

Use of Fire Spread and Hydrology Models to Target Forest Management on a Municipal Watershed

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ABSTRACT

A small town relies on a forested watershed for its water supply. The forest is at risk for a wildfire. To reduce this risk, some of the watershed will be thinned followed by a prescribed burn. This paper reports on a study to evaluate the impact of such watershed disturbances on water yield. To target management activities, a fire spread model was applied to the landscape that contains the watershed. The output from the fire spread model was used to develop input files for a watershed hydrology and erosion model. The resulting erosion map was used to identify hillslope polygons that would generate the greatest amount of erosion following a wildfire, and those polygons were prioritized for treatment. The study found that the change in water yield was less than 1 percent when as much as 20 percent of the watershed was treated.

INTRODUCTION

Wildfire occurrence in forests is common around the world (Roy et al., 2008). In the United States, typically 72,000 wildfires occur every year, burning roughly more than 4 million acres of land (NIFC, 2012). Increases in frequency of severe wildfires have been attributed to climate and human management (Adams, 2013; Westerling et al., 2006). In the western United States, historical fire suppression programs resulted in extensive fuel accumulation, putting forests at risk of severe wildfire. (National Research Council, 2000; McIver et al. 2013).

Undisturbed forests provide high quality water because surface runoff and erosion are negligible (Elliot, 2013). Natural wildfires remove the vegetative cover of soils, dramatically increasing surface runoff and erosion potential (Spigel and Robichaud, 2007; Larsen et al., 2009; Blake et al., 2010). The impact of wildfire on hydrology depends on the degree of burn severity in the watershed (Moody et al., 2013). High severity burns significantly alter the hydrological processes in the watershed, which can lead to extensive floods and erosion (Onodera and Van Stan II, 2011). Sediment delivery into the streams not only degrades the quality of water,

affecting wildlife habitat (Bisson et al. 2003), but also reduces water storage in reservoirs downstream (Moody and Martin, 2009; Neary et al., 2005).

Suitable watershed forest fuel reduction programs can reduce the risk of severe wildfires and the associated risk of water quality degradation (Agee and Skinner, 2005; Reinholt et al., 2008). However, due to financial and technical constraints, it is not feasible to implement such management programs to all areas susceptible to wildfires (GAO, 2007). To overcome this limitation, computer simulation models are becoming increasingly popular in predicting fire behavior (Stratton, 2006; Buckley et al., 2014), and soil erosion following wildfires (Robichaud et al. 2007), as well as investigating various management practices for appropriate decision-making (Elliot, 2013; Moody et al. 2013). The objectives of this study are to 1) to assess the risk of severe wildfires and identify critical hillslopes for forest fuel treatments, and 2) to evaluate the potential changes in water yield from pre-treatment (undisturbed forest) to post-treatment (thinning and prescribed burn) conditions, in the East Deer Creek watershed, Colville National Forest, WA. The results of this study will guide resource managers in the effective application of fuel reduction treatments in this watershed.

METHODS

Study Site. The East Deer Creek watershed (5019 ha) is an ungauged municipal watershed located in the northeast of Ferry County in Colville National Forest (88° 50' 55" N, 118° 11' 37" W) (Figure 1). The watershed elevation ranges 423–1819 m above m.s.l., averaging 1144 m. The watershed receives an average annual precipitation of 575 mm, with 73% of precipitation occurring in the wet season (November–June), the remaining 27% in the dry season (July–October). During winter, precipitation is comprised of 52% snow that starts late October and lasts until March or April. Runoff peaks are typically observed in the months of April and May associated with spring snowmelt. The minimum and maximum temperatures ranges from –5°C in December–January to 17°C in July–August. The most dominant soil in the watershed is Gahee (*Ashy over loamy-skeletal, glassy over isotic Xeric Vitricryand*) that varies from loamy texture to sandy loam over the soil profile depth of 820 mm (Soil Survey Staff, USDA NRCS). Granite rocks dominate the underlying formations in the watershed (Soil Survey Staff, USDA NRCS). Vegetation cover predominantly consists of Douglas-fir (*Pseudotsuga*), Subalpine fir (*Abies lasiocarpa*), and Western hemlock (*Tsuga heterophylla*) (Colville National Forest Data Library; <http://www.fs.fed.us/r6/data-library/gis/colville/index.shtml>).

Wildfire Modeling. Controlling wildfire can be effectively accomplished by identifying fuel buildup areas in watersheds and reducing the fuel load using specific management practices (e.g. thinning; prescribed burn) (North et al., 2007). Hence, the first step of this study was to predict severity of wildfire burns for the current vegetation conditions using a fire behavior model.

FlamMap 5 (Finney, 2001) is a mapping and analysis model for computing and analyzing the spatial variability of fire behaviour characteristics such as spread rate, flame length, and fireline intensity. FlamMap performs calculations on each

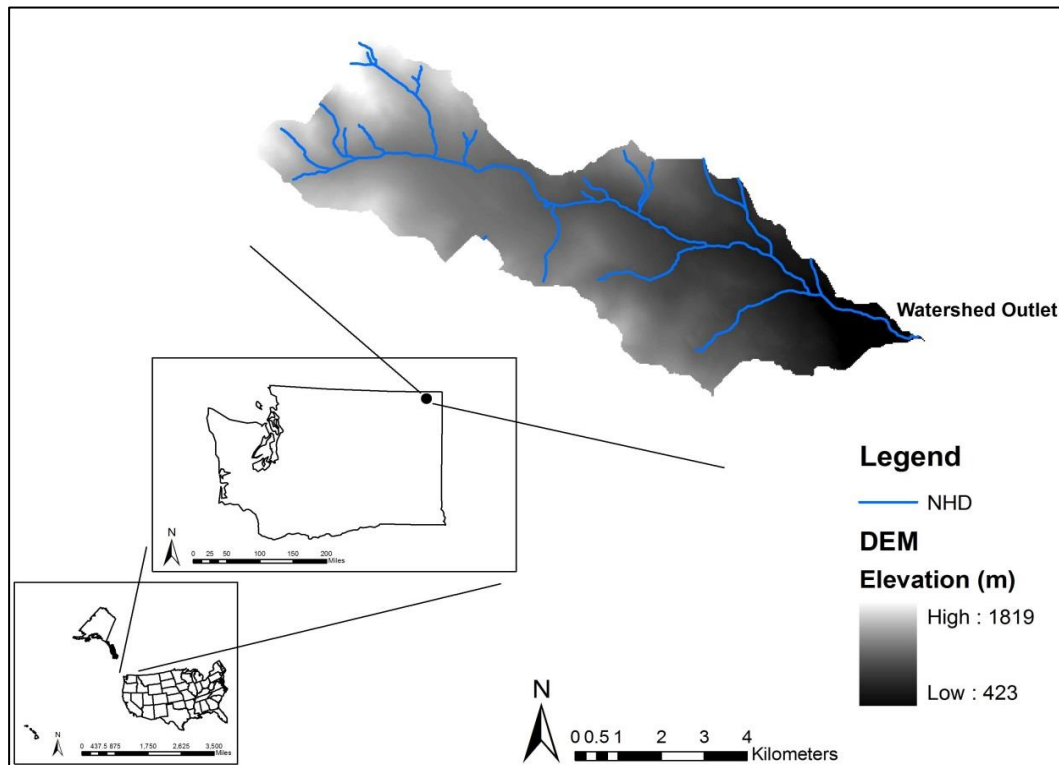


Figure 1. Location of East Deer Creek watershed, Ferry County, WA showing elevation and NHD stream network.

pixel independent of each other on a gridded landscape. FlamMap requires a landscape file (.lcp), fuel moistures (1-, 10-, 100-hour dead fuels, live herbaceous, live woody), and weather data to conduct fire simulations.

The landscape file includes geographic information system (GIS) layers for: elevation (m), slope (degrees), aspect (degrees), fuel model (class), and canopy cover (percent); and optional crown fuels: stand height (m), canopy base height (m), and canopy bulk density (kg m^{-3}). These data were downloaded at a 30-m resolution from the LANDFIRE 2010 data distribution website (<http://landfire.cr.usgs.gov>) for an analysis area of 41,436 ha. Forty fire fuel behavior models (range: 91 to 204) of Scott and Burgan (2005) were used to define fuel layers. Non-burnable fuels in the downloaded fuel model were 91- urban/developed, 92-snow/ice, 93-agriculture, 98-water, and 99-bare ground. The landscape file was further critiqued to identify possible errors following Stratton (2006).

Weather and fuel moistures input files for fire simulations were generated using the nearest Remote Automatic Weather Stations (RAWS). First, the proximity, elevation, and terrain of Lane Creek and Owl Mountain RAWS weather stations (<http://www.raws.dri.edu/waF.html>) were analyzed on GoogleEarth to determine which station best represented fuel moisture and weather conditions of the study watershed. Lane Creek is located 28 km south and Owl Mountain is located 7 km north of East Deer Creek watershed at 1371 m and 1206 m elevation, respectively. Owl mountain RAWS station was selected for FlamMap modeling due to closer proximity to the study watershed, and similar topographical settings, and elevations.

Table 1. Derived weather and fuel moisture information using the Fire Family Plus model at 85th, 90th, and 95th percentile for Lane Creek and Owl Mountain RAWS Station.

Source:	Lane Creek (South of East Deer)			Owl Mountain (North of East Deer)		
Percentile	85th	90th	95th	85th	90th	95th
1-hour (%)	3	3	3	4	4	3
10-hour (%)	4	4	3	5	4	4
100-hour (%)	6	6	5	7	6	6
Live herbaceous (%)	46	40	30	40	31	30
Live Woody (%)	73	67	62	73	68	60
Min Temp (°F)	62	64	66	59	61	63
Max Temp (°F)	88	90	92	83	85	88
Minimum RH (%)	16	15	13	19	17	14
Maximum RH (%)	42	39	34	41	38	33

Initial fuel moistures and weather conditions were derived in the Fire Family Plus model (a system for summarizing and analyzing historical daily fire weather observations) for the months of July and August, the period when the probability of natural wildfire occurrence is highest. Fuel moisture (1-, 10-, 100-hour dead fuels, live herbaceous, live woody) and weather (maximum and minimum temperatures, and relative humidity) parameters for fire simulations were separately identified at 90th percentile conditions using hourly RAWS data (Table 1). FlamMap uses a built-in Wind Ninja program to create gridded wind speed and direction to provide more realistic fire behavior for complex topography. The Wind Ninja basic inputs (air temperature, longitude, latitude and time zone, wind speed and direction) were acquired from the Owl Mountain station (Table 1). From the Owl Mountain RAWS station data the computed wind speed and direction were determined to be 3 mph and SSE-S (<http://www.raws.dri.edu/waf.html>). A one week fuel moisture conditioning period was provided (prior to assumed wildfire on 21st August) using hourly weather and wind RAWS data to account for adequate moisture contents of dead fuels influenced by elevation, slope, aspect, and canopy cover (Nelson, 2000).

The FlamMap model was then run for the analysis area and it generated a flame length gridded output that could subsequently be classified in unburned, low-, moderate-, and high-severity burn pixels (Figure 2). This map was used for erosion modeling with the Water Erosion Prediction Project (WEPP) model.

Erosion and Water Yield Modeling. The WEPP model is a process-based, continuous-simulation, distributed-parameter model for hydrology and water erosion (Flanagan and Nearing, 1995). It is based on the fundamentals of hydrology, plant science, hydraulics, and erosion mechanics (Nearing et al., 1989). The major advantage of the WEPP model is its ability to estimate spatial and temporal distribution of soil loss or deposition along a hillslope, as well as sediment yield at

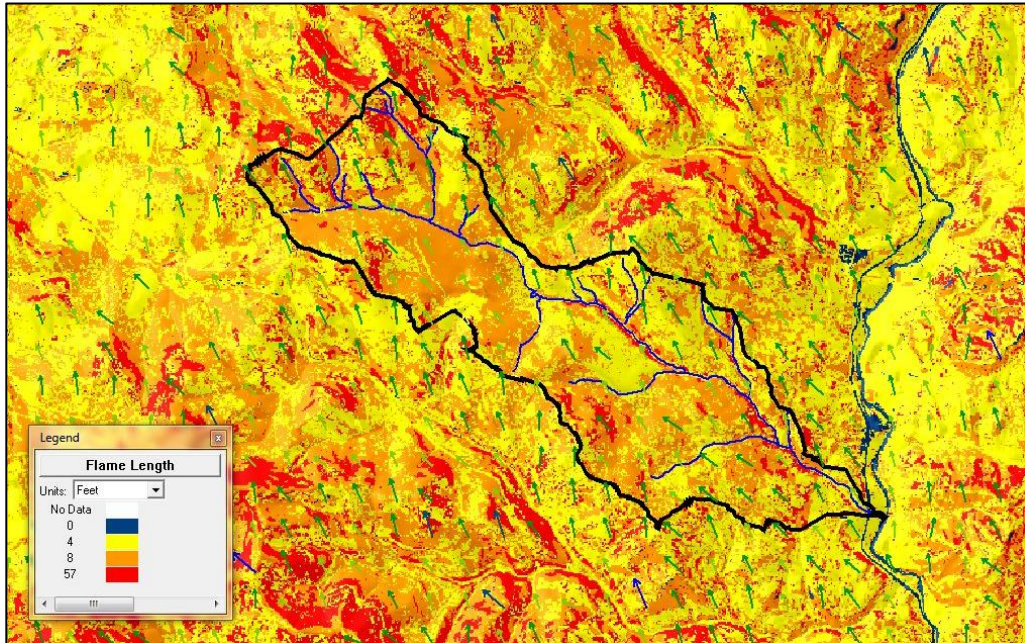


Figure 2. Flame length map obtained from the FlamMap model representing burn severities for the analysis area (0: unburned; 0–4: low severity burn; 4–8: moderate severity burn; 8+: high severity burn). The size of arrows reflects the magnitude of simulated wind speed from Wind Ninja program.

the bottom a hillslope. WEPP characterizes watersheds as hillslopes and channel networks (Baffaut et al., 1997). For watershed applications, the model links all hillslopes to channels. Water balance and erosion calculations are first performed for each hillslope and channel. The flow and sediment yield from each of the hillslopes are combined with the associated channel, and they are then routed through the channels to the watershed outlet.

WEPP simulates winter hydrology, surface hydrology and hydraulics, subsurface hydrology, vegetation growth and residue decomposition, and sediment detachment and transport on each hillslope and channel using four major input files: climate, slope, soil, and management. The surface hydrology component performs calculations for infiltration, rainfall excess, depression storage, and peak discharge. Rainfall excess is calculated internally following the modified Green Ampt Mein-Larson equation (Mein and Larson, 1973). Overland flow routing and peak discharge estimation are performed using a modified kinematic wave equation. The subsurface hydrology component performs sequential calculations for percolation, evapotranspiration (*ET*), and subsurface lateral flow through the soil and slope profile. Subsurface lateral flow from hillslopes is computed using Darcy's law and added to channel flow (Dun et al., 2009). A water balance file is generated for each hillslope and channel component in WEPP. Surface runoff, subsurface lateral flow, *ET*, total soil water content, and deep percolation are reported on a daily basis. Deep percolation values in WEPP v2012.6 are considered lost from the model domain.

Recent improvements in WEPP have significantly enhanced the model's applicability in forested watersheds (Dun et al., 2009). However, the model still lacks a groundwater baseflow component, which is necessary to adequately represent

hydrologic conditions where significant quantities of groundwater flow to perennial streams. For complete water yield assessment from the watershed for the present study, a baseflow component based on a linear reservoir model was incorporated into WEPP. The weighted area average of the daily deep percolation values of all the hillslopes was calculated to represent recharge to the groundwater reservoir. The water from a groundwater storage was partitioned into baseflow (Eq. 1) and deep seepage (Eq. 2) using a linear reservoir model (Maillet, 1905) that assumes outflow from a reservoir is a linear fraction of groundwater storage. Successive groundwater storage was calculated using Eq. 3 for each daily time step. The computed baseflow was added to channel runoff at the watershed outlet to obtain total streamflow.

$$Q_{bi} = k_b \cdot S_i \quad (1)$$

$$Q_{si} = k_s \cdot S_i \quad (2)$$

$$S_i = S_{i-1} + (D_i - Q_{bi} - Q_{si}) \quad (3)$$

where D is deep percolation from the soil profile; Q_b , and Q_s are baseflow, and deep seepage from the groundwater reservoir, respectively; S , groundwater reservoir storage; k_b and k_s are baseflow and deep seepage coefficients, respectively; and subscript i represents successive days.

Identification and Prioritization of Critical Hillslopes. For the study area, a web-based online GIS WEPP interface for Burned Area Emergency Response (BAER) (Frankenberger, 2011) was used for post wildfire erosion estimation (<http://129.101.152.143/baer/>). First, the flame length map from FlamMap representing burn severity was uploaded to the online interface. Then the flame length was used as a surrogate for reflectance in the BAER interface to characterize the burned area of the map based on the nearby Tripod Complex wildfire at Okanogan and Wenatchee National Forest (Lillybridge and Bennett, 2006). The Tripod Complex wildfire that occurred in 2006 had 2 percent unburned, 47 percent low-, 27 percent moderate-, and 24 percent high- severity burn area of the total evaluated area of 59,488 ha. Within the BAER online interface, flame length class breaks were set to give a similar distribution of burn severity (Table 2).

The Online GIS BAER WEPP uses the TOPAZ (Topographic Parameterization, Garbrecht and Martz, 2000) model for watershed structure and topographic inputs, WEPP default management and soil data for burn severities (Elliot, 2004), and a stochastic climate file generated from CLIGEN (Nicks et al., 1995). The hillslopes and channel networks of the study watershed were derived using the default 100-m minimum source channel length and 5- ha critical source area using a 30-m digital elevation model (DEM) (USGS National Elevation Dataset, 2010). The total watershed area of 5019 ha was discretized into 777 hillslopes (4639 ha) and 354 channels (380 ha) with an average hillslope area of 5 ha. The dominant severity class for each hillslope was used to determine the soil and vegetation properties of that hillslope for the WEPP modeling.

To evaluate the erosion risk following wildfire in the watershed, the WEPP model was run for the first-year post-wildfire sediment yield using the CLIGEN daily-generated stochastic climate for 50 years of possible weather. The long-term climate data were used to account for temporal variability of storm patterns occurring

Table 2. WEPP calibrated burn severities for 41,436 ha analysis area based on the Tripod Complex fire that occurred in Okanogan and Wenatchee National Forests in 2006 and the distribution of fire severity for the simulated East Deer Creek Watershed based on flame length values generated by FlamMap.

Burn Severity	Tripod Complex	East Deer Creek	
	Percent of Area	Area (ha)	Percent of Area
Unburned	2		
Low	47	2289	49
Moderate	27	1722	37
High	24	628	14

in different years. The generated climate was based on monthly statistics of long-term weather data from the nearest NOAA National Climatic Data Center weather station, Colville WB AP, WA.

Critical hillslopes were identified based on their average annual sediment yields. The hillslopes were arranged in descending order of sediment yield. Hillslopes were prioritized for the top 10, 20, 30, 40, and 50 percent of the total sediment generated from the watershed. This was done to ascertain which hillslopes in the watershed should be prioritized for forest fuel reduction treatments.

Assessment of the effect of fuel management on water yield. Once the critical hillslopes in the watershed were identified and categorized, the WEPP watershed model (v2012.8) was then applied to evaluate the impact of fuel treatments on water yield. First, pre-treatment simulations were conducted for the existing undisturbed forest that was considered as a baseline run. Then, five post-treatment simulation runs were carried out by setting the thinning/prescribed burn treatment to the top 10, 20, 30, 40, and 50 percent of the sediment generating hillslopes. For this study, model simulations applied the two most common forest fuel managements for reducing the risk of wildfire (McIver et al., 2013; Mickler et al., 2013; Agee and Skinner, 2005). This study aimed to evaluate the combined effects of thinning and prescribed burns to reduce stand density and dead fuels accumulated on the ground.

Two separate soil and management files were created for the pre-treatment and post-treatment simulation conditions. These files were taken from WEPP database and adapted for key parameters for both conditions. A forest sandy loam and a low severity burn soil were used for the pre- and post-treatment, respectively. These two soils differed primarily in effective hydraulic conductivity of the surface soil and rill-erodibility values (Table 3). The other soil parameters such as albedo, initial soil saturation, inter-rill erodibility, and critical shear parameters were kept similar for both conditions. The soil anisotropy parameter, which represents the relative predominance of lateral to vertical flow, was set to 15 following Srivastava et al. (2013). The saturated hydraulic conductivity of granitic rocks (K_{sat}) underlying the soil profile was set to 0.036 mm hr^{-1} following literature values (Dun et al., 2009; Srivastava et al., 2013). For channels, WEPP default forest sandy loam soil was used.

Table 3. WEPP default soil and management parameter values for burn severity hillslopes.

Parameters	Burn Severity			
	Unburned	Low	Moderate	High
Albedo	0.3	0.1	0.1	0.1
Initial saturation level (%)	50	50	50	50
Effective hydraulic conductivity (mm hr ⁻¹)	42	25	25	16
Rill erodibility (kg s m ⁻⁴)	5.0×10^{-4}	6.0×10^{-4}	6.0×10^{-4}	7.0×10^{-4}
Interrill erodibility (s m ⁻¹)	4.0×10^5	4.0×10^5	4.0×10^5	4.0×10^5
Critical shear (Pa)	1.0	1.0	1.0	1.0
Groundcover (%)	90	85	45	30

To describe the pre- and post-treatment vegetation conditions, a forest perennial management file in WEPP database was selected and modified for canopy cover and groundcover. The canopy cover was characterized using the leaf area index (*LAI*), the ratio of the surface area of the plant leaves to the ground area, a sensitive evapotranspiration (*ET*) parameter in WEPP. For pre-treatment, an average *LAI* of 6 m² m⁻² was used following the field-measured literature value (Pocewicz et al., 2004). Dun et al. (2009) and Srivastava et al. (2013) used a similar value for water yield assessment from undisturbed forest watersheds located in northern Idaho. For representing the canopy cover of thinned stands we used a *LAI* value of 2 m² m⁻². Rill and inter-rill groundcover, an important parameter in WEPP was used to describe the surface conditions. For pre-treatment, we used the default value of 90% groundcover for both rill and inter-rills while for post-treatment, we assumed 85% groundcover (Robichaud, 2000; Elliot, 2005). The groundcover was calibrated using the WEPP cover calibration tool by adjusting the default value of biomass energy ratio (*BER*) for undisturbed forest from 15 kg MJ⁻¹ to 1.4 kg MJ⁻¹.

WEPP uses a modified FAO Penman-Monteith method to estimate reference (grass) *ET* (Allen et al., 1998). Actual *ET* is determined by adjusting the mid-season crop coefficient (*K_{cb}*) for vegetation, and readily available water (*RAW*) for environmental conditions. The default values of *K_{cb}* and *RAW* for conifer trees are 0.95 and 0.75, respectively. We used *K_{cb}* of 0.80 and kept the default value of 0.75 for *RAW* following Srivastava et al. (2013).

For baseflow calculations, the *k_b* value was estimated as 0.026 d⁻¹ using the daily discharge data from the nearest USGS gauging station, the Kettle River near Laurier, WA (USGS, 12404500). For this study, we assumed an impermeable confining unit underlying the bedrock. Therefore, we set the value of *k_s* to zero. The initial groundwater storage (0.5 mm) was determined from the preliminary WEPP run by averaging the groundwater storage at the beginning of each year.

To adequately represent the climate for water yield simulations, a climate input file previously generated for wildfire simulations was adjusted for the elevation (1102 m) at the centroid of the watershed. For this, the monthly gridded PRISM (Parameter-elevation Relationships on Independent Slopes Model) (Daly et al., 2008) data were used to adjust the monthly statistics of the CLIGEN-generated monthly

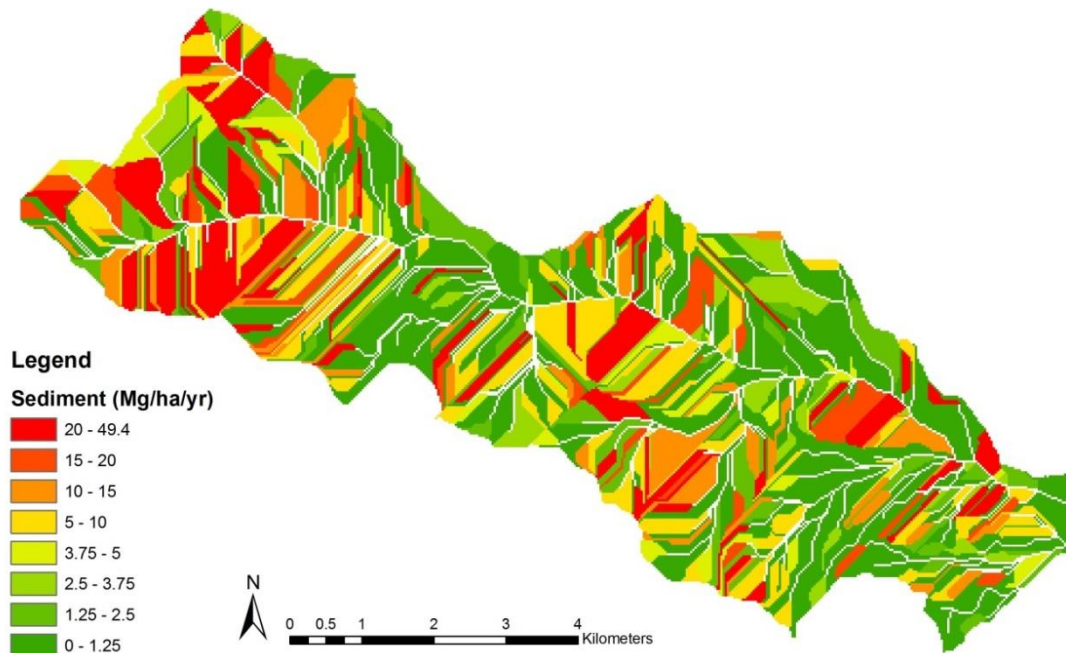


Figure 3. Online GIS BAER WEPP generated average annual sediment yield map for the study watershed.

precipitation, maximum and minimum temperature from the Colville WB AP, WA weather station. The CLIGEN model was then used to generate a 50-year stochastic daily climate data for WEPP simulations.

Changes in water yield at the watershed outlet occur from the changes in hydrologic processes in the treated area. Therefore, the average annual values for each water balance component (soil evaporation, plant transpiration, *ET*, surface runoff, subsurface lateral flow, deep percolation, and baseflow) and water yield were computed at the watershed scale. The average annual values obtained for each post-treatment condition were compared to those of the pre-treatment conditions at the hillslope scale to evaluate the spatial change in surface runoff, subsurface lateral flow, *ET*, and deep percolation.

RESULTS AND DISCUSSION

Identification and Prioritization of Critical Hillslopes. The average annual sediment yields for the first-year following wildfire from Online GIS BAER WEPP varied from 0 to 49.4 Mg ha⁻¹ yr⁻¹ across all hillslopes (Figure 3). Post-fire average annual sediment yield from hillslopes showed weak correlation with slope steepness and length. The regression coefficient of sediment yields with slope length (R^2 , 0.51) was higher than with slope steepness (R^2 , 0.10). In general, hillslopes with moderate slope steepness and slope length yielded higher sediment.

The high severity burn hillslopes generated the highest sediment yields with an average of 11.8 Mg ha⁻¹ yr⁻¹ while the low severity burn hillslopes produced the lowest sediment averaging 3.4 Mg ha⁻¹ yr⁻¹ (Table 4). The magnitude of sediment yield from high severity burn hillslopes was 3.4 times greater than from low severity burn hillslopes. The hillslopes with high severity burns had the highest average slope

Table 4. Distribution of slope steepness and length by fire severity and WEPP-predicted average annual sediment yield by burn severity in the East Deer Creek watershed.

Burn Severity	Avg slope steepness (%)	Avg. slope length (m)	Sediment Yield (Mg ha ⁻¹ yr ⁻¹)
Low burn severity	19	272	3.4
Moderate burn severity	15	316	6.0
High burn severity	28	217	11.8

steepness (28%) and the lowest average slope length (217 m). The moderate severity burn hillslopes had the lowest average slope steepness (15 percent) and the highest average slope length (316 m).

Figure 4 illustrates the spatial variability of annual average sediment yield in the watershed for the top 10, 20, 30, 40, and 50 percent sediment reduction selected hillslopes. Table 5 presents the number of hillslopes, average area, slope steepness, slope length, sediment yield and percent of the watershed for each category. The cumulative average sediment yield from these categorized hillslopes varied from 41.6 to 29.9 Mg ha⁻¹ yr⁻¹.

Following pre-treatment simulation, WEPP was used to evaluate the water yield and each water balance component for post-treatment conditions. Five separate simulations were run by implementing thinning and prescribed burn treatments to reduce sediment generation following wildfire by 10, 20, 30, 40, and 50 percent for post-treatment conditions. Note that to achieve a 50 percent reduction in post fire erosion, only 15.5 percent of the watershed needs to be treated. Change in average annual values of major water balance components for post-treatment conditions are presented in Table 6. The water yield from the watershed increased by less than 1 percent as the treatment area increased from 0 to 16 percent. The reduction in LAI due to thinning operations caused a decrease in plant transpiration E_p and an increase in soil evaporation E_s . The E_p decreased from 455 mm to 437 mm (4 percent decrease), and E_s increased from 31.49 mm to 48.66 mm (55 percent increase), as the area treated increased from 0 to 16 percent of the watershed.

Surface runoff and subsurface lateral flow from hillslopes were predicted to increase by 4.4 percent, and a decrease of 1.3 percent, respectively, over the range of treated area (Table 6). As the treatment area increased, streamflow response showed a 0.9 percent increase in baseflow at the outlet, from 49.71 mm to 50.13 mm, when sufficient area was treated to reduce sediment following wildfire by 50 percent. The increase in surface runoff following fuel treatment increases the likelihood of greater peak flow rates and increased surface erosion until the vegetation recover (Elliot et al., 2013).

SUMMARY AND CONCLUSIONS

The fire behavior model, FlamMap was used to predict wildfire severity for the existing vegetation in the East Deer Creek watershed of Colville National Forest, WA. The Online GIS BAER WEPP model simulation was conducted to determine the first-year post-fire sediment yields from 777 discretized hillslopes. The sediment

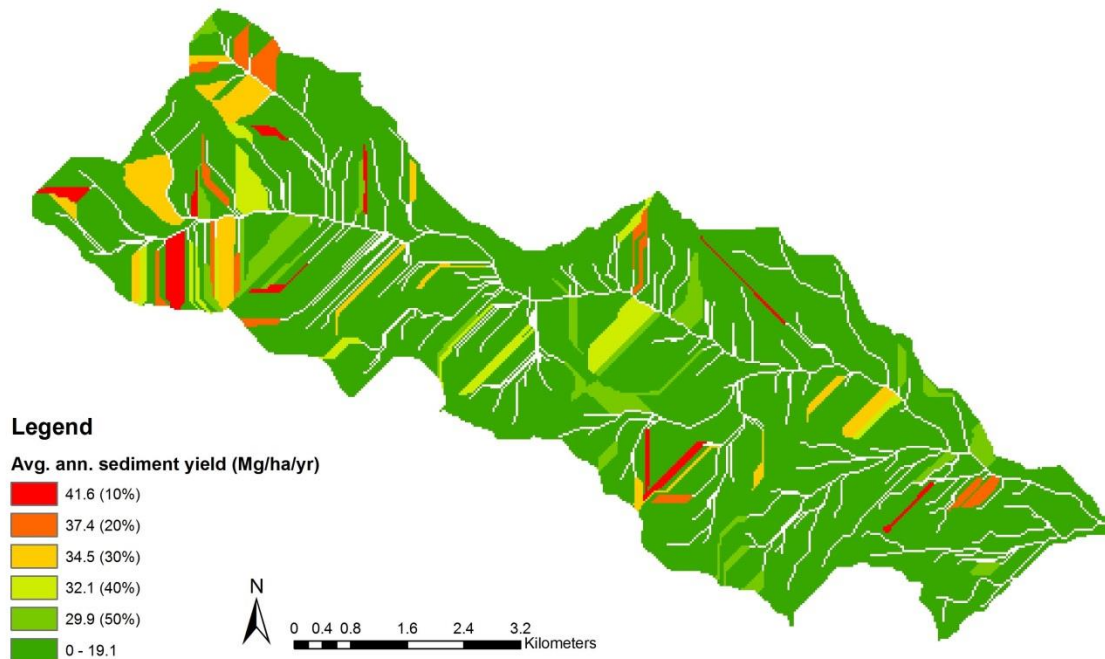


Figure 4. Simulated average annual sediment yield from the top 10%, 20%, 30%, 40%, and 50% of sediment-generating hillslopes in the first year following simulated wildfire covering the entire watershed.

yields across all the hillslopes ranged 0–49.4 Mg ha⁻¹ yr⁻¹. The low-, moderate-, and high-severity burned hillslopes produced 3.4, 6.0, and 11.8 Mg ha⁻¹ yr⁻¹ of sediment. All the hillslopes were ranked by arranging them in descending order of sediment yield. Critical hillslopes that generated the top 10, 20, 30, 40, and 50 percent of sediment were selected to implement both thinning and prescribed burn treatments. WEPP simulations were run for pre-treatment condition (undisturbed forest) and post-treatment conditions (thinning and prescribed burn applied to top 10, 20, 30, 40, and 50 percent of sediment-generating hillslopes) for comparisons of major hydrologic components and water yield at the outlet.

The results suggest that water yield from the watershed slightly increases as the treated area increases. At the watershed scale, the increase in water yield from pre-treatment conditions for the 10, 20, 30, 40, and 50 percent sediment reduction treatments were 0.08, 0.17, 0.34, 0.51, and 0.69 percent, respectively. From 2 to 16 percent treated area, overall, *ET* and subsurface lateral flow from the watershed decreased, and surface runoff and baseflow increased. The increase in surface runoff could lead to an increase in peak flows and sediment delivery.

Implementing thinning and prescribed burn treatments to the proposed hillslopes will have a slight increase on water yield. The approach of this study provides a framework to guide resource managers in the prioritization of fuel reduction treatments in the watershed to reduce the risk of wildfire, and a method to evaluate the likely effects of fuel management on water yield.

Table 5. For the hillslopes selected for treatment based on sediment delivery, the cumulative area, topographic features of the cumulative area, and sediment yield averaged over the cumulative area.

*Treatment (%)	Number of Hillslopes	Area (ha)	Area (% of Total)	Average Slope (%)	Average Slope length (m)	Average Annual Sediment Yield (Mg ha ⁻¹ yr ⁻¹)
10	11	82	1.8	23	764	42
20	24	180	3.9	25	684	37
30	39	361	7.8	24	649	34
40	57	532	11.5	23	702	32
50	78	721	15.5	23	681	30
100	777	5019	100	19	282	6

* Treatment represents hillslopes prioritized for the top 10, 20, 30, 40, and 50 percent of the total sediment generated from the watershed.

Table 6. Water balance for current conditions and percent change in average annual watershed water balance for post-treatment relative to pre-treatment conditions. Average annual precipitation was 575.3 mm.

Treated Area (%)	E_p	E_s	ET	R	R_s	D	Q_b	$Ch. Loss$	Water yield
Untreated	455.1	31.5	486.6	15.3	31.7	49.7	49.7	8.6	88.1
(Percent relative change in water flux from post-treatment conditions relative pre-treatment conditions)									
1.8	-0.45	6.23	-0.02	0.47	-0.13	0.10	0.10	0.07	0.08
3.9	-0.98	13.61	-0.04	1.13	-0.35	0.21	0.21	0.21	0.17
7.8	-1.97	27.32	-0.08	2.33	-0.72	0.44	0.44	0.48	0.34
11.5	-2.90	40.20	-0.11	3.27	-0.95	0.62	0.62	0.63	0.51
15.5	-3.94	54.52	-0.15	4.42	-1.28	0.83	0.83	0.85	0.69

where: E_p , Plant Transpiration; E_s , Soil Evaporation; ET , Evapotranspiration; D , Deep Percolation; R , Surface runoff; R_s , Subsurface Lateral Flow; Q_b , Baseflow; $Ch. Loss$, Channel transmission loss.

(+/-): percent increase/decrease in water flux.

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