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

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1. Introduction

Due to elevated public concerns of forest stream pollution by excessive sedimentation caused by human activities, there is an increasing need in forest management for prediction tools which can provide accurate information about sedimentation from hillslopes to streams and rivers. Yet most quantitative methods for evaluating sedimentation are limited by a poor understanding of the hydrological processes involved (Klemes, 1986). The Water Erosion Prediction Project (WEPP) watershed model, a computer-implemented, physically-based, distributed-parameter erosion prediction software developed by the U.S. Department of Agriculture, has demonstrated its usefulness in such forest applications as modeling erosion from a segment of insloped or outsloped road, harvested units, and burned units (Morfin et al., 1996; Elliot and Hall, 1997; Tysdal et al., 1997). However, when used for modeling flow and sediment discharges from a forest watershed of complex topography and channel systems, WEPP consistently underestimates these quantities, in particular, the flow discharge at the watershed outlet (J. Boll and R. Foltz, personal communication, 1999).

The WEPP watershed model, built as an extension of the WEPP hillslope model (Nearing et al., 1989; Laflen et al., 1991, 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 II et al., 1995). Forestlands, typified by steep slopes, and shallow, young, and coarse-grained soils, are highly different from common croplands. As a result, hydrologic processes in forest settings exhibit significantly different characteristics than in agricultural land uses (Luce, 1995). Hence, WEPP may prove to be a reasonable tool in quantifying surface runoff and soil erosion from agricultural fields; however, for forest watershed applications, the model needs to be modified and refined. Fig. 1 illustrates the differences in the rates and combinations of hydrologic processes in agricultural and forest settings.

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 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

For completeness, a brief description of the WEPP watershed model (version 98.4) structure and major Hydrologic and erosion processes simulated summarized from Ascough II et al. (1995) is presented below. Interested readers are recommended to refer to the original reference for details.

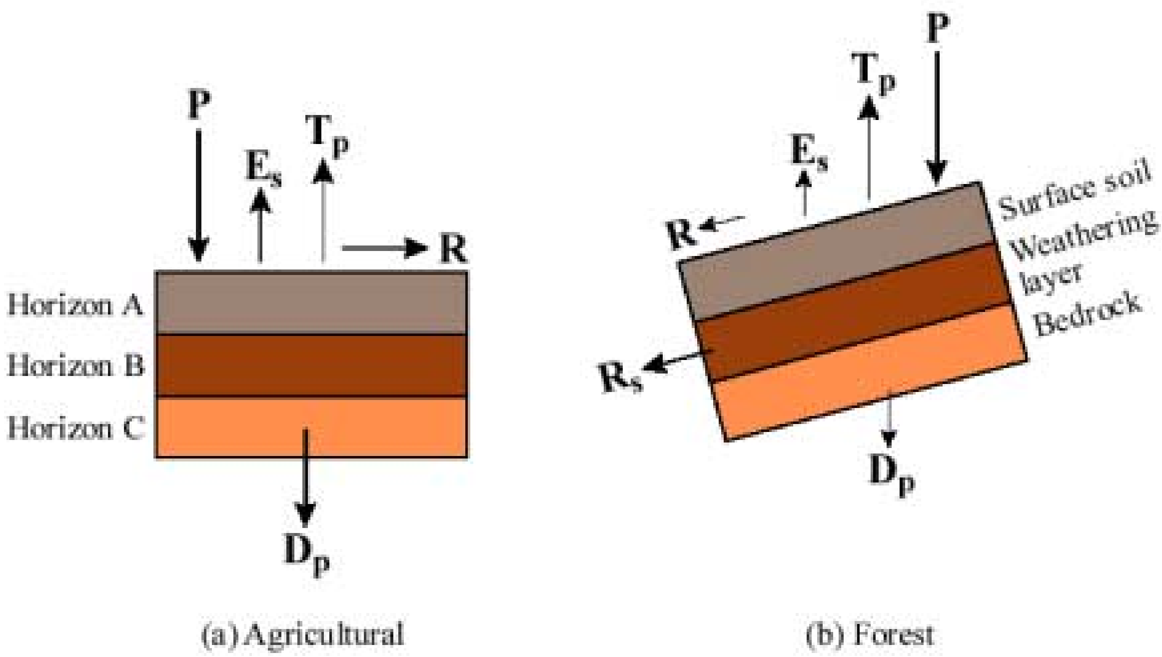

Fig. 1. Diagram showing the difference in hydrologic processes between typical agricultural (a) and forest (b) settings. The sizes of the arrows reflect the relative magnitudes or rates of the individual processes.

The WEPP watershed model contains three major components: hillslope, channel, and impoundment. The hillslope component computes rainfall excess by a Green-Ampt Mein-Larson infiltration equation (Mein and Larson, 1973); peak runoff rate by kinematic wave overland flow routing or simplified regression equations; evapotranspiration (ET) based on a modified Ritchie's model [*Ritchie*, 1972]; 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 sediment load present in the flow. Canopy rainfall interception, surface depressional storage, soil water percolation, and subsurface runoff (lateral flow) are also calculated. Important hillslope hydrologic and erosion outputs, including storm duration, surface hydrograph and sediment graph parameters, are stored in hillslope pass files and then incorporated into a watershed master pass file for use by the channel and impoundment components. The channel component simulates hydrologic processes in the same manner as the hillslope hydrology component, while it considers watershed sediment yield as a result of detachment, transport, and deposition of sediment on both overland flow and channel flow areas. The movement of suspended sediment on overland flow and channel flow areas is described by the steady-state model of Foster and Meyer (1972). Detachment, transport, and deposition within channels are estimated by a steady-state solution to the sediment continuity equation. The impoundment component calculates outflow hydrographs and sediment concentrations for various types of outflow structures such as culverts and rock dams.

2.2. WEPP Modification

From the WEPP watershed model description, it is apparent that subsurface runoff calculated in the WEPP hillslope component is not stored in the hillslope pass file and thus not incorporated in the channel component hydrologic calculation. On the other hand, WEPP hillslope component tends to significantly overestimate soil water deep percolation and underestimates subsurface runoff for three main reasons. First, WEPP allows the saturated hydraulic conductivity (K_{sat}) to be input for only the surface soil layer. The model then estimates K_{sat} for the remaining layers using empirical functions of soil properties, in particular, the percentages of clay and sand. Such a treatment may be reasonable for agricultural soils which are deep and relatively uniform, but is invalid for most forest settings where soils are shallow and often have low-permeability bedrock underneath. An overestimated K_{sat} value for the deeper soil layers leads to overestimated deep percolation. Second, WEPP assumes the modeled soil profile to be isotropic, i.e., the horizontal and vertical K_{sat} values are equal, which again may be adequate for common agricultural fields but inadequate for forest lands where the layered structures with porous soil lying on top of low-permeability bedrock signifies considerably higher horizontal hydraulic conductivity and greater lateral flow. Third, in evaluating hillslope hydrologic processes, WEPP first estimates and adjusts for soil water percolation on a daily basis. If the soil water content is greater than the water content at field capacity (θ_{fc}), the surplus water becomes deep percolation and is removed from the system. Afterwards, if the soil water content is still greater than θ_{fc}, WEPP calculates the lateral flow following Darcy's law with its internally estimated K_{sat} adjusted for the present soil water content. In reality, deep percolation and lateral flow should take place simultaneously, and modeling the two processes in sequence apparently leads to errors. For all these reasons, WEPP generally underestimates the lateral flows from upstream hillslopes to a channel and in turn underestimates the channel erosion, and thus the total flow and sediment discharges at the watershed outlet.

The problem of overestimation of deep percolation and underestimation of subsurface runoff was corrected by adding an extra character variable in the last line of the original WEPP soil input file. This variable serves as a flag signaling whether or not to use the last soil layer specified in the soil input file as a restricting bedrock layer. If this restricting layer is to be used, both the vertical and horizontal hydraulic conductivity values of the bedrock layer will be assigned internally by the modified model based on the type of bedrock according to Domenico and Schwartz (1997).

In order to be able to transfer the information about subsurface runoff and sediment generated from hillslopes to channel or impoundment elements, the original WEPP code for creating pass files (both hillslope and watershed master pass files) was modified. Presently we assume that, due to its slow rate and after undergoing the natural cleansing, subsurface runoff is clear and contains no sediment.

In the original WEPP hillslope pass files, only surface runoff information is stored and labeled as "EVENTS". To include the subsurface runoff information, two methods are used for two different situations. First, if both surface and subsurface runoff occurs within the same day, the subsurface runoff is simply added to the surface runoff without changing the sediment amount in the surface runoff. This treatment stemmed from both our field experiences and the preliminary analysis of WEPP simulation results, which indicate that surface runoff events occur much less frequently but produce much more flow than subsurface runoff events. Second, when only subsurface runoff occurs in a day, the event is recorded in the hillslope pass file with a name "SUBEVENT". This information will be transferred into the watershed master pass file by a WEPP subroutine (WSHPAS), which has been modified to be able to treat a "SUBEVENT". Accordingly, another WEPP subroutine (WSHRED) was 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 component for subsequent calculations.

As the original channel component was not designed to route flow when there is no storm and surface runoff event, a new subroutine (SUBEVENT) was created for routing the subsurface runoff through a channel. The total volume of subsurface runoff is assumed to be evenly distributed in the channel and water balance is calculated by the existing WEPP channel hydrologic component. We further assume that the channel erosion caused by the longer lasting and lower flow-rate subsurface runoff (as compared to surface runoff) is negligible. Thus a "SUBEVENT" will contribute neither to hillslope erosion nor channel erosion. The latter part of this assumption can be problematic and future modification may be needed.

2.3. Model Verification

Watershed Configuration

The modified WEPP model was applied to a hypothetical Pacific Northwest forest watershed, which is composed of three hillslopes and one channel and with a total area of 4.73 ha. Hillslopes 1 and 2 are on the left and right sides of the channel respectively, and Hillslope 3 is on top of the channel. Dimensions of the hillslopes and the channel are presented in Table 1.

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

Watershed Element/ Geometric dimension	Hillslope 1	Hillslope 2	Hillslope 3	Channel
Width, m	200	200	90	2.5
Length, m	100	80	120	200
Area, m^2	20,000	16,000	10,800	500

Model Input Data

<u>Climate</u> A 11-year (1980–1990) climate file for St. Maries, ID, was generated by CLIGEN, a random climate generator imbedded in WEPP (Nicks et al., 1995). Preliminary analysis of WEPP simulation results

indicate that a normal planting date in April implies absence of vegetation prior to this planting date on the modeled watershed, which in turn leads to a year with extreme water budget values (e.g., excessively low plant transpiration and excessively high subsurface runoff). For such a reason, a 11-year climate record was generated but the first year's results should be taken cautiously.

Soil Information on forest soil with a sandy loam texture was obtained from the soils database developed by the USDA Forest Service Rocky Mountain Research Station. For both the hillslopes and the channel, the majority of the soil inputs are the same except K_{sat} and total soil depth, with the two taking slightly higher values for the channel. The vertical K_{sat} of basalt and an anisotropy ratio of 10 were used based on Domenico and Schwartz (1997).

Slope The slope files for the three hillslopes and the channel differ slightly yet all are representative of the forest conditions.

Management The same management file representing 20-year old forest conditions was used for the whole watershed.

Others A watershed structure file and a channel file, describing the layout of the watershed elements and the configuration of the channel respectively, were also prepared.

Model Runs

Model runs with the aforementioned input data were made using both the original WEPP watershed model and the modified model.

3. Results and Discussion

Annual hillslope runoff and erosion predictions for 1989 (the wettest year, precipitation 855.6 mm compared to the 11-year average annual precipitation of 745.2 mm) and 11-year annual average values by using the original and modified WEPP model are shown in Tables 2 and 3. Note that the total subsurface runoff was calculated from the water balance output files for each hillslope. Annual discharges of water and sediment from the watershed outlet for year 1989 and the 11-year mean values are presented in Tables 4 and 5. A comparison of subsurface runoff generated for Hillslope 1 for year 1989 by using the modified and the original WEPP watershed model is shown in Fig. 2.

Tables 2 and 3 indicate that while surface runoff values predicted by the original and modified model are similar, subsurface runoff by the modified model is much higher than that by the original model. From the water balance output (not shown in this paper), the deep percolation from using the modified model is much lower than from the original model, indicating the soundness of the model modification. The slight difference between surface runoff and sediment yield values predicted by the original and modified model respectively is a result of the addition of the restricting layer. The restricting layer changes deep percolation, which in turn leads to changes in temporal soil water status, and thus changes in the infiltration process and the occurrence of surface runoff. Tables 4 and 5 show that the sediment discharges from the watershed outlet predicted by the original and modified WEPP are similar. Yet the water discharge predicted by the modified WEPP is much higher than that by the original model. The increase in delivery ratio is attributed to the increased amount of channel flow and the ability to transport sediment. Fig. 2 demonstrates that the modified WEPP produced more days with subsurface runoff for Hillslope 1, which is consistent with the field observation that subsurface base flow oftentimes lasts from a few days to several weeks after a storm event.
Table 2. Hillslope runoff and soil erosion for year 1989.

Hillslope/	1		2		3	
WEPP Output	Original	Modified	Original	Modified	Original	Modified
Surface runoff, m^3	207.2	205.8	163.2	161.3	44.7	43.8
Lateral flow, m^3	104.8	635.4	57.8	355.4	28.3	188.9
Sediment yield, kg	1,679	1,661	210	201	4	2

Table 3. 11-year annual average hillslope runoff and soil erosion.

Hillslope/	1		2		3	
WEPP Output	Original	Modified	Original	Modified	Original	Modified
Surface runoff, m^3	79.8	86.7	63.0	72.9	20.1	30.0
Lateral flow, m^3	41.3	284.3	33.4	157.6	10.8	82.6
Sediment yield, kg	616	619	124	123	23	23

Table 4. Water and sediment discharges from watershed outlet for year 1989.

WEPP Output	Original	Modified
Water discharge, m^3	333.0	1130.1
Sediment yield, t	2.00	2.01
Unit area yield, t/ha	0.423	0.425
Delivery ratio	0.872	0.883

Table 5. 11-year annual average water and sediment discharges from watershed outlet.

WEPP Output	Original	Modified
Water discharge, m^3	141.0	498.9
Sediment yield, t	0.90	0.92
Unit area yield, t/ha	0.190	0.195
Delivery ratio	0.908	0.926

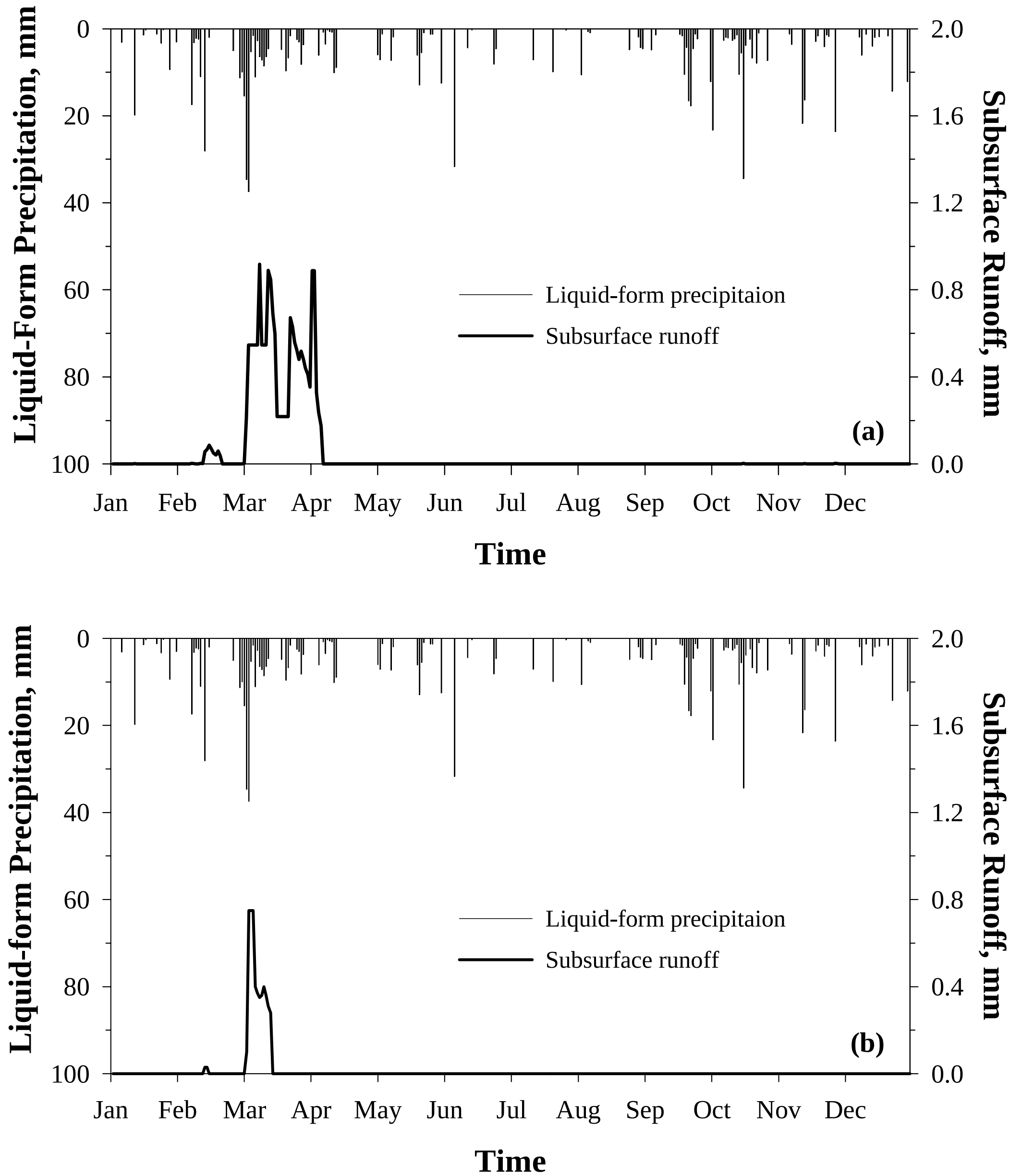

Fig. 2. Comparison of subsurface runoff generated for Hillslope 1 for year 1989 by using (a) the modified and (b) the original WEPP watershed model.

4. Summary and Conclusions

Reliable computer models for predicting flow and sediment discharges from forest watersheds are needed in forest management. The USDA's WEPP model, 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 modified model was applied to a conceptual Pacific Northwest forest watershed using 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 model represents the hydrologic processes in forest settings more realistically and properly.
(2) Application of the modified model produced satisfactory results, demonstrating the adequacy of the model modifications.
(3) Model validation based on real stream flow and sedimentation data from forest watersheds is needed in the future.

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References

Ascough II, J.C., C. Baffaut, M.A. Nearing, and D.C. Flanagan, 1995. Watershed model channel hydrology and erosion processes. In USDA Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation, edited by D.C. Flanagan and M.A. Nearing. Ch. 13. *NSERL Rep., 10*. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN, 1995.

Domenico, P.A., and F.W. Schwartz, 1997. *Physical and Chemical Hydrogeology*. 2nd Ed. pp. 39–40. John Wiley & Sons, Inc., New York.

Elliot, W.J., and D. Hall, 1997. WEPP Forest Applications. General Technical Report (Draft). USDA Intermountain Research Station, Moscow, ID.

Foster, G.R., and L.D. Meyer, 1972. A closed-form soil erosion for upland areas. In Sedimentation: Symposium to Honor Professor H.A. Einstein, edited by H.W. Shen. Ch. 12. pp. 12.1–12.9. Ft. Collins, CO.

Klemes, V., 1986. Dilettantism in hydrology: Transition or destiny? *Water Resour. Res.*, 22, 177–188.

Laflen, J.M., L.J. Lane, and G.R. Foster, 1991. WEPP - A next generation of erosion prediction technology. *J. Soil Water Conserv.*, 46, 34–38.

Laflen, J.M., W.J. Elliott, D.C. Flanagan, C.R. Meyer, and M.A. Nearing, 1997. WEPP-Predicting water erosion using a process-based model. *J. Soil Water Conserv.*, 52, 96–102.

Luce, C.H., 1995. Forests and wetlands. In *Environmental Hydrology*, edited by A.D. Ward and W.J. Elliot. pp. 253–283. Lewis Publishers, Boca Raton.

Mein, R.G., and C.L. Larson, 1973. Modeling infiltration during a steady rain. *Water Resour. Res.*, 9, 384–394.

Moffin, S., W.J. Elliot, R. Foltz, and S. Miller, 1996. Predicting effects of climate, soil, and topography on road erosion with WEPP. *ASAE Pap.* 96-5016. Am. Soc. of Agric. Eng., St. Joseph, MI.

Nearing, M.A., G.R. Foster, L.J. Lane, and S.C. Finkner, 1989. A process-based soil erosion model for USDA-water erosion prediction project technology. *Trans. ASAE*, 32, 1587–1593.

Nicks, A.D., L.J. Lane, and G.A. Gander, 1995. Weather generator. In USDA Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation, edited by D.C. Flanagan and M.A. Nearing. Ch. 2. *NSERL Rep., 10*. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN, 1995.

Ritchie, J.T., 1972. A model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.*, 8, 1204–1213.

Tysdal, L., W.J. Elliot, C. Luce, and T. Black, 1997. Modeling insloping road erosion processes with the WEPP watershed model. *ASAE Pap*. 97-5014. Am. Soc. of Agric. Eng., St. Joseph, MI.