Chapter 13. WATERSHED MODEL CHANNEL HYDROLOGY AND EROSION PROCESSES

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13.1 Watershed Model Overview

The Water Erosion Prediction Project (WEPP) watershed model is a process-based, continuous simulation model built as an extension of the WEPP hillslope model (Flanagan and Nearing, 1995). The model was developed to predict erosion effects from agricultural management practices and to accommodate spatial and temporal variability in topography, soil properties, and land use conditions within small agricultural watersheds. The model contains three primary components: hillslope, channel, and impoundment. The hillslope component calculates rainfall excess by a Green-Ampt Mein-Larson (GAML) infiltration equation; peak runoff rate by kinematic wave overland flow routing or simplified regression equations; interrill erosion as a process of soil detachment by raindrop impact and sediment delivery to rill flow areas; and rill erosion as a function of sediment detachment, sediment transport capacity, and the existing sediment load in the flow. The following hillslope hydrologic and erosion output is stored in a pass file and then read in and used by the channel and impoundment components: 1) storm duration (s); 2) overland flow time of concentration (h); 3) Rational equation dimensionless α; 4) runoff depth (m); 5) runoff volume (m^3); 6) peak runoff ($m^3 \cdot s^{-1}$); 7) total sediment detachment at the end of the hillslope (kg); 8) total sediment deposition at the end of the hillslope (kg); 9) sediment concentration by particle size class at the end of the hillslope ($kg \cdot m^{-3}$); and 10) dimensionless fraction of each particle size in the eroded sediment.

The channel component can be further divided into hydrology and erosion components. The channel hydrology component computes infiltration, evapotranspiration, soil water percolation, canopy rainfall interception, and surface depressional storage in the same manner as the hillslope hydrology component. Rainfall excess is calculated using the identical GAML infiltration routines as found in the hillslope hydrology component. The GAML equation is used regardless of whether the channel is within a developed soil (e.g., an ephemeral gully or grassed waterway) or has an alluvial bed with a high loss rate (e.g., a channel in an arid or semi-arid climate watershed). The WEPP watershed model offers two options for calculating the peak runoff rate at the channel (sub-watershed) or watershed outlet: a modified version of the Rational equation similar to that used in the EPIC model (Williams, 1995) or the method used in the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980).

The reasoning behind the development of the WEPP watershed model erosion component is that watershed sediment yield is a result of detachment, transport, and deposition of sediment on overland (rill and interrill) flow areas and channel flow areas, that is, erosion from both hillslope areas and concentrated flow channels must be simulated by the watershed version. The movement of suspended sediment on rill, interrill, and channel flow areas is based on a steady-state erosion model developed by Foster and Meyer (1972) that solves the sediment continuity equation. Detachment, transport, and deposition within permanent channels (limited to grassed waterways, terrace channels or similar size) or ephemeral gullies are calculated by a steady-state solution to the sediment continuity equation. Flow depth and hydraulic shear stress along the channel are computed by regression equations based on a numerical solution of the steady-state spatially-varied flow equation.

The impoundment component calculates outflow hydrographs and sediment concentration for various types of outflow structures suitable for both large (e.g., farm ponds) or small (e.g., terraces) impoundments including culverts, filter fences, straw bales, drop and emergency spillways, and perforated risers. Deposition of sediment in the impoundment is calculated assuming complete mixing and later adjusted to account for stratification, non-homogeneous concentrations, and the impoundment shape. A continuity mass balance equation is used to predict sediment outflow concentration.

13.2 Runon-Runoff

Surface runon is assumed to enter a channel through a combination of: 1) lateral flow from hillslopes or impoundments; 2) flow into the channel inlet from an upstream hillslope or impoundment; and 3) flow into the channel inlet from upstream channels, and can be written as

$$ro_v = ro_l + ro_i \qquad [13.2.1]$$

where ro_v is the total channel runon volume, ro_l is the lateral runon volume from hillslopes or impoundments, and ro_i is the channel inlet runon volume from upstream hillslopes, impoundments or channels. All runon volumes are in expressed in m^3. ro_v is then converted to runon depth using the equation

$$ro_d = \frac{ro_v}{A_{ch}} \qquad [13.2.2]$$

where ro_d is the runon depth (m) and A_{ch} is the physical channel area (m^2).

The storm (event) duration for the channel is taken to be the maximum duration of: 1) the storm duration of any watershed element (hillslope, impoundment, or channel) that contributes surface runon to the channel; 2) the storm duration for the channel itself (the hillslope component and the channel/impoundment components may use different climate files, although this capability has not been tested); or 3) the duration of any sprinkler irrigation event occurring on the channel

$$dur_c = \max(dur_{runon},\ dur_{chan},\ dur_{irrig}) \qquad [13.2.3]$$

where dur_c is the channel storm duration, dur_{runon} is the maximum storm duration of any watershed element contributing surface runon to the channel, dur_{chan} is the storm duration of the channel itself, and dur_{irrig} is the duration of any sprinkler irrigation event contributing water to the channel. All durations are expressed in seconds.

Once the surface runon volume and depth are computed, the remaining sequence of calculations relevant to channel hydrology runoff processes are infiltration, depressional storage, rainfall excess (runoff), and transmission losses. If there is a precipitation event (rainfall, snow melt, or sprinkler irrigation) for the current day, then the precipitation statistics are passed to the disaggregation routines. The disaggregation routines insert a time step into the rainfall array for the channel infiltration computations. Cumulative channel infiltration is computed using an implementation of the GAML model (Mein and Larson, 1973) as presented by Chu (1978) for the case of unsteady rainfall and multiple times to ponding. A description of the GAML model implementation can be found in Chapter 4, Eqs. 4.2.1 through 4.2.9. Rainfall excess is the amount of rainfall that does not infiltrate when rainfall intensity exceeds the infiltration rate. Before the rainfall excess is calculated, the volume is adjusted for soil saturated conditions and depressional storage as given in Eqs. 4.3.1 through 4.3.4. Average infiltration parameters for the channel are calculated and an average rainfall excess rate for an interval is computed using Eq. 4.3.5. The total rainfall excess amount is then computed and treated as the preliminary or initial channel runoff depth q_{ci} (m). Following the calculation of q_{ci} using the GAML model, there are four general cases which can arise on a channel that determine the final channel runoff depth q_{cf} (m).

Case I: $q_{ci} > 0$, $ro_d > 0$. The first case occurs when there is both channel runon and runoff is produced on the channel itself. In this case, the runon, ro_d, is simply added to q_{ci}.

Case II: $q_{ci} > 0$, $ro_d = 0$. The second case occurs when there is no channel runon, however, runoff is generated on the channel itself. In this case, q_{ci} remains unchanged.

For Cases I and II, q_{ci} is reduced due to recession infiltration caused by partial equilibrium (flat-topped) hydrographs. The definition of rainfall excess (Eq. 4.3.1) does not allow for infiltration after rainfall ceases, therefore partial equilibrium hydrographs occur and the runoff volume can be significantly less than the rainfall excess volume. Thus, q_{cf} is computed by subjecting q_{ci} to runoff volume reduction caused by infiltration during the hydrograph recession (Eqs. 4.4.27 through 4.4.29). A detailed description of the partial equilibrium condition is presented in Chapter 4, Section 4.4.1. Transmission losses (i.e., GAML and hydrograph recession infiltration losses) for Cases I and II are calculated using the equation

$$t_l = (ro_v + rof_c) - rof_f \qquad [13.2.4]$$

where t_l is the transmission volume loss, rof_c is channel runoff volume (before the addition of channel runon volume) and rof_f is the final channel runoff volume (after the addition of channel runon volume and reduction due to recession infiltration caused by partial equilibrium hydrographs). All volumes are in expressed in m^3.

Case III: $q_{ci} = 0$, $ro_d > 0$. The third case occurs when there is no runoff produced on the channel itself, however, channel runon occurs. In this case, channel runon depth may be reduced through channel transmission losses. Transmission losses for Case III are computed by first calculating a potential infiltration volume capacity, f_p (m^3), and comparing it to the volume of water (m^3) entering the channel, f_c. f_p is computed using a Taylor Series expansion approximation of the Green-Ampt model (Stone et al., 1994) and the maximum depressional storage for the channel. f_c is the sum of the channel runon volume plus the precipitation volume. The channel calculations are similar to those for the hillslope component (Eqs. 4.5.4 and 4.5.6) with the exception that they are performed on a volume, rather than on a depth basis. If f_c is less than f_p then all runon volume is assumed to have infiltrated and q_{cf} is set to zero. If f_c is greater than f_p, then q_{cf} is calculated as

$$q_{cf} = \frac{(f_c - f_p)}{A_{ch}} \qquad [13.2.5]$$

The channel transmission loss volume, t_l (m^3), is then calculated using the equation

$$t_l = ro_v - (q_{cf}\, A_{ch}) \qquad [13.2.6]$$

Case IV: $q_{ci} = 0$, $ro_d = 0$. The fourth case occurs when there is no runon or channel runoff. In this case q_{cf} and rof_f are set to zero, and no further runon-runoff calculations are necessary.

13.3 Channel Water Balance

Channel water balance calculations are performed after channel runon-runoff volumes have been computed. The channel water balance and percolation routines are identical to those used in the hillslope component. Input from the climate, infiltration, and crop growth routines are used to estimate soil water content in the root zone, soil evaporation, plant transpiration, interception, and percolation loss below the root zone. The reader is referred to Chapter 5 for a complete description of the WEPP hillslope and watershed model water balance and percolation routines.

13.4 Peak Runoff Rate

13.4.1 Channel Inlet

The peak runoff rate entering a channel depends on the contributing hillslope, channel, and impoundment elements (i.e., one hillslope, one impoundment, or up to three channels may contribute runoff volume at the channel inlet). The peak runoff rate calculations are performed only if the final channel runoff volume (rof_f) is greater than 0.001 m^3. Otherwise, the peak runoff rate and the duration of runoff are set to zero and the next downstream watershed element is considered.

If only one watershed element contributes surface runon to a channel, then the peak runoff rate entering the channel is set equal to the peak runoff rate leaving the contributing watershed element. For example, if a hillslope is the only watershed element contributing runon to a channel then the peak runoff rate entering the channel is the same as the peak runoff rate leaving the final hillslope overland flow element (OFE). The same would be true for a single impoundment contributing outflow runon to a channel. If more than one watershed element, such as multiple channels (up to three are allowed), contribute runon to a channel then the SCS (Triangular) Synthetic Hydrograph method (Haan et al., 1982) is used to calculate the time-discharge hydrographs for each contributing watershed element.

SCS (triangular) synthetic hydrographs are calculated when surface flows from hillslopes, channels and impoundments merge onto a channel or into an impoundment. The triangular hydrograph procedure is based on the assumption that a time distribution for the manner in which storm rainfall is translated into rainfall excess, i.e., surface runoff volume, is available. By definition, rainfall excess equals runoff volume. The time-discharge hydrographs are then superimposed to compute the peak runoff rate entering the channel or impoundment. This is accomplished by first solving for the base time of each hydrograph

$$t_b = \frac{c\ A_w\ q_a}{q_{pi}} \qquad [13.4.1]$$

where t_b is the base time of the hydrograph (min), c is a constant dependent on the system of units being used (with the units indicated here, $c = 1/60$), A_w is the watershed area contributing to the channel or impoundment (m^2), q_a is the average runoff depth from the contributing watershed area (m), and q_{pi} is the the peak runoff rate of the contributing watershed element ($m^3 \cdot s^{-1}$).

Next, the time to peak for each synthetic hydrograph is calculated using the equation

$$t_p = \frac{t_b}{2.67} \qquad [13.4.2]$$

where t_p is the time to peak of the hydrograph (min).

The calculations in Eqs. [13.4.1] and [13.4.2] are repeated for each watershed element contributing to the channel or impoundment. The time-discharge relationship for the combined-flow hydrograph is determined by taking the maximum t_b for all hydrographs and superimposing the hydrographs together over that time period. The peak runoff rate entering the channel or impoundment is computed as the largest discharge value on the superimposed (time-discharge) hydrograph.

13.4.2 Channel Outlet

The WEPP watershed model channel component contains two methods for estimating the peak runoff rate at the channel (sub-watershed) or watershed outlet - the modified Rational equation and the CREAMS peak runoff method.

13.4.2.1 Modified Rational Equation

Implementation of the modified Rational equation in the channel component follows very closely the methodology used in the EPIC model (Williams, 1995), with the exception that in WEPP the equation is used to calculate the peak runoff rate at each channel outlet rather than only at the watershed outlet as is done in EPIC. The rational equation can be written in the form

$$q_{po} = \frac{\alpha\, rof_f}{(3600\, t_c)} \qquad [13.4.3]$$

where q_{po} is the peak runoff discharge at the channel or watershed outlet ($m^3 \cdot s^{-1}$), t_c is the time of concentration at the outlet (h), and α is a dimensionless parameter that expresses the proportion of total rainfall that occurs during t_c. α is calculated for the final hillslope OFE, and for each channel and impoundment watershed element.

A generalized equation for the channel or watershed outlet time of concentration can be developed by adding the overland, channel, and impoundment flow times and is written as

$$t_c = t_{cc} + t_{cs} + t_{ci} \qquad [13.4.4]$$

where t_{cc} is the average channel travel time, t_{cs} is the time of concentration for overland flow, and t_{ci} is the time of concentration for impoundments. All times of concentration are expressed in hours.

13.4.2.1.1 Channel Travel Time. Channel travel time is calculated using an approach similar to that found in the EPIC model

$$t_{cc} = \frac{l_c}{v_c} \qquad [13.4.5]$$

where l_c is the channel flow length (m) and v_c is the average channel flow velocity ($m \cdot s^{-1}$).

Applying Manning's equation to a trapezoidal channel with 2:1 side slopes and 10:1 bottom width-depth ratio, solving for v_c, and substituting into Eq. [13.4.5] gives

$$t_{cc} = \frac{0.0004\, l_c\, n^{0.75}}{(q_c^*)^{0.25}\, (S)^{0.375}} \qquad [13.4.6]$$

where l_c is the channel flow length (m), n is the average channel Manning's roughness coefficient, and S is the average channel slope in $m \cdot m^{-1}$. q_c^* is the average flow rate in the channel ($m^3 \cdot s^{-1}$) and is calculated using the equation

$$q_c^* = \frac{rof_f}{dur_c} \qquad [13.4.7]$$

The values of l_c, n, and S depend on: a) the position of the channel in the watershed; and b) the time of concentration of watershed elements contributing to the channel. The elements which control, or contribute to, the maximum time of concentration at the channel or watershed outlet are tracked. That is, for each channel the flow route (through the watershed) having the longest time of concentration network is known. If there is a continuous network of channels (i.e., no impoundments), then l_c, n, and S are spatially-averaged values representing the flow routing network that contributes the largest time of concentration at the channel outlet. If an impoundment contributes to the channel and has a larger time of concentration than other contributing elements (i.e, the impoundment controls the time of concentration instead of a hillslope or channel), then l_c, n, and S are not spatially-averaged and represent that channel only. The same is true for l_c, n, and S when calculating t_{cc} for first order channels.

13.4.2.1.2 Overland Flow Time of Concentration. Overland flow (surface) time of concentration is calculated using an approach also similar to that found in the EPIC model

$$t_{cs} = \frac{l_s}{v_s} \qquad [13.4.8]$$

where l_s is the surface slope length (m) and v_s is the surface flow velocity ($m \cdot s^{-1}$).

Manning's equation is applied to a strip 1 meter wide down the slope length and flow is assumed to be concentrated into a small trapezoidal channel with 1:1 side slopes and 5:1 bottom width-depth ratio. Solving for v_s and substituting into Eq. [13.4.8] gives

$$t_{cs} = \frac{0.0216\,(l_s\ n)^{0.75}}{(q_o)^{0.25}\,(S)^{0.375}} \qquad [13.4.9]$$

where l_s is the surface slope length (m), n is the average surface Manning's roughness coefficient, q_o is the average surface flow rate ($m^3 \cdot s^{-1}$) and S is the average land surface slope ($m \cdot m^{-1}$).

Since the WEPP hillslope component does not estimate Manning's n for overland flow in rills, it must be derived using the following relationship between the Manning and Darcy-Weisbach roughness coefficients

$$n = \sqrt{\frac{f\,R^{1/3}}{8g}} \qquad [13.4.10]$$

where f is the representative dimensionless Darcy-Weisbach roughness coefficient, R is the representative rill hydraulic radius (m), and g is the acceleration of gravity ($m \cdot s^{-2}$).

The representative Darcy-Weisbach roughness coefficient is calculated by summing the total rill friction factor of each hillslope OFE multiplied by the OFE slope length and then dividing by the total overland flow slope length.

$$f = \frac{\sum_{i=1}^{\#OFE} f_t(i)\ l_{OFE}(i)}{l_s} \qquad [13.4.11]$$

where f_t is the dimensionless Darcy-Weisbach total rill friction factor for the OFE and l_{OFE} is the OFE slope length (m).

The representative rill hydraulic radius is calculated by summing the rill hydraulic radius of each OFE multipled by the OFE slope length and then dividing by the total overland flow slope length.

$$R = \frac{\sum_{i=1}^{\#OFE} R_{OFE}(i)\ l_{OFE}(i)}{l_s} \qquad [13.4.12]$$

where R_{OFE} is the OFE rill hydraulic radius OFE (m).

13.4.2.1.3 Impoundment Time of Concentration. The impoundment time of concentration is calculated using the relationship (Haan et al., 1982)

$$t_{ci} = \frac{t_{lag}}{0.6} \qquad [13.4.13]$$

where t_{lag} is the hydrograph lag time (h) and is calculated using the equation

$$t_{lag} = \left(\frac{t_o}{2}\right) - \left(\frac{t_i}{2}\right) \qquad [13.4.14]$$

where t_o is the duration of outflow from the impoundment (h), and t_i is the duration of inflow entering the impoundment (h). t_o can be computed as

$$t_o = \frac{\dfrac{rof_{ii}}{q_{pio}}}{\dfrac{2}{3600}} \qquad [13.4.15]$$

where rof_{ii} is the impoundment inflow volume (m^3) and q_{pio} is the impoundment peak outflow rate ($m^3 \cdot s^{-1}$).

Substituting Eqs. [13.4.14] and [13.4.15] into Eq. [13.4.13] gives

$$t_{ci} = \frac{\left[\dfrac{\left(\dfrac{rof_{ii}}{q_{pio}}\right)}{\left(\dfrac{2}{3600}\right)}\right] - \left(\dfrac{t_i}{2}\right)}{0.6} \qquad [13.4.16]$$

13.4.2.1.4 Channel Time of Concentration. If the channel is a first order channel, and one or more hillslopes contribute runon to the channel, the channel time of concentration is computed with the equation

$$t_c = t_{cc} + t_{cs\max} \qquad [13.4.17]$$

where $t_{cs\max}$ is the largest time of concentration (h) from contributing hillslopes.

If the channel is a first order channel and one or more impoundments contribute runon to the channel, then a check is made for the maximum time of concentration of: a) any hillslope contributing to the impoundment(s) which contribute to the channel; and b) the time of concentration of the impoundment itself

$$t_{ci} = \max\,(t_{cs\max},\ t_{ci}) \qquad [13.4.18]$$

Finally, t_{ci} is compared to the time of concentration for other hillslopes which may contribute runon to the channel. If t_{ci} is larger than the t_{cs} of these hillslopes then t_{ci} is assumed to control the time of concentration. The channel time of concentration is then computed with the equation

$$t_c = t_{cc} + t_{ci} \qquad [13.4.19]$$

The flow routing network having the largest time of concentration is tracked throughout the watershed for all watershed elements. For higher order channels, this is accomplished by finding the upstream watershed element (hillslope, channel or impoundment) contributing runon to the channel inlet that has the largest time of concentration. This time of concentration is then compared to the time of concentration of any watershed element (hillslope or impoundment) that may contribute lateral runon to the channel. t_{cc} is then calculated as for first order channels, with the exception that the values for l_c, n, and S may or may not be spatially-averaged as previously discussed. The generalized equation for time of concentration for higher order channels is

$$t_c = t_{cc} + t_{cs} + t_{ci} \qquad [13.4.20]$$

If a hillslope controls the time of concentration then the t_{ci} term will be zero. If an impoundment controls the time of concentration then the t_{cs} term will be zero. The channel travel time, t_{cc}, is always calculated for each channel.

13.4.2.1.5 Rational Equation α. For hillslopes, α is computed using the equation

$$\alpha_h = \frac{(3600\ t_{cs}\ q_{ph})}{rof_h} \qquad [13.4.21]$$

where α_h is the dimensionless overland (surface) flow α, q_{ph} is the peak runoff rate leaving the last hillslope OFE ($m^3 \cdot s^{-1}$), and rof_h is the runoff volume leaving the last hillslope OFE (m^3).

For channels, the peak discharge at the channel outlet (q_{po}, Eq. [13.4.3]) is an unknown. A preliminary or initial α is first calculated using the relationship

$$\alpha_c = \frac{r_{tc}}{r_{24}} \qquad [13.4.22]$$

where α_c is the initial dimensionless channel α, r_{tc} is the amount of precipitation (rainfall, snowmelt, sprinkler irrigation) (m) during the time of concentration, t_c, for the outlet, and r_{24} is the 24-hour duration amount of precipitation (m).

For impoundments, α is calculated in the same manner as for hillslopes

$$\alpha_i = \frac{(3600\ t_{ci}\ q_{pio})}{rof_{io}} \qquad [13.4.23]$$

where α_i is the dimensionless impoundment α, q_{pio} is the peak runoff rate leaving the impoundment ($m^3 \cdot s^{-1}$), and rof_{io} is the runoff volume leaving the impoundment (m^3).

The final α (Eq. [13.4.3]) is the maximum of: 1) the α's of the watershed elements contributing to the channel; and 2) the α calculated for the channel itself

$$\alpha = \max(\alpha_h,\ \alpha_c,\ \alpha_i) \qquad [13.4.24]$$

where α_c represents the maximum of the upstream contributing channel α's plus the channel α itself.

13.4.2.2 CREAMS Method

The CREAMS peak runoff equation is the second method for calculating the peak runoff rate at the channel outlet in the WEPP watershed model. This equation was statistically derived using data from watersheds with areas ranging from 70 ha to 6200 ha. The peak discharge at the channel outlet is calculated using the equation

$$q_{po} = (7.172\,E{-}04)\, A_w^{0.7}\, S^{0.159}\, v^{0.71764\,(A_w^{0.0166})}\, lw^{-0.187} \qquad [13.4.25]$$

where q_{po} is the peak discharge at the channel outlet ($m^3 \cdot s^{-1}$), v is the average runoff depth at the channel outlet (in), lw is the watershed length to width ratio, and A_w is the watershed area contributing to the channel (m^2).

13.4.3 Effective Runoff Duration

After the peak discharge at the channel outlet is calculated, the effective runoff duration may be calculated using the equation

$$dur_{rof} = \frac{rof_f}{q_{po}} \qquad [13.4.26]$$

where dur_{rof} is the effective runoff duration (s).

13.5 Channel Erosion

13.5.1 Overview

The WEPP watershed model channel erosion routines have been adapted and modified from the CREAMS model channel erosion routines (Foster et al., 1980). They are similar to those of the hillslope model with major differences being: 1) the flow shear stress is calculated using regression equations developed by Foster et al., (1980) which approximate the spatially-varied flow equations (Chow, 1959); and 2) only entrainment, transport, and deposition by concentrated flow are simulated. The channel element is used to represent flow in terrace channels, diversions, major flow concentrations where topography has caused overland flow to converge, grass waterways, row middles or graded rows, tail ditches, and other similar channels. The channel element does not describe classical gully or large stream channel erosion.

Channel erosion is based on a steady-state sediment continuity equation. Sediment load in the channel is a function of the incoming upstream load (from hillslopes, channels, and impoundments) and the incoming lateral load (from adjacent hillslopes and impoundments), and the ability of the flow to detach channel bed material or soil particles. The flow detachment rate is proportional to the difference between: 1) flow shear stress exerted on the bed material and the critical shear stress; and 2) the transport capacity of the flow and the sediment load. Net detachment occurs when flow shear stress exceeds the critical shear stress of the soil or channel bed material and when sediment load is less than transport capacity. Net deposition occurs when sediment load is greater than transport capacity.

For channel erosion computations, the channel reach is divided into ten segments of equal length. Homogeneous slope segments are then computed for each channel segment by interpolating the slope-distance input pairs. All slope segments are assumed to have identical parameters (i.e., Manning's roughness coefficient). An initial depth and width for the nonerodible layer are also set. Within ephemeral gullies, detachment is assumed to occur initially from the channel bottom until the nonerodible layer (usually the primary tillage depth) is reached. Once the channel reaches the nonerodible layer it starts to widen and the erosion rate decreases with time until the flow is too shallow to cause detachment.

The ephemeral gully cross-sectional geometry is updated after each precipitation event that causes detachment in order to calculate channel hydraulics for subsequent events.

13.5.2 Spatially-Varied Flow

Flow in most field channels is spatially-varied, especially for outlets restricted by ridges and heavy vegetation, and for very flat terrace channels. Also, discharge generally increases along the channel. The channel component approximates the slope of the energy gradeline along the channel at points above the outlet control using a set of normalized curves and assuming steady-flow conditions at peak discharge. When there is no lateral inflow, the spatially-varied flow equations do not apply and the friction slope is set equal to the channel (bed) slope. As an alternative, the user can set the friction slope equal to the bed slope.

The equation for spatially-varied flow with increasing discharge in a triangular channel may be normalized as (Foster et al., 1980)

$$\frac{dy_*}{dx_*} = \left[S_* - C_2 \frac{x_*^2}{y_*^{\frac{16}{3}}} - C_3 \frac{x_*}{y_*^4} \right] \left[1 - C_3 \frac{x_*^2}{y_*^5} \right] \qquad [13.5.1]$$

where $y_* = y / y_e$ (y is the channel flow depth (ft) and y_e is the channel outlet flow depth (ft), $S_* = S\ (l_{eff}/y_e)$ (l_{eff} is the channel effective length (ft), discussed in the next section), x is the channel downslope distance (ft), and $x_* = x / l_{eff}$. y_*, S_*, and x_* are dimensionless. Constants C_1, C_2, and C_3 are given by

$$C_1 = \left[\frac{z^{2.5}}{2\sqrt{z^2+1}} \right]^{\frac{2}{3}} \qquad [13.5.2]$$

$$C_2 = \left[\frac{q_{po}\ n\ \sqrt{l_{eff}}}{C_1\ y_e^{\frac{19}{6}}} \right]^2 \qquad [13.5.3]$$

$$C_3 = \frac{2\ \beta\ q_{po}^2}{g\ z^2\ y_e^5} \qquad [13.5.4]$$

where n is the channel Manning's roughness coefficient, z is the side slope of the channel, and β is an energy coefficient (equal to 1.56, from McCool et al., 1966). Eq. [13.5.1] was solved for a range of typical values of C_1, C_2, and C_3.

The channel friction slope is calculated with the equation

$$S_f = (S_* - SSF)\ \frac{y_e}{l_{eff}} \qquad [13.5.5]$$

where S_f is the channel friction slope ($ft \cdot ft^{-1}$) and SSF is calculated using equations (Foster et al., 1980) fitted by regression to the solutions for [Eq. 13.5.1].

The depth of flow needs to be computed before the C_3 parameter (Eq. [13.5.4]) is calculated. Flow depth y_e at the end of the channel is estimated by assuming either critical flow, normal (uniform) flow, or depth using a rating curve relationship. y_e is also used to compute the friction slope at the channel outlet using the Manning's equation. A triangular channel section, a reasonable approximation to most field channels, was used to develop the friction slope curves because the equations are less complex. In the channel component, a triangular channel is used to estimate the slope of the energy gradeline, but the user may select a triangular or naturally eroded section for the other channel erosion computational routines.

The channel component allows for modeling of deposition in a backwater area at a field outlet by taking into account conditions where S_f is not equal to S. Such deposition is not uncommon, and is important in estimating sediment yields associated with the enrichment of fine sediment during deposition (Foster et al., 1980). The solutions to the spatially-varied flow equations account for field outlet controls, and thus can be used to simulate backwater effects on sediment deposition.

13.5.3 Effective Length

The general case for concentrated flow in a field situation is a channel of length l_c (ft) with an upstream inflow rate q_t ($ft^3 \cdot s^{-1}$) and a lateral inflow rate q_{lat} ($ft^3 \cdot s^{-1}$), along the channel reach. The top inflow rate can be calculated with the equation

$$q_t = (rof_h + rof_i + rof_c) \,/\, dur_{rof} \tag{13.5.6}$$

where rof_h is the channel inlet inflow from a contributing hillslope, rof_i is the channel inlet inflow from a contributing impoundment, and rof_c is the channel inlet inflow from one or more contributing channels. All inflows are in ft^3. The channel lateral inflow rate can be calculated as

$$q_{lat} = \left(\frac{rof_{fc}}{dur_{rof}} \right) - q_t \tag{13.5.7}$$

where rof_{fc} is the channel runoff volume (ft^3).

The top and lateral inflow rates correspond to the peak discharge at steady state and are treated as steady-state spatially-varied flow with increasing discharge along the length of the channel. The effective channel length, l_{eff} (ft), is the length of channel required to produce the outflow (outlet) discharge, q_{po} ($ft^3 \cdot s^{-1}$), given the lateral inflow rate. That is, l_{eff} is the length of the channel if it is extended upslope to where discharge would be zero with the given lateral inflow rate. If there is lateral inflow to the channel then l_{eff} is computed as

$$l_{eff} = l_c \left(1.0 + \frac{q_t}{q_{lat}} \right) \tag{13.5.8}$$

The difference between the actual channel length and the effective channel length, l_{top} (ft), is calculated as

$$l_{top} = l_{eff} - l_c \tag{13.5.9}$$

l_{top} is then proportionally added to each channel computational segment length. If there is no lateral inflow to the channel, then l_{eff} and l_{top} are set to zero. Next, the discharge rate at channel inlet is calculated. If there is lateral inflow, then the upper discharge rate is computed as

$$q_u = q_{po} \frac{l_{top}}{l_{eff}} \qquad [13.5.10]$$

where q_u is the discharge at channel inlet ($ft^3 \cdot s^{-1}$). An effective lateral inflow rate is then calculated with the equation

$$q_{lat\ eff} = \frac{q_{po}}{l_{eff}} \qquad [13.5.11]$$

where $q_{lat\ eff}$ is the effective lateral inflow rate ($ft^3 \cdot s^{-1}$). If the lateral inflow rate (q_{lat}) is zero then q_u is set to q_{po} and $q_{lat\ eff}$ is set to zero. After the initial calculations for q_u and $q_{lat\ eff}$ are performed, the discharge rate at the lower end of each computational segment can be calculated as

$$q_l = q_{po} \frac{x}{l_{eff}} \qquad [13.5.12]$$

where q_l is the discharge at the lower end of the computational segment ($ft^3 \cdot s^{-1}$) and x is the segment downslope distance (ft) from the top of the channel.

The erosion computations proceed down the length of the channel through the computational segments. The procedure used in the channel component is to: 1) set q_u for the downslope segment equal to the upslope segment q_l; 2) solve the spatially-varied flow equations for a channel of length l_{eff} to produce flow depth, velocity, and shear stress along each channel computational segment; and 3) apply the transport and detachment capacity equations segment-by-segment along the original length of channel, l_c, to compute sediment yield for the channel.

13.5.4 Effective Shear Stress

Once the slope of the energy gradeline has been calculated, the effective shear stress of the flow for channels having triangular and naturally eroded cross sections is computed. Shear stress is partitioned between the soil and vegetation. The partitioning is based upon the difference between total Manning's hydraulic roughness and the bare soil Manning's roughness. The shear stress acting on the soil is the shear stress used to compute detachment and transport. Grass and mulch reduce this stress. Total shear is divided into that acting on the vegetation or mulch and that acting on the soil using sediment transport theory (Graf, 1971). The average shear stress of the flow in the channel acting on the soil, $\bar{\tau}$ ($lb \cdot ft^{-2}$), is calculated with the equation

$$\bar{\tau} = \gamma R_s S_f \qquad [13.5.13]$$

where γ is the weight density of the water ($lb \cdot ft^{-3}$) R_s is the channel hydraulic radius due to the soil (ft), and S_f is the friction slope ([Eq. 13.5.5]). R_s is defined as

$$R_s = \left[\frac{V_c\ n_{bch}}{1.49 \sqrt{S_f}} \right]^{\frac{3}{2}} \qquad [13.5.14]$$

where V_c is the channel velocity ($ft \cdot s^{-1}$) and n_{bch} is Manning's n for bare channel conditions. V_c is estimated using

$$V_c = \frac{q}{a} \qquad [13.5.15]$$

where q is the discharge for the computational segment ($ft^3 \cdot s^{-1}$), and a is the channel cross-sectional area (ft^2).

The average shear stress of the flow acting on the vegetation in the channel, τ_{cov} ($lb \cdot ft^{-2}$), is then computed by

$$\tau_{cov} = \gamma \, S_f \left[\frac{V_c \, (n_t - n_{bch})}{1.49\sqrt{S_f}} \right]^{1.5} \qquad [13.5.16]$$

where n_t is the total Manning's roughness coefficient.

If τ_{cov} exceeds the shear stress at which the cover starts to move, the cover fails, thereby increasing the flow shear stress on the soil. Shear stress is assumed to be triangularly distributed in time over the duration of runoff in order to estimate the time that shear stress is greater than the critical shear stress. When shear stress is greater than critical shear stress, shear stress is assumed constant and equal to peak shear stress for the precipitation event. The duration of runoff is then shortened to that required to maintain the mass water balance.

13.5.5 Sediment Load

Sediment load is assumed to be limited by either the amount of sediment made available by detachment or by transport capacity (Foster et al., 1980). A quasi-steady state is assumed and sediment movement downslope obeys continuity of mass expressed by the equation

$$\frac{dq_{sed}}{dx} = D_L + D_F \qquad [13.5.17]$$

where dq_{sed} is the sediment load ($lb \cdot ft^{-1} s^{-1}$), x is the segment downslope distance (ft), D_L is the lateral sediment inflow ($lb \cdot ft^{-2} s^{-1}$), and D_F is the detachment or deposition by flow ($lb \cdot ft^{-2} s^{-1}$). The assumption of quasi-steady state allows deletion of time terms from Eq. [13.5.17].

All sediment load (detachment, transport, and deposition) calculations are performed by particle size class. Similar to the hillslope component, the default number of particle size classes for the channel component is five. Each class is represented by a particle diameter and particle density. The sediment flux entering the channel inlet, $q_{sed\ top}$ ($lb \cdot s^{-1}$), can be calculated as

$$q_{sed\ top} = \frac{q_{sed\ tot}}{dur_{rof}} \qquad [13.5.18]$$

where $q_{sed\ tot}$ is the total sediment load (lb) at the channel inlet from a contributing hillslope, impoundment, or channel(s).

Because the channel erosion equations only use a single lateral sediment inflow rate, the sediment discharge from the lateral contributing watershed elements (adjacent hillslopes and impoundments) are combined into a single value. A weighted average, based upon the relative runoff volume from the left and right channel banks, is used to compute $q_{sed\ lat}$, the average sediment flux ($lb \cdot s^{-1} \cdot ft^{-1}$) entering the channel laterally. If there is no lateral inflow then $q_{sed\ lat}$ is set equal to zero.

For each computational segment, the channel component computes an initial potential sediment load which is the sum of the sediment load from the immediate upslope segment plus that added by lateral inflow within the segment. If this potential load is less than the flow transport capacity, detachment occurs at the lesser of the detachment capacity rate or the rate which will just fill transport capacity. When detachment by flow occurs, it adds particles, having the particle size distribution for detached sediment given as input. These concepts are explained in greater detail in the following section.

13.5.6 Detachment-Transport-Deposition

If the sediment load of all particle classes at the upper boundary is less than the transport capacity of the respective classes, then the potential detachment rate, i.e., the potential rate at which concentrated flow detaches soil particles from the soil matrix, and potential sediment load at the lower boundary of the channel segment is computed. The detachment capacity, D ($lb \cdot ft^{-2} \cdot s^{-1}$), is described with the equation

$$D = K_{ch}(\bar{\tau} - \tau_{cr}) \qquad [13.5.19]$$

where K_{ch} is an erodibility factor (s^{-1}) and τ_{cr} is a critical shear stress ($lb \cdot ft^{-2}$) below which erosion is negligible.

Until the channel reaches the nonerodible layer, an active channel is assumed that is rectangular and erodes at the rate

$$E_{ch} = w_c \, K_{ch}(\bar{\tau} - \tau_{cr}) \qquad [13.5.20]$$

where w_c is the channel width (ft) and E_{ch} is the soil loss per unit channel length ($lb \cdot ft^{-1} \cdot s^{-1}$). Once the channel reaches the nonerodible layer it starts to widen and the erosion rate decreases with time until the flow is too shallow to cause detachment. Foster et al. (1980) describes the equations used for channel widening after the nonerodible layer is reached.

The sediment transport capacity for each particle size class based upon the potential sediment load is then computed using the Yalin sediment transport equation (Yalin, 1963). A complete description of the transport capacity calculations is beyond the scope of this chapter; the reader is referred to Foster et al. (1980) for a comprehensive discussion. If the potential load of each particle class is less than the transport capacity, then the sediment load at the lower boundary of the channel segment is set equal to the potential sediment load. If the potential load of all particle classes exceeds the transport capacity, the amount of detachment which just fills the transport capacity is computed and the new potential sediment load is set equal to the transport capacity. Because the transport capacity is dependent upon the sediment load, a new transport capacity based upon the last estimate of the potential sediment load is computed. This procedure is repeated until the potential load is within 1% of the transport capacity or until 20 iterations have been made. Upon completion of the iteration procedure, the sediment load at the lower boundary of the channel segment is set equal to the transport capacity.

If the sediment load of all particle classes is greater than the transport capacity then deposition is assumed to occur at the rate of

$$D = \alpha_{er} \, (T_c - q_{sed}) \qquad [13.5.21]$$

where D is the deposition rate ($lb \cdot ft^{-2} \cdot s^{-1}$), α_{er} is a first order reaction coefficient (ft^{-1}), T_c is the transport capacity ($lb \cdot ft^{-1} \cdot s^{-1}$), and q_{sed} is the sediment load ($lb \cdot ft^{-1} \cdot s^{-1}$). α_{er} can be estimated from

$$\alpha_{er} = \frac{v_f}{q_w} \qquad [13.5.22]$$

where v_f is the particle fall velocity ($ft \cdot s^{-1}$), and q_w is the discharge per unit width ($ft^3 \cdot ft^{-1} \cdot s^{-1}$). The fall velocity is estimated assuming standard drag relationships for a sphere of a given diameter and density falling in still water (Foster et al., 1980).

The potential sediment load and transport capacity at the lower boundary of the segment is then computed. Net detachment or net deposition may occur, meaning that within each channel segment four different detachment-deposition limiting cases are possible: 1) Case I - net deposition at the upper boundary and net deposition at the lower boundary (deposition may occur over the entire segment); 2) Case II - net deposition at the upper boundary and net detachment by flow at the lower boundary may (but not necessarily) occur when transport capacity increases within the segment; 3) Case III - net detachment by flow at the upper boundary and net deposition at the lower boundary may (but not necessarily) occur when transport capacity decreases in a segment; and 4) Case IV - net detachment by flow at the upper boundary and net detachment by flow at the lower boundary (detachment by flow may occur all along the segment).

For Cases I and II net deposition occurs at the upper boundary of the segment. Given that net deposition occurred at the upper boundary of the segment, a check is made to determine whether net detachment or net deposition occurs at the lower boundary of the segment. If no lateral inflow occurs, the deposition equation reduces to the change in transport capacity of the channel segment. If deposition occurs throughout the entire segment (Case I), the sediment load at the lower boundary is computed and computations proceed to the next segment. For Case II segments, the point of transition between deposition and detachment is determined and the sediment load is computed at this point. The amount of soil detached below the transition point and the sediment load at the segment's lower boundary is then computed.

Case I occurs when $T_c < q_{sed}$ for the entire segment. Where deposition occurs over the entire segment length the deposition rate is (Foster et al., 1980)

$$D = \frac{\phi}{1+\phi}\left[\frac{dT_c}{dx} - D_L\right]\left[1 - \left(\frac{x_u}{x}\right)^{1+\phi}\right] + D_u\left(\frac{x_u}{x}\right)^{1+\phi} \qquad [13.5.23]$$

where ϕ is dimensionless and can be calculated with the equation

$$\phi = \frac{v_f\, w_c}{q_w} \qquad [13.5.24]$$

dT_c / dx is assumed constant over the segment and D_u is the deposition rate at the upper segment boundary, x_u. D_u is estimated by

$$D_u = \alpha_{er}(T_{cu} - q_{sed\ u}) \qquad [13.5.25]$$

where T_{cu} is the transport capacity at x_u and $q_{sed\ u}$ is the sediment load at x_u. The sediment load at x is calculated as

$$q_{sed} = T_c - D/\alpha_{er} \qquad [13.5.26]$$

Case II occurs when $T_{cu} < q_{sed\ u}$, $dT_c / dx > 0$, and T_c becomes greater than q_{sed} within the segment. The transport capacity at the upper end of the segment may drop to a level below the sediment load. Within this area, the sediment load decreases due to deposition while the transport capacity increases from the point of the abrupt decrease. At some point upslope from the lower boundary of the segment, the sediment load equals the transport capacity. At this point, x_{de}, deposition ends (i.e., $D_u = 0$ and $T_c = q_{sed}$). Downslope, detachment by flow occurs. The point where deposition ends is given by (Foster et al., 1980)

$$x_{de} = x_u \left[1 - \frac{1+\phi}{\phi} \left(\frac{D_u}{\frac{dT_c}{dx} - D_L} \right) \right]^{\frac{1}{1+\phi}} \qquad [13.5.27]$$

where

$$D_u = \alpha_{er} \left(T_{cu} - q_{sed\ u} \right) \qquad [13.5.28]$$

T_{cu} is the transport capacity after the decrease at x_u and $q_{sed\ u}$ is the sediment load at x_u. Continuity of sediment load is maintained, but D may be discontinuous at segment ends. Downslope from x_{de}, where detachment by flow occurs, the sediment load is given by (Foster et al., 1980)

$$q_{sed} = \left(D_{Fu} + D_{Lu} + D_{Fl} + D_{Ll} \right) \frac{\Delta x}{2} + q_{sed\ u} \qquad [13.5.29]$$

where the second subscript u or l indicates the upper or lower segment area, and Δx is the length of the segment where detachment by flow is occurring. In this case, Δx is from x_{de} to the lower end of the segment; $q_{sed\ u}$ is at x_{de}, which is T_c at x_{de}, D_{Fu} is 0 at x_{de}, and D_{FL} is either the detachment capacity at x or that which will just fill T_c.

For Cases III and IV net detachment occurs at the upper boundary of the segment First, the potential for deposition is determined. This potential exists if the potential load of each particle class exceeds the transport capacity of the respective class. Next, the point of transition between detachment and deposition is determined and deposition beyond this point and the sediment load at the lower boundary of the segment is computed. If net deposition does not occur within the entire channel segment, detachment may occur over the entire segment or it may end somewhere within the segment. Both are considered Case IV conditions and the net detachment within the channel segment and sediment load at the lower boundary of the segment is then computed if detachment occurs throughout the entire segment. When detachment ends somewhere within the channel segment (Case III), the sediment load leaving the channel equals the transport capacity and the point within the channel segment where detachment ends and deposition begins is computed.

Case III occurs when $T_{cu} > q_{sed\ u}$, $dT_c / dx < 0$, and T_c becomes less than q_{sed} within the segment. If $dT_c / dx < 0$ for a segment where $T_{cu} > q_{sed\ u}$, T_c may decrease below q_{sed} within the segment. The point where $q_{sed} = T_c$ is determined as x_{db}. This becomes x_u in Eq. [13.5.23] with $D_u = 0$. Deposition and sediment load are then computed from Eqs. [13.5.23], [13.5.24] and [13.5.26].

Case IV occurs when $T_c > q_{sed\ u}$ over the entire segment. Sediment load is then computed with Eq. [13.5.29].

13.6 Summary

The WEPP watershed model is capable of: 1) identifying zones of sediment deposition and detachment within permanent channels or ephemeral gullies; 2) accounting for the effects of backwater on sediment detachment, transport, and deposition within channels; 3) representing spatial and temporal variability in erosion and deposition processes as a result of agricultural management practices; and 4) improving estimates of watershed sediment yield by accurately modeling sediment impoundment effects. It is intended for use on small agricultural watersheds (less than 260 ha) in which the sediment yield at the outlet is significantly influenced by hillslope and channel processes. Model application is constrained by the following limitations: 1) no partial area response; 2) no headcutting; 3) no bank sloughing; and 4) no perennial streams.

13.7 References

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13.8 List of Symbols

Symbol	Definition	Units	Variable
a	channel cross-sectional area	ft^2	-
A_{ch}	channel area	m^2	charea
A_w	watershed area contributing to channel or impoundment	m^2	wsarea
α	dimensionless parameter of the EPIC equation	-	walpha
α_c	initial channel flow alpha	-	walpha
α_h	dimensionless hillslope flow α	-	halpha
α_i	dimensionless impoundment α	-	walpha
α_{er}	first order reaction coefficient in erosion equations	ft^{-1}	-
β	energy coefficient	-	beta
C_1	spatially-varied flow equation constant	-	c1
C_2	spatially-varied flow equation constant	-	c2
C_3	spatially-varied flow equation constant	-	c3
Δx	length of segment where detachment by flow occurs	ft	-
D	detachment/deposition rate	$lbs \cdot ft^{-2} \cdot s^{-1}$	du
D_F	detachment or deposition by flow	$lbs \cdot ft^{-2} \cdot s^{-1}$	-
D_{Fl}	detachment or deposition rate by flow at segment lower boundary	$lbs \cdot ft^{-2} \cdot s^{-1}$	-
D_{Fu}	detachment or deposition rate by flow at segment upper boundary	$lbs \cdot ft^{-2} \cdot s^{-1}$	-
D_L	channel lateral sediment inflow	$lbs \cdot ft^{-2} \cdot s^{-1}$	dlat
D_{Ll}	channel lateral sediment inflow at segment lower boundary	$lbs \cdot ft^{-2} \cdot s^{-1}$	dlat
D_{Lu}	channel lateral sediment in flow at segment upper boundary	$lbs \cdot ft^{-2} \cdot s^{-1}$	dlat
D_u	deposition rate at the upper segment boundary	$lbs \cdot s^{-1}$	du
dur_c	channel event duration	s	watdur
dur_{chan}	duration of channel runoff	s	dur
dur_{irrig}	max. duration of any sprinkler irrigation event contributing to channel runoff	s	irdur
dur_{rof}	effective runoff duration	s	rundur
dur_{runon}	max. runon duration of any watershed element contributing to channel runoff	s	watdur
E_{ch}	soil loss per unit channel length	$lbs \cdot ft^{-1} \cdot s^{-1}$	-
f	Darcy-Weisbach roughness coefficient	NOD	hfric
f_c	volume of water entering the channel	m^3	fhat
f_p	potential infiltration volume capacity	m^3	potinf
f_t	Darcy-Weisbach rill friction factor	NOD	fretrl
γ	weight density of water	$lbs \cdot ft^{-3}$	wtdh20
g	acceleration of gravity	$m \cdot s^{-2}$	accgrav
K_{ch}	erodibility factor	s^{-1}	chnk
l_{OFE}	overland flow element slope length	m	slplen
l_c	channel length of the flow path	m	chleng
l_{eff}	channel effective length	ft	leff

l_s	surface flow slope length	m	hleng
l_{top}	channel top length	ft	top1
lw	watershed length to width ratio	$m \cdot m^{-1}$	lw
n	average Manning's roughness coefficient	-	chmann
n_{bch}	channel Manning's roughness coefficient for bare soil	-	nbarch
n_t	total channel Manning's roughness coefficient	-	nt or chnn
OFE	overland flow element	-	iplane
ϕ	dimensionless parameter	NOD	phi
q	discharge for the computational segment	$ft^3 \cdot s^{-1}$	-
q_a	average runoff depth from contributing area	m	rofave
q_{cf}	final channel runoff dept	m	runoff
q_{ci}	initial channel runoff dept	m	runoff
q_c^*	average flow rate in the channel	$m^3 \cdot s^{-1}$	qcstar
q_l	channel flow rate at the end of computational segment	$ft^3 \cdot s^{-1}$	gl
q_{lat}	channel lateral inflow	$ft^3 \cdot s^{-1}$	latvol
$q_{lat\ eff}$	channel effective lateral inflow	$ft^3 \cdot s^{-1}$	glat
q_o	average surface flow rate	$m^3 \cdot s^{-1}$	-
q_{ph}	hillslope peak runoff rate	$m^3 \cdot s^{-1}$	peakro
q_{pi}	peak runoff rate of watershed element	$m^3 \cdot s^{-1}$	peaksu
q_{pio}	peak runoff rate from impoundment	$m^3 \cdot s^{-1}$	-
q_{po}	peak runoff rate at the outlet of a watershed element	$m^3 \cdot s^{-1}$	peakot
q_s	sediment load	$ft^3 \cdot s^{-1}$	qe
q_{sed}	sediment load	$lbs \cdot ft^{-1} \cdot s^{-1}$	dlat
$q_{sed\ lat}$	average sediment flum entering the channel laterally	$lbs \cdot ft^{-1} \cdot s^{-1}$	dlat
$q_{sed\ top}$	sediment flum entering the channel inlet	$lbs \cdot s^{-1}$	qstu
$q_{sed\ tot}$	total sediment load entering the channel inlet	lbs	-
$q_{sed\ u}$	sediment load at x_u	$lbs \cdot ft^{-1} \cdot s^{-1}$	-
q_t	top inflow rate	$ft^3 \cdot s^{-1}$	qu
q_u	channel inlet discharge rate	$ft^3 \cdot s^{-1}$	-
q_w	discharge per unit width	$ft^3 \cdot s^{-1} \cdot ft^{-1}$	-
R	average rill hydraulic radius	m	hyrad
R_{OFE}	rill hydraulic radius for the OFE	m	hydrad
R_s	channel hydraulic radius due to soils	ft	rsh
r_{tc}	amount of precipitation fallen during time of concentration	m	rtc
r_{24}	daily total precipitation	m	rr
ro_d	runon depth	m	runoff
ro_i	inlet runon volume from upstream hillslopes, impoundments or channels	m^3	rvotop
ro_l	lateral runon volume from hillslopes or impoundments	m^3	rvolat
ro_v	total channel runon volume	m^3	rvolon
rof_c	channel runoff volume before addition of runon	m^3	chnfol
rof_f	final channel runoff volume after addition of runon and reduction due to recession infiltration	m^3	runvol
rof_{fc}	channel inflow from contributing channels	ft^3	runvol
rof_h	hillslope runoff volume	m^3	runvol
rof_i	channel inlet inflow from a contributing impoundment	m^3	-
rof_{io}	impoundment outflow volume	m^3	-

rof_{ii}	impoundment inflow volume	m^3	runvol
S	average channel slope over the flow path	$m \cdot m^{-1}$	chslop
SSF	channel energy grade line	$ft \cdot ft{-}1$	sfe
S_f	channel friction slope	$m \cdot m^{-1}$	ssfe, sf
S_*	dimensionless channel slope	NOD	endslp
$\overline{\tau}$	average shear stress of the channel flow on the soil	$lb \cdot ft^{-2}$	effsh
τ_{cov}	average shear stress of the channel flow on the vegetation	$lb \cdot ft^{-2}$	-
τ_{cr}	critical shear stress	$lb \cdot ft^{-2}$	ersh
T_c	transport capacity	$lbs \cdot ft^{-1} \cdot s^{-1}$	-
T_{cu}	transport capacity at x_u	$lbs \cdot ft^{-1} \cdot s^{-1}$	tcu
t_b	base time of the hydrograph	min	timeb
t_c	time of concentration	h	tc
t_{cc}	average channel travel time	h	tcc
t_{cs}	overland flow time of concentration	h	tcs
t_{ci}	impoundment time of concentration	h	tcf
$t_{cs\ \max}$	maximum time of concentration from contributing hillslopes	h	tcsmx
t_i	duration of inflow entering the impoundment	h	-
t_l	transmission losses volume	m^3	rtrans
t_{lag}	hydrograph lag time	h	-
t_o	duration of outflow from the impoundment	h	-
t_p	time to peak of the SCS hydrograph	min	timep
V_c	channel velocity	$ft \cdot s^{-1}$	v
v	average runoff depth at the channel outlet	in	volume
v_c	average channel flow velocity over the flow path	$m \cdot s^{-1}$	-
v_f	particle fall velocity	$ft \cdot s^{-1}$	-
v_s	surface flow velocity	$m \cdot s^{-1}$	-
w_c	channel width	ft	w
x	downslope distance	ft	x
x_*	dimensionless downslope distance	NOD	astar
x_{db}	point where the sediment load equals the transport capacity	ft	-
x_{de}	point where detachment by flow occurs	ft	-
x_u	distance from the channel top to the computational segment	ft	xu
y	channel flow depth	ft	y
y_*	dimensionless channel flow depth	NOD	-
y_e	channel outlet flow depth	ft	ye
z	inverse side slope of the channel	-	z

Note: NOD stands for nondimensional variable.