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Predicting Cumulative Watershed Effects of Fuel Management with Improved WEPP Technology

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Abstract

The increase in severe wildfires in recent years is due in part to an abundance of fuels in forests. In an effort to protect values at risk, and decrease the severity of wildfires, forest managers have embarked on a major program of fuel reduction. Past research has shown that such fuel reduction may have minimal impact at a hillslope scale, but when numerous hillsides are disturbed within a watershed over a number of years, the cumulative effect of such disturbances may be unacceptable. In addition, road networks are necessary to support fuel management activities by providing access for thinning crews, small diameter timber extraction, and fire crews. These road networks were frequently designed and constructed to minimize cost, and do not necessarily minimize adverse watershed impacts. Research findings from wildfire, fuel management, and roads will be presented to provide a context for predictive modeling. There are some new predictive tools to aid in watershed analysis. These include the GeoWEPP GIS wizard, the online WEPP:Road Batch processor and WEPP FuMe fuel management analysis tools, and a revised WEPP hillslope model with improved water balance and lateral flow capabilities. In this paper, we use these new technologies to explore the sources of sediment and runoff within a typical forested watershed. The paper shows improvements in runoff prediction with the revised WEPP model, as well as the relative importance of roads, wildfire, prescribed fire, and thinning operations in generating sediment at the hillslope and watershed scales. The analysis of the performance of the modified WEPP interface showed that there are problems within the WEPP Watershed stream flow routing routines that will need to be addressed before use of this modified model can be recommended.

Introduction

In recent years, an increase in high severity wildfires has lead to an increase in thinning and prescribed fire to reduce forest fuel loads. In planning for such fuel management operations, specialists need erosion and runoff prediction tools to estimate watershed impacts of their proposed actions.

Table 1. Examples of observed erosion rates in the Northern Rocky Mountains

Source of Sediment	Observed amount (Mg/km^2)	Reference
New Roads (Older roads will be about ¼ this amount)	18 Mg/ha, or if 2 km road/ km^2, then 13.4 Mg/km^2	Elliot and Foltz, 2001
Prescribed fire, up to	100 Mg/km^2	Elliot and Foltz, 2001
Wildfire	500 – 1000 Mg/km^2	Elliot and Robichaud, 2004
Typical "Background"	10 Mg/km^2	Megahan, 1974

An undisturbed forest experiences very little, if any, surface erosion. When a forest is disturbed by wildfire, roads, timber harvest, thinning operations, or prescribed fire, erosion rates increase. Forested watersheds are able to recover within a few years from most single disturbance events. As more disturbances are added during a year, and additional disturbances in the years that follow, the forest is less likely to recover to an undisturbed condition. The cumulative effects of numerous disturbances over a number of years must be considered to be able to manage forest lands. Often sediment from disturbed hillslides may take years to decades to be routed through a stream system. Thus, it is difficult to attribute sediment measured in the stream to disturbances that have just occurred. The technology that we are presenting assumes that sediment may take a number of years to be routed, and we have tried to present erosion rates as Megagrams (tonnes) of sediment per square kilometer of watershed wherever possible, averaged out over the time period between disturbances.

The Water Erosion Prediction Project (WEPP) (Flanagan and Livingston, 1995) was developed by a number of research and management agencies in United States Departments of Agriculture and Interior. The WEPP model was released with both a "hillslope" and a "watershed" version. Scientist at the Rocky Mountain Research Station and elsewhere parameterized the hillslope version for forests (Elliot and Hall, 1997). Developing topographic input files for the watershed version was not easily achieved until in 2001, when a Geographic Information System (GIS) tool was developed to assist in spatial analysis and visualization of erosion distribution (Renschler, 2002). In this paper, we will discuss some of the newer applications of the WEPP hillslope and watershed technology to fuel management planning.

Table 1 presents some typical erosion rates observed in or near the Northern Rocky Mountains. These values will be useful for comparison to predicted values presented later in the paper. These are generally hillslope erosion rates, and in many cases, the watershed impact from them may be spread out over decades as the sediment is routed downstream. Erosion processes are highly variable, and the values observed in Table 1 are samples that could easily be twice as great, or half as much on a nearby hillside. Another key aspect of forest erosion processes is that frequently there is a buffer between the disturbance and the stream system, greatly reducing the delivered sediment. With roads in particular, any vegetated buffer between road drainage

Table 2. First output table from a WEPP FuMe run for a typical slope in the Strychnine Creek, ID drainage. Slope length 250 m, slope steepness, 20 percent.

Line	Source of sediment	Erosion in year of disturbance ($Mg\ km^{-2}$)	Return period of disturbance (y)	"Average" annual sedimentation ($Mg\ km^{-2}\ y^{-1}$)
1	Undisturbed forest		1	0
2	Wildfire	1948.	40	48.7
3	Prescribed fire	231.	20	30.1
4	Thinning	9.8	20	0.5
5	Low access roads	0.4 to 2.2	1	0.4 to 2.2
6	High access roads	1.0 to 2.3	1	1.0 to 2.3

structures and a channel will be an area of sediment deposition, greatly reducing the amount of sediment from a road that is actually delivered to a stream.

WEPP Hillslope Scale Tools

In the late 1990s, two hillslope scale erosion prediction tools were introduced to aid in erosion prediction from individual forest road segments (WEPP:Road) and from disturbed forest hillslopes (Disturbed WEPP) (Elliot, 2004a and b). These tools have been extremely popular with thousands of users from around the world. As the tools have been applied to numerous problems, we have identified specific sets of runs that are common, and have developed two new tools that provide multiple runs to aid in watershed analysis. One of them, WEPP:Road Batch allows the user to develop a database of road segments from GPS, GIS, or other sources. The user can format the characteristics of each road segment with a database or spreadsheet, transfer the data to WEPP: Road Batch, and carry out multiple runs (Brooks et al., 2003). Up to 200 road segments can now be run and summarized at a time. The summary output can be copied and incorporated back in to the original spreadsheet, database, or GIS for additional analysis if desired. As the database and file structure for WEPP:Road Batch are identical to WEPP:Road, the validation presented by Elliot and Foltz (2001) showed that predicted erosion rates were similar to observed for a wide range of conditions.

A second new interface released in January, 2005, is WEPP FuMe, a fuel management analysis tool. WEPP FuMe accepts the input for a single hillslope with additional information about a fire return cycle, frequency of thinning, and road density, and carries out 12 different runs with WEPP:Road and Disturbed WEPP that are typical of fuel management analyses. The output is presented in tabular form, along with a

Table 3. A synthesis of fuel management runs from Table 1 and the WEPP FuMe output.

No Action Alternative		Fuel Treatment Alternative	
Source	Sediment Yield ($Mg/km^2/y$)	Source	Sediment Yield ($Mg/km^2/y$)
Undisturbed Forest	0	Undisturbed Forest	0
High Severity Wild Fire	48.7	Moderate Severity Fire	841 Mg/km^2/40 y = 21 $Mg/km^2/y$
Low traffic roads	0.4 to 2.2	High traffic roads	1.0 to 2.3
		Thinning	0.5
		Prescribed fire	30.1
Total	49.1 to 50.9	Total	51.6 – 53.9

narrative to aid the user in synthesizing the results from the 12 WEPP runs. Table 2 presents the WEPP FuMe output from the first 7 runs for a hillslope in a forested area about 25 km NE of Moscow, ID. For many conditions, the erosion from the road network may exceed that from the thinning operations. Additional runs are presented following the output narrative offering the user additional options for describing other fire severities or management treatments. In many cases, the user may wish to demonstrate that erosion from the proposed fuel treatment activities may lead to a less severe wildfire, and a much lower sediment delivery from the hillslope in the long run as a result of the treatment. For the example shown in Table 2, the erosion predicted for a moderate severity fire was only 841 tonnes per sq km, less than half that from the high severity fire that is now common in western watersheds with excessive fuel loads. These kinds of results and discussion on the output screens are designed to aid the user in preparing documentation to support forest fuel management activities. An example of a synthesis with information from Table 2 plus the sediment delivery value for a moderate severity fire given lower on the WEPP FuMe output page can be combined to give a summary of two alternatives as shown in Table 3.

WEPP Watershed Tools

The WEPP watershed technology is part of the WEPP model when it is downloaded. (Flanagan and Livingston, 1995). A database describing forest conditions is included with the WEPP file distribution. The watershed interface, however is difficult to use both in building the watershed files and viewing the distribution of predicted erosion results on the watershed. To address this problem, GeoWEPP, an ArcView extension was developed (Renschler, 2003). GeoWEPP uses digital elevation models (DEMs) and topographical analyses tools to build the necessary input files to run the WEPP watershed version for watersheds containing up to 1,000 hillslope elements.

To demonstrate the suitability of the GeoWEPP tool, an example study was carried out on a the 1490 ha the Strychnine Creek drainage (Figure 1) (Elliot and Foltz,

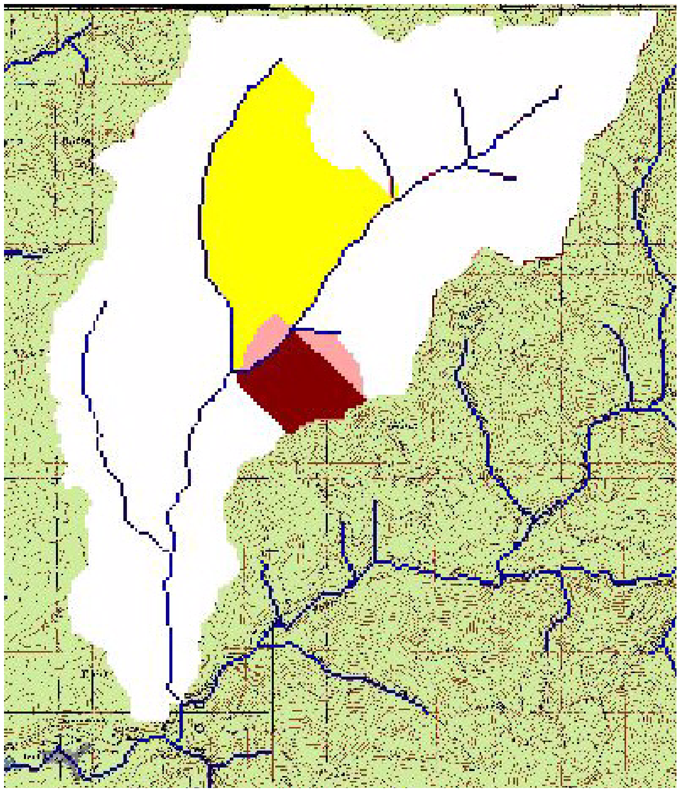

Figure 1. Graphical view of output from year 12 of simulations. Areas near outlet have recovered from fuel treatment, and areas near the center of the watershed are recovering from forest operations and prescribed fire. The darker the area, the greater the erosion rate. Predicted erosion rate in the white is zero, the lighter shade, 10, the medium shade, 30, and the dark shade 140 Mg/km^2.

2003). The GeoWEPP tool divided the watershed into 33 hillslopes, and 13 channel segments. The watershed is currently under consideration for significant fuel reduction activities, including small diameter logging in year 1, prescribed fire in year 2, and recovery of hydrologic stability and vegetative cover during the next five years. Table 4 shows the sequence of vegetation and soil properties necessary to sequentially describe these disturbances and recovery years for each hillslope.

To demonstrate the application of GeoWEPP, each year a hillslope was selected to begin the sequence presented in Table 4, starting with hillslopes at the bottom of the watershed, to initiate the fuel reduction sequence. We assumed that all other hillslopes were covered in forest at the start of the simulations. The GeoWEPP tool predicted values for the hillslopes in this watershed similar to the values predicted for the typical hillslope example presented in Table 2, when it received that treatment. In addition, the GeoWEPP technology allowed the user to analyse these disturbances as distributed in time and space, with Figure 1 giving a snapshot of the distribution of erosion in the watershed in year 12. Figure 2 shows the sediment yields for the first 12 years of analysis, for both the disturbed hillslopes and the road network. Note that the first year assumed that all hillslopes were undisturbed, and the majority of the soil

Table 4. WEPP vegetation and soil template values used for the analysis, assuming a silt loam soil

Year	Vegetation	Hydraulic Conductivity (mm/h)	Rill Erodibility (s/m)
1	Established Forest	28	0.0004
2	Harvest: 80 percent cover, Young forest	23	0.0004
3	Burn: 80 percent cover, Low severity fire	13	0.0005
4	90 percent cover, Short grass	11	0.0004
5	95 percent cover, Tall grass	23	0.0004
6	95 percent cover Young forest	23	0.0004
7	100 percent cover Young forest	23	0.0004
8	Established Forest	28	0.0004

erosion was from the road. During the years of this example, the sediment yields at the watershed scale varied between 40 and 90 tonnes (2.6 to 6 Mg/km^2 over the entire watershed), depending on the area and location of the disturbed hillslopes.

To consider the sediment from roads, sediment delivery was modelled assuming a road erosion rate of 1.33 t/km on roads with heavy traffic, and 0.67 t/km for roads with light traffic. These values were estimated with the WEPP model for multiple 60-m long road segments with a gradients of 4 percent, distances of 20 m between the road and the stream, and with buffers covered in forest. The rill erodibility value was reduced from 0.0003 s/m for the road with high traffic to 0.000075 s/m for the road with low traffic, to reflect the observed surface armouring on roads without traffic (Foltz, 1998). It is apparent from figure 2 that the sediment from the road accounts for about a fourth of the sediment generated from human disturbances during active years, and 96 percent of the sediment in the absence of disturbances. The road sediment delivery values are approximate estimates in this study, as a detailed road map was not available. The relative importance of roads in the analysis, however is unlikely to change with greater detail.

These sediment yield rates need to be compared to the expected sediment yield from natural disturbances. When the entire watershed was described as wildfire, the predicted sediment yield was 4832 Mg in the year of the fire (324 Mg/km^2). If the frequency of fire in this area is assumed to be about 40 years, then the average annual sediment delivered in the years following the wildfire averages about 121 Mg per year (8.1 Mg/km^2/y). These values are lower than the hillslope values shown in Tables 1, 2, and 3 because there is generally considerable deposition in upland channels following wildfire, with the model, and observed in the field. If fuel management operations reduce the likelihood of fire, or the severity of the fire, as has been

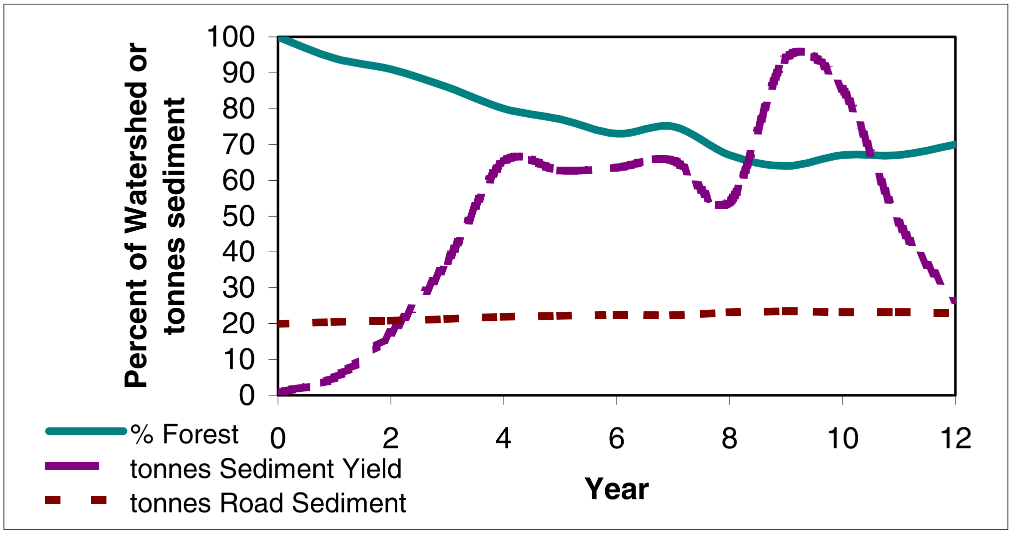

Figure 2. Percent of watershed In forest during the first 12 years of fuel reduction in watershed, and the associated sediment yields from roads and fuel management activities.

observed in recent studies, then the average annual sediment production due to the operations is similar to, or less than sediment from wildfire (Table 3).

To complete a GeoWEPP watershed analysis, some users may wish to add in sediment from landslides. McClelland et al. 1997, found that typical sediment yields averaged over the 20 year return period associated with such events was around 10 Mg/km^2. Fuel management operations are unlikely to decrease this value, but a more dense road network could increase it (McClelland et al., 1997).

Improvements to WEPP Hydrology

Currently, the WEPP model only predicts surface runoff from hillsides and watersheds. Observations in many steep forest watersheds have shown that over 99 percent of all runoff is subsurface flow. Surface runoff prediction is generally adequate for surface erosion prediction and sediment transport through the stream system, as sediment in streams only moves during large runoff events. There is a need for a model to predict total watershed water yield, however, so that forest managers can evaluate the impact of forest management activities on both water quantity and water quality.

The lateral flow subroutines in the WEPP modelwere modified to estimate both surface runoff from precipitation and snowmelt events, and subsurface flow on all days when soil water content was sufficient to cause subsurface flow laterally along steep forest hillslopes to the stream system (Wu et al., 2000). To evaluate the performance of this new technology, and gain insight into the sensitivity of two critical lateral flow parameters, the first fork in the Strychnine Creek drainage (Dry

Table 5. Sensitivity of the watershed runoff and sediment yield as predicted by the prototype WEPP watershed model to changes in anisotropy and soil depth for the Dry Creek Fork of Strychnine Creek, Idaho.

	Depth of Soil								
	800 mm			1200 mm			1600 mm		
Aniso-tropy	RO[1] (mm)	SY[2]	Y[3]	RO (mm)	SY	Y	RO (mm)	SY	Y
Current WEPP	6	25.91	3	12.6	42.20	30	13.1	37.88	30
10	252	0.84	4	10	0.00	1	33.0	18.90	30
25	115	22.26	1	103	29.13	8	39.3	11.22	30
50	132	14.55	1	138	19.25	30	46.9	6.72	30
100	294	32.58	25	148	13.74	30	58.1	5.74	30
500	454	20.52	30	212	8.81	30	121	9.74	30

[1] RO is runoff

[2] SY is the average annual sediment yield in Mg/km^2

[3] Y is number of years of weather used for run, 30 y is the maximum specified

Fork) was selected as an example watershed. For the analysis, we assumed the entire drainage was covered with trees. Past experience has shown that the current version of WEPP seldom predicts any surface runoff from a forested hillslope in this climate, so any runoff that was generated would most likely be associated with lateral flow. The GeoWEPP tool was used to build the necessary watershed hillslope and structure files. The Dry Fork drainage contained 345 ha, and GeoWEPP divided the area up in to 59 hillslopes with 25 channel segments. As the current WEPP Windows and GeoWEPP interfaces can not yet build the customized soil files needed the modified version of WEPP, the runs were completed using WEPP batch commands to link the topographic, soils, vegetation, and climate files to the WEPP model. The two critical parameters within the lateral flow subroutines are the degree of anisotropy (the ratio of lateral hydraulic conductivity to the vertical conductivity value specified for the top soil layer), and the depth of the soil. The results of this analysis are presented in Table 5.

A number of points of discussion arise from an inspection of the results in Table 5. The first is that when the lateral flow capabilities were added to the WEPP model, runoff increased significantly, but in most cases, sediment yield decreased. This is probably because of the processes dominating forest hydrology. In the current version of WEPP, runoff generally occurs when soils are saturated. In the absence of lateral flow, the soils were more likely to be saturated, increasing surface runoff, and with it, surface erosion. When lateral flow was incorporated into the modified WEPP model, soils were less likely to be saturated, so there was less likely to be surface runoff and the erosion associated with it.

Table 5 shows that as anisotropy increases, so does runoff. This result was expected. The decrease in runoff with deeper soils was not expected from the modified WEPP program. The expectation was that deeper soils would have greater transmissivity,

Table 6. Summary of three USGS stream flows near Strychnine Creek, Idaho.

Stream	Drainage Area (sq km)	Years of Record	Avg Runoff (mm)
Potlatch River Nr. Boville	108.2	1960-1970	483
Bloom Creek Nr. Bolville	8.2	1960-1970	531
Palouse River Nr. Potlatch	824.7	1916-1918 1967-2002	293

and be able to deliver greater amounts of water. It appears that this was not the case. It is more likely that the deeper soils were able to retain more water for vegetation, leading to greater evapotranspiration later in the season. Generally, in this climate, the majority of the precipitation occurs as winter snowfall, and there is little precipitation during the summer. The deeper soil appears to be better able to retain the melted snow in the spring for use later in the season, reducing spring time runoff.

It was our intent to run the WEPP model for 30 years for each condition. We found, however, that for some of the conditions that the WEPP model would not complete its run. The hillslope predictions were always complete, but for those runs in Table 5 for less than 30 years, the watershed routing routines were unable to route the runoff and sediment generated by the hillslopes for all 30 years. The source of this problem requires further investigation. Recent studies have suggested that the routing routines within the WEPP watershed version are in need of significant scientific improvement (Conroy et al., 2003), and these findings would support that contention. Because some of the runs in Table 5 were only for a few years, they may not be directly comparable to the others. It appears that the single year runs tend to have less runoff, and relatively high sediment yields for the amount of runoff. A full evaluation of the interactions among soil depth, anisotropy, and runoff is not possible until this problem within the WEPP routing routines is fixed.

The stream flows from three nearby USGS gauging station were obtained (USGS, 2005) and a summary of those stations is presented in Table 6. The two small watersheds near Boville, about 20 km east of the site, will likely have slightly higher precipitation than the site. The larger Palouse River watershed, with the station about 30 km west of the site, includes the Strychnine Watershed and a significant amount of lower elevation area with a drier climate. From the information presented in Table 6, it is apparent that the larger predicted runoff values in Table 5 with shallower soils or higher anisotropy values more closely predict the runoff expected from this site.

Summary

Four recently developed tools based on the Water Erosion Prediction Project (WEPP) model for use with forest fuel management activities were presented. The first was the WEPP:Road Batch online interface, intended for use with GIS or GPS technologies that develop databases of road networks. It allows users to predict the erosion from batches of road segments, rather than the past practice of manually entering road segments one at a time. The second hillslope tool, the WEPP FuMe online interface is intended to be a useful aid in planning individual fuel management activities. It carries out 12 WEPP runs for a single hillslope input, and provides both tabular and narrative summaries on the output screens. Predicted values are in the range of observed values for both interfaces.

Two watershed scale tools are under development to aid in fuel management. The GeoWEPP tool may be a useful tool in analyzing effects of fuel management that are distributed in time and space. It does not, however, have the capability to predict total runoff. A new version of WEPP that includes lateral flow was presented that shows promise in predicting forest stream flows. Before widespread use can be recommended, however, additional work is needed to parameterize the model, and to improve the stream routing algorithms in the existing WEPP Watershed version.

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