

Soil Erosion, Conservation, *and* Rehabilitation

edited by

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Soil Loss Estimation

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I. HISTORY OF EROSION PREDICTION

Zingg (1940) is often credited with the development of the first erosion-prediction equation used to evaluate erosion problems and select conservation practices to reduce excessive erosion. Zingg's equation was a simple expression that related soil erosion to slope steepness and slope length. Smith and Whitt (1948) added terms to Zingg's equation to reflect the influence of cover and management on soil erosion.

Relative differences among conservation practices do not consider important differences among locations caused by differences in rainfall erosivity or soil. Thus, rainfall-erosivity and soil-erodibility terms were added to the Zingg and the Smith and Whitt equations (Musgrave, 1947; Wischmeier and Smith, 1958; Meyer, 1984). Concurrent with the development of these erosion-prediction equations was the development of a soil loss tolerance concept (Stamey and Smith, 1964; ASA, 1982). These terms along with the soil loss tolerance concept allowed users to consider differences among site characteristics and to consider the severity of erosion relative to a measure of how much erosion a soil could "tolerate" before experiencing excessive damage. By the early 1950s a set of regional equations had been developed that used soil-erodibility terms reflective of major soils in each region. Even though these equations proved to be quite

useful, the United States Department of Agriculture (USDA), Soil Conservation Service (SCS), needed a more "universal" soil loss equation than these regionally based equations. Beginning in the mid-1950s W. H. Wischmeier, D. D. Smith, and their associates began to assemble and analyze an extensive quantity of available plot data. The result was the universal soil loss equation (USLE) (Wischmeier and Smith, 1965), which became by far the most widely used equation for estimating interrill and rill erosion.

Development of the USLE continued after 1965, resulting in a major revision of the equation in 1978 (Wischmeier and Smith, 1978). Many of the modifications between 1965 and 1978 used data collected from rainfall simulators (Meyer, 1960). In the 1960s much of the field-erosion research shifted from natural runoff plots to rainfall simulator plots.

The basis of a soil-erodibility nomograph and the cover-management factor values in the 1978 USLE version were derived from rainfall simulators. Another important USLE concept introduced in 1970 was the subfactor method for estimating cover-management factor values (Wischmeier, 1975). This method was originally introduced for computing factor values for range, woodland, and similar land uses where plot data were not available, but where agencies needed to apply the USLE. This method has since been extended to all land uses (Lafren, Foster, and Onstad, 1985) and is central to the revised universal soil loss equation (RUSLE) (Renard et al., 1991).

The USLE and RUSLE are empirically based technologies that compute soil erosion by assigning values to indices that represent the major factors of climate, soil, topography, and land use. An alternative approach based on fundamental hydrologic and erosion processes is emerging in a form that can be easily used to estimate soil loss by sheet and rill erosion and erosion by concentrated flow in field-sized areas. This technology, known as the USDA Water Erosion Prediction Project (WEPP), is intended as 20th-century erosion-prediction technology (Lane and Nearing, 1989). It is based on concepts and relations developed by Ellison (1947). In the late 1960s, Meyer and Wischmeier (1969) utilized Ellison's concepts using computer programming and showed the potential of this approach, especially for dealing with the spatial variation of erosion and deposition along a complex landscape profile. In the early 1970s, the concept of rill-interrill erosion was developed to provide a powerful model structure for representing and connecting the major erosion processes of detachment by rain-drop impact, detachment by surface flow, sediment transport by flow, and deposition by flow (Foster and Meyer, 1975).

Concern for the impact of agricultural practices on surface-water quality in the 1970s led to the development of several models that included process-based erosion components. For example, CREAMS (chemicals, runoff, and erosion from agricultural management systems) (Knisel, 1980), which was a combination of process-based and empirically based components, became widely used

for field-sized areas. Several new concepts were introduced in CREAMS, including the use of hydrologic elements to represent flow patterns on the landscape, sediment as a mixture of primary particles and aggregates, and the effect of a nonerodible layer on erosion by concentrated flow. This model is implemented in a computer program that can be run on desktop computers.

II. THE REVISED UNIVERSAL SOIL LOSS EQUATION

RUSLE is a major revision of the USLE. While retaining the equation structure of the USLE, several concepts from process-based erosion modeling have been incorporated in RUSLE to improve erosion predictions. These concepts provide a basis for estimating factor values for slope length, slope steepness, and supporting practice effects. RUSLE has been developed and distributed in the form of a computer program that readily runs on desktop computers.

The effort to upgrade the USLE was precipitated by recognition that the knowledge acquired after the 1978 USLE release needed to be incorporated to computerize erosion prediction. Thus, the RUSLE effort was initiated in 1985, and the effort to develop the RUSLE model in a computer program was initiated in 1987. Although RUSLE retains the basic six-factor product form of the USLE, the equations used to arrive at the factor values are significantly modified. Furthermore, the decision to computerize the technology permits calculations which address prototype conditions not possible with the USLE. For example, crops for which soil loss ratios were not available in the USLE can now be simulated based on fundamental crop measurements.

Like the USLE, RUSLE retains a regression relation to estimate soil loss. The conceptual equation is

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (1)$$

where

A = computed average spatial and temporal soil loss per unit of area, expressed in units selected for K and for period selected for R (in practice, A is usually expressed in $t \text{ ac}^{-1} \text{ yr}^{-1}$, but other units can be selected (i.e., $mt \text{ ha}^{-1} \text{ yr}^{-1}$)

R = rainfall and runoff erosivity factor—the number of rainfall erosion index units plus a factor for runoff from snowmelt where such runoff is significant

K = soil-erodibility factor—the soil loss rate per erosion index unit for a specified soil as measured on a unit plot, defined as a 72.6-ft (22.1-m) length of uniform 9% slope in continuous clean-tilled fallow

L = slope-length factor—the ratio of soil loss from the field slope length to that for a 72.6-ft length (22.1-m) under the unit plot conditions as above

- S* = slope-steepness factor—the ratio of soil loss from the field slope gradient to that from a 9% slope under unit-plot conditions
- C* = cover and management factor—the ratio of soil loss from an area with specified cover and management to that from a unit plot in tilled continuous fallow
- P* = supporting practice factor—the ratio of soil loss with a support practice like contouring, stripcropping, or terracing to that with straight-row farming up and down the slope

The schematic diagram of the RUSLE computer model is shown in Fig. 1. The RUSLE computer program is designed for inputs and outputs in English units. Foster et al. (1981) list English and SI units and conversions for USLE/RUSLE.

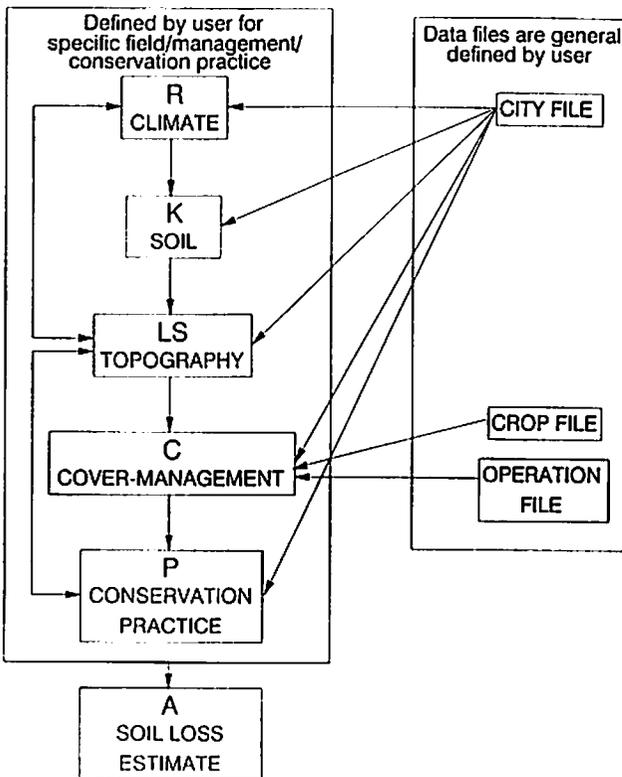


Fig. 1 Schematic of RUSLE soil loss calculations.

RUSLE (Fig. 1) uses three databases to simplify soil loss calculations: CITY, CROP, and OPERATION. The CITY DATABASE contains monthly average temperature and precipitation data used for predicting residue decomposition, R -factor, 10-yr-frequency maximum daily EI used to calculate the contouring subfactor in the support-practice factor, frost-free period used in the time-varying K -factor, and the twice-monthly distribution of the rainfall-runoff erosivity used to weight K - and C -values.

The CROP DATABASE contains information used in calculating the twice-monthly soil loss ratios for the cover-management (C) factor. Essential data include the root mass in the upper 4-in of the soil, fraction of land surface covered by canopy, and the canopy raindrop fall height at 15-day intervals following planting. The file also contains the mass of residue required to cover 30%, 60%, and 90% of the surface and a yield unit, residue/yield ratio, and the rate at which the residue decomposes.

The OPERATION DATABASE describes the impact of soil-disturbing practices and requires information on the percentage of the area disturbed, the amount of residue left following an operation, and the depth of soil disturbance. The database also initiates crop growth or death, specifies residue removal or additions to the field, and crop harvest.

A. Climate: Erosivity Factor (R)

The earlier procedure used to extrapolate limited calculations of R in the western United States using the two-yr-frequency, 6-h-duration precipitation values produced by the National Weather Service (NWS) was useful but not entirely satisfactory. In RUSLE, over 1000 NWS rain gauges with hourly precipitation amounts were used to calculate point values of R using the equation

$$R = \sum_{i=1}^m EI_{30} \quad (2)$$

where m is the number of storm events in a given year and EI_{30} is the product of kinetic energy times the maximum 30-min intensity of individual storm periods (Wischmeier, 1959).

Records for the western U.S. data varied from 5 years to over 20 years. A linear correction was used to adjust the hourly recorded amounts to those which might be obtained if a more conventional short-interval hyetograph were used. The new western U.S. map produced point estimates that vary over a much greater range than those in *Agricultural Handbook 537* (Wischmeier and Smith, 1978).

In the Pacific Northwest (PNW), where much of the erosion occurs from rainfall and melting snow on partially frozen soil, an equivalent R (R_{eq}) was

obtained from

$$R_{eq} = \frac{A}{KLSCP} \quad (3)$$

where A , K , L , S , C , P were based on field measurements.

These R_{eq} values in turn were regressed against annual precipitation to produce isoerodent maps for use in the small-grain-growing areas of the PNW.

Minor changes were also made in the isoerodent map of the eastern United States, but, more significantly, a correction factor was developed to reduce R -values where low slopes occur in regions of long, intense thunderstorms. This correction factor is designed to account for the reduction in raindrop-impact erosivity due to ponded water on the soil. Moss and Green (1983) found that ponded water depths of 2 to 3 drop diameters considerably decreased detachment and transport of soil particles by raindrop impact.

To facilitate the soil loss calculations, a CITY DATABASE file is developed for each of 119 "climatic homogeneous" EI distribution areas of the United States. These data files include station identification codes plus monthly and annual precipitation, monthly average temperature, number of frost-free days, annual R - or R_{eq} -values, distribution of 15-day-period EI_{30} , and 10-yr-frequency annual maximum storm EI_{30} .

One of the problems of developing R -factor values for the CITY DATABASES is the paucity of data used to calculate time-intensity relationships and, in turn, kinetic energy and maximum 30-min intensity. Other authors have attempted to calculate R by correlating annual precipitation and monthly precipitation with known R -factors. Renard and Freimund* recently used U.S. CITY DATABASE information to present the following two regression relations (in SI units):

$$R = 0.0048P^{1.61} \quad (4)$$

and

$$R = 0.074F^{1.85} \quad (5)$$

where

R = rainfall and runoff factor (10^{-2} N h¹ yr⁻¹) [N is newton force]

P = annual precipitation (mm)

F = Fournier (1960) index (mm) = $\sum_{i=1}^{12} P_i^2 / P$

P_i = monthly precipitation (mm)

*Renard, K.G., and J.R. Freimund 1993 (pending). Estimating RUSLE R -factor and 10-yr-storm EI value for locations with monthly precipitation data.

Although both relations had high coefficients of determination ($r^2 = 0.81$), the standard error of estimate was 107 and 108, respectively. At this time, no recommendations can be made regarding the geographic areas for which these relations might best be applied.

The RUSLE CITY DATABASE also requires an estimate of the 10-yr-frequency maximum storm kinetic energy times maximum 30-min intensity. Renard and Freimund likewise developed a regression equation as follows:

$$(EI_{30})_{10} = 2.98R^{0.70} \quad (6)$$

where

$$(EI_{30})_{10} = 10\text{-yr-frequency maximum annual storm kinetic energy } (E) \text{ times} \\ \text{maximum storm intensity for 30-min } (EI_{30}) \text{ (} 10^{-2} \text{ N h}^{-1}\text{)}$$

$$R = \text{average annual rainfall-runoff value (} 10^{-2} \text{ N h}^{-1} \text{ yr}^{-1}\text{)}$$

This equation has a coefficient of determination (r^2) of 0.90 and a standard error of estimate of 30 (10^{-2} N h^{-1}).

B. Soil-Erodibility Factor (K)

In addition to the soil-erodibility nomograph, RUSLE includes equations for estimating K -values where the nomograph does not apply (e.g., volcanic soils and soils with high organic matter). Erodibility data from around the world have been reviewed and an equation developed that gives a useful estimate of K as a function of an "average" soil particle diameter. This function is only recommended where the nomograph does not apply. An equation is also provided for use with volcanic soils such as occur in Hawaii.

Another change incorporated in RUSLE accounts for rock fragments on and in the soil profile. Rock fragments on the soil surface (i.e., erosion pavement) are treated like mulch in the C -factor, while the K -value (in the nomograph) is adjusted to reflect the effects of rock on permeability in the soil profile and, in turn, runoff. The rock fragments in the soil profile are assumed to reduce permeability and thereby increase runoff and soil erodibility.

Experimental data have shown that K varies with season, being highest in spring immediately following freeze-thaw actions. The lowest values occur in mid-fall and in winter. The seasonal variability is addressed by RUSLE with instantaneous estimates of K weighted in proportion to the twice-monthly EI estimates from the CITY DATABASE files. Instantaneous K estimates are obtained with equations relating K to the frost-free period and to the annual R -factor.

C. Topographic Factor (LS)

Users ask more questions and express more concern about selecting a slope length than nearly any other term in RUSLE and USLE. This involves judgment,

and different users choose different slope lengths for similar field conditions. Although the RUSLE handbook provides guidelines which should give consistency among users, the concern is not warranted because soil loss predicted by RUSLE is less sensitive to slope length than slope steepness or other RUSLE factors. For example, a 10% error in slope-length determination results in about a 5% error in computed soil loss, whereas a 10% error in slope steepness results in a predicted soil loss difference of more than 10%.

RUSLE uses three slope-length relations that are functions of the soil's susceptibility to rill erosion relative to interrill erosion, and a separate slope-length relation is used for the small-grain-farming areas in the Pacific Northwest. Guides in the computer program and the RUSLE handbook help the user select the appropriate relationship for the particular field condition encountered.

RUSLE has a more nearly linear slope-steepness relationship than the USLE. Computed soil loss for slopes less than about 20% are similar in RUSLE and the USLE. However, on steep slopes, computed soil loss is significantly less with RUSLE. Experimental data and field observations do not support the USLE quadratic relationship for steep slopes. RUSLE provides a slope-steepness relationship for short slopes subject primarily to interrill erosion (such as might be experienced on bedded fields). RUSLE also incorporates a slope-steepness relationship developed for the small-grain-farming areas in the Pacific Northwest, where partially frozen soil and rain on snow lead to excessive rill erosion.

Of great significance in RUSLE is the ease with which a slope segment previously estimated as a single plane or uniform slope can represent the actual topography. A simple representation can often lead to gross errors in the topographic factor (LS). For example, a three-segment slope consisting of a 100-ft length at 6%, a 150-ft length at 10%, and a 50-ft length at 6% would be represented as a single 300-ft 8% slope segment in the USLE rather than as the three segments with RUSLE. Predicted average soil loss by RUSLE for these slope segments is 13% greater than the USLE for an Indiana cornfield and 12% less than by USLE for a southeastern Arizona rangeland. Thus, the differences cannot be readily generalized, but they can be quite large.

D. Cover Management Factor (C)

The soil loss ratios (SLR) used to calculate the C -factor are perhaps the most important terms in RUSLE because they represent conditions that can be managed most easily to reduce erosion. Furthermore, values of C can vary from near zero for a very well protected soil to about 1.5 for a finely tilled, ridge surface that results in much runoff and leaves the soil susceptible to rill erosion. The changes in RUSLE C -factor calculations are very significant over those of the USLE.

Values for C are average SLRs that represent the predicted soil loss for a given surface condition at a given time to that for a unit plot. SLRs vary during

the year as soil, plant conditions, cover, and random roughness change. RUSLE computes C -values by weighing the 15-day SLRs according to the distribution of EI .

In RUSLE, a subfactor method is used to compute SLRs as a function of five subfactors given by the equation

$$SLR = PLU \cdot CC \cdot SC \cdot SR \cdot SM \quad (7)$$

where

PLU = prior-land-use subfactor

CC = canopy-cover subfactor

SC = surface-cover subfactor

SR = surface-roughness subfactor

SM = soil-moisture subfactor used in small-grain-farming areas in Pacific Northwest.

1. Prior Land Use

The prior-land-use subfactor (PLU) expresses (1) the influence on soil erosion of subsurface residual effects from previous crops and (2) the effect of previous tillage practices on soil consolidation. The relationship is of the form:

$$PLU = C_f \exp(-cB_u) \quad (8)$$

where

C_f = surface-soil consolidation factor

B_u = mass of live and dead roots and buried residue found in the upper 4 in of soil (lb ac^{-1})

c = coefficient representing effectiveness of buried roots and residue in controlling erosion (ac lb^{-1})

The variable C_f expresses the effect of tillage-induced surface-density changes on soil erosion. Tillage operations tend to break soil aggregate bonds, increasing the potential for erosion. This is reflected in the lower erosion rates associated with the undisturbed soils of rangeland or no-till systems. Based on the work of Dissmeyer and Foster (1981), the value of C_f for freshly tilled conditions is 1.0. If the soil is left undisturbed, this value decays exponentially to 0.45 after 7 yr. The impact of a field operation on this factor is determined by the portion of the surface disturbed. For example, if a planting operation disturbs only 30% of the surface which had already consolidated to the point where $C_f = 0.6$, then 70% of the field would have a value of $C_f = 0.6$, and the disturbed 30% would have a value of $C_f = 1.0$; the overall value would be $[(70\%)(0.6) + (30\%)(1.0)]/100\% = 0.72$.

Incorporated residue and roots in the upper 4 in (100 mm) of the soil profile reduce soil erosion significantly, as given by the B_u term in Eq. (8). This residue not only directly reduces erosion, but it also indirectly lowers soil loss by providing energy for microorganisms that produce organic compounds that bond soil particles. Estimates of root mass at various times during the growing season for different agronomic crops are given in the new handbook and obtained from the CROP DATABASE in the computer program.

For many rangeland conditions, values of root mass are not available. Weltz et al. (1987) developed Eq. (9) for estimating root biomass (B_u) on rangelands:

$$B_u = B_a n_i u_i \quad (9)$$

where

B_a = annual aboveground biomass (lb ac⁻¹)

n_i = ratio of root mass in the upper 4 in of soil to the total below-ground root biomass

u_i = ratio of root mass to the aboveground biomass

Suggested values of n_i and u_i for many plant communities in the western United States rangelands are found in the RUSLE manual and the computer program. Estimates of B_a can be made using standard biomass estimating techniques such as clipping, drying, and weighing, or using guides as the USDA's SCS range-site descriptions. On areas that have been grazed within the past six months, B_a should be estimated from published site-potential estimates as given by the SCS or the U.S. Department of the Interior, Bureau of Land Management (BLM). Practices like burning and/or mechanical treatments may remove B_a but leave B_b , below-ground biomass. The user must consider these effects when estimating B_b .

On croplands the amount of both above- and below-ground biomass present at a given time depends on the initial mass of the residue, the root mass, the fraction of crop residue buried by field operations, and the decomposition rate of residue and roots, values of which are presented in the pending RUSLE *Agriculture Handbook* or in the computer program or both.

For RUSLE, residue decomposition is estimated using a relation based on temperature, soil moisture, and plant characteristics (Stott et al., 1990; Stott, 1991).

Continuous pasture, meadow, and rangeland are assumed to be at a stable mature state. Because these lands are not usually disturbed by tillage tools, the below-ground biomass, B_u , becomes the live and dead roots. Even though crop and residue values for these practices change slowly with time, they are considered constant in RUSLE. Therefore, residue decomposition is not used for these conditions.

2. Canopy Cover

The canopy-cover subfactor (CC) expresses the effect of vegetative canopy in reducing the rainfall energy impacting the soil surface. Although most rainfall intercepted by crop canopy eventually reaches the soil surface, it usually does so with much less energy than nonintercepted rainfall. Intercepted rain reforms in drops with less energy or travel down crop stems to the ground. The CC -factor is expressed as

$$CC = 1 - FC \exp(-0.1H) \quad (10)$$

where

CC = canopy-cover subfactor

FC = fraction of land surface covered by canopy

H = distance raindrops fall after striking canopy (ft)

Suggested values of FC and H are given for numerous crops in the handbook and in the CROP DATABASE of the computer program.

3. Surface Cover

The effect of surface ground cover (SC) on erosion has been observed to vary greatly in research studies. In some studies a 50% cover reduced soil loss by about 65%. In other studies a 50% cover reduced soil loss by 95%. To accommodate this varied effectiveness in RUSLE, the following equation for SC is used:

$$SC = \exp \left[-bS_p \left(\frac{0.24}{R_c} \right)^{0.08} \right] \quad (11)$$

where

b = coefficient

S_p = percent of land with surface cover

R_c = current surface roughness

The b coefficient is assigned a value of 0.025, the value in the present USLE; 0.035, the new "typical" value in the RUSLE, or 0.050 for small-grain conditions in the Pacific Northwest. The value of b is increased as the tendency for rill erosion to dominate interrill erosion for the soil increases. SC is the most sensitive of the subfactors and must be carefully treated to obtain reasonable SLRs.

The amount of residue cover can be estimated from residue weight by Gregory's relation (1982):

$$S_p = [1 - \exp(-\alpha B_r)] \cdot 100 \quad (12)$$

where

S_p = percent residue cover

α = ratio of area covered by a piece of residue to the mass of that residue
(ac lb⁻¹)

B_i = weight of crop residue on the surface (lb ac⁻¹)

Typical values for α are given in the RUSLE handbook. If more than one type of residue is present, the resulting total surface cover is calculated by modifying Eq. (12) as

$$S_p = \left[1 - \exp\left(-\sum_{i=1}^N \alpha_i B_{i1}\right) \right] \cdot 100 \quad (13)$$

where N is the number of residue types and α_i is the ratio of the area covered to the mass of that residue for each type encountered.

Within RUSLE, rather than entering a value for α , the computer program requires residue weights associated with specific values of residue cover and calculates the corresponding α -value. The program asks for residue weights at 30%, 60%, and 90% surface cover. Only one of these needs to be entered to calculate an α -value. If more than one weight is entered, the program will calculate an α -value for each and then average them.

4. Surface Roughness

Surface roughness (SR) has been shown to affect soil erosion directly (Cogo, Moldenhauer, and Foster, 1984) and indirectly through the impact on residue effectiveness implied in Eq. (11). In either case this is a function of the soil surface's random roughness, which is defined as the standard deviation of the surface elevations when changes due to land slope or nonrandom tillage marks (dead furrows, traffic marks, disk marks, etc.) are removed from consideration (Allmaras et al., 1966). A rough surface has many microdepressions and flow barriers. During a rainfall event, these trap water and sediment, causing rough surfaces to erode at lower rates than smooth surfaces under similar conditions. Increasing the surface roughness also decreases the transport capacity and runoff detachment by reducing the flow velocity.

Roughness and clodiness of soils also affect the degree and rate of soil sealing by raindrop impact. Rough, cloddy soils typically have high infiltration rates. Finely pulverized soils are usually smooth, seal rapidly, and have low infiltration rates.

Random-roughness (RB) values vary, depending on the type and degree of surface disturbance. Roughness conditions for a field may vary, depending on previous tillage, implement speed, and other field conditions. Additional information is provided in the *Agriculture Handbook* for RUSLE.

The impact of surface roughness on erosion is defined by a baseline condition, which sets SR equal to 1 for unit-plot conditions of clean cultivation smoothed by extended exposure to rainfall of moderate intensity. These conditions yield a random roughness of about 0.24 in. This makes it possible to obtain SR values greater than 1 for practices in which the soil is very finely pulverized and smoothed to a smaller random roughness, as might be the case for some rototilling operations or for repeated cultivations of silt loam soils under dry, fallow conditions.

If a field operation normally leaves a random roughness greater than 0.24 in, the amount of biomass within the top 4 in of the soil has a significant impact on the actual roughness. This effect is defined by the relation

$$R_a = 0.24 + (R_i - 0.24)\{0.8[1 - \exp(-0.0003B_u)] + 0.2\} \quad (14)$$

where

R_a = roughness after biomass adjustment (in)

R_i = original tillage roughness based on assumption of ample subsurface biomass (in)

B_u = total subsurface biomass in top 4 in of soil (lb ac⁻¹)

For field operations that do not disturb the entire soil surface, the roughness following the operation should reflect both the roughness caused by the operation and that already existing in the rest of the field. This combination is handled through a simple weighting procedure, where

$$R_n = R_a F_d + R_u F_u \quad (15)$$

where

R_n = net roughness following the field operation (in)

R_u = roughness of the surface before disturbance and, therefore, also the roughness of the undisturbed portion of the surface (in)

F_d, F_u = fractions of surface disturbed and undisturbed, respectively, so their sum equals 1

Surface roughness has been shown to decay exponentially with the amount of rainfall since the last tillage (Onstad et al., 1984). The change is computed with the roughness decay coefficient (D_r), which decreases exponentially from a value of 1.0 with zero rainfall to asymptotically approach a value of 0.0 for high rainfall amounts. The decay follows the equation

$$D_r = \exp(-0.14P_i) \quad (16)$$

where P_i is the total rainfall since the last operation that disturbed the entire surface (inches).

We now use this roughness decay relation to determine the roughness of the undisturbed portion of the field (R_u), based on the accumulated rainfall since the previous field operation and the net roughness following that operation (R_{np}), as

$$R_u = 0.24 + \frac{R_{np} - 0.24}{D_r} \quad (17)$$

Putting this value of R_u into Eq. (15) gives a value for the net roughness following the field operation, and this value holds until the next operation.

If a tillage does not disturb the entire field, the precipitation since the last complete operation must be adjusted accordingly. This is done by first adjusting the roughness decay coefficient to reflect an overall average, using

$$D_r = D_u F_u + 1.0 F_d \quad (18)$$

where D_u is the decay coefficient for the field before the operation and thus also the decay coefficient for the undisturbed portion. Once this is calculated, we can determine the corresponding value of P_r as

$$P_r = \frac{-\ln(D_r)}{0.14} \quad (19)$$

With the passage of each time segment in the calculations, the total rainfall since tillage is incremented by the amount of rainfall in that segment, so the roughness decay coefficient (D_r) is recalculated and the current roughness (R_c) is recalculated as

$$R_c = 0.24 + D_r(R_n - 0.24) \quad (20)$$

This current roughness value is then used in calculating the surface roughness subfactor for each time segment from the equation

$$SR = \exp[-0.026(R_c - 0.24)] \quad (21)$$

If a field operation results in a random roughness of less than 0.24 in, the impacts of both subsurface biomass and rainfall smoothing are assumed to be negligible, and the surface roughness subfactor SR is defined as

$$SR = 1.17 \exp(-0.026R_r) \quad (22)$$

where R_r is the random roughness produced by the tillage operation. In this case the value of R_c used in Eq. (11) is 0.24. Consolidation because of rainfall decreases surface roughness over time, which is reflected in Eq. (11) through the R_c term.

5. Soil Moisture

Antecedent soil moisture has a substantial influence on infiltration and runoff and, hence, on soil erosion. In general, antecedent-moisture effects are inherent

components of continuous tilled fallow plots, and these effects are reflected in soil-erodibility variation throughout the year. In most of the continental United States, soil moisture is usually high during vulnerable crop stages in the spring and early summer, which is when much of the erosion occurs. Hence, the antecedent soil moisture on cropped plots parallels that on the continuous tilled fallow plots from which soil-erodibility factors are derived. The soil-moisture subfactor is not used for rangelands.

In the nonirrigated portions of the Pacific Northwest, such as eastern Oregon, eastern Washington, and Idaho, soil moisture during critical crop periods is dependent on crop rotation and management. Winter wheat may be seeded after a previous crop of winter wheat, a more-shallow-rooted crop, or summer fallow. When a full year of fallow is used in the rotation, part of the moisture stored during the previous winter is retained in the profile. This is particularly true when an effective mulch system is used, such as either a loose soil and residue mulch in conjunction with a rodweeder, or direct stubble seeding into an untilled residue mulch. This is in contrast to continuous cropping, where soil moisture is at or below the wilting point in the fall prior to the fall and winter precipitation. Addition of a soil-moisture factor (*SM*) is suggested for this region of the Pacific Northwest. The factor reflects these dry fall conditions and the soil-moisture accumulation during the winter. Its subsequent decrease through the summer depends on the crop rooting depth and soil depth, and its replenishment depends on the precipitation amount and soil depth. The *SM* subfactor is then accessed in the computer calculations.

6. Subfactor Summary

One reason for the subfactor approach in the RUSLE is to accommodate applications where SLR values are not available. For example, no experimental erosion data exist for many vegetable and fruit crops, such as asparagus and blueberries. Developing SLR values using the subfactor method in the RUSLE is easier and more accurate than making comparisons with values in *Agricultural Handbook 537*.

RUSLE has computer subroutines for many tillage operations and crops. In other instances, the user must input new data reflecting residue incorporated by a tillage operation and the surface-roughness residual following tillage. For crops not represented in the computer program, data are needed to reflect canopy characteristics and root mass in the upper 4 in of the soil profile. Thus, the user must specify the crops in a rotation; crop yield; and the date of operations, such as tillage and harvest. The computer calculates SLRs and the average annual *C*-factor.

Grazing effects on rangeland, pasture, and meadow are reflected by canopy height, ground cover, and root biomass. Finally, ground cover as used in the

USLE expressed vegetation and litter; in RUSLE, ground cover is given as 1.0 minus the amount of bare soil that reflects the addition of litter in the form of rock and stone besides the conventional vegetative litter.

E. Support Practice Factor (*P*)

Of the RUSLE/USLE factors, values for the support practice (*P*) factor are most uncertain. The *P*-factor mainly represents the effect of surface conditions on flow paths and flow hydraulics. For example, with contouring, tillage marks direct runoff around the slope at much reduced grades. However, slight changes in grade can change runoff erosivity greatly. In experimental field studies, small changes in such features as row grade and their effect on erosion are difficult to document, leading to appreciable scatter in measured data. For example, the contouring effectiveness in field studies conducted on a given slope have ranged from no reduction in soil loss to a 90% reduction. Likewise, identifying these subtle characteristics in the field is difficult when applying RUSLE. Thus, *P*-factor values represent broad, general effects of such practices as contouring and stripcropping.

In RUSLE, extensive data have been analyzed to reevaluate the effect of contouring. Furthermore, simulation studies have been conducted using the CREAMS model (Knisel, 1980). The results have been interpreted to give factor values for contouring as a function of ridge height, furrow grade, and climatic erosivity. New *P*-factor values for the effect of terracing account for grade along the terrace, and a larger array of stripcropping conditions are considered in RUSLE. Finally, *P*-factors have been developed to reflect conservation practices on rangeland. The practices require estimates of surface roughness and runoff reduction as with stripcropping.

F. Applications

The development of the RUSLE computer program permits application to situations not possible with the USLE technology. At the same time, the uncertainty of the simulated result can be increased because of the empirical basis of the equations used and inadequate data with which to verify the results.

Closure of data gaps for estimating *R*-factors, the time-varying *K*-factor, the new algorithms for the topographic factor, and the new technology developed for estimating support practices greatly enhance RUSLE and permit its application to modern farming practices used throughout the United States. The technology also shows promise for use in developing countries.

Of great significance is that *C*-factor values can be estimated with RUSLE for crops where SLRs are not available. Data are not available in tables of *Agriculture Handbook 537* to address many specialty crops and operations. Given that a user can obtain data for developing a CROP DATABASE to cover

the specific conditions for a defined climate, SLRs with which to calculate a *C*-factor can be made for any crop. Furthermore, new tillage implements can be added to the OPERATIONS DATABASE to cover an extensive range of activities with which to simulate their effect on soil loss.

The RUSLE computer program is used to select factor values based on site-specific conditions and computes soil loss. Most of the input values for RUSLE are readily available in database files supplied with the program. Values in these files can be modified and values can be added as necessary.

Rainfall erosivity values for locations where a particular user might apply RUSLE are in a database that can be customized to that particular use. The CITY DATABASE on the computer disk provides values for many cities. Data for additional cities can be added, and unnecessary data can be deleted to accelerate operation of the RUSLE computer program.

Soil-erodibility values are selected from soil survey information available from local offices of the USDA SCS. The particular site is located on a soil survey map, and the erodibility of the soil mapping unit at the site is identified and entered into the RUSLE program.

Slope-length and -steepness values are determined during an on-site visit or from other available topographic information. These values are entered directly in the RUSLE program, and the program computes values for *L* and *S*.

The factors *C* and *P* are most important in RUSLE for conservation planning because they represent the land-use changes available to the land user to reduce erosion. To compute values of *C*, the user selects from the crops in the CROP DATABASE when operating the RUSLE program. The RUSLE program requires values that describe plant characteristics such as canopy. These values are stored in the CROP DATABASE.

In addition to information concerning crops, the RUSLE program uses information on tillage, harvest, and other operations that affect soil and cover conditions, such as roughness and residue cover. The OPERATIONS DATABASE contains information on these operations. Some of the information in this file includes depth of tillage, amount of residue incorporated, and roughness left by each operation. Operations can be added, and existing values can be modified to customize the file. The user selects appropriate operations from this file and enters the dates when the operations occur to represent a cover-management system.

The RUSLE predicts interrill and rill erosion from rainfall and the associated runoff. RUSLE is a tool useful in conservation planning, inventory, and assessment. Soil loss values computed by RUSLE should be used as a guide rather than being considered absolutely accurate erosion rates.

RUSLE is intended for use in field offices of land management agencies such as the Soil Conservation Service and Forest Service of the USDA and the Bureau of Land Management of the U.S. Department of Interior. As such, the technol-

ogy must be user friendly and contain databases for the wide variety of conditions that occur in their applications.

RUSLE computes average annual interrill and rill erosion for a landscape profile. The soil loss value computed for that profile is representative of an area to the degree that the profile represents the area. It does not compute average interrill and rill erosion for a field unless soil loss is computed for several profiles and the results weighted according to the fraction of the field that each profile represents. RUSLE does not compute sediment yield.

III. WATER EROSION PREDICTION PROJECT

The technology in USLE and RUSLE greatly limits their utility for evaluating many natural resource problems associated with man's activities on the land. Empirical limitations and an inability to deal with deposition preclude using RUSLE/USLE technology on larger areas where sediment delivery estimates are needed. Soil erosion from practices such as contouring and ridge tillage is difficult to estimate (Foster, 1991). Practices that drastically change the hydrology are also difficult to address with the RUSLE/USLE technology. The WEPP is an effort to develop a technology for erosion prediction that extends into the next century (Foster and Lane, 1987).

A. Overview of WEPP

WEPP is a daily simulation model that predicts erosion and sediment delivery at different scales. Three versions applicable for different scales are being developed:

1. *Profile*: Computes sediment detachment and transport on the land and sediment delivery to a channel and is common to all versions. The model computes on a daily basis the surface, soil, and crop conditions important to the hydrology and erosion processes. For the soil, these conditions include bulk density, moisture status, and buried residue. For the crop, these conditions include canopy cover, canopy height, and above- and below-ground biomass accumulation. For the surface, these conditions include surface roughness and crop residue mass and cover (Fig. 2).

2. *Watershed*: Takes the sediment delivery computed by the profile version and routes it through the channel system to the exit from the watershed. The model output includes erosion and deposition in the channel system. A watershed will include one or more areas where the profile version is operated (Fig. 3).

3. *Grid*: Computes the sediment delivery from an area that has been divided into small or regular grid elements. Within each of these elements, the profile

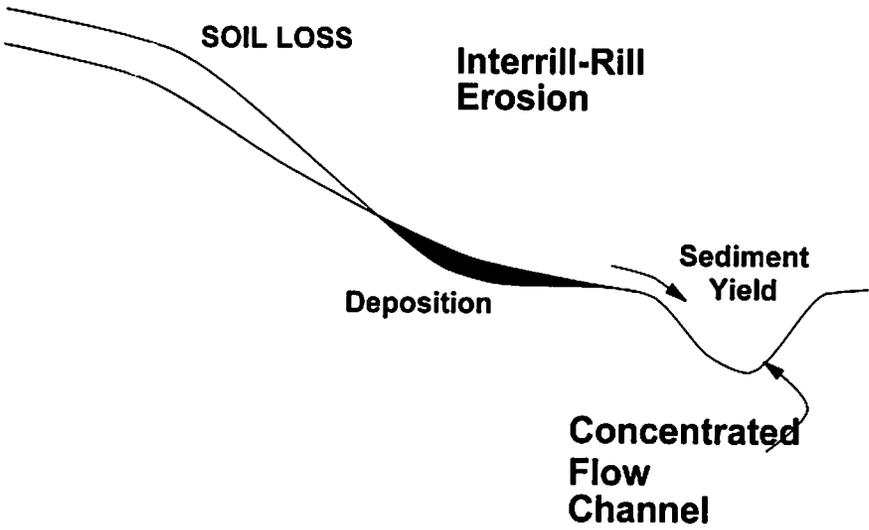


Fig. 2 Separation of a hillslope into overland flow elements (OFEs).

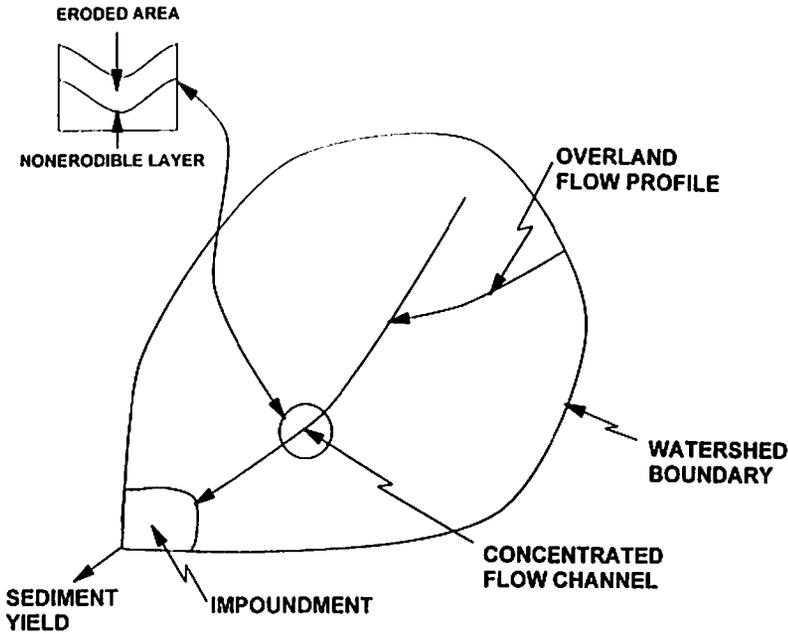


Fig. 3 Representation of watershed-version area of application.

version operates and, with the grid version, represents the transport, erosion, and deposition in the channel system within the area of interest (Fig. 4).

WEPP requires data input files that include soil topography, cropping, and management data. It also requires an input daily climate file. The Climate Generation program (CLIGEN) is part of the WEPP package. CLIGEN (Nicks and Lane, 1989) simulates daily precipitation, temperature, wind, and radiation, and has provision to stochastically disaggregate precipitation into an intensity distribution within a day.

WEPP computes new values for the soil characteristics, soil surface, and crop conditions on a daily basis. If no rainfall occurs, it then proceeds to the next day's conditions. If rainfall does occur, WEPP determines whether runoff (overland flow) occurs based on infiltration rates and rainfall distribution. If it does occur, it computes volumes and rates of runoff and the time over which it occurs and uses them to estimate soil detachment and sediment delivery to the channel system.

One of the advantages of the profile version is to represent a hillslope as a combination of homogeneous portions (Fig. 4) termed overland flow elements (OFE). Each OFE is assumed homogeneous with regard to soils and/or land use and is treated separately with regard to the status of the soil surface, soil characteristics, and crop. Within each OFE, sediment detachment is estimated for 100 points along the length of the OFE. Flow of soil and water from one OFE to another is also estimated.

B. Erosion Processes in WEPP

In the WEPP profile version, erosion consists of rill and interrill processes. Interrill erosion is the detachment and transport of soil particles by raindrops and very shallow flows, while rill erosion is the detachment and transport of sediment by flowing water. Calculations in WEPP are in SI units.

The sediment delivery to rills from interrill areas is estimated from the equation

$$D_i = K_i I_e^2 G_c C_c S_f \quad (23)$$

where

D_i = delivery of sediment from interrill areas to a nearby rill ($\text{kg m}^{-2} \text{s}^{-1}$)

K_i = interrill erodibility ($\text{kg m}^4 \text{s}^{-1}$)

I_e = effective rainfall intensity (m s^{-1})

G_c = ground-cover adjustment factor

C_c = canopy-cover adjustment factor

S_f = slope adjustment factor given by

$$S_f = 1.05 - .85 \exp(-4 \sin \alpha) \quad (24)$$

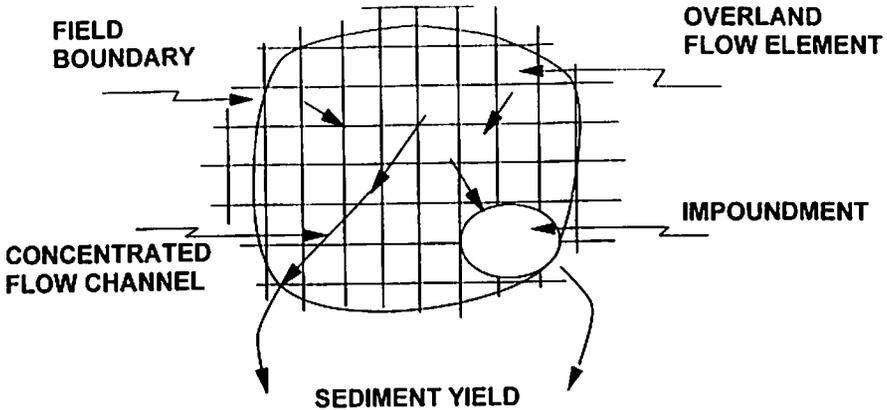


Fig. 4 Representation of grid-version area of application.

where a is the slope of the surface toward a nearby rill. The relationships expressed in Eqs. (23) and (24) are reasonable fits to data reported by Meyer (1981), Meyer and Harmon (1984, 1989), and Watson and Lafren (1986). Equation (23) lumps the processes of sediment detachment, transport, and deposition on interrill areas.

Rill erosion is the detachment and transport of soil particles by concentrated flowing water. Factors affecting rill erosion rates include hydraulic shear, soil resistance to hydraulic shear, sediment load in runoff water, and the sediment transport capacity of runoff. In WEPP, the detachment capacity (D_c) ($\text{kg s}^{-1} \text{m}^{-2}$) by flowing water is expressed as

$$D_c = K_r(\tau - \tau_c) \quad (25)$$

where

K_r = rill erodibility ($\text{s}^{-1} \text{m}^{-1}$)

τ = hydraulic shear of flowing water (Pa)

τ_c = critical hydraulic shear that must be exceeded before rill detachment can occur (Pa)

Hydraulic shear is the force exerted on the channel bed and bank material by flowing water. The detachment capacity is the maximum rill detachment rate, which occurs when there is no sediment in the water. The rill detachment rate is less than detachment capacity when there is sediment in the runoff water. The

detachment rate (D_r) of flowing water is

$$D_r = D_c \left(1 - \frac{G}{T_c} \right) \quad (26)$$

where G is the sediment load per unit width ($\text{kg s}^{-1} \text{m}^{-1}$) and T_c is the sediment transport capacity per unit width ($\text{kg s}^{-1} \text{m}^{-1}$). Sediment transport capacity is computed as

$$T_c = k_r \tau^{1.5} \quad (27)$$

where k_r is a transport coefficient ($\text{m}^{0.5} \text{s}^{-2} \text{kg}^{-0.5}$). The Yalin (1963) equation is used to obtain the transport coefficient (Finker et al., 1989).

When the sediment transport capacity is exceeded by the sediment load, deposition is predicted as

$$D_r = \beta \frac{V_{\text{eff}}}{q} (T_c - G) \quad (28)$$

where

D_r = deposition rate

β = turbulence factor

V_{eff} = effective particle fall velocity (m s^{-1})

q = discharge per unit width ($\text{m}^2 \text{s}^{-1}$)

C. Hydrologic Components in WEPP

WEPP must adequately forecast the hydrologic cycle if erosion and sediment delivery are to be accurately predicted. WEPP uses several climate variables, including storm rainfall volume and duration, ratio of peak rainfall intensity to average rainfall intensity, time that peak intensity occurs, daily maximum and minimum temperatures, wind velocity and direction, and solar radiation. These variables are required in components related to plant growth and residue decomposition, water balance, and in estimating volume, duration, and peak rate of runoff.

The Green and Ampt equation is used in WEPP to compute infiltration. Rainfall excess is computed as the difference between rainfall intensity and infiltration rate during the rainfall event. Overland flow routing procedures include analytic solutions to the kinematic wave equations. Equivalent planes are used to represent areas where flow depth is finite at the upper boundary of an area (stripcropping, for example). These techniques yield runoff rates necessary to compute hydraulic shears for sediment detachment and transport.

The winter component of the model computes soil frost, snowmelt, and snow accumulation. When frost is present, frost and thaw depth, infiltration capacity, and water balance are estimated. If snow is present, snowmelt, infiltration, and

surface runoff are computed. These variables are used in the water-balance and deep-percolation components.

Input for the daily water balance is essential to estimate infiltration and runoff. The water-balance and percolation component uses the climate, plant growth, and infiltration components to compute the status of the soil water at each soil layer of interest, and percolation from the root zone. Daily potential evapotranspiration and soil evaporative and plant transpiration are computed in this component. This component also receives the estimates of infiltration of melted snow from the winter component.

D. Plant Growth and Residue Processes

Quantity and quality of plants and crop residue are vital to the accurate estimation of soil detachment and transport. The status of below- and aboveground biomass must be accurately estimated to evaluate the effect of different managements on soil erosion.

The EPIC plant-growth subroutines (Williams et al., 1984), simplified to include only moisture stress, are used to compute daily plant status. The decomposition and accumulation of residue and litter for both cropland and rangeland are computed on a daily basis. Residue decomposition routines in WEPP are based on the decomposition model of Stroo et al. (1989). Effects of grazing and tillage on residue are incorporated into WEPP.

Important plant-growth characteristics include canopy cover and height, mass of live and dead biomass below and above ground, leaf-area index and basal area, and residue cover. Information about dates and operations are input to the model. Parameters have been determined for many annual and perennial crops, management systems and operations that may occur on cropland, rangeland, forestlands, pastures, vineyards, and gardens.

E. Hydraulic Processes

The hydraulic component of WEPP estimates hydraulic shear for estimation of rill erosion. The hydraulic component uses information about surface runoff volumes, hydraulic roughness, and runoff duration and peak rate. Major differences in hydrology among OFEs create problems in dealing with the hydraulic variables when a hillslope contains several OFEs. It is possible that during a runoff event, runoff may not occur on all OFEs, and, in fact, runoff can occur on an upper-slope OFE, disappear through infiltration into a lower OFE, and then reappear in a lower OFE. This possibility is most likely for smaller storms.

To estimate rill erosion, runoff in individual rills, rill shape, rill width, and flow depth are estimated. Rill spacing is required because it determines flow rate in individual rills. A rectangular channel is assumed, and rill width is expressed as a function of flow discharge. Rill spacing is computed as the aver-

age plant spacing for rangelands, but it is never less than .5 m or greater than 5 m. For croplands, the rill-spacing parameter is set to a default value of 1 m if not specified as input.

F. Soil Processes

The soil component of the model addresses the temporal changes in soil properties affecting erosion and runoff. These properties include random surface roughness, ridge height, saturated hydraulic conductivity, soil erodibilities, and bulk density. The effects of tillage, weathering, consolidation, and rainfall are considered in estimating soil erodibility. Baseline rill erodibility and critical hydraulic shear for a freshly tilled condition are adjusted for changing conditions. Adjustments to interrill erodibility are based on live and dead roots in the upper 150 mm of the soil, and may be adjusted through time, rainfall, or consolidation since last tillage. Rill erodibility is adjusted based on incorporated residue in the upper 150 mm of the soil and time since last tillage. Critical hydraulic shear is adjusted based on time since last tillage. Rainfall effects on bulk density of freshly tilled soils are also estimated in the soil component.

Past efforts to model the erosion processes have often used USLE relation for estimating soil erodibility. Extensive field studies (Simanton et al., 1987; Elliot et al., 1989) were completed to develop new technology to predict erodibility values for WEPP based on soil properties. These efforts have not yet yielded a satisfactory prediction technology; interim equations for predicting soil erodibility have indicated that any prediction technology will likely include parameters related to mineralogy, texture, organic matter, and soil chemistry.

G. Power of WEPP

WEPP incorporates knowledge of soils, crops, tillage, residue, climate, and sediment transport into a soil-erosion prediction tool that is to be used at the farm and field levels. WEPP considers many of the temporal changes that occur on a land area. Because it is a simulation tool, it provides the potential to study many interactive effects of various conditions as they affect soil erosion. Because of its construction, WEPP can be used to estimate erosion caused by snowmelt and irrigation, as well as that caused by rainfall. WEPP does not consider stream or channel erosion processes such as gullyng.

Some of the power of WEPP is demonstrated in Fig. 5 by comparing the average soil erosion rate versus slope length for two different soils. For comparison purposes, the RUSLE slope-length effect recommended for most cropland soils is shown for comparison. The simulation is for a 10-year continuous corn crop at Forest City, Iowa, on a 9% gradient. The soils were assume to differ in baseline rill and interrill erodibility and critical shear values. One of the soils had a very low rill erodibility rate, a high critical shear, and a high

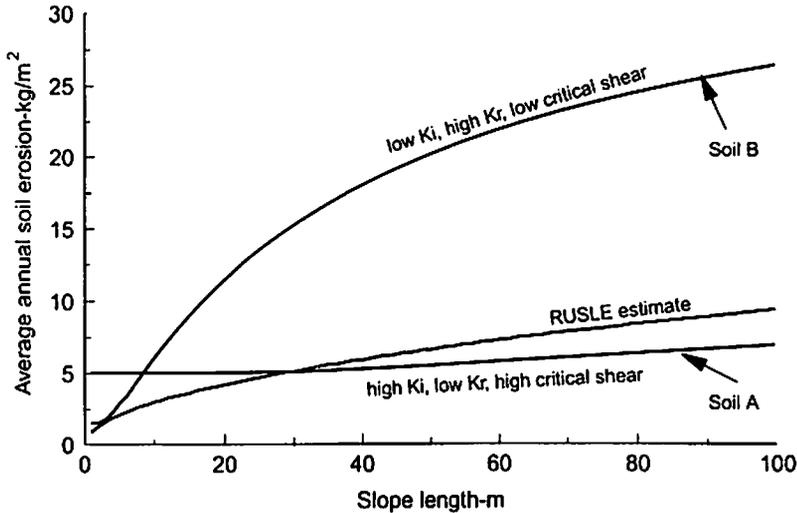


Fig. 5 Average annual soil erosion vs. slope length for a continuous corn crop at Forest City, Iowa (K_i = interrill erodibility and K_r = rill erodibility).

interrill erosion rate (SOIL A). The contrasting soil (SOIL B) had a very low interrill erodibility, a low critical shear, and a high rill erodibility (both of these soils were toward the extremes of the soils reported by Elliot et al., 1989). Both soils had average annual water yields over this 10-year simulation period of about 170 mm.

As shown in Fig. 5, the soil with high interrill erodibility, low rill erodibility, and high critical shear was (B) much less response to slope length than was either the RUSLE estimate or the other soil (A), although rill processes began to detach soil at about 30 m downslope. Interrill processes generally move soil to nearby rills (Young and Wiersma, 1973), and hence interrill contributions are little affected by slope length, as the WEPP application demonstrates. However, when the soil was susceptible to rill erosion, as indicated by a high rill erodibility and a low critical shear (B), soil erosion increased rapidly when hydraulic shear exceeded the critical shear, and sediment transport began to limit erosion rates at a fairly short distance downslope.

Another demonstration of the power of WEPP is indicated in Fig. 6. WEPP was used to simulate a slope with five OFEs, the OFEs are of uniform length (40 m), and the gradient was 9%. Each OFE is in the same rotation, corn-soybeans-wheat-alfalfa-alfalfa, but there is never a row crop grown in an OFE

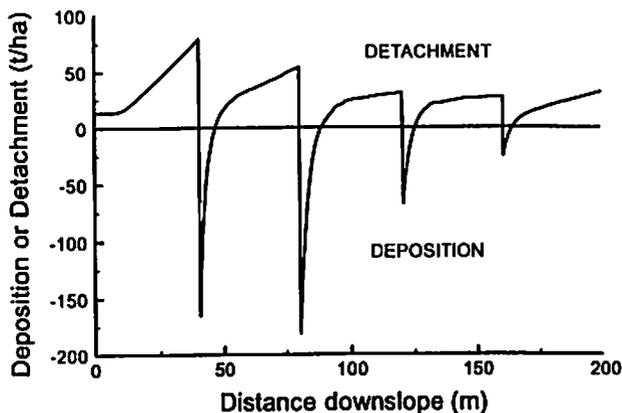


Fig. 6 Annual sediment detachment vs. distance downslope for five overland flow elements in a sod-based rotation. (Negative values indicate deposition.)

directly below an OFE with a row crop in the same year. Negative values indicate deposition. Figure 6 shows the average annual detachment rates (or deposition rates) for each of 100 points within an OFE for all storms that predicted runoff and erosion during the five-year rotation.

WEPP predicted an annual average of almost 20 t ha^{-1} of sediment delivered from the slope, but the soil detached was predicted to be more than 28 t ha^{-1} on areas where detachment occurred; deposition was predicted to average about 43 t ha^{-1} on areas where it occurred. Maximum detachment and deposition rates were predicted to be 79 and 181 t ha^{-1} , respectively. Both detachment and deposition areas may change from storm to storm, and a deposition area may become a detachment area, or vice versa, depending on circumstances.

Surprisingly, the uppermost OFE had the highest predicted erosion rate. The uppermost OFE was in corn the first year and soybeans the second year; predicted erosion was high for these years. The corn followed a meadow that was moldboard-plowed, so there was litter residue for erosion control, and tillage was quite intensive after corn harvest. The other OFEs were either in a close-grown crop or had considerable residue from a previous crop for the first year. Deposition is predicted when runoff velocity is reduced as runoff flows onto a lower OFE. The combination of no residue or cover and severe weather demonstrates the power of the model and the problem in selecting a representative period of record within a feasible computer run time for the simulation to give good estimates for long-term effects. Additionally, it demonstrates its power for

determining probabilities for individual events and annual values. Other examples could be used that demonstrate the interactive effects on erosion and sediment delivery of topography, soils, crops, climate, and tillage.

H. Applications

WEPP applications include those of RUSLE as well as many others. Some of the applications might include

- Anticipating where sediment detachment occurs on a slope, either for individual storms or for long time averages.

- Evaluation of land treatment effects on sediment delivery from a field or farm.

- Evaluation of range management and treatment alternatives, including grazing alternatives, on sediment delivery. Grazing alternatives would include timing and duration of grazing as well as stocking rates. Management alternatives might include various improvement practices including tillage, brush control through herbicides, and burning.

- Recognizing the effect of forest road design, placement, and construction on sediment delivery from forest lands. Additional forest applications would include evaluation of the effect on sediment delivery of clear-cutting certain portions of small watersheds.

- Recognizing the effect of ridge height and row direction on soil detachment and sediment delivery from a field. Evaluation of grassed waterways on sediment delivery is also possible.

- Use of Natural Resource Inventory (NRI) sites for estimates of sediment delivery from fields and farms. NRI sites and real-time weather systems (currently available in some areas of the United States) could be used with WEPP to make same-day estimates of soil loss on fields and sediment delivery from fields, perhaps at county or state levels.

- Recognizing the effect of stubble management and slope aspect on the capture of snow and its consequent effects on soil erosion.

WEPP is designed for use by local government organizations and natural-resource action agencies concerned with sediment transport and deposition. The model's ability to simulate erosion and sedimentation processes that occur and interactively to bring these into play in a modeling and predictive sense are important attributes. WEPP is also expected to become a major component of surface-water-quality models. It is likely that the databases used in WEPP and many of its components will become part of other natural resource models.

IV. INTRODUCTION TO DECISION SUPPORT SYSTEMS

Previously presented material describes past and current soil erosion, conservation, and rehabilitation from a USDA perspective with special emphasis on

development and application of an erosion-prediction technology used by the USDA and other agencies. The following sections describe selected opportunities and implications of some possible future developments in the USDA natural-resource programs.

A. Computer-Based Prediction Technology

As technology evolves from handbook-type soil-erosion models, such as the USLE, to the modern water-erosion-prediction technology requiring the use of computers for their implementation (i.e., RUSLE, and WEPP), erosion modeling and soil conservation design will be computer based. Opportunities presented by these advancements include (1) the potential to utilize processes-based models, (2) the potential to consider rapidly a larger range of soil/climate/management alternatives and interactions, (3) user adoption of improved technology, and, as a result, (4) improved soil conservation. Implications include new responsibilities and methods of operation for research scientists, technology developers, and technology users.

Implications of computer-based erosion prediction and conservation design technology will affect all aspects of soil conservation. Research, technology development, technology transfer, and application will need to be planned, designed, developed, documented, verified, validated, maintained, and monitored as a "life-cycle" project. Research scientists, technology developers, and users should be directly involved in all phases from conception to implementation to eventual replacement of each new technology.

B. National Databases

Opportunities presented by national databases include those that (1) ensure standardized procedures on a national basis, (2) allow rapid extension of analyses and interpretations from local to county to state or national levels, and (3) enhance repeatability of analyses and results. Regional and national databases including climate, soils, topography, land use, management practices, economics, and regulations and policies governing soil conservation will enable technology users at the local, county, state, and national levels access to common data and information. This common access together with a nationally uniform methodology will allow users at all administrative levels to repeat the calculations, duplicate the erosion predictions, and thus meet the test of scientific defensibility.

Standardized handbook procedures allowed repeatability and defensibility in the past. National databases and nationally uniform erosion prediction and soil conservation technology will bring a similar repeatability and defensibility to the computer-based technology. Implications of this national standardization in-

clude the need to sustain the national databases and the technological infrastructure to sustain them.

C. Predicting Sediment Yield

Previously, the USLE was used to predict on-site erosion for parts of the landscape. Portions of the landscape where sediment deposition occurred were not addressed with USLE-type technology, nor could the USLE technology provide information about sediment properties and sediment yield downstream of the eroding portions of the upland areas. Although RUSLE is improved in many ways over the USLE, it still shares these weaknesses.

Hydrologically driven models such as CREAMS and WEPP are designed to deal with sediment detachment, transportation, and deposition. Users now have the opportunity to make on-site erosion predictions (as in the USLE) and to make sediment yield estimates "off-site," including sediment deposited and sediment transported downstream.

Technology that predicts on-site erosion and off-site sediment yield presents the opportunity to consider broader objectives for soil erosion and off-site sediment yields presents the opportunity to consider broader objectives for soil erosion, soil conservation, farm planning, pollution control, resource inventory, and environmental protection.

Implications of the broader objectives involving soil erosion will require a broad-based concept of acceptable on-site erosion and off-site sediment yield. With the new technology, the soil loss tolerance concept directly tied on on-site erosion and USLE is no longer appropriate in defining acceptable rates of on-site erosion. The soil loss tolerance concept needs to be replaced by concepts that are multiobjective and explicitly conclude both on-site erosion and off-site sediment yield.

D. Erosion Prediction, Soil Conservation, and Multiobjective Decision Making

Farm planning, land use, and management decisions should be made with multiobjective decision methodologies. Opportunities for research and application of the new technologies in a multiobjective decision-making context are significant. Soil erosion and soil protection will need to be considered along with decisions affecting water supply, surface water and groundwater quality, local and regional economic factors, biodiversity, wildlife habitat, recreation, aesthetics, and other factors of site-specific concern.

Implications of soil erosion and conservation in a multiobjective decision making context include the need to maintain the soil resource by having it explicitly included in the analyses. For long-range problems of soil protection and sustainable agriculture to receive equitable consideration in these multiob-

jective analyses, the concept of soil loss tolerance must be replaced by concepts that include on-site erosion and off-site sediment yield as important components.

V. OTHER APPROACHES

One of the more widely used approaches for estimating sediment yield not mentioned heretofore is MUSLE (modified universal soil loss equation) (Williams and Berndt, 1977; Williams, 1982). In this model, the rainfall runoff factor (R) of the USLE is replaced by a runoff term in the form $95(Qq_p)^{0.56}$, where Q is the runoff volume (acre-ft), and q_p is the peak flow rate ($\text{ft}^3 \text{ s}^{-1}$). This relation has been used successfully to simulate watershed sediment yield in models such as SWRRB (simulation for water resources in rural basins) (Williams, Nicks, and Arnold, 1985) and SPUR (simulation of production and utilization of rangeland) (Wight and Skiles, 1987).

In the early 1980s, two significant modeling efforts resulted in advancing the technology of erosion prediction and conservation planning and the impact of erosion on water quality. The ANSWERS model (Beasley et al., 1980) is a hydrologically driven model that used cell concepts to describe the heterogeneity of small watersheds on a storm basis to estimate sediment yield. The CREAMS model (Knisel, 1980; Foster et al., 1981) was also hydrologically driven and intended to show management impacts on water quality through continuous simulation using fundamental equations for rill and interrill erosion.

The kinematic runoff and erosion model KINEROS (Woolhiser et al., 1990) is an event-oriented, physically based model describing the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds. The watershed is represented by a cascade of planes and channels, and the partial differential equations describing overland flow, channel flow and erosion, and sediment transport are solved by finite difference techniques. Spatial variability of rainfall and infiltration, runoff, and erosion parameters can be accommodated. KINEROS may be used to determine the effects of various artificial features such as urban developments, small detention reservoirs, or lined channels on flood hydrographs and sediment yield.

The AGNPS (agricultural non-point source) (Young et al., 1981) model is intended for simulating hydrology, erosion, sediment, and chemical transport for larger river basins. The watershed is conceptualized as a series of cells (grid basis) with hydrologic, sediment, and chemical movement in each cell. The model predicts runoff volume and peak discharge, eroded and delivered sediment, and nitrogen, phosphorus, and chemical oxygen demand concentrations in the runoff and the sediment loss for single storm events at all points in the watershed.

Other erosion simulation efforts are ongoing in the United States and other places in the world. Many of these are more local in nature (site specific) and

have not been validated widely or applied to a variety of climatic conditions, varied land uses, and physiographic areas. Their exclusion here is not intended to slight them but rather portrays ignorance on the part of the authors.

VI. SUMMARY AND CONCLUSIONS

Soil erosion (by water) knowledge and technology have undergone major changes in the past two decades. The RUSLE and WEPP developments are two examples of this technology. Essential to such advancement is the need for advances in field experimental and monitoring equipment to parallel explosive improvements in computer science. Soil-erosion model postulations and the formulation of hypotheses have progressed beyond our ability to perform in situ data-gathering experiments with which to test new hypotheses. For example, sampling for sediment concentration in a water system currently involves destructive sampling that, for example, precludes consecutive collection of samples without upsetting an energy grade line. We need to be able to sample repeatedly in the downslope direction to understand spatial variability problems that are important to resource management. Although remote-sensing techniques have been applied to many environmental scenarios, they have not been applied to water erosion problems.

The material of this chapter is presented in less detail than desired for full comprehension of the technology. We hope that the users of this technology will pursue the necessary details in the references and will continue to follow developments in soil erosion in the technical literature.

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