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Adapting the Water Erosion Prediction Project (WEPP) Model to Forest Conditions

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Abstract. *Adequate and reliable erosion prediction tools are needed for sound forest resources management. Numerous watershed models have been developed during the past. These models, however, are often limited in their applications largely due to their inappropriate representations of the hydrological processes involved. The Water Erosion Prediction Project (WEPP) model has demonstrated its usefulness in certain forest applications, such as modeling erosion from a segment of in-sloped or out-sloped road, and harvested or 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 goal of this study was to improve the WEPP model such that it can be applied to adequately simulate forest watershed hydrology and erosion. Specific objectives were to: (1) identify and correct WEPP algorithms that inappropriately represent forest hydrologic processes; and (2) verify the modified model. Substantial changes were made in the approach to, and algorithms for modeling percolation of soil water and subsurface lateral flow in WEPP. The modified codes were subsequently applied to Hermada watershed, a small watershed located in the Boise National Forest in northern Idaho. The modeling results were compared with those obtained by using the original WEPP and the field-observed runoff and erosion data. 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 produced satisfactory results, demonstrating the adequacy of the model modifications.

Keywords. Forest watershed, surface runoff, subsurface lateral flow, soil erosion, hydrologic modeling, WEPP.

Introduction

Recently, there has been an increasing public concern over forest stream pollution by excessive sedimentation resulting from human activities. Adequate and reliable erosion simulation tools are urgently needed for sound forest resource management. Computer models for predicting watershed runoff and erosion have been developed during the past. These models, however, are often limited in their applications largely due to their 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 (USDA), has proved useful in such forest applications as modeling erosion from a segment of in-sloped or out-sloped road, or 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 lateral flow and water discharge at the watershed outlet (J. Boll, University of Idaho, 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). Forest lands, on the other hand, are typified by steep slopes, and shallow, young, and coarse-grained soils, differing remarkably from common crop lands. In addition, the presence of dense canopy cover and thick duff layers further differentiates forest from crop-, urban-, and range lands 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 applications, however, the model needs to be modified to properly represent the hydrologic processes involved. Figure 1 illustrates the differences in characteristics of hydrologic processes in agricultural and forest settings, respectively.

The main purpose of this study was to improve the WEPP watershed model such that it can be used to properly simulate and predict forest watershed hydrology and erosion. Specific objectives were to: (1) identify and correct WEPP algorithms and subroutines that inappropriately represent forest watershed hydrologic processes; and (2) assess the performance of the modified model by applying it to a typical forest watershed in the Pacific Northwest, USA.

Methods

2.1. Model Description

WEPP discretizes a watershed into such elements as hillslopes, channels, and impoundments. A hillslope can be further divided into overland flow elements (OFEs), within which soil and management conditions are unique and regarded homogeneous. Accordingly, the model contains three components simulating major hydrologic and erosion processes within these watershed elements. A recently developed geo-spatial interface, GeoWEPP, allows the use of digital elevation models (DEMs) to generate watershed configuration and topographic inputs for WEPP (Renschler, 2003). For completeness, important functions and routines in each WEPP model component are summarized below following Ascough and Livingston (1995) and Flanagan et al. (1995).

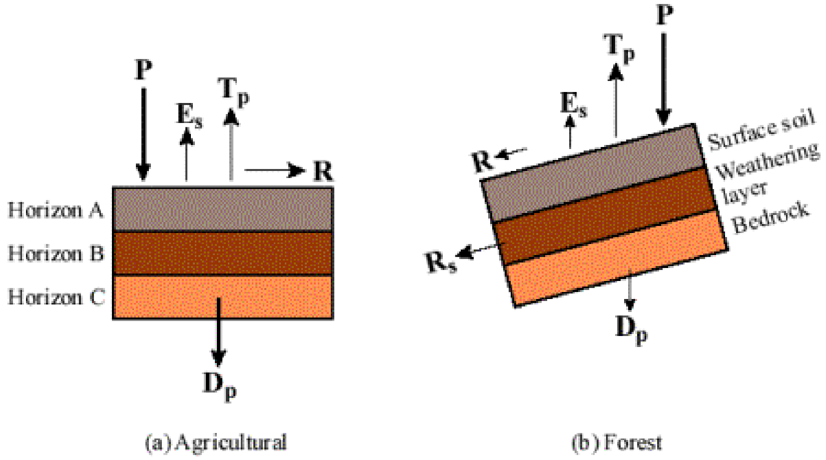

Figure 1. Diagram showing the difference in the rate of hydrologic processes between typical agricultural (a) and forest (b) settings. The size of the arrows reflects the relative magnitude or rate of the individual processes. P, precipitation, T_p, plant transpiration, E_s, soil evaporation, R, surface runoff, R_s, subsurface lateral flow, D_p, deep percolation. (Adapted from Wu et al., 2000).

The hillslope component of WEPP is divided into nine sub-components: winter processes, irrigation, surface hydrology and water balance, subsurface hydrology, soils, plant growth, residue decomposition, and overland-flow hydraulics, and erosion. Daily or single-storm climate can be generated for the WEPP model with CLIGEN, an auxiliary stochastic 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) modified for unsteady rainfall (Chu, 1978). Evapotranspiration (ET) is evaluated by using a modified Ritchie's (1972) model, 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, and soil water percolation 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 primarily based approximations to the solutions of the kinematic wave equations. 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 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 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-flow and channel-flow areas. The major function of an impoundment is to trap eroded materials 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 graphs are stored in hillslope pass files and are incorporated into a watershed master pass file for use by the channel and impoundment components. Information on subsurface lateral flow generated from either a hillslope or a channel, however, is not saved, possibly due to its insignificance in most applications to crop lands.

2.2. WEPP Limitations and Modification

Since the subsurface lateral flow calculated in the WEPP hillslope component is not included in the hillslope and watershed pass files, it is then not added to the channel flow that ultimately discharges from the watershed outlet. On the other hand, WEPP's hillslope component tends to substantially overestimate deep percolation and underestimate subsurface lateral flow for several reasons. First, WEPP allows the saturated hydraulic conductivity (K_s) to be input for the surface soil layer only. The model estimates K_s for the remaining soil layers using empirical functions of soil properties, in particular, the percentages of clay and sand. The minimum K_s is no less than 2.1×10^{-8} m s^{-1}. Such a treatment of K_s may be reasonable for crop lands with relatively uniformly permeable and deep soils or with subsurface drainage systems, but is likely invalid for most forest settings where soils are shallow with lower-permeability bedrocks underneath. Without subsurface drains installed to intercept percolated soil water, overestimated K_s for the deeper soil layers simply signifies an overestimate of percolation at the bottom of the soil profile.

In the WEPP model, individual hydrologic processes (e.g., surface runoff, ET, change in soil water) are evaluated sequentially. Prior to calculating soil water percolation, WEPP estimates and adjusts for soil water status. If the soil water content is greater than that at field capacity (θ_{fc}), percolation (described following Darcy's law with a unit gradient) starts and is removed from the soil profile. If the soil water content is still greater than θ_{fc}, WEPP calculates the lateral flow using the internally estimated K_s adjusted for the present soil water content. In reality, soil water percolation and lateral flow take place simultaneously. Therefore, if the two processes are simulated separately and if the deep percolation is incorrectly overestimated, the subsurface lateral flow would be underestimated. Another source for the underestimate was an error in WEPP codes, in which subsurface lateral flow only occurs when the top soil layer is saturated.

Second, WEPP assumes that the modeled soil layer is isotropic, i.e., the horizontal and vertical K_s values are equal. This assumption, again, may be adequate for many agricultural fields but inadequate for most forest lands where the layered structure of porous soil on top of lower-permeability bedrocks tends to create higher horizontal hydraulic conductivity and large amount of lateral flow. Similarly, the duff layer and the A horizon in forest soils exhibit higher hydraulic conductivity than common soils, facilitating development of "conduits" along the interfaces of duff, A Horizon and deeper soils. Such unique hydraulic conditions cannot be properly represented by the soil property component in current WEPP with isotropic soil layers.

From the analysis of the limitations in subsurface hydrologic routines of current WEPP, we made a series of important modifications. The modifications were on WEPP release v2004.7, which included corrected water balance routines (Wu and Dun, 2004).

To rectify the problem of overestimation of deep percolation, the soil input file was modified to add a new line providing information for a “restrictive” layer at the bottom of a soil profile. The modified code allows a user to choose whether or not to use the restrictive layer with a character variable (solflag) in the soil input file. If solflag = 0, no restrictive layer is assumed and WEPP uses the original algorithms to estimate K_s for deeper soil layers; otherwise, if solflag = 1, the restrictive layer is assumed and a user-specified K_s is input for this restrictive layer.

Currently, the user is allowed to specify a single anisotropy ratio (next to solflg in the soil input file) for the whole soil profile. In the future, an option to input the anisotropy ratio for different soil layers will be incorporated.

As stated earlier, in the original WEPP, only surface runoff information, labeled as “EVENT”, is stored and passed to the watershed master pass file. To include the information on subsurface lateral flow in the hillslope and watershed pass files, two conditions were considered: (i) both surface runoff and subsurface lateral flow occur on the same day, and (ii) only subsurface lateral flow occurs. For both conditions, it was assumed that subsurface lateral flow does not contribute sediment to channels due to its low flow rate.

Under the first condition, the surface runoff was assumed to dominate the water flow and sediment transport processes, and the subsurface lateral flow is simply added to the surface runoff by volume without changing the sediment amount in the runoff. This approach is consistent with field observations, and a preliminary analysis of WEPP simulation results that indicated that surface runoff occurs much less frequently but can produce much greater amount of flow compared to subsurface lateral flow on an event basis. For the second situation, the hillslope pass files were modified to include subsurface lateral flow events, named “SUBEVENT” and with a presumed 24-hr flow duration. Relevant subroutines were modified to transfer information on subsurface lateral flow from the hillslope pass files to the watershed master pass file, which in turn passes the information to the channel or impoundment components for subsequent routing.

In the original WEPP, the channel or impoundment component does not route flow when there is no storm, irrigation, or surface runoff. In this study, modifications were made to route subsurface lateral flow under these water input and runoff conditions. Generally, the amount of subsurface lateral flow (by volume) generated by an upstream hillslope was assumed to be evenly distributed along the fed channel section. Since the subsurface lateral flow adds to the channel flow without adding sediment, the transport capacity of the channel increases and so does the potential channel erosion. Hence, the modified WEPP potentially predicts higher channel erosion than the original model, which may result in errors under certain conditions, e.g., where stream banks are steep, scarcely vegetated, and prone to sap erosion.

Accordingly, modification was made to add the information on subsurface lateral flow from hillslopes to the watershed output file, allowing comparison between WEPP-predicted and field-observed hillslope and watershed discharge.

Finally, changes were made to the crop growth subroutine to enhance the flexibility of WEPP in representing the physiological processes of vegetation in forested watersheds. In the original model, a user-specified perennial vegetation will continually grow year after year, as in tree growth, only if the dates for planting, stop of growth, and start of senescence are all set to zero. However, if the date of senescence is zero then no residue accumulation is calculated. On the other hand, if the date of senescence is not zero then no vegetation growth is calculated for any time during the year. Therefore, one could not simulate continuous vegetation growth and residue accumulation as in the forest settings using the original WEPP. The codes were modified such that vegetation growth is calculated whenever the Julian day is less than the senescence date.

2.3. WEPP Application

An assessment of the WEPP model (v2002.7, with flawed water balance routines) with initial modifications to the subsurface lateral flow routines (Wu et al., 2000) was performed by Covert et al. (2005). In their study, WEPP was applied to three selected watersheds in the interior northwestern US. They concluded that the modifications to the lateral flow routines in WEPP improved runoff predictions in the study watersheds. Since their study, WEPP has been substantially refined. Major modifications incorporated into WEPP v2004.7 included corrected water balance routines and newly added Penman-Monteith ET model. During the last two years, additional effort was made to integrate the initial modifications and further refinement to the subsurface lateral flow routines (Wu et al., 2005a; Wu et al., 2005b). The newly modified WEPP was tested with numerous, designed conceptual model runs. Meantime, these modifications were independently evaluated by WEPP researchers at the USDA National Soil Erosion Research Laboratory, and WEPP v2006.5, updated from v2004.7, was recently released.

2.3.1. Study site

Hermada watershed, one of the three forest watersheds evaluated in Covert et al. (2005), was chosen for testing the new WEPP model (v2006.5) in this study. Located in the Boise National Forest in northern Idaho at 43.87°N and 115.35°W, the Hermada watershed is 9 ha in size and has an elevation ranging 1760–1880 m. Trees were harvested in 1992 using cable-yarded technique and was burned by prescribed fire on October 17, 1995 (Covert et al., 2005). The watershed was extensively monitored for runoff and erosion from November 3, 1995 to September 30, 2000 (Covert et al., 2005).

2.3.2. WEPP simulation time and inputs

The years of 1995–2000, encompassing the period of field monitoring, were used as the simulation time for this study. Part of the input data was directly taken from those developed by Covert et al. (2005), while others were modified to better represent the physical conditions of the study watershed.

2.3.2.1. Topography

The watershed structure and slope files for the WEPP model were adapted from Covert et al. (2005). 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 and north slopes while leaving the south slope and channel unburned (Robichaud, 2000).

Table 1. Configuration of the Hermada watershed in the WEPP model

Hillslope	West	North	South	Channel
Length (m)	240	242	129	120
Width (m)	142	175	175	1
Area (m^2)	34,200	42,298	22,500	120

2.3.2.2. Climate

Monitored climate data for the Hermada watershed contained two sets of measurements: one by a tipping-bucket rain gage in one-minute intervals, and the other by a weighing-bucket gauge in 15-minute intervals (R.E. Brown, RMRS, USDA Forest Service, personal communication, 2006). The weighing-bucket gage was equipped with shielding wings, more suitable to and effective in catching snow in winter. In addition to precipitation, the weighing-bucket gage measured temperature, relative humidity, solar radiation, wind velocity, and wind direction

The climate data used in Covert et al. (2005) were re-processed in this study. First, data from the two gages were thoroughly examined and evaluated in order to develop daily precipitation data. Recordings from the weighing-bucket gage exhibited frequent abnormal fluctuations, while data from the tipping-bucket rain gage were more consistent. Hence, daily precipitation was prepared based on the tipping-bucket data and was substituted with data from the weighing-bucket gage when it generally caught more during winter seasons.

Additionally, faulty data due to equipment malfunction were identified and adjusted. Small gaps of precipitation and daily maximum and minimum temperature were filled with data for the same period from the closest SNOTEL site, the Graham Guard station (at 43.95°N and 115.27°W, 1734 m a.s.l.) in the State of Idaho (NRCS, 2006). Small gaps of other data considered less sensitive in WEPP, including solar radiation and wind, were generated using CLIGEN based on the daily precipitation, maximum and minimum temperatures for the study site and long-term statistics of climate parameters (USDA, 2006) for Deadwood Dam (at 44.32°N and 115.63°W, 1639 m a.s.l.) in Idaho. The Deadwood Dam station is about 55 km from the study site, and is the closet climate station with long-term climate data and at an elevation similar to that of the study site.

The recorded temperature data for the year of 2000 considerably exceeded the values for the other years and PRISM-estimated normal ranges (OCS, 2006). Hence, the temperature data for 2000 were estimated based on data for the same period from the Graham Guard station using a linear regression function relating monthly averages of daily maximum and minimum temperatures for the two sites. Additionally, anomalies of solar radiation and wind data for 1998 were replaced with CLIGEN-generated data.

The re-processed precipitation data were considered realistic and adequate for the study area as suggested by Figure 2, which shows comparison of monthly precipitation for the monitored period as re-processed in this study, from PRISM estimation, and SNOTEL observations at the Graham Guard station. Figure 3a–d illustrates the climate inputs for the WEPP application.

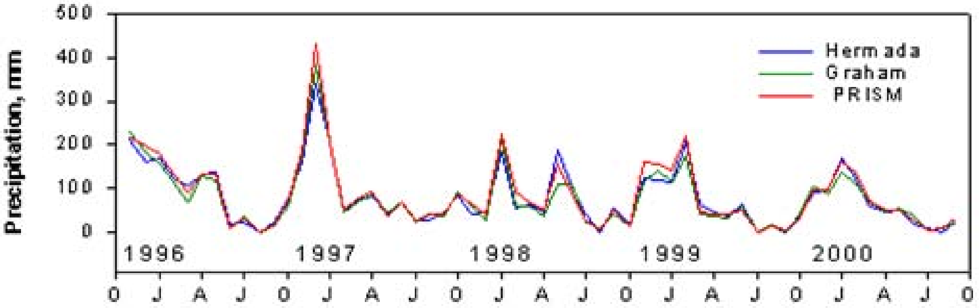

Figure 2. Comparison of monthly precipitation: Hermada, re-processed data in this study; Graham, SNOTEL observations; PRISM, spatially interpreted data.

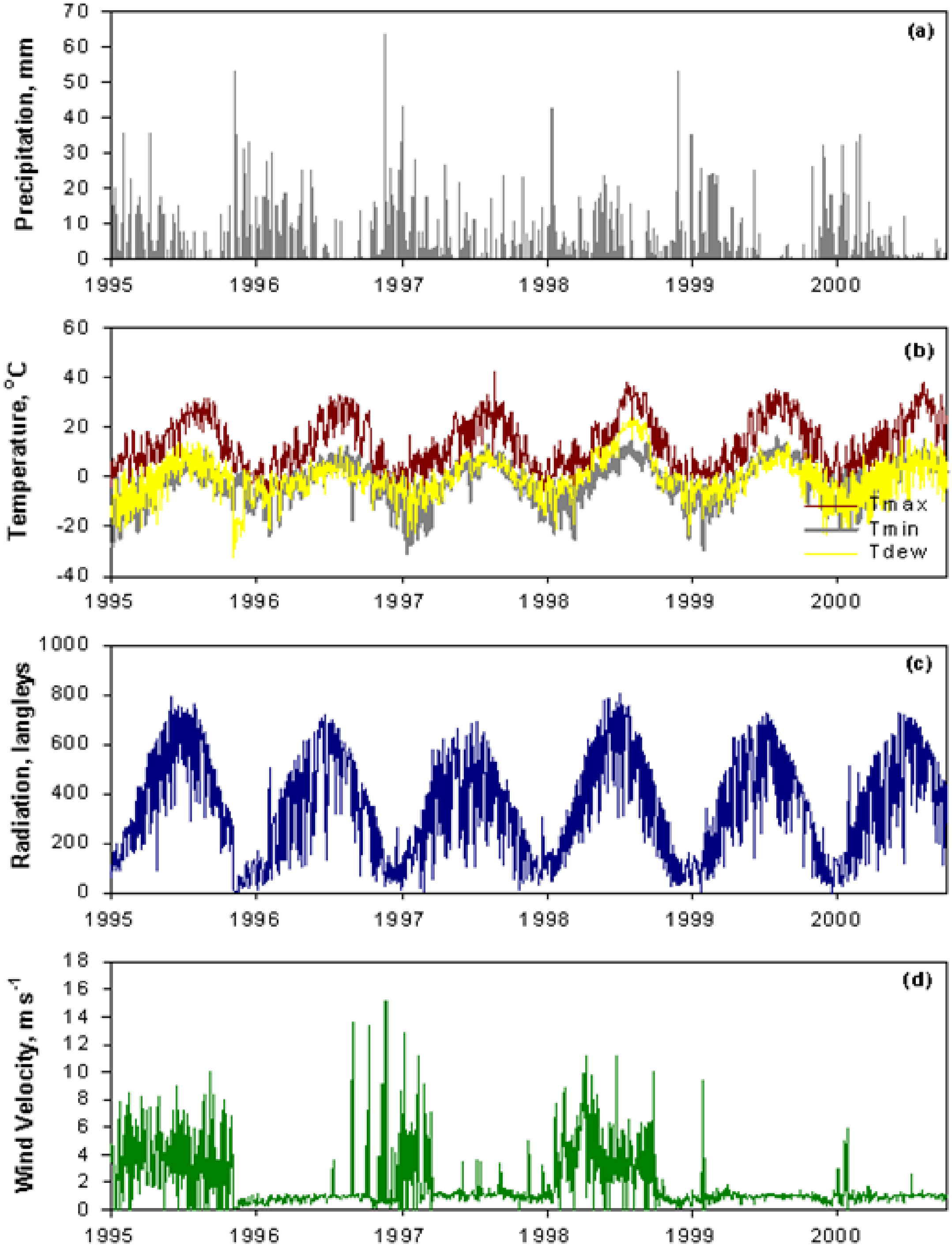

Figure 3. Daily climate inputs to WEPP, (a) precipitation, (b) maximum, minimum, and dew-point temperature, (c) solar radiation, and (d) wind velocity.

2.3.2.3. Soil

Soil input was primarily adapted from Covert (2003). A single soil layer with a depth of 500 mm, consistent with field observation, was specified. An anisotropy ratio of 25 was used to account for the difference between horizontal and vertical hydraulic conductivities of the soil profile for the study site. The initial soil saturation level was changed from75% as in Covert (2003) to 45%, considering the effect of the prescribed fire in the previous fall on the soil water status. This setting was also consistent with the soil water condition immediately after a relatively dry year of 1994 (OCS, 2006) based a preliminary WEPP run.

Other changes were on the depth to non-erodible layer in mid-channel, from the default 0.50 m to 0.05 m; and the depth to non-erodible layer along the sides of the channel, from 0.10 m to 0.01 m, based on field observations.

2.3.2.4. Management

Substantial changes were made to the management input file. In Covert et al. (2005), annual crop, instead of perennial vegetation, was used to represent trees. WEPP-simulated ground cover by plants was reasonable yet the simulated growth curve, with annual peaks, appeared unrealistic for forest conditions. In this study, perennial vegetation was used, together with the modified vegetation growth routines in WEPP v2006.5.

2.3.3. Model Runs

Model runs were performed using the WEPP v2004.7 and v2006.5 with the same inputs for the Hermada watershed. Simulation results from these runs were contrasted and then compared with the field-observed runoff and sediment yield.

Results and Discussion

3.1. Vegetation

The simulated above-ground living biomass and ground cover from WEPP v2004.7 and v2006.5 for the burned and unburned conditions are shown in Figures 4 and 5.

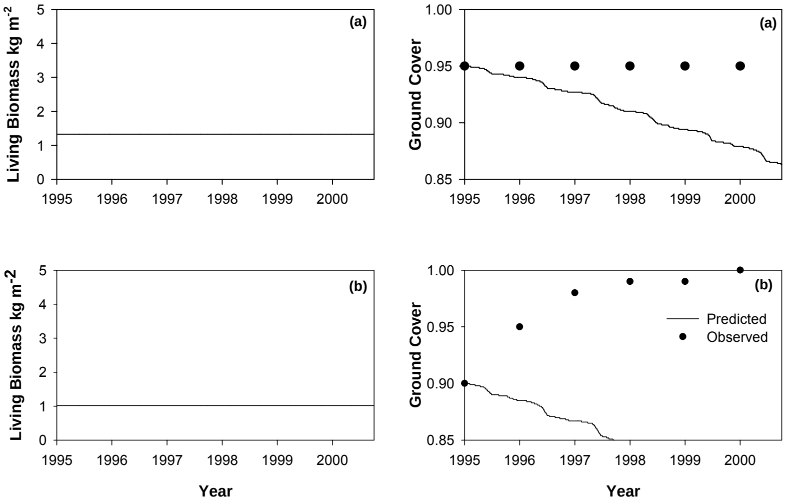

Figure 4. Above-ground living biomass and ground cover predicted by WEPP v2004.7. (a) unburned. (b) low-severity burn.

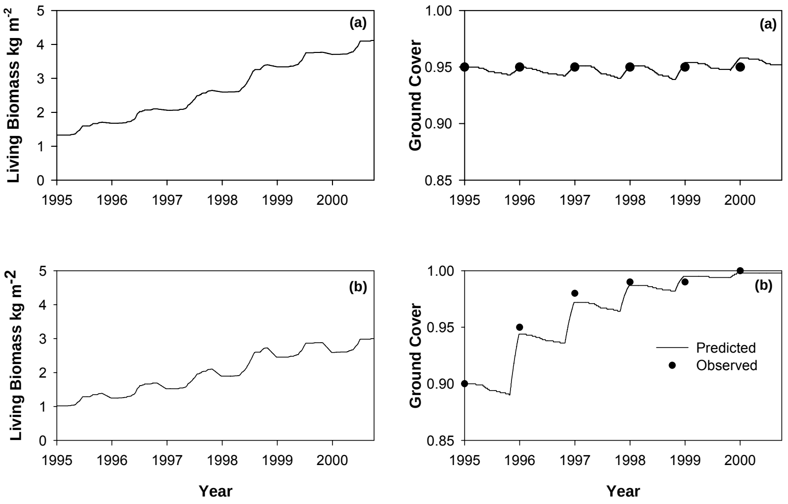

Figure 5. Above-ground living biomass and ground cover predicted by WEPP v2006.5.
(a) unburned. (b) low-severity burn.

In comparison to field observations, the vegetation growth and residue accumulation simulated using WEPP v2004.7 were erroneous. The decreases in ground cover with time were due to residue decomposition. Thus, v2004.7 was not able to generate an adequate biomass growth curve and a residue accumulations curve at the same time for the modeled watershed.

In contrast, the growth rate of the above-ground living biomass simulated using v2006.5 was 0.3–0.4 kg m^{-2}. Schultz and McAdoo (2002) discovered that annual growth of above-ground biomass ranges 0.08–0.25 kg m^{-2} in a sagebrush steppe area in Nevada, USA. Suárez et al. (2004) reported that the above-ground biomass growth rate may reach 0.5 kg m^{-2} for a tropical forest. The simulated vegetation growth rate for the study area falls in between these values from extremely dry to wet climatic conditions, suggesting the adequacy of the simulation results. Detailed field observations of ground cover were documented in Robichaud (1996). The ground cover simulated with v 2006.5 was highly agreeable with the field observations (Figure 5), further indicating the validity the changes made to the plant growth routines.

3.2. Water Balance

Annual water balance simulated by WEPP v2004.7 and v2006.5 are presented in Tables 2 and 3.

ET and percolation through the bottom of the soil profile as predicted by WEPP v2004.7 accounted for the majority of the water balance. Surface runoff and subsurface lateral flow from the hillslopes and watershed discharge were essentially negligible. However, field observations indicated that runoff at the watershed outlet occurred in each of the monitored year. For the last three observation years, watershed discharge amounted to 25% of annual precipitation. Evidently, WEPP v2004.7 underestimated watershed discharge for the study watershed.

Watershed discharge simulated using WEPP v2006.5 increased dramatically, with a five-year average of 290 mm or about 30% of average annual precipitation. Notice that water flow from the hillslopes was dominated by subsurface lateral flow as observed in typical forest watersheds.

With the definition of a restrictive layer, soil water percolation from v2006.5 decreased dramatically, from more than 40% to less than 4% of average annual precipitation, while subsurface lateral flow increased substantially. As a result, watershed discharge largely increased. The restrictive layer also resulted in saturation-excess runoff, another major form of runoff beside infiltration-excess runoff, for two years.

Table 2. Annual water balance in depth from WEPP v2004.7.

Slope	Water Year	$P^{\dagger}$ (mm)	Q (mm)	E_{p} (mm)	E_{s} (mm)	D_{p} (mm)	UpQ (mm)	Q_{s} (mm)	SWT (mm)	Observed Q (mm)
West	1995–1996	1106	0	530	0	601	0	0	58	
North		1106	0	587	0	530	0	0	55	
South		1106	0	548	0	577	0	0	58	
Channel		1106	0	572	0	548	0	0	56	
Watershed		1106	0	559	0	565		0	57	87
West	1996–1997	1200	0	535	0	663	0	0	50	
North		1200	0	597	0	602	0	0	46	
South		1200	0	552	0	646	0	0	48	
Channel		1200	0	578	0	621	0	0	47	
Watershed		1200	0	565	0	633		0	48	89
West	1997–1998	919	1	592	0	327	0	0	49	
North		919	1	684	0	234	0	0	39	
South		919	2	618	0	300	0	0	47	
Channel		919	2	657	0	261	0	0	43	
Watershed		919	0	637	0	281		0	44	322
West	1998–1999	809	0	397	0	413	0	0	40	
North		809	0	440	0	369	0	0	38	
South		809	0	394	0	416	0	0	40	
Channel		809	0	428	0	381	0	0	39	
Watershed		809	0	415	0	395		0	39	172
West	1999–2000	737	0	515	0	221	0	0	42	
North		737	0	574	0	162	0	0	36	
South		737	0	516	0	220	0	0	41	
Channel		737	0	543	0	193	0	0	39	
Watershed		737	0	541	0	196		0	39	142

[†] P, precipitation; Q, surface runoff; E_{p}, plant transpiration; E_{s}, soil evaporation; D_{p}, deep percolation; UpQ, inflow from upstream element; Q_{s}, subsurface lateral flow; SWT, total soil water.

Table 3. Annual water balance in depth from WEPP v2006.5.

Slope	Water Year	P[†] (mm)	Q (mm)	E_p (mm)	E_s (mm)	D_p (mm)	UpQ (mm)	Q_s (mm)	SWT (mm)	Observed Q (mm)
West	1995–1996	1106	0	615	0	56	0	460	122	
North		1106	0	670	0	49	0	399	114	
South		1106	0	616	0	41	0	466	104	
Channel		1106	356720[‡]	817	0	70	358795	2308	225	
Watershed		1106	432	639	0	50		3	115	87
West	1996 –1997	1200	57	627	0	43	0	470	106	
North		1200	33	709	0	39	0	419	96	
South		1200	0	643	0	32	0	523	88	
Channel		1200	405406	835	0	70	407409	2298	206	
Watershed		1200	491	666	0	39		3	98	89
West	1997–1998	919	2	652	0	22	0	246	84	
North		919	0	739	0	15	0	166	62	
South		919	1	667	0	15	0	239	72	
Channel		919	171840	893	0	69	173741	1860	182	
Watershed		919	208	692	0	18		2	72	322
West	1998–1999	809	0	533	0	33	0	245	76	
North		809	0	575	0	30	0	205	69	
South		809	0	502	0	28	0	280	68	
Channel		809	192530	786	0	63	194556	1987	180	
Watershed		809	233	544	0	30		2	71	172
West	1999–2000	737	0	608	0	16	0	112	68	
North		737	0	665	0	9	0	63	51	
South		737	0	597	0	12	0	128	62	
Channel		737	76080	851	0	63	78075	1817	178	
Watershed		737	92	630	0	12		2	59	142

[†] P, precipitation; Q, surface runoff; E_p, plant transpiration; E_s, soil evaporation; D_p, deep percolation; UpQ, inflow from upstream element; Q_s, subsurface lateral flow; SWT, average total soil water; R, observed channel flow.

[‡] The large values of surface runoff for channels are due to their small area, on which water flow from the entire contributing area accumulates.

3.3. Water Flow and Sediment Yield

No runoff or sediment yield was simulated from WEPP v2004.7. Runoff and sediment yield from WEPP v2006.5 are given in Table 4.

Table 4. Runoff and sediment yield from WEPP v2006.5

Water Year	Precipitation (mm)	Observed Runoff (mm)	Observed Sediment (t ha^{-1})	Simulated Hillslope Avg. Runoff (mm)	Simulated Hillslope Avg. Sediment (t ha^{-1})	Simulated Watershed Runoff (mm)	Simulated Watershed Sediment (t ha^{-1})
1995–1996	1106	87	0	0	0.0	432	0
1996–1997	1200	89	0	45	0.0	491	0.2
1997–1998	919	322	0	1	0.0	208	0
1998–1999	809	172	0	0	0.0	233	0
1999–2000	737	142	0	0	0.0	92	0.0
Average	863	162	0	0	0	256	0.04

It appeared that WEPP v2006.5 overestimated watershed discharge for the first two monitored years. For the remaining years, the predicted runoff was generally agreeable with observed values. A likely reason was that field observation may be incorrect due to difficulties in properly measuring runoff by flumes in winter times. Water years 1995–1996 and 1996–1997 were both wet years with annual precipitation exceeding 1100 mm, much higher than the multiple-year average of 860 mm. Yet the field-observed runoff was only one fourth of the runoff in water year 1997–1998, a year slightly wetter than average. While runoff is governed by a multitude of factors, including the characteristics of storms (type, timing, intensity), under-recording due to ice accumulation and freezing of water in the measuring flume is not uncommon for mountainous study areas at high elevations (R.E. Brown, RMRS, USDA Forest Service, 2006, personal communication).

Comparison of WEPP-simulated and field-observed hydrographs indicates that the majority of observed stream flow occurred in the spring snowmelt season (Figure 6). For the first water year that spanned October 1995–September 1996, both simulated and observed hydrographs included winter and spring runoff with agreeable timing. However, the simulated runoff was five times greater than the observed. For the second water year, the modeled runoff had a high winter runoff peak yet field observation only shows a spring peak.

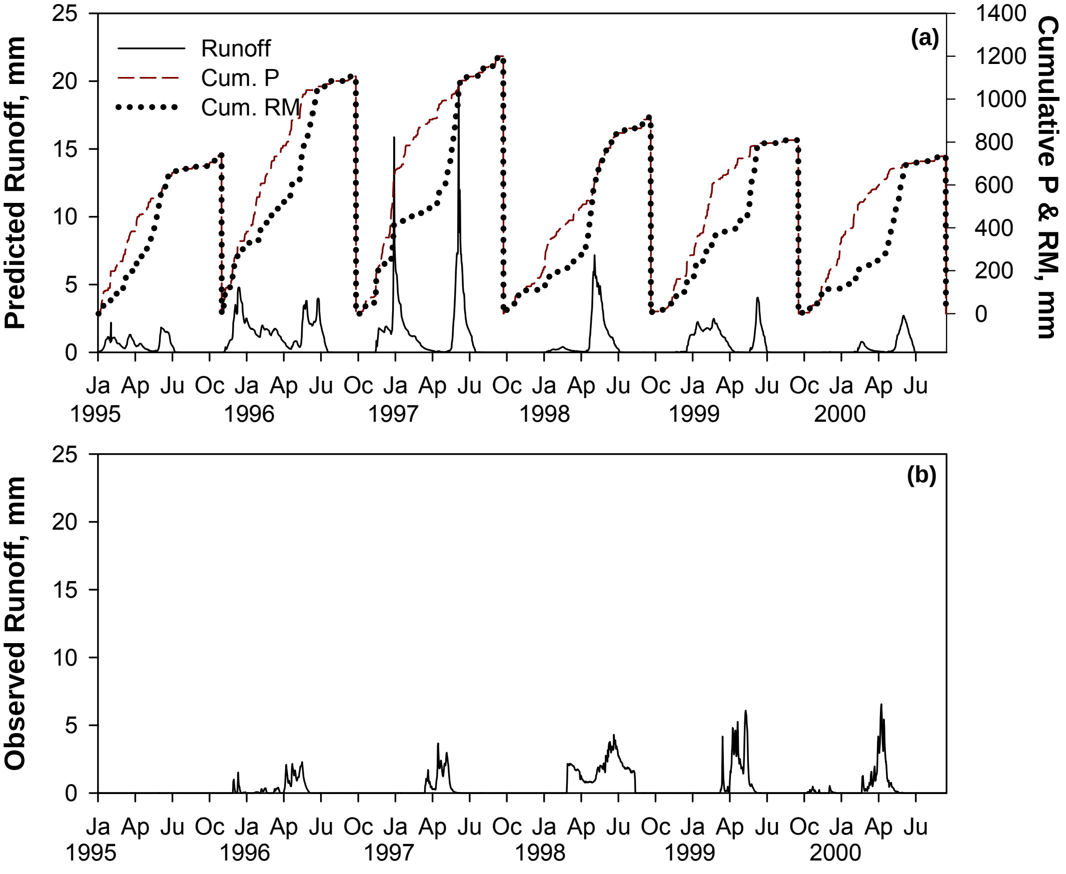

Figure 6. (a) predicted and (b) observed hydrograph. In (a), dashed lines represent cumulative precipitation, and dotted lines represent cumulative liquid water input (rain and snowmelt) that can directly cause runoff.

The third water year of 1997–1998 was rather special with substantial summer runoff. The observed hydrograph exhibited two peaks. WEPP simulated substantial summer runoff and two peaks. However, WEPP underestimated the yearly runoff. The simulated runoff was much lower than the observed for early spring. Yet a high peak was predicted for late spring as a result of concentrated rainfall events and rapid snowmelt. WEPP even predicted hillslope surface runoff due to saturation of the soil profile. It appears that the simulated snowmelt season started much later than occurred in reality. The concentrated snowmelt predicted for late spring possibly led to a joint spring and summer hydrograph.

In the last two water years, the observed runoff seems to have mainly originated from spring snowmelt. WEPP predicted somewhat larger amount of winter runoff for these two years, suggesting that the winter hydrology routines in WEPP may not be appropriate.

Small amount of runoff was observed during the fall of 1999. Nonetheless, the simulated soil water content during this time was low (0.01 $m^3\ m^{-3}$). The amount of rainfall was not sufficient to replenish soil water and to generate runoff in the simulation. A possible reason for some runoff to occur when the entire watershed is still dry is that the lower part of the watershed has reached saturation (W.J. Elliot, RMRS, USDA Forest Service, personal communication, 2006). The use of multiple OFEs may be help to more properly represent such conditions.

There was essentially no difference in predicted sediment yield by the two versions of WEPP model. The slightly increased sediment yield for 1997 was due to increase in channel erosion as caused by elevated channel flow. The predicted runoff mainly originated from hillslope subsurface lateral flow. In consequence, hillslope soil erosion was negligible and watershed sediment yield was low, consistent with field observations.

Summary and Conclusion

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 soil water percolation and subsurface lateral flow. The refined WEPP model has the ability to appropriately partition infiltrated water between percolation and subsurface lateral flow through the use of a restrictive layer specified by 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 the original model, the modified WEPP (v2006.5) more realistically and properly represents the hydrologic processes in forest settings. Additionally, with changes made to the vegetation growth routines, v2006.5 could properly simulate living biomass and ground-cover for perennial vegetation, crucial to forest applications.

Model application to Hearmada watershed, a representative forest watershed in central Idaho, yielded good agreement between model predictions and field observations, demonstrating the adequacy of the model modifications.

Future efforts should be devoted to evaluating the suitability of the modified WEPP for applications to forest watersheds under a wide range of climatic, plant, and soil conditions. In addition, the winter hydrology routines of WEPP should be thoroughly evaluated for reliable applications to forest settings.

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