PREDICTING AND COMPARING MEASURED BULKING AND PEAK DISCHARGE USING MULTIPLE METHODS FOR POST FIRE HYDROLOGIC AND SEDIMENTATION ANALYSIS ON THE DUMP FIRE IN SARATOGA SPRINGS

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Abstract: As part of the 2012 Utah fire season, analysis of the Dump Fire was conducted to design sediment basins. The event was estimated to be a 1.25-inch storm that lasted 25 minutes and dropped an estimated bedload of 70,000 tons of material, which damaged houses, inundated basements, and overtopped a small basin. The event is comparable to two times the 100-year (1% chance event) flow. The Dump Fire was analyzed as a part of the United States Department of Agriculture Natural Resources Conservation Service Emergency Watershed Protection Program.

The Dump Fire watershed is located near Saratoga Springs, Utah, which is on the eastern edge of the Basin and Range physiographic region. It was analyzed using the United State Department of Agriculture Agricultural Research Service Automated Geospatial Watershed Assessment Tool (USDA-ARS AGWA). The runoff curve number (CN) and derived hydrologic characteristics were calibrated using local stream gage networks, regression equations (USGS StreamStats), National Oceanic and Atmospheric Administration (NOAA), National Weather Service NOAA Atlas 14 rainfall distribution, and modified cumulative Kirpich time of concentration methods for the pre-fire condition.

Furthermore, specific papers and their methods were analyzed and compared for modifications to CN based on burn severity and reduction of cover, changes to lag time, and other basin characteristics. Peak discharge and area of basin burned based on lithology and peak discharge was considered. Lag times were changed due to relative increases in CN. Fire related debris flow volumes from the Western U.S. regression model were used to compare final results.

Of the 70,000 tons of bedload material, about 15% made it to a housing development downstream. Typically, the ratio of sands and colloidal to bedload was estimated at 10:1 or 3:1 ratios. Since the AGWA value was within reason for the total sediment and sands as a percentage (i.e. 10%), it was assumed to be comparable to total bedload in this case. Overall, AGWA was found to be a reliable to tool for sedimentation / bulking values in this situation.

BACKGROUND

In late June 2012 wildfire burned the watershed above the Utah communities of Saratoga Springs and Eagle Mountain, about 40 miles south of Salt Lake City. Reported to have been sparked by target shooters, the fire burned approximately 6,000 acres and required the evacuation of an estimated 9,000 residents. No serious injuries or damages were reported as a result of the event, which became known at the Dump Fire. Local residents protested the name, which came about because the fire was started near an old dump. This case study will refer to the event as the Saratoga Springs Fire. See Figure 1 for location.

The wildfire prompted the City of Saratoga Springs to request assistance from the NRCS through the Emergency Watershed Protection Program (EWP). Storm damages following an early September rainfall event (only about a month after the fire) occurred before counter-measures could be installed. NRCS performed a post-fire hydrologic analysis in support of the design of a sediment basin to protect residents from the accelerated erosion and sedimentation caused by the fire. Figures 2 and 3 illustrate the burning watershed from the point of view of the community of Eagle Mountain.

The storm of 1 September 2012 was centered over an unnamed tributary and Israel Canyon, which drain into Saratoga Springs. Local officials reported that the rainfall was 1.25 inches over a 25-minute duration. NRCS engineers estimated that the subsequent runoff deposited a bedload estimated at 70,000 tons. The mud slurry damaged houses, inundated basements, and filled and overtopped a small debris basin. The event was comparable to two times the 100-year (1% chance event) flow. The flow direction into the residential areas of Saratoga Springs is shown in Figure 4. The drainages discharge onto an alluvial fan that slopes into residential development where mud slurry, small boulders, cobbles, and gravel were deposited during the storm (Figures 5 and 6). This debris

damage was caused by the vulnerability of the watershed immediately following the fire, which increased erosion and mudflows in the steep gradient alluvial fan.

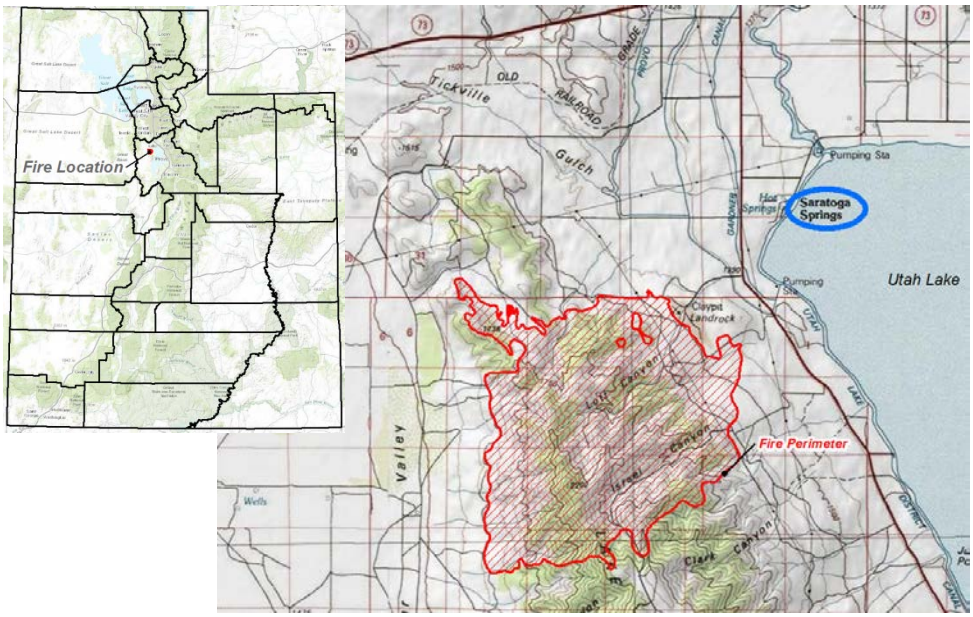

Figure 1. State of Utah and fire location, about 40 miles south of Salt Lake City.

Figure 2. Burning watershed from Eagle Mountain UT, 21 June 2012. photo by Cindi Braby, Eagle Mountain UT.

Figure 3. Burning watershed from Eagle Mountain UT, 22 June 2012.photo by Cindi Braby, Eagle Mountain UT.

Figure 4. Burned watershed flow direction into Saratoga Springs UT from 1 Sep 2012 event.

Figure 5. Sediment laden flow through residential neighborhood (credit Utah County)

Figure 6. Typical sediment composition in residential area. (credit City of Saratoga Springs)

METHODS

As part of the post-fire hydrologic analysis for the Saratoga Springs fire, a number of computer programs were used. Runoff hydrographs were determined using the NRCS hydrology program WinTR-20 (USDA-NRCS(a) 2004). The model Automated Geospatial Watershed Assessment Tool, or AGWA, (Goodrich et al. 2006 and USDA-ARS 2014) was used to determine sedimentation rates. AGWA was created by the USDA Agricultural Research Service, Southwest Watershed Research Center in Tuscon AZ. It combines previously existing models KINEROS2 (Smith et al. 1995, Woolhiser et al. 1990) and SWAT (Arnold et al. 2012).

The runoff curve number (CN) and derived hydrologic characteristics from local stream gage networks and regression equations (USGS StreamStats) were used to determine the logical pre-fire inputs. NOAA Atlas 14 rainfall distribution and modified cumulative Kirpich time of concentration methods were also used.

Changes to the time of concentration, T_c, and CN inputs into WinTR-20 and AGWA were based on past studies for post-fire analysis. Goodrich et al., (2005) provides support for modification of CN values, given reduction of cover and burn severity. McLin et al. (2001) provides a method to estimate change in lag time associated to relative increases in CN.

Two methods were used to analyze the viability of derived post-fire peaks and debris flow volumes. These include the Cannon and Gartner (2005) regression equations for estimating peak debris flow, given burn area and lithology of burn area, basin gradient, and storm rainfall; and the Gartner et al. (2008) regression equations for estimation of debris flow volumes.

Typically, the ratio of sands and colloidal grain sizes to bedload is estimated at 10:1 or 3:1 ratios. Since the AGWA value was within reason for the total sediment and sands as a percentage (i.e. 10%), it was assumed to be comparable to total bedload in this case.

For the hydrologic analysis of the burned watershed above Saratoga Springs, the entire watershed was assumed to have experienced moderate burn severity.

An initial estimate of pre-fire sedimentation conditions was made using the map of Bridges (1973) which shows estimated yearly sediment yield and a breakdown between sheet and rill erosion versus channel and gully erosion. For the Saratoga watershed, pre-fire sediment yield is estimated to range between 0.1-0.2 acre-feet per square mile per year. with sources being 60% sheet and rill and 40% channel and gully.

Pre-fire Flow Ranges The first step in estimating the pre-fire watershed condition was to review existing gages in the area to determine reasonable pre-fire flows for the 25-, 50-, and 100-year (4%-, 2%- and 1%-chance) events.

After this was completed, WinTR-20 was used with NOAA Atlas distributions and a modified cumulative Kirpich equation. Runoff curve numbers were modified between ground cover conditions and used USDA – NRCS National Engineering Handbook, Part 630, Hydrology, Chapter 9, Hydrologic Soil-Cover Complexes (USDA NRCS(b), 2004), the United States Geologic Survey (USGS) National Land Cover Database (NLCD) (Fry et al, 2011), and the NRCS SSURGO database (USDA-NRCS(c), 2012).

Stream Gages Six nearby stream gages were analyzed to help estimate peak flows for the pre-fire watershed above Saratoga Springs. The stream gages are listed in Table 1 and are shown on the Figure 7 map. Their statistics were taken from the StreamStats report appendix (Kenney et al. 2007). Discharge per unit area (cubic feet per second / square mile, CSM) was computed for each probability and graphed (Figure 8).

Table 1. Six stream gages near Saratoga Springs, UT

# on fig. CS5-8	USGS #	Drainage (sq. mi.)	gage name
1	10172790	5.77	Settlement Canyon nr Tooele UT
2	10172805	5.38	N. Willow Creek nr Grantsville UT
3	10172800	4.19	S. Willow Creek nr Grantsville UT
4	10166430	26.5	W. Canyon Creek nr Cedar Fort UT
5	10172765	6.7	Clover Creek abv Big Hollow nr Clover UT
6	10172910	16.8	Settlement Creek abv Resvr nr Tooele UT

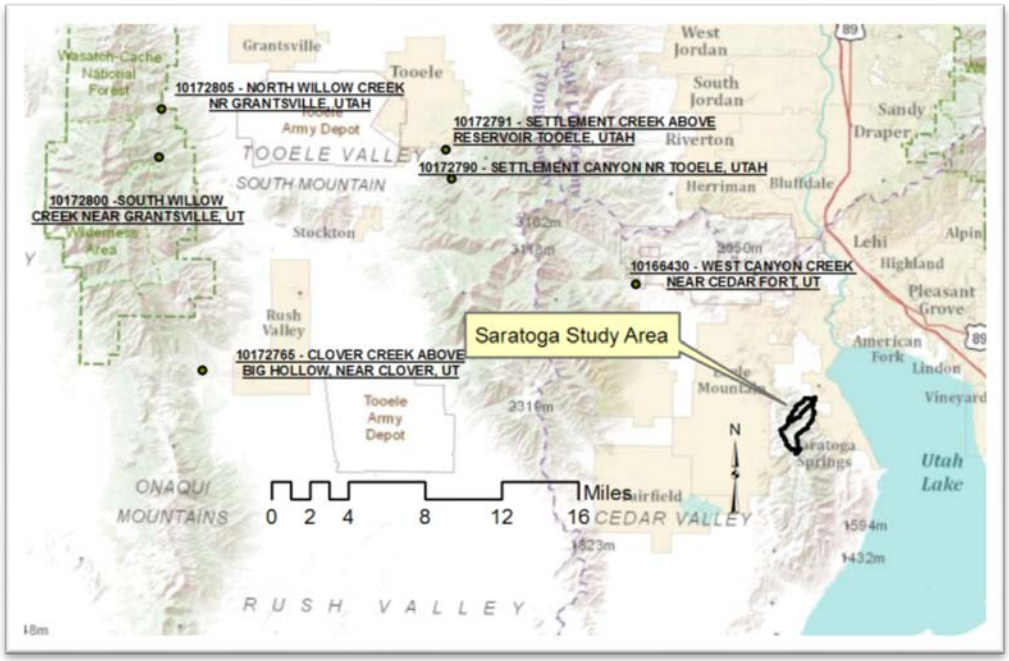

Figure 7. Location of stream gages and study area

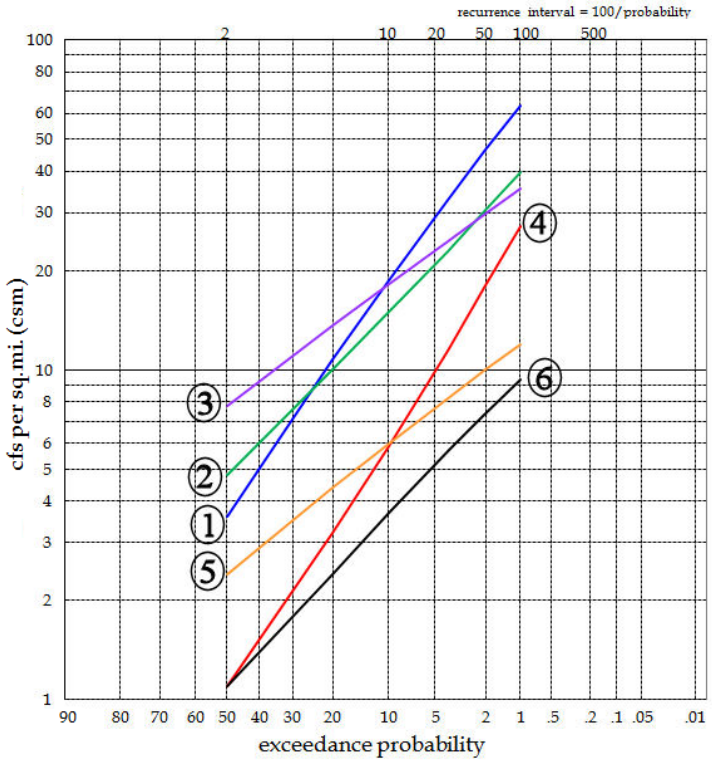

Figure 8. Stream gage regression output converted to discharge per unit area

Of the six nearby gaged watersheds, numbers 1 through 3 (Table 1) are most similar in drainage area, although the modeled watershed area above Saratoga Springs is 2.5 square miles, which is about half the size of three nearby gages. In Figure 8, the graphs of those three gages are the higher ones: blue, green, and violet.

T_c Pre-fire The upper range CSM exceedance probability was used to determine the pre-fire inputs into WinTR-20. The T_c was estimated to be 1 hour, or an average velocity of 6.0 feet per second. The upper elevation of the watershed is 7,500 feet above mean sea level, the watershed outlet is at 4,875 feet above mean sea level, and the longest flow path is 3.8 miles in length.

CN Pre-fire The CN look-up values were adjusted pending NEH, part 630, Chapter 9 ground cover conditions (USDA-NRCS(b), 2004) based on NLCD and SSURGO data. The generated T_c, adjusted CN, and NOAA Atlas 14 rainfall distribution were entered into WinTR-20. The CN was adjusted until the WinTR-20 output and calculated CSM matched the range of CSM of nearby stream gages.

Post Fire Peaks and volumes of sediment The burned watershed above Saratoga Springs has a total drainage area of 4.91 square miles. For WinTR-20 analysis, the burned area was divided into three subareas, as shown in Figure 9. Subareas 1 and 2 converge and provide outlet to the Saratoga Springs residential areas shown in Figures 4 through 6. Subarea 1 is known as Israel Canyon. See Tables 2 and 3 for WinTR-20 basic input related to these subareas, including selected pre-fire and post-fire CN.

Table 2. Burned watershed subarea input to WinTR-20.

subarea	drainage (sq.mi.)	CN (pre-fire)	CN (post-fire)	T_c (hrs, pre-fire)	T_c (hrs, post-fire)
1	1.81	62	74	0.92	0.85
2	0.60	74	80	0.40	0.37
1 + 2	2.50	65	75	1.00	0.92

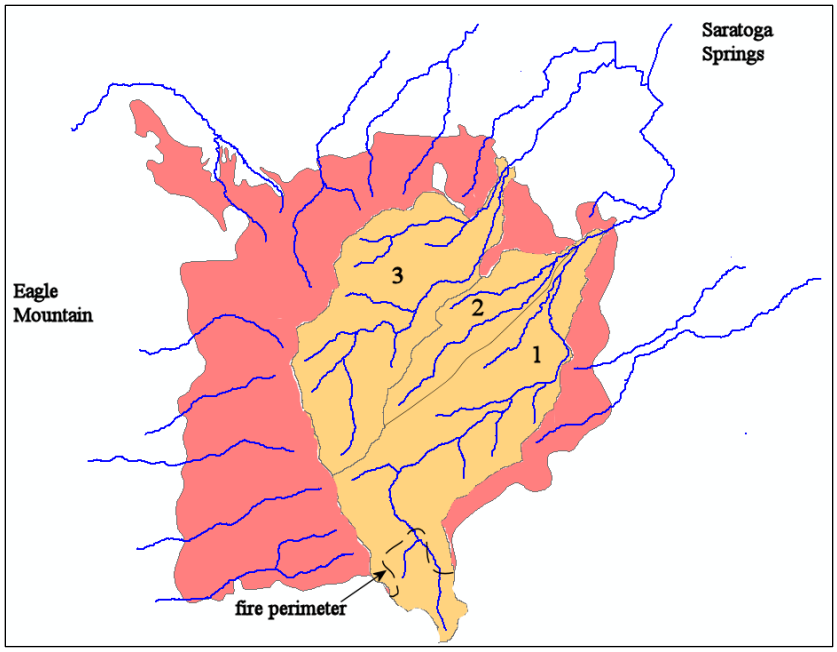

Figure 9. Burned zone (red) and sub-areas upstream of Saratoga Springs.

CN Post-fire Modification Post-fire CN were selected based on Goodrich (et al. 2005), which stated that, "there [is] a 15% reduction in cover for low-severity burns, a 32% reduction for moderate-severity burns, and a 50% reduction for high-severity burns" (Figure 10).

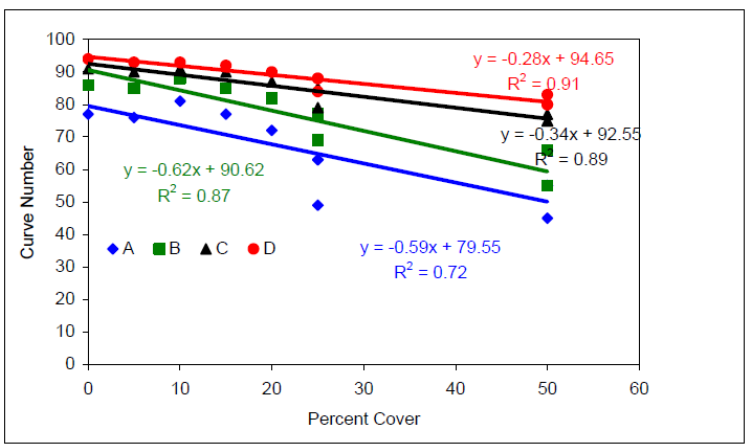

Figure 10. Curve number from cover, for hydrologic soil groups (Goodrich et al. 2005).

Table 3 shows the CN increase from pre-fire to post-fire CN used in this study. The table associates these with the standard National Land Cover Dataset (NLCD) and hydrologic soil groupings (hsg).

Table 3. Increase in runoff curve number from pre-fire to post-fire conditions.

burn severity	NLCD	cover name	hsg A	hsg B	hsg C	hsg D
Low	41	Deciduous Forest	4	5	3	2
	42	Evergreen Forest	4	16	10	8
	43	Mixed Forest	4	5	3	2
	51	Shrubland	2	2	1	1
Moderate	41	Deciduous Forest	10	10	5	5

	42	Evergreen Forest	10	21	12	11
	43	Mixed Forest	10	10	5	5
	51	Shrubland	5	5	3	2
High	41	Deciduous Forest	15	16	8	7
	42	Evergreen Forest	15	27	15	13
	43	Mixed Forest	15	16	8	7
	51	Shrubland	10	11	6	3

Time of Concentration Post-fire Modification T_c was adjusted using McLin et al. (2001), which suggest that lag time decreases from the pre-burn to post-burn condition as a result of increase in CN (Figure 11). Note that this depends on channel blockages caused by the fire, and frequency that the watershed experiences wildfire. Channel blockages can possibly increase lag times. In this case, however, the watershed cover is generally mixed with deciduous forest and low-lying shrubs and no channel blockages were assumed. Furthermore, the roughness of the watershed was assumed to decrease as a result of fire. For this case study, the following rule of thumb was adopted for changes in runoff velocity and associated change in time of concentration: velocity increases 0.5 feet per second for low severity burns, 1.0 feet per second for moderate severity burns, and 1.5 feet per second for high severity burns.

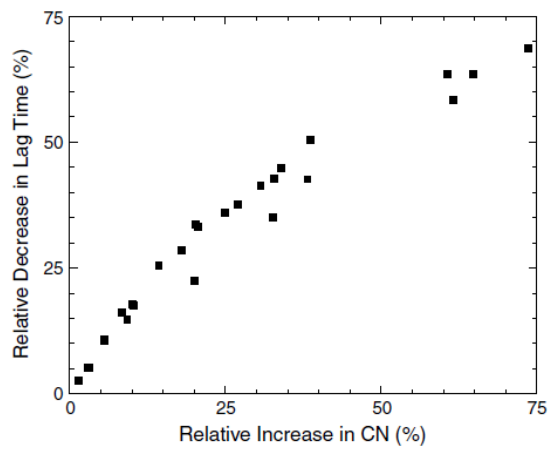

Figure 11. Interdependency of CN and lag time, Cerro Grande Wildfire McLin (et al. 2001)* *Relative change is defined as the sum of pre-fire and post-fire values divided by pre-fire values.

AGWA The AGWA model was used to model sediment rates. AGWA has a GIS interface and uses one of two routines to route runoff using the kinematic wave equation in the sub-model KINEROS2. In AGWA the landscape, including land uses and management practices, are handled by the sub-model SWAT. Table 4 shows output parameters for KINEROS and SWAT. Although AGWA produces both flow hydrographs and sedimentation rates, only the latter was used for the current study.

Table 4. Output Variables Available in AGWA.

KINEROS - ■ Infiltration (mm; m^3/km), ■ Infiltration (in; ac-ft/mi), ■ Runoff (mm), Runoff (m3), ■ Sediment yield (kg/ha), ■ Peak flow (m^3/s), Peak flow (mm/hr), ■ Sediment discharge (kg/s)	SWAT-■ Channel Discharge (m^3/day), ■ ET (mm), ■ Percolation (mm), Surface runoff (mm), ■ Transmission loss (mm), ■ Water yield (mm), ■ Sediment yield (t/ha), ■ Precipitation (mm)

Bulking Another way to estimate sedimentation is to consider typical runoff bulking factors for recently burned watersheds. This was done to further support concentration volumes that were deposited on the alluvial fan. Considering a 20% bulking factor, an event sedimentation volume can be estimated and applied to WinTR-20 post fire results.

Western Regional Equation The empirical Western U.S. regression model to estimate fire-related debris-flow volumes Gartner et al. (2008) was used to estimate post fire sediment. The equation used is presented below (Equation 1). The Western U.S. regression model to estimate fire-related debris-flow volumes Gartner et al. (2008) was taken from the Giraud and Castleton (2009) investigation.

$$lnV = 0.59(lnS) + 0.65B^{1/2} + 0.18R^{1/2} + 7.21 \qquad \text{(eq 1)}$$

V = volume (cubic meters)
S = basin area with slopes greater than or equal to 30% (square kilometers)
B = basin area burned at moderate and high severity (square kilometers), and
R = total storm rainfall (millimeters)

Comparative Analysis to Existing Studies: Figure 12 from McLin et al. (2001) illustrates that the change in peak discharge per unit area caused by wildfire can be quite large, therefore the pre and post fire ranges from Figure 12 were considered.

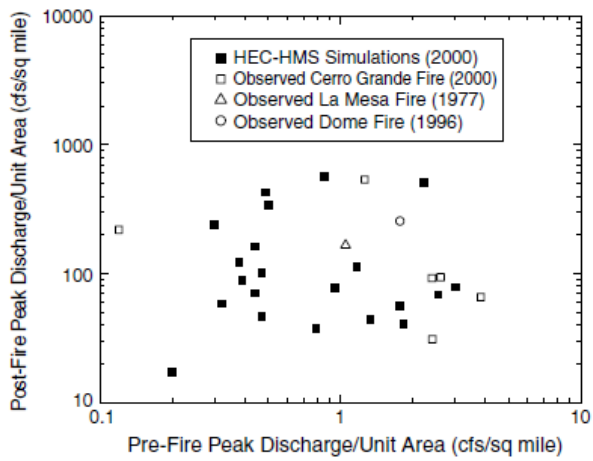

Figure 12. Comparison of observed and simulated pre-and post-fire peak discharges per unit drainage basin area in New Mexico. (McLin et al, 2001)

Regional Equations The regression equations of Cannon and Gartner (2005) were also used to estimate post-fire flow. Since the Saratoga Springs watershed is sedimentary, the regression equation (eq. 2) from Cannon and Gartner (2005) was used to compute an estimated peak discharge. Since the equation units are SI, conversions are required. For the Saratoga Springs watershed, 2.5 square miles converts to 6.47 square kilometers.

$$Q_p = 17A_b^{0.4} \qquad R^2 = 0.42 \qquad \text{(eq. 2)}$$

Bridges Map The Bridges (1973) map entitled "Estimated Sediment Yield Rates for the State of Utah" references many data sources as part of the map, including: 1) Great Basin Upper Colorado and Lower Colorado Regions, Comprehensive Framework Study, Appendices VIII, Water Management, June 1971, Pacific Southwest Inter-Agency Committee/Water Resources Council, 2) Utah State soils map and soil descriptions, 3) Reservoir Surveys by SCS and USBR, 4) suspended load measurements by USGS, USGR and SCS, 5) Watershed studies by SCS, and 6) General knowledge of the state from regular SCS program work. The author notes, "Do not use these rates to determine sediment yields at specific sites. Large variations in sediment rates may occur within the delineated areas".

According to the United States Department of Agriculture, Soil Conservation Service map (Bridges, 1973) the sediment yield for the Saratoga watershed ranges between 0.1-0.2 acre-feet/square mile/year with a 60% sheet and rill erosion and 40% channel and gully erosion.

The range of erosion rates for the Saratoga Springs watershed from the 1973 map are plotted (Figure 13). On the graph, the red squares represent the acre-feet/square mile/year rate that correlates to the tons for 2.5 square miles, pre-burn condition. The blue diamonds on the graph show values assuming a 0.45 acre-feet/square mile/year rate plotted in total tons, a conservative pre-fire condition. Finally, the green triangles represent the breakdown of erosion types (60% sheet / rill erosion, 60% other colloidal material, 40% channel and gully erosion), a post-fire condition.

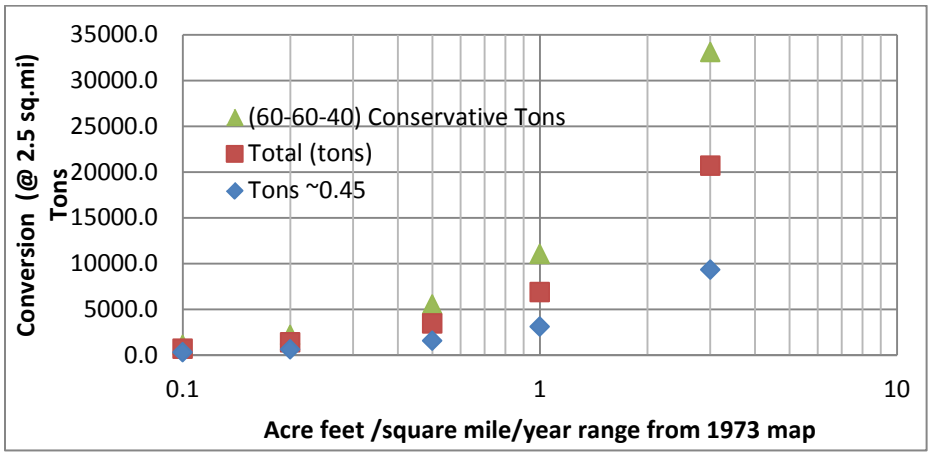

Figure 13. Range of annual erosion rates from Bridges (1973).

RESULTS

WinTR-20 Pre and Post Fire: The WinTR-20 provides pre-fire flow calculations that correlated well to the USGS stream gages CSM provided in Figure 8. Table 5 below illustrates these results. The lower return intervals from WinTR-20 pre-fire results are higher and the higher return intervals are lower than USGS calculated CSM. For estimation purposes, the upper results for the 25 year (4% chance), 50 year (2% chance) and 100 year (1% chance) will be focused on during the rest of the paper. Table 6 reflects the pre and post fire peak discharges.

Table 5. Cubic feet per second per square mile (CSM) from WinTR20 pre-fire results and selected stream gages

	2-year (50% chance) (CSM)	5 year (20% chance) (CSM)	10 year (10% chance) (CSM)	25 year (4% chance) (CSM)	50 year (2% chance) (CSM)	100 year (1% chance) (CSM)
WinTR-20 Pre-fire	0	2.5	6.8	28.4	58	100.8
Observed CSM from Figure 8	~5	12	<20	30	45	60

Table 6. Burned watershed pre-fire and post-fire peak flow output from WinTR-20.

Subarea	2-year (cfs)	5-year (cfs)	10-year (cfs)	25-year (cfs)	50-year (cfs)	100-year (cfs)
1 (pre-fire)	0	0	0	25	65	127
1 (post-fire)	14	57	118	234	359	514
2 (pre-fire)	6	29	62	126	195	280
2 (post-fire)	39	92	149	248	347	466
1+2 (pre-fire)	0	6	17	71	145	252
1+2 (post-fire)	26	92	179	342	516	728

The WinTR-20 output in Figure 14 shows the considerable increase in runoff peaks and volumes due to the fire. The peaks are predicted to more than double, with the 25-year (4% chance) event (red dashed for post-fire versus black dashed for pre-fire) rising from 71 cfs to 342 cfs. The runoff volume (represented by the area under each

curve and in Table 6) is predicted to increase runoff from the pre-fire to post-fire event, 192% to 122% for the 25-year to 100-year events.

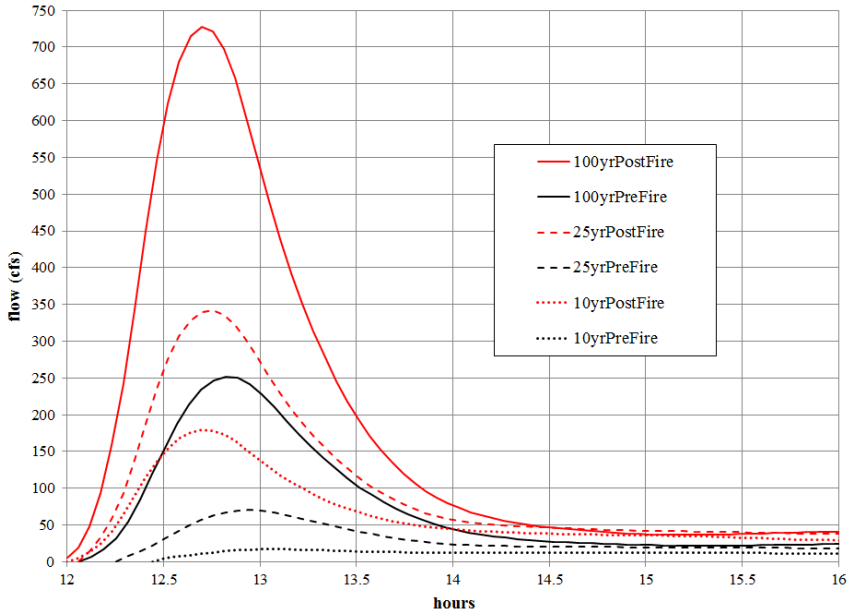

Figure 14. Burned watershed pre-fire and post-fire hydrographs from WinTR-20.

Table 6. Storm totals runoff for various recurrence intervals, input to WinTR-20 and post fire runoff values for Subarea 1+2.

Percent Chance	2-year (50% chance)	5-yr (25% chance	10-yr (10% chance)	25-yr (4% chance)	50-yr (2% chance)	100-yr (1% chance	200-yr (0.5% chance	500-yr (0.2 chance
Pre-Fire runoff (inches) Subarea 1+2	0.01	0.03	0.07	0.13	0.19	0.27	0.35	0.48
Post Fire runoff (inches) Subarea 1+2	0.09	0.17	0.25	0.38	0.48	0.60	0.73	0.92
Pre Fire - Runoff in acre feet over 2.5 sq.mi	1	4	9	17	25	36	47	64
Post Fire - Runoff in acre feet over 2.5 sq.mi	12	23	33	51	64	80	97	123

AGWA The sediment for the 25-year (4% chance) storm was estimated to be 10,303 tons and the 100-year (1% chance event) storm was estimated to be 27,897 tons.

Bulking An event sedimentation volume was estimated considering a 20% bulking factor on the WinTR-20 post fire results. The information in Table 7 was derived by taking the post-fire clear flow hydrographs of Figure 14, from WinTR-20, and considering the event sedimentation rate to be 20% at each time-step. The area under the sedimentation hydrograph provided a volume, which was converted to tons by assuming a sediment unit weight of 108 pounds per cubic foot in Table 7.

Table 7. Burned watershed post-fire event total sediment runoff in tons.

event totals	25-yr (4% chnance) (tons)	50-yr (2% chance) (tons)	100-yr (1% chance) (tons)
sediment	23,705	29,943	37,429

Western U.S. Regression Model The empirical Western U.S. regression model to estimate fire-related debris-flow volumes Gartner et al. (2008) was estimated to be between 34,550 – 51,182 tons for the 2- to 100-year (50% to 1% chance) rainfall events. These numbers are high since the model assumes that watersheds typically have moderate to high severity burns.

Table 8 shows the WinTR-20 pre-fire and post-fire peaks (in cfs per square mile) for comparison with Figure 12. The current case study results would plot generally lower on the figure than the New Mexico watersheds, the WinTR-20 results are considered reasonable.

Table 8. Saratoga Springs burned watershed pre-fire and post-fire peaks (csm) from WinTR-20.

flood	25-year (4% chance)	50-year (2% chance)	100-year (1% chance)
Pre-fire (CSM)	28.4	58	100.8
Post-fire (CSM	136.8	206.4	291.2

Regional Equations The regression equations of Cannon and Gartner (2005) after inserting 6.47 as A_b into the equation results in a Q_p of 35.88 cubic meters per second, or a Q_p of 1267 cfs after converting to English units . This results in 506 CSM; and the WinTR20 post-fire result is 728 cfs or 291 CSM.

CONCLUSIONS

The review of USGS stream gages and making modification to the CN to have both values correlate was an attempt to familiarize one on potential results, pre-fire. Once this was done a post-fire CN was applied and T_c was lowered. This resulted in both higher peaks and bigger volumes of runoff. AGWA, a 20% bulking to WinTR-20 post fire results, and the Western Regional Equation overall correlated well. These results were compared to McLin et al (2001) pre- and post- fire peak discharges per unit drainage basin area and to a range or potential erosion values, Bridges sedimentation map (1973).

Typically, one would think of using the peak discharge of post-fire analysis using WinTR-20, while increasing the CN and decreasing the $_{Tc}$. The peak discharge during the flood event and high water marks were observed as being in range for the post-fire WinTR-20 results. The Cannon and Gartner (2005) estimate of over 1,200 cfs may be reasonable and could be used for preliminary or lower and upper bound limits; the lower limit at 75% of the total, and the upper at 100% of the total.

The range of sediment, bulking and mud slurries were in a range of 10,000 tons to over 50,000 tons for the post-fire 25- to 100-year (4% to 1% chance) events. The AGWA range is between 10,000 and 50,000 tons for the 25- to 100-year (50% to 1% chance) post-fire event. The bulking at 20% is 23,000 to 37,000 tons for the post-fire event. The western regional equation produced a number of 34,600 – 51,200 tons. Between the sand, colloidal, and bedload the percentages can vary. For the sediment, sand and colloidal the numbers above could still be a low estimate. Bedload at either 1:3 or 1:10 ratio could be still be small. However, due to the system being flushed by previous storm events, these ratios may be accurate. A range of 5,000 to 17,000 tons could be accounted for bedload.

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