EVALUATION OF RUNOFF PREDICTION FROM WEPP-BASED EROSION MODELS FOR HARVESTED AND BURNED FOREST WATERSHEDS

S. A. Covert, P. R. Robichaud, W. J. Elliot, T. E. Link

ABSTRACT. *This study evaluates runoff predictions generated by GeoWEPP (Geo-spatial interface to the Water Erosion Prediction Project) and a modified version of WEPP v98.4 for forest soils. Three small (2 to 9 ha) watersheds in the mountains of the interior Northwest were monitored for several years following timber harvest and prescribed fires. Observed climate variables, percent ground cover, soil erodibility values, and GIS-derived slope data were used to drive the models. Predictions of total yearly runoff generated by GeoWEPP (WEPP v2002.7) and the modified WEPP model were compared to total yearly runoff measured at each watershed. In addition, measured seasonal values were compared to the predictions generated by the modified WEPP model. GeoWEPP significantly underpredicted the total yearly runoff for all three sites. The modified WEPP model, with algorithm changes to account for deep percolation and subsurface lateral flow, predicted total yearly runoff for two of the three sites with an index of agreement (d) of 0.8 and 0.9 for each. The third site performed less accurately, with d = 0.3. In the seasonal runoff predictions, the modified WEPP model was most accurate for the spring months (higher runoff) but was a poor predictor for other seasons when the measured runoff rates were low. The GeoWEPP model successfully incorporates digital elevation data, but the WEPP version used to process the data does not adequately represent the hydrological processes of forests. The lateral flow modifications that were added to the WEPP model improved predictions of runoff in forests, thus suggesting that further refinement of these calculations may improve the accuracy of WEPP-based models when applied to forest environments.*

Keywords. *GeoWEPP, Model evaluation, Prescribed fire, Runoff prediction, Timber harvest, Watershed, WEPP.*

Undisturbed forests are a source of clean water necessary to sustain ecosystem health as well as for urban and agricultural use. High infiltration rates and low levels of overland flow result from the vegetation and litter that protect the soil against the forces of erosion (Baker, 1990; Croke et al., 1999). Although forest managers attempt to minimize impacts of their activities, the removal of vegetation and the alteration of soil properties due to logging, road building, and prescribed fire may adversely impact forest runoff and water quality (Lindeburgh, 1990; Lousier, 1990; Rice, 1999; Tiedemann et al., 1979).

Watershed modeling is useful for evaluating the hydrologic effects of potential management decisions before they are applied to the landscape. Process-based models can be tailored and applied to a wide variety of individual locations, making them extremely versatile tools. However, it is imperative to validate the predictive ability and limitations of a new model or a new adaptation to a model before it is used as a management tool (Westervelt, 2000).

The Water Erosion Prediction Project (WEPP) model is a physically based, numerical process model used to predict runoff and erosion on a simple hillslope or in a watershed mode (including hillslopes combined with channels and impoundment elements) for agriculture, forestry, and range management (Flanagan et al., 1995). The WEPP model has undergone continuous development since first released in 1989 to improve its accuracy and extend its applicability to a broader range of conditions. Although the WEPP model has been successfully applied to agricultural environments (Elliot et al., 1991; Povilaitis et al., 1995; Tiwari et al., 2000), predictions of forest runoff and erosion have been less successful. Elliot et al. (1996) conducted a WEPP accuracy assessment within a harvested forest watershed and found that WEPP predicted only half of the observed runoff and ten times the observed sediment.

Geographic information systems (GIS) are being used for advanced modeling in complex, less accessible, and more spatially variable mountainous terrain. The GeoWEPP model (GeoWEPP ArcX 2003; Renschler, 2003) combines the WEPP v2002.7 model (Flanagan et al., 1995) with Topography Parameterization software (TOPAZ) (Garbrecht and Martz, 1997) within the ArcView 3.2 GIS program (ESRI, 2000) to predict runoff and erosion at the hillslope and watershed scale. GeoWEPP was developed to allow WEPP hillslope parameterization to be based on digital data sources, such as digital elevation models (DEMs), and for digital outputs to be viewed and analyzed in a GIS environment (Renschler, 2003).

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A GeoWEPP validation study was done using six small forest watersheds in the western U.S. that had been burned at high severity by wildfires. Using 30 m DEMs, GeoWEPP overpredicted runoff by 10 to 50 times relative to observed values and underpredicted sediment yield by one-half of the observed values for these six watersheds (Koopman, 2002). Although this evaluation of GeoWEPP is contrary to the evaluation of WEPP by Elliot et al. (1996), both studies reflect the problems of using the WEPP-based models for runoff and erosion predictions in forest environments.

WEPP was originally developed to model runoff and erosion on small agricultural watersheds; however, forest soils have some significant differences from agricultural lands. Runoff flow type (overland or subsurface) and intensity influence the amount of erosion that will occur, and effective erosion modeling requires that those runoff factors be accurately simulated. Although overland flow results in the majority of hillslope erosion (Wondzell and King, 2003), subsurface flow, because it is deposited in channels and streams, increases channel flow rates and erosions. Wu et al. (2000) found that the WEPP model overestimates soil water deep percolation and underestimates subsurface lateral flow in forest conditions for three main reasons. First, WEPP estimates saturated hydraulic conductivity (k_{sat}) for the lower soil layers based on an empirical formula that assumes that the soils are deep and relatively uniform in structure and texture; however, forest soils are often shallow and have an impermeable bedrock layer (Luce, 1995). An overestimation of k_{sat} for the lower layers of a forest soil results in an overestimation of the soil water content. Soil water exceeding field capacity is subject to percolation through the succeeding layer, and when this water moves below the root zone, it is considered lost and is not traced by WEPP (Savabi and Williams, 1995). Second, WEPP assumes that the soil profile is isotropic (i.e., the horizontal and vertical k_{sat} are equal), as is more common in agricultural soils. This is an inadequate assumption for forest soils, where k_{sat} values are higher parallel to the soil surface (lateral flow) than perpendicular to the surface. Higher lateral flow is due to ground cover and complex root systems that allow water to flow horizontally through the soil, as well as young, shallow soils with underlying bedrock and sloping terrain that are typical in forests (Luce, 1995). Third, WEPP calculates the amount of lateral flow separately, after the removal of the excess water through deep percolation, when in reality these processes take place simultaneously. The combination of these reasons causes WEPP to underestimate lateral flow in forest watersheds.

To account for this underestimation, Wu et al. (2000) developed a modified version of WEPP v98.4 for forest soils, which, for the purposes of this study, will be referred to as “modified WEPP.” The modified WEPP model contains two primary changes: (1) the addition of a bedrock layer (hydraulic conductivity approximately zero) to the soil profile to limit the amount of water allocated to deep percolation and increase the amount of subsurface lateral flow reaching the bottom of the hillslope, and (2) the addition of subsurface lateral flow to the channel flow to increase total water yield. Wu et al. (2000) made a preliminary assessment of the modified WEPP model using a conceptual watershed and found that outputs of runoff and sediment resulting from the modified algorithms appeared to represent forest hydrologic processes in a more realistic manner than the original WEPP algorithms.

The purpose of this study is to evaluate the predictions of: (1) yearly runoff from the GeoWEPP model interface, and (2) yearly and seasonal runoff from the modified WEPP model v98.4 for disturbed forest watersheds using previously unpublished runoff data from three small (2 to 9 ha) harvested and burned forest watersheds (collected by researchers at the Rocky Mountain Research Station in Moscow, Idaho).

STUDY SITES

Three watersheds, located in the interior Northwest (fig. 1), were burned following timber harvest. The monitoring of each site began within two to three weeks following the burns. The harvest method varied from site to site based on the objectives of the forest manager, and the burns were conducted by USDA Forest Service personnel without the influence of the specific research objectives. Post-fire burn severity classification was conducted using techniques described by Phillips and Abercrombie (1987) and Ryan and Noste (1983).

HERMADA

The Hermada site is located in the Boise National Forest, southeast of Lowman, Idaho (fig. 1). The 9 ha site contains slopes from 40% to 60% with southeastern and northeastern aspects. The elevation ranges from 1760 to 1880 m. The soils (Typic Cryumbrept) contain 85% sand, 13% silt, and 2% clay, formed from weathered granite (Robichaud, 2000). The primary tree species, ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*), were harvested in 1992 using a cable-yarding system. The harvest objective was a seed tree cut, leaving 5 to 10 trees ha^{-1}. The prescribed fire, conducted on 17 October 1995, produced an overall low-severity burn with a large portion of the site unburned (table 1) (Robichaud, 2000).

SLATE POINT

Slate Point is located in the Bitterroot National Forest near Painted Rocks Reservoir, south of Sula, Montana (fig. 1). The 7 ha site contains slopes from 40% to 63% on predominantly north aspects. The elevation ranges from 1620 to 1780 m. The

Figure 1. Locations of the three watersheds used in this study.

Table 1. Summary of site information for each watershed.

Site Parameters	Hermada	Slate Point	Round-Up
Location (decimal degrees)	43.87 N, 115.35 W	45.71 N, 114.27 W	45.12 N, 116.38 W
Size (ha)	9	7	2
Harvest year and technique	1992: Cable-yarded	1993: Cable-yarded (lower); ground-based skid (upper)	1991: Ground-based skid
Burn date	17 Oct. 1995	29 June 1994	15 June 1993
Dates monitored	3 Nov. 1995 to 30 Sept. 2000	6 July 1994 to 9 June 1998	6 July 1993 to 22 July 1996
Percent of area (and number of 1 m^2 plots):			
undisturbed	40 (3)	20 (2)	60 (2)
with low-severity burn	55 (3)	65 (8)	23 (10)
with high-severity burn	5 (5)	15 (4)	0
with bladed skid trail	0	0	17 (8)

soils (Typic Cryoboralf and Dystric Cryochrept) contain 83% sand, 12% silt, and 5% clay, formed from weathered rhyolite (Robichaud, 2000). The main tree species, Douglas fir and lodgepole pine (*Pinus contorta*), were harvested in 1993 using a ground-based skidding system in the upper third of the site (which was divided by a road) and a cable-yarding system in the lower portion. The harvest objective was a clearcut with snag replacements, leaving 7 to 12 trees ha^{-1}. The burn was conducted on 29 June 1994, one year after timber harvest. Ignition technique, fuel moisture, and weather during the burn produced an intense fire concentrated in the center of the site, while the portion above the road burned very slowly and cool. The result was a mosaic of fire severity ranging from a small portion of high-severity burn to a much larger portion of low-severity burn (table 1) (Robichaud, 2000).

Round Up

The Round Up site, located in the Payette National Forest, northwest of New Meadows, Idaho (fig. 1), is a 2 ha watershed located on a 50% slope, with a predominantly northwest-facing aspect. The elevation ranges from 1480 to 1600 m. The soils (Typic Cryochrept) contain 35% sand, 40% silt, and 25% clay, derived from basalt parent material (Elliot et al., 1996). The main tree species (Douglas fir and ponderosa pine) were clearcut in 1991 using a ground-based skidding system, which left eight bladed skid trails parallel to the contour that occupy approximately 17% of the area. The Round Up burn was conducted on 15 June 1993. At the time of burning, the site was covered in shrub regrowth up to 1 m high and did not ignite easily or burn at a high intensity due to high fuel moisture content. The result was a patchy mosaic of low severity and unburned areas (table 1) (Elliot et al., 1996).

Data Collection

To run a simulation, WEPP-based models require four user-input files that describe the climate, soil, management, and slope (Flanagan et al., 1995). Climate, soil erodibility, ground cover, and slope parameters, as well as watershed outputs, were measured (or estimated when needed) for each of the three watersheds. All input parameters and output data from each site were corrected for instrument errors and converted into formats suitable for the WEPP-based models.

Slope Input Variables

The slope profiles for three watersheds were derived through the TOPAZ application in GeoWEPP using 30 m DEMs downloaded from the USDA-NRCS Geo-spatial Data Gateway (NRCS, 2002). TOPAZ generated three hillslopes and a channel for each watershed that were used in both the GeoWEPP and the modified WEPP simulations.

The watersheds derived from TOPAZ are shown in figures 2, 3, and 4, where the shaded, pixilated areas are the individual hillslopes and channels overlaid on a contour map. The solid outline represents the watershed boundary, and a star represents the approximate location of the instrumented catchment basin. Each hillslope was named based on its geographic location on the watershed: north (N), south (S), east (E), and west (W). The TOPAZ-delineated watersheds and hillslopes were used for all simulations.

The errors associated with TOPAZ watershed generation are size and location. TOPAZ overestimated the size of the small Round Up watershed due to the large pixel size of the DEM (fig. 4). Due to a discrepancy in the geographic projections of the DEM and contour map, there is a slight offset between the TOPAZ-generated watersheds and the actual watershed location as depicted on the contour map, specifically at Slate Point (fig. 3).

Climate Input Variables

A climate file was made for each study that covered the period each watershed was monitored. Maximum and minimum air temperature, relative humidity, precipitation, solar radiation, and wind speed were recorded at each

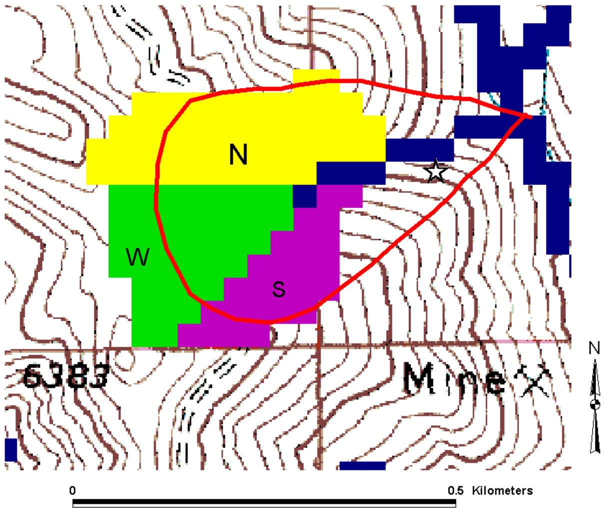

Figure 2. Hermada watershed outlined (9.0 ha) and hillslopes and channel delineated by TOPAZ (9.9 ha) on 6.1 m (20 ft) contour map.

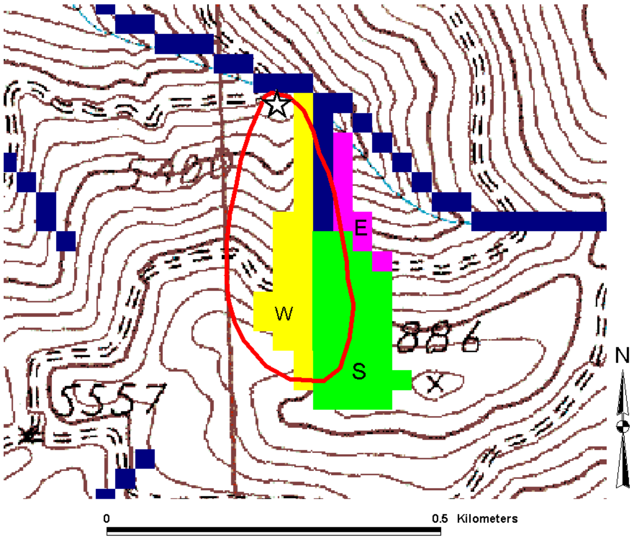

Figure 3. Slate Point watershed outlined (7.0 ha) and hillslopes and channel delineated by TOPAZ (6.0 ha) on 6.1 m (20 ft) contour map.

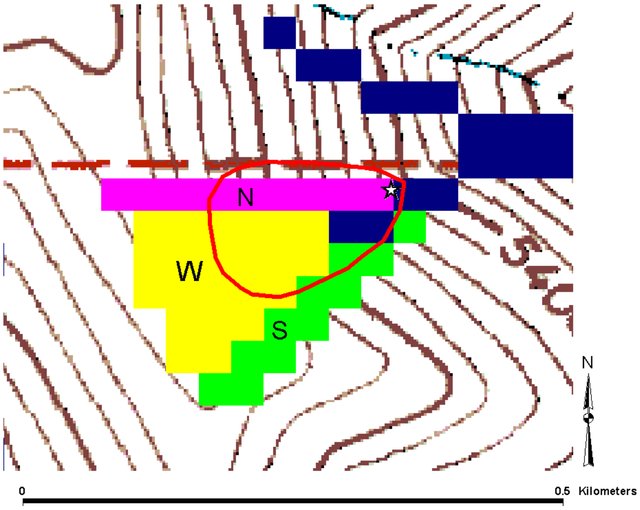

Figure 4. Round Up watershed outlined (2.0 ha) and hillslopes delineated by TOPAZ (3.8 ha) on 6.1 m (20 ft) contour map.

watershed for the duration that instrumentation was installed (see table 1 for monitoring dates). Small data gaps caused by sensor malfunctions were filled with weather data stochastically generated for the same location using Rock:Clime (a climate generation interface of FSWEPP) (Elliot and Hall, 2000). Of the total days each watershed was monitored, approximately 4%, 3%, and 10% of the climate data were missing for Hermada, Slate Point, and Round Up, respectively.

SOIL INPUT VARIABLES

Previous studies (Robichaud, 2000) suggest that infiltration can be related to four distinct hydrologic/surface conditions: high-severity burns, low-severity burns, bare mineral soil (roads, skid trails, landings), and undisturbed (natural) conditions. Plots of 1 m^2 were randomly located within each of the identified hydrologic/surface conditions at each study site (table 1). Runoff and sediment were collected at each plot from simulated rainfall experiments using 30 min rainfall events of approximately 94 mm h^{-1} intensities and were used to calculate hydraulic conductivity and interrill erodibility in each hydrologic/surface condition. These methods are described in detail by Robichaud (2000) and Elliot et al. (1996). Hydraulic conductivity was estimated from the Green-Ampt effective hydraulic conductivity equation used in the WEPP model based on rainfall amount, surface cover, and runoff (Alberts et al., 1995; Robichaud, 1996). Interrill erodibility, the susceptibility of soil particles to be dislodged by the impact of raindrops (Ward and Elliot, 1995), was calculated from a modified version of the sediment delivery equation (Laflen et al., 1991; Robichaud, 1996).

Rill erodibility, the susceptibility of soil detachment and transport by a concentrated stream of water (Ward and Elliot, 1995), has been calculated for locations throughout the interior Northwest within high and low burn severities and different soil types (sand, silt, clay, and loam) (P. R. Robichaud, USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho: unpublished data, 2003). Using 3 m wide by 9 m long plots, a continuous, calibrated stream of water was applied at the top of the plot, and sediment and runoff were collected at the bottom at specific time intervals throughout the run. Rill erodibility values (table 2) were selected from the database of measured rill erodibility values (P. R. Robichaud, USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho: unpublished data, 2003) for each hillslope based on burn severity and soil type.

Saturated hydraulic conductivity values for different bedrock types were chosen from a list of measured values compiled by Domenico and Schwartz (1990) and used in the modified WEPP simulations based on the observed parent material at each watershed. The bedrock hydraulic conductivities used were 5.2×10^{-5}, 0.01, and 2.0×10^{-11} mm h^{-1} for Hermada, Slate Point, and Round Up, respectively.

Each hillslope was assigned a hydrologic/surface condition based on the prominent disturbance type. Soil files for each hydrologic/surface condition were built in WEPP by entering the associated, measured values of hydraulic conductivity, interrill erodibility, rill erodibility, and soil texture into an existing forest soil file. Default values for other soil parameters were left unchanged for all soil files. The same soil parameters were used for the first and second years of simulation, assuming little change would occur from fall of the first year to the spring of the second year due to winter conditions. For the subsequent years, soil files were generated by increasing hydraulic conductivity and reducing interrill and rill erodibility values to one disturbance severity level less than the previous year until reaching undisturbed site values (table 2). This method represents an approximate recovery rate of 3 years for low-severity burns and 4 to 6 years for high-severity burns and skid trails, which are similar to the recovery rates observed by Robichaud and Brown (1999). For example, in 1994, Slate Point received low-severity burns on the east and south hillslopes, while the west had a high-severity burn. In 1995, the values were left unchanged. In 1996, the low-severity hillslopes were considered to have recovered to the unburned condition, while the high-severity hillslope was reduced to low severity. Each year was changed in this manner until the hillslope reached an undisturbed condition or the end of the simulation period, whichever came first. At the Hermada site, the hydraulic conductivity

Table 2. Input parameter values used for model simulations, observed yearly precipitation, and observed runoff for each watershed and its hillslopes. In the hydrologic/surface condition column, low = low burn severity and high = high burn severity.

Site and Year	Hillslope	Hydrologic/ Surface Condition	Rill Erodibility (s m^{-1})	Interrill Erodibility (kg s m^{-4} × 1000)	Hydraulic Conductivity (mm h^{-1})	Ground Cover (%)	Observed Precipitation (mm)	Observed Runoff (mm)
Hermada								
1995	West/north	Low	0.00034	3994	17.1	90	207	8[a]
	South	Unburned	0.00001	2715	16.6	95		
1996	West/north	Low	0.00034	3994	17.1	95	870	78
	South	Unburned	0.00001	2715	16.6	95		
1997	West/north	Low	0.00001	2715	16.6	98	673	89
	South	Unburned	0.00001	1436	16.6	95		
1998	West/north	Low	0.00001	1436	16.6	99	1196	322
	South	Unburned	0.00001	1436	16.6	95		
1999	West/north	Low	0.00001	1436	16.6	99	474	179
	South	Unburned	0.00001	1436	16.6	95		
2000	West/north	Low	0.00001	1436	16.6	100	528	136[b]
	South	Unburned	0.00001	1436	16.6	95		
Slate Point								
1994	East/south	Low	0.00040	3279	14.0	97	221	0[a]
	West	High	0.00060	5572	13.9	69		
1995	East/south	Low	0.00040	3279	14.0	98	568	43
	West	High	0.00060	5572	13.9	85		
1996	East/south	Low	0.00037	1202	16.1	99	519	53
	West	High	0.00050	3279	14.0	92		
1997	East/south	Low	0.00034	1202	16.1	100	714	97
	West	High	0.00040	1202	16.1	96		
1998	East/south	Low	0.00030	1202	16.1	100	242	33[b]
	West	High	0.00037	1202	16.1	98		
Round Up								
1993	South	Low	0.00035	3000	11.0	84	190	0[a]
	West	Unburned	0.00015	200	80.0	100		
	North	Skid trail	0.00055	1000	12.0	58		
1994	South	Low	0.00035	3000	11.0	92	300	51
	West	Unburned	0.00015	200	80.0	100		
	North	Skid trail	0.00055	1000	12.0	79		
1995	South	Low	0.00025	1000	15.0	96	537	13[c]
	West	Unburned	0.00015	150	80.0	100		
	North	Skid trail	0.00035	800	18.0	89		
1996	South	Low	0.00015	1000	18.0	98	265	32[b]
	West	Unburned	0.00015	150	80.0	100		
	North	Skid trail	0.00033	800	20.0	95		

[a] First year of study does not include spring runoff. See monitoring dates in table 1.

[b] Last year of study does not include a full year of data. See monitoring dates in table 1.

[c] Runoff for Round Up in 1995 only includes data from January through April due to a sensor malfunction.

appears to decrease slightly over time (17.1 to 16.6 mm h^{-1}); however, these were measured values. The hydraulic conductivity value for unburned sites at Round Up is very high (80 mm h^{-1}) due to a thick layer of litter. The generated values in the following years do not reach this value because it would take many years to develop the depth of litter that was observed on the undisturbed sites.

Management Input Variables

For each of the study sites, management files were created to represent an undisturbed forest condition followed by a fire that reduced the amount of ground cover to the amount measured in each hydrologic/surface condition, followed by subsequent recovery of ground cover each consecutive year. The percent ground cover (including vegetation, duff, litter, and woody debris) was measured immediately after each fire on the 1 m^2 rainfall simulation plots by characterizing the surface at each 100 mm intersection of a grid frame (Robichaud, 1996). The initial ground cover assessment was used to estimate the following years by assuming an increase of half of the difference between the previous year and the unburned cover values (table 2) (Elliot et al., 2001). The results derived from this method are consistent with measured values from Noste (1982).

Measured Watershed Outputs

After each burn, a 1 m^3 sediment trap fitted with a calibrated, 1 foot, H-flume was constructed at the bottom of each watershed to measure runoff. Total watershed runoff was estimated using pressure transducers and flow depth float measurements at the watershed outlet. In 1995, runoff data for the Round Up site was not recorded properly from May to December due to a faulty sensor. This is noted in table 2, and in the following Results section. At all of the study sites, the observed runoff was low in the first year due to the fact that the instrumentation was not installed until the summer, after the spring runoff events (table 2). Similarly, the last year of each study does not include a full year of data.

MODEL IMPLEMENTATION

The watershed simulation mode (which includes hillslope and channel erosion) was not used in this study because TOPAZ generated significantly larger channels than actually existed in the small watersheds used in this study. Both GeoWEPP and modified WEPP were run in hillslope simulation mode using the TOPAZ-generated hillslopes and excluded channel effects. The runoff values from the three hillslopes in a given watershed were added together to estimate total watershed runoff.

ANALYSIS METHODS

Yearly runoff outputs from GeoWEPP and modified WEPP, and seasonal runoff outputs from modified WEPP, were compared to measured watershed runoff to evaluate the accuracy of each model. Each year was partitioned into four seasons such that winter was December through February, spring was March through May, summer was June through August, and fall was September through November. GeoWEPP outputs are only available in yearly outputs; therefore, no seasonal comparisons were made with those data.

The root mean squared error (RMSE) (Willmott, 1981, 1984) was used to evaluate the predictive ability of the models. This method has been used to evaluate prediction performance of other models (Elliot et al., 1991; Povilaitis et al., 1995; Zacharias and Heatwole, 1994). The following assessment descriptors were used in this study:

- Observed and predicted means ($\overline{O}$ and $\overline{P}$, respectively).
- Observed and predicted standard deviations (s_o and s_p, respectively).
- Total root mean squared error (RMSE) represents the error or difference between the observed and predicted values, and can be used to derive other useful information about the nature of the error. The RMSE, which has the same units as the predicted and observed values (Willmott, 1981), is expressed as:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (P_i - O_i)^2}{N}} \qquad (1)$$

  where N is the number of paired observations, P is the predicted value, and O is the observed value.
- Systematic error (RMSE_s) shows how far the data fluctuate from the 1:1 line in a plot of predicted versus observed values, indicating errors due to under- or overprediction by the model.
- Unsystematic error (RMSE_u) is the amount of error not accounted for in the systematic error and represents random errors associated with the data. When the systematic error is minimized and unsystematic error approaches RMSE, the model is performing with maximum accuracy:

$$\text{RMSE}_s = \sqrt{\frac{\sum_{i=1}^{N} (\hat{P}_i - O_i)^2}{N}} \qquad (2)$$

$$\text{RMSE}_u = \sqrt{\frac{\sum_{i=1}^{N} (P_i - \hat{P}_i)^2}{N}} \qquad (3)$$

  where $\hat{P}_i = a + bO_i$, and a and b are the intercept and slope of the least-squares simple linear regression, respectively.
- Index of agreement (d) (Willmott, 1984) is a dimensionless value that gives an overall assessment of the prediction accuracy by describing the degree to which O is approached by P. It is calculated:

$$d = 1 - \left[\frac{\sum_{i=1}^{N} \left| P_i - O_i \right|}{\sum_{i=1}^{N} \left[(P_i - \overline{O}) + (O_i - \overline{O}) \right]} \right] \qquad (4)$$

  where the resulting d has a value ranging from 0.0 to 1.0 (0.0 meaning no agreement, and 1.0 meaning a perfect fit between the observed and predicted values).

RESULTS AND DISCUSSION

FIELD OBSERVATIONS

Overall, the management on all three sites caused relatively little runoff, which is likely due to the management techniques used. Values of all measured and estimated model input parameters and watershed outputs are shown in table 2 for the three watersheds.

GEOWEPP

The GeoWEPP simulations predicted no runoff on any of the sites for any year, with the exception of a small amount in 1998 at the Hermada site. The hillslopes generated by TOPAZ should have resulted in an overprediction of runoff due to the slightly oversized watersheds. Closer investigation of the water output from the GeoWEPP runs indicated that the lack of runoff was due to errors in the WEPP v2002.7 code, as described earlier. The results from these simulations indicate that the predictive ability of the GeoWEPP model for runoff in small, harvested, and burned forest watersheds is poor.

MODIFIED WEPP V98.4

The modified WEPP model predicted more realistic yearly runoff values than the GeoWEPP model. The yearly simulations consistently overpredicted runoff at Hermada (fig. 5) and significantly improved the runoff outputs for Slate Point (fig. 6) and Round Up (fig. 7).

Of the three sites, Slate Point has the highest index of agreement (0.9) and a low RMSE_u approaching the RMSE (table 3). Hermada also has a high index of agreement (0.8);

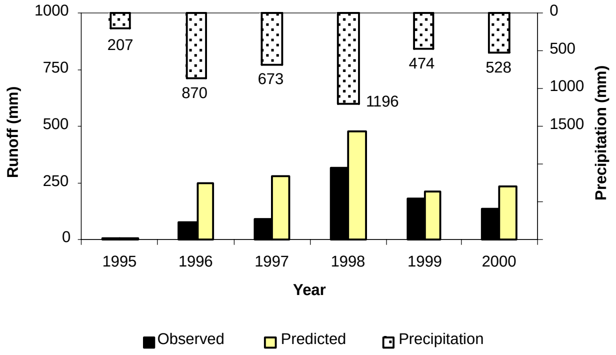

Figure 5. Comparison of modified WEPP total yearly observed and predicted runoff for Hermada hillslopes.

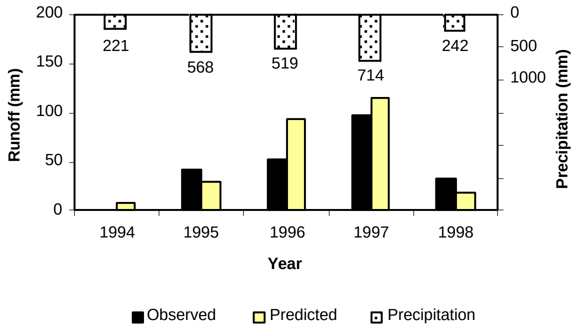

Figure 6. Comparison of modified WEPP total yearly observed and predicted runoff for Slate Point hillslopes.

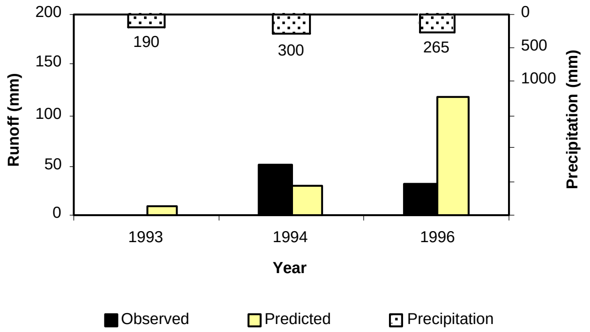

Figure 7. Comparison of modified WEPP total yearly observed and predicted runoff for Round Up hillslopes (excludes 1995 due to sensor malfunction).

Table 3. RMSE statistics for modified WEPP yearly simulations for the three watersheds.

	Runoff (mm)					
	Hermada		Slate Point		Round Up[a]	
	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
Mean	135	245	45	53	28	53
Std Dev.	108	150	35	48	25	54
Intercept *a*	83.2		−1.9		33.0	
Slope *b*	1.2		1.2		0.7	
N	6		5		3	
RMSE	131		22		52	
$RMSE_s$	111		11		26	
$RMSE_u$	70		19		45	
Index of agreement	0.8		0.9		0.3	

[a] 1995 data for Round Up was not included in yearly analysis due to missing runoff data.

however, the high $RMSE_s$ indicates that the model overpredicted the runoff for this site. The Round Up site has the poorest yearly simulations results (d = 0.3), which are attributed to the small watershed size, lost data, and a short monitoring period. In addition to the missing data in 1995, runoff was overpredicted in 1996 as a result of substituting stochastically generated climate data from 1 January to 1 March 1996 in order to replace data lost due to a rain gauge malfunction. In general, the modified WEPP model overpredicted runoff, which was likely due to the oversized watersheds generated by TOPAZ. Other possible discrepancies may have come from the bedrock hydraulic conductivity values. Runoff output was very sensitive to the bedrock hydraulic conductivity values, and although the most suitable values based on the known bedrock were used, these may not have been completely accurate. Modified WEPP significantly improved yearly runoff predictions, which indicates that the model has the potential to accurately predict runoff. However, the inconsistent results between sites imply that further modification to the model is needed.

The seasonal runoff predictions from modified WEPP were, in general, more accurate for spring than for the other three seasons. As with the yearly simulations, seasonal runoff was overpredicted, but less severely at Slate Point and Round Up (fig. 8, 9, and 10). At all three sites, the greatest amount of simulated runoff occurs in the spring, which is consistent with the observations at all three watersheds. In summer, fall, and winter, runoff is overpredicted because the modified WEPP model generates runoff from all rain events in the form of subsurface lateral flow, which results in a continuous water output (Wu et al., 2000).

On average, modified WEPP overpredicted seasonal runoff (table 4). The best overall results occur in the spring months, suggesting that runoff prediction accuracy is higher for the larger observed runoff events. The least accurate results occurred where little or no runoff was measured in summer, fall, and winter. Slate Point had the best results of the three watersheds due to the higher observed values each season. Inconsistency between sites indicates that further modification to the model is necessary to improve predictions for different environmental conditions.

The seasonal analysis shows that modified WEPP improved overall runoff predictions as compared to the WEPP model used in GeoWEPP, but modified WEPP overpredicted runoff in drier months when no runoff was measured. This overprediction is due, in part, to the increased lateral flow generated by the modified algorithms in the model and oversized watersheds generated by TOPAZ. Again, as with the yearly simulations, the inconsistent accuracy of results between sites implies that further refinement of the model is necessary.

CONCLUSIONS

The GeoWEPP model, which incorporates digital elevation data with WEPP v2002.7 to generate runoff and sediment outputs for complex topographic regions, has the potential to be a useful management tool for forestry applications. However, the version of WEPP used in

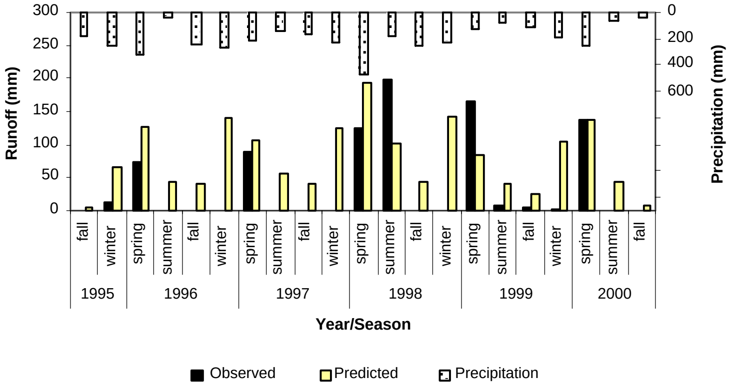

Figure 8. Comparison of observations and modified WEPP predictions of seasonal runoff for Hermada hillslopes.

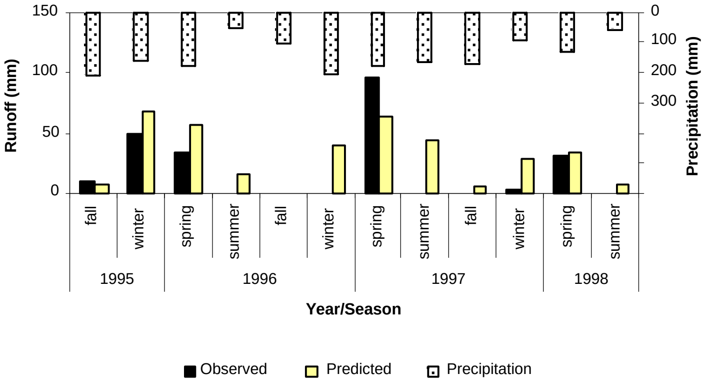

Figure 9. Comparison of observations and modified WEPP predictions of seasonal runoff for Slate Point hillslopes.

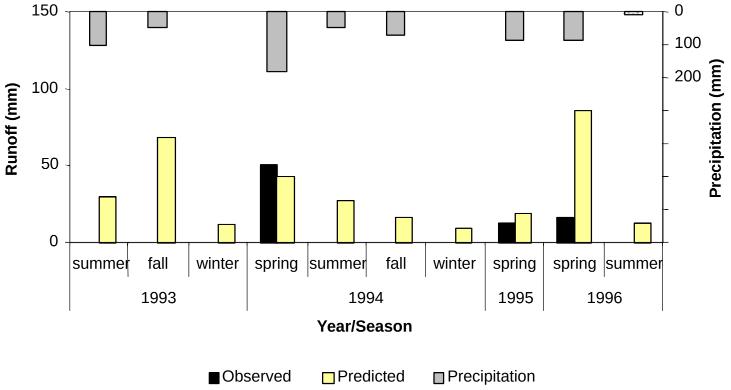

Figure 10. Comparison of observations and modified WEPP predictions of seasonal runoff for Round Up hillslopes (runoff data were not recorded from May through December 1995 due to a sensor malfunction.)

GeoWEPP at the time of this study did not accurately predict runoff in the three small harvested and burned forest watersheds. GeoWEPP is currently being refined to incorporate more detailed spatial data, which will improve the accuracy of watershed delineation and spatial variability within hillslopes (Renschler, 2003). However, GeoWEPP predictions of forest erosion would be improved if a refined and validated version of modified WEPP was also incorporated.

The modified version of WEPP v98.4 for forest conditions (Wu et al., 2000) generated more accurate yearly runoff predictions than WEPP v2002.7 (used in GeoWEPP); however, runoff was overpredicted at all sites. Seasonal predictions were most accurate when measured runoff was highest. Modified WEPP generates runoff from all rain events in the form of subsurface lateral flow, which results in a continuous water output, and leads to an overprediction of runoff when little or no runoff is measured. Although the modified WEPP model generated more realistic values of forest runoff, further refinement of the water balance algorithms is required to ensure that hydrologic processes are simulated correctly for a variety of conditions and seasons.

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Table 4. Seasonal runoff RMSE statistics from modified WEPP simulations for the three watersheds.

	Runoff (mm)					
	Hermada		Slate Point		Round Up	
	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
Spring						
Mean	117.3	128.5	54.0	51.0	26.3	49.0
Std Dev.	36.9	42.3	37.0	15.6	21.2	34.0
Intercept a	151.1		34.9		52.9	
Slope b	−0.2		0.3		−0.1	
N	5		3		3	
RMSE	55.4		23.2		40.9	
RMSE$_s$	40.9		21.4		30.2	
RMSE$_u$	37.3		9.0		27.6	
Index of agreement	0.2		0.7		0.3	
Summer						
Mean	41.4	56.2	0.0	22.1	0.1	22.6
Std Dev.	88.0	25.5	0.0	19.1	0.1	9.6
Intercept *a*	44.5		0		34.6	
Slope *b*	0.3		0		−123.4	
N	5		3		4	
RMSE	58.5		27.1		23.9	
RMSE$_s$	58.4		0.0		23.9	
RMSE$_u$	4.7		27.1		1.1	
Index of agreement	0.7		0.0		0.0	
Fall						
Mean	0.7	26.8	3.6	4.1	0.1	41.7
Std Dev.	1.6	17.5	5.6	3.6	0.2	37.1
Intercept *a*	27.4		2.7		68.4	
Slope *b*	−0.8		0.4		−228.4	
N	6		3		3	
RMSE	30.7		3.6		49.3	
RMSE$_s$	26.2		2.8		49.3	
RMSE$_u$	15.9		2.3		0.0	
Index of agreement	0.1		0.8		0.0	
Winter						
Mean	2.9	115.1	17.6	45.5	0.0	29.9
Std Dev.	5.2	31.9	28.1	20.6	0.0	35.5
Intercept *a*	131.8		33.3		37.7	
Slope *b*	−5.8		0.7		−618.9	
N	5		3		3	
RMSE	116.9		29.3		9.5	
RMSE$_s$	116.6		28.8		9.5	
RMSE$_u$	9.3		5.2		0.0	
Index of agreement	0.0		0.7		0.0	

REFERENCES

Alberts, E. E., M. A. Nearing, M. A. Weltz, L. M. Risse, F. B. Pierson, X. C. Zhang, J. M. Laflen, and J. R. Simanton. 1995. Soil component. In *USDA-Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation,* 7.1-7.47. NSERL Report No. 10. D. C. Flanagan and M. A. Nearing, eds. West Lafayette, Ind.: National Soil Erosion Research Laboratory.

Baker, M. B., Jr. 1990. Hydrologic and water quality effects of fire. Gen. Tech. Report RM-191. Fort Collins, Colo.: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station.

Croke, J., P. Hairsine, and P. Fogarty. 1999. Runoff generation and re-distribution in logged eucalyptus forests, southeastern Australia. *J. Hydrol.* 216(1/2): 56-77.

Domenico, P. A., and F. W. Schwartz. 1990. *Physical and Chemical Hydrogeology.* New York, N.Y.: John Wiley and Sons.

Elliot, W. J., A. V. Elliot, W. Qiong, and J. M. Laflen. 1991. Validation of the WEPP model with rill erosion plot data. ASAE Paper No. 912557. St. Joseph, Mich.: ASAE.

Elliot, W. J., and D. E. Hall. 2000. Rock:Clime, Beta CD Version, Rocky Mountain Research Station, Stochastic Weather Generator, Technical Documentation. Moscow, Idaho: USDA Forest Service, Rocky Mountain Research Station. Available at: http://forest.moscowfsl.wsu.edu/fswepp/docs/0007RockClimCD.html. Accessed 9 September 2003.

Elliot, W. J., C. H. Luce, and P. R. Robichaud. 1996. Predicting sedimentation from timber harvest areas with the WEPP model. In *Proc. 6th Federal Interagency Sedimentation Conf.*, 46-53. Washington, D.C.: USGS Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data.

Elliot, W. J., P. R. Robichaud, D. E. Hall, C. O. Cuhaciyan, F. B. Pierson, and P. M. Wohlgemuth. 2001. A probabilistic approach to modeling erosion for spatially varied conditions. ASAE Paper No. 018006. St. Joseph, Mich.: ASAE.

ESRI. 2000. *ArcView.* Ver. 3.2a. Redlands, Cal.: Environmental Research Systems Institute, Inc.

Flanagan, D. C., J. C. Ascough II, A. D. Nicks, M. A. Nearing, and J. M. Laflen. 1995. Overview of the WEPP erosion prediction model. In *USDA-Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation*, 1.1-1.12. NSERL Report No. 10. D. C. Flanagan and M. A. Nearing, eds. West Lafayette, Ind.: National Soil Erosion Research Laboratory.

Garbrecht, J., and L. W. Martz. 1997. TOPAZ: Topographic Parameterization Software. El Reno, Okla.: USDA-ARS Grazinglands Research Laboratory. Available at: http://grl.ars.usda.gov/topaz/TOPAZ1.HTM. Accessed 9 September 2003.

Koopman, M. 2002. Geo-spatial prediction tools in forest management: Modeling post-burn hydrology of soil erosion in three western forests. MA thesis. Buffalo, N.Y.: State University of New York. Department of Geography.

Laflen, J. M., L. L. Lane, and G. R. Foster. 1991. WEPP, a new generation of erosion prediction technology. *J. Soil and Water Conserv.* 46(1): 34-38.

Lindeburgh, S. B. 1990. Effects of prescribed fire on site productivity: A literature review. B.C. Ministry of Forests, Land Management Report No. 66. Victoria, B.C., Canada: Crown Publications.

Lousier, J. D. 1990. Impacts of forest harvesting and regeneration on forest sites. B.C. Ministry of Forests, Land Management Report No. 67. Victoria, B.C., Canada: Crown Publications.

Luce, C. H. 1995. Forests and wetlands. In *Environmental Hydrology*, ch. 8, 253-284. A. D. Ward and W. J. Elliot, eds. Boca Raton, Fla.: Lewis Publishers.

Noste, N. V. 1982. Vegetation response to spring and fall burning for wildlife habitat improvement. In *Proc. Site Preparation and Fuels Management on Steep Terrain*, 125-132. D. M. Baumgartner, ed. Spokane, Wash.: Washington State University Cooperative Extension.

NRCS. 2002 Geo-spatial Data Gateway. Washington, D.C.: USDA Natural Resources Conservation Service and National Cartography and Geospatial Center. Available at: http://lighthouse.nrcs.usda.gov/gateway. Accessed 5 October 2002.

Phillips, D. R., and J. A. Abercrombie. 1987. Pine-hardwood mixtures - A new concept in regeneration. *Southern J. Applied Forestry* 11(4): 192-197.

Povilaitis, A., P. Robichaud, A. Dumbrauskas, R. Tumas, and J. Ruseckas. 1995. Erosion prediction in the republic of Lithuania with the WEPP model. In *Proc. Water Quality Modeling,* 333-340. St Joseph, Mich.: ASAE.

Renschler, C. 2003. Designing geo-spatial interfaces to scale process models: The GeoWEPP approach. *Hydrol. Process.* 17(5): 1005-1017.

Rice, R. M. 1999. Erosion on logging roads in Redwood Creek, northwestern California. *J. American Water Res. Assoc*. 34(5): 1171-1182.

Robichaud, P. R. 1996. Spatially varied erosion potential from harvested hillslopes after prescribed fire in the interior Northwest. PhD diss. Moscow, Idaho: University of Idaho, Department of Agricultural Engineering.

Robichaud, P. R. 2000. Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA. *J. Hydrol*. 231/232: 220-229.

Robichaud, P. R., and R. E. Brown. 1999. What happened after the smoke cleared: Onsite erosion rates after a wildfire in eastern Oregon. In *Proc. Annual Summer Specialty Conference* (Track 2: Wildland hydrology), 419-426. Middleburg, Va.: American Water Resources Association.

Ryan, K. C., and N. V. Noste. 1983. Evaluating prescribed fires. In *Symposium and Workshop of Wilderness Fire*, 230-429. J. E. Lotan, B. M. Kilgore, W. C. Fischer, and R. W. Mutch, tech. coord. Gen. Tech. Report INT-182. Ogden, Utah: USDA Forest Service, Intermountain Research Station.

Savabi, M. R., and J. R. Williams. 1995. Water balance and percolation. In *USDA-Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation*, 5.1-5.14. NSERL Report No. 10. D. C. Flanagan and M. A. Nearing, eds. West Lafayette, Ind.: National Soil Erosion Research Laboratory.

Tiedemann, A. R., C. E. Conrad, J. H. Dietrich, J. W. Hornbeck, W. F. Megahan, L. A. Viereck, and D. D. Wade. 1979. Effects of fire on water: A state-of-knowledge review. Gen. Tech. Report WO-10. Washington, D.C.: USDA Forest Service.

Tiwari, A. K., L. M. Risse, and M. A. Nearing. 2000. Evaluation of WEPP and its comparison with USLE and RUSLE. *Trans. ASAE* 43(5): 1129-1135.

Ward, A. D., and W. J. Elliot. 1995. *Environmental Hydrology.* Boca Raton, Fla.: Lewis Publishers.

Westervelt, J. 2000. *Simulation Modeling for Watershed Management.* New York, N.Y.: Springer.

Willmott, C. J. 1981. On the validation of models. *Physical Geography* 2(2): 184-194.

Willmott, C. J. 1984. On the evaluation of model performance in physical geography. In *Spatial Statistics and Models*, 443-460. G. L. Gaile and C. J. Willmott, eds. Boston, Mass.: D. Reidel Publishing.

Wondzell, S., and J. King. 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. *Forest Ecology and Management* 178(1/2): 75-87.

Wu, J. Q., A. C. Xu, and W. J. Elliot. 2000. Adapting WEPP (Water Erosion Prediction Project) for forest watershed erosion modeling. ASAE Paper No. 002069. St. Joseph, Mich.: ASAE.

Zacharias, S., and C. D. Heatwole. 1994. Evaluation of GLEAMS and PRSM for predicting pesticide leaching under field conditions. *Trans. ASAE* 37(2): 439-451.