USDA - WATER EROSION PREDICTION PROJECT:

HILLSLOPE PROFILE MODEL DOCUMENTATION

August, 1989

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NSERL Report No. 2
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ABSTRACT

The objective of the Water Erosion Prediction Project is to develop new generation prediction technology for use by the USDA-Soil Conservation Service, USDA-Forest Service, USDI-Bureau of Land Management, and other organizations involved in soil and water conservation and environmental planning and assessment. This improved erosion prediction technology is based on modern hydrologic and erosion science, process oriented, and computer implemented. The technology includes three versions: a hillslope profile version, a watershed version, and a grid version. This document is a detailed description of the hillslope profile version of the technology.

The hillslope profile erosion model is a continuous simulation computer model which predicts soil loss and deposition on a hillslope. It includes a climate component which uses a stochastic generator to provide daily weather information, an infiltration component which is based on the Green-Ampt infiltration equation, a surface runoff component which is based on the kinematic wave equations, a daily water balance component, a plant growth and residue decay component, and a rill-interrill erosion component. The profile erosion model computes spatial and temporal distributions of soil loss and deposition. It provides explicit estimates of when and where on the hillslope erosion is occurring so that conservation measures can be designed to most effectively control soil loss and sediment yield.

The hillslope profile erosion model is based on the best available science for predicting soil erosion on hillslopes. The relationships in the model are based on sound scientific theory and the parameters in the model were derived from a broad base of experimental data. The model runs on standard computer hardware and is easily used, applicable to a broad range of conditions, robust, and valid.

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Chapter 6. SOIL COMPONENT

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6.1 Introduction and Objectives

Soil properties influence the basic water erosion processes of infiltration and surface runoff, soil detachment by raindrops and concentrated flow, and sediment transport. The purpose of this chapter is to provide the WEPP user with background information on the soil and soil-related variables currently predicted in the WEPP model.

6.2 Background

6.2.1 Hydrology Parameters

Four soil variables that influence the hydrology portion of the erosion process are predicted in this component, including: 1) random roughness, 2) ridge height, 3) bulk density, and 4) saturated hydraulic conductivity. Random roughness is most often associated with tillage of cropland soil, but any tillage or soil disturbing operation creates soil roughness. Ridge height, which is a form of oriented roughness, results when the soil is arranged in a regular way by a tillage implement and varies by a factor of two or more depending upon implement type. Depressional storage of rainfall and hydraulic resistance to overland flow are positively correlated with soil roughness. Soil roughness changes temporarily due to tillage, rainfall weathering, and freezing and thawing. Bulk density reflects the total pore volume of the soil and is used to predict several infiltration parameters, including wetting front suction (see Chapter 4 for details) and saturated hydraulic conductivity. Bulk density changes temporally due to tillage, wetting and drying, freezing and thawing, and wheel and livestock compaction. Adjustments to bulk density are needed to account for factors such as the volumes of entrapped air and coarse fragments in the soil.

6.2.2 Soil Detachment Parameters

Interrill erodibility (K_i) is a measure of sediment delivery rate to rills as a function of rainfall intensity. For cropland and rangeland soils, base K_i values were predicted from relationships developed from field experiments conducted in 1987 and 1988 (Laflen et al., 1987; Simanton et al., 1987). Base K_i values for cropland soils are measured when the soil is in a loose, unconsolidated condition typical of that found after primary and secondary tillage using conventional tillage practices. Base K_i values for rangeland are measured on undisturbed soils with all vegetation and coarse fragments removed. Base K_i values for cropland and rangeland soils need to be adjusted for factors that influence the resistance of the soil to detachment, such as live and dead root biomass, soil freezing and thawing, and mechanical and livestock compaction.

Rill erodibility (K_r) is a measure of soil susceptibility to detachment by concentrated flow, and is often defined as the increase in soil detachment per unit increase in shear stress of clear water flow. Critical shear stress (τ_c) is an important term in the rill detachment equation, and is the shear stress below which no soil detachment occurs. Critical shear stress (τ_c) is the shear intercept on a plot of detachment by clear water vs. shear stress in rills. Rate of detachment in rills may be influenced by a number of variables including soil disturbance by tillage, living root biomass, incorporated residue, coarse fragments, soil consolidation, freezing and thawing, and wheel and livestock compaction.

6.3 User and Climatic Inputs

The number of overland elements existing on the hillslope profile is specified by the user, with an overland flow element being defined as an area of uniform cropping, management and soil characteristics. Soil information at the mapping unit level is stored in a soil input file. If the hillslope segment begins on a ridge and ends in a alluvial valley, the location of each mapping unit can be specified and soil properties of each read into the model from the soil input file. Mapping units on the hillslope profile are specified to better predict the effects of basic soil physical and chemical properties on infiltration and soil erodibility parameters.

Because tillage is one major process altering soil properties, the user must specify information on any tillage operation that occurs during the erosion simulation. Specific inputs include: 1) implement type, 2) tillage date, 3) tillage depth, and 4) tillage direction relative to the slope (see Chapter 8 for more information on tillage management and user input options).

After tillage, temporal changes in soil roughness, bulk density, and saturated hydraulic conductivity occur due to soil wetting and drying and freezing and thawing. Daily rainfall, max-min air temperatures, and soil water content are important variables in some equations that predict temporal soil properties.

6.4 Time Invariant Soil Properties

Time invariant soil properties are used to calculate baseline soil infiltration and erodibility parameters. Most baseline soil infiltration and erodibility parameters are calculated internal to the model using data read in from the soil input file (see User Summary for more information).

6.5 Random Roughness

Random roughness following a tillage operation is estimated based upon measured averages for an implement, which is similar to the approach used in EPIC (Williams et al., 1984). Table 6.5.1 shows the random roughness value assigned to each tillage implement in the current crop management input file.

Soil random roughness immediately after a tillage operation is predicted from:

$$R_{ri} = R_{ro}\, T_i + R_{r(t-1)} \left[1 - T_i\right] \qquad [6.5.1]$$

where R_{ri} is the random roughness immediately after tillage, R_{ro} is the random roughness created by a tillage implement, T_i is the tillage intensity value associated with an implement, and $R_{r(t-1)}$ is the random roughness immediately prior to tillage. This approach accounts for the effect of prior random roughness on random roughness after tillage.

Random roughness decay with time after tillage is predicted from:

$$R_{r(t)} = R_{ri}\, e^{\alpha_{rr} R_c} \qquad [6.5.2]$$

where $R_{r(t)}$ is the random roughness at time t (m), R_{ri} is the random roughness immediately after tillage (m), α_{rr} is a random roughness parameter, and R_c is the cumulative rainfall since tillage (m).

α_{rr} is predicted from:

$$\alpha_{rr} = 2.8 - 30\, S_i \qquad [6.5.3]$$

where S_i is the silt content of the soil (0-1). If $\alpha_{rr} \geq 0$, then α_{rr} is set to -0.1.

Table 6.5.1. Residue and soil parameters for original 27 WEPP tillage implements. †

Implement	Tillage Intensity‡ Corn	Tillage Intensity‡ Soybeans	Other Tillage Parameters§ TDMEAN	RRo	RHo	RINT
	(0 to 1)		--------------------m-------------------			
1 Moldboard Plow	0.93	0.96	0.150	0.043	0.050	0.360
2 Chisel Plow, Straight	0.25	0.45	0.125	0.023	0.050	0.100
3 Chisel Plow, Twisted	0.45	0.65	0.125	0.026	0.075	0.100
4 Field Cultivator	0.25	0.35	0.100	0.015	0.025	0.150
5 Tandem Disk	0.50	0.65	0.100	0.026	0.050	0.230
6 Offset Disk	0.55	0.70	0.100	0.038	0.050	0.230
7 One-way Disk	0.40	0.50	0.100	0.026	0.050	0.230
8 Paraplow	0.20	0.25	0.150	0.010	0.025	0.360
9 Spike Tooth Harrow	0.20	0.25	0.025	0.015	0.025	0.050
10 Spring Tooth Harrow	0.30	0.45	0.050	0.018	0.025	0.100
11 Rotary Hoe	0.10	0.15	0.025	0.012	0.000	0.000
12 Bedder Ridge, Lister	0.75	0.80	0.150	0.025	0.150	1.000
13 V-Blade Sweep	0.10	0.15	0.075	0.015	0.075	1.524
14 Subsoiler	0.20	0.30	0.350	0.015	0.075	0.300
15 Rototiller	0.55	0.70	0.075	0.015	0.000	0.000
16 Roller Packer	0.10	0.10	0.000	0.010	0.025	0.075
17 Row Planter w/ Smooth Coulter	0.08	0.11	0.000	0.010	0.010	1.000
18 Row Planter w/ Fluted Coulter	0.15	0.18	0.000	0.012	0.025	1.000
19 Row Planter w/ Sweeps	0.20	0.30	0.000	0.013	0.075	1.000
20 Lister Planter	0.40	0.50	0.000	0.025	0.100	1.000
21 Drill	0.15	0.15	0.000	0.012	0.050	1.000
22 Drill w/ Chain Drag	0.15	0.15	0.000	0.009	0.025	1.000
23 Row Cultivator w/ Sweeps	0.25	0.30	0.000	0.015	0.075	1.000

Table 6.5.1. Residue and soil parameters for original 27 WEPP tillage implements. † (Continued)

Implement	Tillage Intensity‡ Corn	Soybeans	Other Tillage Parameters§ TDMEAN	RRo	RHo	RINT
	(0 to 1)		----------m----------			
24 Row Cultivator w/ Spider Wheels	0.25	0.30	0.000	0.015	0.050	1.000
25 Rod Weeder	0.15	0.20	0.000	0.010	0.025	0.125
26 Rolling Cultivator	0.50	0.55	0.000	0.015	0.150	1.000
27 NH_3 Applicator	0.15	0.20	0.000	0.013	0.025	0.300

† List is being expanded to approximately 80 tillage implements.

‡ Tillage intensity values are used for altering soil and residue properties. Values for corn are used for all crops except those that have residue classified as fragile. WEPP crops that produce fragile residue include soybeans, peanuts, and potatoes.

§ TDMEAN's represent an average tillage depth and are used to adjust the fraction of residue cover remaining for certain primary and secondary tillage depths specified by the user (See Chapter 8 for more detail).

RRo and RHo are random roughness and ridge height parameters.

RINT represents the on-center ridge interval. If RINT = 1.0, then RINT is set to row width (RW) in the model.

6.6 Ridge Height

A ridge height value is assigned to a tillage implement based upon measured averages for an implement (see Table 6.5.1 for assigned ridge height values), which is similar to the approach used in EPIC (Williams et al., 1984).

Ridge height decay following tillage is predicted from:

$$R_{h(t)} = R_{ho}\, e^{\alpha_{rh} R_c} \qquad [6.6.1]$$

where $R_{h(t)}$ is the ridge height at time t (m), R_{ho} is the ridge height immediately after tillage (m), α_{rh} is a ridge height parameter, and R_c is the cumulative rainfall since tillage (m). α_{rh} is currently set equal to the random roughness parameter (α_{rr}).

Large ridges made by a rolling cultivator or a similar ridging implement do not decay as fast as smaller ridges made by a disk or chisel plow. Criteria used to identify a well-defined ridge furrow system is that ridge height after tillage is ≥ 0.1 m and the ridge interval is equal to the row spacing. For this condition, ridge height cannot decay below 0.1 m.

6.7 Bulk Density

6.7.1 Tillage Effects

Soil bulk density changes are used to predict changes in infiltration parameters. Bulk density after tillage is difficult to predict because of limited knowledge, particularly for point- and rolling-type implements, of how an implement interacts with a soil as influenced by tillage speed, tillage depth, and soil cohesion.

The approach chosen to account for the influence of tillage on soil bulk density is to use a classification scheme where each implement is assigned a tillage intensity value from 0 to 1, which is similar to the approach used in EPIC (Williams et al., 1984). The concept is based, in part, on measured effects of various tillage implements on residue cover.

Flat residue cover following a tillage operation is predicted from (Chapter 8):

$$C_{rf(t)} = C_{rf(t-1)} R_{mf} \qquad [6.7.1]$$

where $C_{rf(t)}$ is the flat residue cover after tillage (0-1), $C_{rf(t-1)}$ is flat residue cover before tillage (0-1), and R_{mf} is the residue mixing factor (0-1).

The base R_{mf} value is predicted from:

$$R_{mf} = 1 - T_i . \qquad [6.7.2]$$

The T_i variable, then, reflects the relative amount of soil disturbance caused by a tillage implement. A soil inverting implement, like a moldboard plow, disturbs the soil more than point- or rolling-type implements. Table 6.5.1 shows the tillage intensity value assigned to each tillage implement in the current crop management input file.

The equation used to predict soil bulk density after tillage is (Williams et al., 1984):

$$\rho_t = \rho_{(t-1)} - \left[\left[\rho_{(t-1)} - 0.667 \, \rho_c \right] T_i \right] \qquad [6.7.3]$$

where ρ_t is the bulk density after tillage ($kg \; m^{-3}$), $\rho_{(t-1)}$ is the bulk density before tillage ($kg \; m^{-3}$), ρ_c is the consolidation soil bulk density at 0.033 MPa ($kg \; m^{-3}$), and T_i is the tillage intensity value (0-1).

Consolidated soil bulk density, ρ_c, is calculated by the model from the soil input data from the relationship:

$$\rho_c = \left[1.514 + 0.25 \, S_a - 13.0 \, S_a \, O_m - 6.0 \, C_l \, O_m - 0.48 \, C_1 \, CEC_r \right] 10^3 \qquad [6.7.4]$$

where ρ_c is the consolidated soil bulk density at 0.033 MPa ($kg \; m^{-3}$), S_a is the sand content (0-1), O_m is the organic matter content (0-1), C_l is the clay content (0-1), and CEC_r is the ratio of the cation exchange capacity of the clay (CEC_c) to the clay content of the soil.

The cation exchange capacity of the clay fraction of the soil is calculated from:

$$CEC_c = CEC - O_m \left[142 + 170 \, D_g \right] \qquad [6.7.5]$$

where CEC is the cation exchange capacity of the soil ($cmol \; kg^{-1}$) and D_g is the average depth of the horizon of interest (m).

Soil properties for the average depth of all primary tillage implements used in one tillage sequence are initialized from the data in the soil input file. If the depth of primary tillage is less than the depth of the first soil horizon, one new soil layer is created. Another new soil layer is created if the average depth of all secondary tillage implements in the same tillage sequence is less than the average primary tillage depth. If the primary tillage depth is greater than the depth of the first soil horizon, soil properties of the tillage layer are depth-weighted averages of the soil properties of the soil horizons mixed by the tillage implement. Uniform mixing is assumed. All processes that influence soil bulk density are modeled within the primary and secondary tillage zones.

Three additional factors, including: 1) soil water content, 2) rainfall consolidation, and 3) weathering consolidation that influence temporal changes in soil bulk density are predicted.

6.7.2 Soil Water Content Effects

The influence of soil water content on bulk density changes is predicted from:

$$\rho_{(t)} = \rho_{(t-1)} + \Delta\rho_{wc} \left[\Theta_{(t)} - \Theta_{(t-1)}\right] \qquad [6.7.6]$$

where $\rho_{(t)}$ is the bulk density ($kg\ m^{-3}$), $\rho_{(t-1)}$ is the bulk density of the previous day ($kg\ m^{-3}$), $\Delta\rho_{wc}$ is the parameter describing the change in bulk density with water content ($kg\ m^{-3}$), Θ_t is the water content ($m^3\ m^{-3}$), and $\Theta_{(t-1)}$ is the water content of the previous day ($m^3\ m^{-3}$).

The change in soil bulk density with soil water content ($\Delta\rho_{wc}$) is predicted from:

$$\Delta\rho_{wc} = \frac{\rho_d - \rho_c}{\Theta_r - \Theta_{fc}} \qquad [6.7.7]$$

where ρ_d is the oven dry bulk density ($kg\ m^{-3}$), ρ_c is the consolidated bulk density at 0.033 MPa ($kg\ m^{-3}$), Θ_r is the residual water content ($m^3\ m^{-3}$), and Θ_{fc} is the water content of the consolidated soil at 0.033 MPa ($m^3\ m^{-3}$).

Oven dry bulk density is read into the model from the soil input file. If the value is zero, ρ_d is predicted from:

$$\rho_d = \left[-0.024 + 0.001\,\rho_c + 1.55\,C_l\,CEC_r + C_l^2\,CEC_r^2 - 1.1\,CEC_r^2\,C_l - 1.4\,O_m\right] 10^3. \qquad [6.7.8]$$

The residual water content of the soil is predicted from (Baumer, personal communication):

$$\Theta_r = \left[0.000002 + 0.0001\,O_m + 0.00025\,C_l\,CEC_r^{0.45}\right] \rho_{(t)} \qquad [6.7.9]$$

where Θ_r is the residual volumetric water content of the soil ($m^3\ m^{-3}$).

The gravimetric soil water content at 0.033 MPa (kg water /kg of < 0.002-m soil material) is read into the model from the soil input file and is converted to a volumetric basis by multiplying by the bulk density of the soil. If the value is zero, the volumetric water content is predicted from:

$$\Theta_{fc} = 0.2391 - 0.19\,S_a + 2.1\,O_m + 0.72\,\Theta_d \qquad [6.7.10]$$

where Θ_{fc} is the volumetric water content at 0.033 MPa ($m^3\ m^{-3}$).

The gravimetric soil water content at 1.5 MPa (kg water/kg of < 0.002-m soil material) is read into the model from the soil input file and is converted to a volumetric basis by multiplying by the bulk density of the soil. If the value is zero, the volumetric water content is predicted from:

$$\Theta_d = 0.0022 + 0.383\,C_l - 0.5\,C_l^2\,S_a^2 + 0.265\,C_l\,CEC_r^2 - \left[0.06\,C_l^2 + 0.108\,C_l\right] \left[\frac{\rho_{(t)}}{1000}\right]^2 \qquad [6.7.11]$$

where Θ_d is the volumetric water content at 1.5 MPa ($m^3\ m^{-3}$).

6.7.3 Rainfall Consolidation

Rainfall on freshly tilled soil consolidates it and increases soil bulk density. Soil bulk density increases by rainfall are predicted from (Onstad et al., 1984):

$$\rho_{(t)} = \rho_t + \Delta\rho_{rf} \qquad [6.7.12]$$

where $\rho_{(t)}$ is the bulk density after rainfall ($kg\ m^{-3}$), ρ_t is the bulk density after tillage ($kg\ m^{-3}$), and $\Delta\rho_{rf}$ is the bulk density increase due to consolidation by rainfall ($kg\ m^{-3}$).

The increase in soil bulk density from rainfall consolidation ($\Delta\rho_{rf}$) is calculated from:

$$\Delta\rho_{rf} = \Delta\rho_{mx} \frac{R_c}{0.01 + R_c} \qquad [6.7.13]$$

where $\Delta\rho_{mx}$ is the maximum increase in soil bulk density with rainfall and R_c is the cumulative rainfall since tillage (m).

The maximum increase in soil bulk density with rainfall is predicted from:

$$\Delta\rho_{mx} = 1650 - 2900\, C_l + 3000\, C_l^2 - 0.92\, \rho_t. \qquad [6.7.14]$$

The upper boundary for soil bulk density change with rainfall is reached after a freshly tilled soil receives 0.1 m of rainfall.

6.7.4 Weathering Consolidation

For most soils, 0.1 m of rainfall does not fully consolidate the soil. Consolidated soil bulk density (ρ_c) is assumed to be the upper boundary to which a soil naturally tends to consolidate.

The difference between the naturally consolidated bulk density and the bulk density after 0.1 m of rainfall is:

$$\Delta\rho_c = \rho_c - \rho_{(t)} \qquad [6.7.15]$$

where $\Delta\rho_c$ is the difference in soil bulk density between a soil that is naturally consolidated and one that has received 0.1 m of rainfall. $\rho_{(t)}$ is soil bulk density on the day cumulative rainfall since tillage equals 0.1 m.

The adjustment for increasing bulk density due to weathering and longer-term soil consolidation is computed from:

$$\Delta\rho_{wt} = \Delta\rho_c\, F_{dc} \qquad [6.7.16]$$

where $\Delta\rho_{wt}$ is the daily increase in soil bulk density after 0.1 m of rainfall ($kg\ m^{-3}$), and F_{dc} is the daily consolidation factor.

The daily bulk density consolidation factor is predicted from:

$$F_{dc} = 1 - e^{-\alpha_{bd}} \qquad [6.7.17]$$

where α_{bd} is a bulk density parameter. α_{bd} is currently set to 0.005, which generally causes the soil to consolidate to its natural bulk density in about 200 days if no tillage occurs.

Soil bulk density changes following tillage are predicted from:

$$\rho_{(t)} = \rho_t + \sum \rho_{wc} + \Delta \rho_{rf} \qquad [6.7.18]$$

where $\sum \rho_{wc}$ is the cumulative bulk density change with water content from tillage until the soil receives 0.1 m of rainfall.

After the soil receives 0.1 m of rainfall, soil bulk density changes are predicted from:

$$\rho_{(t)} = \rho_{(t-1)} + \Delta \rho_{wc} \left[\Theta_{(t)} - \Theta_{(t-1)} \right] + \Delta \rho_{wt} \qquad [6.7.19]$$

where $(t-1)$ refers to the previous day.

6.8 Porosity

Total soil porosity (ϕ_t) is predicted from soil bulk density by:

$$\phi_t = 1 - \frac{\rho_{(t)}}{2650} \qquad [6.8.1]$$

where $\rho_{(t)}$ is the bulk density at time t ($kg\ m^{-3}$).

The volume of entrapped air in the soil (F_a) is calculated from (Baumer, personal communication):

$$F_a = 1.0 - \frac{3.8 + 1.9\, C_l^2 - 3.365\, S_a + 12.6\, CEC_r\, C_l + 100\, O_m \left[\frac{S_a}{2} \right]^2}{100} \qquad [6.8.2]$$

where the clay, sand, and organic matter contents of the soil are given as a fraction (0-1).

The correction for the volume of coarse fragments in the soil (F_{cf}) is predicted from (Brakensiek et al., 1986):

$$F_{cf} = 1 - V_{cf}. \qquad [6.8.3]$$

V_{cf} is the fraction of coarse fragments by volume (0-1) and is predicted from:

$$V_{cf} = \frac{M_{cf} \frac{\rho_{(t)}}{1000}}{2.65 \left[1 - M_{cf} \right]} \qquad [6.8.4]$$

where M_{cf} is the fraction of coarse fragments by weight (0-1).

The effective porosity of the soil (ϕ_e) is calculated from the total porosity determined from soil bulk density (< 2-mm material) and adjusted for the volumes of entrapped air and residual water. ϕ_e is computed from:

$$\phi_e = \left[\phi_t\, F_a \right] - \Theta_r. \qquad [6.8.5]$$

Soil porosity calculated in Eq. [6.8.1] and volumetric soil water contents at 0.020, 0.033, and 1.5 MPa are adjusted for the volumes of entrapped air (F_a) and coarse fragments (F_{cf}). These adjusted soil parameters are used in soil water storage computations (see Chapter 7).

6.9 Saturated Hydraulic Conductivity

The saturated hydraulic conductivity of the soil is predicted from:

$$K_s = \frac{\phi_e^3}{\left[1 - \phi_t F_a\right]^2 \left[\frac{0.001\, \rho_{(t)}}{\Theta_r}\right]^2 0.00020\, C^2} \qquad [6.9.1]$$

where K_s is the saturated hydraulic conductivity of the soil ($m\ s^{-1}$).

The parameter C is predicted from:

$$C = -0.17 + 18.1\, C_l - 69.0\, S_a^2\, C_l^2 - 41.0\, S_a^2\, S_i^2 + 1.18\, S_a^2 \left[\frac{\rho_{(t)}}{1000}\right]^2 + 6.9\, C_l^2 \left[\frac{\rho_{(t)}}{1000}\right]^2 + 49.0\, S_a^2\, C_l - 85.0\, S_i\, C_l^2 \qquad [6.9.2]$$

where $\rho_{(t)}$ is the bulk density of the soil at time t.

The saturated hydraulic conductivity of the soil (K_s) is adjusted for 1) weight of coarse fragments, 2) frozen soil, 3) crust, 4) macroporosity, and 5) soil cover. See Chapter 4 for information on crust, macroporosity, and soil cover adjustments.

6.9.1 Coarse Fragments in Soil

The saturated hydraulic conductivity adjustment for the weight of coarse fragments is predicted from:

$$K_s = K_s \left[1 - M_{cf}\right] \qquad [6.9.3]$$

where M_{cf} is the fraction of coarse fragments in the soil by weight (0-1).

6.9.2 Frozen Soil

The saturated hydraulic conductivity adjustment for frozen soil (FS_a) is predicted from (Lee, 1983):

$$FS_a = 2 - 0.019\, F_\Theta. \qquad [6.9.4]$$

F_Θ is predicted from:

$$F_\Theta = \frac{\Theta_f}{\Theta_{fc}}\, 100 \qquad [6.9.5]$$

where Θ_f is the volumetric soil water content at freezing ($m^3\ m^{-3}$). If $F_\Theta \geq 100$, then FS_a is set to 0.1.

If the average daily air temperature is < 0 °C, then:

$$K_s = K_s\, FS_a \qquad [6.9.6]$$

6.10 Baseline Interrill Erodibility for Croplands

Data collected from a study of 36 cropland soils throughout the U.S. in 1987 and 1988 were analyzed to develop relationships between baseline interrill erodibility parameters and soil physical and chemical properties (Elliot et al., 1988). The interrill sediment delivery rate is (see Chapter 10 for more detail):

$$D_i = K_i I^2 \qquad [6.10.1]$$

where D_i is the sediment delivery rate ($kg\ s^{-1}\ m^{-2}$), K_i is the interrill soil erodibility parameter ($kg\ s^{-1}\ m^{-4}$), and I is rainfall intensity ($m\ s^{-1}$).

The baseline K_i parameter for a soil in a seedbed condition is calculated from:

$$K_i = \left[-2.92 - 2.71 \left[\frac{C_{lwd}}{C_l} \right] - 0.51\, M_g + 10.0\, C_{lwd} + 4.19 \left[\frac{C_l}{F_e + A_l} \right]^{0.16} + 1.24\, C_d \right] 10^6 \qquad [6.10.2]$$

where K_i is the baseline interrill erodibility parameter for a cropland soil ($kg\ s^{-1}\ m^{-2}$), C_{lwd} is the fraction of water dispersible clay (0-1), C_l is the clay content (0-1), M_g is the magnesium content ($cmol\ kg^{-1}$), F_e and A_l are the iron and aluminum contents (0-1), and C_d is the electrical conductivity ($mmhos\ cm^{-1}$).

For soils with a clay fraction greater then 0.35, baseline K_i is predicted from:

$$K_i = \left[2.67 - 0.115 \ln \left[\left[0.18 - A_g \right] 100 \right]^2 \right] 10^6 \qquad [6.10.3]$$

where A_g is the aggregate stability of the soil (fraction of 1- to 2-mm aggregates retained on a sieve with 0.5-mm openings after wet sieving).

6.11 Interrill Erodibility Adjustments for Cropland Soils

Effects of dead and live root biomass within the 0- to 0.15-m soil zone on interrill erodibility of a cropland soil are predicted separately. The effect of dead roots on interrill erodibility is predicted from (Alberts and Ghidey, unpublished data):

$$CK_{id} = 1.1\, e^{-0.56\, M_r} \qquad [6.11.1]$$

where CK_{id} is the interrill erodibility adjustment for dead roots and M_r is dead root mass ($kg\ m^{-2}$) within the 0- to 0.15-m soil zone.

The effect of live roots on interrill erodibility is predicted from:

$$CK_{il} = 1.0 e^{-0.56\, B_{r1}} \qquad [6.11.2]$$

where CK_{il} is the interrill erodibility adjustment for live roots and B_{r1} is live root biomass ($kg\ m^{-2}$) within the 0- to 0.15-m soil zone.

6.12 Baseline Interrill Erodibility for Rangeland Soil

Data collected from a study of 19 rangeland sites in 1987 and 1988 were analyzed to develop a relationship between interrill erodibility and soil physical and chemical properties (Simanton et al., 1987). Baseline K_i is predicted from:

$$K_i = \left[1709 - 1765\, S_a - 645\, S_i - 4557\, O_m - 902\, \Theta_{fc}\right] 10^3 \qquad [6.12.1]$$

where K_i is the baseline interrill erodibility parameter for a rangeland soil ($kg\ s^{-1}\ m^{-4}$), S_a and S_i are the fractions of sand and silt (0-1), O_m is the fraction of organic matter (0-1), and Θ_{fc} is the volumetric water content of the soil at 0.033 MPa ($m^3\ m^{-3}$).

6.13 Baseline Rill Erodibility and Critical Shear for Cropland Soils

Data collected from a study of 36 soils throughout the U.S. in 1987 and 1988 were analyzed to develop relationships between rill erodibility and critical shear stress and soil physical and chemical properties (Elliot et al., 1988). For a detailed description of these parameters and their significance, see Chapter 10. Rill detachment capacity is predicted from:

$$D_r = K_r \left[\tau - \tau_c\right] \qquad [6.13.1]$$

where D_r is the soil detachment capacity in a rill ($kg\ s^{-1}\ m^{-2}$), K_r is the rill soil erodibility parameter ($s\ m^{-1}$), τ is the shear stress of the flow (Pa), and τ_c is the critical shear stress of the flow necessary to initiate significant soil detachment (Pa).

The following equation is used to predict K_r:

$$K_r = \frac{196 + 0.015\left[M - 3500\, M^{0.2}\right] - \dfrac{32.7}{CEC^{0.4}} + 35.0\left[1 + e^{(1 - 312\, O_m)}\right] + \dfrac{0.16}{100\, A_l\, S_{ar}^{0.75}} - 8\, S_{ar}}{1000} \qquad [6.13.2]$$

where K_r is the baseline rill erodibility parameter of a cropland soil ($s\ m^{-1}$), CEC is the cation exchange capacity ($cmol\ kg^{-1}$), and S_{ar} is the sodium adsorption ratio.

The textural parameter M is calculated from:

$$M = \left[S_i + S_{avf}\right] \left[1.0 - C_l\right] 10^2 \qquad [6.13.3]$$

where S_{avf} is the fraction of very fine sand in the soil (0-1).

Baseline critical shear stress of a cropland soil is predicted from:

$$\tau_c = -2.85 - \frac{8.87}{(100\, S_{avf} + 0.1)^{0.2}} - 16.0\, C_c + 3.65\, S_{ar} + 3.79\, S_s^{0.2} + \frac{28.1}{100\, S_a^{0.3}} \left[\frac{C_{lwd}}{C_l}\right]^{0.8} \qquad [6.13.4]$$

where τ_c is the critical shear stress of the flow (Pa), and S_s is the specific surface of the soil (mg of ethylene glycol mono-ethyl ether adsorbed/g of soil).

For cropland soils with a clay fraction greater than 0.30, baseline τ_c is predicted from:

$$\tau_c = -0.5 - 284\, \Theta_{(t)} \left[\Theta_{(t)} - 0.3\right] \qquad [6.13.5]$$

where $\Theta_{(t)}$ is the volumetric soil water content ($m^3\ m^{-3}$).

6.14 Rill Erodibility Adjustments for Croplands

6.14.1 Incorporated Residue

The following relationship is used to predict the effect of incorporated residue on K_r for a cropland soil (Brown and Foster, 1987; Alberts and Gantzer, 1988):

$$CK_{rm} = 1.1e^{-0.56\,M_b} \qquad [6.14.1]$$

where CK_{rm} is the rill erodibility adjustment for buried residue and M_b is the mass of buried residue ($kg\ m^{-2}$) within the 0- to 0.15-m soil zone.

6.14.2 Soil Consolidation

This routine estimates erodibility changes with time after tillage due to weathering and thixotropy. Details of the consolidation model, including equations for adjusting K_r and τ_c were described in detail by Nearing et al., 1988. The model calculates a relative increase in soil resistance due to drying and time, R'. The adjustment to K_r due to consolidation, CK_{rc}, is estimated by:

$$CK_{rc} = \frac{1}{R'} \qquad [6.14.2]$$

where R' is the normalized rill erodibility adjustment due to consolidation.

The adjustment of τ_c, $C\tau_{cc}$, is predicted from:

$$C\tau_{cc} = 0.5\left[R' + 1\right]. \qquad [6.14.3]$$

6.15 Baseline Rill Erodibility and Critical Shear for Rangeland Soil

Data collected from a study of 19 rangeland soils in 1987 and 1988 were analyzed to develop relationships between rill erodibility and critical shear stress and soil physical and chemical properties. Baseline K_r is predicted from:

$$K_r = 0.0017 + 0.0024\,C_l - .0088\,O_m - 0.00088\left[\frac{\rho_{(t)}}{1000}\right] - 0.00048\,R_i \qquad [6.15.1]$$

where K_r is the baseline rill erodibility parameter for a rangeland soil, C_l and O_m are fractions of clay and organic matter (0-1), $\rho_{(t)}$ is the soil bulk density ($kg\ m^{-3}$), and R_i is the total root biomass ($kg\ m^{-2}$) within the 0- to 0.10-m soil zone.

τ_c is predicted from:

$$\tau_c = 3.23 - 5.6\,S_a - 24.4\,O_m + 0.90\left[\frac{\rho_{(t)}}{1000}\right] \qquad [6.15.2]$$

where τ_c is the critical shear stress of the flow necessary to detach soil (Pa).

6.16 References

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6.17 List of Symbols

Symbol	Definition	Unit	Variable
A_g	Wet aggregate stability parameter	Fraction	AS
A_l	Aluminum content	Fraction	AL
α_{bd}	Soil bulk density parameter	Fraction	BDE
α_{rh}	Ridge height parameter	Fraction	RHE
α_{rr}	Random roughness parameter	Fraction	RRE
B_{r1}	Live root biomass in the 0- to 0.15-m soil zone	$kg\ m^{-2}$	RTM15
C	Saturated hydraulic conductivity parameter	Fraction	C1
C_c	Calcium carbonate content	Fraction	CACO3
C_d	Electrical conductivity	$mmhos\ cm^{-1}$	COND
C_l	Clay content	Fraction	CLAY
C_{wd}	Water-dispersible clay	Fraction	WDCLAY
C_{rf}	Flat residue cover	Fraction	FLRCOV
CEC	Cation exchange capacity of the soil	$cmol\ kg^{-1}$	CEC
CEC_c	Cation exchange capacity of the clay	$cmol\ kg^{-1}$	CECC
CEC_r	Ratio of cation exchange capacity of the clay to the fraction of clay in the soil	$cmol\ kg^{-1}$	SOLCON
CK_{id}	Cropland interrill soil erodibility adjustment for dead root mass	Fraction	CKIADR
CK_{il}	Cropland interrill soil erodibility adjustment for live root biomass	Fraction	CKIALR
CK_{rc}	Cropland rill erodibility adjustment for soil consolidation	Fraction	CKRCON
CK_{rm}	Cropland rill erodibility adjustment for buried residue biomass	Fraction	CKRASR
$C\tau_{cc}$	Cropland critical shear stress adjustment for soil consolidation	Fraction	CTCCON
D_g	Depth of the soil horizon of interest	m	DG
D_i	Interrill sediment delivery rate	$kg\ s^{-1}\ m^{-2}$	Di

D_r	Rill soil detachment capacity	$kg\ s^{-1}\ m^{-2}$	Dr
F_a	Volume of entrapped air in the soil	Fraction	COCA
F_{cf}	Coarse fragment adjustment for soil porosity	Fraction	CPM
F_{dc}	Daily soil bulk density consolidation factor	Fraction	DAYCON
F_e	Fraction of iron in the soil	Fraction	FE
FS_a	Saturated hydraulic conductivity adjustment for frozen soil	Fraction	FROF
F_Θ	Soil water volume at freezing/soil water volume at 0.033 MPa	Fraction	PFC
I	Rainfall intensity	$m\ s^{-1}$	I
K_i	Interrill soil erodibility parameter	$kg\ s^{-1}\ m^{-4}$	Ki
K_r	Rill soil erodibility parameter	$s\ m^{-1}$	Kr
K_s	Saturated hydraulic conductivity of the soil	$m\ s^{-1}$	SSC
M	Soil texture parameter	Fraction	M
M_b	Buried residue mass in the 0- to 0.15-m soil zone	$kg\ m^{-2}$	SMRM
M_{cf}	Coarse fragment content by weight	Fraction	RFG
M_g	Magnesium content	$cmol\ kg^{-1}$	MG
M_r	Dead root biomass in the 0- to 0.15-m soil zone	$kg\ m^{-2}$	RTM
O_c	Organic carbon content	Fraction	ORGC
O_m	Organic matter content	Fraction	ORGMAT
ϕ_e	Effective porosity	Fraction	EPOR
ϕ_t	Total porosity	Fraction	POR
R_c	Cumulative rainfall since tillage	m	RFCUM
R_{mf}	Residue mixing factor	Fraction	RMF
R_{ho}	Ridge height immediately after tillage	m	RHo
R_h	Ridge height at time t	m	RHt
R_i	Total root mass in the 0- to 0.10-m zone of rangeland soil	$kg\ m^{-2}$	ROOT
R_r	Random roughness at time t	m	RRt
R_{ri}	Random roughness immediately after tillage	m	RRINIT
R_{ro}	Random roughness of a tillage implement	m	RRo
R'	Normalized rill erodibility resistance due to consolidation	Fraction	RPRIME
ρ	Soil bulk density	$kg\ m^{-3}$	BD
ρ_c	Consolidated soil bulk density at 0.033 MPa	$kg\ m^{-3}$	BDCONS
$\Delta\rho_c$	Difference in soil bulk density between a soil that is naturally consolidated and one that has received 0.1 m of rainfall	$kg\ m^{-3}$	BDDIFF
ρ_d	Oven-dry soil bulk density	$kg\ m^{-3}$	BDDRY
$\Delta\rho_{mx}$	Maximum increase in soil bulk density with rainfall	$kg\ m^{-3}$	Ao
$\Delta\rho_{rf}$	Adjustment for increasing soil bulk density due to consolidation by rainfall	$kg\ m^{-3}$	BDIRF
$\Delta\rho_{wt}$	Daily increase in soil bulk density after 0.1 m of rainfall	$kg\ m^{-3}$	BDIWT
ρ_t	Soil bulk density after tillage	$kg\ m^{-3}$	BDTILL
$\Delta\rho_{wc}$	Change in soil bulk density with water content	$kg\ m^{-3}$	Bo
$\sum\rho_{wc}$	Cumulative bulk density change with water content from tillage until 0.1 m of rainfall	$kg\ m^{-3}$	SBDIWC
S_a	Sand content	Fraction	SAND
S_{ar}	Sodium adsorption ratio	Fraction	SAR
S_{avf}	Very fine sand content	Fraction	VFS

S_i	Silt content	Fraction	SILT
S_s	Specific surface	$mg\ g^{-1}$	SS
τ	Shear stress of the flow	Pa	TAU
τ_c	Critical shear stress of the flow necessary to initiate detachment	Pa	TAUc
Θ	Soil water content by volume	Fraction	THET
Θ_d	Soil water content at 1.5 MPa by volume	Fraction	THETDR
Θ_f	Soil water content at freezing by volume	Fraction	SMF
Θ_{fc}	Soil water content at 0.033 MPa by volume	Fraction	THETFC
Θ_r	Residual soil water content by volume	Fraction	WRD
T_i	Tillage intensity	Fraction	TI
V_{cf}	Coarse fragment content by volume	Fraction	VCF