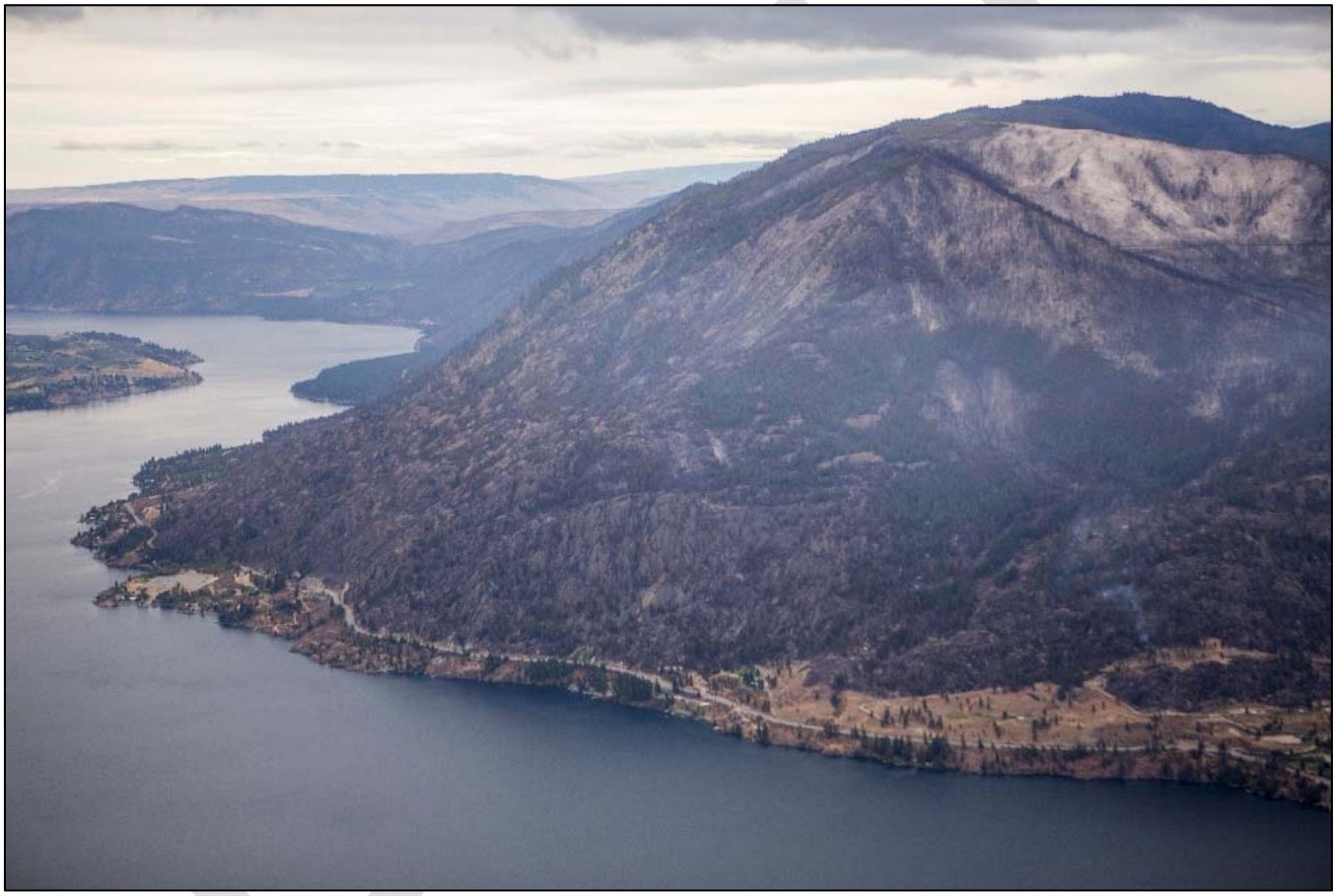
Appendix F: Case Study 6

First Creek Fire, Washington

Background

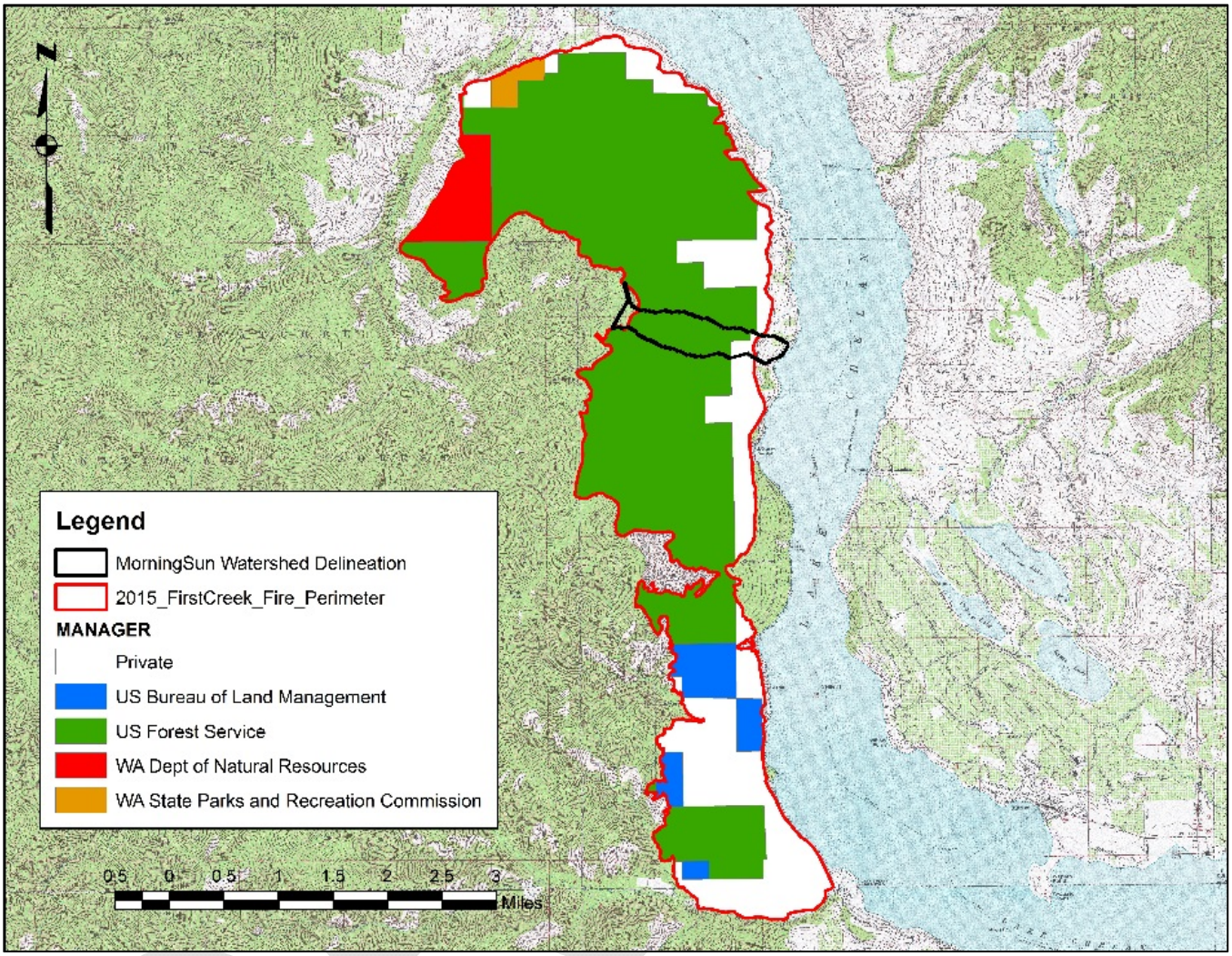
The First Creek fire started on August 14, 2015 and burned a total of 7,443 acres above the south shore of Lake Chelan, WA (figures F-1 and F-2), extending from the First Creek drainage to 25 Mile Creek, and encompassing several named and unnamed ephemeral tributaries that drain directly into Lake Chelan. The fire burned primarily in very steep, rocky, forested terrain, with average slopes ranging from 30 to 90 percent and elevations ranging from 1,100 to 5,080 feet.

Figure F–1 Aerial photo of Lake Chelan south shore and First Creek fire area near 25 Mile Creek.



Of the burned acreage, 5,031 acres (68 percent) were on National Forest Systems (NFS) lands within the Chelan Ranger District of the Okanogan-Wenatchee National Forest. A post-wildfire assessment was completed by a U.S. Forest Service (FS) Burned Area Emergency Response (BAER) team for the drainage areas containing NFS lands. All of these catchments contain private lands at the downstream end. Chelan County was concerned with increased flood hazard potential to these downstream private lands and requested assistance from the NRCS through the Emergency Watershed Protection Program (EWP). Of particular interest were peak flow and runoff volume estimates for post-wildfire conditions to assess threats to life and/or property. This case study provides an overview of the analyses performed to provide the estimate specifically for the Morning Sun drainage area located within the First Creek fire perimeter.

Figure F–2 Land ownership within First Creek fire perimeter and modeled basin.



Method

Often in a response to an emergency it is necessary to perform tasks within a very short timeframe while still achieving reasonably accurate results. Such is the case sometimes with a post wildfire response. When this condition occurs, a relatively quick and easy to use hydrologic model can sometimes be used with good results.

This case study provides an example of a rainfall-runoff model. WILDCAT5 for Windows (Hawkins and Barreto-Munoz, 2016) was used to simulate the expected runoff response for both pre- and post-wildfire conditions to assess peak flow estimates and hydrographs used for mitigation planning activities by both the FS and NRCS. The modeling included relevant hydrologic mechanisms such as variability in vegetation type and differences in runoff between soil burn severity areas. The modeled drainage area, Morning Sun, is presented in figure F-3 and has a drainage area of 269 acres (0.42 square miles).

WILDCAT5 for Windows (WILDCAT5) is an interactive Windows™ Excel software package designed to assist watershed specialists in analyzing rainfall runoff events to predict peak flow and runoff volumes generated by single event rainstorms for a variety of watershed soil and vegetation conditions. The distinct advantage that WILDCAT5 offers over most other models is the ability to easily and quickly

calculate the direct runoff using the distributed CN method. The distributed CN method calculates direct runoff, using the NRCS runoff Curve Number (CN) method, by summing the runoff for each individual hydrologic soil-cover complex (source areas). It does not use the average (weighted) CN method. The difference between these two methods are shown in example F-1.

Example F–1 Determine the difference between post-fire hydrologic modeling by distributed CN and average CN methods.

Given: A 1,000 acre watershed has recently burned in a wildfire. The watershed sustains 230 acres (23%) high soil burn severity, 320 acres (32%) moderate soil burn severity, and 450 acres (45%) low soil burn severity. The design storm has 1.0 inches of rainfall, the Antecedent Runoff Condition (ARC) is II, and Ia/S is 0.20. The pre-wildfire CN is 60. The post-wildfire CNs are:

High soil burn severity, CN = 95
Moderate soil burn severity, CN = 85
Low soil burn severity, CN = pre-wildfire CN + 5 = 65

Determine: Estimate the direct runoff by both the distributed CN and the average CN methods.

Solution:

Distributed CN Method

Step 1. Determine the runoff, proportioning by hydrologic soil-cover complex.

$$S_{05} = (1000 / CN_{20}) - 10 \quad \text{and} \quad Q = (P - 0.20 \times S_{20})^2 / (P + 0.80 \times S_{20})$$

Where (CN) is the curve number, (S) is the storage index (inches), (A) is the drainage area (acres), (P) is rainfall (inches), and (Q) is runoff (inches).

Cover	CN	S	A	Q	Q×A
Low SBS	65	5.4	450	0.00	0
Moderate SBS	85	1.8	320	0.17	54
High SBS	95	0.5	230	0.56	129
Totals			1,000		183

Step 2. Determine the distributed CN weighted runoff.

The distributed CN weighted $Q = \frac{\Sigma Q \times A}{\Sigma A} = \frac{183 \text{ acre-in}}{1{,}000 \text{ acres}} = 0.18 \text{ in}$

Average CN Method

Step 1. Determine the average CN, proportioning by hydrologic soil-cover complex.

Cover	CN	A	CN×A
Low SBS	65	450	29,250
Moderate SBS	85	320	27,200
High SBS	95	230	21,850
Totals		1,000	78,300

The average $CN = \frac{\Sigma CN \times A}{\Sigma A} = \frac{78{,}300 \text{ acres}}{1{,}000 \text{ acres}} = 78.3$. Use 78.

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Step 2. Determine the average CN runoff.

$$S_{20} = (1000 / 78) - 10 = 2.8$$

The average CN $Q = (1 - 0.2 \times 2.8)^2 / (1 + 0.8 \times 2.8) = 0.06$ in

Note that the runoff estimate using the distributed CN method is 3 times greater than the runoff estimate using the average CN method.

Example F-1 illustrates limitations of the average CN method and the importance of using the Distributed CN method for post-fire analysis. Only 23% of the area is high soil burn severity, yet that area produces 77% of the total runoff when using the Distributed CN method. Where differences in CN for a watershed are large, the average CN method either under- or over-estimates Q, depending on the size of the storm (USDA-NRCS, 2004b). For burned watersheds, the average CN method under-estimates the amount of runoff, as shown in this example. The method of weighted Q (Distributed CN) always gives the correct result (in terms of the given data) but it requires more work than the weighted-CN (Average CN) method especially when a watershed has many complexes (USDA-NRCS, 2004b).

Runoff hydrographs are then developed by applying the runoff volume, estimated by the CN method, and a time of concentration to a dimensionless unit hydrograph. Support for software development of WILDCAT5 was provided through a cost-share agreement between the University of Arizona and the USDA Forest Service, Stream Systems Technology Center. WILDCAT5 model inputs include: (1) rainstorm characteristics; (2) watershed soil and cover-related parameters; (3) runoff timing parameters; and (4) unit hydrograph shape and scale sections.

Runoff CN Estimation

Runoff CNs were assigned according to hydrologic soil group, vegetative type, soil burn severity, and ground cover condition (percent cover). The dominant vegetation types within the fire boundary were Subalpine fir, Engelmann spruce, lodgepole pine, larch, ponderosa pine, Douglas-fir, shrubland, and some transitional sagebrush grasslands (BAER 2015). Hydrologic soil group (HSG) classification was selected using soils data published in the NRCS Soil Survey Geographic (SSURGO) database which is contained in the Cashmere Mountain Area Survey (WA 608), published in 2015.

Using a good ground cover condition, NRCS recommended values (USDA-NRCS 2004a) were applied by hydrologic soil group for pre-fire (unburned) conditions. The pre-wildfire CN values are provided in table F-1.

Table F–1 Pre-wildfire CN assignments used in hydrologic modeling (ARC II, Ia/S=0.20).

Pre-wildfire condition	HSG	CN_{05} values	Acres	% of Area
Woods, good condition	B	55	234	87
Rock	-	90	35	13

Loss of vegetation and hydrophobic soil conditions, as estimated using soil burn severity map (figure F-3), are the principle drivers of increased flow in post-wildfire runoff predictions. The FS Remote Sensing Application Center (RSAC) provided the BAER team with an initial Burned Area Reflectance Classification (BARC) map derived from a LANDSAT 8 scene acquisition. The BAER team conducted reconnaissance and field verification surveys to finalize the soil burn severity map. The BAER team assessment estimated 39 acres of high soil burn severity, 74 acres of moderate soil burn severity, 91 acres of low soil burn severity, 91 acres of unburned area, and 35 acres of rock outcrop.

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Field assessments of the First Creek fire area, conducted by the BAER team, determined that 100 percent of high soil burn severity areas and 50 percent of moderate soil burn severity areas had a strong water-repellent (hydrophobic) tendency. The same percentage was then transferred to the Morning Sun watershed.

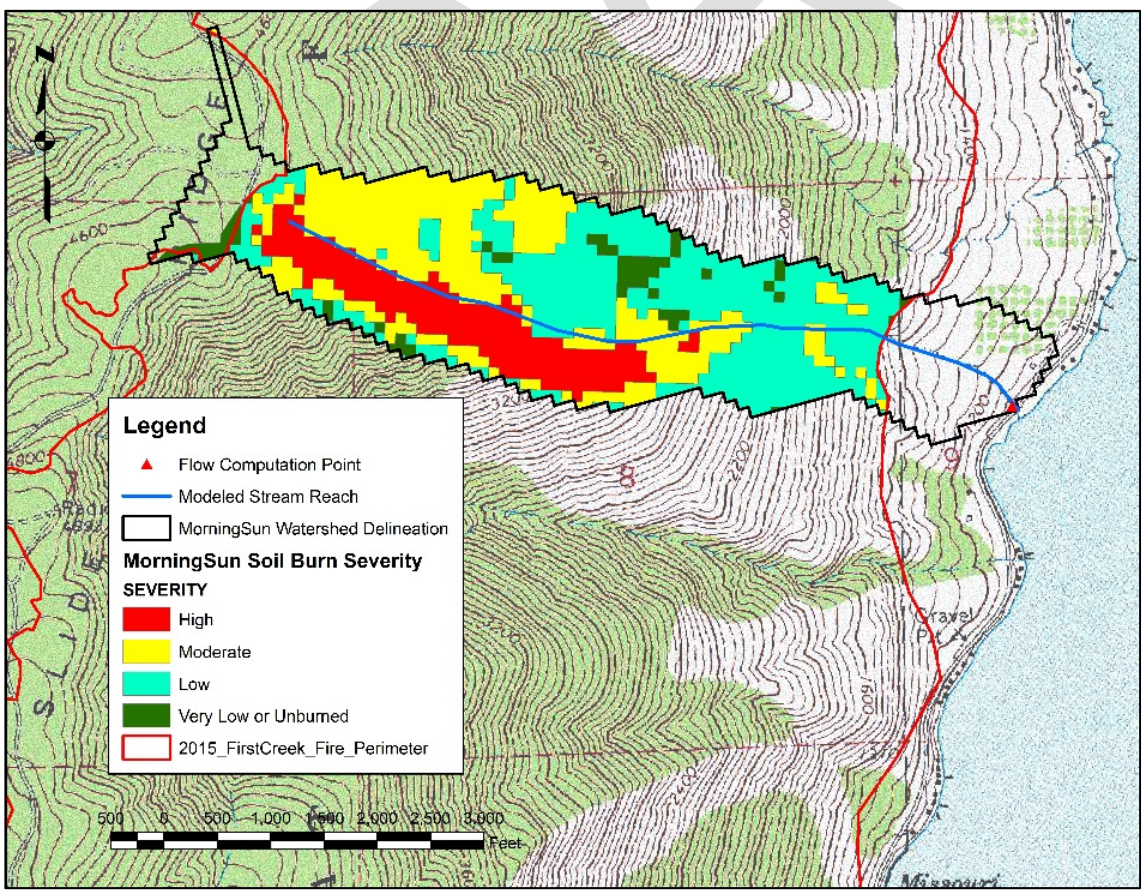
The post-wildfire CN_{20} values are provided in table F-2. Low, moderate, and high soil burn severity areas, with and without water repellent soils, were estimated using CN values from the FS BAER Road Treatment Tools, Curve Number Methods Supplement, Kuyumjian Curve Numbers (USDA-FS, 2014). The original CN_{20} values have been adjusted from ARC II to ARC III. ARC III values were chosen to provide a worst-case scenario, producing the highest peak flow, from the possibility of a convective storm on wet soils.

Table F–2 Post-wildfire CN assignments used in hydrologic modeling (ARC III, Ia/S=0.20).

Post-wildfire condition	CN_{20} values	Acres	% of Area
High soil burn severity with water repellent soils	98	39	14.5
High soil burn severity without water repellent soils	96	0	0
Moderate soil burn severity with water repellent soils	98*	37	14.5
Moderate soil burn severity without water repellent soils	94	37	14.5
Low soil burn severity	Pre-fire CN + 5	91	34
Unburned	Pre-fire CN	30	11
Rock	Pre-fire CN	35	13

* The original CN_{20} value from FS BAER Road Treatment Tools has changed from 90 to 95 from personal communication with the author (Kuyumjian, 2015-2017). The CN_{20}, ARC II value (95) was then changed to the CN_{20}, ARC III value (98).

Figure F–3 Morning Sun watershed soil burn severity.



Recurrence Interval

Every design has a chance of failure. Therefore, designers and decision makers must assess what level of risk is acceptable. With respect to a design recurrence interval, the design could be at risk of failure when the recurrence interval is exceeded. NRCS has established design recurrence interval criteria within Conservation Practice Standards and engineering policy. However, for post-wildfire mitigation measures, one may want to know what the probability of occurrence would be due to post-wildfire effects on a watershed. The probability of occurrence (p_n), that a given annual event will not be equaled or exceeded at least once in the next n years, is the product of the non-occurrence probabilities for those n years. The probability of occurrence can then be solved by using the following equation:

$$p_n = 1 - [(T_r - 1)/T_r]^n \qquad \text{eq. F-1}$$

where;

p_n = the probability of occurrence (decimal)

T_r = the recurrence interval (years)

n = the design life (years)

For post-wildfire mitigation measures, the design life could be selected on the premise that the burn severity of the watershed corresponds to the recovery period of the watershed. DeBano (1996) found that sediment yields from a low severity fire recovered to normal after 3 years, but moderate and severely burned watersheds took 7 and 14 years, respectively. Elliot and others (2005) found that past studies of post-fire hydrology indicate that a drainage basin recovery period of about 5 years may be typical. The recovery period can be as little as 1 year to more than 14 years and may be difficult to correlate to burn severity. A rule-of-thumb used by some hydrologists is a 3 to 5 year after fire recovery period.

Assuming that the watershed will recover to a near pre-fire hydrologic response condition within 5 years, a probability of occurrence can then be determined for each specific recurrence interval. For example, using a 25-year recurrence interval, the probability that the design storm event will be equaled or exceeded during the next 5 years is calculated as:

$$p_n = 1\text{-}[(25\text{-}1)/25]^{5} = 0.18$$

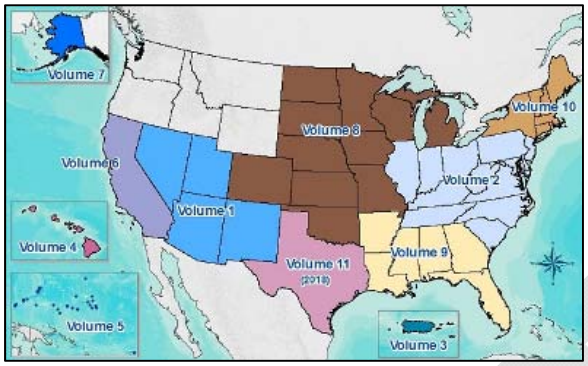
A 25-year storm has a 4% chance of occurring in any given year. However, there is an 18% chance of experiencing a 25-year storm within a 5-year period. The chance for a significant flood event is then quite probable when the increased runoff potential due to post-fire effects are then evaluated over an extended period of years. Most landowners are unaware of the increased flood risk due to post-fire effects and the new danger that they are now threatened with. It is common for a landowner to say, "*There has never been any flooding here before*".

Rainfall

Precipitation, as used here in this case study, means rainfall only and does not include snow, sleet, hail or other forms of precipitation.

The unit peak discharge response increases abruptly when the 30-minute maximum rainfall intensity is greater than about 0.2 inches per hour. The threshold value is about 0.3 inches per hour for the year of the wildfire (Moody, 2011). In recognition of this, the 1-hour storm duration was used due to the association with a short duration, high intensity rainfall caused from a convective thunderstorm. These storms generally occur during the summer months from May through September along the east slopes of Cascade Mountain Range in Washington State which also coincides with the typical fire season.
NOAA Atlas 14 was not available in Washington at the time of this study (Figure F-4). Therefore, Precipitation-Frequency values are found in NOAA Atlas 2, Volume 9 for Washington (Miller, Frederick and Tracy, 1973).

Figure F–4 NOAA Atlas 14 Project Areas.



NOAA Atlas 2, Volume 9 only provides precipitation values for the 6- and 24-hour durations. Therefore, the 1-hour duration value must be calculated.

The first step is to determine the region of applicability by finding the site on the Regions map (NOAA Atlas 2, Volume 9, Figure 18). For this case study the site is in Region 1.

Next, the 1-hour duration values for the 2- and 100-year return periods are calculated using the following equations for the appropriate region (Region 1).

$$Y_2 = 0.019 + 0.711[(X_1)(X_1/X_2)] + 0.001Z \qquad \text{eq. F-2}$$

$$Y_{100} = 0.338 + 0.670[(X_3)(X_3/X_4)] + 0.001Z \qquad \text{eq. F-3}$$

where,

Y_2 = 2-year 1-hour estimated value (inches)

Y_{100} = 100-year 1-hour estimated value (inches)

X_1 = 2-year 6-hour value from precipitation-frequency maps (inches)

X_2 = 2-year 24-hour value from precipitation-frequency maps (inches)

X_3 = 100-year 6-hour value from precipitation-frequency maps (inches)

X_4 = 100-year 24-hour value from precipitation-frequency maps (inches)

X_5 = latitude (in decimals) minus 40°

X_6 = longitude (in decimals) minus 100°

Z = point elevation (hundreds of feet)

An alternative to the Atlas Maps are precipitation-frequency values determined from the NOAA Atlas 2 website (http://www.nws.noaa.gov/ohd/hdsc/noaaatlas2.htm) by entering the site latitude and longitude coordinates (47.9454° and -120.2113° respectively). This method produces the following values:

X_1 = 0.79 (inches)

X_2 = 1.38 (inches)

X_3 = 1.69 (inches)

X_4 = 3.44 (inches)

X_5 = 7.9454 (in decimals)

X_6 = 20.2113 (in decimals)

Z = 11.20 (hundreds of feet)

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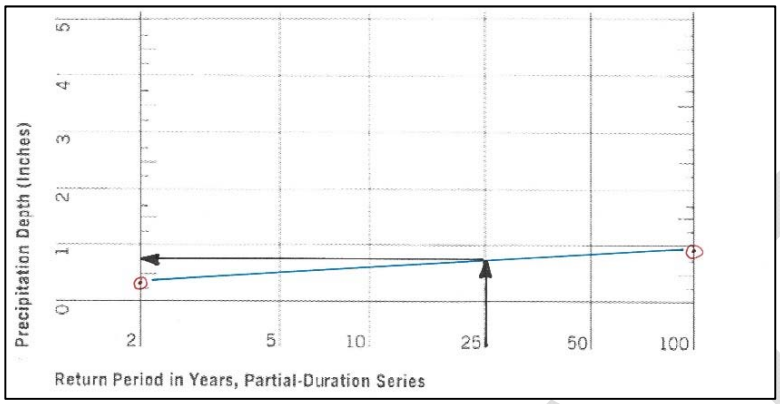
The 2- and 100-yr 1-hour values are then be calculated by using equations F-2 and F3.

$$Y_2 = 0.019 + 0.711[(0.79)(0.79/1.38)] + 0.001(11.2) = 0.35”$$
$$Y_{100} = 0.338 + 0.670[(1.69)(1.69/3.44)] + 0.001(11.2) = 0.91”$$

The 1-hour precipitation depths for the 2- and 100-year return periods are then plotted onto the nomogram (Figure F-5) to obtain the value for the 25-year return period.

Figure F–5 Precipitation depth versus return period for partial-duration series (NOAA Atlas 2, Volume 9, Figure 6).



The precipitation depth is then estimated by entering the horizontal axis for a return period of 25 years, then vertically to the line intercept, then horizontally to the vertical axis intercept. The resulting value for the 25-year 1-hour precipitation (rainfall) depth is approximately 0.75 inches.

Storm Distribution

There are five (5) alternatives for storm distributions offered in WILDCAT5 which are: 1) NEH4B, 2) Farmer-Fletcher, 3) Uniform, 4) Custom, and 5) Generic. Post-wildfire runoff is significantly dependent on rainfall intensity so it is imperative to accurately simulate the high intensity rainfall typically associated with the site (case study area is a convective storm). With this in mind the “Custom” storm distribution was chosen which uses specific distribution data based on research conducted by the National Weather Service (Arkell and Richards, 1985). The research provides regionalized storm distributions from parts of the Western U.S. for the 2- and 100-year, 1-hour storms at periods of 5, 10, 15, and 30 minutes (8.3%, 16.7%, 25%, and 50% respectively).

The first step of customizing the storm distribution is to determine the region of applicability by finding the site on the Study Area and Regions map (Arkell and Richards, 1985, Figure 1). This case study site is in Region 2.

Next, determine the ratios to 1-hour values of the 2- and 100-year return periods, at the 5, 10, 15, and 30 minute periods, from Table 1 (Arkell and Richards, 1985) for the appropriate region (Region 2 for this case study). Then plot these ratios on the nomogram (Figure F-6). The ratios to 1-hour values for the 25-year return period are thus obtained by drawing a line between the 2-year and 100-year points and reading the Y-axis at the 25-year intersection.

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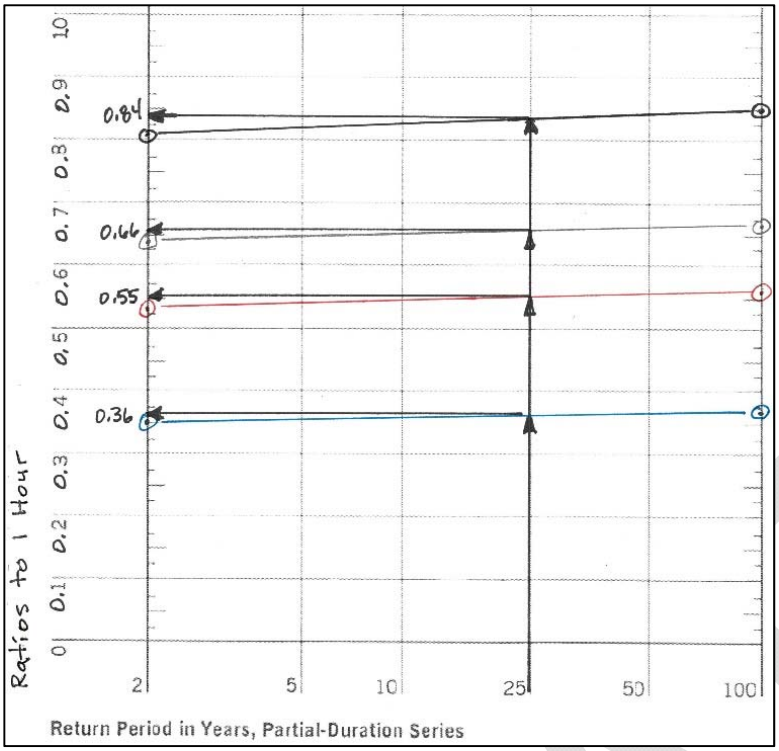
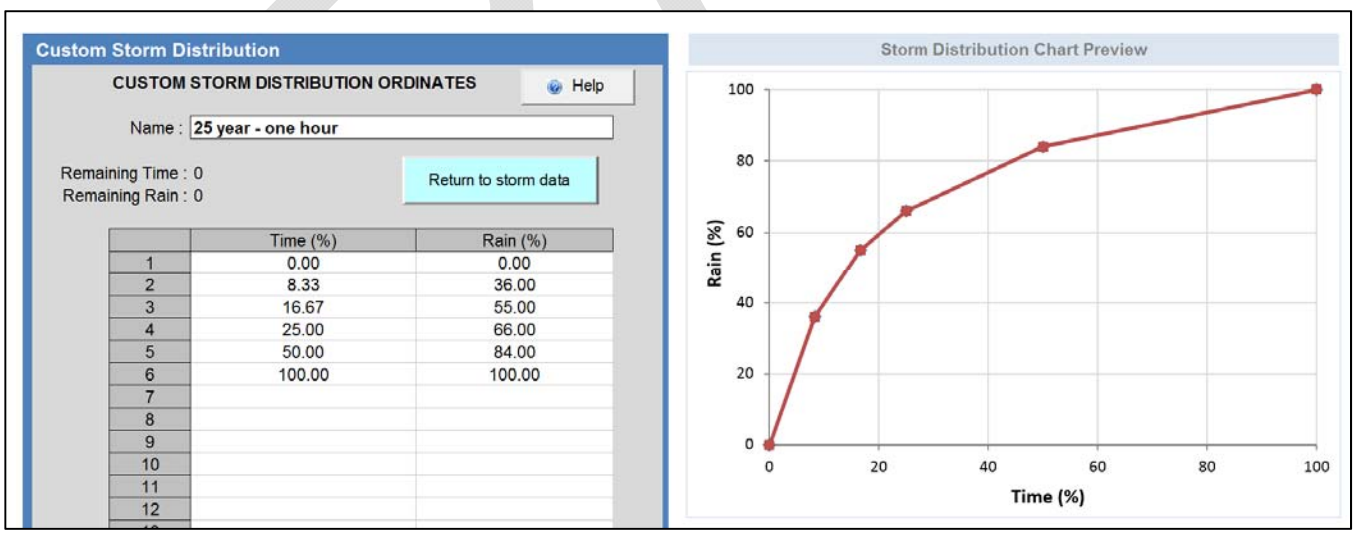
Figure F–6 Ratios to 1-hour (%) versus return period for partial-duration series (NOAA Atlas 2, Volume 9, Figure 6).



The ratios to 1-hour values (%) for the 25-year return period are then entered into WILDCAT5 as a percent of cumulative rain along with the corresponding time as a percent to the 1-hour storm as shown in figure F-7 below.

Figure F–7 Custom Storm Distribution input screen from WILDCAT5.



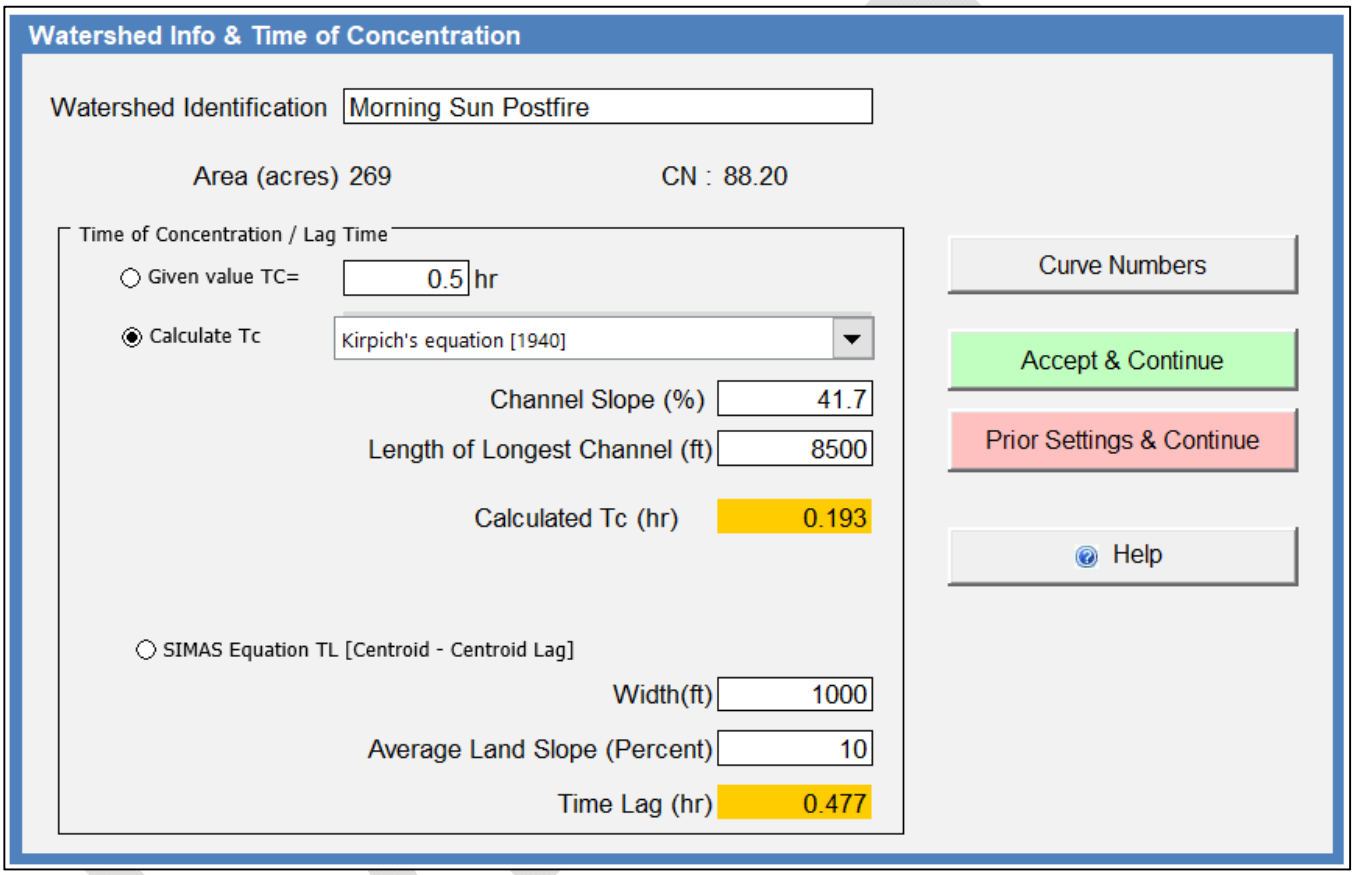
Time Parameters

The timing descriptors in WILDCAT5, time of concentration (T_c) or lag time (T_L), are used in scaling the unit hydrographs. From these, the unit hydrograph time base (T_b), time to peak (T_p), and the time increment (Δt) used to step through the design storm are calculated (Hawkins and Barreto-Munoz, 2016). There are four time parameter alternatives offered in WILDCAT5: 1) User's Choice Over-Ride; 2) Direct

Time of Concentration equation (Kirpich, 1940); 3) Lag Time equation (Kent, 1968); and an option for the Centroid-Centroid Lag (Simas, 1996).

One dilemma of post-wildfire hydrologic modeling is the fact that runoff computation is very sensitive to time parameter estimates, however these estimates can be difficult to calculate accurately. When dealing with emergency situations where there is a risk to loss of life, it may be prudent for the user to be conservative and estimate the highest reasonable peak flow. One method to accomplish this is to select a short time duration of T_c. Both the Kent and Simas equations tend to produce longer times of T_c in comparison to the Kirpich equation. Therefore, the Kirpich equation should be the equation of choice for post-wildfire modeling in an exigency.

Figure F–8 Time of Concentration input screen from WILDCAT5.



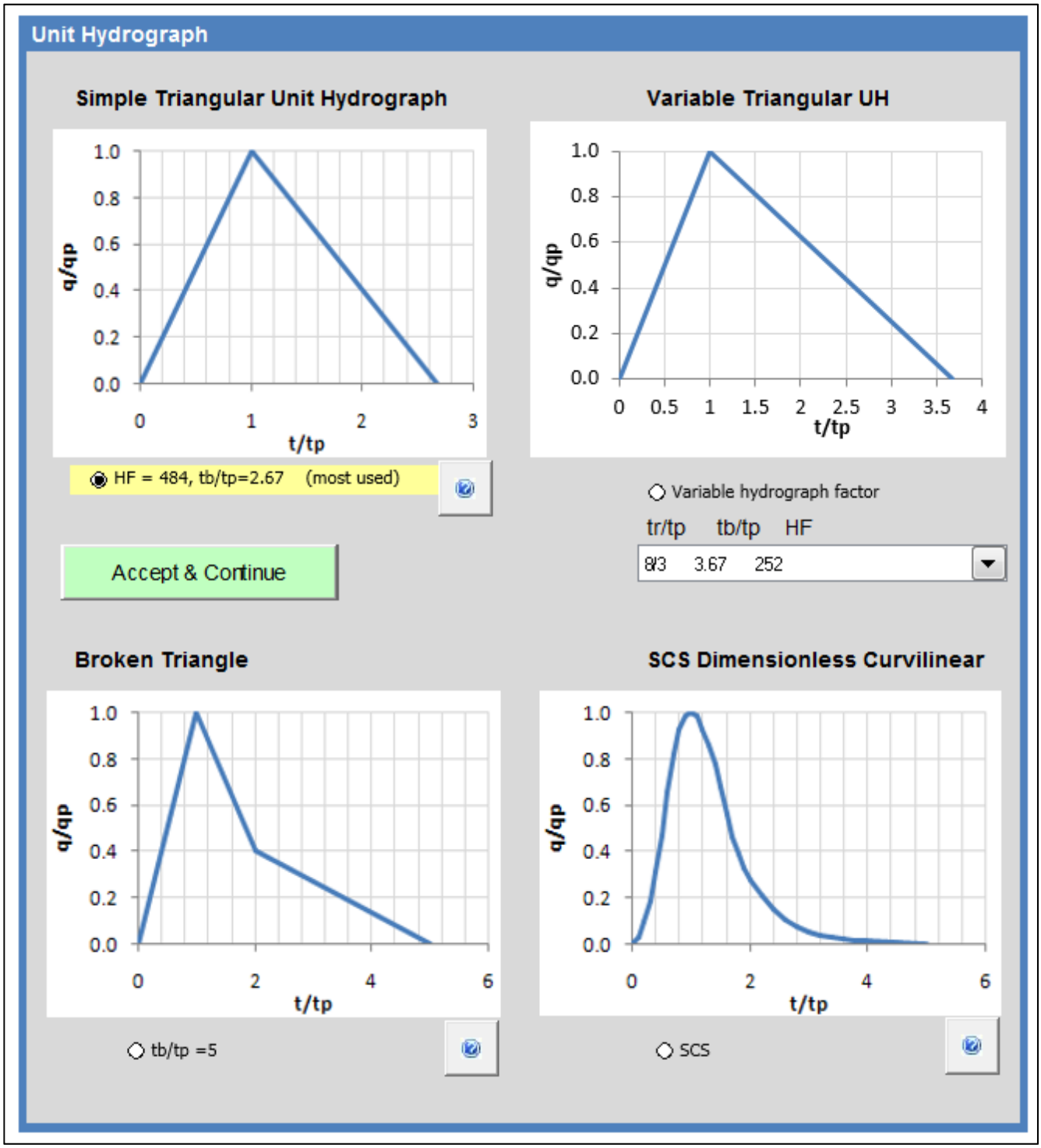
For the post-wildfire conditions, if the same input values are used for the lag time equation (Kent, 1968), a significantly higher T_c value (0.343 hours) is calculated. An even higher T_c value (0.712 hours) is calculated for the pre-wildfire condition since the lag time equation is dependent on the CN. Since the T_c value from the Direct Time of Concentration equation was the shortest time duration (0.19 hours), it was chosen to be used for the hydrologic modeling to provide a more conservatively high peak flow estimate.

Unit Hydrograph Shape

WILDCAT5 uses the unit hydrograph (UH) theory to transform spatially distributed runoff to an outlet. Four (4) shape alternatives for the UH are offered in WILDCAT5 (Figure F-9) which are: 1) Simple Triangular Unit Hydrograph; 2) Variable Triangular Unit Hydrograph; 3) Broken Triangular Unit Hydrograph; and 4) SCS Dimensionless Curvilinear Unit Hydrograph. Both the Simple Triangular UH and Dimensionless Curvilinear UH have a fixed peak rate factor (PRF), also known as the Hydrograph

Factor (HF), of 484. The Broken Triangular UH has a fixed PRF of 358.52. The Variable Triangular UH has nine PRF options ranging between 215.11 to 645.33. Given all other variables remaining constant, the higher the PRF, the higher the peak discharge.

Figure F–9 Unit Hydrograph input screen from WILDCAT5.

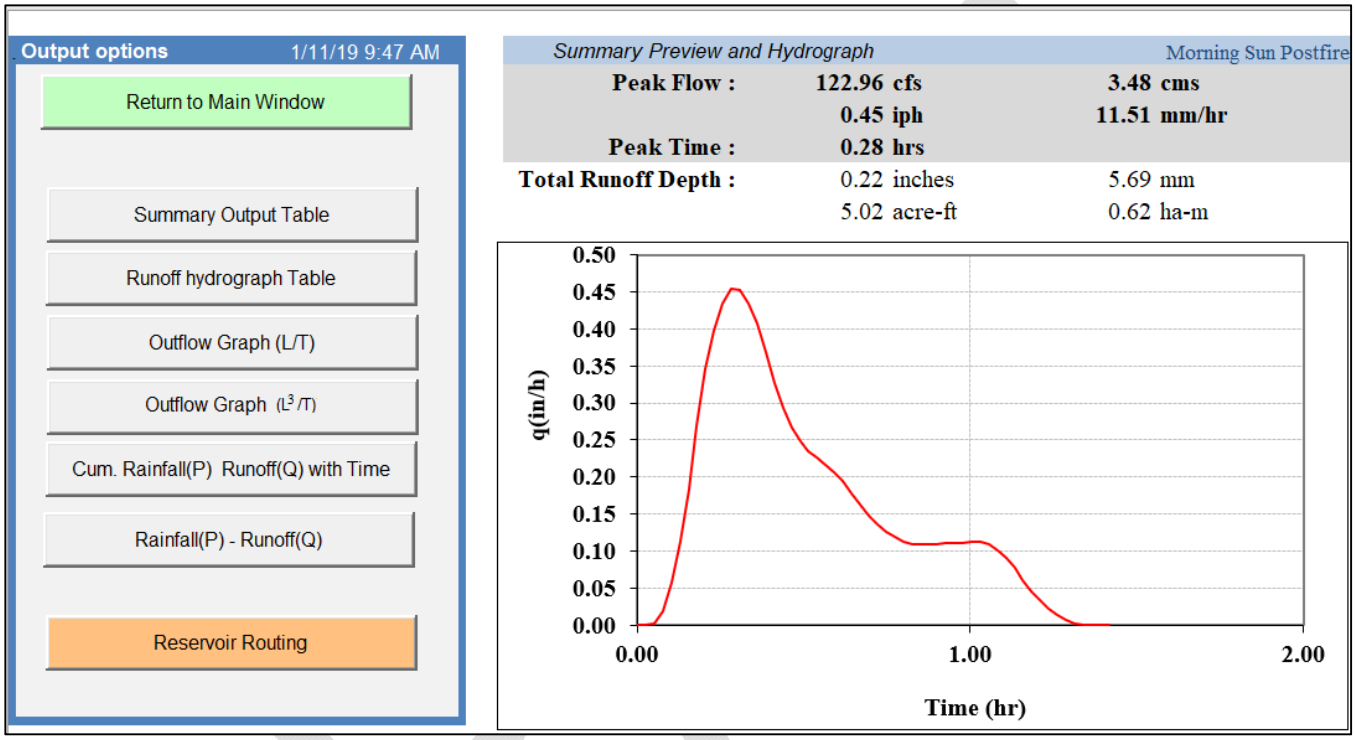


Of the four UH alternatives, the Simple Triangular UH produces the highest peak discharge except for the Variable Triangular UH while using a PRF of 516.27 or 645.33 which is then often less than 1% greater. Therefore, the Simple Triangular UH was used for the hydrologic modeling because it would produce the highest peak discharge for a PRF of 484.

Model Output Options

Seven (7) output options are available in WILDCAT5 which are: 1) Summary Preview and Hydrograph (Default option – shown in Figure F-10 below); 2) Summary Output Table; 3) Runoff Hydrograph Table; 4) Outflow Graph (L/T); 5) Outflow Graph (L^3/T); 6) Cumulative Rainfall, Rainfall Excess, and Runoff; and 7) Rainfall, Rainfall Excess, and Runoff. In addition to the output options, there is also the option to perform reservoir routing.

Figure F–10 Output options screen from WILDCAT5 post-wildfire conditions.



The Summary Output Table provides both input and output data summaries as shown in figures F-11 and F-12 below.

Figure F–11 Summary Output Table (INPUT) screen from WILDCAT5 post-wildfire conditions.

SUMMARY : Morning Sun Postfire **1/11/2019 9:47**

INPUT Operator: JML

Rainfall Excess Method :	Curve Number, Average CN(0.20)= 86.97	
Rainfall :	0.75 in	19.05 mm
Storm Duration :	1 hr	
Storm Distribution :	Custom 25 year - one hour	
Unit Hydrograph :	Simple Triangular Unit Hydrograph	
Total Drainage Area :	269.0 Acres	108.9 Hectares
Timing :	Kirpich's Equation	
Time of concentration :	0.193 hrs	11.6 mins
Unit hydrograph Δt :	0.026 hrs	1.5 mins
Unit Hydrograph T_p :	0.129 hrs	7.7 mins
Unit hydrograph T_b :	0.343 hrs	20.6 mins

Figure F–12 Summary Output Table (OUTPUT) screen from WILDCAT5 post-wildfire conditions.

OUTPUT

Initial Abstraction :	0.2997	inches	7.61	mm
Total Runoff Depth :	0.2239	inches	5.69	mm
	5.020	acre-ft	0.62	ha-m
Peak Flow :	**123.0**	**cfs**	**3.4820**	**cms**
	0.45	**iph**	**11.51**	**mm/hr**
Peak Time :	**0.283**	**hrs**		
Event Rational C :	0.140	[C=qp/imax]		
Event Runoff Ratio :	0.299	[=Q/P]		
Event Effective CN :	91.83	CN (0.05) =	87.81	
CN_2 after event :	95.68	CN_2 (0.05) after =	94.94	
Event Hydrograph Factor :	0.343	[K=Q/(tb*qp)]		
Duration of rainfall excess :	1.004	hrs		
Duration of runoff :	1.313	hrs		
Effective loss rate :	0.526	in/hr	12.89	mm/hr
Maximum Transient Storage :	0.072	in	1.83	mm
at Time :	0.206	hr		
Maximum Contribution Area :	100.00	%		
	269	Acres	108.9	Hectares

CN (0.20)	CN (0.05)	HU (Desc)	Area (acres)	Event Runoff Source (in)	(Ac-ft)	(Pct)
98.00	98.00	high	39.0	0.551	1.8	35.66
98.00	98.00	mod h	37.0	0.551	1.7	33.83
94.00	92.65	mod	37.0	0.307	0.9	18.87
78.00	69.53	low	91.0	0.011	0.1	1.74
74.00	63.93	unburned	30.0	0.001	0.0	0.03
90.00	86.95	rock	35.0	0.170	0.5	9.88
86.97	82.39		269.0		5.0	100.00

Using the Runoff Hydrograph Table option, the user can save the runoff hydrograph as a *.txt file (shown in figure F-13 below). The runoff hydrograph file can then be used in a separate flow or channel routing procedure to simulate accumulated effects from multiple sub-basins. It can also be imported into a hydraulic model to produce inundation flood maps.

Figure F–13 Runoff Hydrograph Table screen from WILDCAT5 post-wildfire conditions.

RUNOFF HYDROGRAPH RESULTS

Show Transient Storage

PROJECT: Morning Sun Postfire
WATERSHED: Morning Sun Postfire
STORM: 25 year - one hour

1/11/2019 9:47
Operator: JML

Save to Fil

TIME	CUMULATIVE RAINFALL		CONTRIB	INCR RUNOFF	CUMULATIVE OUTFLOW		OUTFLOW RATE		TRANSIENT STORAGE
	DEPTH	EXCESS-Q							
(hrs)	(in)	(in)	(%)	(in)	(in)	(acre-ft)	iph	(cfs)	(in)
0.000	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.00	0.0000
0.026	0.0835	0.0021	0.00	0.0021	0.0000	0.0000	0.0000	0.00	0.0021
0.052	0.1669	0.0139	28.25	0.0118	0.0001	0.0014	0.00242	0.66	0.0139
0.077	0.2504	0.0328	42.01	0.0189	0.0005	0.0121	0.0186	5.05	0.0323
0.103	0.3037	0.0478	55.02	0.0149	0.0020	0.0449	0.0568	15.40	0.0458
0.129	0.3477	0.0615	55.02	0.0137	0.0049	0.1097	0.1123	30.46	0.0566
0.155	0.3917	0.0762	55.02	0.0147	0.0096	0.2158	0.1838	49.85	0.0666
0.180	0.4259	0.0883	55.02	0.0121	0.0165	0.3708	0.2685	72.83	0.0717
0.206	0.4514	0.0976	55.02	0.0093	0.0254	0.5701	0.3453	93.65	0.0721
0.232	0.4769	0.1071	55.02	0.0095	0.0357	0.7996	0.3977	107.87	0.0714
0.258	0.4991	0.1155	55.02	0.0084	0.0468	1.0498	0.4334	117.54	0.0687
0.283	0.5130	0.1209	55.02	0.0054	0.0585	1.3115	0.4533	122.96	0.0624
0.309	0.5269	0.1264	55.02	0.0054	0.0701	1.5725	0.4522	122.65	0.0562
0.335	0.5408	0.1319	55.02	0.0055	0.0813	1.8235	0.4349	117.95	0.0505
0.361	0.5547	0.1374	55.02	0.0055	0.0918	2.0582	0.4066	110.30	0.0456
0.386	0.5686	0.1430	55.02	0.0056	0.1013	2.2707	0.3681	99.85	0.0417
0.412	0.5825	0.1487	88.85	0.0057	0.1097	2.4591	0.3264	88.54	0.0390
0.438	0.5964	0.1545	88.85	0.0058	0.1172	2.6282	0.2929	79.43	0.0372
0.464	0.6103	0.1604	88.85	0.0059	0.1241	2.7824	0.2672	72.48	0.0362
0.489	0.6242	0.1663	88.85	0.0060	0.1305	2.9256	0.2480	67.28	0.0358
0.515	0.6336	0.1704	88.85	0.0041	0.1366	3.0616	0.2355	63.88	0.0338
0.541	0.6398	0.1731	88.85	0.0027	0.1424	3.1922	0.2263	61.40	0.0307
0.567	0.6460	0.1758	88.85	0.0027	0.1480	3.3174	0.2169	58.83	0.0278
0.592	0.6521	0.1785	88.85	0.0027	0.1533	3.4365	0.2064	55.98	0.0252
0.618	0.6583	0.1813	88.85	0.0027	0.1583	3.5487	0.1943	52.71	0.0230
0.644	0.6645	0.1840	88.85	0.0028	0.1629	3.6519	0.1788	48.50	0.0211
0.670	0.6707	0.1868	88.85	0.0028	0.1671	3.7459	0.1627	44.14	0.0197
0.695	0.6769	0.1896	88.85	0.0028	0.1709	3.8317	0.1487	40.33	0.0187
0.721	0.6830	0.1924	88.85	0.0028	0.1745	3.9106	0.1367	37.08	0.0180
0.747	0.6892	0.1953	88.85	0.0028	0.1777	3.9838	0.1268	34.39	0.0176
0.773	0.6954	0.1981	88.85	0.0028	0.1808	4.0525	0.1190	32.27	0.0173
0.798	0.7016	0.2010	88.85	0.0029	0.1837	4.1179	0.1134	30.75	0.0173
0.824	0.7078	0.2038	88.85	0.0029	0.1865	4.1814	0.1100	29.82	0.0173
0.850	0.7139	0.2067	100.00	0.0029	0.1893	4.2442	0.1088	29.52	0.0174
0.876	0.7201	0.2096	100.00	0.0029	0.1921	4.3072	0.1091	29.59	0.0175
0.901	0.7263	0.2126	100.00	0.0029	0.1950	4.3705	0.1097	29.76	0.0176
0.927	0.7325	0.2155	100.00	0.0029	0.1978	4.4342	0.1103	29.92	0.0177
0.953	0.7387	0.2185	100.00	0.0030	0.2007	4.4982	0.1109	30.09	0.0178
0.979	0.7448	0.2214	100.00	0.0030	0.2035	4.5626	0.1116	30.26	0.0179
1.004	0.7500	0.2239	100.00	0.0025	0.2064	4.6274	0.1122	30.43	0.0175
1.030	0.7500	0.2239	100.00	0.0000	0.2093	4.6922	0.1122	30.44	0.0146
1.056	0.7500	0.2239	100.00	0.0000	0.2121	4.7550	0.1088	29.51	0.0118
1.082	0.7500	0.2239	100.00	0.0000	0.2147	4.8138	0.1019	27.63	0.0092
1.107	0.7500	0.2239	100.00	0.0000	0.2171	4.8665	0.0914	24.78	0.0068
1.133	0.7500	0.2239	100.00	0.0000	0.2191	4.9112	0.0773	20.98	0.0048
1.159	0.7500	0.2239	100.00	0.0000	0.2206	4.9462	0.0607	16.45	0.0033
1.185	0.7500	0.2239	100.00	0.0000	0.2218	4.9727	0.0460	12.47	0.0021
1.210	0.7500	0.2239	100.00	0.0000	0.2227	4.9919	0.0333	9.04	0.0012
1.236	0.7500	0.2239	100.00	0.0000	0.2233	5.0050	0.0227	6.15	0.0006
1.262	0.7500	0.2239	100.00	0.0000	0.2236	5.0132	0.0141	3.82	0.0003
1.288	0.7500	0.2239	100.00	0.0000	0.2238	5.0175	0.0075	2.04	0.0001
1.313	0.7500	0.2239	100.00	0.0000	0.2239	5.0192	0.0030	0.82	0.0000
1.339	0.7500	0.2239	100.00	0.0000	0.2239	5.0196	0.0006	0.16	0.0000
1.365	0.7500	0.2239	100.00	0.0000	0.2239	5.0196	0.0000	0.00	0.0000
1.391	0.7500	0.2239	100.00	0.0000	0.2239	5.0196	0.0000	0.00	0.0000
1.416	0.7500	0.2239	100.00	0.0000	0.2239	5.0196	0.0000	0.00	0.0000

* * * * END OF RUNOFF HYDROGRAPH RESULTS * * * *

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Sediment Bulking

The hydrographs from WILDCAT5 are for clear water flow and do not account for any entrained sediment. Sediment bulking refers to the overall raising of hydrograph flows and stages due to significant sediment load (USDA-NRCS, 2016). Entrained sediment can increase modeled clear water flows by 4 times or more. Therefore, sediment bulking should always be accounted for in any post-fire modeling.

The upper limit of sediment concentration, by volume, in a typical "water flood" is 20 percent. The amount of suspended sediment is insufficient to substantially affect how flowing water behaves. Newtonian fluid properties are preserved. Water may appear very muddy; but most of the suspended sediment is transported near the bed. Bedload may include material up to boulder-size (Elliot, 2005, and others).

Volumetric sediment concentration in a "hyperconcentrated flow" ranges from 20 to 47 percent. With hyperconcentrated flow, the amount of suspended sediment is sufficient to significantly change fluid properties and sediment-transport mechanisms. Large volumes of sand are transported in dynamic suspension throughout the water column, although maintenance of high sediment loads depends on flow velocity and turbulence. Flows can be highly erosive (Elliot, 2005, and others).

Rapid runoff with extremely high concentrations of entrained sediment (47 to 77 percent) is known as a "mudflow" or "debris flow". Mudflows have no more than 50 percent of the sediment coarser than gravel size, whereas debris flows have greater than 50 percent. Debris flows are produced frequently in response to summer convective thunderstorm activity over drainage basins burned by wildfire. Debris flow peak velocities are dependent on flow depth and can range from 3 to 30 m/s (10 to 100 ft/s) (Elliot, 2005, and others).

A sediment bulking factor (BF) is used to account for the entrained sediment not included in the WILDCAT5 post-wildfire hydrograph. The BF can be calculated using the following equation:

$$BF = 1/(1-C_v) \qquad \text{eq. F-4}$$

where; BF is the sediment bulking factor and C_v is the sediment concentration by volume (decimal).

Currently there is very little information available for determining C_v for post-fire flows. Estimating bulking factors is complicated and dependent on site-specific conditions; including comparisons of the geology, geomorphology, soils, slope, and vegetation with that of a watershed where bulking factor data are available (Pierson and Costa, 1987). If the site has a high probability of hyperconcentrated flows or debris flows, then the USGS Landslides Hazards Program may be a tool to determine a BF. Unfortunately, the USGS Landslides Hazards Program model was not available for this fire area. Where debris flows are common a BF of 2.5 may be appropriate. This site did not have a history of debris flows. Therefore, in this case, a reasonable assumption is to base the BF on the upper limit in a typical "water-flood" which is 20 percent (Costa, 1988). For a sediment concentration of 20 percent, the BF can then be calculated as:

$$BF = 1/(1-0.2) = 1.25$$

A BF of 1.25 was then applied to the post-wildfire peak flow modeled with WILDCAT5 to account for sediment bulking.

StreamStats

The regional USGS regression equations for predicting peak flows in Washington (Sumioka, Kresch and Kasnick 1998), embedded in StreamStats, was used to assess the reasonableness of the pre-wildfire peak flow modeled with WILDCAT5.

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Specific characteristics of the basin and peak flow statistics calculated from StreamStats are shown in figures F-13 and F-14. It is important to keep in mind that the basin characteristics and flows calculated from StreamStats are for normal (pre-wildfire) conditions. The 25-year peak flow was calculated to be ~10 cfs (9.42 cfs).

Figure F–13 Basin Characteristics Reports from USGS StreamStats.

StreamStats Version 3.0

Basin Characteristics Ungaged Site Report

Date: Fri Nov 18, 2016 3:38:00 PM GMT-8
Study Area: Washington
NAD 1983 Latitude: 47.9454 (47 56 44)
NAD 1983 Longitude: -120.2113 (-120 12 41)

Label	Value	Units	Definition
DRNAREA	0.42	square miles	Area that drains to a point on a stream
RELIEF	3540	feet	Maximum - minimum elevation
ELEVMAX	4660	feet	Maximum basin elevation
MINBELEV	1120	feet	Minimum basin elevation
ELEV	3010	feet	Mean Basin Elevation
CANOPY_PCT	17.6	percent	Percentage of drainage area covered by canopy as described in OK SIR 2009_5267
PRECIP	25	inches	Mean Annual Precipitation
SLOP30_30M	81	percent	Percent area with slopes greater than 30 percent from 30-meter DEM.
BSLDEM30M	49.4	percent	Mean basin slope computed from 30 m DEM
NFSL30	3.05	percent	North-Facing Slopes Greater Than 30 Percent

Accessibility FOIA Privacy Policies and Notices
U.S. Department of the Interior | U.S. Geological Survey
URL: http://streamstatsags.cr.usgs.gov/v3_beta/BCreport.htm
Page Contact Information: StreamStats Help
Page Last Modified: 01/26/2016 08:44:09 (Web2)
Streamstats Status News
USA.gov

Figure F–14 Flow Statistics Reports from USGS StreamStats.

StreamStats Version 3.0

Flow Statistics Ungaged Site Report

Date: Fri Nov 18, 2016 3:39:43 PM GMT-8
Study Area: Washington
NAD 1983 Latitude: 47.9454 (47 56 43)
NAD 1983 Longitude: -120.2113 (-120 12 41)
Drainage Area: 0.42 mi2

Peak-Flow Basin Characteristics

100% Region 4 (0.42 mi2)

Parameter	Value	Regression Equation Valid Range	
		Min	Max
Drainage Area (square miles)	0.42 (below min value 0.66)	0.66	2220
Mean Annual Precipitation (inches)	25	12	108

Warning: Some parameters are outside the suggested range. Estimates will be extrapolations with unknown errors.

Peak-Flow Statistics

Statistic	Value	Unit	Prediction Error (percent)	Equivalent years of record	90-Percent Prediction Interval	
					Min	Max
PK2	2.77	cfs				
PK10	7.01	cfs				
PK25	9.42	cfs				
PK50	11.5	cfs				
PK100	13.7	cfs				
PK500	19.1	cfs				

http://pubs.er.usgs.gov/usgspubs/wri/wri974277 (http://pubs.er.usgs.gov/usgspubs/wri/wri974277)
Sumioka_S.S._Kresch_D.L._and Kasnick_K.D._1998_Magnitude and Frequency of Floods in Washington: U.S. Geological Survey Water-Resources Investigations Report 97-4277_91 p.

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URL: http://streamstatsags.cr.usgs.gov/v3_beta/FTreport.htm
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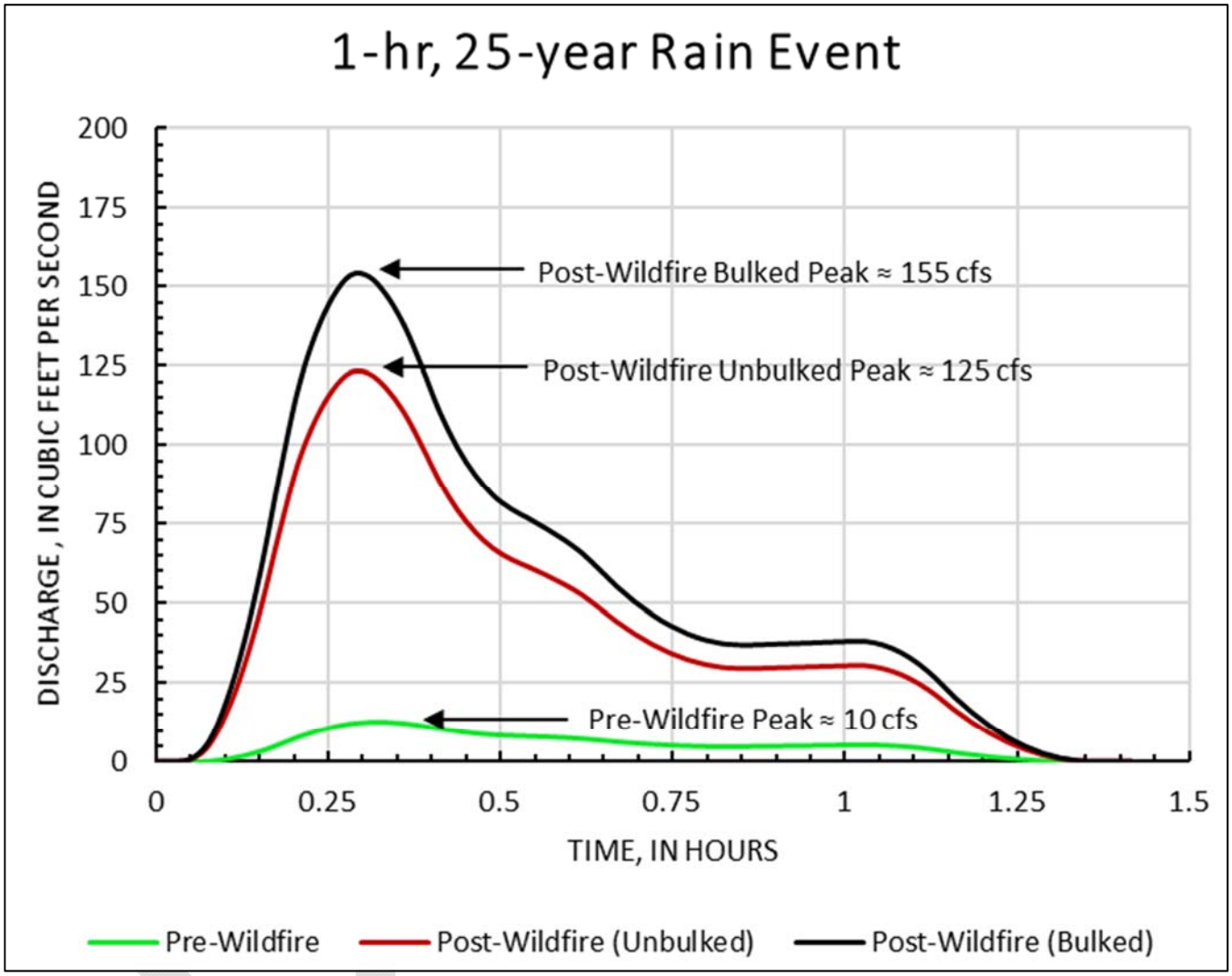
USA.gov

Results and Discussion

The hydrologic modeling for this case study was performed in a relatively short time to develop prompt yet reasonable estimates of increased flood hazard and identify potential threats to life and/or property. The pre- and post-wildfire hydrographs (Figure F-15) show the expected response to a 1-hour, 25-year rainfall distributed uniformly over the entire watershed.

Figure F–15 Hydrographs for the 1-hour, 25-year rain event



The peak flow enhancement ratio (*Qpost / Qpre*) can be used to easily communicate the degree to which the watershed hydrology has been affected by fire. The 1-hour, 25-year peak flow (un-bulked) enhancement ratio is 125/10 = 12.5. If sediment bulking is accounted for with a BF value of 1.25, the Qpost then becomes approximately 155 cfs and the peak flow enhancement ration is 15.5.

Peak flow enhancement ratios can be more than 100 in severely burned watersheds. The lower peak flow enhancement ratio value for this case study may be attributed to the low area of high burn severity (14.5 percent) and the high amount of rock outcrop (13%), which has a CN = 90, and was unchanged by the fire. If the rock outcrop area had been in similar ground cover conditions as the rest of the basin (woods, good condition, CN = 60), then the pre-wildfire peak flow would have been significantly lower which in turn would make the peak flow enhancement ratio significantly higher. This example also helps illustrate the importance to accurately identify the watershed soil (including rock outcrop areas) and vegetation conditions.

Comparison with Regression Predictions

In this case study, as with most other applications using regional equations, the regression equations should serve only as an order-of-magnitude check on the reasonableness of the pre-wildfire modeled results. Always check the equation limitations and standard error of prediction when using regression equations. For Washington State Region 4, the standard error of prediction associated for the 25-year recurrence interval is 87 percent, the maximum and minimum basin area is 2,198 mi.^{2} and 0.66 mi.^{2} respectively, and the maximum and minimum mean annual precipitation is 108 in. and 12 in. respectively (Sumioka, Kresch and Kasnick 1998). This basin is outside of the regression equation valid range because the basin area is 0.42 mi.^{2}. Therefore, the calculated peak flow values should be used with caution. The regression equation calculated the peak flow as 9.42 cfs while WILDCAT5 calculated the pre-wildfire peak flow as 9.49 cfs, a remarkable difference of about 0.7% and within the standard error of prediction and well within the same order-of-magnitude. This type of close comparison of the results seldom occurs and should not be considered normal. Due to the variability of these hydrologic methods, the predicted values should never be extended out to several significant digits. With this in mind, both predictions are approximately 10 cfs and should be considered equivalent in value while being quite reasonable in comparison.

Additionally, it should be noted that if the basin did not have the large area of rock outcrop (13%), that the percent difference would be much higher.

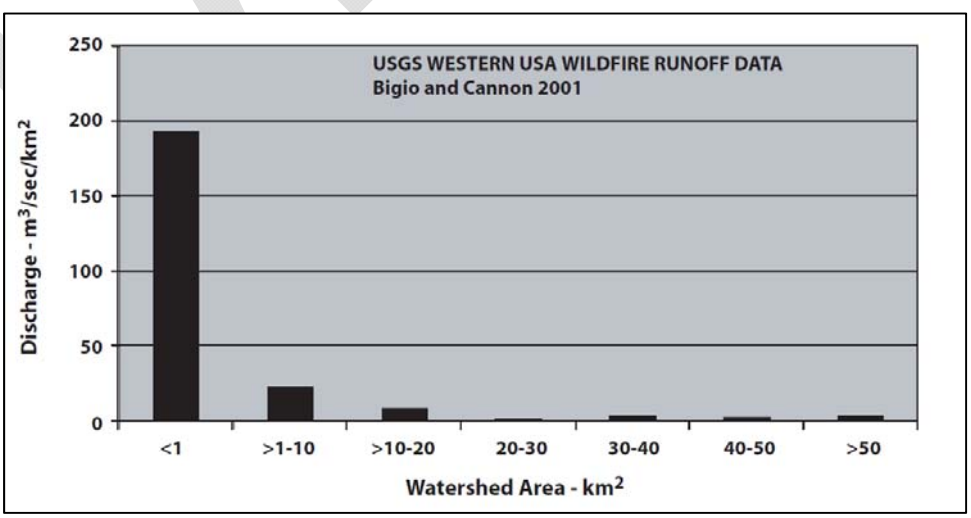
Accuracy and Limitations

The estimates provided by the WILDCAT5 simulations, as with all hydrologic models, are approximate. These approximations should always be communicated effectively to assure that decision makers use them with caution.

Modeling with WILDCAT5 can only be performed on a single watershed or sub-basin. Modeling of multiple sub-basins can be a limitation with WILDCAT5. If modeling of multiple sub-basins is required, then multiple WILDCAT5 models must be developed and an independent method used for flow or channel routing. Refer to NEH Part 630 if guidance on hydrologic flood routing is required.

Neary (2005), stated that the largest discharges often occur from smaller areas. Biggio and Cannon (2001) examined runoff after wildfires in the Western United States and found that specific discharges were greatest from relatively small watersheds less than 0.4 mile^2 (Figure F-13). Therefore, modeling the effects of smaller watersheds should not be discounted as these may pose the greatest risk to loss of life and/or property.

Figure F–13 Post-wildfire specific discharge and watershed area. (Adapted from Biggio and Cannon 2001).



Hawkins and Barreto-Munoz (2016), state that the time of concentration must be greater than 1/360 of the storm duration. There is no minimum or maximum limitation to the size of the drainage area that can be modeled. However, the accuracy of the model decreases as the complexity of the drainage area increases. Therefore, the size of the drainage area to be modeled should be governed by the complexity and not the size.

Hawkins and Barreto-Munoz (2016), state that WILDCAT5 does not distribute rainfall in space and that all rainfall is assumed uniform across the watershed. Therefore, when modeling convective storms, the watershed size should be limited to a maximum of approximately 5 square miles which is the maximum size of a convective storm.

Despite these limitations, WILDCAT5 is a preferred tool for many hydrologists tasked to predict flood responses of wildfire areas due to its relative simplicity, achievable data requirements, prompt model development time, and accuracy.

Conclusions

WILDCAT5 was used to predict pre- and post-wildfire condition peak flows and runoff volumes for watersheds in the First Creek fire area. This case study of the Morning Sun drainage provides an example that a direct runoff hydrograph model using the distributed CN method, such as WILDCAT5, can be used to develop prompt yet reasonable estimates and the advantages over the average CN method. The model has considerable benefits for identifying areas of greatest threat to life and/or property and may be of most significance when modeling single watersheds for EWP projects. In addition to peak flows and runoff volumes, the use of enhancement ratios (*Qpost/Qpre*) as predicted by the model can be used to communicate estimated increases in runoff with landowner and agency decision makers.

Fortunately, no post-wildfire flood events occurred in the Morning Sun drainage. However, on October 16, 2016, fourteen months after the fire, a rain event produced flood flows on the two drainages directly north of the Morning Sun drainage. The largest of the two flows occurred on the drainage, known as “Site #8”, which is adjacent to the Morning Sun drainage.

The drainage characteristics of Site #8 is very similar to Morning Sun except that it is about half again as big (429 acres). It did however have a higher burn severity. Forty-six percent of Site #8 had high soil burn severity and thirty-two percent was moderate soil burn severity (BAER 2015). NRCS staff conducted a risk assessment immediately after the 2015 fire and determined that the site was eligible for the EWP program. Unfortunately, the Sponsor declined to pursue EWP funds.

The clear water pre-wildfire peak flow was estimated to be 12 cfs although none of the residents had ever seen water flowing in the channel prior to the fire. The clear water post-wildfire peak flow was estimated to be 260 cfs with a bulked flow of 325 cfs. The enhancement ratio for the bulked flow is 27. Figures F-14 through F-17 shows the damage from the October 2016 event. According to witnesses, the sound of the approaching flood was said to be like an oncoming freight train. Luckily there were no injuries and only one residence suffered damaged. Approximately 1,000 cubic yards of debris was removed from around the residence with private funds. After the 2016 flood event, NRCS staff again conducted a risk assessment and determined that the site was again eligible for the EWP program. This time a different Sponsor pursued and received EWP funding. In June of 2016 EWP funds were used to construct dikes and restore the channel.

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Figure F–14 Channel scour and debris dikes from October 2016 event.

Figure F–15 Channel scour and debris dikes from October 2016 event.

Figure F–16 Debris at residence from October 2016 event.

Figure F–17 Debris at residence from October 2016 event.

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