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Adapting the Water Erosion Prediction Project (WEPP) model for forest applications

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SUMMARY

There has been an increasing public concern over forest stream pollution by excessive sedimentation due to natural or human disturbances. Adequate erosion simulation tools are needed for sound management of forest resources. The Water Erosion Prediction Project (WEPP) watershed model has proved useful in forest applications where Hortonian flow is the major form of runoff, such as modeling erosion from roads, harvested units, and burned areas by wildfire or prescribed fire. Nevertheless, when used for modeling water flow and sediment discharge from natural forest watersheds where subsurface flow is dominant, WEPP (v2004.7) underestimates these quantities, in particular, the water flow at the watershed outlet.

The main goal of this study was to improve the WEPP v2004.7 so that it can be applied to adequately simulate forest watershed hydrology and erosion. The specific objectives were to modify WEPP v2004.7 algorithms and subroutines that improperly represent forest subsurface hydrologic processes; and, to assess the performance of the modified model by applying it to a research forest watershed in the Pacific Northwest, USA.

Changes were made in WEPP v2004.7 to better model percolation of soil water and subsurface lateral flow. The modified model, WEPP v2008.9, was applied to the Hermada watershed located in the Boise National Forest, in southern Idaho, USA. The results from v2008.9 and v2004.7 as well as the field observations were compared. For the period of 1995–2000, average annual precipitation for the study area was 954 mm. Simulated annual watershed discharge was negligible using WEPP v2004.7, and was 262 mm using WEPP v2008.9, agreeable with field-observed 275 mm.

Introduction

Many areas of the world depend on forest watersheds as sources of high-quality surface water for domestic supply, industrial use, and agricultural production (Dissmeyer, 2000). There is increasing public concern over forest stream pollution by excessive sedimentation resulting from forest management activities. Adequate erosion simulation tools are needed for sound forest resource management. The Water Erosion Prediction Project (WEPP) model (Flanagan et al., 2001), a physically-based erosion prediction software program developed by the US Department of Agriculture (USDA), has proved useful in areas where Hortonian flow dominates, e.g., in forest applications of modeling erosion from insloped or outsloped roads, or harvested or burned areas by wildfire or prescribed fire (Elliot et al., 1999; Elliot and Tysdal, 1999; Elliot, 2004; Robichaud et al., 2007). In most natural forests, however, subsurface lateral flow and channel flow are predominant (Luce, 1995). When used under such forest conditions, WEPP (v2004.7) underestimates subsurface lateral flow and discharge at the watershed outlet (Elliot et al., 1995).

WEPP was intended to be applied to agriculture, rangelands and forests (Foster and Lane, 1987). Runoff generation was by the mechanism of rainfall-excess described by the modified Green-Ampt infiltration model (Mein and Larson, 1973; Chu, 1978). Recently, scientists have increasingly realized that rainfall-excess is not the only runoff-generation mechanism that influences forest hydrology and erosion (Elliot et al., 1996; Covert, 2003). Forest lands are exemplified by steep slopes, and young, shallow, and coarse-grained soils, differing markedly from typical agricultural lands. In addition, forest canopy and residue covers differ from those in crop- and rangelands causing the rates and combinations of individual hydrologic processes to differ (Luce, 1995). Fig. 1 illustrates the differences in major characteristics of hydrologic processes in agricultural and forest settings. WEPP is a reasonable tool in quantifying runoff and erosion from typical agricultural

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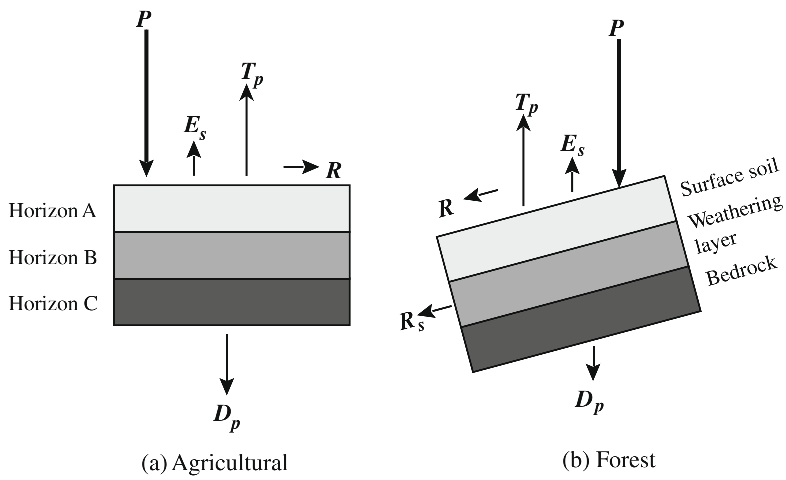

Fig. 1. Diagram showing the difference in primary hydrologic processes between typical (a) agricultural soil profile and (b) forest setting. The size of the arrows reflects the relative magnitude or rate of the individual processes: *P*, precipitation; T_p, plant transpiration; E_s, soil evaporation;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

fields (Laflen et al., 2004). For forest watershed applications, however, the model needs to be modified to properly represent the hydrologic processes involved. Covert et al. (2005), in an application of WEPP for simulating runoff and erosion on disturbed forest watersheds, emphasized the need for adequately representing lateral flow processes in WEPP.

The main purpose of this study was to improve the WEPP (v2004.7) watershed model such that it can be used to simulate and predict forest watershed hydrology and erosion. The specific objectives were to identify and improve WEPP (v2004.7) subroutines for subsurface lateral flow process; and to assess the performance of the modified model by applying it to a typical forested watershed in the US Pacific Northwest.

Method

Model description

WEPP partitions a watershed into hillslopes and a channel network that includes channel segments and impoundments. Overland flow from hillslopes feeds into the channel network. A hillslope can be further divided into overland-flow elements (OFEs), within which soil, vegetation, and management conditions are assumed homogeneous. A recently developed geo-spatial interface, GeoWEPP, allows the use of digital elevation models (DEMs) to generate watershed configurations and topographic inputs for the WEPP model (Renschler, 2003). Important functions and routines in WEPP are summarized below after Flanagan et al. (1995).

The hillslope component of WEPP simulates the following processes: surface hydrology and hydraulics, subsurface hydrology, vegetation growth and residue decomposition, winter processes, and sediment detachment and transport. The surface hydrology routines use information on weather, vegetation and management practices, and maintain a continuous balance of the soil water on a daily basis. The hydraulics routine performs overland-flow routing based on the solutions to the kinematic wave equations, and adjusts hydraulic properties with changes in soil and vegetation conditions. The subsurface hydrology routines compute lateral flows following Darcy's law. The vegetation growth and residue decomposition routines calculate biomass production and residue decomposition under common management practices. The winter routines simulate soil frost-thaw, snow accumulation and melt. The erosion routines estimate interrill and rill erosion as well as sediment transport in channels. The channel component consists of channel hydrology and erosion. Channel hydrology routines generate hydrographs by combining channel runoff with the surface runoff from upstream watershed elements, i.e., hillslopes, channels or impoundments. The channel erosion routines simulate soil detachment from channel bed and bank due to excess flow shear stress through downcutting and widening as well as sediment transport and deposition.

Simulation of subsurface water flow in WEPP

WEPP conceptualizes a hillslope as a rectangular strip with a representative slope profile and multiple OFEs (Cochrane and Flanagan, 2003). Rainfall excess, in intervals of minutes, is calculated as the difference between rainfall rate and infiltration estimated using a modified Green-Ampt- Mein–Larson equation (Mein and Larson, 1973; Chu, 1978), with rainfall interception in the canopy and residue as well as surface depression storage taken into consideration. Overland flow rate on an OFE is determined from the average rainfall excess of the immediately upstream, consecutively feeding OFEs weighted by their lengths. Redistribution of infiltrated water, including evapotranspiration (ET), percolation, and subsurface lateral flow, is simulated within each OFE on a daily basis. Transmission of subsurface lateral flow is between two adjacent OFEs.

Within an OFE, a soil profile can be divided into layers of 10 cm for the top two (for better description of surface conditions, e.g., tillage effect) and 20 cm for the remainder. Soil physical properties for each layer, such as saturated hydraulic conductivity (K_s), field capacity (θ_{fc}) and plant wilting point (θ_{wp}) (considered as the soil water content θ at matric potential of about 30 kPa and 1.5 MPa, respectively), are estimated using the soil texture input. WEPP allows a user to define an effective saturated hydraulic conductivity for the top two soil layers, which is adjusted for tillage practices and soil consolidation, and is used in the Green-Ampt- Mein–Larson infiltration equation.

WEPP simulates percolation (Q_p) when soil water content exceeds field capacity. The amount is calculated using the unsaturated hydraulic conductivity (estimated from K_s, θ, θ_{fc}, and θ_{wp}) and available water for percolation in the current (*i*th) soil layer as well as the degree of saturation of the layer below ($i+1$th).

$$Q_p = vv_i\sqrt{1-S_{i+1}}[1-\exp(-\Delta t/t_i)] \quad (1a)$$
$$vv_i = (\theta_i - \theta_{fci})d_i \quad (1b)$$
$$S_{i+1} = \frac{\theta_{i+1}-\theta_{wpi+1}}{\phi_{i+1}-\theta_{wpi+1}} \quad (1c)$$
$$t_i = \frac{\theta_i - \theta_{fci}}{K_{ui}} \quad (1d)$$
$$K_{ui} = K_{si}S_i^{-2.655\log\left[\frac{\theta_{fci}-\theta_{wpi}}{\phi_i-\theta_{wpi}}\right]} \quad (1e)$$

Where Δt (s) is time interval, and Q_p (m s^{-1}), S_i [−], θ_i (m^3 m^{-3}), θ_{fci} (m^3 m^{-3}), θ_{wpi} (m^3 m^{-3}), ϕ_i (m^3 m^{-3}), d_i (m), K_{si} (m s^{-1}), K_{ui} (m s^{-1}), vv_i (m), and t_i (s) are percolation, degree of saturation, soil water content, field capacity, wilting point, porosity, soil thickness, saturated hydraulic conductivity, unsaturated hydraulic conductivity, available water for percolation, and travel time of percolating water of the ith soil layer, respectively. S_{i+1} [−], θ_{i+1} (m^3 m^{-3}), θ_{wpi+1} (m^3 m^{-3}), and ϕ_{i+1} (m^3 m^{-3}) are degree of saturation, soil water content, wilting point, and porosity of the $i+1$th soil layer, respectively.

Percolation through the last layer is considered as deep percolation that leaves the model domain, and is estimated following Eq. (1) except that the degree of saturation for the media below this bottom layer is set to zero.

WEPP next estimates evapotranspiration (ET) from the soil. WEPP calculates soil evaporation and plant transpiration separately. Potential ET is estimated using the Penman (1963) method when wind data are available. Soil water is withdrawn when residue and plant rainfall interception cannot fulfill the potential ET. The potential soil evaporation is a fraction of the potential ET based on the fraction of uncovered soil. Actual soil evaporation is assumed to take place only in the top soil layer, and is estimated using the Ritchie's (1972) model. WEPP assumes that ET is solely from plant transpiration when the plant leaf area index (LAI) exceeds three. Potential plant transpiration is calculated as a fraction of total potential ET using one third of the plant LAI. Water is withdrawn from the soil layers in the root zone when plant rainfall interception is insufficient to satisfy potential plant transpiration. Water uptake from the soil profile is estimated using the following equations (Flanagan and Nearing, 1995)

$$U_i = U_{pi} \quad \theta_i > \theta_{ci} \quad (2a)$$
$$U_i = U_{pi}\frac{\theta_i}{\theta_{ci}} \quad \theta_i < \theta_{ci} \quad (2b)$$
$$U_{pi} = \frac{E_p}{1-e^{-c}}[1-e^{(ch_i/h_{rz})}] - \sum_{j=1}^{i-1} U_j \quad (2c)$$

where U_i (m s^{-1}), U_{pi} (m s^{-1}), h_i (m), θ_i (m^3 m^{-3}), and θ_{ci} (m^3 m^{-3}) are, respectively, actual water uptake, potential water uptake, depth of the soil layer, soil water content, and critical soil water content below which plant growth is subject to water stress for the ith layer; h_{rz} (m) is the depth of the root zone, c is a parameter for plant uptake distribution; and E_p is potential plant transpiration.

In the WEPP model, subsurface lateral flow is simulated when soil water content in a layer exceeds its drainable threshold defined as field capacity corrected for entrapped air. Subsurface lateral flow is calculated from Darcy's law using unsaturated hydraulic conductivity of the draining layer and the average surface gradient across the OFE as follows:

$$R_s = K_l S_p \frac{D_d}{L} \quad (3a)$$
$$D_d = \Sigma d_i \quad (3b)$$
$$K_l = \frac{\Sigma(d_i K_{ui})}{D_d} \quad (3c)$$

where R_s (m s^{-1}) is subsurface lateral flow, K_l (m s^{-1}) is the equivalent lateral hydraulic conductivity, S_p (m m^{-1}) is the average slope gradient of the OFE, D_d (m) is the total thickness of the drainable layers, L (m) is the slope length of the OFE, d_i (m) is thickness, and K_{ui} (m s^{-1}) is unsaturated hydraulic conductivity as previously defined.

In WEPP, subsurface lateral flow from the upland OFE is included in the soil water input to the current OFE. Simulation of daily soil water redistribution follows the order of percolation, soil evaporation, subsurface lateral flow, saturation-excess, and plant transpiration; and soil water content is adjusted after each process. WEPP simulates saturation-excess by comparing soil water content against the porosity for each layer bottom to top. The excess water for a layer is added to the layer immediately above. When soil water content in the first layer exceeds its porosity, surface runoff occurs due to saturation-excess.

Limitations and modifications of subsurface lateral flow routines of WEPP

Surface runoff is transferred to the channel network in WEPP (v2004.7). Subsurface lateral flow, however, was neglected. Such simplification may be adequate for agricultural settings with relatively uniform and deep soil layers, but can cause underestimates of watershed discharge for steep forested areas. Further, WEPP (v2004.7) tends to under-predict subsurface lateral flow due to its over-prediction of the deep percolation for two reasons. First, WEPP uses user-specified effective saturated hydraulic conductivity for the top two soil layers, but estimates K_s for the remaining layers using pedo-transfer functions, with a lower limit of 2.0×10^{-8} m s^{-1} (Flanagan and Livingston, 1995). The estimated K_s is generally greater than that for bedrocks, which potentially leads to overestimated deep percolation and underestimated subsurface lateral flow (calculated after percolation and soil water reduction) for most forest settings with shallow soils overlying low-permeability bedrock. Second, WEPP assumes isotropic soil layers. This assumption is inadequate for forest lands where the layering of porous soil and low-permeability bedrock, together with the effect of lateral tree roots, leads to an anisotropic system with a lateral K_s value greater than the vertical value (Bear, 1972; Brooks et al., 2004).

To adapt the model for forest applications, we modified the WEPP soil input files to allow the definition of a "restrictive" bedrock layer beneath a soil profile with user-specified K_s for deep percolation. In addition, the user is allowed to input an anisotropy ratio of the soil K_s, and the value is used for the whole soil profile. With the presence of a restrictive layer, deep percolation is estimated following Eq. (1) except that K_{ui} in Eq. (1d) is replaced by the harmonic mean of the hydraulic conductivities of the bottom soil layer and the restrictive layer.

Subsurface lateral flow from a hillslope was added to the channel flow under two conditions: (i) when surface runoff and subsurface lateral flow occur simultaneously, and (ii) only subsurface lateral flow occurs. In both cases, we assumed that subsurface lateral flow does not contribute sediment to the stream channels. Under the first condition, surface runoff is presumed to dominate erosion and channel flow processes, and subsurface lateral flow is simply added to the channel flow by volume without changing hydrograph characteristics and the amount of sediment. Under the second condition, a uniform flow rate and a 24-h flow duration were assumed.

The modifications were made on WEPP v2004.7 and included in WEPP v2008.9 (accessible to public at http://topsoil.nserl.purdue.edu/nserlweb/weppmain).

Model application

Study site

The 9-ha Hermada watershed was chosen as the test watershed for this study. A brief site description, summarized from Covert et al. (2005), is given below. The Hermada watershed is located in the Boise National Forest, Idaho (43.87°N and 115.35°W) with an elevation range of 1760–1880 m and slope gradients of 40–60%. Trees, predominantly ponderosa pine and Douglas fir, were harvested in 1992 using a cable-yarding system, and a prescribed fire was ignited on October 17, 1995 for site preparation. The watershed was extensively monitored for discharge using a Parshall flume and sediment with a sediment trap from November 3, 1995 through September 30, 2000.

WEPP inputs

The period of field monitoring was used as the simulation time for this study. The majority of the input data were based on field observation and measurements, while the remaining parameters were from the WEPP User Summary and Technical Documentation (Flanagan and Livingston, 1995; Flanagan and Nearing, 1995).

Topography and burn severity. The watershed structure and slope files for the WEPP model were generated from GeoWEPP. The watershed was delineated into one channel section and three single-OFE hillslopes to the south, north and the west of the channel (Table 1). The prescribed fire on October 17, 1995 produced an overall low-severity burn on the west (aspect 48° from due north) and north (aspect 170°) slopes while leaving the south (aspect 295°) slope and lower channel unburned (Robichaud, 2000).The prescribed fire resulted in a low-severity burn following the classification of Ryan and Noste (1983) in which only a small portion of the litter and duff were burned with little effect on the remaining standing trees. Infiltration capacity was not substantially altered based on the results of the field study of Robichaud (2000).

Climate. Field-observed precipitation data for the Hermada watershed contained two sets of measurements: one by a tipping-bucket rain gage in one-min intervals, and the other by a weighing-bucket gage in 15-min intervals. The weighing-bucket gage was equipped with Alter-type shields for wind, more suitable for catching snow in the winter. In addition to precipitation, an on-site weather station recorded temperature, relative humidity, solar radiation, wind velocity, and wind direction.

Precipitation data from the two gages were examined and combined to develop daily precipitation data (amount, duration, time to peak, and peak intensity). Generally, data from the gage that exhibited greater consistency and caught more precipitation was used.

Additionally, faulty data due to equipment malfunction were corrected. Small gaps of precipitation and daily maximum and minimum temperature (roughly 6% of the total data) were filled with the data for the same period from the closest Snowpack Telemetry (SNOTEL) site, the Graham Guard Station (43.95°N, 115.27°W, 1734 m a.s.l., 11 km to the northeast) in Idaho (USDA, 2006). Dew-point temperature, solar radiation and wind velocity were missing for the spring and summer of 1998. Dew-point temperature data were replaced with estimates based on daily maximum and minimum temperatures following Kimball et al. (1997). An erroneous wind velocity (or solar radiation) value for a specific day was replaced by the average of the wind velocities (or solar radiation data) for the same day in other years.

The processed climate data are compatible with PRISM-estimated (OCS, 2006) data and data observed from the nearby Graham Guard SNOTEL Station for the same period of time. Fig. 2 shows the comparison of monthly precipitation as an example. Fig. 3 presents the climate inputs: daily precipitation, temperature, solar radiation, and wind velocity, for the WEPP application.

Soil. Soil in the study area is a loamy sand (Typic Cryumbrept) from granitic parent material (Robichaud, 2000). Soils of this type in Idaho generally exceed 1 m in depth and are mostly dry in late summer (Cooper et al., 1991). Major soil inputs for the WEPP model were based on field and laboratory measurements (Covert, 2003) as shown in Table 2. Effective hydraulic conductivity, a sensitive parameter for infiltration, was calibrated as 2.5×10^{-5} m s^{-1}, slightly higher than the value of 1.8×10^{-5} m s^{-1} measured in a field infiltration study using rainfall simulator (Robichaud, 2000). A restrictive layer with a calibrated K_s of 9.7×10^{-9} m s^{-1}, which was between the K_s values of weathered and unfractured granite (Domenico and Schwartz, 1998), was used to represent the bedrock beneath the soil profile. The soil depth was 750 mm based on field observation. An anisotropy ratio of 25 for the soil profile was specified to reflect the difference between horizontal and vertical hydraulic conductivities for the Pacific Northwest forest watershed conditions following Zhang et al. (2008) and Brooks et al. (2004). The initial soil saturation level was set at 45%, considering the effect of the prescribed fire in the late fall of the first year of simulation. This setting reflects the soil conditions after a relatively dry year of 1994 (OCS, 2006) based on the results from a preliminary WEPP run. The depths to a non-erodible layer in mid-channel and along the side of the channel were set to 0.05 m and 0.01 m, respectively, consistent with field conditions.

Management. A perennial setting was used to represent the regenerating forest. Management inputs were either from field investigation or the literature. Initial ground cover, including grasses, duff and debris, was 95% for the unburned condition and 90% for the burned condition based on field measurements. Major parameters for vegetation growth were taken from the auxiliary database of the WEPP model for five-year-old trees (Elliot and Hall, 1997). Other parameters were adjusted to represent the tree growth processes for the study area and to attain agreement between the simulated and observed ground cover over time. These parameters include the initial canopy cover, senescence date and length, frac-

Table 1
Configuration of the Hermada watershed in WEPP simulations.

Hillslope	West	North	South	Channel
Length, m	240	242	129	120
Width, m	142	175	175	1
Average slope, m m^{-1}	0.467	0.476	0.399	0.266
Area, m^2	34,080	42,350	22,575	120

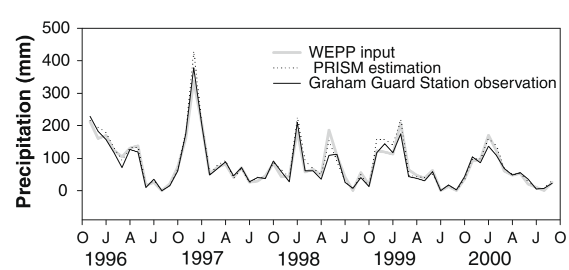

Fig. 2. Comparison of monthly precipitation for the Hermada watershed. The thick gray line represents monthly sum of WEPP daily inputs from observed data, the dotted line shows PRISM monthly spatial interpolations, and the solid line represents the monthly sum of SNOTEL daily observations at the Graham Guard Station.

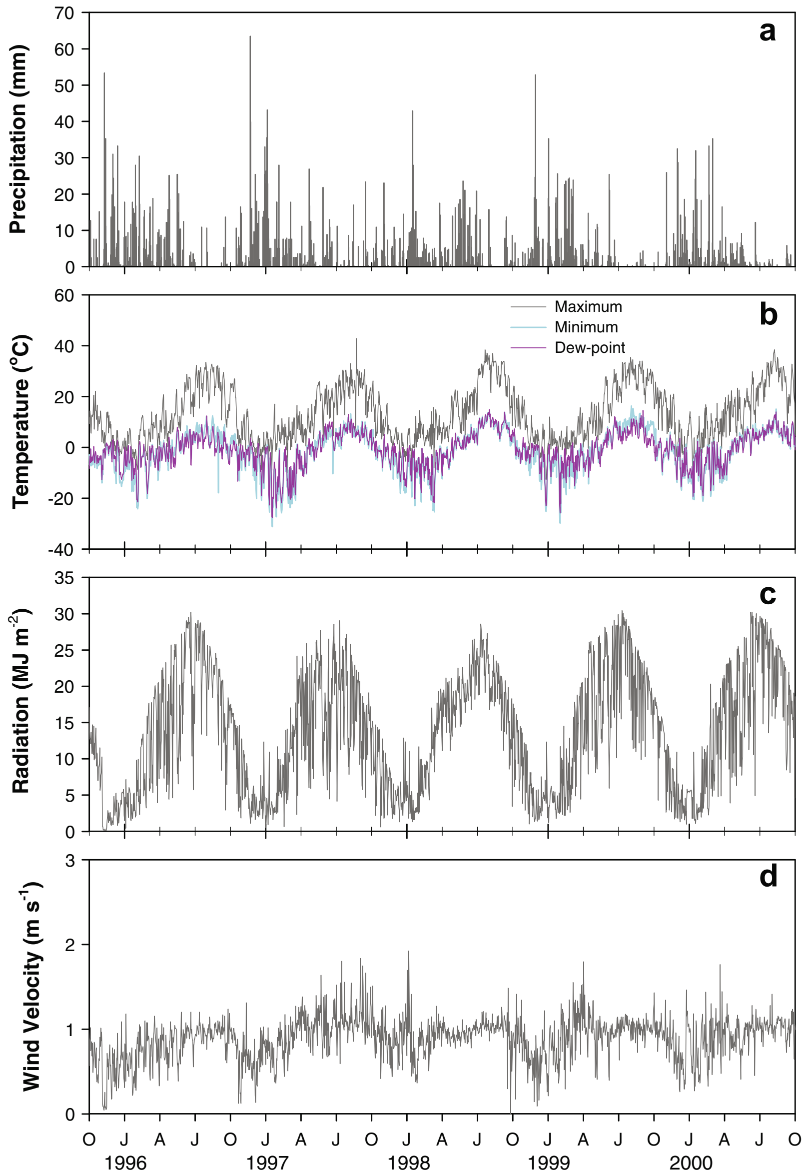

Fig. 3. Observed Hermada watershed daily weather inputs used in WEPP, (a) precipitation, (b) maximum, minimum temperature and dew-point temperature, (c) solar radiation, and (d) daily average wind speed.

Table 2
Major soil inputs for WEPP applications to the Hermada watershed.

Parameters	Unburned	Low-burn severity
Soil depth (mm)	750	
Sand (%)	85	
Clay (%)	2	
Organic matter (% volume)	5	
Cation exchange capacity (cmol kg^{-1})	1.5	
Rock fragments (% volume)	20	
Albedo	0.1	
Initial soil saturation (%)	45	
Baseline interrill erodibility (kg s m^{-4})	2.7×10^6	4.0×10^6
Baseline rill erodibility (s m^{-1})	1.0×10^{-5}	3.4×10^{-4}
Baseline critical shear (N m^{-2})	1.6	
Effective hydraulic conductivity of surface soil (m s^{-1})	2.5×10^{-5}	2.5×10^{-5}
Saturated hydraulic conductivity of restricted layer (m s^{-1})	9.7×10^{-9}	
Soil anisotropy ratio	25	

tions of canopy and biomass remaining after senescence, and decomposition constant for above-ground biomass (Table 3).

WEPP runs and model performance assessment

Model runs were performed with the same inputs using the WEPP v2004.7 and v2008.9, respectively. Model results from both versions were contrasted and compared with field observations. Simulated growth rate of above-ground living biomass was compared with literature data, and modeled residue ground cover was compared with the field-observed values. Simulated streamflow and sediment yield were compared with monitoring data at the study site. Additionally, nonparametric analyses of variance (ANOVA) were performed at $\alpha = 0.05$ (SAS Institute Inc., 1990) and model efficiency coefficients (Nash and Sutcliffe, 1970) were calculated for simulated annual and daily watershed discharge from WEPP v2004.7 and v2008.9, respectively. Nonparametric tests were used because of the lack of independence, non-normality, and small population size, typically associated with annual and daily streamflow samples.

Table 3
Major management inputs for WEPP applications to the Hermada watershed.

Parameters	Unburned	Low-burn severity
Initial ground cover (%)	95	90
Date to reach senescence (Julian day)	300	300
Period over which senescence occurs (days)	90	90
Fraction of canopy remaining after senescence	0.70	0.70
Fraction of biomass remaining after senescence	0.95	0.75
Decomposition constant for above-ground biomass ($kg\ m^{-2}\ d^{-1}$)	3.0×10^{-3}	2.0×10^{-3}

Results and discussion

Vegetation cover

In comparison to field observations, WEPP (v2008.9) adequately simulated plant growth and ground cover over time (Fig. 4). The ground cover on the unburned south slope remained at 95% during the five-year field monitoring period, and it increased gradually after the low-severity burn from 90% to full cover on the north slope.

The average annual growth rate of the above-ground living biomass simulated using v2008.9 was 0.4 $kg\ m^{-2}$ for the unburned slope and 0.3 $kg\ m^{-2}$ for the burned slopes (Fig. 4). Herman and Lavender (1990) state that typical growth rates for Douglas Fir forests range from 0.16 to 0.7 $kg\ m^{-2}$, depending on climate, soil and age of trees. The range of growth rates was for a climate on the US Pacific Northwest coast that is generally wetter than the study site. The estimated growth rates for Hermada watershed appear to be well within the observed range of growth rates for western US forests.

Water balance and sediment yield

Major water balance components for the hillslopes and entire watershed simulated with WEPP v2004.7 and v2008.9 are presented in Tables 4 and 5, respectively. Annual ET and deep percolation simulated by WEPP v2004.7 essentially accounted for the whole water balance. The former averaged 64% and the latter 36% of annual precipitation, and no runoff was predicted. Simulated annual average volumetric soil water content varied between 0.08 and 0.12, averaging 0.09 for the five-year period. Simulated subsurface lateral flow from the hillslopes was negligible, accounting for 0.15% of annual precipitation on average, as a result of the inadequate simulation of subsurface lateral flow by WEPP v2004.7. Because there was no predicted surface runoff from hillslopes and because subsurface lateral flow was not passed to the channel, WEPP v2004.7 predicted no watershed discharge. Yet watershed discharge was recorded in all monitored years. For the five monitored years, the observed watershed discharge amounted to 275 mm or 29% of annual precipitation. Hence, WEPP v2004.7 underestimated watershed discharge for the Hermada watershed.

Watershed discharge simulated using WEPP v2008.9 improved substantially, with a five-year average of 262 mm accounting for 28% of average annual precipitation (Table 5). Simulated water flow from the hillslopes was entirely subsurface lateral flow as observed in the field during this study. Increase in the simulated subsurface lateral flow and thus watershed discharge was a direct consequence of the reduced simulated soil water percolation due to the restrictive layer specified in the model. Hydraulic conductivity for an unfractured granitic restrictive layer ranges 10^{-14}–$10^{-10}\ m\ s^{-1}$ (Domenico and Schwartz, 1998), much lower than the hydraulic conductivity of the soil at the Hermada watershed. Consequently, soil water percolation by WEPP was not sensitive to minor changes in the hydraulic conductivity of the restrictive layer.

Simulated soil water content of hillslopes is typically replenished over the winter-spring season and starts to decline from early summer until the dry months of July and August. Fig. 5 shows the seasonal change in profile-averaged soil water content for the west slope as an example. ET from WEPP v2008.9 was 565 mm on average, accounting for 59% of annual precipitation. Law et al. (2002) presented ET values on evergreen coniferous forest determined by eddy covariance by various researchers from different study sites. The observed yearly ET varied from 350 to 680 mm when annual precipitation was between 700 and 1250 mm, the range of annual precipitation observed at the Hermada watershed during the study period. Hence, ET simulated from WEPP v2008.9 is compatible with the literature values. Notice the differences in simulated lateral flow and deep percolation among the three hillslopes (Table 5). Simulated lateral flow for the south slope was

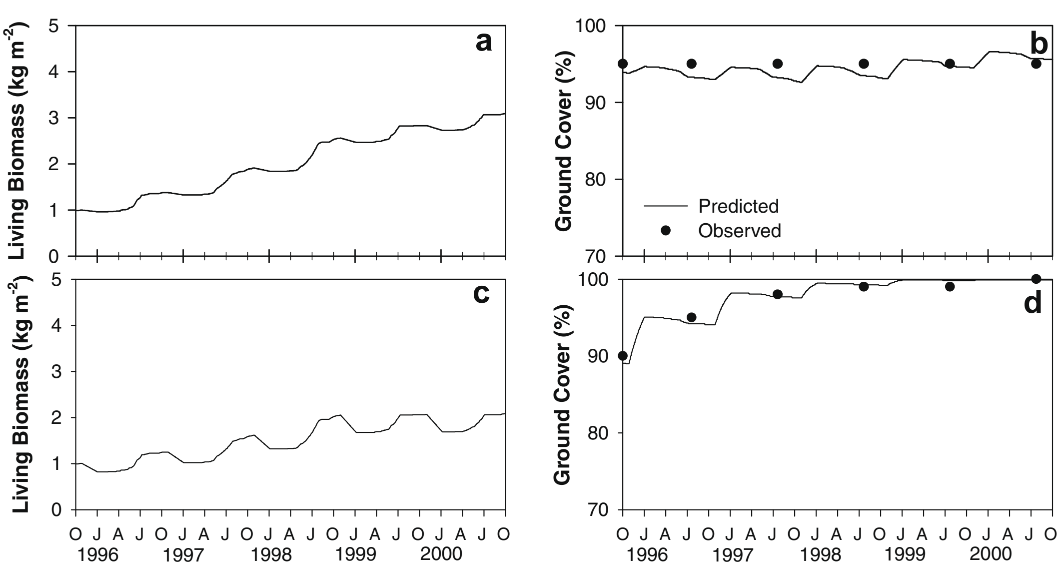

Fig. 4. WEPP v2008.9 simulations: (a) Above-ground living biomass and (b) ground cover simulated for unburned south slope; (c) Above-ground living biomass and (d) ground cover simulated for low-severity burn north slope.

Table 4
Annual water balance, in mm, for the Hermada watershed from WEPP v2004.7.

Water year[a]	P	Slope/watershed[b]	Q	ET	D_p	Q_s	SW
1995–1996	1106	W	0	497	636	2	87
		N	0	575	545	2	85
		S	0	575	551	2	88
		WS	0 (321)[c]	548	578	0	86
1996–1997	1200	W	0	621	576	2	82
		N	0	649	546	2	74
		S	0	647	549	3	79
		WS	0 (421)	639	557	0	78
1997–1998	919	W	0	800	123	1	74
		N	0	871	49	0	56
		S	0	827	95	1	69
		WS	0 (224)	837	85	0	65
1998–1999	809	W	0	460	352	1	59
		N	0	463	347	1	55
		S	0	461	350	1	60
		WS	0(237)	461	349	0	57
1999–2000	737	W	0	532	203	1	62
		N	0	576	159	1	49
		S	0	546	189	1	61
		WS	0 (174)	554	181	0	56

P = precipitation, Q = surface runoff, ET = evapotranspiration, D_P = deep percolation, Q_s = subsurface lateral flow, and SW = average soil water storage.
[a] Water year refers to the period of October 1–September 30 in this study.
[b] W, N, S, and WS refer to west, north and south slopes and watershed, respectively.
[c] Predicted and observed (in parentheses) watershed discharge.

Table 5
Annual water balance, in mm, for Hermada watershed from WEPP v2008.9.

Year[a]	P	Slope/watershed[b]	Q	ET	D_p	Q_s	SW
1995–1996	1106	W	0	497	231	396	144
		N	0	497	231	396	144
		S	0	492	178	453	132
		WS	399(321)[c]	495	219	10	141
1996–1997	1200	W	0	646	144	406	127
		N	0	645	144	407	127
		S	0	640	109	448	116
		WS	403(421)	644	136	11	125
1997–1998	919	W	0	699	92	126	94
		N	0	699	91	127	94
		S	0	704	64	151	89
		WS	125 (224)	701	86	6	93
1998–1999	809	W	0	492	106	219	96
		N	0	490	109	219	97
		S	0	475	90	252	97
		WS	218 (237)	488	104	8	97
1999–2000	737	W	0	496	74	167	67
		N	0	496	73	168	68
		S	0	493	55	189	64
		WS	167 (174)	495	69	5	67

P = precipitation, Q = surface runoff, ET = evapotranspiration, D_P = deep percolation, Q_s = subsurface lateral flow, and SW = average soil water storage.
[a] Water year refers to the period of October 1–September 30 in this study.
[b] W, N, S, and WS refer to west, north and south slopes and watershed, respectively.
[c] Predicted and observed (in parentheses) watershed discharge.

more than those for the west and north slopes because of its shorter slope length (see Table 1). Greater simulated lateral flow in turn led to less simulated deep percolation for the south slope.

For the study area, observed streamflow mostly occurred in the spring snowmelt season and occasionally in warm winter or wet summer (Fig. 6). WEPP v2008.9 generated substantial winter runoff for the 1996 and 1997 water years. WEPP-simulated winter runoff for the 1996 water year corresponded to the warm winter

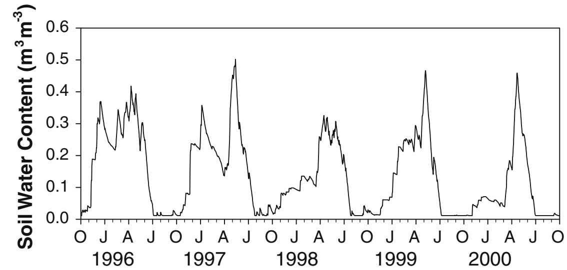

Fig. 5. Profile-averaged soil water content for the west slope simulated using WEPP v2008.9.

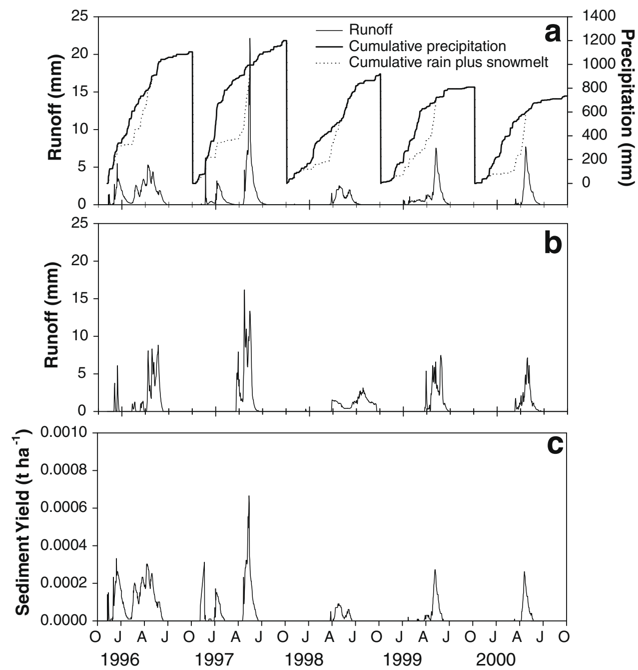

Fig. 6. Hydrograph and sedimentograph for the Hermada watershed. Daily watershed discharge (a) simulated by WEPP v2008.9 and (b) observed, and (c) daily sediment simulated by WEPP v2008.9.

of 1995–1996, as corroborated by field observation. Winter runoff was not recorded between November, 1996 and February, 1997 in our study due to a malfunction in the data acquisition device; however, the large simulated winter runoff coincided with the 1996–1997 winter flooding in the western US due to heavy precipitation and warm temperatures (Lott et al., 1997). Overall, simulated and observed daily runoff during spring snowmelt seasons for the Hermada watershed were agreeable. Good agreement was also found for simulated and observed annual runoff (Fig. 7).

Sediment yield of individual storm events was monitored during the study period, but no sediment-producing event, i.e., with a sediment yield $\geqslant 0.005\ t\ \mathrm{ha}^{-1}$, was observed (Covert, 2003). WEPP v2004.7 simulated no runoff from either the hillslopes or channel and thus no soil loss. WEPP v2008.9 also simulated no soil loss from hillslopes. WEPP-generated erosion was due to channel flow with a maximum daily sediment yield less than $0.001\ t\ \mathrm{ha}^{-1}$ (Fig. 6c). WEPP-simulated annual sediment yield varied from $0.028\ t\ \mathrm{ha}^{-1}$ in the first year to $0.005\ t\ \mathrm{ha}^{-1}$ in the fifth year after the prescribed fire (Fig. 7). These values are rather low for recently burned areas, but greater than the field-observed values during those years (Covert, 2003). Annual soil erosion rates after prescribed fires can vary from $0.1\ t\ \mathrm{ha}^{-1}$ for low-severity burns to

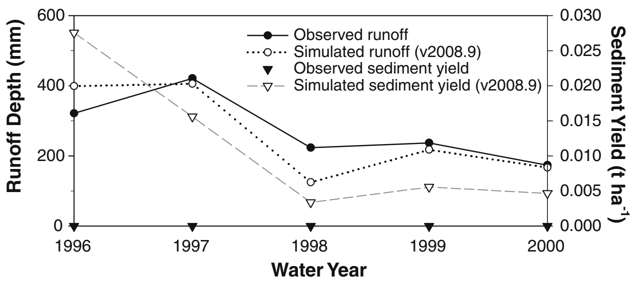

Fig. 7. Annual runoff and sediment yield from the Hermada watershed.

Table 6
Nonparametric ANOVA results and Nash–Sutcliffe model performance coefficients from comparing means of observed and WEPP-simulated annual or daily watershed discharge ($\alpha = 0.05$).

WEPP version	Nonparametric ANOVA				Nash–Sutcliffe coefficient	
	Annual		Daily		Annual	Daily
	F-value	*P*-value	*F*-value	*P*-value		
2004.7	40.3	0.0002**	302.8	<0.0001**	−10.0	−0.17
2008.9	0.03	0.86	0.35	0.56	0.57	0.45

** Significantly different.

6.0 t ha^{-1} for high-severity burns (Robichaud and Waldrop, 1994). Sediment yields after fire depend on many factors, such as climate, vegetation, topography, and soil (Swanson, 1981). The low post-fire erosion rate at the study watershed was likely due to the low impact from the low-severity burn on ground cover and its rapid recovery (Fig. 4b).

Statistical analysis

No runoff was generated using WEPP v2004.7. Nonparametric ANOVA results (Table 6) show that both annual and daily mean watershed discharges simulated using WEPP v2004.7 differed significantly from field-observed values. Runoff results from WEPP v2008.9 were substantially improved as demonstrated by the non-significant ANOVA test results for both annual and daily values. The Nash-Sutcliffe coefficient for daily watershed discharge further indicates the inadequacy of WEPP 2004.7 (−0.17) and agreement between WEPP 2008.9 simulation results and field observations (0.45).

Compared to v2004.7, v2008.9 yielded daily hydrograph and annual streamflow values that were more agreeable with field observations. Yet there are limitations of WEPP for applications to certain conditions. In the current version of WEPP, deep percolation contributes to ground water, which does not interchange with watershed streamflow. Hence, WEPP cannot be used for areas where surface- and ground-water interaction is important.

WEPP is a network-based, hydrologic-unit model. It discretizes a watershed into hillslopes and a channel network. A hillslope can be divided into the basic simulation units of OFEs representing different vegetation, soil and topography conditions. Consequently, WEPP can simulate saturation-excess runoff due to changes in hillslope conditions, including the changes in soil and vegetation as well as convergence of the slope. The extensive database of WEPP on soil, vegetation, and management of crop-, range- and forest-land allows more broad applications. Existing grid-based hydrology and erosion models, such as the DHSVM (Wigmosta et al., 1994; Doten et al., 2006) and MIKE-SHE (Refsgaard and Storm, 1995), also have the ability to simulate both infiltration- and saturation-excess runoff as well as water erosion. They apply finite-difference or finite-element techniques to solve the governing partial differential equations for major hydrological processes, and therefore can be more data-demanding and computation-expensive. These models do not have options as comprehensive as the WEPP model for assessing the effects of different management practices (e.g., culvert and settling basin) on site-specific hilllslope erosion, thus limiting their applicability at forest project scales.

Summary and conclusions

Reliable models for simulating water flow and sediment discharge from forest watersheds are needed for sound forest management. WEPP, a process-based, continuous erosion prediction model, was adapted for forest watershed applications. Specifically, modifications were made in modeling deep percolation of soil water and subsurface lateral flow. The refined WEPP model has the ability to simulate subsurface lateral flow through the use of a restrictive layer and an anisotropy ratio specified by the user. Further, it is capable of transferring subsurface lateral flow from the hillslopes to watershed channels, and then routing it to the watershed outlet. Compared to WEPP v2004.7, WEPP v2008.9 may be used to more realistically represent hydrologic processes in forest settings.

The comparison of WEPP model results from v2004.7 and v2008.9 for the Hermada watershed, a representative, small forest watershed in southern Idaho, showed the improvement of the modified model in simulating subsurface lateral flow from hillslopes and daily and annual streamflow. WEPP v2008.9 yielded predominant seasonal subsurface lateral flows, consistent with field observation.

For steep mountainous forested watersheds with granitic bedrock underneath shallow soils, such as the Hermada watershed, the hydraulic conductivity of the bedrock is sufficiently low that the small changes in the hydraulic conductivity would not greatly affect deep seepage; and, lateral flow may oftentimes be the major contributor to observed streamflow. The use of a perennial plant setting in this study reasonably described vegetation regeneration and ground cover under forest conditions.

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