PEDOTRANSFER FUNCTIONS FOR SOIL EROSION MODELS

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1. INTRODUCTION

Some of the most practical applications of soil pedotransfer functions are in the realm of runoff and soil erosion prediction equations or models, for use by field conservationists and environmental planners in estimating sediment losses from farm fields, rangelands, forest harvest regions, and other land uses. To these end users, it is important to have sound technology that provides reasonable representation across the wide range of soils across the United States (or their country or region of interest) that soil erosion by water may occur on. This section will discuss some historical soil pedotransfer functions for erosion prediction, some pedotransfer functions for modern erosion models, and procedures to develop infiltration and erodibility parameters for these types of models.

2. HISTORY OF EARLY U.S. EROSION RESEARCH

Research on soil erosion by water has been conducted in the United States for about 90 years on field experimental plot and small watersheds. The earliest soil erosion research in the United States was conducted on overgrazed rangeland in central Utah beginning in 1912 (Sampson and Weyl, 1918). Field erosion plot research began in 1917 at the Missouri Agricultural Experiment Station in Columbia, Missouri (Miller, 1926).

In 1929, the United States Congress provided an appropriation of $160,000 for field research on soil erosion. This resulted in the establishment of 10 experiment stations at Guthrie, OK, Temple, TX, Hays, KS, Tyler, TX, Bethany, MO, Statesville, NC, Pullman, WA, Clarinda, IA, La Crosse, WI, and Zanesville, OH.

The federal erosion research stations conducted experimental studies that used plot design based on the work of Miller at the University of Missouri. The most common plots were 6 ft wide by 72.6 ft long, which comprised 1% of an acre. Research studies examined a variety of factors affecting erosion, including slope steepness, slope length, type of crop and crop rotations, conservation practices such as contouring, etc. The results from these studies as well as from additional research sites added in the 1940s and 1950s provided a large database of information on runoff and soil loss as affected by location (climate), slope, soil, and management conditions.
Early erosion researchers beginning in the 1940s also developed mathematical equations to estimate the amount of soil erosion and the impact of the use of alternative cropping management practices and/or conservation practices. Zingg (1940) conducted extensive experiments on the effect of slope length and steepness on erosion and developed a prediction equation:

\[ A = CS^{1.4}L^{0.6} \]  

(1)

where \( A \) was the average soil loss per unit of area, \( C \) was a constant, \( S \) was land slope (%), and \( L \) was slope length (ft).

This work was followed by Smith (1941), who added cropping and support practice factors to Zingg’s function. Smith’s equation was \( A = CS^{1.4}L^{0.6}P \), where \( P \) was the ratio of soil loss with a mechanical conservation practice to soil loss without the practice. The \( C \) factor in this equation included the effects of soil, weather, and cropping system. Smith used this equation to create a graphic procedure to select conservation practices in the Midwest.

Browning et al. (1947) added soil erodibility and management factors to the Smith equation, and used it throughout Iowa beginning in the 1940s. The equation was rewritten as:

\[ L = \frac{A_1^{5/3}}{PC}S^{-7/3} \]  

(2)

where \( L \) is the slope length limit (ft), \( A_1 \) is the permissible soil loss (e.g., 5 t ac\(^{-1}\)), \( P \) is the conservation practice factor (1.0 if no practices), \( S \) is slope steepness in percent, and \( C \) is a constant expressing the effects of weather, soil, crop rotation, degree of erosion, or soil treatment on soil losses (for Browning’s base Marshall soil at Clarinda, Iowa, the value of \( C \) was 0.035). Browning et al. (1947) also listed in their paper comparative erodibility factors for 12 other soils relative to the Marshall soil. Thus, this was one of the first instances of a limited pedotransfer function for soil erosion prediction.

Problems with application of the various equations arose when erosion predictions had to be made outside the climate region and soils used in their original database. There was a need for a widely applicable equation that could be applied over a broad geographic region and take into account climatic and soil variation.

In 1954, the USDA-ARS National Runoff and Soil Loss Data Center was created at Purdue University under the direction of Walt Wischmeier, and was to be the central location for the soil erosion data that had been collected across the U.S. since the 1930s. Part of the Center’s task was to locate and assemble the wide assortment of experimental data from across the U.S. and then also to utilize this data in further development of erosion prediction equations. A substantial database of the measured runoff and soil loss data was eventually created from 47 research stations in 24 of the 37 states east of the Rocky Mountains as well as Pullman, Washington and Mayaguez, Puerto Rico, totaling over 10,000 plot years.
3. THE UNIVERSAL SOIL LOSS EQUATION

Wischmeier utilized the database to determine relationships between rainfall characteristics and soil loss, as well as effects of slope length, slope gradient and soil factors. The work ultimately resulted in creation of the universal soil loss equation (USLE), first published in USDA Agriculture Handbook 282 (Wischmeier and Smith, 1965). The USLE is:

\[ A = R \times K \times L \times S \times C \times P \]  

(3)

where \( A \) is the average annual soil loss (t ac\(^{-1}\)), \( R \) is the rainfall and runoff factor (100 ft t in ac\(^{-1}\) h\(^{-1}\)), \( K \) is the soil erodibility factor (0.01 t ac h ac\(^{-1}\) ft t\(^{-1}\) in\(^{-1}\)), \( L \) is a slope-length factor, \( S \) is a slope-steepness factor, \( C \) is a cropping-management factor, and \( P \) is supporting erosion control practice factor.

The soil erodibility factor, \( K \), is the soil loss per unit of \( R \) for a unit plot. For USLE, a unit plot was 72.6 ft long on a uniform 9% slope maintained in continuous tilled fallow. Table 1 in Agriculture Handbook 282 listed computed \( K \) values for 23 soils at erosion research stations. These values were based largely upon work of Olson and Wischmeier (1963), which evaluated data from fallow and cropped plots. For application of the USLE on a multitude of other soils, values of \( K \) were assigned at joint ARS–SCS regional workshops, based upon comparisons of soils to the original 23 soils’ characteristics. However, a more scientific approach for obtaining \( K \) values for soils was needed.

In order to determine inherent soil erodibility values as a function of soil properties, a five-year field, laboratory and statistical study was conducted by Wischmeier and Mannering (1969). Rainfall simulation was used on 55 U.S. Corn Belt soils, and an empirical relationship was derived to compute \( K \) values based upon 24 soil parameter terms. The equation they developed for \( K \) was:

\[
K = 0.013[18.82 + 0.62(\%\text{Silt}/\%\text{OM}) + 0.043(\%\text{Silt} \times \text{Reaction}) \\
- 0.07(\%\text{Silt} \times \%\text{SS}) + 0.0082(\%\text{Silt} \times \%\text{Sand}) - 0.10(\%\text{Sand} \times \%\text{OM}) \\
- 0.214(\%\text{Sand} \times \%\text{AI}) + 1.73(\text{Clay ratio}) - 0.0062(\text{Clay ratio} \times \%\text{Silt}) \\
- 0.26(\text{Clay ratio} \times \%\text{OM}) - 2.42(\text{Clay ratio}/\%\text{OM}) \\
+ 0.30(\text{Clay ratio} \times \%\text{AI}) - 0.024(\text{Clay ratio}/\%\text{AI}) \\
- 21.5(\%\text{AI}) - 0.18(\%\text{ASM}) + 1.0(\%\text{Increase in acidity below plow zone}) \\
+ 5.4(\%\text{Structure}) + 4.4(\%\text{SS}) + 0.65(\%\text{Structure change below plow layer}) \\
- 0.39(\%\text{Thickness of “granular” material}) \\
+ 0.043(\%\text{Depth from “friable” to “firm”}) - 2.82(\%\text{Loess} = 1, \%\text{other} = 0) \\
+ 3.3(\%\text{Over calcareous base} = 1, \%\text{other} = 0) + 3.29(\%\text{OM} \times \%\text{AI}) \\
- 1.38(\%\text{Reaction} \times \%\text{Structure})] 
\]  

(4)
where OM is the organic matter, AI, aggregation index, SS, structure strength, and ASM, antecedent soil moisture. This complex pedotransfer function accounted for 98% of the total experimental variance on the 55 soils studied.

While the equation developed by Wischmeier and Mannering (1969) explained most of the experimental variance, the large number of terms made it difficult to apply by most field users. Further work by Wischmeier et al. (1971) resulted in a simplified equation and soil erodibility nomograph that can be used to calculate $K$ values for soils with less than 70% silt and very fine sand:

$$100K = 2.1[\%\text{Silt} \times (100 - \%\text{Clay})]^{1.14}(10^{-4})(12 - \%\text{OM}) + 3.25(b - 2) + 2.5(c - 3)$$ (5)

where $b$ is the soil structure code used in soil classification, and $c$ is the profile permeability class. The equation and nomograph were also presented in Agriculture Handbook 537 (Wischmeier and Smith, 1978), allowing for a rapid graphical solution for $K$ by field users of USLE.

In the revised universal soil loss equation (RUSLE) handbook (Renard et al., 1997), all available published global data (225 soils) were used to derive a relationship for soil erodibility as:

$$K = 7.594 \left\{ 0.0034 + 0.0405 \exp \left[ -\frac{1}{2} \left( \frac{\log(D_g) + 1.659}{0.7101} \right)^2 \right] \right\}$$ (6)

where

$$D_g = \exp(0.01 \sum f_i \ln(m_i))$$ (7)

with $D_g$ being the geometric mean particle diameter (mm), $f_i$ the primary particle size fraction in percent, and $m_i$ is the arithmetic mean of the particle size limits of the size fraction. Coefficient of determination ($r^2$) for this relationship was reported to be 0.983.

4. PARAMETERIZATION OF EROSION PREDICTION MODELS

4.1. Erosion prediction models

Where the development of the USLE had almost solely been an activity within the United States, beginning in the 1960s and 1970s scientists and conservationists in many countries utilized or tried to utilize USLE and develop the necessary databases to apply it. Also, a variety of soil erosion prediction tools and models began to be developed both inside and outside the U.S. beginning in the 1970s and 1980s. The increasing power of computing systems allowed for development and application of more physical process-based soil erosion models or model components.

Outside the U.S., Elwell (1978) developed the Soil-Loss Estimation Model for South Africa (SLEMSA), as an alternative and simpler approach to USLE. Major considerations with SLEMSA were climate and cropping-management representations that were different.
from those in the U.S. In Australia, Rosewell and Edwards (1988) developed the 
SOILOSS computer program, to evaluate changes in land management on soil erosion by 
water. SOILOSS used a somewhat different approach to compute rainfall energy than that 
of the USLE, and contained the USLE soil erodibility nomograph and new experimentally 
obtained values for New South Wales in Australia. Many of the approaches used in 
SOILOSS are similar to those present in RUSLE.

Other erosion prediction tools developed outside the U.S. include EUROSEM (Morgan 
et al., 1998), GUEST (Misra and Rose, 1996), and the Hairsine–Rose (1992a,b) model. 
EUROSEM (European Soil Erosion Model) is a fully dynamic process-based water 
erosion model that utilizes the runoff and sediment routing components of KINEROS 
(Woolhiser et al., 1990). The Hairsine–Rose model computes erosion as an instantaneous 
process of sediment entrainment, deposition and re-entrainment. GUEST (Griffith 
University Erosion System Template) uses many of the same concepts of entrainment, 
deposition and re-entrainment, but was designed as a practical conservation tool for field 
application. All of these models require input parameterization to represent soil 
conditions.

Major erosion prediction models developed in the U.S. during the same time were 
CREAMS (Knisel, 1980), EPIC (Williams et al., 1984), RUSLE (Renard et al., 1997) and 
Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995). EPIC (Erosion 
Productivity Impact Calculator) was developed to quantify the economic costs of soil 
erosion and the effects of soil conservation practices, and it can use USLE or alternately 
modifications of USLE for sediment predictions (various rainfall and/or runoff erosivity 
factors). RUSLE is a revision of the USLE, with improved subfactor component 
calculations, and user-friendly interfaces for application at the field-office level. WEPP 
was designed to be a physical process-based computer simulation model with user-
friendly interfaces and extensive databases for field applications on hillslope profiles and 
small watersheds. Erosion estimates in WEPP are a function of daily rainfall and 
detachment by raindrops and flowing water, and the model can also predict sediment 
deposition and delivery off-site.

The USDA-ARS CREAMS (Chemicals, Runoff and Erosion from Agricultural 
Management Systems) model (Knisel, 1980) was the first to separate erosion processes 
into those on rill and interrill areas (Foster et al., 1980). The CREAMS model computed 
sediment detachment by raindrop impact and by flowing water, sediment transport and 
sediment deposition. However, CREAMS still relied upon USLE erodibility values for 
parameterization and generally used SCS Curve Number procedures to estimate runoff. 
To adequately simulate the sediment transport processes, however, information on the 
sediment characteristics was needed, including size fractions, diameters and densities.

4.2. Sediment particle fractions and particle composition

In the initial CREAMS model (Knisel, 1980) released in 1980, sets of equations to 

estimate sediment particle fractions and characteristics were included. However, a more 

thorough set of equations was presented by Foster et al. (1985) which utilized a larger data 

set from 28 soils in creating the final equations. The approach assumes that sediment is 

composed of five size classes: primary clay, primary silt, small aggregates, large 

aggregates, and primary sand.
Fraction of primary clay in the eroded sediment is based upon results from a wide range of experiments, and is:

\[ F_{\text{clay}} = 0.26 O_{\text{clay}} \quad (8) \]

where \( F_{\text{clay}} \) is the fraction of primary clay in the detached sediment and \( O_{\text{clay}} \) is the fraction of clay in the matrix soil. For small aggregates, when the matrix soil clay content is less than 25%:

\[ F_{\text{sagg}} = 1.8 O_{\text{clay}} \quad (9) \]

when the matrix soil clay content is between 25 and 50%,

\[ F_{\text{sagg}} = 0.45 - 0.6 (O_{\text{clay}} - 0.25) \quad (10) \]

and when the matrix soil clay content exceeds 50%,

\[ F_{\text{sagg}} = 0.6 O_{\text{clay}} \quad (11) \]

The fraction of primary silt is computed as

\[ F_{\text{silt}} = O_{\text{silt}} - F_{\text{sagg}} \quad (12) \]

where \( O_{\text{silt}} \) is the fraction of silt in the matrix soil. If the equation results in a negative value for \( F_{\text{silt}} \), \( F_{\text{sagg}} \) is set equal to \( O_{\text{silt}} \), and \( F_{\text{silt}} \) is set equal to zero.

Primary sand fraction is calculated in Foster et al.’s (1985) procedure as:

\[ F_{\text{sand}} = O_{\text{sand}} (1.0 - O_{\text{clay}})^5 \quad (13) \]

where \( O_{\text{sand}} \) is the fraction of sand in the matrix soil. Fraction of large aggregates in the sediment is computed as:

\[ F_{\text{lagg}} = 1.0 - F_{\text{clay}} - F_{\text{silt}} - F_{\text{sagg}} - F_{\text{sand}} \quad (14) \]

The make-up of the small aggregate and large aggregate fractions must also be determined. For the small aggregates:

\[ f_{\text{clay:sagg}} = \frac{O_{\text{clay}}}{O_{\text{clay}} + O_{\text{silt}}} \quad (15) \]

\[ f_{\text{silt:sagg}} = \frac{O_{\text{silt}}}{O_{\text{clay}} + O_{\text{silt}}} \quad (16) \]

where \( f_{\text{clay:sagg}} \) is the fraction of clay in the small aggregates and \( f_{\text{silt:sagg}} \) is the fraction of silt in the small aggregates. Fraction of sand in the small aggregates is zero. For the large aggregates:

\[ f_{\text{clay:lagg}} = \frac{[O_{\text{clay}} - F_{\text{clay}} - (F_{\text{sagg}} \times f_{\text{clay:sagg}})]}{F_{\text{lagg}}} \quad (17) \]
\[ f_{\text{silt:lagg}} = \left[ O_{\text{silt}} - F_{\text{silt}} - (F_{\text{sagg}} \times f_{\text{silt:lagg}}) \right] / F_{\text{lagg}} \]  
\[ f_{\text{sand:lagg}} = \left( O_{\text{sand}} - F_{\text{sand}} \right) / F_{\text{lagg}} \]

where \( f_{\text{clay:lagg}} \) is the fraction of clay in the large aggregates, \( f_{\text{silt:lagg}} \) is the fraction of silt in the large aggregates, and \( f_{\text{sand:lagg}} \) is the fraction of sand in the large aggregates. Foster et al. (1985) also assign specific gravities and particle diameters for each of the size classes. The equations presented here for estimation of soil particle fractions and characteristics are also utilized in the WEPP model (Flanagan and Nearing, 1995).

4.3. WEPP infiltration parameterization

The WEPP model was developed from 1985 to 1995 by a team of federal and university scientists within the U.S. WEPP is a physical process-based, distributed parameter, continuous simulation erosion prediction model. Daily climate inputs to the model drive the simulation of the rainfall-infiltration-runoff processes.

WEPP uses a Green–Ampt Mein–Larson (GAML) procedure (Mein and Larson, 1973), modified for unsteady rainfall (Chu, 1978) to compute infiltration during a rainstorm event. For the situation where there is ponding within a rainfall interval, the cumulative infiltration depth is computed using:

\[ K_{\text{e}} t_c = F_i - \Psi \theta_d \ln \left[ 1 + \frac{F_i}{\Psi \theta_d} \right] \]

where \( K_{\text{e}} \) is the effective hydraulic conductivity (m s\(^{-1}\)), \( t_c \) is the corrected time to ponding (s), \( \psi \) is the average capillary potential (m), \( F \) is the cumulative infiltration depth at time \( i \) (m), and \( \theta_d \) is the soil moisture deficit (m m\(^{-1}\)). Full details on the model procedures are presented in Stone et al. (1995). It is important to note that the effective hydraulic conductivity of a soil is not the same as the saturated hydraulic conductivity, nor equal in value to it (Alberts et al., 1995). Saturated hydraulic conductivity is a measure of a soil’s ability to transmit water in a saturated state, a condition that very rarely occurs in the field.

The effective hydraulic conductivity is a critical parameter in WEPP model simulations. This value and any adjustments to it directly impact the amount and rates of infiltration and related runoff. WEPP can be applied using either constant or temporally varying values of conductivity. See Alberts et al. (1995) on methods to estimate time-invariant hydraulic conductivity for cropland and rangeland.

The power of the continuous simulation WEPP model is through the daily updating of soil, plant, and residue conditions – thus use of time-varying effective hydraulic conductivity is most often recommended. For cropland, baseline conditions are for a freshly tilled soil with no residue and no vegetation present. The conductivity of the soil in this state is called the baseline effective hydraulic conductivity. Adjustments to soil parameters are then made to the baseline values, as a function of the daily soil, plant and residue status.

For croplands, extensive model optimization runs on 43 soils were conducted using measured and curve number predictions for tilled fallow management (Alberts et al., 1995). The following equations are used within WEPP to predict baseline effective
hydraulic conductivity. For soils with clay content less than or equal to 40%:

\[ K_b = -0.265 + 0.0086 \text{SAND}^{1.8} + 11.46 \text{CEC}^{-0.75} \]  \hspace{1cm} (21)

For soils having clay content greater than 40%:

\[ K_b = 0.0066 e^{(244/\text{CLAY})} \]  \hspace{1cm} (22)

where \( K_b \) is baseline effective hydraulic conductivity (mm h\(^{-1}\)), \text{SAND} is percent sand content in the surface soil, \text{CLAY} is percent clay content in the surface soil, and \text{CEC} is the cation exchange capacity in the surface soil in meq per 100 g (Alberts et al., 1995; Flanagan and Livingston, 1995).

Data from natural rainfall studies on fallow, row-cropped, and perennial-cropped plots (Risse et al., 1994; Zhang et al., 1995a,b) were used to develop adjustment factors. A soil crusting and tillage adjustment can be computed based upon the amount of surface cover, the soil random roughness, the cumulative rainfall kinetic energy since the last tillage operation, a soil stability factor, and a crust factor. The adjustments to conductivity for row crops are a function of effective canopy cover, residue cover, and the storm rainfall amount. The following equations are used:

\[ K_e = K_{bare}(1 - \text{scovef}) + (0.0534 + 0.01179K_b)\text{(rain)}\text{(scovef)} \]  \hspace{1cm} (23)

\[ K_{bare} = K_b[\text{CF} + (1 - \text{CF})e^{-C_{ss}E_a(1-RR/0.04)}] \]  \hspace{1cm} (24)

where \( K_{bare} \) is the effective hydraulic conductivity for bare soil regions after adjustments for crusting and tillage (m s\(^{-1}\)), \text{CF} is the crust factor (Rawls et al., 1990), \( C_{ss} \) is the soil stability factor (m\(^2\) J\(^{-1}\)), RR is the random roughness of the soil surface (m), \( E_a \) is the cumulative kinetic energy of rainfall since the last tillage operation (J m\(^{-2}\)), scovef is the total effective surface cover, and rain is the storm rainfall amount (mm). Analysis of 88 plot-years of measured data under perennial crops found that on average the effective hydraulic conductivity is about 1.8 times greater than that from row crop conditions. See Alberts et al. (1995) for complete details on cropland hydraulic conductivity adjustments in WEPP.

Other sets of experiments were conducted to determine conductivity values for rangeland conditions. For rangelands, when rill surface cover is less than 45%, effective conductivity is predicted using:

\[ K_{range} = 57.99 - 14.05 \ln(\text{CEC}) + 6.20 \ln(\text{ROOT10}) \]
\[ - 473.39 \text{BASR}^2 + 4.78 \text{RESI} \]  \hspace{1cm} (25)

while for rangelands when rill cover is greater than or equal to 45%

\[ K_{range} = -14.29 - 3.40 \ln(\text{ROOT10}) + 0.3783 \text{SAND} + 2.0886 \text{ORGMAT} \]
\[ + 398.64 \text{RR} - 27.39 \text{RESI} + 64.14 \text{BASI} \]  \hspace{1cm} (26)

where \( K_{range} \) is effective rangeland hydraulic conductivity in mm h\(^{-1}\), \text{CEC} is cation exchange capacity (meq per 100 g), \text{ROOT10} is root biomass in the top 10 cm of
the soil in kg m$^{-2}$, BASR is the product of the fraction of basal surface cover in rill areas and total basal surface cover, RESI is the product of the fraction of litter surface cover in inter-rill areas and the total litter surface cover, SAND is percent sand content of the surface soil, ORGMAT is percent organic matter in the surface soil and BASI is the product of the fraction of litter surface cover in interrill areas and the total basal surface cover (Alberts et al., 1995).

**4.4. WEPP erodibility parameterization**

WEPP uses four values from the hydrology component to estimate soil detachment: effective rainfall intensity, effective rainfall duration, peak runoff rate, and effective runoff duration. The equation in the model to estimate detachment on interrill areas is (Foster et al., 1995):

$$D_i = K_{iadj} I_e s_{ir} SDR_{RR} \frac{R_s}{w}$$

where $D_i$ is the rate of interrill sediment delivery to the rills (kg s$^{-1}$ m$^{-2}$), $K_{iadj}$ is the adjusted interrill erodibility (kg s m$^{-4}$), $I_e$ is the effective rainfall intensity (m s$^{-1}$), $s_{ir}$ is the interrill runoff rate (m s$^{-1}$), SDR$_{RR}$ is a sediment delivery ratio that is a function of random roughness, the row side-slope and the interrill sediment particle size distribution, $F_{nozzle}$ is a nozzle energy factor for sprinkler irrigation, $R_s$ is the spacing of the rills (m) and $w$ is the rill width (m).

Detachment by flowing water at a point in a rill is computed using an excess flow shear stress equation (Foster et al., 1995):

$$D_f = K_{radj} \left( \frac{t_f}{t_{cadj}} \right) \left[ 1 - \frac{G}{T_c} \right]$$

where $D_f$ is the rill detachment rate (kg s$^{-1}$ m$^{-2}$), $K_{radj}$ is the adjusted rill erodibility (s m$^{-1}$), $t_f$ is the flow shear stress (Pa), $t_{cadj}$ is the adjusted soil critical shear stress (Pa), $G$ is the sediment load (kg s$^{-1}$ m$^{-1}$), and $T_c$ is the sediment transport capacity at that point in the rill (kg s$^{-1}$ m$^{-1}$).

Baseline conditions for cropland are for a freshly-tilled soil with no plant or residue cover. The adjusted interrill and rill erodibilities and critical shear stresses used in Equations (27) and (28) are obtained by multiplying the baseline values by a set of adjustment factors.

Field experiments conducted on 33 cropland soils (Elliot et al., 1989) and 18 rangeland sites (Simanton et al., 1987) provided information that allows the baseline $K_i$, $K_r$, and $\tau_c$ parameters to be estimated from site-specific soil properties.

For cropland soils with surface soil sand content of 30% or more, the WEPP erodibility estimation equations are (Flanagan and Livingston, 1995; Alberts et al., 1995):

$$K_{ib} = 2728000 + 192100 \text{ VFS}$$

$$K_{rb} = 0.00197 + 0.00030 \text{ VFS} + 0.03863 e^{-1.84 \text{ ORGMAT}}$$
\[ \tau_c = 2.67 + 0.065 \text{CLAY} - 0.058 \text{VFS} \]  
\[ (31) \]

and for cropland soils having less than 30% sand, the equations are:

\[ K_{ib} = 6054000 - 55130 \text{CLAY} \]  
\[ (32) \]

\[ K_{rb} = 0.0069 + 0.134 e^{-0.20 \text{CLAY}} \]  
\[ (33) \]

\[ \tau_c = 3.5 \]  
\[ (34) \]

where \( K_{ib} \) is baseline interrill erodibility (kg s m\(^{-4}\)), \( K_{rb} \) is baseline rill erodibility (s m\(^{-1}\)), \( \tau_c \) is baseline critical shear stress (Pa), VFS is percent very fine sand in the surface soil (particle diameter size range 0.05–0.1 mm), CLAY is percent clay in the surface soil, and ORGMAT is the percent organic matter in the surface soil.

Baseline interrill erodibility on cropland is adjusted daily for a large number of factors. These include canopy cover, ground cover, roots, sealing and crusting, and freezing and thawing. Baseline rill erodibility is adjusted for incorporated residue, roots, sealing and crusting, and freezing and thawing effects. Baseline critical shear stress is adjusted daily for the effects of random roughness, sealing and crusting, and freezing and thawing.

For rangelands, interrill erodibility, rill erodibility and critical hydraulic shear stress are estimated using the following equations (Alberts et al., 1995; Flanagan and Livingston, 1995):

\[ K_{irange} = 1810000 - 19100 \text{SAND} - 63270 \text{ORGMAT} - 8460000\theta_{fc} \]  
\[ (35) \]

\[ K_{rrange} = 0.0017 + 0.000024 \text{CLAY} - 0.000088 \text{ORGMAT} - (0.00088 \text{BD}_{\text{dry}}/1000) - 0.00048 \text{ROOT10} \]  
\[ (36) \]

\[ \tau_{crange} = 3.23 - 0.056 \text{SAND} - 0.244 \text{ORGMAT} + (0.9 \text{BD}_{\text{dry}}/1000) \]  
\[ (37) \]

where \( K_{irange} \) is baseline interrill erodibility (kg s m\(^{-4}\)), \( K_{rrange} \) is baseline rill erodibility (s m\(^{-1}\)), \( \tau_{crange} \) is baseline critical shear stress (Pa), \( \text{BD}_{\text{dry}} \) is the dry soil bulk density (kg m\(^{-3}\)), and \( \theta_{fc} \) is the volumetric water content of the soil at 0.033 MPa (m\(^{3}\) m\(^{-3}\)).

Adjustments are made to rangeland interrill erodibility for ground cover and freezing and thawing effects. Freezing and thawing adjustments are also made to the rangeland rill erodibility and critical shear stress values (Alberts et al., 1995).

5. PROCEDURES TO DEVELOP EROSION MODEL PEDOTRANSFER FUNCTIONS

A range of techniques are available to parameterize soil erosion models and develop appropriate pedotransfer functions. Experimental techniques, simulation and statistical procedures will be discussed here.
5.1. Experimental techniques

Development of the USLE was based upon thousands of plot-years of field erosion experiment data, largely from long-term natural rainfall plots. A unit plot for the USLE was 72.6 ft long at a 9% slope and maintained in a continuous tilled-fallow. Plots with other lengths and gradients were also often used, and then observed soil loss values were adjusted back to those that would be expected from a unit plot. The experiment stations also had additional plots that would have different cropping and management practices as well as conservation practices. Runoff and sediment collected from the plots, as well as observed rain storm data on rainfall depths and intensities could then be used to develop the USLE factors. Given sufficient time and resources, these same approaches can still be used today (and are in some locations of the world), though it is often difficult to obtain sufficient resources to build, operate and maintain long-term natural rainfall erosion plots for a sufficient number of years to obtain meaningful data (Figure 1).

Alternative or supplemental experimental techniques to natural rainfall plots usually entail the use of rainfall simulators. Rainfall simulators are mechanical equipment developed to apply rainfall having intensities, depths, drop characteristics and energies that are similar to natural rainfall. Simulators allow the rapid generation of runoff and erosion data, often in weeks or months, compared to years or decades of natural rainfall experiments.

A rainfall simulator experiment should be designed to simulate the hydrologic and/or erosion processes of interest, and be able to adequately measure the desired variables. For process-based erosion models, most often the measurements of interest will be the rainfall rate, runoff rate, flow velocity, flow depth, sediment concentrations, and sediment particle size distributions. The compendium by Elliot et al. (1989) provides in-depth information on the procedures used in the WEPP cropland field rainfall simulator experiments on 33 U.S. soils. There, for each soil studied, they installed six long rill subplots that were 9 m long by 0.46 m wide, and six smaller interrill plots that were 0.75 m long by 0.5 m wide.
They also had four small plots 0.75 m long by 0.5 m wide for infiltration measurements. Soil pits were dug at each site, and extensive physical and chemical soil property analyses were conducted on the soil samples by the USDA-SCS National Soil Survey Laboratory in Lincoln, Nebraska.

5.2. Interrill erodibility

Rainfall simulation studies are most often conducted at uniform rainfall intensity rates, and water is applied so that runoff rates reach steady-state. Runoff samples are collected to analyze for sediment concentration throughout the event as well as to determine the size fractions of the sediment. With steady-state runoff rate and corresponding sediment discharge rate, the interrill erodibility value in Equation (27) can be back-calculated. A range of rainfall intensities can also be applied, to provide for a better average estimate of interrill erodibility. Often interrill erosion plots are set up so that they have relatively steep side-slopes to a collection trough, bare soil with no residue, and little roughness. In these cases, the adjusted interrill erodibility is approximately equal to the baseline interrill erodibility. Assuming that the plot conditions allow for all detached sediment on the interrill side-slopes to reach the rill and that the simulator nozzle produces rainfall equivalent to natural rainfall, Equation (27) can be rearranged to give:

\[ K_{ib} = \frac{D_i}{I_e \sigma_{ir}} \]  

(38)

If the interrill plot conditions are different from baseline, then appropriate adjustments to the calculation of \( K_{ib} \) need to be made to correct for residue, canopy, slope or roughness effects. For each soil studied, an average \( K_{ib} \) can be computed, and then using these values from a group of soils as well as measured soil properties, pedotransfer functions can be developed through statistical regression techniques.

5.3. Rill erodibility and critical shear stress

Rill erosion parameters are dependent upon some characteristic of the water flowing in the rills. This may be flow discharge, flow velocity, flow shear stress, or flow stream power. In the WEPP model, an excess flow shear stress equation (Equation (28)) is used. To develop rill erodibility and critical shear stress values, experiments can be conducted in which increasing levels of water flow are added to rills, and the corresponding runoff and sediment discharge measured. If clear water is used as the inflow, then the sediment load term in Equation (28) can be assumed to be approximately zero, and the equation becomes:

\[ D_f = K_{radj} (\tau_f - \tau_{cadj}) \]  

(39)

If the rill plot conditions are in a baseline state (bare, freshly tilled soil with no residue or canopy), then the adjusted rill erodibility and critical shear stress can be assumed to be the same as the baseline values. In a rainfall simulation study such as shown in Figure 2, under rainfall conditions the sediment discharge collected at the end of the plot must have an estimated interrill contribution subtracted from it in order to approximate the rill detachment rate. In the studies by Elliot et al. (1989), they took measurements on the rill
plots under both rainfall and no rainfall conditions. In those experiments, measurements were also made of the rill geometry, flow depths and flow velocities so that values of flow shear stress could be estimated using:

\[ \tau_f = \gamma RS \]  

where \( \gamma \) is the density of water (N m\(^{-3}\)), \( R \) is the hydraulic radius of the rill flow (m), and \( S \) is the hydraulic gradient that was approximated with the slope of the rill bottom (m m\(^{-1}\)).

With values for flow shear stress for the various levels of inflow water and corresponding rill detachment rates, values of \( K_r \) and \( \tau_c \) can be determined through linear regression. Some judgment may be necessary to identify and use only observed values where the flow shear stress has exceeded critical shear stress (non-zero detachment rates). Figure 3 shows an example plot of measured rill detachment rate (sediment discharge rate) vs. flow shear stress from a laboratory experiment. If these experiments are conducted over a range of soils and the soil physical and chemical properties measured, then pedotransfer functions for rill erodibility and critical shear stress can be developed through appropriate regression analyses.

5.4. Effective hydraulic conductivity

Information from rainfall simulation studies as well as from long-term natural rainfall erosion plots can be used to estimate hydraulic conductivity values for erosion models using Green–Ampt type equations. Several methods exist for these types of evaluations.
In rainfall simulation studies, small plots in a baseline condition (for cropland – a freshly tilled, bare soil with no canopy or residue cover), can be covered with a porous material that will absorb the raindrop impact but still allow the water to infiltrate to the plot (e.g., fibrous furnace filter). Comparisons of runoff from these covered plots to uncovered plots exposed to raindrop impact and sealing can provide information on baseline conductivity as well as adjustments needed for soil sealing and crusting and consolidation. On both small and long plots that have been brought to steady-state runoff after considerable applications of rainfall, infiltration rate can be estimated and Equation (20) used to compute conductivity.

Another approach for estimation of the baseline effective hydraulic conductivity is to use the model as an optimization tool, and run multiple simulations until some determinant factor is minimized. For example with the WEPP model, input values for \( K_b \) can be set, the model run, then output values for total runoff depth over the period of simulation evaluated and compared to observed values. The minimization criteria may be to minimize the least square error, maximize the coefficient of determination, or maximize the model efficiency for individual storm event runoff, or monthly, annual, or average annual runoff values. These procedures can be automated to allow rapid multiple simulations and then estimation of the deviance of the model predictions from the observed runoff depths. For the WEPP model \( K_b \) estimations, a minimization procedure using the Nash–Sutcliffe model efficiency (Nash and Sutcliffe, 1970) on a storm-by-storm runoff basis (Alberts et al., 1995; Flanagan and Livingston, 1995) was used. Some of the large USLE database was used in these evaluations, and USLE data are available via the internet for other model parameterization efforts (http://topsoil.nserl.purdue.edu/nserlweb/usle).

6. SUMMARY

For wide-spread applicability, soil erosion prediction models often rely upon a variety of soil pedotransfer functions. These most often address soil erodibility and soil infiltration parameters. Development of these functions may be accomplished through experimental...
studies on a representative group of soils that cover the range of properties of the larger set of soils where the erosion model is to be applied. In some cases, existing long-term historical erosion plot data (e.g., the USLE database) may provide sufficient information to create erosion model pedotransfer equations.

REFERENCES


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