

THE WEPP WATERSHED MODEL: I. HYDROLOGY AND EROSION

J. C. Ascough II, C. Baffaut, M. A. Nearing, B. Y. Liu

ABSTRACT. *The Water Erosion Prediction Project (WEPP) watershed scale model is a continuous simulation tool that extends the capability of the WEPP hillslope model to provide erosion prediction technology for small cropland and rangeland watersheds. The model is based on fundamentals of erosion theory, soil and plant science, channel flow hydraulics, and rainfall-runoff relationships, and contains hillslopes, channels, and impoundments as the primary components. The hillslope and channel components can be further divided into hydrology and erosion components. Channel infiltration is calculated by a Green-Ampt Mein-Larson infiltration equation. A continuous channel water balance is maintained, including calculation of evapotranspiration, soil water percolation, canopy rainfall interception, and surface depressional storage. The channel peak runoff rate is calculated using either a modified Rational equation or the equation used in the CREAMS model. 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 equations. Detachment, transport, and deposition within constructed channels or concentrated flow gullies are calculated by a steady state solution to the sediment continuity equation. The impoundment component routes runoff and sediment through several types of impoundment structures, including farm ponds, culverts, filter fences, and check dams. The purpose of this article is to provide an overview of the model conceptual framework and structure. In addition, detailed mathematical representations of the processes simulated by the channel hydrology and erosion components are presented. The processes simulated by the impoundment component are not described in this article, but it does include impoundment effects on watershed model channel peak discharge and time of concentration calculations.*

Keywords. *WEPP, Soil erosion, Watersheds, Modeling, Water quality, Erosion models.*

USDA-Agricultural Research Service (ARS) scientists and engineers initiated the Water Erosion Prediction Project (WEPP) to develop new and improved erosion prediction technology. The technology was to be process oriented, and conceptually a significant enhancement over the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). Therefore, the WEPP model was developed as "new generation water erosion prediction technology for use . . . in soil and water conservation and environmental planning and assessment" (Foster and Lane, 1987). WEPP is based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics (Flanagan et al., 1995). The hillslope or landscape profile application of the model (the fundamental core of the watershed model) provides advantages over existing erosion prediction technology, including: (1) state-of-the-art capability for estimating spatial and temporal distributions of net soil loss (or gain, in the case of deposition) for an entire hillslope or for

discrete points on the hillslope; and (2) the ability to extrapolate over a broad range of conditions that may not be practical or economical to field test (Nearing et al., 1989).

Following the original publication (Lane and Nearing, 1989) and distribution of the WEPP hillslope model in 1989, a substantial number of modifications have been made to increase model applicability/usability and to improve reliability. Most notable among these are the addition of process-based components for sprinkler and furrow irrigation; spatially varying nonuniform overland flow hydrology; winter routines for snow accumulation and density, snowmelt, and soil frost and thaw; and subsurface lateral drainage. The plant growth and residue decomposition components have also undergone major revisions, resulting in improved plant growth and residue tracking. Some of the improvements were contained completely within the computer code and did not require changes in model input [e.g., representation of nonuniform overland flow hydrology (Stone et al., 1992)]. Most modifications, however, required changes in input, either as new variables or in redimensioning the input as well as expansion of output [e.g., the irrigation component (Kottwitz, 1995)]. Other improvements, such as development of the WEPP Interface Programs (Flanagan et al., 1994), were significant enhancements to model usability.

The WEPP watershed model is an extension of the WEPP hillslope model. A beta version of the watershed model was completed in 1991 (Stone et al., 1990; van der Zweep and Stone, 1991), but was not officially released.

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The authors are James C. Ascough II, ASAE Member Engineer, Hydraulic Engineer, USDA-ARS-NPA, Great Plains System Research Unit, Fort Collins, Colo.; Claire Baffaut, Agricultural Engineer, Mark A. Nearing, ASAE Member Engineer, Agricultural Engineer, and Bao-Yuan Liu, Agricultural Engineer, USDA-ARS-MWA, National Soil Erosion Research Laboratory, West Lafayette, Ind. Corresponding author: Dr. James C. Ascough II, USDA-ARS-NPA, GPSRU, 301 S. Howes, P.O. Box E, Fort Collins, CO 80522; tel.: (970) 490-8371; fax: (970) 490-8310; e-mail: <ascough@gpsr.colostate.edu>.

The beta version contained simple empirical equations for prediction of channel transmission losses and peak runoff rates, and did not maintain a continuous water balance for the channels. The watershed model continued to evolve (Ascough et al., 1993a,b) as impoundment routines were added, linkages to the hillslope model became fully operational, channel hydrology was updated using hillslope model hydrology components, and the channel erosion equations were tested and improved.

The WEPP model official CD-ROM delivery release (Version 95.7 or WEPP95; Flanagan et al., 1995) contains hillslopes, channels, and impoundments as the three primary components. The channel and impoundment components encompass the watershed application (estimation of sediment yield from small watersheds) of WEPP. Figure 1 depicts a small example watershed containing the three primary components of the model. The watershed model has also been used for non-agricultural applications to predict sediment yield from surface mine watersheds (Elliot et al., 1993), and large forested areas (Elliot et al., 1996).

This article provides a description of the model conceptual framework and structure, and presents mathematical representations of the processes simulated by the channel hydrology and erosion components. The processes simulated by the impoundment component are not described here, however, impoundment effects on watershed model channel peak discharge and time of concentration calculations are. This article is the first of a three-article series describing and evaluating the WEPP95 watershed model. Baffaut et al. (1997) (article II) analyze the sensitivity of the model to watershed discretization and channel input parameters. Liu et al. (1997) (article III) evaluate model applicability and accuracy for 15 small watersheds from six locations under different climates, topographies, soil types, and cropping management systems.

MODEL DEVELOPMENT

LIMITATIONS

The watershed model was originally intended for use on field-sized areas and conservation treatment units, with a maximum size field limitation of roughly a section (~260 ha) (Foster and Lane, 1987). It was also anticipated that the model could be applied on rangeland watersheds of up to 800 ha (Foster and Lane, 1987), but Baffaut et al. (1997) recommend that the model not be used on

watersheds larger than 40 ha and that hillslope lengths should not exceed 100 m. Basic modifications to the WEPP hillslope model rill erosion equations are required for these restrictions to be removed (Baffaut et al., 1997).

The watershed model is not applicable to areas containing classical gullies or stream channels which may have the following hydrologic or erosion processes: (1) headcut erosion; (2) sloughing of gully sidewalls; (3) seepage effects on erosion in concentrated flow channels; (4) perennial stream channels; and (5) partial area hydrology. The model does not contain a baseflow estimation component, so it cannot be used for stream channel erosion prediction. Furthermore, the watershed model cannot be used for classical gully erosion prediction because it lacks a failure mechanism component for gully sidewall sloughing. However, the model is applicable to constructed waterways (e.g., terrace channels and grassed waterways) and to concentrated flow and cropland ephemeral gullies. In range and forest land applications, fields can include gullies up to the size of typical concentrated flow gullies occurring in cropland fields (channels ranging from 1 to 2 m in width and up to 1 m in depth).

The WEPP watershed technology is designed to be used on personal computers (PCs), and to operate quickly so that complex watersheds can be evaluated in a relatively short period of time. Expected users of the WEPP hillslope and watershed models include all current users of the USLE and the Revised Universal Soil Loss Equation (RUSLE) (Yoder and Lown, 1995; Renard et al., 1997). A comprehensive review of targeted USDA users and expected applications for the watershed model are reported in Foster and Lane (1987).

CONCEPTUAL FRAMEWORK AND STRUCTURE

The WEPP hillslope and watershed models and associated interface programs have been developed and tested on IBM-compatible PCs running under MS-DOS 5.0+ operating system environments (Flanagan et al., 1995). The computer program was developed in a modular fashion, integrating in a top-down design all the specialized modules (program components) which perform the basic computations. This modular structure was designed to facilitate substitution of different components and/or subroutines as improved technology is developed (Flanagan et al., 1995). No restrictions have been imposed on input or internal data storage, with the only storage limitations being hardware capacity. The source code is written in ANSI FORTRAN 77 for efficiency and portability. Work continues on code analysis and reprogramming to a standard coding convention in order to improve WEPP model maintainability and computational performance. Figure 2 presents a flow chart of the major computation blocks and decision sequences in WEPP95.

The WEPP hillslope erosion model first computes soil loss along a slope and sediment yield at the end of a hillslope. Details of the hillslope erosion model are presented by Nearing et al. (1989) and Flanagan et al. (1995) and are summarized here. Overland flow processes are conceptualized as a mixture of broad sheet flow occurring in interrill areas and concentrated flow in rill areas. Interrill erosion is described as a process of soil detachment by raindrop impact, transport by shallow sheet flow, and sediment delivery to rill channels. Rill erosion is

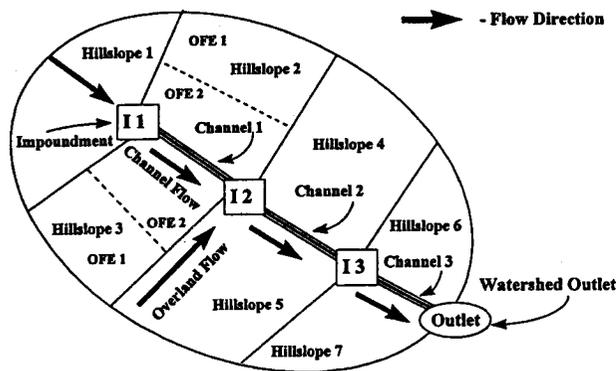


Figure 1—Schematic of a small watershed containing the hillslope (with overland flow elements), channel, and impoundment components of the watershed model.

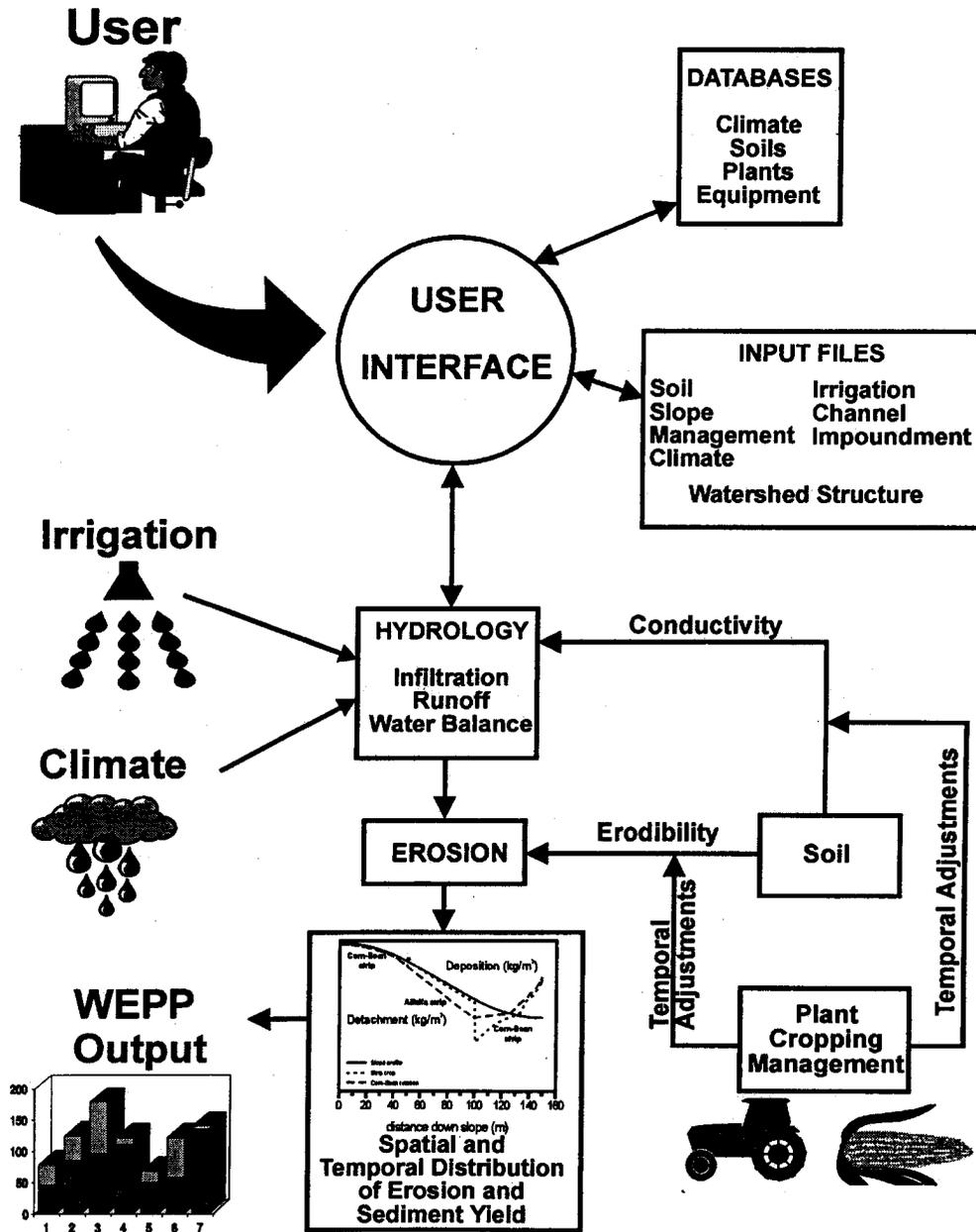


Figure 2—Flow chart of the major computation blocks and decision sequences represented in the WEPP95 erosion model.

described as a function of sediment detachment and transport capacity in rills, and the sediment load in the flow. Overland flow routing procedures include both an analytical solution to the kinematic wave equations and regression equations derived from the kinematic approximation for a range of slope steepness and lengths, surface roughness coefficients, soil textural classes, and rainfall distributions. Once the peak runoff rate and runoff duration have been determined from the overland flow routing, steady state conditions are assumed at the peak runoff rate for erosion calculations. Runoff duration is calculated so as to maintain conservation of mass for total runoff volume. The erosion equations are normalized to the discharge of water and flow shear stress at the end of a uniform slope, and then used to calculate sediment

detachment, transport, and deposition at all segments along the hillslope profile.

The hillslope hydrologic and sediment information required by the watershed model is stored in a pass file and includes: (1) storm duration; (2) overland flow time of concentration; (3) a parameter α that expresses the proportion of total rainfall occurring during overland flow time of concentration; (4) runoff depth; (5) runoff volume; (6) peak runoff rate; (7) total sediment detachment at the end of the hillslope; (8) total sediment deposition at the end of the hillslope; (9) sediment concentration by particle size class at the end of the hillslope; and (10) the fraction of each particle size in the eroded sediment. Only the hydrologic and sediment information from the last hillslope segment is transferred to the watershed model.

The watershed model contains run version flags controlling the application sequence. Run version 1 is the hillslope model alone. Run version 2 executes both the hillslope and watershed models. Hillslope pass files can be created for both run versions 1 and 2. If the hillslope pass files are not present, run version 2 creates them; otherwise the necessary hydrologic and sediment information is read in from existing hillslope pass files. The pass files from each hillslope element are then merged into a hillslope-to-watershed master pass file. Run version 3 reads information from an existing hillslope-to-watershed master pass file and only the watershed model is executed. In other words, version 3 can only be run if version 2 has been run previously for the same watershed and with identical hillslope and climate files.

Watershed configurations are represented by the manner in which hillslope, channel, and/or impoundment elements feed watershed (channel and impoundment) elements, and how the channels and impoundments are fed (either from the top or laterally from the left or right). This is illustrated by the watershed configuration shown in figure 3. This watershed is similar to the example watershed in figure 1, except that the hillslope, channel, and impoundment elements are isolated and numbered. The hillslope model generates hydrologic and sediment output for hillslope elements 1 through 7 and creates a hillslope-to-watershed master pass file. Watershed flow routing begins at the highest upstream watershed element (impoundment element 8, fed by hillslope element 4). Flow routing then continues to the next downstream element (channel element 9, fed by hillslope elements 3 and 5, and impoundment element 8), and proceeds downstream through all of the remaining watershed elements (impoundment elements 10 and 12, and channel elements 11 and 13) until the watershed outlet is reached.

The direction from which upstream elements drain into a channel is always relative to the direction of flow in the channel element. For an impoundment, it is relative to the direction of flow in the next downstream channel. Some restrictions apply to watershed element configuration, including: (1) hillslopes are fed by nothing, and may feed channels and impoundments; (2) channels are fed by hillslopes, other channels, and impoundments, and may

feed other channels and impoundments; and (3) impoundments are fed by channels and hillslopes, and may only feed channels. Further explanation of watershed configuration restrictions can be found in Flanagan and Livingston (1995).

Other information necessary to run the watershed model channel component includes the channel slope, soil, management, climate, and the channel hydraulic characteristics (watershed channel) files. The channel slope, soil, management, and climate files are nearly identical to the corresponding hillslope input files. Information required by the watershed model impoundment component includes an impoundment structures inventory file, and a file containing impoundment characteristics and stage-area-length relationships. A complete description of all watershed input files is given by Flanagan and Livingston (1995). The information needed to run the WEPP watershed model can be built automatically into the required files using the WEPP Interface Programs (Flanagan and Livingston, 1995). A tutorial demonstrating the programs and how to use them is also presented in Flanagan and Livingston (1995).

OVERVIEW OF SIMULATED PROCESSES

The WEPP computer program modeling approach is a combination of process-based modules (components) and physically based empirical relationships. This section lists in general terms the process-based components used in the WEPP hillslope and watershed models. Components added specifically for the watershed model are discussed in detail in later sections of this article. The modeling approach employed to represent agricultural watershed systems in WEPP95 is briefly described by the following sources:

1. Climate simulation, using the CLIGEN weather generator (Nicks et al., 1995).
2. Winter processes, including frost and thaw development in the soil, snow accumulation and snowmelt (Hendrick et al., 1971; Savabi et al., 1995).
3. Sprinkler (solid-set, side-roll, and hand-move) and furrow irrigation systems (Kottwitz, 1995).
4. Water balance, based on the water balance component of the Simulator for Water Resources in Rural Basins (SWRRB) model (Arnold et al., 1990), with some modifications for improving estimation of percolation and soil evaporation parameters (Savabi and Williams, 1995). Redistribution of water within the soil profile is accounted for by the Ritchie (1972) evapotranspiration model and by percolation through soil layers based on a storage routing technique (Williams et al., 1984).
5. Plant growth, as based on the Environmental Policy Integrated Climate (EPIC, formerly Erosion Productivity Impact Calculator) model (Williams, 1995), for predicting biomass accumulation as a function of heat units and photosynthetically active radiation, with potential growth reduced by moisture and temperature stress. Crop growth variables computed in the plant growth model include growing degree days, mass of vegetative dry matter, canopy cover and height, root growth, leaf area index, and plant basal area. The cropland plant growth model accommodates mono, double, rotation, and strip cropping practices.

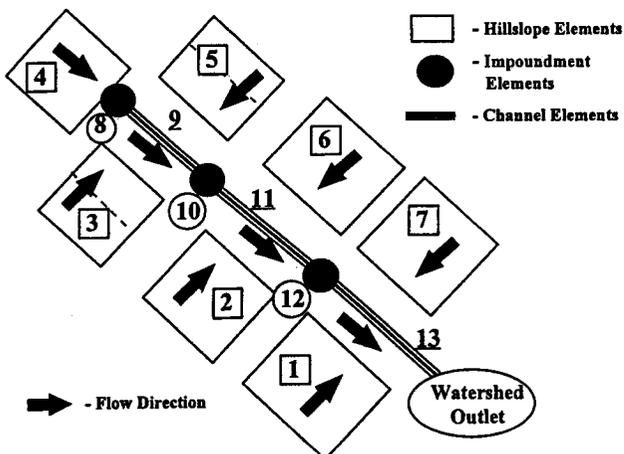


Figure 3—Example of WEPP watershed model flow routing using hillslope, channel, and impoundment elements.

6. Residue decomposition and tracking, for estimating decomposition of dead root mass and flat, standing, and buried residue mass. The decomposition component partitions total residue mass into standing and flat components based upon residue management techniques such as shredding or cutting, burning, and straw harvesting (Stott et al., 1995). Tillage intensity by implement and crop is used as the classification variable to adjust standing and flat residue cover based on the effects of tillage.
7. Soil parameters, and their effects on hydrology and erosion (Alberts et al., 1995). Predicted parameters that influence the hydrology portion of the erosion process include: (a) random surface roughness; (b) ridge height; (c) soil bulk density; (d) wetting-front suction; and (e) effective hydraulic conductivity. These parameters are adjusted for tillage effects, and bulk density is also adjusted for rainfall and weathering consolidation. Predicted soil detachment parameters that directly influence the erosion process include: (a) interrill erodibility; (b) rill erodibility; and (c) critical shear stress. Interrill erodibility is adjusted for the effects of canopy and ground cover, roots, surface sealing and crusting, interrill slope, and freezing/thawing. Rill erodibility is adjusted for the effects of incorporated residue, roots, surface sealing and crusting, and freezing/thawing. Critical hydraulic shear stress is adjusted for the effects of random roughness, surface sealing and crusting, and freezing/thawing.
8. Channel hydrology and water balance (Ascough et al., 1995), as represented by calculations for infiltration, evapotranspiration, soil water percolation, canopy rainfall interception, and surface depressional storage in the same manner as does the hillslope hydrology component for overland flow areas. Rainfall excess is calculated using a Green-Ampt Mein-Larson infiltration equation (Mein and Larson, 1973). The peak runoff rate at the channel (sub-watershed) or watershed outlet is calculated using either a modified Rational equation or the equation used in the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel et al., 1980). A detailed mathematical representation of watershed model channel hydrology processes is presented in the next section of this article.
9. Channel erosion (Ascough et al., 1995), with the assumption that watershed sediment yield is a result of detachment, transport, and deposition of sediment on overland (rill and interrill) flow areas, and permanent channel (limited to grassed waterways, terrace channels or similar sized channels) or ephemeral gully flow areas. 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 movement of suspended sediment (i.e., detachment, transport, and deposition) on rill, interrill, and channel flow areas is based on a steady state erosion model (Foster and Meyer, 1972) that solves the sediment continuity equation. A detailed mathematical representation of

watershed model channel erosion processes is presented in a later section of this article.

10. Impoundment trapping of incoming sediment, thereby reducing sediment yield at the watershed outlet. Impoundments represented in the watershed model include terraces, farm ponds, and check dams. Outflow hydrographs and sediment concentration are calculated for various types of outflow structures suitable for both large (e.g., farm ponds) and small (e.g., terraces) impoundments including culverts, filter fences, straw bales, drop and emergency spillways, and perforated risers. Deposition of sediment in impoundments is calculated assuming complete mixing and later adjusted to account for stratification, non-homogeneous concentrations, and impoundment shape. A continuity mass balance equation is used to predict sediment outflow concentration. The impoundment component performs both hydraulic and sedimentation simulations. The reader is referred to Lindley et al. (1997a,b) for a complete description of the hydraulic and sedimentation processes simulated by the watershed model impoundment component.

MATHEMATICAL REPRESENTATION OF CHANNEL HYDROLOGY PROCESSES

RUNOFF VOLUME

Surface runoff entering a channel is assumed to be the sum of: (1) lateral inflow 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:

$$\text{runoff}_v = \text{runoff}_l + \text{runoff}_i \quad (1)$$

where runoff_v represents total channel inflow volume (m^3); runoff_l is lateral inflow volume from hillslopes or impoundments (m^3); and runoff_i is channel inflow volume from upstream hillslopes, impoundments, or channels (m^3). The total channel inflow volume, runoff_v , is divided by the physical channel area to obtain the channel inflow runoff depth, runoff_d (m).

The storm (event) duration for the channel, dur_c (s), is taken to be the maximum duration of: (1) the storm duration of any watershed element (hillslope, impoundment, or channel) that contributes surface runoff to the channel; (2) the storm duration for the channel itself; or (3) the duration of any sprinkler irrigation event occurring on the channel. Once the channel inflow volume (runoff_v) and depth (runoff_d) are known, channel infiltration, depressional storage, rainfall excess, and transmission losses are calculated. If there is a precipitation event (rainfall, snowmelt, or sprinkler irrigation) for the current day, the precipitation statistics are passed to storm disaggregation routines.

Cumulative channel infiltration is computed using an implementation of the Green-Ampt Mein-Larson (GAML) model (Mein and Larson, 1973), as presented by Chu (1978) for the case of unsteady rainfall and multiple times to ponding. The basis for this implementation can be found

in Stone et al. (1995). Infiltration parameters for the channel are calculated and an average rainfall excess rate for an interval is computed. Rainfall excess is the amount of rainfall that does not infiltrate when rainfall intensity exceeds the infiltration rate. Before the total rainfall excess amount is calculated, the volume is adjusted for soil saturation conditions and depressional storage. The total rainfall excess amount is then computed using the GAML model and treated as the preliminary or initial channel runoff depth, r_{ci} (m).

Following the calculation of r_{ci} , there are four general cases which can arise on a channel that determine the calculation of the final channel runoff depth, r_{cf} (m):

Case I: $r_{ci} > 0$; $runoff_d > 0$. The first case occurs when there is rainfall excess from both the upstream contributing watershed elements and the channel itself. In this case, the channel inflow depth, $runoff_d$, is simply added to the initial channel runoff depth, r_{ci} .

Case II: $r_{ci} > 0$; $runoff_d = 0$. The second case occurs when there is no channel inflow, but rainfall excess, rov_c (m^3), is produced on the channel itself. In this case, r_{ci} remains unchanged.

For Cases I and II, r_{ci} is reduced because of recession infiltration caused by partial equilibrium (flat-topped) hydrographs. The definition of rainfall excess 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, the final channel runoff volume, rov_f (m^3), and depth, r_{cf} , are computed by subjecting r_{ci} to runoff volume reduction caused by infiltration during the hydrograph recession. Transmission losses for Cases I and II are calculated by adding $runoff_v$ and the initial channel runoff volume, rov_c , and then subtracting rov_f (the final channel runoff volume after reduction due to recession infiltration).

Case III: $r_{ci} = 0$; $runoff_d > 0$. The third case occurs when there is channel inflow, but a precipitation event results in no rainfall excess produced on the channel itself. This could occur if channel inflow is due to irrigation but no precipitation or irrigation water is applied directly to the channel. In this case, the channel runoff depth can also be reduced through channel transmission losses. Transmission losses for Case III are computed by first calculating a potential infiltration volume capacity, f_p , and comparing it to the volume of water entering the channel, f_c . The parameter f_p is computed using a Taylor Series expansion approximation of the Green-Ampt model (Stone et al., 1995) and the maximum depressional storage for the channel. Included in f_c is water from a potential daily precipitation event (i.e., rainfall, snowmelt, or sprinkler irrigation). If f_c is less than f_p , then all runoff is assumed to have infiltrated and r_{cf} is set to equal zero. If f_c is greater than f_p , then r_{cf} is calculated as:

$$r_{cf} = \frac{(f_c - f_p)}{a_{ch}} \quad (2)$$

where f_c is the volume of water entering the channel (m^3); f_p is channel potential infiltration volume capacity (m^3); and a_{ch} represents the physical channel area (m^2). The channel transmission loss volume, t_l (m^3), is then calculated with the equation:

$$t_l = runoff_v - (r_{cf} a_{ch}) \quad (3)$$

Case IV: $r_{ci} = 0$; $runoff_d = 0$. The fourth case occurs when there is no channel inflow or rainfall excess on the channel itself. In this case r_{cf} and rov_f are set equal to zero, and no further calculations are necessary.

CHANNEL WATER BALANCE

Channel water balance calculations are performed after channel inflow and outflow have been computed. The channel water balance and percolation routines are identical to those used in the hillslope model 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. A complete description of the WEPP hillslope and watershed model water balance and percolation routines is given by Savabi and Williams (1995).

CHANNEL PEAK RUNOFF RATE

The peak runoff rate entering a channel depends on the configuration of contributing hillslope, channel, and impoundment elements. A maximum of three watershed elements may contribute runoff to a channel element; a mixture of hillslopes, channels, and impoundments is allowed. The peak runoff rate calculations are performed only if the final channel runoff volume (rov_f) is greater than $0.001 m^3$. Otherwise, the peak runoff rate and the runoff duration are set equal to zero and calculations are continued for the next downstream channel or impoundment element. If only one watershed element contributes runoff to a channel, the peak runoff rate entering the channel is set equal to the peak runoff rate leaving the contributing element. For example, if a hillslope is the only watershed element contributing runoff to a channel, then the peak runoff rate entering the channel is the peak runoff rate leaving the final hillslope overland flow element (OFE). The same would be true for a single impoundment contributing runoff to a channel.

The SCS (Triangular) Synthetic Hydrograph method (Huggins and Burney, 1982) is used when runoff from hillslopes, channels and impoundments merges onto a channel or into an impoundment. The time-discharge hydrographs for each watershed element contributing to the channel or impoundment are first calculated. The time-discharge relationship for the combined-element flow hydrograph is then calculated by taking the maximum base time for all element hydrographs and superimposing the hydrographs together over that time period. Finally, the peak runoff rate entering the channel or impoundment is set equal to the largest discharge value on the superimposed hydrograph.

The WEPP watershed model channel component contains two methods for estimating the peak runoff rate at the channel (sub-watershed) or watershed outlet: (1) the modified Rational equation; and (2) the CREAMS peak runoff equation. The modified Rational equation is recommended for estimating peak runoff. The CREAMS peak runoff equation (Smith and Williams, 1980) was statistically derived using data from watersheds much larger than the 40 ha maximum watershed area recommended for watershed model applications. It is expected that for applications to watersheds smaller than

40 ha the modified Rational equation will produce more accurate peak discharge results, although no formal study has been conducted to verify this.

Modified Rational Equation. Implementation of the modified Rational equation in the channel component closely follows 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 at the watershed outlet as in EPIC. The Rational equation can be written as:

$$q_{po} = \frac{\alpha \text{rov}_f}{(3600 t_c)} \quad (4)$$

where q_{po} is peak runoff discharge at the channel or watershed outlet (m^3/s); rov_f is final channel runoff volume (m^3); t_c is the time of concentration at the channel or watershed outlet (h); and 3600 is a time conversion constant.

The dimensionless parameter α expresses the proportion of total rainfall that occurs during t_c , and 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 estimated by adding the overland, channel, and impoundment flow times over the slowest flow path and is given by:

$$t_c = t_{cc} + t_{cs} + t_{ci} \quad (5)$$

where t_{cc} is the average channel travel time (h); t_{cs} is time of concentration for overland flow (h); and t_{ci} is time of concentration for impoundments (h).

Channel Travel Time. Average channel travel time is calculated by applying Manning's equation to a trapezoidal channel with 2:1 side slopes and a 10:1 bottom width-depth ratio. These channel attributes were selected as a reasonable approximation for most field channels and for ease of computation. The resulting equation is similar to the channel travel time equation found in the EPIC model and can be written as:

$$t_{cc} = \frac{0.0004 l_c n_c^{0.75}}{(q_c^*)^{0.25} (S_c)^{0.375}} \quad (6)$$

where l_c is total channel flow length (m); n_c is average channel Manning's n ; q_c^* is average flowrate in the channel (m^3/s); S_c is average channel slope (m/m); and 0.0004 is a units conversion constant.

The values of l_c , n_c , and S_c depend on the position of the channel in the watershed; and the time of concentration of watershed elements contributing to the channel. The program tracks the elements which control, or contribute to, the maximum time of concentration at the channel or watershed outlet. That is, for each channel, the flow route having the longest time of concentration network is known. The total length of the network is l_c . If there is a continuous system of channels (i.e., no impoundments), then n_c and S_c 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 a channel and has a larger time of concentration than other

contributing elements (i.e., the time of concentration is controlled by the impoundment instead of a hillslope or channel element), then n_c and S_c are not spatially averaged and are for that channel only. The same is true for values of n_c and S_c for first order channels.

Time of Concentration for Overland Flow. Time of concentration for overland flow is calculated by applying Manning's equation to a flow path down the slope length and assuming flow through a 1 m wide trapezoidal channel with 1:1 side slopes and a 5:1 bottom width-depth ratio.

These channel attributes were selected as a reasonable approximation for most field channels and for ease of computation. The resulting equation is similar to the overland flow time of concentration equation found in the EPIC model, and may be written as:

$$t_{cs} = \frac{0.0216 (l_s n_s)^{0.75}}{(q_o)^{0.25} (S_s)^{0.375}} \quad (7)$$

where l_s is surface slope length (m); n_s is average surface Manning's n ; q_o is average surface flow rate (m^3/s); S_s is average land surface slope (m/m); and 0.0216 is a units conversion constant.

Time of Concentration for Impoundments. Time of concentration for impoundments is calculated using the relationship (Huggins and Burney, 1982):

$$t_{ci} = \frac{t_{lag}}{0.6} \quad (8)$$

where t_{lag} represents the impoundment hydrograph lag time (h); and 0.6 is an empirical constant.

For impoundments, t_{lag} is calculated using the equation:

$$t_{lag} = \left(\frac{t_o}{2}\right) - \left(\frac{t_i}{2}\right) \quad (9)$$

where t_o is the duration of outflow from the impoundment (h); and t_i is the duration of inflow entering the impoundment (h).

The duration of outflow from the impoundment, t_o , can be computed as:

$$t_o = \frac{\left(\frac{\text{rov}_i}{q_{pi}}\right)}{\left(\frac{2}{3600}\right)} \quad (10)$$

where rov_i is the impoundment inflow volume (m^3); q_{pi} represents the impoundment peak outflow rate (m^3/s); and 3600 is a time conversion constant. Substituting equations 9 and 10 into equation 8 gives the final impoundment time of concentration, t_{ci} (h):

$$t_{ci} = \frac{\left[\frac{\left(\frac{rov_i}{q_{pi}} \right)}{\left(\frac{2}{3600} \right)} - \left(\frac{t_i}{2} \right) \right]}{0.6} \quad (11)$$

Time of Concentration for the Channel or Watershed Outlet. If the channel is a first order channel, and one or more hillslopes contribute runoff to the channel, the channel time of concentration is computed with the equation:

$$t_c = t_{cc} + t_{cs \max} \quad (12)$$

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

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

$$t_{ci} = \max(t_{cs \max}, t_{ci}) \quad (13)$$

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

$$t_c = t_{cc} + t_{ci} \quad (14)$$

The program tracks the flow routing network having the largest time of concentration 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 runoff 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 runoff (inflow) to the channel. The average channel travel time, t_{cc} , is then calculated as for first order channels, with the exception that the values for n_c and S_c may or may not be spatially averaged as previously discussed. The generalized time of concentration for higher order channels is given by equation 5. If a hillslope controls the time of concentration, t_{ci} will be zero. If an impoundment controls the time of concentration, t_{cs} will be zero. The average channel travel time, t_{cc} , must be calculated for each channel.

Dimensionless Parameter α . The dimensionless parameter α , used in the Rational equation, is required for calculating the peak runoff rate. For hillslopes, α is obtained by using the Rational equation in the following form:

$$\alpha_h = \frac{(3600 t_{cs} q_{ph})}{rov_h} \quad (15)$$

where α_h is the dimensionless overland flow α ; q_{ph} is peak runoff rate leaving the last hillslope OFE (m^3/s); rov_h is runoff volume leaving the last hillslope OFE (m^3); and 3600 is a time conversion constant.

For channels, the peak discharge at the channel outlet, q_{po} (eq. 4), is an unknown. Therefore, a preliminary or initial α is first calculated using the relationship:

$$\alpha_c = \frac{r_{tc}}{r_{24}} \quad (16)$$

where α_c is the initial dimensionless channel α ; r_{tc} is the precipitation amount during the time of concentration of the channel (m); and r_{24} represents the 24 hour precipitation amount (m). For impoundments, α is calculated in the same manner as for hillslopes:

$$\alpha_i = \frac{(3600 t_{ci} q_{pi})}{rov_{io}} \quad (17)$$

where α_i is the dimensionless impoundment α ; rov_{io} is runoff volume leaving the impoundment (m^3); and 3600 is a time conversion constant.

The final α used for the peak runoff calculation (eq. 4) is the maximum of the α s of the watershed elements contributing to the channel and the α calculated for the channel itself:

$$\alpha = \max(\alpha_h, \alpha_c, \alpha_i) \quad (18)$$

where α is the dimensionless final α used for peak runoff calculation.

CREAMS Equation. The CREAMS peak runoff equation (Smith and Williams, 1980) is the second method for calculating the peak runoff rate at the channel outlet in the WEPP watershed model. The equation was statistically derived using data from watersheds with areas ranging from 70 to 6200 ha. The peak discharge at the channel or watershed outlet is calculated with the equation:

$$q_{po} = (7.172e - 04) a_w^{0.7} s^{0.159} (39.37v)^{0.71764} (A_w^{0.0166})_{lw}^{-0.187} \quad (19)$$

where q_{po} is peak discharge at the channel outlet (m^3/s); a_w represents watershed area contributing to the channel (m^2); s is the average land surface slope (m/m); v is average runoff depth at the channel outlet (m); lw is a dimensionless watershed length to width ratio; and 7.172e-04 and 39.37 are unit conversion constants.

The CREAMS peak runoff equation may produce acceptable results on watersheds approaching the 40 ha maximum area recommended for watershed model applications, however, the Rational equation should be used until modifications are made to the hillslope model rill erosion equations that will allow longer overland flow lengths, and consequently larger watershed areas to be modeled.

EFFECTIVE RUNOFF DURATION

After the peak discharge at the channel or watershed outlet is calculated, an effective runoff duration is calculated as:

$$\text{dur}_{ro} = \frac{rov_f}{q_{po}} \quad (20)$$

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

MATHEMATICAL REPRESENTATION OF CHANNEL EROSION PROCESSES

The WEPP watershed model channel erosion routines have been adapted and modified from the CREAMS model channel component (Knisel, 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 of 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, diversions, row middles or graded rows, tail water 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), the incoming lateral load (from adjacent hillslopes and impoundments), and the ability of the flow to detach and transport channel bed material or soil particles. The flow detachment rate is proportional to the differences between the flow shear stress exerted on the bed material and the critical shear stress, and depends on the transport capacity of the flow and the sediment load. Net detachment occurs when the flow shear stress exceeds the critical shear stress of the soil or channel bed material and the sediment load is less than the transport capacity. Net deposition occurs when sediment load is greater than transport capacity. For channel erosion computations, the channel reach (element) 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 within a channel element are assumed to have identical parameter values (e.g., Manning's roughness coefficient). A non-erodible layer having an initial depth and width is assumed to exist at some depth below the bottom of the channel. Within ephemeral gullies, detachment is assumed to occur initially from the channel bottom until the non-erodible layer (usually the primary tillage depth) is reached. Once the channel encounters the non-erodible 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.

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 length. 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. As an alternative, the user can set the friction slope equal to the channel slope. When there is no lateral inflow, the spatially varied flow equations (Foster et al., 1980) do not apply and the friction slope is automatically set equal to the channel slope. The flow depth at the end of the channel is estimated by assuming one of the following outlet controls: (1) critical flow; (2) normal (uniform) flow; or (3) a calculated depth using a rating curve relationship. The flow depth is also used to compute the friction slope at the channel outlet using 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, rectangular, 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 the friction slope does not equal the bed slope. Such deposition is not uncommon, and is important in estimating sediment yields associated with the enrichment of fine sediment during deposition. 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.

EFFECTIVE CHANNEL LENGTH

The general case for concentrated flow in a field situation is a channel of length l_{ch} with an upstream inflow rate q_t and a lateral inflow rate q_l along the channel reach. The upstream inflow rate, q_t , is equal to the peak runoff rate (discharge), q_{po} , of the upstream contributing watershed element(s). The channel lateral inflow rate can be calculated with the equation:

$$q_l = \left(\frac{rov_f}{\text{dur}_{ro}} \right) - q_t \quad (21)$$

where q_l is the initial channel lateral inflow rate (L^3/T); and q_t is the channel inlet inflow rate (L^3/T).

The upstream 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} , is the length of channel required to produce the channel outlet discharge, q_{po} , 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, l_{eff} is computed as:

$$l_{\text{eff}} = l_{\text{ch}} \left(1.0 + \frac{q_l}{q_i} \right) \quad (22)$$

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

$$q_u = q_{\text{po}} \frac{l_{\text{top}}}{l_{\text{eff}}} \quad (23)$$

where q_u represents discharge at channel inlet (L^3/T). The effective lateral inflow rate, q_{lat} (L^2/T), used for the lateral sediment inflow calculations is then calculated as:

$$q_{\text{lat}} = \frac{q_{\text{po}}}{l_{\text{eff}}} \quad (24)$$

If the initial lateral inflow rate, q_l , is zero, then q_u is set equal to q_{po} and q_{lat} is set equal to zero. After the initial calculations for q_u and q_{lat} are performed, the discharge rate at the lower end of each computational segment, q_{ls} (L^3/T), can be calculated as:

$$q_{\text{ls}} = q_{\text{po}} \frac{x}{l_{\text{eff}}} \quad (25)$$

where x is the segment downslope distance from the top of the channel (L). 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_{ls} ; (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_{ch} , to compute sediment yield for the channel.

EFFECTIVE SHEAR STRESS

Once the slope of the energy gradeline has been calculated, the effective shear stress of the flow for channels having triangular, rectangular 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. Using sediment transport theory (Graf, 1971), total shear is divided into that acting on the vegetation or mulch and that acting on the soil. Foster et al. (1980) give the equations used for calculating average shear stress of the flow in the channel acting on the soil and vegetation. 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.

SEDIMENT LOAD

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

$$\frac{dq_{\text{sed}}}{dx} = D_L + D_F \quad (26)$$

where q_{sed} is the sediment load ($M/L/T$); D_L is the lateral sediment inflow ($M/L^2/T$); and D_F is detachment or deposition by flow ($M/L^2/T$). The assumption of quasi-steady state allows deletion of time terms from equation 26. All sediment load (detachment, transport, and deposition) calculations are done for each 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, $q_{\text{sed top}}$ (M/T), can be calculated as:

$$q_{\text{sed top}} = \frac{q_{\text{sed tot}}}{\text{dur}_{\text{ro}}} \quad (27)$$

where $q_{\text{sed tot}}$ is the total sediment load at the channel inlet (M).

Because the channel erosion equations use a single lateral sediment inflow rate, the sediment discharges from any lateral contributing watershed elements 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 $q_{\text{sed lat}}$ (M), the average sediment flux entering the channel laterally on a length basis. If there is no lateral inflow $q_{\text{sed lat}}$ 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, soil particles are added to the flow having the same particle size distribution for detached sediment given as input. These concepts are explained in greater detail in the following section.

SEDIMENT 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 rate at which concentrated flow detaches soil particles from the soil matrix and potential sediment load at the lower boundary of the channel segment are computed. The detachment capacity, D_c ($M/L^2/T$), is described with the equation:

$$D_c = K_{ch} (\bar{\tau} - \tau_{cr}) \quad (28)$$

where K_{ch} is an erodibility factor ($1/T$); $\bar{\tau}$ is average shear stress (M/L^2); and τ_{cr} is the critical shear stress below which erosion is negligible (M/L^2).

Until the channel reaches the non-erodible layer, an active channel of rectangular shape is assumed to erode at the rate:

$$E_{ch} = w_c K_{ch} (\bar{\tau} - \tau_{cr}) \quad (29)$$

where E_{ch} represents soil loss per unit channel length ($M/L/T$); and w_c is channel width (L).

It should be noted that equations 28 and 29 are not the CREAMS equations for detachment capacity and channel erosion, but rather are similar to the WEPP hillslope model rill erosion equations. Once the channel reaches the non-erodible 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) describe the equations used for channel widening after the non-erodible layer is reached.

The sediment transport capacity for each particle size class, based upon the potential sediment load, is computed using the Yalin sediment transport equation (Yalin, 1963). A complete description of the transport capacity calculations is presented by Foster et al. (1980). 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 total 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 one percent of the transport capacity or until 20 iterations have been made. Upon completion of the iterative 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:

$$D_r = \alpha_{er} (T_c - q_{sed}) \quad (30)$$

where D_r is the deposition rate ($M/L^2/T$); α_{er} is a first-order reaction coefficient ($1/L$); T_c is transport capacity ($M/L/T$); and q_{sed} is sediment load ($M/L/T$). The parameter α_{er} can be estimated from:

$$\alpha_{er} = \frac{v_f}{q_w} \quad (31)$$

where v_f is particle fall velocity (L/T); and q_w represents discharge per unit width ($L^3/L/T$). The particle fall velocity, v_f , is estimated assuming standard drag

relationships for a sphere of a given diameter and density falling in quiescent water (Foster et al., 1980).

The potential sediment load and transport capacity at the lower boundary of the segment are then computed. Net detachment or net deposition may occur, meaning that within each channel segment four different detachment-deposition limiting cases are possible:

Case I: Net deposition at the upper boundary and net deposition at the lower boundary (deposition may occur over the entire segment).

Case II: Net deposition at the upper boundary and net detachment by flow at the lower boundary may occur when transport capacity increases within the segment.

Case III: Net detachment by flow at the upper boundary and net deposition at the lower boundary may occur when transport capacity decreases in a segment.

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. 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 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.

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 for that 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 are computed. If net deposition does not occur anywhere within the 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 are 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 is equal to the transport capacity, and the point within the channel segment where detachment ends and deposition begins is computed.

SUMMARY

The USDA Water Erosion Prediction Project (WEPP) watershed model is a process-based, continuous simulation model built as an extension of the WEPP hillslope model. The model was developed to predict erosion effects from agricultural management practices and to accommodate topographic, soil type, and land use variability within small cropland and rangeland watersheds.

Overland flow hydrologic and sediment output (e.g., runoff volume, peak runoff rate, and sediment

concentration) is linked to channel and impoundment components, allowing water and sediment from one or more hillslopes to be routed through a field-scale watershed system. The watershed model is capable of: (1) identifying zones of sediment transport, deposition and detachment within constructed channels (grassed waterways or terraces) or concentrated flow (ephemeral) gullies; (2) simulating backwater flow conditions for channels with heavy vegetation or for channels with a restricted outlet such as a weir or ridge; (3) accounting for the ability of impoundments such as farm ponds, filter fences, and check dams to trap incoming sediment, thereby reducing sediment yield at the watershed outlet; and (4) representing spatial and temporal variability in erosion and deposition processes as a result of agricultural management practices. It is applicable at the small watershed scale (up to 40 ha) where the sediment yield at the outlet is significantly influenced by hillslope and channel processes.

Additional important features of the WEPP watershed model include: (1) the ability to spatially and temporally simulate hillslope erosion for an entire hillslope or for discrete points on the hillslope; (2) process-based descriptions of hillslope and channel water balance, plant residue decomposition, and crop growth, including daily updating of explicit relationships between surface conditions (e.g., roughness, canopy and residue cover etc.) and infiltration/erosion parameters (e.g., Green-Ampt effective hydraulic conductivity and interrill/rill erodibility); (3) the integration and use of the well-known CREAMS channel erosion equations; (4) the flexibility to evaluate small watersheds quickly by running the watershed model as a standalone version (using hydrologic and sediment information from the hillslope-to-watershed master pass file); and (5) the ability to rapidly and accurately assemble watershed input files using the graphically based WEPP Interface Programs. WEPP may be obtained from the USDA National Soil Erosion Research Laboratory (NSERL) home page on the World Wide Web (WWW) through a WWW browser with the URL path name <http://soils.ecn.purdue.edu/~wepp/wepp.html>.

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