Adapting Wepp (Water Erosion Prediction Project) for Forest Watershed Erosion Modeling

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Abstract: Recently, there has been an increasing public concern for forest stream pollution by excessive sedimentation resulting from human activities. Adequate and reliable erosion simulation and prediction tools are urgently needed for sound forest resources management. Computer models for predicting watershed runoff and erosion have been developed during the past. These models, however, are often limited in their applications due to limited understanding and inappropriate representation of the hydrological processes involved. The Water Erosion Prediction Project (WEPP) watershed model has demonstrated its usefulness in certain forest applications such as modeling erosion from a segment of insloped or outsloped road, harvested units, and burned units. Nevertheless, when used for modeling water flow and sediment discharge from a forest watershed of complex topography and channel systems, WEPP consistently underestimates these quantities, in particular, the water flow at the watershed outlet. The main purpose of this study is to improve the WEPP watershed model such that it can be applied to adequately simulate forest watershed hydrology and erosion. The specific objectives are to: (1) identify and correct WEPP algorithms and subroutines which inappropriately represent forest watershed hydrologic processes; and (2) verify the modified model. In modifying the WEPP model, changes were primarily made in the approach to, and algorithms for modeling deep percolation of soil water and subsurface lateral flow. The modified model was then applied to a conceptual forest watershed in the Pacific Northwest with local data. The modeling results were compared with those obtained by using the original model. Conclusions of this study include: (1) compared to the original model, the modified WEPP more realistically and properly represents the hydrologic processes in a forest setting; and (2) application of the modified model to the conceptual watershed produced satisfactory results, demonstrating the adequacy of the model modifications.
Keywords: watershed, WEPP model, surface and subsurface runoff, soil erosion, hydraulic conductivity

1 Introduction

Recently, there has been an increasing public concern for forest stream pollution by excessive sedimentation resulting from human activities. Adequate and reliable erosion simulation and prediction tools are urgently needed for sound forest resources management. Computer models for predicting watershed runoff and erosion have been developed during the past. These models, however, are often limited in their applications due to limited understanding and inappropriate representation of the hydrological processes involved (Klemes, 1986). The Water Erosion Prediction Project (WEPP) watershed model, a physically-based erosion prediction software developed by the US Department of Agriculture, has demonstrated its usefulness in such forest applications as modeling erosion from a segment of insloped or outsloped road, harvested or burned units of simple geometry (Morfin *et al*., 1996; Elliot and Hall, 1997; Tysdal *et al*., 1997). Nevertheless, when used for forest watersheds of complex topography and channel systems, WEPP consistently underestimates subsurface runoff and water discharge at the watershed outlet (J. Boll and R. Foltz, personal communication, 2001).

The WEPP watershed model, an extension of the WEPP hillslope model (Nearing *et al*., 1989; Laflen *et al*., 1997), was originally developed to evaluate the erosion effects of agricultural management practices, spatial and temporal variability in topography, soil properties, and land use conditions within small agricultural watersheds (Ascough *et al*., 1995). Forestlands, on the other hand, are typified by steep slopes, and shallow, young, and coarse-grained soils, differing remarkably from common croplands. In addition, the presence of dense canopy cover further differentiates forest from cropland, urban, and rangeland with respect to the rates and combinations of individual hydrologic processes (Luce, 1995). WEPP may be a reasonable tool in quantifying runoff and erosion from agricultural fields. For forest watershed applications, however, the model needs to be modified to properly represent the hydrologic processes involved. Fig. 1 illustrates the differences in characteristics of hydrologic processes in agricultural and forest settings.

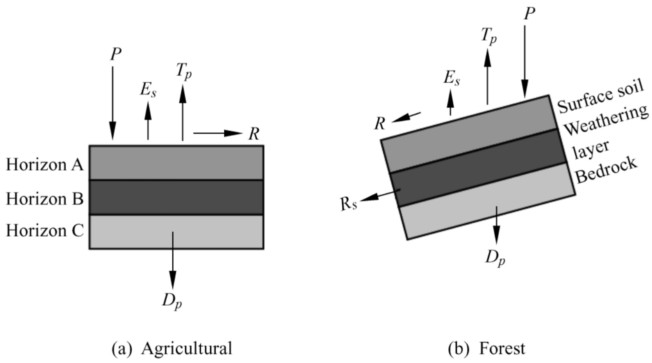

Fig. 1 Diagram showing the difference in the rate of hydrologic processes between typical agricultural (a) and forest (b) settings. The size of the arrows reflects the relative magnitude or rate of the individual processes. *P*, precipitation, T_p, plant transpiration, E_s, soil evaporation, *R*, surface runoff, R_s, subsurface runoff, D_p, deep percolation.

The main purpose of this study is to improve the WEPP watershed model such that it can be used to simulate and predict forest watershed hydrology and erosion. The specific objectives are to: (1) identify and correct WEPP algorithms and subroutines that inappropriately represent forest watershed hydrologic processes; and (2) verify the modified model by applying it to a conceptual forest watershed and comparing the modeling results with those obtained from using the original model.

2 Methods

2.1 Model description

The WEPP watershed model contains three major components: hillslope, channel, and impoundment. For completeness, the major functions and hydrologic and erosion processes included in these components summarized from Ascough and Livingston (1995) and Flanagan *et al*. (1995) are presented below.

The hillslope component of WEPP is divided into nine sub-components: climate generation, winter processes, irrigation, surface hydrology and water balance, subsurface hydrology, soils, plant growth, residue decomposition, overland-flow hydraulics, and erosion. Daily or single-storm climate can be generated for the WEPP model with CLIGEN, the random climate generator (Nicks *et al*., 1995). The winter processes account for soil frost and thaw development, snowfall and snow melting. The irrigation sub-component simulates stationary sprinkler and furrow irrigation systems. The surface hydrology and water balance routines use information on weather, vegetation and cultural practice, and maintain a continuous balance of the soil water on a daily basis. Infiltration is computed by a Green-Ampt Mein-Larson equation (Mein and Larson, 1973). Actual ET is evaluated by using a modified Ritchie's model (Ritchie, 1972), with reference potential ET estimated from the Penman (1963) equation or Priestly-Taylor (1972) method depending on the availability of wind and humidity data. Rainfall interception by canopy, surface depressional storage, soil water percolation, and subsurface runoff (lateral flow) are also considered. The subsurface hydrology routines compute lateral flows following a mass continuity approach developed by Sloan and Moore (1984). The soil sub-component assesses effects of tillage on various soil properties. The plant growth routines calculate biomass production for both crops and rangeland plants. The plant residue decomposition routines model common residue management practices and the change of residue with time. The overland-flow hydraulics sub-component performs overland flow routing based on the solutions to the kinematic wave equations or their approximations. In addition, this sub-component estimates hydraulic properties as affected by surface soil and vegetation cover conditions. The erosion sub-component estimates interrill and rill erosion, with the former treated as soil detachment by raindrop impact and subsequent sediment delivery to rills, and the latter a function of sediment detachment and transport capacity of concentrated flow, and the load already in the flow.

The channel component of the WEPP watershed model consists of channel hydrology and erosion. Channel hydrology routines simulate hydrologic processes and compute water balance in the same way as the hillslope hydrology routines, and generate hydrograph by combining channel runoff with the runoff from upstream watershed elements, i.e., hillslopes, channels or impoundments. The channel erosion routines predict soil detachment and deposition similar to the hillslope erosion routines. Watershed sediment yield is taken as a result of the detachment, transport, and deposition of sediment on both overland- and channel-flow areas. The major function of an impoundment is to trap sediment and reduce sediment yield. Impoundments generally include culverts, filter fences, straw bales, drop and emergency spillways, rock-fill check dams, and perforated risers. The impoundment component of the WEPP model calculates outflow hydrographs and sediment concentration for the impoundment structures.

WEPP uses pass files to transfer information between different model components. Upon completion of the execution of hillslope routines, information on surface runoff hydrograph and sediment graph are stored in hillslope pass files and are then incorporated into a watershed master pass file for use by the channel and impoundment components. Information on subsurface runoff generated from either a hillslope or a channel, however, is not saved.

2.2 WEPP modification

From the preceeding model description, the subsurface runoff calculated in the WEPP hillslope component is not included in the hillslope and watershed pass files, meaning that subsurface runoff is not incorporated in the channel flow that ultimately discharges at the watershed outlet. On the other hand, WEPP's hillslope component tends to substantially overestimate deep percolation and underestimate subsurface runoff for several reasons. First, WEPP allows the saturated hydraulic conductivity (K_{sat}) to be input for the surface soil layer only. The model estimates K_{sat} for the remaining layer(s) using empirical functions of soil properties, in particular, the percentages of clay and sand. All these empirical equations lead to a minimum K_{sat} no less than 2.1 H 10^{-8} m • s^{-1} even under extreme conditions, e.g., zero percent of sand content or a clay content of 100 percent, and a CEC (cation exchange capacity) value as high as 50. Such a treatment of K_{sat} may be reasonable for agricultural lands with relatively uniform and deep soils or with subsurface drainage systems, but is perhaps invalid for most forest settings where soils are shallow and have low-permeability bedrock underneath. Without subsurface drain pipes installed to intercept percolated soil water, an overestimated K_{sat} value for the deeper soil layers simply signifies an overestimated deep percolation.

Second, WEPP assumes that the modeled soil profile is isotropic, i.e., the horizontal and vertical K_{sat} values are equal. This assumption, again, may be adequate for many agricultural fields but inadequate for forestland where the layered structure of porous soil lying on top of low-permeability bedrock creates higher horizontal hydraulic conductivity and greater lateral flow. Last, in evaluating hillslope hydrologic processes, WEPP first estimates and adjusts for soil water percolation. If soil water content is greater than the water content at field capacity (2_{fc}), deep percolation starts and is removed from the soil profile. Afterwards, if the soil water content is still greater than 2_{fc}, WEPP calculates the lateral flow following Darcy's law using the internally estimated K_{sat} adjusted for the present soil water content. In reality, deep percolation and lateral flow take place simultaneously. Modeling the two processes in sequence apparently causes errors.

To correct WEPP's problem of overestimation of deep percolation, we added a line in the soil input file providing information for a "restricting" layer at the bottom of a soil profile. The modified code allows a user to choose whether or not to use the restricting layer with a character variable (solflag) in the soil input file. When solflag = 0, no restricting layer is assumed and WEPP uses the original algorithms to estimate K_{sat} for deeper soil layers; otherwise, the restricting layer is assumed and the following methods are used to determine the K_{sat} value for this restricting layer. If there exists an in-situ field measurement or a reliable estimation of K_{sat}, the user may provide the value. Otherwise, the user can simply specify the underlying bedrock and have WEPP assign the vertical K_{sat} value internally. In either case, the K_{sat} in the horizontal direction will be increased by 10 times by referring to Domenico and Schwartz (1997). The general types of bedrock included in the modified WEPP code are those given by Domenico and Schwartz (1997), representing the most commonly occurring sedimentary and crystalline rocks. For these rocks, the vertical K_{sat} values range from 3 H 10^{-14} m • s^{-1} for unfractured igneous and metamorphic rocks to 3 H 10^{-2} m • s^{-1} for gravel.

As mentioned earlier, in the original WEPP code, only surface runoff information, labeled as "EVENT", is stored and passed to the watershed master pass file. To include the subsurface runoff information in the hillslope and watershed pass files, two different methods are used, and for both it was assumed that, due to its slow rate and after undergoing natural filtration, subsurface runoff is essentially clear and contains no sediment. In the first method, when both surface runoff and subsurface runoff occur in a day, the surface runoff is assumed to dominate the water flow and sediment transport processes, and the subsurface runoff, in regard to volume, is simply added to the surface runoff without changing the sediment amount in it. This approach is consistent with field observations, and a preliminary analysis of WEPP simulation results which indicate that surface runoff occurs much less frequently than subsurface runoff but it can produce much more flow than subsurface runoff on an event basis. The second method deals with situations when only subsurface runoff occurs. In the new WEPP code, subsurface runoff event is also recorded in the hillslope pass file, with a label "SUBEVENT". This information is then transferred to the watershed master pass file by a WEPP subroutine (WSHPAS) which has been modified for handling subsurface events also. Accordingly, another subroutine (WSHRED) is modified such that it can properly read the information stored in the watershed master pass file, and then pass the information to the channel or impoundment model component for subsequent calculations.

Another important change made was the newly added subroutine (SUBEVENT). In the original WEPP model, the channel or impoundment component cannot route flow when there is no storm, irrigation, or surface runoff event occurring. SUBEVENT was thus created to route subsurface runoff under these conditions. Generally, the total volume of subsurface runoff generated by an upstream hillslope is assumed to be evenly distributed along the channel and water balance is calculated by the existing WEPP channel hydrologic routines. As mentioned earlier, compared to surface runoff that often occurs within a short duration at a high intensity, subsurface runoff tends to last much longer at a much lower rate. Therefore, the subsurface runoff itself would contain little sediment. Upon entering a channel, however, the subsurface runoff adds to the channel flow, increasing the transport capacity of the channel and potential channel erosion. Hence, the modified WEPP would generally be expected to predict higher channel erosion than the original model.

Finally, modification was made to add a new output file to record daily runoff from individual hillslope and channel elements and net discharge at the watershed outlet. The new output file enables easy comparison of WEPP-predicted and field-observed hillslope and watershed hydrograph for future studies.

2.3 Model verification

The modified WEPP watershed model was applied to a hypothetical Pacific Northwest forest watershed. The watershed is composed of three hillslopes and one channel, with a total area of 6.54 ha. Hillslopes 1 and 2 are on the left and right sides of the channel respectively, and Hillslope 3 is on the top of the channel. Dimensions of the hillslopes and the channel are given in Table 1.

Major WEPP input includes climatic, soil, slope, and management practice data. The climate data consists of a 10-year (1986—1995) record for St. Maries, Idaho, generated by the CLIGEN program embedded in WEPP. Soil data were prepared by referring to the soil database developed by the Rocky Mountain Research Station, US Department of Agriculture Forest Service. The soil data describe a sandy loam, typical for the forests in the region. Minor changes were made to reflect the differences in soil

Table 1　Dimensions of the components of the hypothetical watershed used in model verification

	Hillslope 1	Hillslope 2	Hillslope 3	Channel
Number of OFE†	1	2	3	N/A
Length of Element, m	200	250	300	90
Width of Element, m	90	90	80	10
Area of Element, m^2	18,000	22,500	24,000	900

† OFE, overland flow element, a region of homogeneous soil, cropping, and management practice.

properties between the channel and hillslopes. Several key soil hydraulic and erosion parameters for the three hillslopes were also assigned slightly different values for algorithm verification purposes. The broadly distributed basalt bedrock in this region was set as the restricting layer, with a K_{sat} value of 1.0 H 10^{-9} m • s^{-1}. The slope files for the three hillslopes and the channel differed to a varying extent yet all were representative of the forest slope conditions in the Pacific Northwest. A management file representing 20 year-old forest settings was used for the entire watershed.

In addition to the basic climate, soil, slope and management files, a watershed structure file and a channel file respectively describing the layout of the watershed elements and the configuration of the channel were also prepared. Multiple preliminary runs with the refined WEPP model and the input data described above were first made in order to determine the sensitivity of the crucial model outputs, in particular runoff and erosion, to model inputs. Certain key input parameters, e.g., the optimum temperature for tree growth, were further adjusted to best represent forest conditions. Model runs with both the original WEPP and the modified WEPP were then carried out.

3　Results and discussion

Annual runoff and erosion predictions for 1994 (the wettest year in the 10 year series, precipitation 855.6 mm compared to the 10 year average of 746.0 mm) and 10 year average annual values by the original and refined WEPP model are shown in Tables 2 and 3. Note that the subsurface runoff obtained from the original model was estimated from the water balance output because the original code lacked the functions to output subsurface runoff.

Table 2　Predicted runoff and erosion for 1994†

	Hillslope 1	Hillslope 2	Hillslope 3	Watershed Outlet
Surface runoff, m^3	213.3 (257.8)	322.5 (320.8)	288.1 (271.1)	874.0 (22,721.6)
Lateral flow, m^3	104.8 (6,521.7)	57.8 (8,037.3)	28.3 (9,033.0)	--‡
Sediment yield, kg	2,154.1 (2,100.6)	601.4 (659.4)	978.3 (888.7)	4,200 (5,200)

† Shown are predictions from the original WEPP and the modified WEPP (in parentheses and in bold face).

‡ The subsurface runoff at the watershed outlet is essentially the subsurface runoff generated by the watershed's main channel. It does not discharge at the watershed outlet and is not reported.

Table 3　10 year (1986—1995) average annual runoff and erosion†

	Hillslope 1	Hillslope 2	Hillslope 3	Watershed Outlet
Surface runoff, m^3	73.2 (94.9)	72.1 (97.9)	119.5 (113.7)	232.0 (14,838.4)
Lateral flow, m^3	41.3 (284.3)	33.4 (5,193.0)	10.8 (5,999.9)	--†
Sediment yield, kg	1,269.5 (2,379.1)	372.9 (698.5)	724.7 (697.4)	2,200 (4,800)

† Shown are predictions from the original WEPP and the modified WEPP (in parentheses and in bold face).

‡ The subsurface runoff at the watershed outlet is essentially the subsurface runoff generated by the watershed's main channel. It does not discharge at the watershed outlet and is not reported.

Tables 2 and 3 indicate that surface runoff values, depending mainly on climatic, vegetation and surface soil conditions, were predicted similarly by the original and modified WEPP. However, subsurface runoff from the modified model was much higher than from the original model. The water balance output revealed that the deep percolation from using the modified model was much lower than from the original model, indicating the soundness of the model modification. The slight to moderate differences in surface runoff and sediment yield predicted respectively by the original and modified WEPP were caused by the addition of the restricting layer. The restricting layer impedes deep percolation, which in turn leads to changes in transient soil water status and thus changes in the infiltration and surface runoff processes. Both water flow and sediment discharge at the watershed outlet predicted by the modified WEPP were significantly higher than those predicted by the original model. The increase in water discharge was a direct result of increases in subsurface runoff originated from the three hillslopes. The increase in sediment yield, on the other hand, is primarily a consequence of the increased channel transport capacity. K_{sat} for basalt ranges 4.2 H 10^{-7}—2.0 H 10^{-11} m • s^{-1} (Domenico and Schwartz, 1997). The use of an intermediate K_{sat} value of 1.0 H 10^{-9} m • s^{-1} in this study yielded roughly 30% of precipitation as runoff, which is a reasonable result.

Summary

Reliable models for predicting water flow and sediment discharge from forest watersheds are needed in forest management. WEPP, a process-based, continuous erosion prediction model, was adapted for forest watershed applications. Modifications were made in the approach to, and algorithms for, modeling deep percolation of soil water and subsurface lateral flow. The refined WEPP model has the ability to adjust water distribution between the deep percolation and subsurface lateral flow through a restricting layer specified by the user. Further, it is capable of transferring subsurface runoff from the hillslopes to watershed channels, and then routing it to the watershed outlet. Compared to the original model, the modified model represents the hydrologic processes in forest settings more realistically and properly. Application of the modified model produced reasonable results, demonstrating the adequacy of the model modifications. Efforts are currently being devoted to evaluating the suitability of the modified WEPP for applications to forest watershed under a wide range of climatic, plant and soil conditions.

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