Second Edition

SOIL EROSION
RESEARCH METHODS

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STL
Soil loss is defined in erosion literature as the amount of soil lost in a specified time period over an area of land which has experienced net soil loss. Soil loss is expressed in units of mass per unit area, such as t/ha or kg/m², and may be for a single storm event, an average value for a number of years, or for any other specified time period. Soil loss is of interest primarily in terms of on-site effects of erosion such as loss of crop productivity. Sediment yield is defined as the amount of sediment which leaves a specified area of land in a given time period. Sediment yield refers to a mass of sediment which crosses a boundary, such as the edge of a field or outlet of a watershed, and may be expressed in units of total mass (kg), mass per unit width of the boundary (kg/m), or mass per unit area (kg/m²). Sediment yield is important in terms of off-site effects of erosion such as siltation in ditches, streams, and reservoirs. Sediment is also a primary carrier of agricultural chemicals which can pollute streams and lakes. In most cases not all soil lost on a field becomes sediment yield, as some of the soil particles are deposited on the field before leaving the field boundary. In other words, most fields have some areas which experience net soil loss over time and some areas which experience net deposition over time. The difference between the spatially integrated net soil loss and the spatially integrated net deposition is what leaves the field, herein termed sediment yield.

Modeling soil erosion is the process of mathematically describing soil particle detachment, transport, and deposition on land surfaces. There are at least three reasons for modeling erosion: (a) erosion models can be used as predictive tools for assessing soil loss for conservation planning, project planning, soil erosion inventories, and for regulation; (b) physically-based mathematical models can predict where and when erosion is occurring, thus helping the conservation planner target efforts to reduce erosion; (c) models can be used as tools for understanding erosion processes and their interactions and for setting research priorities.
There are basically three types of erosion models (21): empirical, conceptual, and physically-based. Empirical models are based primarily on observation and are usually statistical in nature. Empirical models are based on inductive logic, and generally are applicable only to those conditions for which the parameters have been calibrated. The Universal Soil Loss Equation (USLE) is the empirical erosion model which has been used most widely for predicting soil erosion. The greatest criticism of the USLE has been its ineffectiveness in applications outside the range of conditions for which it was developed. Adaptation of the USLE to a new environment requires a major investment of resources and time to develop the database required to drive the model. The primary focus of the empirical models has been in predicting average soil loss, although some extensions to sediment yield estimates have been developed (33, 37).

Conceptual models lie somewhere between physically-based models and empirical models, and are based on spatially lumped forms of water and sediment continuity equations (21). The focus of the conceptual models has been to predict sediment yields, primarily using the concept of the unit hydrograph.

Physically-based models are intended to represent the essential mechanisms controlling erosion. The power of physically-based models is that they represent a synthesis of the individual components which affect erosion, including the complex interactions between various factors and their spatial and temporal variabilities. The result is synergistic, the model as a whole represents more than the sum of the individual pieces. The research scientist can use the physically-based erosion models to help identify which parts of the system are the most important to the overall erosion process, and therefore should be given attention in research and development of erosion prediction and control technology. The conservation planner can use a physically-based model as an interactive conservation design tool, targeting critical seasons or months in which major erosion events occur as well as critical positions on the hillslopes where the greatest soil loss takes place. The planner can also quickly suggest and evaluate new conservation strategies for individual fields.

The focus of this chapter is on development of physically-based erosion models. Chapter 5 discusses current developments in the more empirically-based Universal Soil Loss Equation. We will discuss only models for erosion by water; erosion by wind is discussed in Chapter 11. Also, in this chapter we draw much upon experiences related to the development of the USDA-Water Erosion Prediction Project (WEPP) erosion models (22). The objective of WEPP is to develop new generation erosion prediction technology for use by the conservation planner at the field level. The technology is based on fundamentals of erosion and hydrologic sci-
ences and is computer driven. The two WEPP models referred to herein as examples of physically-based models are the WEPP hillslope profile model and the WEPP watershed model.

MECHANICS OF EROSION BY WATER

Erosion encompasses detachment, transport, and deposition of soil particles by the erosive forces of raindrops and surface flow of water. It is common in erosion models to divide, conceptually, the process of erosion on hillslopes into that related to rill flow mechanisms and interrill mechanisms. Within this framework rill flow may act to detach soil particles whenever the hydraulic shear stress in the rill is sufficient to overcome the binding forces between individual particles in the soil mass. The flow in the rill also acts as the transporting agent to carry detached soil, i.e. sediment, from both rill and interrill areas. Detachment on interrill areas is primarily induced by raindrop impact, since flow depths on interrill areas are by definition of negligible erosive power. Transport on interrill areas is primarily by broad shallow surface flow. The energy required to move (entrain) sediment is much less than that required to detach in-situ soil particles. Net transport by raindrop splash is very small, with only a small net downslope movement due to the slope effect (39).

Most erosion models rely upon the concept of transport capacity, which is defined as the maximum amount of sediment that a flow can carry without net deposition occurring. Several transport capacity equations have been developed for transport of sediment in large channels and adapted for use in upland erosion models. Choice of the “best” sediment transport equation is subjective, and opinions vary as to the most appropriate equation to use (19). Instead of which equation to use, a more important issue in modeling fundamental erosion processes is what transport capacity means and how it is used in the model. Transport capacity is basically a balance between entrainment and deposition rates of the sediment in the flow. The description of the entrainment process does not include a factor for cohesive soil forces, but considers only gravity forces of the sediment which must be overcome for the particle to be lifted into the flow. The implicit assumption, then, for erosion of cohesive soils is that cohesive forces are negligible once the soil has been initially detached from the in-situ soil mass.

Another implicit assumption when using a sediment transport equation to describe erosion is that deposition is a continual process. When we refer to “detachment” in describing soil loss we mean the process of removing in-situ soil particles from the bulk soil mass. The term “net detachment” refers to a balance between detachment, entrainment of previously detached
particles, and deposition for the case when net movement of particles is from the soil surface into the flow. Some recent erosion models have avoided the explicit use of an existing sediment transport equation entirely. Hairsine (15) calculates rates for five simultaneous processes: detachment of soil by flow, entrainment of sediment by flow, detachment of soil by rainfall, entrainment of sediment by rainfall, and deposition of sediment. In that model net detachment is the case where the sum of detachment and entrainment rates exceeds the rate of deposition. Lopes and Lane (25) take a similar approach except that their model does not differentiate between entrainment of sediment and detachment of soil.

Interrill processes

Interrill areas are defined as the areas wherein erosion is dominated by detachment by raindrop impacts and transport by very shallow sheet flows. As mentioned above, net transport by splash is negligible, since splash has only a small net downslope movement. Obviously, however, raindrop impact on shallow flows may enhance the capacity of the flow to transport sediment (16). The three other factors which influence transport on interrill areas are runoff rate, interrill slope gradient, and surface roughness.

Many erosion models, including the WEPP model (70, 31), do not treat the individual process of detachment and transport on interrill areas, but only estimate sediment yield from interrill areas to rills as some function of rainfall intensity. The equation used in the WEPP erosion models is

\[ D_i = K_i I^2 \]  

where \( D_i \) is rate of interrill sediment delivery to rills, \( K_i \) is an interrill erodibility parameter, and \( I \) is average rainfall intensity integrated over the duration of rainfall excess. Equation 1 is an empirical relationship based on extensive rainfall simulation studies on a number of different soils (26). Interrill models which lump processes to estimate only sediment yield are simple, stable, and give reasonable results. Kirkby (17) argues that sediment yields from interrill areas are relatively low compared to rill erosion rates for cases where soil losses are high, which is true in general. Interrill erosion may dominate, however, in certain cases, such as on rangelands and no-till situations or where slope angles are low and slope lengths are short (32).

Models which treat the individual processes of detachment and transport on interrill areas may have an advantage over models which predict only sediment yield from interrill areas if the individual processes can be described simply and effectively, and if the parameters within the model
can be experimentally determined. Gilley et al. (12) proposed a model which explicitly treats detachment and transport processes on interrill areas. Detachment was described using a semi-empirical relationship between raindrop size and velocity distributions and splash detachment rates. Sediment transport capacity was calculated using the Bagnold equation, which is based on stream power. The model agreed well with the reported experimental data from the study (13). Several different relationships have been proposed to represent splash detachment as a function of raindrop properties. Gilley et al. (11) evaluated several different functions for splash detachment and recommended kinetic energy times drop circumference as the best, although several others, including kinetic energy alone, were evaluated to predict splash nearly as well. Sharma (35) found kinetic energy to relate well to drop splash, but their data indicated a need for the introduction of a critical energy for detachment. Splash studies of Al-Durrah and Bradford (1) on nine soils showed a zero intercept between splash and kinetic energy, which contradicts Sharma's data. Sharma (35) attributes the different results to the fact that drop heights in his study were shorter; another possible explanation is that not all of the soil splash could be collected in the splash cup for the very low drop heights. In any case, the drop kinetic energies of interest are primarily for drops at or near terminal velocity, and for that case a threshold kinetic energy for splash detachment is not justified.

Rill processes

Rills are defined as concentrated flow channels which are small enough to be tilled over (9). Flow in rills acts as a transporting agent to carry sediment from rill and interrill sources downslope. If the shear stress in the rill is high enough, rill flow may also detach a significant amount of soil. A common model for rills describes detachment as a linear function of shear stress, but in fact, experimental results of flume studies show that detachment vs. shear stress relationships are typically non-linear. Figure 6.1 shows the results from a study at the National Soil Erosion Research Laboratory of detachment by surface flow vs. flow shear stress for a Miami silt loam soil. Most erosion models would describe flow detachment as a linear function of flow shear stress (or energy) with a positive intercept on the shear stress axis, which is typically called the critical shear stress of the soil. For instance, the WEPP model uses a function of the form

\[ D_c = K_r (\tau - \tau_c) \]  

[2]
where $D_c$ is the detachment capacity of clear water flow, $K_r$ is the soil’s rill erodibility, $\tau$ is the shear stress of the flow, and $\tau_c$ is the soil’s critical hydraulic shear strength.

The concept of the critical shear stress of the soil should not be given more physical significance than is warranted. There has been much discussion and experimentation about the physical meaning of the critical shear stress. Grass (14) conceptualizes entrainment as the overlap of two probability distributions, one for the instantaneous and localized flow shear stresses associated with turbulent “bursting” phenomenon and one for the resistance of individual soil particles on the boundary between soil and flow. In Equation 2, critical shear stress of the soil is a mathematical entity which results from the linearization of the model. It is not, and should

Figure 6.1 Detachment rate by surface flow vs. average hydraulic shear stress as measured in a hydraulic flume on a Miami silt loam soil.
not be interpreted as being, the threshold level of shear stress below which there is no soil detachment and above which the first soil particles begin to move.

DEVELOPMENT OF A PHYSICALLY-BASED EROSION MODEL

Model development may be divided into two phases. The first is the creation of the physical model prototype and the second is model evaluation. The steps involved in model development are outlined in Figure 6.2. The process begins with conceptualizing the natural system through the use of existing information. An example of the conceptualization process for erosion modeling is the set of equations presented by Meyer and Wischmeier (24). They presented a mathematical formulation of the erosion process based on observations by Ellison (6) which included descriptions of (a) detachment by rainfall, (b) detachment by flow, (c) transport by rainfall, and (d) transport by flow. The second step in the process of model development is to solve the equations and write the solutions in the form of computer code, assuming that the resultant model is to be com-
puter driven. This step includes development of the overall computer model structure, which involves linking the various components of the technology into a complete working unit. Experimentation for developing a parameter database may begin simultaneously with the development of the computer code, since at this point the fundamental equation structure of the model is set.

After the model code and parameter-experiments are completed, the parameter estimation stage can begin. Parameter estimation involves two distinct steps: (a) parameter identification and (b) development of parameter prediction equations or techniques. Parameter identification is determining the model parameters from an experimental data set (30). It involves using the existing computer model and an optimization technique to analyze the experimental data to obtain model parameters for the measured data set. The second step is to develop a method for predicting model parameters for soils or environmental conditions not represented in the measured data set. The completed and tested computer code along with the parameter prediction techniques constitutes the prototype physical model, and represents completion of the first phase of the model development.

The second phase of erosion model development is the model evaluation phase, which includes (a) sensitivity analysis, (b) confidence limit analysis, and (c) validation with data. The results of the model evaluation are used to assess the validity of the model and to make the changes in basic equations, model structure, or parameter estimation procedures necessary to development of the validated working model. It is important that changes dictated by the model evaluation phase are followed through in a complete and logical manner. If changes in model structure are required to produce a valid working model, then the entire model development process must be followed again. The new structure will require a new set of parameters, which means that the measured experimental data will need to be re-analyzed and new parameters identified from the data. Then the parameter estimation procedures will need to be re-evaluated and a new "prototype" model proposed and evaluated. The process is iterative. The model developers must be cognizant of and sensitive to the user's needs in making the decision as to when the process stops and the model is deemed "valid."

There are four major mechanisms for introduction of error in the modeling process. The first is in the formulation of the basic equations. Any mathematical representation of a natural process is approximate, at least when dealing on the scales related to soil erosion, and will cause the introduction of some error in terms of describing the system. These errors can be large, particularly where a minor factor for most cases, and hence ne-
neglected in the mathematical descriptions, is a major factor in a specific case. The second source of error is in the solution and coding of the equations. This should be a minor source of error except in certain cases where approximate solution techniques must be used for the sake of computational efficiency. A third source of error is experimental error and variation in experimental data. Experimental data associated with erosion experiments typically have a high degree of variation. A fourth source of error is in the parameter prediction procedure. Any statistical method developed for predicting model parameters for untested situations will have some, and usually a large amount, of error associated with it.

Erosion equations for a steady-state model

The WEPP hillslope profile erosion model is a recent example of a physically-based erosion model. This model has been described in detail elsewhere (22, 31) and hence its description here will be brief. The WEPP erosion model uses a steady state sediment continuity equation to describe downslope movement of sediment:

\[
\frac{dG}{dx} = D_f + D_i \tag{3}
\]

where \( x \) (m) represents distance downslope, \( G \) (kg/s/m) is sediment load, \( D_i \) (kg/s/m\(^2\)) is lateral sediment flow from interrill areas, and \( D_f \) (kg/s/m\(^2\)) is rill erosion or deposition rate. Intermill sediment delivery, \( D_i \), is considered to be independent of \( x \). Rill erosion, \( D_f \), is positive for detachment and negative for deposition.

Interrill erosion in the model is conceptualized as a process of sediment delivery to rills, whereby the interrill sediment is then either carried off the hillslope by the flow in the rill or deposited in the rill. Sediment delivery from the interrill areas is considered to be proportional to the square of rainfall intensity, with the constant of proportionality being the interrill erodibility parameter. The function for interrill sediment delivery also includes terms to account for ground and canopy cover effects, which are discussed below. The interrill function was presented in Equation 1.

Net soil detachment in rills is calculated for the case when hydraulic shear stress exceeds the critical shear stress of the soil and when sediment load is less than sediment transport capacity. For the case of rill detachment

\[
D_f = D_c \left[ 1 - \frac{G}{T_c} \right] \tag{4}
\]

where \( D_c \) is detachment capacity by flow as given in Equation 2 and \( T_c \) (kg/s/m) is sediment transport capacity in the rill. Rill detachment is consid-
Nearing, Lane, and Lopes

Net deposition is computed when sediment load, \( G \), is greater than sediment transport capacity, \( T_c \). For the case of deposition

\[
D_t = \left[ \frac{V_f}{q} \right] (T_c - G)
\]

where \( V_f \) (m/s) is effective fall velocity for the sediment, and \( q \) (m³/s) is flow discharge per unit width.

Representations of the effects of land use and management practices on erosion control are perhaps the most important part of an erosion prediction tool if the purpose is help plan land and farm management systems to control erosion. Residue management and tillage practices on croplands are the mechanisms through which the farmer usually can most directly impact soil loss and effect erosion control. Table 6.1 shows the effects of soil and residue management on rill and interrill erosion rates as they are represented in the WEPP model. In the WEPP erosion model interrill sediment delivery is adjusted to account for effects of ground cover, dead roots, live roots, and canopy cover. Plant and soil management practices also affect infiltration processes greatly; these effects are discussed in Lane and Nearing (22).

The effect of surface cover in rills is probably overall the greatest single management effect on erosion, because it strongly influences both detachment and sediment transport processes. This effect is incorporated into the WEPP model via the hydraulic friction factor terms, which enable partitioning of the flow energy into that acting on the soil from that acting on the surface cover, including residue and rocks. The effect of buried residue is also accounted for in the WEPP model.

Rill erodibility is also affected by disturbance due to tillage. In the WEPP model, baseline rill erodibility for croplands is for the completely disturbed state, which for practical purposes is defined as that found immediately after moldboard tillage. Each tillage implement is defined with a tillage intensity term to reflect the fact that disturbance may be less (or more, if needed) than for the moldboard plow. From the disturbed state the soil consolidates. Computation of consolidation and changes in rill erodibility as a function of time and weathering are made using a fundamentally-based consolidation model of Nearing et al. (29).

Interrill erodibility is not adjusted for time in the WEPP model. Various data suggest that interrill erodibility does not greatly change with time (3, 4). A further indication of this can be seen by comparing rangeland and cropland interrill erodibilities. Rangelands represent essentially a fully consolidated soil condition and freshly tilled croplands represent a fully un-
### Table 6.1 Effects of plant and soil management on erosion.

<table>
<thead>
<tr>
<th>Above Ground Residue Cover</th>
<th>Below Ground Biomass</th>
<th>Plant Canopy Cover</th>
<th>Soil Consolidation After Tillage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>Kid,Kil</td>
<td>Ce</td>
<td><strong>NA</strong></td>
</tr>
<tr>
<td>Rill Erosion (fc)</td>
<td>Krb</td>
<td><strong>NA</strong></td>
<td>K r c</td>
</tr>
</tbody>
</table>

Consolidated soil condition. A comparison of average cropland erodibilities for 36 soils (18) and 11 rangeland soils (36) indicates that interrill erodibility for croplands is about four times that for rangelands. A challenge for the future is to develop a method for predicting which soils will change in interrill erodibility with time, and whether erodibility will increase or decrease for a given soil.

**Continuous simulation models**

The full benefit of an erosion prediction model is gained through the use of a continuous simulation model. By continuous simulation it is meant that the model "mimics" the processes which are important to erosion prediction as a function of time, and as affected by management decisions and climatic environment. Surface residue, for example, plays an important role in terms of predicting the amount of soil lost during a given rainfall event. An erosion model may use a plant growth and residue decay model to estimate the amount of crop residue present on the soil surface for each day through the year. A certain amount of residue is generated by leaf drop during senescence and by harvesting, and a pass of a given tillage implement will bury a certain percentage of a given type of residue. An erosion model should adjust surface cover as a function of those and other processes which affect residue cover. With a continuous simulation model, the user does not need to specify the amount of residue cover as a function of time. Soil parameter, residue amount, crop growth, soil water content, surface roughness, and essentially all other adjustments to model parameters should be calculated on at least a daily time step.

The output of the continuous simulation model represents time integrated estimates of erosion. In nature, as well as in the model predictions, a large percentage of erosion occurs due to a small percentage of rainfall...
events. The model simulates some number of years of erosion and sums
the total soil loss over those years for each point on the hillslope to obtain
average annual values of erosion along the hillslope. The model calculates
both detachment and deposition. It predicts where deposition begins and/
or ends on a hillslope, which may vary from storm to storm. Certain points
on the hillslope may experience detachment during some rainfall events
and deposition during other events. The output of the continuous simula-
tion model represents an average over all of the erosion events.

A physically-based erosion model may also be executed in the single-
storm mode. In that case, all of the parameters used to drive the hydrology
and erosion components of the model must be input by the user, including
soil conditions for the day of the rainfall event, crop canopy, surface resi-
due, days since last disturbance, surface random roughness, oriented rough-
ness, etc. In the continuous simulation mode the influence of these user
inputs, which represent the initial conditions for the simulation, is small
since the model adjusts each of those variables through the continuous
simulation. In the single storm mode those inputs have a major influence
on the output. The single-storm option of the model requires a great deal
more knowledge on the part of the user to interpret and use the output for
planning, evaluation, and conservation design purposes. The single-storm
model helps in understanding and evaluating the factors which influence
erosion on a hillslope; it is of limited value in evaluating conservation
systems wherein conditions change as a function of time through the year
and from year to year.

Parameter estimation

Soil erodibility for an erosion model is defined relative to the form of
the erosion equations used. The approach is to first formulate the erosion
equations for the model then to analyze experimental results relative to the
particular set of erosion equations used. The equations should as accu-
ately as possible describe the physical processes involved and the effects
of various environmental factors on the physical processes, but in the model
parameterization process we must recognize that every model is a simpli-
ification of reality. The physical significance of the erodibility parameters
is limited to the degree to which the erosion equations fully describe the
physical processes of erosion. The best alternative for parameterizing a
model with experimental data is to use the model to analyze the data. This
usually involves using an optimization technique which executes the model
and searches for the set of erodibility parameters which provide the best
fit between measured and calculated soil loss (2, 30).
An example whereby too much physical significance may be placed into the erodibility parameters is with regards to the rill erodibility, $K_r$. The WEPP model assumes that the primary mode of detachment in rills is scour, i.e., by way of the shear stress acting at the fluid/soil interface along the relatively well defined rill wetted perimeter. We recognize, however, that other mechanisms also act to detach soil in rills, including headcutting and sidewall sloughing. The erodibility parameters in the physically-based models are more fundamental in nature than erodibility parameters for the USLE, for example, but still represent a simplification of the erosion processes.

The discussion above does not imply that more fundamentally-based predictors for erodibility parameters are not needed. Better, more fundamentally based predictors of erodibility will go along with improved erosion equations. Universal, fundamentally derived equations for relating soil properties to soil erodibility are very much needed. Current methodology is to perform as many physical, chemical, mineralogical, mechanical, and erosion tests as possible on as many soils as possible and relate the soil properties to erodibility using statistical regression techniques. The problem with this approach is that it relies on inductive logic, and hence the results are questionable for applications outside the range for which they were derived.

Model analysis

Analysis of an erosion model is a critical step in developing a usable and valid erosion prediction tool, and one often not given the attention and allocation of resources of the total modeling process that it requires. Conventional attitudes are that if the pieces of the entire model are "correct," then the overall model with all components linked will be "correct." Experience shows otherwise. Often it is not possible to test the individual components thoroughly until they are within the framework of the simulation model. Also, interactions between components may cause the model to respond differently than expected a priori. Model analysis is an integral part of the modeling process.

Model analysis consists of three distinct parts: (a) comparisons of model predictions with existing data, (b) sensitivity analysis, and (c) confidence limit analysis. Data that was used to develop the model parameter base should not be used to validate the model. In the case of WEPP, data collected on USLE natural runoff plots are being used to test the model predictions. Historical weather data and crop/management information is being input to the model and comparisons between measured and predicted runoff and soil loss are being made. One comparison to make, obviously,
is the overall average of soil loss or runoff volume over the period of data collection. This is a valid comparison, but doesn't give much information on how the model is not working if comparisons are not within the desired range of accuracy, particularly for plots with crop rotations. Storm-by-storm comparisons of measured vs. predicted runoff and erosion provide more useful information. In general, event based comparisons will not give a high correlation for a continuous simulation.

A more important data comparison is that between the frequency distributions of the measured events and predicted events; the critical question is if the model accurately reflects those distributions. Also, from these analyses we may begin to assess the length of simulation necessary for the long-term results to be statistically valid. Figure 6.3 shows a plot of cumulative frequency distributions for a fallow runoff plot at Castana, Iowa, for the years 1960-1969. The predicted values were made using an early version of the WEPP hillslope profile erosion model (April, 1989). For this case the distributions were very similar in form, but the distribution for predicted values was shifted to the right, indicating that the model was overpredicting runoff for this case. This information was used, along with other similar analyses, to evaluate and adjust the model's runoff predictions.

Care must be taken not to make general statements about model validity based on one or two data sets. Erosion is highly variable, and that fact is reflected in measured erosion data. A large number of varied data sets should be evaluated to decide when and how a model must be adjusted to provide more accurate erosion predictions.

Sensitivity analysis is an evaluation of the relative changes in the model's output as a function of relative changes in the values of model input parameters. A detailed evaluation of a model's response can yield a great deal of insight into the nature of the model, and, to the extent that the model accurately represents the physical system which it simulates, sensitivity analysis can provide insight into the factors which influence the response of the physical system. Sensitivity analysis provides a method for examining the response of a model that eliminates the influence of error related to natural variation of the model input parameters. The rationality of the model and the influence of input error can thus be evaluated in detail (24).

Three limitations to current methods in sensitivity analysis were discussed by McCuen and Snyder (24):

1. The linear form of the sensitivity coefficient does not reflect sensitivity of the variable over the entire range of the parameter because of the non-linear response of the model. However, as pointed out by
McCuen and Snyder (24), the sensitivity of the extreme values which represent the physical conditions are often of primary interest.

2. The sensitivity coefficient is a univariate parameter, which implies that there is no interaction between variables. This can be a serious limitation which can lead to misinterpretations of the model. A variable which is insensitive with a given set of companion inputs might be quite sensitive with another set of inputs.

3. The sensitivity coefficient is single valued. A distribution of the output as a function of input parameter distribution might better describe sensitivity. This third point is related to confidence limit analysis discussed below.

In addition to the three limitations listed above the value of sensitivity analysis is limited by the “goodness” of the model. The power of a predic-
Nearing et al. (32) performed sensitivity analysis on the WEPP hillslope profile erosion model. They evaluated the model's response, relative to soil, slope profile, plant, and hydrologic input parameters. Both the single-storm version of the model and the erosion component alone were used in order to delineate the relative effects of factors on hydrology estimates and erosion estimates. The approach was to use an average linear sensitivity coefficient which represented the overall change in model response relative to the values of input which represent the extremes in the physical conditions represented.

A summary of the results from Nearing et al. (32) of the sensitivity analyses for the erosion model are presented in Table 6.2 and for the single storm model in Table 6.3. Hydrologic factors are key to obtaining good soil loss estimates from the model as shown in both tables. Factors related to rill detachment and transport are also very important. Rill erodibility, critical hydraulic shear of the soil, surface cover in the rills, and rill hydraulic friction factors are major factors in terms of model response. Texture is an important soil property for the model. Much of the sensitivity to texture is introduced through the prediction of rill hydraulic friction factors. Friction factors for both soil roughness and ground cover are very important parameters for erosion calculations, particularly for rills where hydraulic roughness has a major effect on sediment transport calculations. Saturated hydraulic conductivity and interrill erodibility parameters fall into the moderately sensitive range of the parameters. However, as discussed by Nearing et al. (32), both of these factors play a greater or lesser role in the predictions depending on the conditions. Interrill erodibility is important on short, flat slopes and in rangeland and no-till conditions. Saturated conductivity is more important for shorter duration, less intense storms and less important for the larger storms. This is because a smaller fraction of the total rainfall becomes runoff for the smaller storms. Interrill cover is important when interrill erosion is important, it responds similarly as the interrill erodibility term. Plant canopy cover is not a dominant factor. Its influence, again, is greater on short flat slopes, but not as great as interrill cover or erodibility. Canopy height is relatively insignificant overall to predicting erosion. Terms related to the suction term of the infiltration equation, those being bulk density and saturation, do not have a major influence on the output. Peak rainfall intensity, time to peak rainfall inten-
Table 6.2 Summary of average sensitivity values (S) for erosion component.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average S value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity &amp; Runoff</td>
<td>1.1836</td>
</tr>
<tr>
<td>Ground Cover (corn)</td>
<td>-0.8134</td>
</tr>
<tr>
<td>Runoff</td>
<td>0.8100</td>
</tr>
<tr>
<td>Rill Cover (corn)</td>
<td>-0.6504</td>
</tr>
<tr>
<td>Ground Cover (wheat)</td>
<td>-0.6080</td>
</tr>
<tr>
<td>Rill Erodibility</td>
<td>0.5008</td>
</tr>
<tr>
<td>Intensity</td>
<td>0.4697</td>
</tr>
<tr>
<td>Critical Shear</td>
<td>-0.4194</td>
</tr>
<tr>
<td>Rill Cover (wheat)</td>
<td>-0.4155</td>
</tr>
<tr>
<td>Incorporated Residue</td>
<td>-0.3843</td>
</tr>
<tr>
<td>Soil Friction Factor*</td>
<td>0.3565</td>
</tr>
<tr>
<td>Interrill Erodibility*</td>
<td>0.2515</td>
</tr>
<tr>
<td>Interrill Cover</td>
<td>-0.1101</td>
</tr>
<tr>
<td>Canopy Cover</td>
<td>-0.0999</td>
</tr>
<tr>
<td>Rill Spacing*</td>
<td>0.0943</td>
</tr>
<tr>
<td>Canopy Height</td>
<td>0.0542</td>
</tr>
<tr>
<td>Rill Width*</td>
<td>0.0530</td>
</tr>
<tr>
<td>Sediment Transportability*</td>
<td>0.0188</td>
</tr>
</tbody>
</table>

*Sensitivity values averaged over sediment loss from slope lengths of 22.13, 50.0, and 200 m at slope gradients of 5 and 9 percent.

*Sensitivity values averaged over sediment loss from slope lengths of 50 m and 5 percent gradient.

*Sensitivity values averaged over sediment loss from Kt values of 0.5 x 10^6 - 5.0 x 10^4 kg s/m

*Sensitivity values averaged over sediment loss from rill space values of 0.5 and 5 m.

Sediment, rill spacing and width, and sediment transportability (i.e., sediment size distributions) do not play a major role in the predictions of total soil loss in the WEPP model. Obviously, sediment size distributions would play a major role in terms of sediment enrichment.

Confidence limit analysis addresses the issue of how accurate erosion estimates from the model are. Given the expected variation of the data input values, confidence limit analyses evaluate the variation of the model response. Methods such as Monte-Carlo simulation or the point estimate method (34) may be used. Figure 6.4 shows the results of an analysis of the coefficient of variation of the WEPP model response as a function of variation in erodibility input parameters, which was calculated from field rainfall simulator experiments on the Miami silt loam soil. Variation was computed using the point-estimate method (32). This analysis was done for a fallow soil condition and a relatively highly erodible soil condition. For other conditions where residue is present or where the soil is highly
Table 6.3 Summary of average sensitivity values (S) for detachment per area in single storm component.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average S value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>1.12</td>
</tr>
<tr>
<td>$K_r$, Rill Erodibility*</td>
<td>0.81</td>
</tr>
<tr>
<td>Rill Cover</td>
<td>-0.794</td>
</tr>
</tbody>
</table>
| Sand                             | -0.455 to -0.630
| Clay                             | 0.245 to 0.630
| Silt                             | -0.245 to 0.455
| $K_r^*$                          | -0.43
| Duration at constant precipitation | -0.344          |
| $K_s$, Interrill Erodibility*     | 0.19            |
| $i_p$                            | -0.156          |
| Canopy cover                     | -0.111          |
| Saturation (init)*               | 0.1015          |
| Interrill Cover                  | -0.087          |
| Canopy height                    | 0.0455          |
| Bulk Density*                    | -0.017          |
| $i_p$                            | -0.0130         |

* End Slope = 0 percent.

Dependent on fraction of other size classes.

consolidated, as for rangelands and no-till, the response of the coefficient of variation would be much different.

MODELING ON WATERSHED SCALES

The mechanics of detachment, transport, and deposition of soil particles in a watershed is extremely complex to describe in detail. Therefore abstraction is necessary if we are to describe some aspects of erosion and deposition processes on watershed scales. Abstraction consists of replacing the system under consideration with a conceptual model of similar but simpler structure. To develop a conceptual model for describing the erosion and deposition processes on watersheds it is natural to begin with two sets of partial differential equations expressing the conservation of mass and momentum: the free surface flow equation (portraying the flow velocity field) and the sediment continuity equation (portraying the sediment concentration distribution). Conceptually, these equations along with initial and boundary conditions would enable one to describe the erosion-sedimentation system.
According to Woolhiser (38) there are four levels of abstractions in modeling of watershed systems: (1) watershed process models, (2) watershed component models, (3) integrated watershed models, and (4) global watershed models.

A watershed process model is a mathematical model describing an individual process in the watershed system, for example, mathematical models of infiltration, unsteady free surface flow, sediment detachment, deposition, etc.
Watershed component models include linked mathematical models of individual processes with a component operator for describing processes occurring in a particular subspace of the watershed system. Examples in this category of mathematical models include models of evapotranspiration, direct surface runoff, and sediment yield. A mathematical model of watershed sediment yield, for example, would include individual process models describing interception, infiltration, soil water content, plant growth, free surface flow, sediment detachment, sediment transport, and deposition. This chapter emphasizes the erosion and sediment yield component of the WEPP model, which is a component model.

An integrated watershed model is an example of a comprehensive watershed model. Often this category of watershed models is developed by a process of synthesis of components and has a well-defined structure that is usually determined by the modeler's concepts of the physical nature of the watershed.

Global watershed models are an alternative to integrated watershed models. Their structure is much simpler. They assume that there is a functional relationship between a set of input and output variables rather than a linkage of individual components.

Erosion models consisting of sets of partial differential equations can be simplified by dropping certain terms from the equations, leading, for example, to steady-state conditions (absence of time variable), plane conditions (absence of one space variable), or uniform conditions (absence of velocity and sediment concentration gradients in the flow direction).

Another simplification consists of reducing the number of independent variables by averaging the equations with respect to the variable to be removed. This procedure is quite common in environmental sciences where the extension and complexity of geometries generally do not allow a detailed and complete description of the processes.

As a further simplification the watershed system might be represented as a "lumped" system where runoff and sediment transport, for example, are assumed to be related to precipitation, without any explicit assumption regarding the internal structure of the runoff-sediment generation system.

The WEPP watershed model is made up of four major components: hillslope, channel, impoundment, and irrigation. The hillslope component is the WEPP hillslope model which calculates erosion and deposition on rill and interrill flow areas. The channel component calculates erosion and deposition within concentrated flow areas which can be represented as permanent channels or ephemeral gullies. The impoundment component calculates deposition of sediment within terrace impoundments and stock tanks. The irrigation component calculates erosion and deposition on border irrigation areas.
Channel flow hydraulics

As in the case of hydraulics of overland flow, the primary purpose of channel hydraulic calculations is to provide flow peak, duration, and shear stress for calculation of detachment, transport, and deposition of sediment within the channel network. The channel hydraulic calculations follow a similar logic to those of the overland flow hydraulics.

A model developed by Lane (20) may be used to estimate transmission losses in alluvial streams. This model was developed by regression analysis of observed streamflow data from 14 channel systems in Arizona and Texas. If the volume of inflow to the channel does not satisfy the infiltration capacity of the channel then there will be no flow out of the channel reach. However, if there is inflow at the top of a channel reach, then the model computes the distance that inflow will advance down the reach before stopping.

In the event that upstream inflow is sufficiently large, the flow may traverse the entire channel reach, but its volume and peak rate are reduced by transmission losses. In the WEPP watershed model, the method of estimating the peak discharge at the watershed outlet involves aggregating a watershed made up of a cascade of planes and channels into an equivalent plane and applying regression equations developed from solutions of the kinematic wave equation for a range of plane characteristics and lateral inflow distributions. The watershed is aggregated or reduced to a single plane (or two lateral flow planes and a single channel) by calculating the storage of water on the watershed at kinematic equilibrium and using the storage to calculate an equivalent roughness for routing. The regression equations are derived by obtaining solutions of the kinematic wave equation for a single plane (or two planes and a single channel) for a range of plane and channel characteristics.

Hydraulic shear stress is calculated in two ways. In the case of absence of lateral inflow from adjacent overland flow areas, the channel flow is assumed to be normal flow and the hydraulic shear stress is constant along the channel reach. However, for the case of lateral inflow or in steady flow, the hydraulic radius and friction slope vary with the distance along the channel reach. Because many of the applications of the WEPP model will be for cases where lateral inflow influences the channel discharge, the spatially varied flow equation is used to calculate the friction slope and the hydraulic radius at points along the channel reach.

The steady spatially varied flow equation (5) is solved in the WEPP watershed version by regression equations developed by Foster et al. (8). A control section is assumed at the channel outlet and can be described by a critical depth, a depth discharge relationship, or normal depth. Given a
control section, the regression equations are applied at distance increments upstream from the control section assuming subcritical flow for the entire length of the reach.

Channel erosion and deposition

Channel erosion is based on a steady state sediment continuity equation similar to rill erosion in the overland flow profile component. The sediment load in the channel is a function of the incoming sediment load from adjacent overland flow areas and the ability of the flow to detach soil particles. The ability of the flow to detach depends on the force the flow exerts on the soil and transport capacity of the flow. Net soil detachment will occur when the shear stress of the flow exceeds the critical shear stress of the soil and when the sediment load is less than the transport capacity. Net soil deposition will occur when the sediment load is greater than the transport capacity.

For the channel computations, the channel is divided along its length into segments which are determined by changes in the channel characteristics (slope, surface roughness, etc.) or the contributing hillslope areas. The model computes the initial potential sediment load and the transport capacity for each segment. From this, it can be determined whether detachment, deposition, or both will occur within the segment.

The channel detachment routines assume a rectangular channel cross section for the permanent channels and ephemeral gullies. On ephemeral gullies, detachment initially occurs from the channel bottom until it reaches a nonerodible layer (usually the primary tillage depth). Once the channel reaches this boundary, the channel begins to widen and the erosion rate decreases with time until the flow is too shallow to cause detachment. Channel dimensions are updated after each storm that causes detachment in order to estimate channel hydraulics for subsequent storms.

Impoundment sedimentation

Impoundment terraces are designed to reduce sediment loss from croplands. They function by collecting and detaining runoff from an upslope area for a period of time to allow sediment deposition. The impoundment drains via an underground conduit which connects to the bottom of the impoundment so it drains completely between each storm.

The amount of sediment deposited in the impoundment terrace is a function of the amount of time available for settling. The terrace impoundment routines in WEPP estimate the fraction of each particle size class that leaves
the impoundment as a function of the particle size distribution of the incoming sediment, the depth of water in the pond, and the diameter of the outlet pipe.

Reservoir impoundments are designed to collect and store surface runoff for later use. These include stock tanks and farm ponds. As with impoundment terraces, deposition is the main sedimentation process. Runoff from a reservoir impoundment is produced only when it is full and more runoff is introduced. When the pond becomes full, extra runoff is routed over spillways. Estimation of the discharge rate requires either a rating table for the spillway or the spillway dimensions.

Watershed representation

A watershed must be represented by at least one hillslope element. In the WEPP watershed model, hillslope elements can contain up to 10 overland flow sub-elements which may represent changes in cropping patterns (strip cropping), soil variation in the downslope direction, different land use patterns, or changes in grazing intensities. A hillslope element can drain into a channel either at the headwaters or laterally, or into an impoundment. A channel element can receive water and sediment input from hillslope elements, upstream channel elements (up to three channel elements), or an impoundment. An impoundment element can receive input from hillslope or channel elements.

Figure 6.5 illustrates how a typical watershed is represented in the WEPP model and how the hillslope, channel, and impoundment elements are linked together.

Integrated systems for water erosion prediction

Erosion prediction technology must be usable by technicians at the field level. To meet that objective the technology must encompass an integrated system of tools on three levels: database generation, user interface, and simulation models (Figure 6.6). Development on all three levels is a research function. The WEPP landscape profile version erosion model requires four input data files to execute: a soil file, a slope profile file, a crop management file, and a climate file. The user must have file building tools and access to appropriate soil, tillage implement, plant, and climate databases in order to build the four data files. One approach which should be investigated for both database development and user interface development aspects of the prediction technology is expert systems. Engel (7) developed an expert system to interface with an early, single-storm version
of the WEPP technology, but such development has not continued. Expert systems are a logical choice to act as the interface between the user, the databases, and the simulation model in order that the user can provide the necessary input and obtain the desired output from the model.

The climate databases and the file building tools required to use the WEPP models within the U.S. are available and will be distributed with the computer model. Likewise, all of the soils information necessary to build the soils data files for within the U.S. will be available when the model is distributed to the user. Plant growth and residue decay parameters for the model are available for only a few crop types. An expert system or some related tool should be developed which is able to communicate with an agronomist who is knowledgeable about a specific crop. The expert system would then translate that knowledge from the agronomist’s terminology to the crop parameters required in the crop growth component of the erosion prediction technology. The same approach could be used to build databases for new tillage implements, each of which will have a different effect on soil disturbance, random roughness, and burial of surface residue.

Ultimately, if the computer-based erosion prediction technology is to be usable worldwide, it must be an integrated system of tools. A potential
user should have the tools to use regional information and expert knowledge, not necessarily in the form of collected data, to build climate, plant, tillage implement, and soils databases. The user interface should be flexible enough for the user to apply it in the new environment with the new databases for the region, or alternatively, technology must be available to readily adapt the interface to the new environment. Obviously, the process of database development and user interfacing must include a major research component, along with aspects of training and technology transfer.

The WEPP prediction technology can be used as an interactive tool for designing conservation systems. The output for the model provides spe-
pecific information concerning how much soil loss is occurring at each point along the hillslope profile and the time distribution of soil loss. That information allows the user then to “experiment” with alternative management systems, based on the spatial and temporal soil loss distribution estimates, and quickly assess the impact of the proposed systems for the site-specific information. Changes in tillage dates, different tillage implements, new crop rotations, strip cropping, contour farming, buffer strips, terraces, and reduced tillage can all be evaluated for potential in controlling erosion and reducing offsite sediment delivery. Research is needed to provide guidelines and methods for using the technology as an interactive systems design tool for soil conservationists and project planners.

RESEARCH NEEDS FOR EROSION MODELING

Development and transfer of technology is vital to a scientific discipline. Without it there is ultimately no need for research. But technology transfer can also stifle creativity. Research scientists to some degree have their approaches molded by the current trends in scientific thought, which to some extent is good and necessary. But major advances must come from outside the current mold of scientific thought. For that reason it isn’t possible to discuss in detail the next generation of soil erosion prediction technology. Some general thoughts for the future of soil erosion modeling are discussed below.

Deposition calculations are very important in terms estimating the sediment delivery rates and enrichment ratios from a slope profile. Good deposition relationships are critical to providing accurate predictions of off-site sediment problems, and much work is needed in the area of predicting deposition on complex slope profiles. This work may be classified into three general areas: 1) If a single effective fall velocity term is to be used to calculate net deposition, improved methods of calculating an effective fall velocity must be developed. 2) Reliable deposition data, particularly for non-uniform slopes in the field, is essentially non-existent. Collection of such data will require innovative techniques and careful experimental procedures. Exact profile descriptions will be essential to interpreting the data. Also, the rate of sediment delivery to the area of net deposition must be accurately measured as a function of time through the experiments. 3) More basic theoretical work needs to be performed to provide better estimates of transport and deposition rates for individual particle size classes. Both CREAMS and WEPP models allow for transport capacity to be shifted between particle size classes. Until more and better data are available, it is difficult to assess the validity of those procedures or to test alternatives.
Physically-based erosion technology represents a major advance in predicting soil movement on complex hillslope profiles. The next generation of technology should be able to represent complex landscape surfaces and the movement of sediment on those surfaces. Digital terrain models can be used to describe landscape surface elevations (28). Methods for calculating overland routing on the complex surfaces will need to be developed and then linked to process-based erosion equations (27). Data input for soil, topography, crop management, and climate could be accessed through a Geographical Information System.

A continued research effort in terms of technology transfer techniques is essential. Application of knowledge-based engineering to database development and user interfacing is only beginning and should come to fruition with the next generation of erosion prediction technology.

REFERENCES


logic modeling of small watersheds. ASAE Monograph No. 5, American Society of Agricultural Engineers, St. Joseph, Michigan. pp. 1-16.