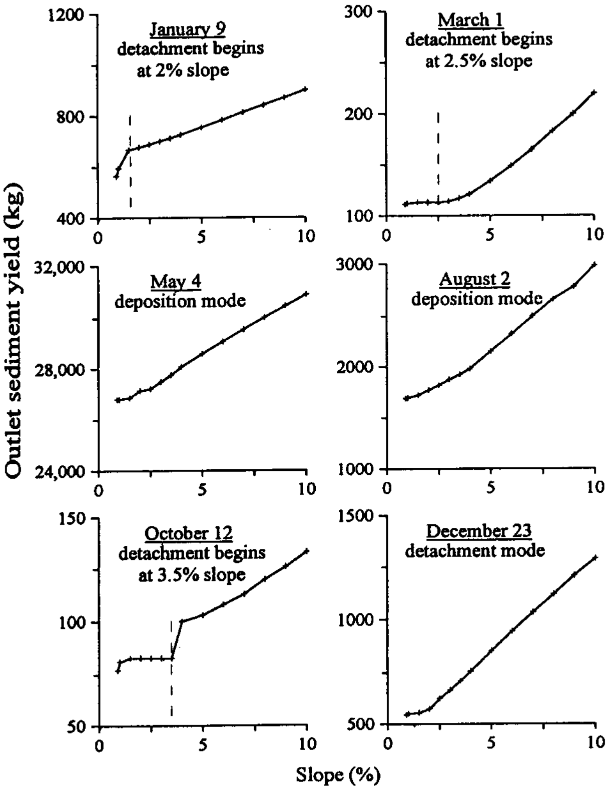

Figure 4–Impact of channel slope on simulated sediment yield for the six selected events.

In addition, when using the approximation equations, the user should perform some sensitivity study around the slope value to insure that it is not in an unstable region.

For all events, we observed a sharp increase of the sediment yield as the slope increased when slope values were low. The yield then generally reached a plateau before increasing again. For the two events of 4 May and 2 August, the plateau did not appear. These three phases of the yield variation correspond to a deposition stage, a stage at which only transport and neither deposition nor detachment was occurring, and a. detachment stage. During the events of 4 May and 2 August, deposition occurred in the channel for all the slope values that were considered, which explains why there was no plateau for these events.

To study the effect of the channel side slope value, its value was modified between the minimum and maximum values of 2% and 30% for all channels, as well as for the outlet structures (fig. 5). Sensitivity values (table 4) were calculated between side slope values of 2% and 10% except for the 12 October event where it was calculated between side slope values of 2% and 6%. For this event, detachment ended for a side slope of 7% and the sediment yield remained constant for higher values. The effect of the channel side slope parameter was different depending on processes occurring in the channel (fig. 5). When the flow rate and the transport capacity were large enough for detachment to occur, the outlet sediment yield was sensitive to the side slope of the channel. When transport capacity decreased enough so that detachment did not occur any more, the yield was independent of the side slope value. Finally, when deposition occurred in the channel, the sediment yield decreased again as the side slope increased, but generally less so than in the detachment case.

Sensitivity to Hydraulic Roughness Parameters. Results were sensitive to both the total Manning's coefficient (which takes into account vegetation) and the bare soil Manning's coefficient (figs. 6 and 7). The sensitivity values (table 4) indicated that the Manning's coefficients, along with the channel slope, were the parameters to which erosion and deposition in the channels were most sensitive.

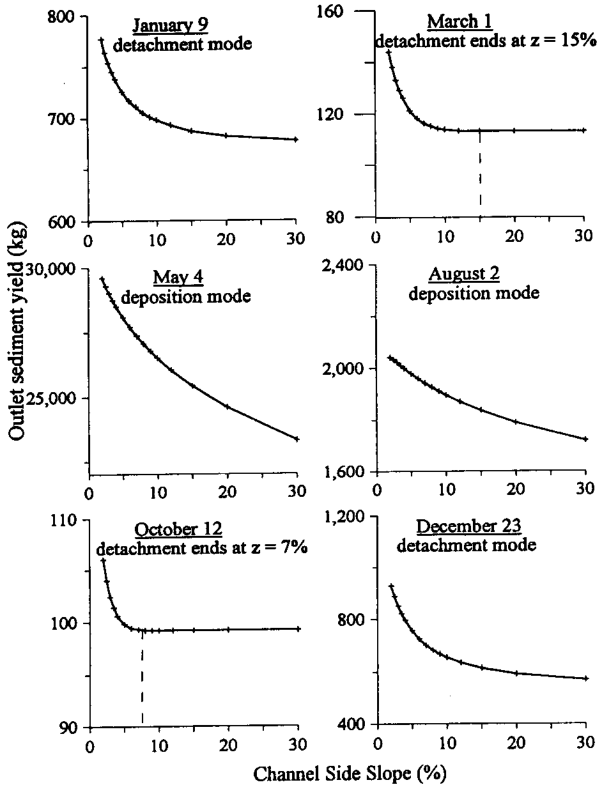

Figure 5–Impact of channel side slope value on simulated sediment yield for the six selected events.

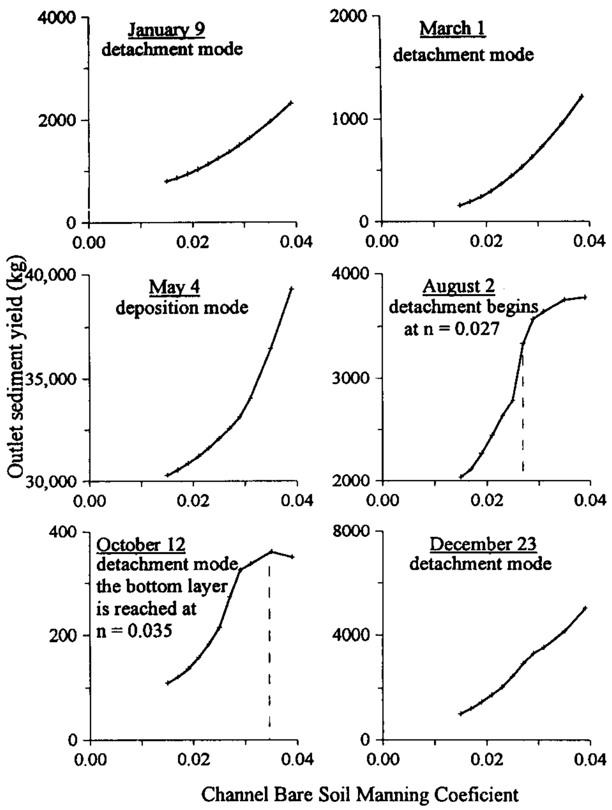

Figure 7–Impact of the bare soil Manning's coefficient on simulated sediment yield for the six selected events.

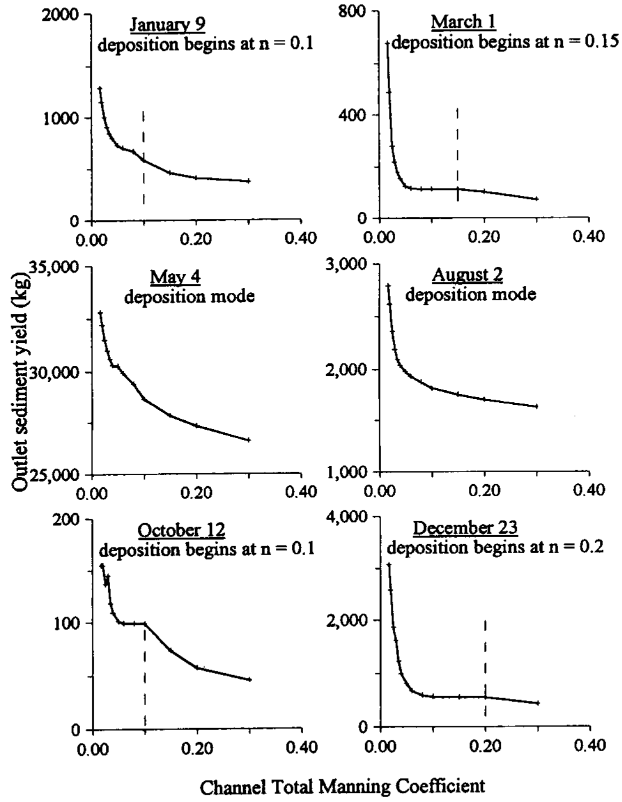

Figure 6–Impact of the total Manning's coefficient on simulated sediment yield for the six selected events.

The total Manning's coefficient is used for the calculation of the peak flow rate (through the computation of the time of concentration), the flow shear stress on the vegetation, and the channel friction slope. Both channel and channel outlet Manning's were changed identically in the analysis. Because the inverse value of the Manning's coefficient is used in the Manning formula, results were more sensitive when the magnitude of the Manning's coefficient was small (fig. 6). Sensitivity values were calculated in the range of the more commonly used Manning's values of 0.017 to 0.1, or until detachment no longer occurred, whichever was lowest. For all events, the sediment yield at the outlet was very sensitive to this parameter, indicating that its value should be determined with care. A limitation of the WEPP model is that only an average value of the total Manning's coefficient is entered to represent a system which may have varying stages of vegetation states during the year. Given the sensitivity of the results to this parameter, we think the model could be improved if the value of the Manning's coefficient was updated as a function of the height and density of the vegetation during the year, as well as the flow rate or depth.

The bare soil Manning's coefficient (n_{bare}), or more precisely the ratio of the bare soil coefficient to the total Manning's coefficient, is used in WEPP to partition the total shear stress of flow between that which acts to detach and transport sediment and that which is lost to friction on the vegetation. Its value should always be less than the total Manning's coefficient. In the CREAMS code the Manning's coefficient for bare soil in the channels is fixed to a value of 0.03. In the WEPP code, it is entered by the user who can choose a value between 0.01 and the total Manning's coefficient. Sensitivity values were great (in excess of one) in cases of channel detachment (table 4). They were lower in case of deposition (4 May and 2 August) but still indicated a high sensitivity of the outlet sediment yield to the bare soil Manning's coefficient.

One other point of note is visible in the results of the sensitivity analysis relative to roughness. Since the results for this study were obtained in a continuous simulation mode, results for one event were dependent on previous events, including the amount of erodible material left in the channel. For example, for higher values of the Manning's coefficient for bare soil, which in general produced greater erosion, the non-erodible layer of soil was reached on 12 October. Consequently there was less soil available for erosion at this time of the year and the outlet sediment yield for a bare Manning's coefficient of 0.039 was less than for a value of 0.03 5 (fig. 7).

Sensitivity to Soil Erodibility and Infiltration Parameters. As expected, both the soil erodibility and its critical shear stress were sensitive parameters for channel detachment cases. When hillslope sediment inputs were great and scour did not occur in the channels, the erodibility and critical shear stress values for the channel itself had no influence on the resulting outlet yields. The 4 May and 2 August events were examples of such cases (figs. 8 and 9).

As expected for erosion cases, the outlet yield decreased as the critical shear stress value increased (fig. 8). On 1 March and 12 October, the outlet yield remained constant for the higher values of the critical shear stress. For these cases, the flow shear stress was not high enough to trigger erosion and there was consequently no detachment calculated in the channels.

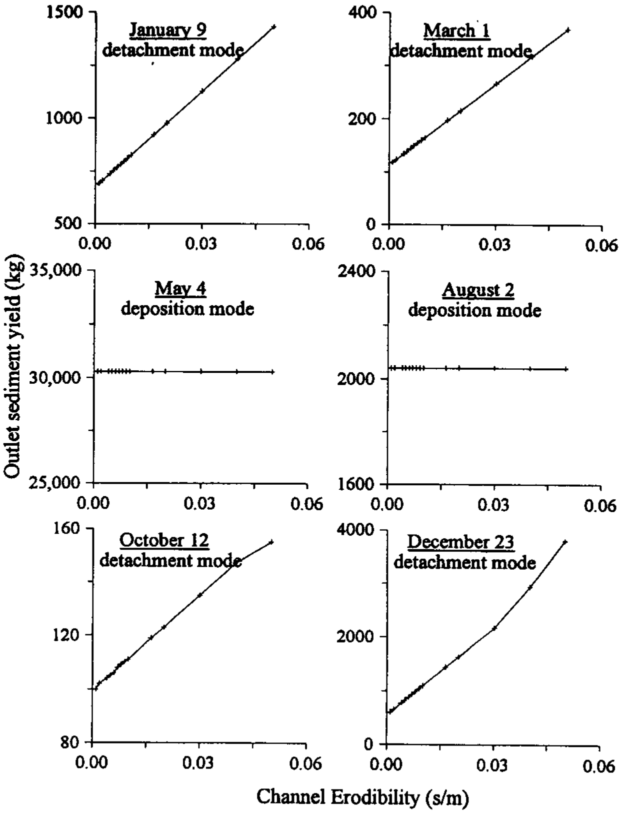

Figure 9–Impact of channel erodibility on simulated sediment yield for the six selected events.

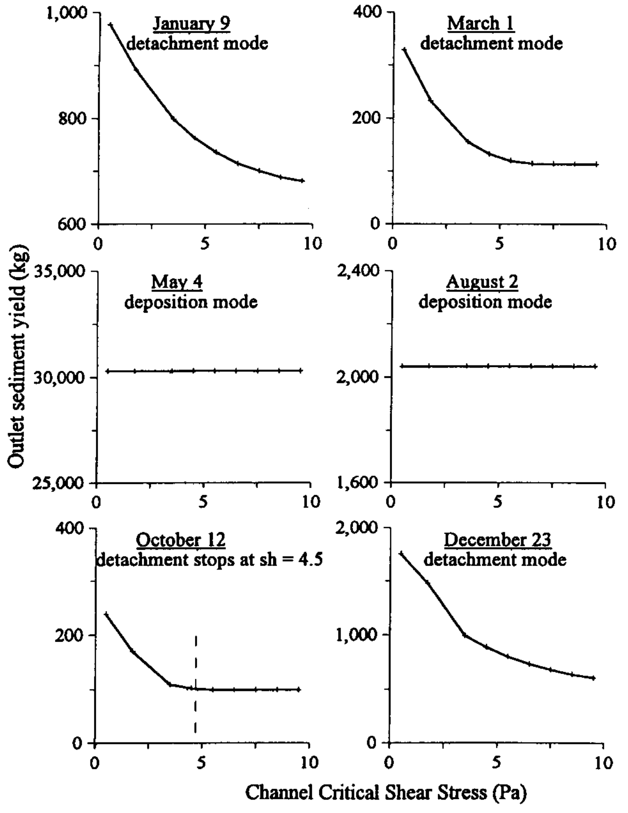

Figure 8–Impact of channel critical shear stress on simulated sediment yield for the six selected events.

In general, sediment yield increased as channel erodibility increased (fig. 9). However, as for the case of the bare soil Manning's coefficient, other tests (not shown here) showed that outlet yields could sometimes be lower for greater erodibility values than they were for lower ones. This was due to the fact that when erodibility values were high, all the erodible surface material was lost during the previous events. When more erodible material was available (deeper erodible layer), this phenomenon disappeared. The results shown here are only for the case of the deeper erodible layer.

The outlet yield was sensitive to the hydraulic conductivity of the channel itself only for the 2 August and 12 October events (fig. 10). For all other events, the sensitivity parameter was on the order of 10^{-3}. For these two events the incoming runoff from hillslopes was low (less than 70 m^3 compared to more than 120 m^3 for the other storms), which may explain this phenomenon. When the incoming runoff rate was large, the infiltration capacity of the channel was not high enough to cause a significant change in the runoff volume. The transport capacity of the channel flow and therefore the sediment load remained constant. On the other hand, when the incoming runoff was low, the fraction of it that could infiltrate into the channel was of the same order of magnitude and the transport capacity was greatly reduced. For the very small event of 12 October, all runoff infiltrated in the channel at the greater values of the hydraulic conductivity.

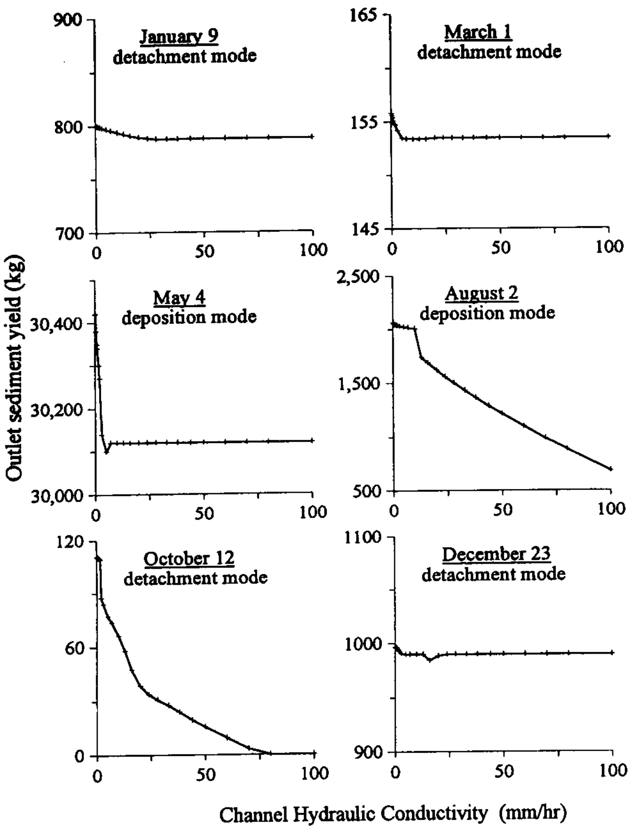

Figure 10–Impact of channel hydraulic conductivity on simulated sediment yield for the six selected events.

CONCLUSIONS

Several series of tests were designed to test the WEPP watershed model behavior and to determine which steps of the watershed characterization process were particularly important. With certain notable exceptions, the WEPP model behaved in a rational and consistent manner. Model response in a small number of cases were somewhat counter intuitive, and those instances are reported as possibilities for model improvement.

With regard to discretization, or how the watershed should be represented by the sizes, numbers, and configuration of its various hillslope and channel elements, we found three important results: (1) the lengths of the hillslope elements are important; (2) the number of channels may significantly influence results; and (3) whether hillslopes feed the top or the sides of the channel makes a difference in the predicted sediment delivered from the area. The recommendation is that the user should be aware of the sensitivity and that these factors should represent actual field conditions as much as possible. Hillslope lengths should not normally exceed 100 m for use in the current WEPP model. This restriction is severe and must be alleviated if the model is to be applied to larger watersheds (i.e., greater than approximately 40 ha). That change will require basic modifications to the WEPP rill erosion equations in the hillslope portion of the model. Also, with regard to point (2) above, we recommend that changes be considered for the WEPP watershed model to better reflect the effects of recession infiltration on runoff amounts and flow discharge rates.

Model sensitivity analysis indicated that the selection of the Manning's 'n' value for bare soil is critical for the model. The total Manning's value and the channel slope are next in level of model sensitivity. Also, it was determined that sensitivity to calculated erosion varied greatly on a storm-by-storm basis, depending on the state of the system and the storm characteristics. For certain storms the channel erodibility and critical shear stress were important factors in the predicted soil loss; whereas, for other storms they were unimportant.

REFERENCES

Ascough II, J. C., M. A. Nearing, C. Baffaut and B. Y. Liu. 1997. The WEPP watershed model: I. Hydrology and erosion. *Transactions of the ASAE* 40(4):921-933.

Chaves, H. M. L. and M. A. Nearing. 1991. Uncertainty analysis of the WEPP Soil Erosion Model. *Transactions of the ASAE* 34(6):2437-2444.

Deer-Ascough, L. A. 1995. A framework for uncertainty analysis of complex process-based models. Ph.D. diss. West Lafayette, Ind.: Purdue University.

Flanagan, D. C. and M. A. Nearing, eds. 1995. USDA — Water erosion prediction project: Hillslope profile and watershed model documentation. NSERL Report No. 10. West Lafayette, Ind.

Foster, G. R. and L. J. Lane. 1987. User requirements, USDA-Water Erosion Prediction Project (WEPP). NSERL Report No. 1. West Lafayette, Ind.

Green, W. H. and G. A. Ampt. 1911. Studies in soil physics. I. The flow of air and water through soils. *J. Agric. Sci.* 4:1-24.

Harr, M. E. 1987. *Reliability-based Design in Civil Engineering.* New York, N.Y.: McGraw Hill.

Knisel, W.G., ed. 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. Conservation Research Report No. 26. Washington D.C.: USDA-Sci. and Educ. Admin., U.S. GPO.

Liu, B. Y., M. A. Nearing, C. Baffaut and J. C. Ascough II. 1997. The WEPP watershed model: III. Comparisons to measured data. *Transactions of the ASAE* 40(4):945-952.

McCuen, R. H. and W. M. Snyder. 1986. *Hydrologic Modeling: Statistical Methods and Applications.* Englewood Cliffs, N.J.: Prentice Hall.

Mein, R. G. and C. Larson. 1973. Modeling infiltration during a steady rain. *Water Resour. Res.* 9(2):384-394.

Nearing M. A., L. Deer-Ascough and J. M. Laflen. 1990. Sensitivity analysis of the WEPP hillslope profile erosion model. *Transactions of the ASAE* 33(3):839-849.

Nearing, M. A. and A. D. Nicks. 1997. Evaluation of WEPP: Hillslopes and small watersheds. In NATO-ASI book *Global Change: Modelling Soil Erosion by Water.* Oxford, England, 11-14 Sept. 1995. (In press)

Nicks, A. D., L. J. Lane and G. A. Gander. 1995. Ch. 2: Weather Generator. In *USDA Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation*, eds. D. C. Flanagan and M. A. Nearing. NSERL Report No. 10. West Lafayette, Ind.

Smith, R. E. and J. R. Williams. 1980. Simulation of the surface water hydrology in CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. USDA, Conservation Research Report No. 26. Washington D.C.: U.S. GPO.

Tiscareno-Lopez, M., V. L. Lopes, J. J. Stone and L. J. Lane. 1993. Sensitivity analysis of the WEPP watershed model for rangeland applications, I. Hillslope processes. *Transactions of the ASAE* 36(6):1559-1672

Tiscareno-Lopez M., V. L. Lopes, J. J. Stone and L. J. Lane. 1994. Sensitivity analysis of the WEPP Watershed model for Rangeland applications, II. Channel processes. *Transactions of the ASAE* 37(1):151-158.

Wischmeier, W. H. and D. D. Smith. 1978. Predicting rainfall erosion losses — A guide to conservation planning. USDA, Agriculture Handbook No. 537. Washington D.C.: U.S. GPO.