Modeling Erosion from Forest Roads with WEPP

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ABSTRACT

Forest roads can be major sources of soil erosion from forest watersheds. Sediments from forest roads are a concern due to their potential delivery to stream systems resulting in degradation of water quality. The Water Erosion Prediction Project (WEPP) was used to predict erosion from forest road components under different management practices. WEPP estimates are compared to measured erosion rates in the southern Appalachians from 24 road sideslope erosion plots on the Talladega National Forest and three road sections on the Chattahoochee National Forest. The first study was conducted to investigate four road sideslope management practices which included RECP (rolled erosion control product) treatment, two vegetation mixtures, and an untreated condition. Sediment yield from treatments was compared to untreated (bare soil) southern Appalachian road sideslopes over the 8-year period. The rate of soil loss was greatest during the first 6 months and decreased thereafter for treated cut- and fillslopes. Mean sediment yield from treated slopes was less than 0.01 t/ha/mm of precipitation. Erosion rates and runoff observed from erosion plots for each management condition over an eight year period were compared to WEPP predictions. Relationships were also developed for soil loss over the study period for treated slopes and the control. These relationships revealed that sediment yield during the first year accounted for 60 to 90 percent of cumulative total sediment yield over the eight year period for the treatments. In the second study, soil erosion from three road sections was compared to WEPP predictions for eight storms of varying size. WEPP predictions were in agreement with measured erosion rates for the forest road components in the investigations. The applicability of WEPP to model these southern Appalachian forest roads was evaluated with a model efficiency statistic using the observed field experiment data.

KEYWORDS: forest roads; modeling, WEPP, erosion, storm runoff

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1.0 INTRODUCTION

Soil erosion and sediment delivery to waterways are major concerns in forest management primarily due to the degrading impacts on water quality. Sedimentation can negatively impact fish spawning and aquatic macroinvertebrate habitat in addition to transporting attached nutrient constituents directly to streams (Davies-Colley and Smith, 2001).

Undisturbed forests typically have minimal soil erosion losses because these are areas with increased surface cover and high infiltration rates. Forest with some form of disturbance, conversely, can have accelerated erosion losses due to disturbance of one or more of the conditions that provide erosion protection i.e. surface cover, infiltration rates, surface roughness, and/or flow path (Grace, 2002a, 2005a). In forest watersheds, roads are a primary area of concern due to the majority of soil erosion and sediments are attributed to the road system (van Lear et al., 1997). Roads have accelerated erosion potential due to the removal of surface cover, modifications to the natural soil structure, compaction resulting in decreased infiltration, alterations in subsurface hydrology, and concentrated flow due to the interception of natural flow paths (Grace 1999). Previous work has reported how this accelerated erosion potential relates to sediment transport distances downslope (Grace 2005b). Increased awareness of sustainability issues surrounding soil erosion and sedimentation has highlighted the need for reliable prediction technology. Such technology can be used to identify problem road sections requiring additional control measures to reduce erosion losses as well as to plan and locate environmentally sustainable road systems.

The Water Erosion Prediction Project (WEPP) has been developed as a tool to address the need for forest road erosion prediction technology. Originally developed for agricultural scenarios, the WEPP model is a physically based soil erosion model (Laflen et al., 1997; Flanagan and Nearing, 1995) developed to be more robust than empirical models like USLE and RUSLE. WEPP erosion processes consider both sheet (interrill) and rill erosion and erosion occurring due to detachment by hydraulic shear in channels. The mechanism that drives interrill erosion is detachment and transport of sediment by raindrop impact and shallow overland flow. Rill erosion is driven by the detachment and transport of sediment by concentrated channel flow (Elliot et al., 1993). In recent years, WEPP has been expanded to forest applications including forest roads (Elliot and Hall, 1997).

1.1 Objectives

The purpose of this study was to evaluate WEPP's capability in modeling selected forest road scenarios and assess the accuracy of WEPP (hillslope model) predictions using field experiment data from an erosion plot and a road section study conducted on southern Appalachian forest roads during two distinct study periods (1995-2003 and 2003-2004).

2.0 METHODS

2.1 Shoal Creek

The Shoal Creek (SHC) study investigated sediment yield from road cut and fillslope erosion plots. The SHC site is located at approximately 33^{o} latitude and 85^{o} longitude on the Talladega National Forest near Heflin, Alabama. Elevation at the site is 400 m above mean sea level (msl). The study area receives a long-term average annual precipitation of 1400 mm. Soils are Tatum series (fine-loamy mixed-thermic Typic Hapudult) featuring a 0.10 m thick silt loam surface soil overlaying a clay loam subsoil. The study road was a mid-slope half-bench crowned road constructed for tract access during the summer of 1995.

The SHC study experimental design was a randomized complete block design with three blocks of four treatments on each slope. A total of 24, 1.5 x 3.1 m bound erosion plots were established on the road sideslopes to monitor sediment and runoff yield from three levels of erosion control treatment and untreated controls. Data collection and sample analysis procedures have been presented by Grace (2002b, 2005c). Three replications of each treatment and control were monitored on a 2.2:1 cutslope and a 1.5:1 fillslope during a study period from September 1995 to December 2003. The following three treatments were monitored:

1) Exotic vegetation. Exotic vegetation erosion plots were seeded with a mixture of Kentucky 31 tall fescue (*Festuca arundinacea*), annual lespedza (*Lespedza cuneata*), white clover (*Trifolium repens*), and Pensacola bahiagrass (*Paspalum notatum*).

2) Native vegetation. Native vegetation erosion plots were seeded with a mixture of Alamo switchgrass (*Panicum virgatum*), big bluestem (*Andropogon gerardii*), and little bluestem (*Andropogon scoparius*).

3) RECP. RECP erosion plots were seeded with the exotic vegetation mixture and anchored with a wood excelsior erosion mat.

4) Untreated. Untreated erosion plots had neither seed nor mulch application and were allowed to naturally vegetate during the study period.

All vegetation treatments were hand seeded immediately following road construction and mulched with fescue hay at a rate of 4.5 t ha^{-1}. Fertilizer was applied at a rate of 1.0 t ha^{-1} of fertilizer with an equal fraction of N-P-K (13%). Lime application was accomplished with agricultural limestone at a rate of 4.5 t ha^{-1}.

WEPP input files which included slope, climate, soil, and management files were developed for the road cut- and fillslope scenarios for each level of treatment. As previously mentioned, the erosion plots on the sideslopes were bound, thereby isolating them from the surrounding slope and roadbed. Consequently, the slope file was simple with only one element for each treatment. The cutslope and fillslope were characterized as uniform 45 and 67 percent slopes for the 3.1 m slope length, respectively. The climate generator provided by WEPP (CLIGEN, Version 5.2) was used to simulate a 50-year climate input file for Heflin, Alabama. The cutslope was characterized as a clay loam cutslope and the fillslope characterized as a silt loam fillslope. A management file was created for each treatment level based on initial conditions and percent cover measurements observed each year of the 8-year study period. The percent cover observations for each of the eight study years were presented by Grace (2005c). The cutslope was initially characterized with a bulk density of 2.0 g cm^{-3} and the fillslope was characterized with a bulk density of 1.5 g cm^{-3}. In addition, the initial management condition for all treatments on each slope was defined as fallow immediately following tillage and modified to a perennial condition for subsequent years. The RECP treatment was characterized as having an initial condition with 100 percent cover throughout the study period.

2.2 Coleman River

The Coleman River (CR) study investigates soil erosion from forest road sections and sediment control treatment effectiveness in reducing sediment yield onto the forest floor. The CR site is located within the Coleman River Wildlife Management Area at approximately 35^{o} latitude and 83^{o} longitude on the Chattahoochee National Forest near Dillard, Georgia. Elevation at the site is 900 m above msl. The study area receives a long-term average annual precipitation of 1800 mm. Soils were Hayesville fine sandy loam surface soil overlaying a clay loam subsoil. The study road was a mid-slope half-bench crowned road.

Three road sections with similar hydrology, soils, forest cover, and road design were delineated to monitor sediment yield at lead-off ditch structures and subsequent trap efficiency of sediment control structures located at lead-off outlets. Road section lengths were constrained to 50 m for consistency in area drained by each associated lead-off ditch structure. Sediment yield at each lead-off structure is attributed to the section of road drained (contributing area) by the structure (Figure 1). Study design and road delineation procedures have been presented by Grace (2006).

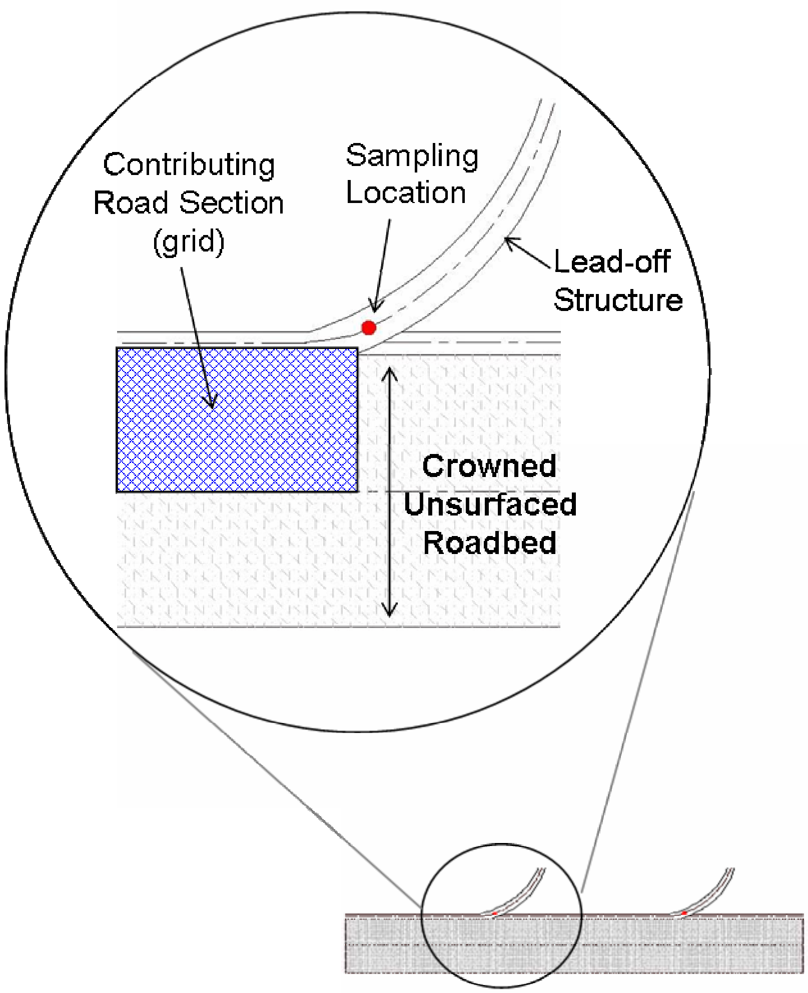


Figure 1. Illustration of contributing road section for the Coleman River road study.

Sediment and runoff yield was monitored from the 3 road sections during a study period from October 2003 through October 2004. Road section hydrology data were determined using an Extra Large (EL) 60^o V Trapezoidal flume in combination with a submerged pressure transducer connected to a water level logger. Water quality samples were collected with storm water samplers as a composite of sub-samples collected from associated storm events. Instrumentation and data collection procedures for the study have been detailed by Grace (2006). Total sediment load at the lead-off structure was computed as the product of concentration and flow data. This paper utilizes field experimental data from the three study road sections to evaluate WEPP's applicability in predicting runoff and sediment yield occurring during eight storm events.

WEPP slope, climate, soil, and management input files were created to describe the three road sections in the CR study. The cutslope, fillslope, and drainage from surrounding areas was excluded since the road design isolated these areas from contributing storm runoff (and soil erosion) to the selected road sections (Figure 1). The description of the road sections for modeling purposes was simplified since to the roadbed was the only overland flow element considered in the WEPP model. The surrounding slopes (cutslope, fillslope, and adjacent road sections) were excluded from the contributing area due to the road design isolated these areas from contributing storm runoff (and soil erosion) to the study road sections. The slope file was created as a uniform 4 percent slope over the 50 m road section length. The WEPP climate generator (CLIGEN, Version 5.2) was used to generate a 50-year climate input file for the Coweeta Experimental Station near Otto, NC. The soil file was created as a native surface Hayesville fine sandy loam road surface. The management file was used to characterize the crowned unrutted road surface with no cover and a bulk density of 2.0 g cm^{-3}.

2.3 Model Evaluation

Observed and WEPP predicted sediment yield for each treatment and road section were statistically summarized and subjected to regression analysis. Statistics determined for each treatment included mean, maximum, minimum, and coefficient of variation (CV). Regression analysis was performed on predicted versus observed values to test the hypothesis that the regression slopes equal 1 and regression intercepts equal zero. The model's "goodness-of-fit" was determined by procedures defined by Grace (2005c) using the Nash and Sutcliffe (1970) model efficiency (ME) statistic. Perfect agreement between predicted and observed soil loss is indicated by a ME coefficient equal to 1.

3.0 RESULTS AND DISCUSSION

3.1 Shoal Creek

Sediment yield data were collected for each treatment on both the cutslope and fillslope in the SHC study over an 8-year study period (Figure 2). Consistent with results from previous investigations (Burroughs and King 1989; Megahan 1974; Swift 1984), sediment yield from treatments was greatest during the first year of vegetation establishment following disturbance. During the first year after establishment, the vegetation treatments (native and exotic) had observed sediment yield which represented from 60 to 90 percent of the total sediment yield for the 8-year study period (Table 1). The RECP treatment had 81 percent of its observed total sediment yield on the cutslope during the first year and only 38 percent of its observed total yield on the fillslope during year 1. However, sediment yield from the control on both the cut- and fillslope continued at a greatly accelerated rate until the fourth year following disturbance.

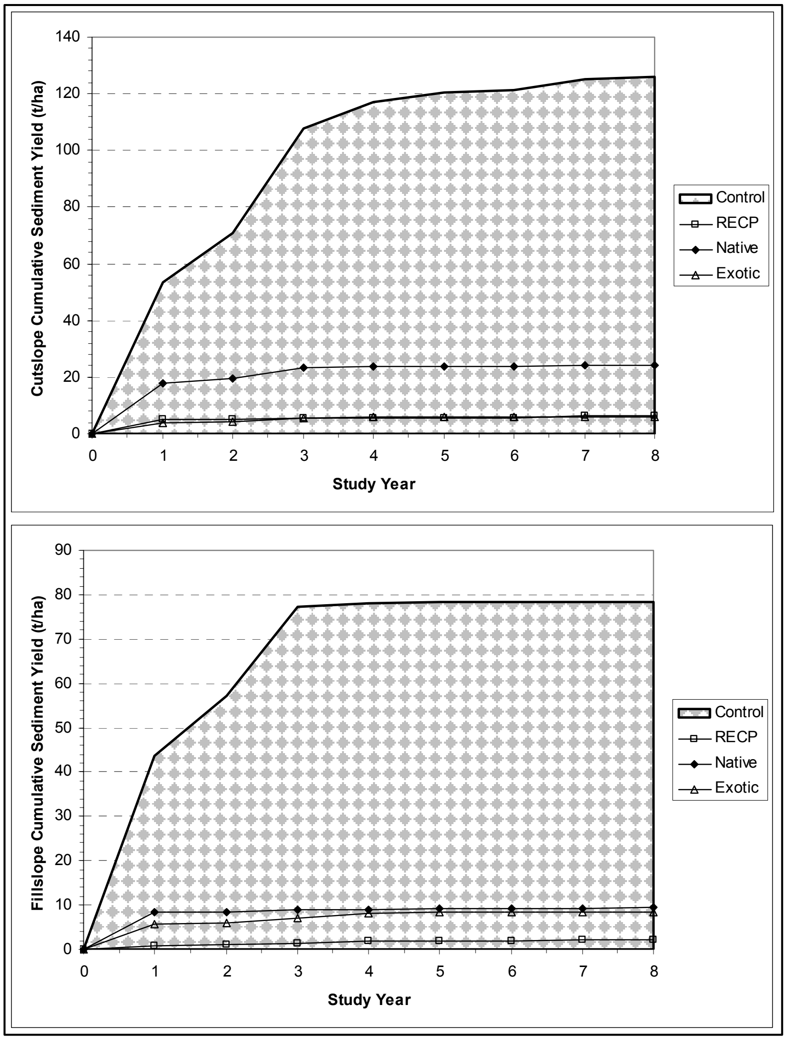


Figure 2. Observed cumulative sediment yield from erosion plots in the SHC study over the 8-year study period (1995-2003).

WEPP predictions of annual sediment yield (50-year average) for the first study year were in agreement with observed data (Table 1). Predicted sediment yield during the first study year represented the greatest percentage of the total sediment yield over the study period. Predicted sediment yield during the first year ranged from 25 to 72 percent of total sediment yield over the study period for the cutslope. Predicted sediment yield during the first year from erosion plots on the fillslope ranged from 40 to 97 percent of total loss for the study period. This observed consistency between observed and predicted sediment yield during the first year suggests adequate initial characterization (initial conditions) of soil, slope, and management for the erosion treatments.

Table 1. Sediment yield means and statistics observed from the SHC erosion plots, WEPP predicted yields, and model efficiency in predicting sediment yields in the study.

Treatment	N	Observed Sediment Yield t ha^{-1} yr^{-1}	Std. Dev.	CV	ME	Predicted Sediment Yield t ha^{-1} yr^{-1}	Observed 1st year Loss %	Predicted 1st year Loss %
Cutslope								
Control	8	15.8	19.4	123	0.51	25.3	42	25
Exotic	8	0.77	1.31	171	0.51	0.49	61	42
Native	8	3.00	6.22	207	0.92	3.32	75	59
RECP	8	0.79	1.75	222	0.96	0.98	81	72
Fillslope								
Control	8	9.81	15.7	160	0.97	8.60	56	60
Exotic	8	1.06	1.95	184	0.53	1.15	68	97
Native	8	1.18	2.90	246	0.99	1.36	88	83
RECP	8	0.26	0.27	104	0.81	0.20	38	40

Observed soil loss regressed against WEPP predictions of soil loss for each treatment and the control for the cut- and fillslope are presented in Figure 3. Regression analysis indicated that WEPP over predicted soil loss for all scenarios with the exception of the cutslope exotic, fillslope control, and fillslope RECP. The F-statistics for the hypotheses that the regression slope equals one and the intercept equals zero for each scenario were significant at the five percent level and ranged from 36.4 to 420.7 on the cutslope and 74.5 to 334.1 on the fillslope. Regression slopes were not detected as significantly different from one (p-values ranging from 0.123 to 0.696), however intercepts were significantly different from zero ($p < 0.0001$). The R^2 values of the regressions were high (>0.85), which indicated a highly correlated relationship between predicted and observed soil loss.

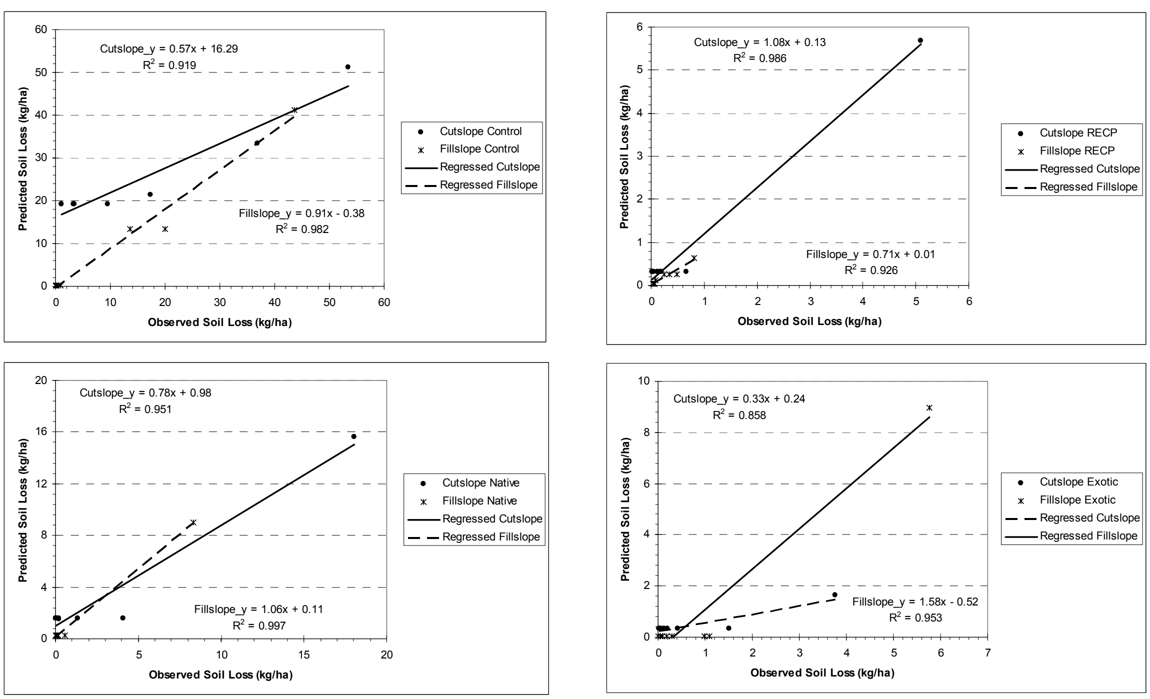


Figure 3. Regression relationships between observed and WEPP predicted soil loss for control, RECP, native, and exotic treatment on the cut- and fillslopes in the SC study.

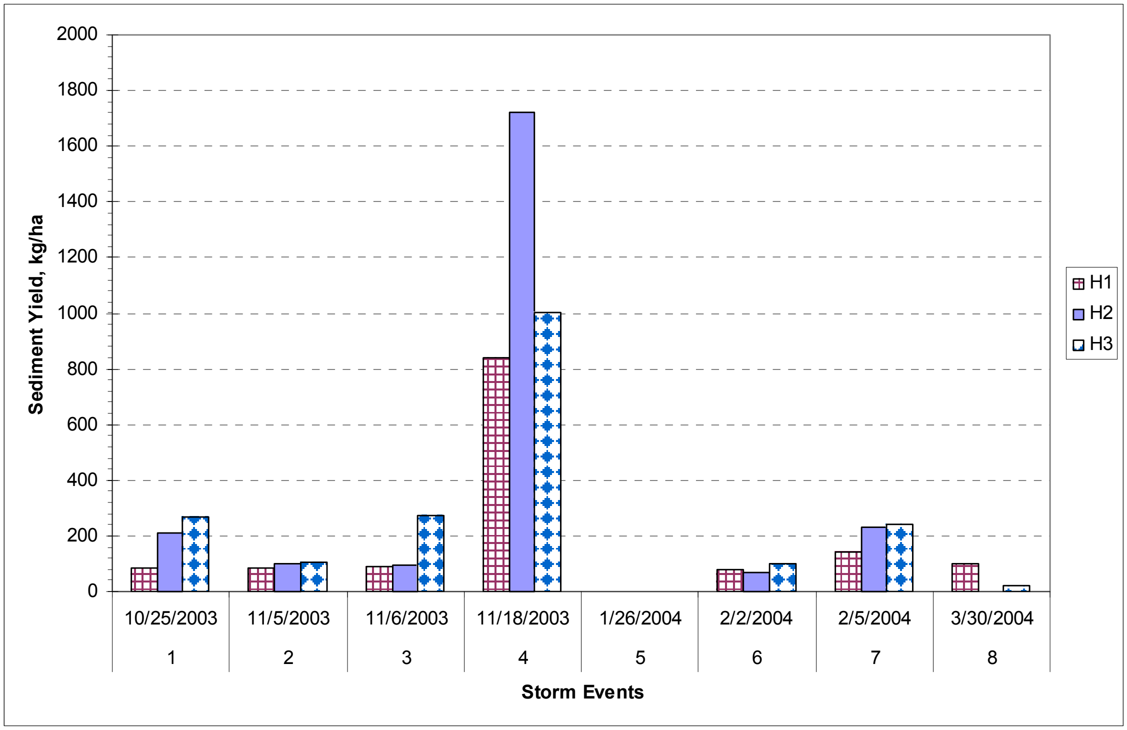
The differences in the observed and predicted soil loss are reflected in the ME statistic which tests the model's ability to predict observed yields. Results indicate that the model was most efficient (ME>0.92) in predicting soil loss from the native treatment on both slopes (Table 1). The ME values were also high for the RECP treatment on both slopes with values greater than 0.81. The cutslope control and the exotic treatment on both slopes had relatively low ME values ranging from 0.51 to 0.53. These low ME values indicate some bias in the predicted soil loss. In addition, the models ability to predict soil loss from the exotic treatment was likely a function of the characterization of the treatment (rooting parameters and residue parameters) in the WEPP management file. The exotic treatment was seeded with a combination of exotic vegetation species which may not have been adequately characterized in the management file. The low efficiency on the cutslope control can likely be attributed to the fact that the majority of the easily eroded sediment was removed during the first two study years while the WEPP predictions did not account for this depletion of source sediment.

3.2 Coleman River

Flow and sediment concentration data was collected for selected storms from 3 road sections in the CR study (Figure 4). Precipitation, duration, and event yields for events in this analysis are presented for each road section (Table 2). Event precipitation ranged from 2.5 - 140.2 mm for the eight storms considered in this comparison. Generally, WEPP predicted runoff yield was twice the observed runoff yield for all but three storm events (Events 2, 4, and 8). Storm event 4 had the greatest observed runoff and sediment yield of the storms considered in this modeling effort. In fact, observed runoff yield (11.1-14.3 m^3 or 111 - 143 mm) was near or equal to recorded precipitation for the storm. This large storm (Event 4) occurred during a period when road sections and upslope area had a high antecedent moisture content which reduced infiltration capacity of storm precipitation and resulted in a runoff coefficient of 0.90 on average.

The means and statistics for predicted and observed sediment and runoff yields for the eight simulated storm events are presented in Table 3 for the road sections. Observed values for sediment and runoff yield for storm events were highly variable with large standard deviations and coefficients of variation (CV) (Table 3). This is an expected result due to the variability in the event precipitation as well as inherent variability in the three road sections due to variability in soils and topography. Drainage characteristics for the road sections likely influenced the yield results, specifically for one large storm event (Event 4) in which nearly all precipitation resulted in runoff.

WEPP predictions of sediment yield for the road sections were consistent (in good agreement) with observed yields for the simulated storms. The efficiency coefficients were greater than 0.73 for all three road sections (Table 3). These high ME values indicate that the model adequately predicted sediment yields for the simulated storms. The F-statistics for the hypotheses that the regression slope equal one and the intercept equal zero for each scenario were significant at the five percent level and ranged from 30.5 to 73.1 for the road sections. The regression analysis on observed and predicted sediment yield detected that regression slopes were not significantly different from one for road sections H1, H2, and H3 ($p = 0.804$, 0.389, and 0.390, respectively). However, regression intercepts were significantly different from zero for H1, H2, and H3 ($p = 0.001$, 0.0001, and 0.030, respectively). These results indicate that the relationship between predicted and observed sediment yield for road sections were strong, but were different from one-to-one relationships.



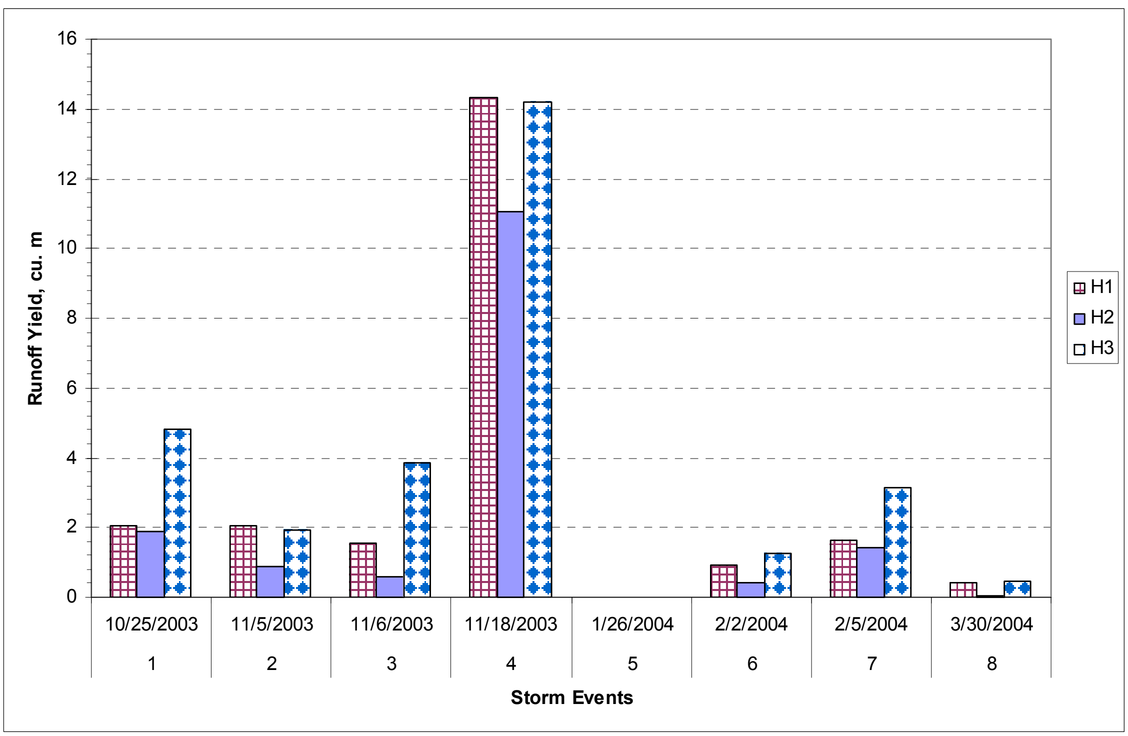


Figure 4. Observed sediment and runoff yield from three road sections (H1, H2, and H3) for the eight storms in the Coleman River study.

Table 2. Observed and predicted storm event data for eight storms in the CR study over the period covered in this modeling effort.

Storm	Date	Road Section	Precipitation (mm)	Duration (hrs)	Observed Event Soil Loss (kg)	Observed Event Runoff Yield (m^3)	Predicted Event Soil Loss (kg)	Predicted Event Runoff Yield (m^3)
1	10/25/2003	H1	71.9	22	0.9	2.0	7.6	6.3
		H2		19	2.1	1.9	5.6	6.0
		H3		22	2.7	4.8	3.9	6.0
2	11/5/2003	H1	32.0	21	0.9	2.1	0.9	2.1
		H2		20	1.0	0.9	0.9	1.9
		H3		20	1.1	1.9	0.8	1.9
3	11/6/2003	H1	57.7	21	1.0	1.5	3.3	4.3
		H2		22	0.9	0.6	2.1	4.1
		H3		22	2.7	3.8	7.0	4.1
4	11/18/2003	H1	140.2	31	8.4	14	9.1	5.7
		H2		20	17.2	11	15.3	6.1
		H3		32	10.0	14	10.8	5.7
5	1/26/2004	H1	2.5	2	0.002	0.002	0	0.04
		H2		0	0	0	0	0.01
		H3		1	0.001	0.001	0	0.01
6	2/2/2004	H1	43.5	13	0.9	0.9	0	3.5
		H2		4	0.7	0.4	0.7	3.3
		H3		15	1.0	1.3	0.6	3.3
7	2/5/2004	H1	65.7	14	1.5	1.6	1.1	6.0
		H2		11	2.3	1.4	1.0	5.6
		H3		32	2.4	3.1	1.6	5.6
8	3/30/2004	H1	15.9	5	1.0	0.4	0	0.2
		H2		14	0	0.02	0	0.2
		H3		23	0.2	0.5	0.1	0.2

Table 3. Means and statistics for observed and predicted sediment yield and runoff yield in the Coleman River study.

Treatment	N	Observed Yield	Std. Dev.	CV	Predicted Yield	ME
<u>Sediment (kg)</u>						
H1	8	1.88	2.87	152.6	2.71	0.86
H2	8	3.03	5.80	191.4	3.20	0.92
H3	8	2.51	3.21	128.1	3.10	0.73
<u>Runoff (m^3)</u>						
H1	8	2.87	4.69	163.5	3.52	0.32
H2	8	2.04	3.71	182.1	3.40	0.22
H3	8	3.71	4.55	122.8	3.35	0.57

Runoff yield predicted with the WEPP model did not show the same agreement as the sediment yield simulation results. Runoff yield was over predicted for all but two storm events (Events 4 & 8) (Tables 2 and 3). This inability for the model to adequately predict runoff yield is reflected in the efficiency values presented in Table 3. The model was not efficient in predicting runoff yield from the road sections for the examined storm events as reflected by ME values of 0.32, 0.22, and 0.53 for road sections H1, H2, and H3, respectively. The low ME values for runoff predictions can likely be attributed to characterization of the soil properties in the model. The effective hydraulic conductivity data used to characterize the Hayesville soil in the simulation may underestimate conductivities. Increasing the effective hydraulic conductivity in the soil description would provide more efficient runoff predictions; however, a trade-off occurs with accuracy of soil loss predictions.

4.0 CONCLUSIONS

Field experimental data were collected over an 8-year period (1995-2003) from a total of 24 1.5 x 3.1 m bound erosion plots on forest road sideslopes representing three levels of erosion control treatment and an untreated control. First year sediment yields accounted for greater than 40 percent of the cumulative total sediment yield over the eight year period for the control on both slopes. Whereas, sediment yield during the first year for the three treatments in the study ranged from 60 to 90 percent of cumulative total sediment yield.

WEPP was used to simulate sediment and runoff yield observed from field experiments on two southern Appalachian forest roads during two distinct study periods (1995-2003 and 2003-2004). In the first application, forest road sideslope erosion plots representing four slope conditions were simulated over an 8-year period in the SHC study. The second application involved simulating sediment and runoff yield for eight storms from three crowned road sections in the CR study. Observed and predicted yields for both studies were compared using the Nash-Sutcliffe model efficiency coefficient.

Overall, WEPP model predictions of sediment yield were in good agreement with values observed in the SHC erosion plots. This agreement was characterized by high model efficiency values (>0.80) for the native and RECP treatment scenarios on both the cut- and fillslope in the SHC study. Analysis revealed that the model was least efficient in predicting the exotic treatment on both slopes and the cutslope control treatment. The low efficiencies in predicting the exotic treatment are attributed to the inability to characterize the vegetation mixture in the WEPP management file.

Consistent with the application of WEPP in the SHC study, sediment yield predictions were in good agreement with observed data for the CR study. Model efficiencies determined for the CR study were greater than 0.73 for all three road sections for the eight storms in the analysis. These relatively high model efficiencies indicate that the model adequately describes the observed data. However, runoff yields predicted by WEPP were in poor agreement with the field experiment data in the CR study. The low model efficiency in predicting runoff yields in this study are attributed to inability to adequately describe the effective hydraulic conductivity and soil texture for optimization of sediment and runoff yield predictions simultaneously. Additional field data collection (soils properties and events) and simulation work is required to test applicability of WEPP to predict sediment and runoff yields in this southern Appalachian setting.

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