Hydrologic Analyses of Post-Wildfire Conditions

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Cover photo: Nabours Mountain directly east of Glenwood NM.

Courtesy of: USDA Forest Service, Gila National Forest, Silver City NM
## Contents

13 **Introduction** ..................................................................................................................................................... 1

14 **The role of NRCS in post-fire assessments and modeling** ............................................................... 1

15 **Important terms and terminology** .................................................................................................................... 4

16 **Burned area reflectance classification (BARC)** ....................................................................................... 4

17 **Burn severity** ........................................................................................................................................... 4

18 **Fire intensity** ............................................................................................................................................ 5

19 **Fire severity** ............................................................................................................................................. 6

20 **Hydrophobicity or soil water repellency** ...................................................................................................... 6

21 **Landsat differenced normalized burn ratio (dNBR)** ................................................................................ 7

22 **Rapid assessments of vegetation condition after wildfire (RAVG)** ......................................................... 7

23 **Soil burn severity mapping** .......................................................................................................................... 7

24 **Low soil burn severity** ............................................................................................................................. 7

25 **Moderate soil burn severity** ..................................................................................................................... 8

26 **High soil burn severity** ............................................................................................................................ 8

27 **Wildfire impacts on watershed hydrology**....................................................................................................... 8

28 **Assessment of post-fire soil and vegetation conditions** ........................................................................... 9

29 **Assessment of post-fire soil hydrophobic conditions** ............................................................................ 11

30 **Hydrologic modeling of burned watersheds** .......................................................................................... 13

31 **Methods and models** .................................................................................................................................. 13

32 **Adjustment of event-based runoff modeling components for burned areas** ............................................ 16

33 **Runoff curve numbers** ............................................................................................................................... 16

34 **Adjustment of curve numbers for wildfire effects** ................................................................................ 18

35 **Limitations of the CN method** ................................................................................................................ 22

36 **Time of concentration** ............................................................................................................................. 23

37 **Watershed lag method** ........................................................................................................................... 23

38 **Velocity method** .................................................................................................................................... 23

39 **Adjustment of runoff flow time for wildfire effects** .............................................................................. 26

40 **Infiltration parameters** ............................................................................................................................ 28

41 **Adjustment of infiltration parameters for wildfire effects** ..................................................................... 31

42 **Unit hydrographs** ....................................................................................................................................... 32

43 **NRCS dimensionless unit hydrograph** .................................................................................................... 34

44 **Adjustment of unit hydrograph for wildfire effects** ............................................................................. 36

45 **Kinematic wave transformation** ............................................................................................................ 38
## Adjustment of kinematic wave transformation parameters for wildfire effects
- Page 38

## Time-area histogram synthetic unit hydrograph development
- Page 39

## Sedimentation estimation
- Page 41

## Models for estimating sediment transport
- Page 46

## Adjustments for modeling sediment transport from burned areas
- Page 48

## Sediment bulking
- Page 48

## Model uncertainties, calibration, validation
- Page 52

## References
- Page 53

### Case Study 1: High Park Fire Colorado
- CS1-1

#### Background
- CS1-1

#### Methods
- CS1-3

#### Runoff Curve Number (CN) Estimation
- CS1-5

#### Rainfall
- CS1-7

#### Lag Time
- CS1-7

#### Flow Routing
- CS1-8

#### Sediment Bulking
- CS1-8

#### StreamStats
- CS1-8

#### Results and Discussion
- CS1-9

#### Comparison with Regression Predictions
- CS1-11

#### Accuracy and Limitations
- CS1-12

#### Conclusions
- CS1-13

#### Acknowledgements
- CS1-14

#### References
- CS1-14

### Case Study 2: Bitterroot Wildfires, Montana
- CS2-1

#### Background
- CS2-1

#### Methods
- CS2-4

#### Runoff Curve Number (RCN) Estimation for Burn Areas
- CS2-8

#### Hydrophobic Soils
- CS2-13

#### Time of Concentration ($T_c$) and Assumed Watershed Shape
- CS2-14

#### Results and Discussion
- CS2-15

#### Limitations
- CS2-18

#### References
- CS2-19

### Case Study 3: West Fork Complex Fire, Colorado
- CS3-1

#### Background
- CS3-1
<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>Methods................................................................................................................. CS3-4</td>
</tr>
<tr>
<td>82</td>
<td>Runoff Curve Number (CN) Estimation ................................................................. CS3-6</td>
</tr>
<tr>
<td>83</td>
<td>Rainfall ............................................................................................................... CS3-7</td>
</tr>
<tr>
<td>84</td>
<td>Lag Time .............................................................................................................. CS3-9</td>
</tr>
<tr>
<td>85</td>
<td>Flow Routing ..................................................................................................... CS3-9</td>
</tr>
<tr>
<td>86</td>
<td>Sediment Bulking .............................................................................................. CS3-10</td>
</tr>
<tr>
<td>87</td>
<td>Erosion Modeling ............................................................................................... CS3-10</td>
</tr>
<tr>
<td>88</td>
<td>Results and Discussion ..................................................................................... CS3-18</td>
</tr>
<tr>
<td>89</td>
<td>Runoff Modeling Results .................................................................................. CS3-20</td>
</tr>
<tr>
<td>90</td>
<td>Sediment Modeling Results ............................................................................... CS3-21</td>
</tr>
<tr>
<td>91</td>
<td>Modeling Limitations ....................................................................................... CS3-23</td>
</tr>
<tr>
<td>92</td>
<td>Rainfall-Runoff Modeling Limitations ............................................................... CS3-23</td>
</tr>
<tr>
<td>93</td>
<td>Sediment Modeling Limitations ....................................................................... CS3-25</td>
</tr>
<tr>
<td>94</td>
<td>Conclusions ........................................................................................................ CS3-25</td>
</tr>
<tr>
<td>95</td>
<td>Acknowledgements ............................................................................................. CS3-26</td>
</tr>
<tr>
<td>96</td>
<td>References .......................................................................................................... CS3-26</td>
</tr>
<tr>
<td>97</td>
<td>Case Study 4: Whitewater Creek, Gila Wilderness, New Mexico ..................... CS4-1</td>
</tr>
<tr>
<td>98</td>
<td>Background ......................................................................................................... CS4-1</td>
</tr>
<tr>
<td>99</td>
<td>NRCS Involvement .............................................................................................. CS4-4</td>
</tr>
<tr>
<td>100</td>
<td>Methods and Application .................................................................................. CS4-6</td>
</tr>
<tr>
<td>101</td>
<td>Choice of hydrologic computer model: HEC-HMS .............................................. CS4-7</td>
</tr>
<tr>
<td>102</td>
<td>Time-area histogram and synthetic UH Estimation ............................................ CS4-9</td>
</tr>
<tr>
<td>103</td>
<td>Roughness in GIS .............................................................................................. CS4-10</td>
</tr>
<tr>
<td>104</td>
<td>Flow slope in GIS ............................................................................................ CS4-13</td>
</tr>
<tr>
<td>105</td>
<td>Velocity relationships used in Whitewater Creek .......................................... CS4-18</td>
</tr>
<tr>
<td>106</td>
<td>Travel time in GIS ............................................................................................ CS4-19</td>
</tr>
<tr>
<td>107</td>
<td>Spreadsheet derivation of time-area histogram and unit hydrograph ................ CS4-20</td>
</tr>
<tr>
<td>108</td>
<td>Infiltration Loss Method: Green &amp; Ampt Equation .......................................... CS4-24</td>
</tr>
<tr>
<td>109</td>
<td>Initial Abstraction, Surface Ponding, Canopy Loss ........................................ CS4-25</td>
</tr>
<tr>
<td>110</td>
<td>Baseflow ............................................................................................................ CS4-26</td>
</tr>
<tr>
<td>111</td>
<td>Rainfall events examined ................................................................................ CS4-26</td>
</tr>
<tr>
<td>112</td>
<td>Sediment Bulking ............................................................................................. CS4-29</td>
</tr>
<tr>
<td>113</td>
<td>Results and Discussion .................................................................................... CS4-30</td>
</tr>
<tr>
<td>114</td>
<td>Modeling observed data .................................................................................. CS4-37</td>
</tr>
<tr>
<td>115</td>
<td>Conclusions ....................................................................................................... CS4-40</td>
</tr>
<tr>
<td>References .........................................................................................................................</td>
<td>CS4-41</td>
</tr>
<tr>
<td>Case Study 5: Saratoga Springs, UT .......................................................................................</td>
<td>CS5-1</td>
</tr>
<tr>
<td>Abstract ...............................................................................................................................</td>
<td>CS5-1</td>
</tr>
<tr>
<td>Background ..........................................................................................................................</td>
<td>CS5-2</td>
</tr>
<tr>
<td>Methods ...............................................................................................................................</td>
<td>CS5-6</td>
</tr>
<tr>
<td>Pre-fire flow ranges ............................................................................................................</td>
<td>CS5-8</td>
</tr>
<tr>
<td>Post-fire peaks and volumes of sediment ............................................................................</td>
<td>CS5-10</td>
</tr>
<tr>
<td>Results ..................................................................................................................................</td>
<td>CS5-16</td>
</tr>
<tr>
<td>AGWA ....................................................................................................................................</td>
<td>CS5-19</td>
</tr>
<tr>
<td>Bulking ..................................................................................................................................</td>
<td>CS5-19</td>
</tr>
<tr>
<td>Western U.S. regression model .............................................................................................</td>
<td>CS5-19</td>
</tr>
<tr>
<td>Regional equations ..............................................................................................................</td>
<td>CS5-20</td>
</tr>
<tr>
<td>Conclusions .........................................................................................................................</td>
<td>CS5-20</td>
</tr>
<tr>
<td>Acknowledgements ..............................................................................................................</td>
<td>CS5-21</td>
</tr>
<tr>
<td>References ...........................................................................................................................</td>
<td>CS5-21</td>
</tr>
</tbody>
</table>

### List of Figures

| Figure 1. Differentiating between fire intensity and burn severity (from Parsons, et al. 2010) | 5 |
| Figure 2. Soil-water repellency (hydrophobicity) as altered by wildfire (from DeBano 2000b) | 6 |
| Figure 3. The hydrologic cycle (NASA 2012) | 8 |
| Figure 4. Example of burn severity mapping (red=high, orange=med, yellow=low, green=no burn) | 10 |
| Figure 5. Oregon vegetation types, as mapped by LandFire (2010) | 11 |
| Figure 6. Water droplets resisting infiltration into soil due to extreme hydrophobicity. (Doerr et al. 2000) | 12 |
| Figure 7. Graphical solution of the CN runoff equation (USDA-NRCS 2004b) | 18 |
| Figure 8. USDA Forest Service Regions | 20 |
| Figure 9. Runoff generating processes on a hillslope terminating at a watercourse (Garen and Moore 2005) | 22 |
| Figure 10. Hydrographs from the same hillslope, with different surface conditions (Canfield, et al. 2005) | 27 |
| Figure 11. Green-Ampt infiltration into the soil column | 28 |
| Figure 12. Optimal hillslope hydraulic conductivity, Cerro Grande NM fire (Canfield, et al. 2005) | 31 |
| Figure 13. HEC-HMS Green and Ampt input interface (USCOE-HEC 2013) | 32 |
| Figure 14. Runoff hydrographs by convolution and superposition, using 30-minute unit hydrograph | 33 |
| Figure 15. S curve developed from 30-minute unit hydrograph | 33 |
| Figure 16. Dimensionless unit hydrograph, with time of concentration and lag (USDA-NRCS 2010) | 34 |
Figure 17. Baldy Creek pre-fire and post-fire 30-minute unit hydrographs ................................................ 37
Figure 18. Example of an n-value raster, with progressively higher roughness with darker color.........40
Figure 19. Example of high burn severity raster (red pixels) ................................................................. 40
Figure 20. Example of flow slope raster, progressively steeper with darker color ................................. 40
Figure 21. 2010 post-wildfire debris flow from San Gabriel Mountains, CA .............................................. 42
Figure 22. Alluvial fan, Death Valley National Park .............................................................................. 43
Figure 23. A stream cross-section with isolines of velocity, maximized over the thalweg .................43
Figure 24. Riffle-pool morphology ........................................................................................................ 44
Figure 25. Hypothetical storm using equation 21b (all discharges converted to cfs) ............................... 50
Figure 26. Sediment production and bulking factors for debris production area 7 (LACDPW 2006) .... 51

Figure CS1- 1. Sunset through smoke plumes, from Fort Collins on Day 1 of the High Park Fire. ..... CS1-2
Figure CS1- 2. Aerial extent and soil burn severity of the High Park Fire, based on a BARC image. . CS1-2
Figure CS1- 3. Modeled catchments and stream channels, with flow computation points with soil burn  severity as background ................................................................. CS1-4
Figure CS1- 4. Example estimated pre- and post-fire hydrographs for the 10-year rain event .......... CS1-10
Figure CS1- 5. Example map with pre- and post-fire flood prediction estimates for the Poudre Park area.  .......................................................................................................................................................... CS1-11
Figure CS1- 6. Estimated 25-year peak flow enhancement ratios for the High Park Fire ............... CS1-11

Figure CS2- 1. State of Montana, with inset of Bitterroot River valley .............................................. CS2-1
Figure CS2- 2. Bitterroot River Watershed with inset of area of the wildfires in the year 2000 ........ CS2-1
Figure CS2- 3. Bitterroot fire severity for the fires of 2000 (Mahlum et al. 2011) ............................ CS2-2
Figure CS2- 4. Lightning strikes in the Bitterroot Valley of Montana, initiating the wildfires of 2000. .... 175
Figure CS2- 5. One of the most poignant wildfire scenes ever captured, from the Bitterroot in 2000. CS2-3
Figure CS2- 6. Fully loaded silt fence placed in the aftermath of the 2000 Bitterroot Valley Complex wildfire. .................................................................................................................................................. CS2-7
Figure CS2- 7. Laird Creek in 2001 within what was the Bitterroot Fire Valley Complex .................... CS2-7
Figure CS2- 8. Sheafman Point in October 2008 ............................................................................... CS2-7
Figure CS2- 9. Glen Lake trail in the summer of 2012 .................................................................... CS2-8
Figure CS2- 10. The landscape around Glen Lake in the summer of 2012 ...................................... CS2-8
Figure CS2- 11. Satellite imagery used to detail burn severity of the 2000 Bitterroot Valley Complex wildfire .................................................................................................................................................. CS2-12
Figure CS2- 12. Burn severity map and rain gage data for a rain event that happened a year after the 2000 Bitterroot Valley Complex wildfire .................................................................................................................................................. CS2-12
| Figure CS3-1 | State of Colorado with zoom into the upper Rio Grande watershed ........................................ CS3-1 |
| Figure CS3-2 | Area of the West Fork Complex wildfire, west of South Fork CO .............................................. CS3-1 |
| Figure CS3-3 | Aerial extent of three fires known together as the West Fork Complex fire ................................. CS3-2 |
| Figure CS3-4 | Soil burn severity, model pour points, sub-watersheds, and stream channels ............................... CS3-5 |
| Figure CS3-5 | 25-year cumulative rainfall distributions used in modeling ......................................................... CS3-8 |
| Figure CS3-6 | Flow direction raster cell example* ............................................................................................. CS3-12 |
| Figure CS3-7 | Conceptual diagram of sediment yield estimation on hillslope zone breaks .................................. CS3-17 |
| Figure CS3-8 | Example of an area-weighted RUSLE sediment yield raster ......................................................... CS3-18 |
| Figure CS3-9 | Example of estimated pre- and post-fire hydrographs for the 25-year event ................................. CS3-19 |
| Figure CS3-10 | Example map providing pre- and post-fire flood predictions for the S. F. of the Rio Grande .......... CS3-19 |
| Figure CS3-11 | Peak flow magnification ratios for the West Fork Complex wildfire ............................................. CS3-20 |
| Figure CS3-12 | Sediment magnification ratios for the West Fork Complex wildfire ............................................. CS3-21 |
| Figure CS3-13 | Infiltration excell and saturation excess overland flow (Laboratory of Ecohydrology, EPFL) .......... CS3-24 |
| Figure CS4-1 | Location of concern: State of New Mexico with county boundaries, USFS Gila National Forest in green, Gila Wilderness area in yellow ......................................................... CS4-2 |
| Figure CS4-2 | Location of concern, with Whitewater-Baldy Complex Fire location in red ...................................... CS4-2 |
| Figure CS4-3 | Location of concern, showing fire location in red, nearby communities and highways .................. CS4-3 |
| Figure CS4-4 | Whitewater Creek watershed and the community of Glenwood NM ............................................. CS4-3 |
| Figure CS4-5 | Gages in the vicinity of Whitewater Creek ..................................................................................... CS4-4 |
| Figure CS4-6 | Burned trees near Hummingbird Saddle, Gila National Forest ....................................................... CS4-5 |
| Figure CS4-7 | HEC-HMS input window for modeling options in a single sub-basin ............................................. CS4-8 |
| Figure CS4-8 | Whitewater Creek hydrologic subareas ......................................................................................... CS4-8 |
| Figure CS4-9 | Upper Whitewater subarea (called “Baldy Fork”) ........................................................................... CS4-9 |
| Figure CS4-10 | ArcMap Raster Calculator expression creating a pre-fire roughness layer ...................................... CS4-12 |
| Figure CS4-11 | Burn raster (red = high, orange = medium, yellow = low, green = no burn) ..................................... CS4-13 |
| Figure CS4-12 | Flow direction codes .................................................................................................................... CS4-14 |
| Figure CS4-13 | Trapezoidal channel dimensions ................................................................................................. CS4-17 |
| Figure CS4-14 | Twenty-one five-minute travel time bands for Baldy Fork, with Attribute Table ........................ CS4-20 |
| Figure CS4-15 | Pre-fire time-area histogram for Baldy Fork .................................................................................. CS4-21 |
| Figure CS4-16 | Pre-fire spreadsheet. (30-minute unit hydrograph in column H) ..................................................... CS4-22 |
| Figure CS4-17 | Unit Hydrographs, 30-minute duration for Baldy Fork ................................................................ CS4-22 |
| Figure CS4-18 | S-curve from lagged and summed 30-minute unit hydrographs ...................................................... CS4-23 |
| Figure CS4-19 | Baldy Fork S-curves for HecHMS, three scenarios ..................................................................... CS4-24 |
Figure CS4-20. Areal reduction factors developed for 6-hour duration storms at Walnut Gulch ..... CS4-28
Figure CS4-21. Two storm centerings for Whitewater Creek and 10km radii. ......................... CS4-29
Figure CS4-22. Whitewater debris flow hazard (Tillery, Matherne, and Verdin (2012))............ CS4-30
Figure CS4-23. Locations of reported HEC-HMS modeling output ...................................... CS4-31
Figure CS4-24. HecHMS results, 100-year storm peaks at Glenwood (no areal reduction) ....... CS4-33
Figure CS4-25. HecHMS results, 100-year storm peaks at Glenwood (areal reduction with centering over the upper Whitewood sub-basin) .............................................................. CS4-35
Figure CS4-26. 100-year post-fire hydrographs at Glenwood between storm centerings in the upper Whitewater sub-basin and the SF Whitewater sub-basin ........................................ CS4-36
Figure CS4-27. 25-year post-fire hydrographs at Glenwood between storm centerings in the upper Whitewater sub-basin ......................................................... CS4-36
Figure CS4-28. Whitewater Creek NM flood event of 14-15 Sep 2013, gaged rainfall and streamflow .... CS4-39
Figure CS4-29. Whitewater Creek flood 14-15 Sep 2013, observed and modeled ....................... CS4-40
Figure CS5-1. State of Utah and fire location, about 40 miles south of Salt Lake City .............. CS5-3
Figure CS5-2. Burning watershed from Eagle Mountain, UT, 21 June 2012 ......................... CS5-3
Figure CS5-3. Burning watershed from Eagle Mountain, UT, 22 June 2012 ......................... CS5-5
Figure CS5-4. Burned watershed flow direction into Saratoga Springs, UT from 1 September 2012 event. CS5-5
Figure CS5-5. Sediment laden flow through residential neighborhood .................................. CS5-6
Figure CS5-6. Typical sediment composition in residential area ........................................... CS5-6
Figure CS5-7. Location of stream gages and study area ....................................................... CS5-9
Figure CS5-8. Stream gage regression output converted to discharge per unit area ............... CS5-9
Figure CS5-9. Burned zone (red) and sub-areas upstream of Saratoga Springs ..................... CS5-11
Figure CS5-10. Curve number from cover, for hydrologic soil groups (Goodrich et al. 2005) .... CS5-12
Figure CS5-11. Interdependency of CN and lag time, Cerro Grande Wildfire (McLin et al. 2001) .. CS5-13
Figure CS5-12. Comparison of observed and simulated pre-and post-fire peak discharges per unit drainage basin area in New Mexico. (McLin et al, 2001) .................................................. CS5-15
Figure CS5-13. Range of annual erosion rates from Bridges (1973) ........................................ CS5-16
Figure CS5-14. Burned watershed pre-fire and post-fire hydrographs from WinTR-20 .......... CS5-18

List of Tables
Table 1. Federal agencies and their roles concerning wildfire events ....................................... 3
Table 2. Computer models for rainfall-runoff analysis ............................................................. 14
Table 3. Runoff curve numbers for arid and semiarid rangelands (USDA-NRCS 2004a) .......... 17
Table 4. Suggested runoff curve numbers for burned areas from Cerrelli (2005) ......................................................... 19
Table 5. Forest Region 1 curve numbers (Story 2003) ........................................................................................................ 20
Table 6. Forest Region 1 curve numbers (Stuart 2000) ........................................................................................................ 20
Table 7. Forest Region 3 curve numbers .......................................................................................................................... 21
Table 8. Forest Region 3 curve numbers .......................................................................................................................... 21
Table 9. Forest Region 3 pre-fire and post-fire curve numbers. ......................................................................................... 21
Table 10. Manning’s roughness coefficients for sheet flow (depth generally ≤ 0.1 ft) ......................................................... 24
Table 11. Shallow-concentrated flow velocity equations, where S=flow slope in ft/ft......................................................... 25
Table 13. Size classification and potential consequences of debris flows (Santi and Morandi, 2012) ............................... 45

Table CS1- 1. CN assignments implemented in High Park Fire hydrologic modeling. (Highlighted columns indicate values extracted from USDA-NRCS 2004a. .............................................................. CS1-6
Table CS1- 2. Comparison of CN modeling with USGS regression results from StreamStats. .................. CS1-12

Table CS2- 1. Runoff curve numbers for high severity burned areas of southwest Montana* .................. CS2-9
Table CS2- 2. Recommended runoff curve numbers for moderate severity burned areas.................. CS2-9
Table CS2- 3. Recommended RCNs for low severity burned and unburned areas with north and east facing slopes ........................................................................................................................................ CS2-10
Table CS2- 4. Recommended RCNs for low severity burned and unburned areas with south and west facing slopes ........................................................................................................................................ CS2-11

Table CS3- 1. CN assignments implemented in West Fork Complex Fire hydrologic modeling .......... CS3-7
Table CS3- 2. Rainfall depths (inches) implemented in the modeling ............................................................. CS3-8
Table CS3- 3. Spatial datasets used for the six RUSLE factors .................................................................................. CS3-12
Table CS3- 4. C factors for common land covers (Theobald et al. 2010) ..................................................... CS3-16

Table CS4- 1. Pre-fire roughness assumptions ..................................................................................................................... CS4-10
Table CS4- 2. Post-fire (immediately) roughness assumptions ......................................................................................... CS4-10
Table CS4- 3. Post-fire (1 year) roughness assumptions ................................................................................................. CS4-11
Table CS4- 4. Values of φ, given assumptions of overland flow width and depth ........................................ CS4-15
Table CS4- 5. Shallow-concentrated flow parameters ................................................................................................. CS4-16
Table CS4- 6. Trapezoidal channel parameters ............................................................................................................. CS4-18
Table CS4- 7. Whitewater Creek watershed 6-hour duration storm totals ...................................................... CS4-27
Table CS4- 8. HecHMS output: hydrograph peaks at four locations (no areal reduction) .......................... CS4-32
Table CS4-9. HecHMS output: hydrograph peaks at four locations (areal reductions applied, with centerings as shown in figure CS4-22)................................................................................................ CS4-34
Table CS4-10. Sediment bulked flows for Whitewater Creek ........................................................................................................ CS4-37
Table CS4-11. NOAA Precip-Frequency values and Sep 2013 rainfall event from Catwalk gage.... CS4-38

Table CS5-1. Six stream gages near Saratoga Springs, UT................................................................. CS5-8
Table CS5-2. Burned watershed subarea input to WinTr-20................................................................. CS5-11
Table CS5-3. Increase in runoff curve number from pre-fire to post-fire conditions....................... CS5-12
Table CS5-4. Output variables available in AGWA. ........................................................................ CS5-14
Table CS5-5. Cubic feet per second per square mile (CSM) from WinTR-20 pre-fire results and selected stream gages........................................................................................................ CS5-17
Table CS5-6. Burned watershed pre-fire and post-fire peak flow output from WinTR-20. ............ CS5-17
Table CS5-7. Storm totals runoff for various recurrence intervals, input to WinTR-20 and post-fire runoff values for Subarea 1+2........................................................................................................ CS5-18
Table CS5-8. Burned watershed post-fire event total sediment runoff in tons............................... CS5-19
Table CS5-9. Saratoga Springs burned watershed pre-fire and post-fire peaks (CSM) from WinTR-20.
.............................................................................................................................................................. CS5-20

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Introduction

Periodic wildfire is a normal occurrence on forests in the Western United States. Wildfire imposes immediate, extensive, and long-term landscape changes, specifically removal of protective vegetation and, sometimes, inhibited soil infiltration, changing the hydrology of landscape and resulting in radically larger flood events following a fire. Often these floods results in excessive streambank erosion, and unusual amounts of sediment and debris.

To account for these landscape changes, hydrologists use predictive rainfall-runoff models to illustrate and evaluate the range of flood magnitudes and durations expected from given rainfall events in the watershed. These models also assist in planning re-vegetation efforts in burned watersheds, by revealing areas that will provide the greatest positive effect from the application of conservation activities.

This technical note provides hydrologic guidance for analysis of burned watersheds. It discusses the specific impacts of wildfire on the runoff process; and gives detailed information on several alternative ways to account for wildfire effects in hydrologic computer models. It discusses several hydrologic models and demonstrates specific analysis techniques for obtaining useful estimates of post-wildfire flooding and sedimentation. Five case studies document the use of these techniques for modeling actual wildfire-burned watersheds.

The role of NRCS in post-fire assessments and modeling

Many Federal agencies provide assistance related to wildfire (table 1). In contrast to the public-land focus of many agencies, NRCS helps private landowners with conservation practices that enable good management of their land. As individual landowners seek to take advantage of the benefits of conservation, they rely on NRCS’ technical expertise in agronomy, rangeland management, nutrient and pesticide management, biology, and hydrology, among other disciplines. After a fire, NRCS can provide rapid assessments of expected increased flood peaks, sediment flow in streams, and other hazards on the watershed. As post-fire spatial data becomes available, NRCS can provide downstream communities with more thorough technical analyses of ongoing streamflow and sedimentation potential. NRCS assistance may augment that of the
USDA Forest Service, as discussed below, or it may serve as the only technical assistance available.

The USDA Forest Service is authorized to carry out burned area emergency response (BAER) assessments to identify imminent post-wildfire threats to human life and safety, property, and critical natural or cultural resources on National Forest System (NFS) lands and take immediate actions to manage unacceptable risks. The USDA Forest Service typically organizes the BAER process, but other Federal, Tribal, State, and local agencies often participate to cover other Federal and non-Federal lands adjacent to or intermingled with NFS lands in the event of fires exceeding defined thresholds for size, severity, and/or soil resource damage (Safford, et al. 2008).

The intent of the BAER program is to determine whether wildfire-caused changes in soil hydrologic function resulted in hazardous conditions that threaten life, health, property, or critical cultural and natural resources due to flooding, erosion, and debris flows. BAER teams often provide immediate hydrologic assessments. Communities value these rapid assessments precisely because they provide some gauge of the sudden and new vulnerability of the watershed. However, rapid production may also entail a sacrifice in accuracy.
Table 1. Federal agencies and their roles concerning wildfire events.

<table>
<thead>
<tr>
<th>Agency</th>
<th>Roles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>USDA Forest Service</strong></td>
<td><strong>Pre-event</strong> Forest management, information dissemination, training, fire tower lookout staffing, status monitoring</td>
</tr>
<tr>
<td><strong>During-event</strong></td>
<td>Infrastructure protection</td>
</tr>
<tr>
<td><strong>Post-event</strong></td>
<td>Damage assessment, Emergency Watershed Protection, Burned Area Emergency Response (BAER Teams)</td>
</tr>
<tr>
<td><strong>Nat. Interagency Fire Center</strong></td>
<td><strong>Pre-event</strong> Info dissemination, training, agency coordination</td>
</tr>
<tr>
<td></td>
<td><strong>During-event</strong> Fire-fight coordination</td>
</tr>
<tr>
<td><strong>US National Weather Service</strong></td>
<td><strong>During-event</strong> Forecasting fire conditions</td>
</tr>
<tr>
<td></td>
<td><strong>Post-event</strong> Flash flood warnings</td>
</tr>
<tr>
<td><strong>US Geological Survey</strong></td>
<td><strong>Pre-event</strong> Data collection through gage network</td>
</tr>
<tr>
<td></td>
<td><strong>Post-event</strong> Short-term gage installation and data collection, research on hazards caused by wildfire</td>
</tr>
<tr>
<td><strong>Fed. Emergency Mgt. Agency</strong></td>
<td><strong>Pre-event</strong> Disaster preparedness, information dissemination</td>
</tr>
<tr>
<td></td>
<td><strong>Post-event</strong> Financial assistance</td>
</tr>
<tr>
<td><strong>US Bureau of Land Management</strong></td>
<td><strong>Pre-event</strong> Federal rangeland management</td>
</tr>
</tbody>
</table>


The congressionally-authorized Emergency Watershed Protection (EWP) program encourages implementation of emergency measures after a natural disaster to help protect against imminent...
hazards to life and property. Through EWP, NRCS provides financial assistance through cost-390 share arrangements, and technical assistance for such measures as upland mulching, debris and 391 sediments basins, removal of debris and/or excess sediment from streambeds, establishment of 392 cover on critically eroding lands or streambanks, repair of conservation practices, and purchase 393 of floodplain easements.

**Important terms and terminology**

Because wildfire affects a watershed in more aspects than hydrology, terminology is sometimes confusing. The ecosystem response, for example, may include soil erosion, vegetation regeneration, microbial community structure restoration, faunal recolonization, and invasive species introduction (Keeley 2009). As specifically related to hydrologic response, a short list of terms and definitions follows. The National Wildfire Coordinating Group (NWCG 2006), among others, provides glossaries of wildland fire terminology larger in scope than hydrology. See [http://www.nwcg.gov/pms/pubs/glossary/index.htm](http://www.nwcg.gov/pms/pubs/glossary/index.htm). Parsons, et al. (2010) contains similar clarifications of wildfire terminology.

Agencies and personnel involved with wildfires use the following terms extensively. These terms relate to the driving mechanisms of hydrologic modeling and to pertinent GIS spatial data.

**Burned area reflectance classification (BARC)**

The BARC process is a spatial data analysis technique for creating GIS layers of soil burn severity by comparing the reflectance difference in certain wavelengths between pre- and post-fire aerial images (Safford, et al. 2008). BARC informs BAER decisions about locations requiring field visits. The imagery processing is also called “Landsat differenced Normalized Burn Ratio” or dNBR, which is defined below. Comparison with field-collected data has shown that BARC products tend to be more indicative of post-fire vegetative condition than of soil condition, especially in low to moderately burned areas (Hudak et al. 2004).

**Burn severity**

Burn severity is a qualitative assessment of the heat pulse directed toward the ground during a fire. It relates to soil heating, large fuel and duff consumption, consumption of the litter and
organic layer beneath trees and isolated shrubs, and mortality of buried plant parts (NWCG 2006). Burn severity is subdivided into two indices, one for soil and one for vegetation. Figure 1 illustrates a comparison between burn severity and the term fire intensity.

Observations of the following changes in soil characteristics (Parsons et al. 2010) form the basis for soil burn-severity evaluations:

- loss of effective ground cover due to consumption of litter and duff
- surface color change due to char, ash cover, or soil oxidation
- loss of soil structure due to consumption of soil organic matter
- consumption of fine roots in the surface soil horizon
- formation of water repellent layers that reduce infiltration

**Fire intensity**

Fire intensity is a description of the physical combustion process of energy release from organic matter; and represents the energy released during various phases of a wildfire (Keeley 2009). The concept applies to various aspects of a currently ongoing wildfire event, such as fire line intensity, which is the rate of heat transfer per unit length of the fire line. By contrast, burn severity is a post-fire condition. (See figure 1.)

**Figure 1. Differentiating between fire intensity and burn severity (from Parsons, et al. 2010).**
Fire severity
The term fire severity is most commonly used in empirical studies to refer to the immediate impact on soil and vegetation of heat pulses above and below ground, particularly by indexing the degree of organic matter consumed (Keeley 2009). This term is very similar to the term burn severity, which is preferred by BAER specialists.

Hydrophobicity or soil water repellency
A characteristic of soil generally related to organic matter, soil hydrophobicity is the tendency of the soil to resist wetting or infiltration of moisture. A relatively thin hydrophobic layer can form in an unburned forest, due to the leaching of organic matter from the duff into the soil. During wildfire, the hydrophobic layer can shift downward in the soil and increase in thickness. The intense heat of the wildfire produces a marked temperature gradient in the upper soil layer because dry soil is a poor heat conductor (DeBano 1981). That temperature gradient tends to transport vaporized organic matter downward in the soil column until cooler layers can condense it. Subsequent organic coating of soil particles results in a water repellent layer. Refer to figure 2 for a schematic between unburned and burned condition. DeBano 2000a and 2000b also provide a review of this topic.

Figure 2. Soil-water repellency (hydrophobicity) as altered by wildfire (from DeBano 2000b).
Landsat differenced normalized burn ratio (dNBR)
By comparing pre-fire and post-fire Landsat imagery, the differenced normalized burn ratio, or dNBR, analysis enables classification of burn severity. The BARC classification for soil burn severity uses this process. A modification of dNBR called RdNBR, where R stands for relative, is used to assign vegetation burn severity. Comparing the absolute difference in images using dNBR tends to assign too much weight to pre-burn vegetation conditions. The relative version, RdNBR, removes this bias (Safford, et al. 2008; Miller and Thode 2007).

Rapid assessments of vegetation condition after wildfire (RAVG)
A process used by USDA Forest Service specialists to prepare spatial mapping of wildfire effects on vegetation, rapid assessments of vegetation condition after wildfire (RAVG) uses Landsat thematic map images and accounts for before and after wildfire conditions. The reduction of vegetation due to wildfire is indexed by basal area loss, where basal area is a forest management term referring to the sum of cross-sectional areas of trees and stems at breast-height for a given section of land. Although the BAER teams generally focus on rapid assessment of soil burn severity using BARC, the RAVG project creates maps of wildfire on vegetation, usually within thirty days of fire containment.

Soil burn severity mapping
The USDA Forest Service BAER teams assess soil burn severity and produce high-resolution GIS-based maps. The process uses remote sensing (BARC) with field verification (Parsons et al. 2010). The GIS soil burn severity layers generally use three categories that are defined as follows (Parsons et al. 2010):

Low soil burn severity
Surface organic layers are not completely consumed and roots are generally unchanged, due to minimal heat penetration of the soil. While exposed mineral soil may appear lightly charred, the canopy and understory vegetation generally appears unchanged.
Moderate soil burn severity
Up to eighty percent of the pre-fire ground cover may be consumed. Roots may be scorched but generally not completely consumed, and soil structure is unchanged.

High soil burn severity
All or nearly all of the pre-fire ground cover is generally consumed, along with roots up to 0.1 inches (0.25 cm) in diameter. Charring may be visible on larger roots. Significant bare or ash-covered soil is exposed and soil structure is less stable due to loss of root mass.

Wildfire impacts on watershed hydrology
A diagram of the hydrologic cycle succinctly shows water processes of Earth and transport mechanisms (figure 3, NASA 2012). For example, evaporation changes the water phase from liquid to vapor, while transporting it from the surface to the atmosphere.

Figure 3. The hydrologic cycle (NASA 2012).
For wildfire-impacted watersheds, the most pertinent part of the hydrologic cycle is the phase change from vapor to liquid, accompanied by transport to higher elevations of the land. The rainfall, returning with higher potential energy, must infiltrate or run off as gravity draws it back to the ocean sink. Wildfire tends to speed up this return and proportion more to runoff rather than to infiltration.

As a highly effective solvent and with considerable momentum and energy, liquid water begins the erosive process upon first contact with the Earth’s surface—as raindrops impact bare soil. Concentrating flows, whether in small rivulets or larger streams, easily entrain silt, sand, and clay particles, leaving erosion scars on land surfaces and stream banks. Vegetation offers some protection, shielding the soil surface from raindrop impact, holding soil in place with root structures, and impeding flow with branches and leaves. Forest litter can also help protect the soil surface. Plants help the soil resist the erosive forces of flowing water both within overland pathways as well as within stream corridors.

Destruction of vegetation and the infusion of soil hydrophobicity affect runoff by increasing runoff volume and velocity, thus increasing erosivity. Consequently, the healing of a watershed after a fire depends on the return of vegetation to pre-fire conditions and the breakdown of soil hydrophobicity. Over the course of several years, these processes gradually diminish elevated runoff volume, velocity, and erosivity to pre-fire levels. One study found that 10-year rainfall events on a wildfire-impacted landscape resulted in 100-year or 200-year peak floods (Conedera et al. 2003). Another study found that wildfire increased runoff proportionally more for smaller watersheds than for larger ones (Stoof et al. 2011).

Assessment of post-fire soil and vegetation conditions

One of the most convenient ways to assess the post-fire runoff surface condition is to use soil burn severity mapping (figure 4) derived by the BARC process. Using this process, the hydrologist can determine vegetation loss as a percentage of drainage area for any drainage subarea. Another useful spatial data product derived through the RAVG process, produces maps that relate specifically to vegetation rather than soil condition. Historical information on
vegetation effects is available through the cooperative project Monitoring Trends in Burn Severity (MTBS) through the website http://www.mtbs.gov/.

Another useful data product (Figure 5) is from a Federal mapping initiative called LandFire (2010). Also known as Landscape Fire and Resource Management Planning Tools this initiative was established by the US Department of Interior and the USDA Forest Service, with the goal of providing “a comprehensive, consistent, scientifically credible suite of spatial data layers for the entire United States,” (LandFire 2010) including vegetation types, forest canopy, canopy heights, fire regime classes, and more. Subdivided by geographic region, these high-resolution maps are available through the LandFire website at: http://www.landfire.gov/index.php.

Figure 4. Example of burn severity mapping.

(red=high, orange=med, yellow=low, green=no burn)
Figure 5. Oregon vegetation types, as mapped by LandFire (2010).

Assessment of post-fire soil hydrophobic conditions

The development of soil hydrophobicity is multi-factored and does not necessarily correlate with soil burn severity (Parsons et al. 2010). The depth and thickness of wildfire-induced soil hydrophobicity is dependent upon vegetation type, amount of soil organic matter, soil texture, fire residence time, and burn temperature (DeBano 1981, Huffman, et al. 2001). An important pre-condition is that organic matter must exist for the wildfire to vaporize, leading to condensation of the hydrophobic compounds within the soil profile (DeBano et al. 1967).

Greater water repellency is generally associated with coarse-grained soil texture. Given a limited supply of condensing hydrophobic substances, the smaller surface areas of coarse-grained soils are more completely covered than the greater surface area of silts and clays (Doerr et al. 2000).

In addition, the susceptibility of soil texture to hydrophobicity may be related to hydrologic soil group classification (MacDonald, et al. 2000). The four hydrologic soil groups (HSGs) are a standard parameter of the NRCS soil survey, fully described in USDA-NRCS 2009b. The soils of HSG A typically have less than 10 percent clay and more than 90 percent sand or gravel. The
soils of HSG B typically have 50 to 90 percent sand, whereas HSGs C and D have less than 50 percent sand content. The coarseness of HSGs A and B gives them a greater tendency toward hydrophobicity, while the higher silt and clay content of HSGs C and D renders them less susceptible to hydrophobicity. However, HSG is specifically assigned based on saturated hydraulic conductivity of the least transmissive soil layer, not to particle size or hydrophobic susceptibility, and should not be considered a definitive precursor for water repellency. (USDA-NRCS 2009b.)

Hydrophobicity of the upper mineral soil layer can be determined in the field through a simple procedure:

1. Scrape away any ash layer.
2. Place several individual drops of water on the air-dried surface.
3. Soil later is considered hydrophobic if drops remain after one minute. (See figure 6.)

Figure 6. Water droplets resisting infiltration into soil due to extreme hydrophobicity. (Doerr et al. 2000).

The depth of the water repellent layer can depend on fire temperature. Less severe burning may produce hydrophobicity of the soil surface. Locations of greater burn severity may result in the top of the hydrophobic layer being at some depth, say 0.5 to 3 inches. Recognizing this possibility, test the lower layers if the top layer is not water repellent. Scrape away 0.5 to 1 inch of soil depth and repeat the water drop test. By continuing this procedure, both the depth of the top and bottom of the hydrophobic layer may be determined for that location. Repeat this field
procedure over time to investigate hydrophobicity persistence. Expect considerable spatial variability in hydrophobicity.

More extensive field procedures are available to quantify the degree of hydrophobicity, such as measuring the water drop penetration time (WDPT). For more severe hydrophobicity, ethanol drops are sometimes used in a critical surface tension (CST) test. Huffman et al. 2001, Scott 2000, Doerr 1998, and Robichaud et al. 2008 discuss these and other more extensive procedures.

The persistence of hydrophobicity is dependent upon several factors, including wetting-drying cycles, and both physical and biological action (Huffman, et al. 2001 and DeBano, 1981).

Contact by moisture is a factor in the breakdown of hydrophobicity. Although first contact with moisture is repelled, when the soil moisture threshold is exceeded, the layer will allow some infiltration. Upon drying, the layer may again become hydrophobic. This wetting and drying process, along with other physical and biological factors, removes hydrophobicity over time. Among the other factors that help break down hydrophobicity are impact of wildlife treading, impact of falling vegetation such as branches, root penetration of the water repellent layer, and the freeze-thaw process. The hydrophobicity may be minimized in as short a time as a few months (Huffman et al. 2001), but more extensive hydrophobic layers can persist for up to six years (Dyrness 1976).

Hydrologic modeling of burned watersheds

Methods and models

Numerous methods and computer programs, varying in complexity, are available for modeling rainfall-runoff processes. In general, these models account for the pertinent aspects of the landscape, including land cover, soils, elevation, slope, sub-basin shape, vegetation character, and flow time of concentration. Meteorology is characterized using either actual storm hyetographs of one or more precipitation gages, or theoretical less-frequent event storms, such as the 100-year, 24-hour storm. Precipitation is distributed over time using pre-determined synthetic storm distribution curves that define rainfall intensity throughout the storm. The shape of the runoff hydrograph is often estimated using one of several possible unit-hydrograph
estimation methods. For larger watersheds flow routing may be needed to transform and
attenuate flow through stream systems.

Several commonly used computer models for rainfall-runoff analysis are listed in table 2.
Continuous simulation models, such as Agricultural Non-Points Source Pollution Model
(AGNPS, USDA-ARS, 2013a) and the Soil and Water Assessment Tool (SWAT, USDA-ARS,
2013b) help analyze runoff, sedimentation, and water quality issues over long time periods, such
as decades. For assessment of rainfall-runoff after wildfire, single flood events are usually the
concern. To model single events, commonly used computer models are the US Army Corps of
Engineers program Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS,
USACE-HEC, 2013); and the NRCS models, Computer Program for Project Formulation –
Hydrology (WinTR-20, USDA-NRCS 2004c) and Small Watershed Hydrology (WinTR-55,
USDA-NRCS 2009a). BAER teams also use WILDCAT (Hawkins and Greenberg 1990). The
ARS program, KINEROS2 (A Kinematic Runoff and Erosion Model, Smith et al. 2005, Canfield
and Goodrich 2005) is also used for wildfire area runoff simulation, through the Automated
Geospatial Watershed Assessment (AGWA) GIS-based tool for watershed assessments. The
AGWA tool is a GIS interface that automates the parameterization and execution of the SWAT
and KINEROS2 models.

Table 2. Computer models for rainfall-runoff analysis

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Name</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGNPS</td>
<td>Agricultural Non-Point Source Pollution Model</td>
<td>USDA-ARS 2013a</td>
</tr>
<tr>
<td>SWAT</td>
<td>Soil and Water Assessment Tool</td>
<td>USDA-ARS 2013b</td>
</tr>
<tr>
<td>HecHMS</td>
<td>Hydrologic Engineering Center - Hydrologic Modeling System</td>
<td>USCOE-HEC 2013</td>
</tr>
<tr>
<td>WinTR-20</td>
<td>Computer Program for Project Formulation - Hydrology</td>
<td>USDA-NRCS 2004c</td>
</tr>
<tr>
<td>WinTR-55</td>
<td>Small Watershed Hydrology</td>
<td>USDA-NRCS 2009a</td>
</tr>
</tbody>
</table>
In modeling a storm event, given precipitation volume distributed over time (a hyetograph), the hydrologist must determine what fraction infiltrates and/or is stored in surface depressions. The models of table 2 handle these phenomena in one of two general ways, the NRCS curve number (CN) method or physically based methods, such as Green and Ampt (GA). However, runoff analysis is not complete, with either the CN or GA methods. The CN runoff method provides a total runoff volume estimate at a watershed outlet, but nothing about peak flow rate or hydrograph shape. The GA method provides the fraction of precipitation that infiltrates, leaving that which is ready to runoff, but does not route that runoff to the outlet.

With the NRCS models, WinTR-20 and WinTR-55, runoff volume is computed using the NRCS runoff curve number (CN) method. Runoff hydrographs are developed by applying the runoff volume, estimated using the CN method, and time of concentration to a dimensionless unit hydrograph. Infiltration methods, such as GA, available in models such as HEC-HMS, do not employ runoff curve numbers (although HEC-HMS also has a CN option).

Several case studies presented in this Technical Note as appendices A through E illustrate the use of these models individually or various combinations of these models. Case studies 1 (appendix A) and 3 (appendix C) illustrate the use of HEC-HMS with the runoff curve number method. Case study 2 (appendix B) illustrates the use of the fire hydrology, or FIRE HYDRO, spreadsheet, an adaptation of the runoff curve number method. Case study 4 (appendix D) illustrates the use of HEC-HMS with the Green and Ampt infiltration method. Finally, case study 5 (appendix E) illustrates the use of AGWA and WinTR-20.

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wildcat4</td>
<td>WILDCAT4 flow model</td>
<td>Hawkins &amp; Greenberg 1990</td>
</tr>
<tr>
<td>KINEROS2</td>
<td>Kinematic Runoff and Erosion Model</td>
<td>Smith, et al. 2005</td>
</tr>
<tr>
<td>AGWA</td>
<td>Automated Geospatial Watershed Assessment Tool</td>
<td>Canfield and Goodrich 2005</td>
</tr>
</tbody>
</table>
Adjustment of event-based runoff modeling components for burned areas

The phenomena of rainfall, interception, surface storage, infiltration, and runoff transformation are discussed in hydrology textbooks, such as Bendient, Huber, and Vieux (2012). To use any of the computer models in table 2 for post-wildfire hydrology, the analyst should understand the impact of fire on these various physical processes. Adjustment of hydrologic model features allows comparison of pre-fire versus post-fire estimates of runoff peaks and hydrograph shapes.

Accounting for changes in runoff hydrology due to wildfire is generally a matter of determining the extent to which runoff has accelerated due to the loss of vegetation or the lack of infiltration due to soil hydrophobicity. Wildfire may alter any or all of several runoff modeling components. Adjustment to CNs, time of concentration estimates, including flow travel times, Manning’s roughness coefficients, soil infiltration characteristics, and unit hydrographs are detailed in the following sections.

Runoff curve numbers

The NRCS National Engineering Handbook, Part 630, Hydrology, Chapter 9, Hydrologic Soil-Cover Complexes (USDA-NRCS 2004a), documents the general process of determining curve numbers, providing tables of curve numbers for agricultural lands and for arid and semi-arid rangelands (table 3). Figure 7 provides a graphical solution of the curve number equation used to compute Q, runoff volume. The CN method depends on the determination of the curve number index for a given watershed and given hydrologic condition. Hydrologic condition is based on combination of vegetation and land surface characteristics as they affect infiltration. The tables also demonstrate the variance of curve number with hydrologic soil group.
Table 3. Runoff curve numbers for arid and semiarid rangelands (USDA-NRCS 2004a)

<table>
<thead>
<tr>
<th>Cover type</th>
<th>Hydrologic condition</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbaceous-mixture of grass, weeds, and low-growing brush,</td>
<td>poor</td>
<td>80</td>
<td>87</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>with brush the minor element</td>
<td>fair</td>
<td>71</td>
<td>81</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>good</td>
<td>62</td>
<td>74</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Oak-aspen-mountain brush mixture of oak brush, aspen,</td>
<td>poor</td>
<td>66</td>
<td>74</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>mountain mahogany, bitter brush, maple, and other brush</td>
<td>fair</td>
<td>48</td>
<td>57</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>good</td>
<td>30</td>
<td>41</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Pinyon-juniper-pinyon, juniper, or both; grass understory</td>
<td>poor</td>
<td>75</td>
<td>85</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fair</td>
<td>58</td>
<td>73</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>good</td>
<td>41</td>
<td>61</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Sagebrush with grass understory</td>
<td>poor</td>
<td>67</td>
<td>80</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fair</td>
<td>51</td>
<td>63</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>good</td>
<td>35</td>
<td>47</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Desert shrub-major plants include saltbush greasewood,</td>
<td>poor</td>
<td>63</td>
<td>77</td>
<td>85</td>
<td>88</td>
</tr>
<tr>
<td>creosotebush, blackbrush, bursage, palo verde, mesquite,</td>
<td>fair</td>
<td>55</td>
<td>72</td>
<td>81</td>
<td>86</td>
</tr>
<tr>
<td>and cactus</td>
<td>good</td>
<td>49</td>
<td>68</td>
<td>79</td>
<td>84</td>
</tr>
</tbody>
</table>

Note: Average runoff conditions. (group A only developed for desert shrub)

Hydrologic condition defined as follows:
- poor: < 30% ground cover (litter, grass, and brush overstory)
- fair: 30 to 70% ground cover
- good: >70% ground cover
Existing methods for adjusting runoff curve numbers to account for wildfire effects are for the most part based heavily upon the hydrologic judgment of practitioners who have studied burned watersheds. A number of publications, including Foltz, et al. (2009) have documented these methods. For a synopsis of the state of the art, research issues related to post-wildfire runoff and erosion processes, and suggested areas needing further work, see Moody, et al. (2013).

**Adjustment of curve numbers for wildfire effects**

One of the first efforts to establish some methodology for adjustment of runoff curve numbers for the effects of wildfire was Cerrelli (2005). Studying Montana wildfire events in 2000 and 2001, Cerrelli created an Excel spreadsheet that computes watershed curve numbers for four conditions: 1) pre-fire, 2) early post-fire with possible hydrophobicity, 3) medium term post-fire with hydrophobicity no longer in effect, but little re-emergent vegetation, and 4) later post fire, after one growing season. For high burn severity areas, the investigation included a table of wildfire affected curve numbers, table 4. The Fire Hydrology, or FIRE HYDRO, spreadsheet and user notes are available at [ftp://ftp.wcc.nrcs.usda.gov/wntsc/H&H/wildfire/](ftp://ftp.wcc.nrcs.usda.gov/wntsc/H&H/wildfire/).
Table 4. Suggested runoff curve numbers for burned areas from Cerrelli (2005).

<table>
<thead>
<tr>
<th>Hydrologic soil group</th>
<th>High burn severity CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>64</td>
</tr>
<tr>
<td>B</td>
<td>78</td>
</tr>
<tr>
<td>C</td>
<td>85</td>
</tr>
<tr>
<td>D</td>
<td>88</td>
</tr>
</tbody>
</table>

In addition, the guidance for moderate burn severity is to use the published curve number tables, but with cover type in fair condition, and for low burn severity, to adjust CN to the aspect of the fire-burned slopes. For low burn severity, with north and east facing slopes, the guidance is to use cover type good condition, and for south and west facing slopes to use a curve number between cover type fair and good condition.

Case study 2 of this Technical Note documents Cerrelli’s investigation, method development, and use on the Montana Bitterroot wildfires of 2000.

The USDA Forest Service provides web-based guidance for determination of wildfire affected runoff curve numbers, which includes Cerrelli (2005). (See: [http://forest.moscowfsl.wsu.edu/BAERTOOLS/ROADTRT/Peakflow/CN/](http://forest.moscowfsl.wsu.edu/BAERTOOLS/ROADTRT/Peakflow/CN/). Tables 5 through 9 are from this reference.) Tables 5 and 6 show post-fire runoff curve numbers suggested by two different investigators (Story, 2003, and Stuart, 2000) for Forest Service Region 1. (See figure 8 for a map of the USDA Forest Service Regions.)
Table 5. Forest Region 1 curve numbers (Story 2003)

<table>
<thead>
<tr>
<th>Post-fire condition</th>
<th>CN range</th>
</tr>
</thead>
<tbody>
<tr>
<td>High burn severity, with hydrophobic soils</td>
<td>93-98</td>
</tr>
<tr>
<td>High burn severity, without hydrophobic soils</td>
<td>90-95</td>
</tr>
</tbody>
</table>

Table 6. Forest Region 1 curve numbers (Stuart 2000)

<table>
<thead>
<tr>
<th>Post-fire condition</th>
<th>CN range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate burn severity</td>
<td>80</td>
</tr>
<tr>
<td>Low burn severity</td>
<td>70-72</td>
</tr>
<tr>
<td>Unburned</td>
<td>60-64</td>
</tr>
<tr>
<td>Moderate burn severity, with BAER treatments</td>
<td>75</td>
</tr>
<tr>
<td>Moderate burn severity, with hydrophobic soils</td>
<td>66</td>
</tr>
</tbody>
</table>

Figure 8. USDA Forest Service Regions

Tables 7 and 8 show CNs suggested by forest service hydrologists for Forest Service Region 3 (Arizona and New Mexico).
Table 7. Forest Region 3 curve numbers

<table>
<thead>
<tr>
<th>Post-fire condition</th>
<th>CN range</th>
</tr>
</thead>
<tbody>
<tr>
<td>High burn severity, with hydrophobic soils</td>
<td>95</td>
</tr>
<tr>
<td>High burn severity, without hydrophobic soils</td>
<td>92</td>
</tr>
<tr>
<td>Moderate burn severity, with hydrophobic soils</td>
<td>89</td>
</tr>
<tr>
<td>Moderate burn severity, without hydrophobic soils</td>
<td>87</td>
</tr>
<tr>
<td>Low burn severity</td>
<td>80-83</td>
</tr>
<tr>
<td>Unburned</td>
<td>55-75</td>
</tr>
</tbody>
</table>

Table 8. Forest Region 3 curve numbers

<table>
<thead>
<tr>
<th>Post-fire condition</th>
<th>CN range</th>
</tr>
</thead>
<tbody>
<tr>
<td>High burn severity, with hydrophobic soils</td>
<td>95</td>
</tr>
<tr>
<td>High burn severity, without hydrophobic soils</td>
<td>90-91</td>
</tr>
<tr>
<td>Moderate burn severity, with hydrophobic soils</td>
<td>90</td>
</tr>
<tr>
<td>Moderate burn severity, without hydrophobic soils</td>
<td>85</td>
</tr>
<tr>
<td>Low burn severity</td>
<td>CN_{pre-fire} + 5</td>
</tr>
<tr>
<td>Straw mulch with good coverage</td>
<td>60</td>
</tr>
<tr>
<td>Seeding with log erosion barriers, 1-year post-fire</td>
<td>75</td>
</tr>
<tr>
<td>Log erosion barriers without hydrophobic soils</td>
<td>85</td>
</tr>
</tbody>
</table>

Another investigation by the Forest Service produced a table comparing pre-fire to post-fire runoff curve numbers for the 2003 Aspen Fire in Arizona. (See table 9.) Although these Forest Service studies generally use NRCS hydrology models, case study 1 in this technical note demonstrates the use of CNs within the HEC-HMS model.

Table 9. Forest Region 3 pre-fire and post-fire curve numbers.

<table>
<thead>
<tr>
<th>Hydrologic soil group</th>
<th>CN_{pre-fire}</th>
<th>CN_{post-fire}</th>
<th>CN_{post-fire}</th>
<th>CN_{post-fire}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low burn severity</td>
<td>Moderate burn severity</td>
<td>High burn severity</td>
</tr>
<tr>
<td>B</td>
<td>56</td>
<td>65</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>C</td>
<td>67</td>
<td>70-75</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>D</td>
<td>77</td>
<td>80-85</td>
<td>90</td>
<td>95</td>
</tr>
</tbody>
</table>
Limitations of the CN method

The lack of field data in burned catchments and related research to verify the effect on CN hampers post-fire runoff modeling with curve numbers. There is little research adequate to determine best-fit runoff curve numbers for unburned mountain and forested watersheds. One study of ten Appalachian forested watersheds, however, found that measured CNs varied significantly from published suggested values (Tedela, et al. 2012). The study also found very wide confidence limits for the measured values. One watershed, with a measured mean CN of 57, had 95% confidence interval of 32 to 83. Other studies also found inability to achieve a stable CN value (Hawkins 1993, and Springer and Hawkins 2005).

Hydrologists modeling forested watersheds should understand the difference between two major runoff-generating processes and their likelihood during storms of different magnitudes pre-fire versus post-fire. Forested watersheds in unburned conditions may tend toward saturation-excess overland flow, with runoff generated from relatively small fractions of the subareas, where rainfall depths exceed the soil capacity to retain water. Newly burned watersheds, however, may tend toward more significant infiltration-excess (also called Hortonian) overland flow, with surface runoff due to rainfall intensities exceeding soil infiltration rate. See figure 9.

Figure 9. Runoff generating processes on a hillslope terminating at a watercourse (Garen and Moore 2005)
Time of concentration

Watershed time of concentration $T_c$ is defined as the time required for runoff from the most hydraulically remote point in the watershed to its outlet. In hydrograph analysis, $T_c$ is considered a representation of the time from the end of excess rainfall to the point of inflection on the receding limb. Watershed lag time is defined as the time from the center of excess rainfall to the hydrograph peak. Both lag and $T_c$ are shown on the dimensionless unit hydrograph schematic, Figure 16. These definitions and methods of computation are discussed in NRCS NEH Part 630, Hydrology, Chapter 15, Time of Concentration, USDA-NRCS (2010).

The estimation of $T_c$ is often accomplished using either the Watershed Lag Method or the Velocity Method.

Watershed lag method

Time of concentration can be estimated using the following equation, called the Watershed Lag Method.

$$T_c = \frac{l^{0.8} (\frac{1000}{CN} - 9)^{0.7}}{1140Y^{0.5}}$$  \hspace{1cm} \text{(eq. 1)}

where:

- $T_c =$ time of concentration (hr)
- $l =$ flow length (ft)
- $CN =$ curve number (dimensionless)
- $Y =$ average land slope (percent)

Velocity method

Another way to estimate $T_c$ described in NEH 630 Chapter 15 (USDA-NRCS, 2010) is the velocity method. This method equates $T_c$ to the sum of estimated flow times for three types of flow from the hydraulically most distant point in the watershed, namely, sheet flow, shallow concentrated flow, and channel flow.

The following equation for sheet flow travel time, provided in NEH 630 Chapter 15, is a derivative of the kinematic wave equation:
\[ T_{\text{sheet}} = \frac{0.007 \ (nb)^{0.8}}{P^{0.5} S^{0.4}} \]  

(eq. 2)

where:

\( T_{\text{sheet}} \) = travel time (hr)

\( n \) = Manning’s roughness coefficient for overland flow, obtained from Table 10

\( l \) = sheet flow length (ft < 100)

\( P \) = 2-year, 24-hour rainfall (in)

\( S \) = land slope (ft/ft)

Table 10. Manning’s roughness coefficients for sheet flow (depth generally ≤ 0.1 ft)

<table>
<thead>
<tr>
<th>Surface description</th>
<th>Mannings n value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth (concrete, asphalt, gravel, or bare soil)</td>
<td>0.011</td>
</tr>
<tr>
<td>Fallow fields (no residue)</td>
<td>0.05</td>
</tr>
<tr>
<td>Cultivated soil, with residue &lt;= 20%</td>
<td>0.06</td>
</tr>
<tr>
<td>Cultivated soil, with residue &gt; 20%</td>
<td>0.17</td>
</tr>
<tr>
<td>Short-grass prairie</td>
<td>0.15</td>
</tr>
<tr>
<td>Dense grasses</td>
<td>0.24</td>
</tr>
<tr>
<td>Bermuda grass</td>
<td>0.41</td>
</tr>
<tr>
<td>Natural rangeland</td>
<td>0.13</td>
</tr>
<tr>
<td>Woods with light underbrush</td>
<td>0.40</td>
</tr>
<tr>
<td>Woods with dense underbrush</td>
<td>0.80</td>
</tr>
</tbody>
</table>

For the shallow, concentrated flow and channel flow segments, the following equations may be used. For shallow concentrated flow, velocity may be estimated using table 11. Channel velocity may be estimated with Manning’s equation (equation 4).

\[ T_{\text{shallow}} = \frac{I_{\text{shallow}}}{3600V_{\text{shallow}}} \quad T_{\text{channel}} = \frac{I_{\text{channel}}}{3600V_{\text{channel}}} \]  

(eq. 3)
where:

\( T_{\text{shallow}} \) = travel time, shallow concentrated flow (hr)

\( T_{\text{channel}} \) = travel time, channel flow (hr)

\( l_{\text{shallow}} \) = flow length, shallow concentrated flow (ft, generally less than 1000)

\( l_{\text{channel}} \) = flow length, channel flow (ft)

\( V_{\text{shallow}} \) = flow velocity, shallow concentrated flow (ft/sec)

\( V_{\text{channel}} \) = flow velocity, channel flow (ft/sec)

### Table 11. Shallow-concentrated flow velocity equations, where \( S \) = flow slope in ft/ft

<table>
<thead>
<tr>
<th>Flow type</th>
<th>Manning's ( n ) value</th>
<th>Velocity equation (ft/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement and small upland gullies</td>
<td>0.025</td>
<td>( V_{\text{shallow}} = 20.328 \sqrt{S} )</td>
</tr>
<tr>
<td>Grassed waterways</td>
<td>0.050</td>
<td>( V_{\text{shallow}} = 16.135 \sqrt{S} )</td>
</tr>
<tr>
<td>Nearly bare/untilled or alluvial fan flow</td>
<td>0.051</td>
<td>( V_{\text{shallow}} = 9.965 \sqrt{S} )</td>
</tr>
<tr>
<td>Cultivated straight row crops</td>
<td>0.058</td>
<td>( V_{\text{shallow}} = 8.762 \sqrt{S} )</td>
</tr>
<tr>
<td>Short-grass pasture</td>
<td>0.073</td>
<td>( V_{\text{shallow}} = 6.962 \sqrt{S} )</td>
</tr>
<tr>
<td>Minimum tillage cultivation, contoured or strip-cropped, or woodlands</td>
<td>0.101</td>
<td>( V_{\text{shallow}} = 5.032 \sqrt{S} )</td>
</tr>
<tr>
<td>Forest with heavy ground litter or hay meadows</td>
<td>0.202</td>
<td>( V_{\text{shallow}} = 2.516 \sqrt{S} )</td>
</tr>
</tbody>
</table>

\[
V_{\text{channel}} = \frac{1.486R^{2/3}S^{1/2}}{n} \quad \text{(eq. 4)}
\]

where:

\( V_{\text{channel}} \) = average cross-sectional flow velocity (ft/sec)

\( R \) = hydraulic radius (ft) = \( A/P_w \), where:

\( A \) = cross-sectional flow area, ft²

\( P_w \) = wetted perimeter, ft

\( S \) = flow slope (ft/ft)

\( n \) = Manning’s \( n \) value for channel flow
Adjustment of runoff flow time for wildfire effects

For the Watershed Lag Method, post-wildfire effects are entirely accounted for by adjusting the CN. See the section “Adjustment of curve number for wildfire effects.”

For the sheet flow portion of the Velocity Method, post-wildfire effects are entirely accounted for using Manning’s roughness coefficient. The analyst must decide whether and how much to reduce the n-value, based on reduction of vegetation caused by the fire. Using table 10, for example, a pre-fire condition might justify an n-value of 0.13 or 0.15, associated with natural range or short-grass prairie, reduced to a post-fire n-value of 0.05 or 0.011, associated with fallow ground or smooth surface, (caused by total burning of vegetation).

Hydrologists should also keep in mind that Manning’s roughness coefficients are of a different scale between overland flow and channel flow, due to the phenomenon of relative roughness, which is a measure of flow depth (or hydraulic radius) over surface roughness height. Given a homogeneous surface, the Manning’s roughness value will not necessarily be the same at all depths. For very shallow flow, at or near the boundary roughness height, Manning’s n-value will be larger. At depths much greater than roughness height, Manning’s n-value will tend to settle to a single value (for a homogeneous surface).

Overland flow generally has a larger relative roughness than channel flow. The effects of wildfire tend to lower both relative roughness and Manning’s n-value for overland flow, while raising them for collector channels. Early post-fire overland flow roughness values may be set to that of bare soil. Moody and Kinner (2006) suggest that wildfire basically results in overland flow Manning’s roughness values near that of bare soil and that minor variation from this value (0.011) has much less effect on model results than changes in effective rainfall. In addition, the effect of hydrophobicity can be accounted for by lower overland flow roughness values, near those of rough concrete. Canfield, et al. 2005 measured the runoff from a single hillslope with varying roughness conditions and found the roughness effect significant (figure 10).
Figure 10. Hydrographs from the same hillslope, with different surface conditions (Canfield, et al. 2005).

Channels clogged with post-fire debris or sediment have higher Manning’s roughness values than their pre-fire condition. The modeler should consider that, immediately post-fire, channels have elevated roughness values due to transport of significant newly available sediment and debris. With time, these channel roughness values change, although return to pre-fire roughness may take many years. In addition, for several years after the fire, smaller channels, such as collectors, tend to a more pronounced effect of relative roughness. Bed material such as cobbles and debris result in Manning’s $n$ values that decrease as flow depth increases. Riparian vegetation is often extensive in the bed of intermittently flowing channels, and provides additional flow resistance for the first seasonal flood.

Research has shown that pre-fire steep mountain streams have significantly higher roughness values than lower elevation streams, with Manning’s $n$ values often ranging from 0.1 to 0.2 (Yochum et al. 2012). These higher values are due to the presence of large cobbles and boulders, relative to stream cross-section size, as well as step-pools, instream wood, and extreme variability along the longitudinal profile. A single large boulder can sometimes so restrict flow area that significantly greater out of bank flow occurs only for a short section.

References for selection of roughness values for high gradient streams include both photographic guidance (Barnes 1967, Aldridge and Garrett 1973, Hicks and Mason 1998, Yochum and

Hydrologic modeling of conditions both pre- and post-fire may benefit from a more extensive examination of sub-basin drainage by development of time-area histograms. These are derived using GIS, and can verify whether the estimated longest path in a partially burned watershed is truly the longest, timewise, rather than lengthwise. The time-area histogram also helps determine hydrograph peaking factors for the use of unit hydrograph transformations. (See the Unit Hydrographs section.)

**Infiltration parameters**

Physically-based infiltration methods, such as GA, do not attempt to index overall watershed conditions, but rather assume that physical processes at a given point on the landscape may be applied at a wider spatial scale. The GA method is a simplification of infiltration equations that incorporate soil characteristics, such as hydraulic conductivity, and physical aspects such as pressure of surface water and matric suction of the soil (due to capillary action). The GA method represents infiltration as a depth of wetted soil, with moisture gradually moving downward in the soil column as a front, and that this movement can be estimated using soil porosity, soil hydraulic conductivity, initial soil water content, and the soil matric suction at the wetted front. Figure 11 shows the Green-Ampt conception of the soil column.

**Figure 11. Green-Ampt infiltration into the soil column**

![Green-Ampt infiltration into the soil column diagram](image-url)
The GA method is a simplification of Richard’s equation (USCOE-HEC, 2013) for infiltration that has a limited number of parameters that can be reasonably estimated using soils data. As discussed in the HEC-HMS User Manual (USCOE-HEC, 2013) GA infiltration is estimated using equation 5, with parameters correlated with soil texture (Table 13).

\[
f_i = K \left[ \frac{1 + (\phi - \theta_i)S_f}{F_t} \right]  \tag{eq. 5}
\]

where:

- \( f_i \) = loss during time period, \( t \)
- \( K \) = saturated hydraulic conductivity
- \( \phi \) = soil porosity (volume air/volume soil)
- \( \theta_i \) = initial soil water content (volume water/volume soil)
- \( S_f \) = wetting front suction
- \( F_t \) = cumulative loss at time \( t \)

The remaining parameter from equation 5 is initial soil moisture content, which ranges between zero (a completely dry soil) and the effective porosity. The user estimates this value using an antecedent soil moisture index and values from table 12 for field capacity and wilting point.

<table>
<thead>
<tr>
<th>texture</th>
<th>horizon</th>
<th>θ_{effective}</th>
<th>K_s</th>
<th>S_f</th>
<th>θ_{fieldCap}</th>
<th>θ_{wiltingPt}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(cm$^3$/cm$^3$)</td>
<td>(cm/hr)</td>
<td>(cm)</td>
<td>(cm$^3$/cm$^3$)</td>
<td>(cm$^3$/cm$^3$)</td>
</tr>
<tr>
<td>sand</td>
<td>combined</td>
<td>0.417</td>
<td>23.56</td>
<td>4.95</td>
<td>0.13</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.431</td>
<td>--</td>
<td>5.34</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.421</td>
<td>--</td>
<td>6.38</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.408</td>
<td>--</td>
<td>2.07</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>loamy sand</td>
<td>combined</td>
<td>0.401</td>
<td>5.98</td>
<td>6.13</td>
<td>0.15</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.424</td>
<td>--</td>
<td>6.01</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.412</td>
<td>--</td>
<td>4.21</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.385</td>
<td>--</td>
<td>5.16</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>sandy loam</td>
<td>combined</td>
<td>0.412</td>
<td>2.18</td>
<td>11.01</td>
<td>0.20</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.469</td>
<td>--</td>
<td>15.24</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.428</td>
<td>--</td>
<td>8.89</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.389</td>
<td>--</td>
<td>6.79</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>loam</td>
<td>combined</td>
<td>0.434</td>
<td>0.68</td>
<td>8.89</td>
<td>0.26</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.476</td>
<td>--</td>
<td>10.01</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.489</td>
<td>--</td>
<td>6.40</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.382</td>
<td>--</td>
<td>9.27</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>silt loam</td>
<td>combined</td>
<td>0.486</td>
<td>1.30</td>
<td>16.68</td>
<td>0.29</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.514</td>
<td>--</td>
<td>10.91</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.515</td>
<td>--</td>
<td>7.21</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.460</td>
<td>--</td>
<td>12.62</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>sandy clay loam</td>
<td>combined</td>
<td>0.330</td>
<td>0.30</td>
<td>21.85</td>
<td>0.26</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.330</td>
<td>--</td>
<td>26.10</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.332</td>
<td>--</td>
<td>23.90</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>clay</td>
<td>combined</td>
<td>0.309</td>
<td>0.20</td>
<td>20.88</td>
<td>0.33</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.430</td>
<td>--</td>
<td>27.00</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.397</td>
<td>--</td>
<td>18.52</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.400</td>
<td>--</td>
<td>15.21</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>silty clay loam</td>
<td>combined</td>
<td>0.432</td>
<td>0.20</td>
<td>27.30</td>
<td>0.37</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.477</td>
<td>--</td>
<td>13.97</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.441</td>
<td>--</td>
<td>18.56</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.451</td>
<td>--</td>
<td>21.54</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>sandy clay</td>
<td>combined</td>
<td>0.321</td>
<td>0.12</td>
<td>23.90</td>
<td>0.35</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.335</td>
<td>--</td>
<td>36.74</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>silty clay</td>
<td>0.423</td>
<td>0.10</td>
<td>29.22</td>
<td>0.42</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.424</td>
<td>--</td>
<td>30.66</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.416</td>
<td>--</td>
<td>45.65</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>clay</td>
<td>combined</td>
<td>0.385</td>
<td>0.06</td>
<td>31.63</td>
<td>0.48</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>B</td>
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<td>--</td>
<td>27.72</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.419</td>
<td>--</td>
<td>54.65</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
Adjustment of infiltration parameters for wildfire effects

When wildfire results in hydrophobic soil, the spatial extent is generally not over the entire drainage area. The extent to which the hydrophobicity has reduced infiltration also varies from place to place. Along with soil burn severity mapping, field investigation may give the hydrologist considerable insight as to the extent of infiltration reduction caused by hydrophobicity. However, since it is impossible to visit and test every square foot of ground, the hydrologist must estimate the widespread effect of hydrophobicity, and the rate that infiltration returns to normal as water repellency breaks down over time.

Two modeling options are available to account for hydrophobicity. The hydraulic conductivity may be reduced (GA method) or the percentage of impervious area may be increased. Canfield, et al. (2005), in their field studies of post-wildfire conditions, examined of the effect on saturated hydraulic conductivity. The increase over time of $K_{sat}$ (Figure 12) may be an indication of the breakdown of hydrophobicity and return of vegetation.

Figure 12. Optimal hillslope hydraulic conductivity, Cerro Grande NM fire (Canfield, et al. 2005)

In the HEC-HMS model, both options are available in the same interface, as shown in Figure 13.
Figure 13. HEC-HMS Green and Ampt input interface (USCOE-HEC 2013)

Unit hydrographs

The process of converting a runoff volume to a hydrograph shape is called transformation.

Several of the computer models in table 2 perform the transformation of spatially distributed runoff to an outlet using some variation of unit hydrograph (UH) theory. UH theory, advanced by L.K. Sherman in the 1930s, suggests that the runoff behavior of a watershed can be typed, given its physical characteristics, so that whenever a unit of direct runoff is produced in a watershed over a given duration, the hydrograph peak and shape at the outlet will be that of the unit hydrograph. If a rainfall event produces more than one unit of direct runoff, then the outlet hydrograph can be computed by multiplying each ordinate of the UH by the amount of runoff in that duration.

The following list details a number of assumptions inherent in the theory:

1. A given sub-basin has a different unit hydrograph for each possible duration of direct runoff.
2. The effective rainfall, defined as the rainfall that becomes direct runoff occurs uniformly over the sub-basin.
3. The shape and duration of the UH are independent of the effective rainfall intensity, which only effects the magnitude of flow in each UH time interval.
4. If a given rainfall event is divided into subsequent 30-minute intervals of effective rainfall, a 30-minute UH is applied to each interval of effective rainfall, to obtain an outflow for that time interval. The total outflow is the sum of the runoff hydrographs produced from each time interval. This is called the superposition principle. (See figure 14.)
5. The S curve, derived by summing a series of UHs of a given duration, each shifted by that duration, allows for the computation of runoff hydrographs from a single curve regardless of effective rainfall duration. (See figure 15.)

Figure 14. Runoff hydrographs by convolution and superposition, using 30-minute unit hydrograph.

Figure 15. S curve developed from 30-minute unit hydrograph.
NRCS dimensionless unit hydrograph

As documented in the NRCS National Engineering Handbook, Part 630, Hydrology, Chapter 16, Hydrographs (USDA-NRCS 2007), the NRCS approach is to use a standard dimensionless curvilinear hydrograph estimation (figure 16).

Figure 16. Dimensionless unit hydrograph, with time of concentration and lag (USDA-NRCS 2010).

\[
T_p = 0.667T_c \quad \text{(eq. 6)} \quad q_p = \frac{484AQ}{0.667T_c} \quad \text{(eq. 7)}
\]

Lag = Lag (hr)

\[\text{T}_c = \text{time of concentration (hr)}\]

\[\text{T}_p = \text{time to peak (hr)}\]

\[\text{T}_r = \text{time of recession (hr)}\]

\[\text{T}_b = \text{time base of triangular approximation (hr)}\]

\[\Delta D = \text{duration of excess rainfall (hr)}\]
t/Tp = ratio between time interval and time to peak (dimensionless)
q = discharge rate at time t (ft³/sec)
q_p = peak discharge rate at time Tp, (ft³/sec)
Q_a = runoff volume up to t (in)
A = watershed drainage area (mi²)
Q = total runoff volume (in)

The coefficient 484 in equation 7 is called the peak rate factor (PRF). The PRF is a ratio of the runoff under the rising limb of the unit hydrograph to the total time base. For the default PRF of 484, the rising side of the dimensionless unit hydrograph represents 37.5 percent of the total runoff volume.

The PRF may be estimated using drainage times (equation 8) or the proportion of the watershed drained before the peak (equation 9).

\[
PRF = \frac{1290.67 T_p}{(T_p + T_r)} \quad (eq. 8) \quad \text{or} \quad PRF = \frac{1290.67 A_{rise}}{A_{total}} \quad (eq. 9)
\]

where:
T_p = time to peak = 1 hour for the dimensionless unit hydrograph
T_r = time of recession
A_{rise} = basin area drained before peak
A_{total} = total basin drainage area

If the PRF of actual watersheds is determined using equation 8 or 9, the effect of overall basin slope becomes apparent. Flatter sloped ones with more storage effects tend to have lower PRFs, whereas steeper watersheds with fewer storage effects tend to have higher PRFs. For example, one Southwest Florida watershed had peak rate factors ranging from between 188 to 257 and another ranging from between 302 to 390 (Dendy 1987). On the other hand, Whitewater Creek in New Mexico (Case Study 4 in this Technical Note) was found to have PRFs over 700.
Note that the curvilinear UH of figure 16 was developed graphically and not an equation, but is a smooth curve fitted to the triangular estimation, achieving a natural hydrograph shape. If a different PRF is used, the curvilinear UH has a different shape. The reference Appendix 16B (USDA-NRCS 2007) provides tables of dimensionless UHs for several other peak rate factors.

The HEC-HMS model gives the user several options for runoff transformation, including the NRCS dimensionless UH. However, the user should bear in mind that HEC-HMS has encoded only the default NRCS dimensionless UH, PRF 484, with no option to use a different PRF.

**Adjustment of unit hydrograph for wildfire effects**

Generally, the hydrologist does not have the benefit data from studies and instrumentation from burned watersheds. The best option for estimation of timing is hydrologic judgement of changes in Manning’s roughness, changes in watershed storage, and changes in peak factor. Of these, general watershed storage effects may be the least important. Steeper mountainous watersheds do not tend to have significant wetland or ponding areas. If they do, then the effect of wildfire may be minimal, except that sedimentation would tend to somewhat reduce storage effects. The HEC-HMS user manual states, “…many studies have found that the storage coefficient, divided by the sum of the time of concentration and storage coefficient, is reasonably constant over a region.” However, the hydrologist working with a burned watershed will generally discover that no such regionally derived storage coefficients exist.

Changes in PRF may be more. Figure 17 shows the change in the 30-minute unit hydrograph at Baldy Creek (part of case study 4 of this Technical Note). The pre-fire PRF was already above 600, but the wildfire effect was to raise it further from 720 to 769. While the PRF can be estimated using times of concentration (equation 8) the availability of GIS layers may facilitate a better estimate using time-area histograms.
The HEC-HMS model offers several synthetic UH transformation methods, which, similarly to the NRCS dimensionless unit hydrograph, require some estimate of the magnitude and timing of the UH peak. For the Snyder UH, for example, HEC-HMS requires input of standard lag and peaking coefficient. For the Clark UH, the model requires input of time of concentration and storage coefficient. For the NRCS dimensionless UH, time of concentration is required, along with peak discharge computed from equation 7 (with the option to use a different peak factor than the standard).

Similarly, to the NRCS peak factor, the HEC-HMS Snyder synthetic unit hydrograph peaking constant has no small effect on the hydrograph. The HEC-HMS user manual (USACE 2013) states that “it ranges from 0.4 to 0.8, with lower values associated with steeprising hydrographs.” The user manual also states that the peaking constant “is estimated using the best judgment of the user, or possibly from locally-developed relationships to watershed physical features.”

While the NRCS hydrology program WinTR-20 facilitates the use of unit hydrographs up to 600 in peak factor (see Appendix 16B of USDA-NRCS 2007), the HEC-HMS model accepts input of user-derived unit hydrographs and S-curves. See Case Study 4.
Kinematic wave transformation

The models KINEROS2 and AGWA perform runoff transformation using kinematic wave transform. HEC-HMS also offers the kinematic wave transform as an option. The kinematic wave model refers to an approximation of the full unsteady flow routing equations of Saint Venant. A number of variations on these equations exist based on ignoring terms that, in certain applications, are considered negligible. (See Ponce and Simons 1977.) The kinematic wave model retains only one of four terms, and thus cannot accommodate diffusion of hydrograph peaks. For watershed hydrology applications, the kinematic wave transform is considered perfectly adequate. For further discussion of applicability, see the HEC-HMS Technical Reference Manual (USACE 2013).

The kinematic wave technique performs time-step calculations using differential equations for flow on various land surface types (overland, collector channels, and stream channels). Ponce (1991) suggested that the kinematic wave transform not be applied to sub-areas larger than one square mile because larger areas subject the differential equation solutions to artificial numerical effects. However, Woolhiser (1992) and Goodrich (1992) point out that difficulties with numerical stability do not render a model inapplicable to larger watersheds. Goodrich had, at the time, successfully modeled sub-basins up to 2.5 square miles. These discussions alert the user to be aware of numerical stability issues related to drainage area.

As discussed in the HEC-HMS Technical Reference Manual (USACE 2013), the equations used in the kinematic wave transform reduce to various approximations of Manning’s equation. The user, then, must provide estimations of $n$-value for the various surfaces (for which tables 10 and 11 may be referenced).

Adjustment of kinematic wave transformation parameters for wildfire effects

Whether direct runoff is transformed into an outlet hydrograph using unit hydrographs or kinematic wave equations, the hydrologist must assess the post-fire change in runoff travel time. The alteration of Mannings roughness coefficient is one consideration. Hydrophobicity may also speed up overland flow runoff. By limiting infiltration, water repellency deepens the flow on the
overland surface, while also tending to smooth it. Transport of loose soil above the hydrophobic layer, however, tends to raise roughness coefficient.

**Time-area histogram synthetic unit hydrograph development**

Unit hydrographs may be developed using streamflow and precipitation records, but gages for the pre-fire condition may not exist. Even if they do, the records will not facilitate development of a post-fire UH. Another option is to develop a synthetic unit hydrograph using estimated time-area histograms of runoff from the burned watersheds. The procedure can also be used to estimate peak rate factors or to develop dimensionless unit hydrographs for use in NRCS computer models.

To develop this terrain-based synthetic unit hydrograph, the user creates GIS raster information that ultimately allows the estimation of time-bands of raster cells, each band defining the area of a sub-basin that drains to the outlet in the same time interval. To obtain flow velocity, the user develops a Manning’s roughness raster, based on whether the cell contains overland, shallow-concentrated, or channel flow (figure 18). Other factors taken into account in the derivation of the roughness layer are soil types, vegetation types, and burn severity. Figure 19 shows a sub-basin raster of high burn severity locations. A flow slope raster can also be developed from the DEM layer (figure 20). Details on the creation of these raster layers with ArcMap (ESRI 2010) is provided with Case Study 4, Whitewater Creek, Gila Wilderness New Mexico.
Flow velocity relationships may be derived from equations 2, 3, and 4 above. Case Study 4 shows the use of similar flow velocity equations developed with reference to kinematic wave routing theory. Note that Manning’s roughness values vary significantly between overland flow and channel values, as shown in Tables 4 and 5. Further guidance on selection of post-wildfire
roughness coefficients is provided in the section on adjustment of runoff flow time for wildfire
effects.

In addition, the Manning’s equation for stream velocity estimation (equation 4) is dependent on
flow cross-sectional area (within the hydraulic radius term). One way to estimate this parameter
for any location in a watershed is to use hydraulic geometry relations of, say, bankfull flow area
as a function of drainage area. Case study 4 provides further details on these procedures. Since
a hydrograph runs through a range of flow depths and velocities, the use of bankfull parameters
may result in low velocity estimates if the runoff being modeled is a rare event. Recall, however,
that UH theory assumes the timing is identical no matter the intensity of effective rainfall.

From the velocity raster a drainage time raster can be created to determine the number of cells
that drain to the outlet in successive time bands of, say, five minutes. This velocity raster enables
the derivation of a time-area histogram of the watershed. Standard hydrology textbooks such as
Bedient, Huber, and Vieux (2012) show how a unit hydrograph can be easily created in a
spreadsheet, using a time-area histogram. Case Study 4 demonstrates the derivation of synthetic
unit hydrographs by this methodology.

**Sedimentation estimation**

Estimation of flow rates and velocities of clear streamflow (free of sediment and debris) benefits
from the fact that liquid water has very stable properties, such as density, viscosity,
incompressibility, and homogeneity. Predicting the movement of woody debris is difficult
because the size, shape, and availability of any given mass is random. With sediment, unit
weight is not highly variable, but the range of particle sizes and cohesiveness is extremely wide,
from micron sized cohesive clays, through the range of silts and sands, to enormous boulders.
The susceptibility of gravels and cobbles to the lift and drag forces of streamflow partly depend
on imbrication, or shielding, provided by other larger particles. Once in motion, the distance a
particle will travel depends on the energy of the stream current, which varies longitudinally with
drainage slope and transversely in a flow cross-section both horizontally and vertically.
Increased sediment transport by floodwater after watershed burn is common and often damaging, as shown in figure 21. The steepness of mountain streams provides energy to move sediment. Whenever some physical attribute of the stream lessens its ability to carry sediment, the stream responds by depositing whatever it can no longer transport. Figure 22 shows the result of a steep stream emerging from a canyon onto a plain. No longer confined by canyon walls, the stream may break out in various directions across an alluvial fan. In any of its chosen paths cross the alluvial fan, the sediment-transport capability is greatly reduced, compared to that in the canyon from which it emerged. Resulting deposition creates the fan itself, but the location of flood channels from any given event varies significantly over time.

Figure 21. 2010 post-wildfire debris flow from San Gabriel Mountains, CA

(photo by Robert Looper, USGS)
Rivers in unburned watersheds transport sediment via natural channel processes, depending on stream type. A number of stream classification systems exist, which evaluate river geomorphology based on channel size, shape, slope, and bed material. While the velocity and sediment transport capacity of a stream can vary significantly along its profile, it can also vary considerably within a single cross-section. The fastest flow is not usually on the surface, but at about three-quarters of the maximum depth and over the thalweg. (See figure 23.) Velocity is reduced toward the flow boundaries, especially in the presence of vegetation.

Velocity currents flow not only longitudinally, downstream, but also circulate sideways, in what are termed transverse or secondary currents. This phenomenon is responsible for the meandering behavior of rivers (figure 24), as downwelling tends to scour out pools on the outside of bends, while gravel and sand deposition forms bars on the inside of bends.
Wildfire destroys the erosion protection of vegetation, leaving watersheds vulnerable to not only elevated sediment-transport levels in otherwise clear streamflow, but also to debris flows and mudflows. Vegetation removal leaves overland flow slopes highly vulnerable to erosion; swales and gullies clog with sediment and debris; and hydrophobic soil at a depth of as little as two inches leaves the unconsolidated soil above it vulnerable to erosive flow. With wildfire, not only is sediment more vulnerable to erosion, but debris such as logs and partially burned branches are often washed into the streams. Sometimes the flowing water is so clogged with sediment, that the flowing mass is termed mudflow or debris flow. Having a higher density and viscosity than clear water flow, debris flows can be extremely dangerous.

Santi, et al. 2006 define debris-flow as “the rapid flow of saturated material consisting of more than 20% gravel and coarse material through a steep channel or over steep hillsides.” Because the volume of debris flows can often be correlated with property damage and other hazards, a number of studies have examined size classification (Jakob, 2005) and prediction (Santi and Morandi, 2012; Prochaska, et al., 2008). See table 13. As relates to post-wildfire recovery in the Western US, Santi and Morandi (2012) state: “...there is a clear progression in decreasing volume of debris flows as basins recover from the wildfire: it takes approximately 1 year, or at a...
few locations, as much as 3 years, for debris production to return to pre-fire rates.” Note that accelerated sediment transport rates, as opposed to debris-flows, may persist much longer.

Table 13. Size classification and potential consequences of debris flows (Santi and Morandi, 2012)

<table>
<thead>
<tr>
<th>Size class</th>
<th>Volume $(10^3 \text{ m}^3)$</th>
<th>Potential consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$&lt; 0.1$</td>
<td>Localized damage, known to have killed foresters in small gullies, damage small buildings</td>
</tr>
<tr>
<td>2</td>
<td>0.1 - 1</td>
<td>Could bury cars, destroy small wooden buildings, break trees, block culverts, derail trains</td>
</tr>
<tr>
<td>3</td>
<td>1 - 10</td>
<td>Could destroy larger buildings, damage concrete bridge piers, damage highways or pipelines</td>
</tr>
<tr>
<td>4</td>
<td>10 - 100</td>
<td>Could block creeks, destroy parts of villages, destroy bridges, damage infrastructure corridors</td>
</tr>
<tr>
<td>5</td>
<td>100 - 1000</td>
<td>Could destroy larger urban areas, dam up creeks and small rivers</td>
</tr>
<tr>
<td>6 - 10</td>
<td>$&gt; 5000$</td>
<td>Generally restricted to volcanic events, capable of destroying entire cities, damming large rivers</td>
</tr>
</tbody>
</table>

Another finding from Santi, et al. (2006) is that “the majority of material in post-fire debris flows is eroded from the channels—only a small percentage of the total volume is contributed from hillslope rilling and sheetwash.” Again, the analyst must distinguish between the much more sediment-bulked debris flow events and rainfall-runoff events with elevated sediment transport. The latter may well originate on hillslopes subjected to vegetation removal and hydrophobic soils associated with wildfire.

Concerning sediment, the design or evaluation of engineering structures in wildfire-impacted areas may take a number of approaches. Hydrographs modeled as clear flow are often increased by considering the bulking effect of entrained sediment. A specific sediment-transport computer model may be used to estimate locations and magnitudes of sediment aggradation or degradation. Debris flow or mud flow may be estimated or modeled. HEC-RAS has sediment transport modeling capability, but the available empirical sediment transport equations come with
significant uncertainties and generally require calibration. Considerable field measurements of sediment supply and channel geometry are required.

Although the two-dimensional flood-routing model FLO-2D (O’Brien, et al. 1993) is used to model debris flow (Elliott, et al. 2005) rapid post-wildfire assessments generally preclude its use due to extensive input requirements and model complexity. For estimation of debris flow impacts, the analyst should consider storm event frequency, source material availability, and location of concern relative to location of source material. Modeling debris flow generally requires a less frequent (higher rainfall peak) storm, such as a ten-year event, although immediately after the wildfire a 2-year event may suffice. Availability of source material can be assessed by field observations of channel conditions, primarily, but also steep hillslope conditions. The further the location of concern from the source material the less likely the effect of debris flow (as differentiated from sediment-bulked flow). Cannon, et al. (2003), for example, found that relative degree of debris flow hazard could be assessed by examining the abundance of colluvium available in stream channels, the degree of channel confinement, and channel gradient. The study concluded that further research is needed.

Models for estimating sediment transport

For estimating elevated sediment transport, as opposed to debris-flow, three models are discussed GeoWEPP, AGWA, and RUSLE2.

GeoWEPP is a geo-spatial interface for the Water Erosion Prediction Project (WEPP) model (Flanagan, et al. 2001). GeoWEPP for ArcGIS is available from: https://lesami.geog.buffalo.edu/projects/active/geowepp/. The WEPP model itself is available c: http://www.ars.usda.gov/Research/docs.htm?docid=10621. WEPP is a continuous simulation process-based model, applicable to hillslope erosion processes (sheet and rill erosion). It uses stochastically derived climate data from the CLIGEN model (Zhang and Garbrecht, 2003). WEPP has two distinct disadvantages. First, WEPP is designed for continuous simulation. As a result, it is less applicable to storm events, which tend to drive post-fire runoff and sediment transport. Second, existing climate generator models such as CLIGEN and GEM6 are not
designed to produce less frequent storm event peaks (Theurer, et al. 2010) but rather the day-to-day kinds of rainfall events evaluated by continuous simulation models.

KINEROS2 (A Kinematic Runoff and Erosion Model, Canfield, Goodrich, and Burns 2005) is an event oriented, physically based model describing the processes of interception, infiltration, surface runoff and erosion from small agricultural watersheds. KINEROS2 may be run independently, or as an option within the Automated Geospatial Watershed Assessment (AGWA) modeling tool (Goodrich, et al. 2005). AGWA is a GIS-based hydrologic modeling tool using standardized datasets to develop input parameter files for KINEROS2 and SWAT. The KINEROS model is applicable to storm events. and AGWA has had recent improvements for post-wildfire use (Canfield and Goodrich, and Burns, 2005). The KINEROS2 model is available as a separate download from the USDA-Agricultural Research Service (ARS), Southwest Watershed Research Center (SWRC) at: [http://www.tucson.ars.ag.gov/kineros/](http://www.tucson.ars.ag.gov/kineros/). AGWA modeling tool and documentation are available from USDA-ARS-SWRC at: [http://www.tucson.ars.ag.gov/agwa/](http://www.tucson.ars.ag.gov/agwa/). See Case study 5 for an example of the implementation of AGWA.

Another model sometimes used for post-fire sedimentation estimation is RUSLE2. This planning-level erosion model, according to the ARS documentation (USDA-NRCS 2013d), is used to estimate rill and interrill erosion where mineral soil is exposed to the erosive forces of impacting raindrops, water falling from vegetation, and surface runoff produced by Hortonian overland flow. The document states that RUSLE2 is applicable to forestlands; however, the model is intended to estimate annual average erosion from the above sources rather than event-based erosion. In fact, long-term datasets of stochastically generated climate variables used in the model tend to represent day-to-day conditions rather than the rarer storm events such as that of a 100-year recurrence (Theurer et al. 2010). The simplicity of the model and its conduciveness to spatial estimation using GIS, make RUSLE2 a possible tool for evaluating sedimentation due to wildfire. See case study 3 of this technical note for example. Theobald et al. (2010) documents the GIS manipulations involved and Litschert et al. (2014) applies RUSLE2 and GIS to wildfire in the Southern Rockies Ecoregion.
Adjustments for modeling sediment transport from burned areas

Regardless of which estimation methods or models are applied, the modeler is advised to pay attention to burn severity. One study (Benavides-Solorio and MacDonald, 2001) in Colorado found relatively small differences in runoff rates as a function of burn severity, but a much higher correlation for sediment yield. That study stated, “...percent ground cover accounted for 81% of the observed variability in sediment yields” and “...large differences in sediment yields with burn severity should be attributed primarily to the differences in ground cover rather than the differences in runoff, water repellency, or antecedent soil moisture.” These results imply that watershed recovery and return of sediment yield to unburned rates should be a function of vegetation and ground cover, and the study indicates that full recovery may take from three to nine years.

Sediment bulking

The post-fire hydrographs produced by the models previously discussed do not account for the phenomenon of sediment bulking. As defined above, debris flow is considered that which entrains at least 20% gravel and coarse material. Elliott, et al. (2005) delineates hyperconcentrated flows as ranging from 20 to 47 percent sediment concentration and mudflows as having a greater than 47% sediment concentration.

A flood of rare recurrence interval, such as the 50-year event, occurring shortly after wildfire, may cause hyperconcentrated sediment flows or mudflows. One study (Cannon, et al. 2003) found significant post-wildfire debris flows occurring with storms as frequent as the two-year event. The study suggests that the generation of high sediment concentrated flows is possible by progressive sediment bulking over time. Another study (Giraud and McDonald, 2007) found that debris flows tend to result from channel incision rather than hillslope erosion, but agree with Cannon, et al. (2003) that smaller events, merely bulked rather than hyperconcentrated.

Post-wildfire flows that do not reach the 20% threshold nevertheless transport considerable sediment loads. This entrained sediment raises (or bulks) the overall flow rate and, at any particular location, raises the flood depth. For a hydrograph, the total bulked flow rate is the sum of the water discharge and the sediment discharge.
One way to account for sediment bulking in post-wildfire hydrograph analyses is to apply a bulking factor to the flood peak (O’Brien and Fullerton 1989, Elliott et al. 2005):

\[ BF = \frac{Q_w + Q_{sed}}{Q_s} = \frac{1}{1 - C_v} \]  
(eq. 10)

where \( C_v \) is the maximum sediment concentration by volume in percent.

As discussed in Elliott, et al. (2005), if the event contains a sediment concentration just under hyperconcentrated (20 percent) then the resulting bulking factor is 1.25:

\[ BF = \frac{1}{1 - 0.2} = 1.25 \]  
(eq. 11)

Sediment concentration varies during a storm and generally peaks before that of the water discharge. One way researchers estimate sediment discharge over time is to measure data and derive simple regression equations. For example, Moody and Martin (2001) found, for two recently burned Colorado watersheds,

\[ Q_{sed} = 4.4Q_w^{1.5} \]  
(eq. 12a)

\[ Q_{sed} = 23Q_w^{1.3} \]  
(eq. 12b)

where:

- \( Q_w \) = water flow (m³/s)
- \( Q_{sed} \) = sediment flow (kg/s)

The study reported statistical correlations of \( r^2=0.89 \) for equation 21a and \( r^2=0.96 \) for equation 21b.
Using a hypothetical storm hydrograph, with a peak of about 580 cfs in the second watershed, and translating both discharges into cfs, a bulk factor for the peak of 1.06 is derived (figure 25).

Figure 25. Hypothetical storm using equation 21b (all discharges converted to cfs).

For post-fire hydrologic analyses, if previous studies for the watershed of concern exist, then maximum sediment concentrations and bulk factors are better estimated. The bulk factor can be much higher than the hypothetical one from above. For example, LACDPW (2006) has compiled curves for debris production and bulk factors for the Los Angeles River, Santa Clara River, and Antelope Valley watersheds, with wide variation from place to place. Figure 26 shows the data for one of their lower debris production areas with bulking factors in the range of 1.5.

A factsheet from the USGS (Pierson, 2005) provides guidance on field investigations to distinguish between debris flows and normal flow sediment deposits. The reference suggests that normal suspended sediment concentrations are five to ten percent by volume, but that even with hyperconcentrated flow (volumes between 20 and 60 percent) the flow behavior is
controlled by water, whereas mud flows (even higher sediment concentrations) have behavior controlled by the entrained sediment.

Among the field indicators listed are, for water flow deposits, most grains are rounded, beds are stratified with good sorting both horizontally and vertically, with loose consistency when dry. Debris flow deposits, on the other hand, tend to be angular sand and fine gravel (indicating a hillslope source), non-stratified, and extremely poorly sorted, with coherent consistency rather than loose.

Note that when using post-wildfire streamflow records to calibrate modeled hydrographs these measurements are already bulked.

Figure 26. Sediment production and bulking factors for debris production area 7 (LACDPW 2006)
The ideal watershed for which to model the rainfall-runoff process is one with an extensive spatially-distributed data collection network. If instrumented, the instrumentation would produce an historic record of rainfall amounts in time and space, soil moisture levels, baseflow levels, and sedimentation rates. However, even a spatially dense network of instruments; say every half mile, leaves considerable uncertainty, since conditions at points other than the station locations would have to be assumed. As discussed in Beven (2001), for example, the use of distributed hydrologic models for prediction of future states suffers a number of limitations, namely problems of non-linearity, scale, uniqueness, equifinality, and uncertainty. Other researchers suggest, more generally, that verification and validation of numerical models of natural systems is impossible (Oreskes, Shrader-Frechette, and Belitz, 1994).

In the real world, the number of data collection stations in a watershed never comes close to true spatial adequacy. The watershed model is inherently an open system, subject to equifinality—that a given end state (say, a certain magnitude storm runoff peak at the outlet) can be caused by many potential combinations of circumstances (say, storms of similar intensity but different areal extent, centered over different points in the basin). Even if such an extensive data station network existed, the radical and sudden change wrought by wildfire renders the historical dataset inapplicable.

Although calibration and validation are be possible with post wildfire hydrologic modeling, the hydrologist should at least report sources of known uncertainty. If hydrophobicity exists, the hydrologist should report the evidence of spatial extent or persistence of significant water repellent layering, and by what means they accounted for it in the model. If data stations are installed after a fire, this recorded evidence of post-fire events should be used to show the reasonability of the hydrologic model. Such data does not generally support claims of calibration or validation, since scarcity of stations leaves open the possibility of more than one spatial layout of storms having the same impact at the stations. However, one or more hypothetical storm distributions, which reproduce the measured data could be modeled, to show whether the model responds reasonably. Case study 4 demonstrates this approach.
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Case Study 1: High Park Fire Colorado

Background

The High Park Fire, in the foothills west of Fort Collins, Colorado (figures CS1-1 and CS1-2), burned within an area of 88,600 acres between June 9th and July 1st, 2012. The fire burned primarily in steep, forested terrain, with average slopes ranging from 14 to 49 percent and elevations ranging from 5,300 to 10,200 feet. It was a fast burning fire, with about 37,000 acres burned in the first three days. It was also a “dirty burn,” with a substantial amount of unburned area (21,100 acres, 23%) distributed as a patchy mosaic throughout the fire extent. Of the impacted area, 9,800 acres burned at high soil burn severity (11%), 36,300 acres burned at moderate severity (40%), and 21,300 acres burned at low severity (23%). Just as wildfire containment was achieved, the summer monsoon season started. Increased flooding and debris flows were observed in streams draining numerous portions of the fire, with local residents noting that some of these floods were the most severe since the Big Thomson Flood of 1976. Ash mobilized due to the enhanced runoff flowed into the Cache la Poudre River, a primary source of drinking and irrigation water for the northern Colorado Front Range. Since part of the Horsetooth Reservoir watershed was also burned, water supply storage in this reservoir was threatened with contamination. As expected, the most severe flooding was in catchments with the highest percentages of high soil burn severity. In these areas the vegetation cover and soil litter were consumed, leaving surfaces dominated by a bare mineral condition, reduced surface roughness, and possible hydrophobicity. These high severity burn areas also likely had substantial destruction of seed banks, forcing longer vegetative recovery rates and resulting in longer periods of enhanced flooding. Increased flood peaks, flow volumes, sediment transport, nutrient enrichment, and stream channel destabilization are expected for a number of years in many streams draining the fire area, threatening life, property, infrastructure, and water quality.

An initial hydrologic analysis was provided by a Burned Area Emergency Response (BAER) report for the large catchments draining this fire. Local and state officials, however, concerned with increased flood hazard potential and noting the preliminary
nature of the BAER report, requested assistance from the Natural Resources Conservation Service (NRCS). Of particular interest were flow frequency estimates for post fire conditions. This case study provides an overview of the analyses performed to provide these estimates.

Figure CS1-1. Sunset through smoke plumes, from Fort Collins on Day 1 of the High Park Fire.

Figure CS1-2. Aerial extent and soil burn severity of the High Park Fire, based on a BARC image.
Methods

A rainfall-runoff model was developed to simulate the expected runoff response for both pre- and post-fire conditions, for the 2-year, 10-, 25-, 50-, and 100-year 1-hour rainfall events. Hydrologic modeling was performed using the program HEC-HMS (version 3.5), developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center. The NRCS curve number (CN) technique for estimating direct runoff from rain events was used in this analysis. As quality control, peak flows estimated using U.S. Geological Survey (USGS) regression equations (Capesius and Stephens 2009), embedded in USGS Streamstats, were compared to the CN runoff results for unburned conditions.

The BAER assessment led by the U.S. Forest Service (USFS) provided initial peak flow estimates used for post-fire flood mitigation planning activities (BAER 2012). This hydrologic analysis used the WILDCAT model (Hawkins and Greenberg 1990), which also relies on the CN method. The analysis was constrained to a deadline of one week after fire containment, per USFS requirements. Hence, the modeling was relatively coarse and neglected relevant hydrologic mechanisms such as variability in lag time between pre- and post-fire conditions, vegetation type, differences in runoff between moderate and high soil burn severity areas, as well as flood attenuation in larger catchments. Additionally, the BAER modeling used relatively large catchments in some areas, which, given the large burn area of the High Park Fire, added to the courseness of the BAER results. For example, the modeling was less able to account for flood wave attenuation.

NRCS initiated a more detailed hydrologic analysis of streams draining the High Park Fire area, likely enhancing the accuracy of predictions for flood mitigation efforts. Initial results of this modeling were obtained for key catchments just before the monsoon season started in early July, which provide preliminary flooding estimates to local and state officials. These results were refined throughout the summer and the analysis expanded to provide flood estimates for most streams draining the fire extent (Yochum 2012a, Yochum 2012b). While the results provide reasonable estimates of the increased flooding expected from the burned watershed, further monitoring and research underway in some areas may enable future modeling refinements. These could employ, for example, more
mechanistic rainfall-runoff simulations than the CN method. Hence, post-wildfire flood
simulation modeling, especially large events involving substantial private land
ownership, more dense settlement, and higher risks to life, property, and infrastructure,
should be viewed as an iterative process with models of varying complexity developed
over time to satisfy specific needs.

The NRCS model estimated runoff using the CN procedure documented in Estimation of
Direct Runoff from Storm Rainfall (USDA-NRCS 2004b). The CN is a simple
catchment-scale method that gives estimates of flood peaks and volumes at watershed
outlets, with more accurate results expected for larger, higher-intensity rain events. The
method is also discussed in Hydrologic Soil Cover Complexes (USDA-NRCS 2004b),
Rallison (1980), and numerous other publications. However, little quantitative
information has been published of the database on which it was developed (Maidment
1992) and many of the curves used in the development have been lost (Woodward 2005).
In general, the method was developed for rural watersheds in various parts of the United
States, within 24 states, was developed for single storms, not continuous or partial storm
simulation, and was not intended to recreate a specific response from an actual storm
(Rallison, 1980).

Figure CS1-3. Modeled catchments and stream channels, with flow computation points with soil
burn severity as background.
Catchments and modeled stream channels implemented in the analyses are presented in figure CS1-3. Overall, 105 delineated catchments were utilized in the modeling. The average catchment area was 1.6 square miles, with the individual sizes determined by required computation points (to provide needed flood predictions at roadway crossing, homes at risk, etc.), catchment morphologic characteristics, and the need for simulating flood routing and attenuation in the modeled stream channels.

Runoff Curve Number (CN) Estimation

Curve numbers were assigned to the modeled catchments according to hydrologic soil group, vegetative type, soil burn severity, and ground cover condition (percent cover). The average catchment CN was computed using an aerial averaging methodology in GIS, with more than 51,000 polygons computed for the entire modeled extent.

Soil burn severity (figure CS1-3) is the principle driver for increasing flow in runoff predictions. For this modeling, soil burn severity was measured using the Burned Area Reflectance Classification (BARC) process from satellite data collected on 7/20/2012, by researchers at Colorado State University (CSU). BARC uses reflectance recorded in satellite images to quantify soil burn severity. For defining soil burn severity, BARC images have the advantage of being comprehensive and relatively-rapidly developable. However, comparison with field-collected data has indicated that this remotely-sensed product can be more indicative of post-fire vegetative condition than soil condition, especially in low to moderately burned areas (Hudak et al. 2004). Qualitative field assessment of the High Park Fire BARC image indicated a reasonable prediction of burn severity in high and moderate areas. The soil burn severity imagery depicted in figure CS1-3 was developed by the USGS Earth Resources Observation and Science Center (from the same 7/20 satellite data), rather than the CSU interpretation implemented in the hydrologic modeling. This BARC interpretation was not available at the time of the analysis, though the burn severity estimates are relatively comparable and substantial variations in flood peaks are not expected.
Hydrologic soil group (HSG) classification was selected using soils data published in the NRCS SSURGO (Soil Survey Geographic) database. Two soil surveys cover the fire extent: NRCS Larimer County survey (CO644), published in 1980; and USFS Arapahoe-Roosevelt survey (CO 645), published in 2001. The USFS survey covers the western 1/3 of the fire area.

Vegetation type, from SWReGAP (Southwest Regional Gap Analysis Project) land cover mapping, was included in the CN assignments used for the modeling. The dominant vegetation types within the fire boundary were lodgepole, mixed conifer, ponderosa, shrubs and grass.

The assigned CN values are provided in table CS1-1. Using a fair ground cover condition, NRCS recommended values (USDA-NRCS 2004a) were applied by hydrologic soil group for unburned conditions. The CN values for low, moderate and high severity burn areas, at the four hydrologic conductivity classifications, were estimated based on CN values developed from post-fire runoff measurements (Livingston et al. 2005), with additional guidance from Wright et al. (2005) and Goodrich et al. (2005).

Table CS1-1. CN assignments implemented in High Park Fire hydrologic modeling. (Highlighted columns indicate values extracted from USDA-NRCS 2004a.)

<table>
<thead>
<tr>
<th>Cover Description</th>
<th>A HSG Unburned</th>
<th>A HSG Low</th>
<th>A HSG Moderate</th>
<th>A HSG High</th>
<th>B HSG Unburned</th>
<th>B HSG Low</th>
<th>B HSG Moderate</th>
<th>B HSG High</th>
<th>C HSG Unburned</th>
<th>C HSG Low</th>
<th>C HSG Moderate</th>
<th>C HSG High</th>
<th>D HSG Unburned</th>
<th>D HSG Low</th>
<th>D HSG Moderate</th>
<th>D HSG High</th>
</tr>
</thead>
<tbody>
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<td>Herbaceous, Pasture, Alpine Meadow, Park</td>
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<td>55</td>
<td>67</td>
<td>77</td>
<td>61*</td>
<td>68</td>
<td>80</td>
<td>86</td>
<td>74*</td>
<td>81</td>
<td>88</td>
<td>89</td>
<td>82*</td>
<td>86</td>
<td>92*</td>
<td>95</td>
</tr>
<tr>
<td>Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush</td>
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<td>52*</td>
<td>65</td>
<td>77</td>
<td>48</td>
<td>55</td>
<td>65</td>
<td>86</td>
<td>57</td>
<td>70*</td>
<td>80*</td>
<td>89</td>
<td>63</td>
<td>70</td>
<td>80</td>
<td>92</td>
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<td>Ponderosa pine-juniper (grass understory)</td>
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<td>57*</td>
<td>65</td>
<td>77</td>
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<td>92</td>
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<td>Sagebrush (grass understory)</td>
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<td>54*</td>
<td>65</td>
<td>77</td>
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<td>60</td>
<td>75</td>
<td>86</td>
<td>63</td>
<td>70</td>
<td>80*</td>
<td>89</td>
<td>70</td>
<td>75</td>
<td>85</td>
<td>92</td>
</tr>
<tr>
<td>Lodgepole Pine Forest</td>
<td>49*</td>
<td>57*</td>
<td>65</td>
<td>77</td>
<td>60</td>
<td>65</td>
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<td>86</td>
<td>73</td>
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<td>92</td>
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<td>77</td>
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<td>98</td>
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<td>98</td>
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<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
</tbody>
</table>

* Updated value based on Black Forest and West Fork Complex Wildfires. Not as implemented in High Park analysis.
Rainfall
Since the High Park Fire area is most susceptible to flooding from relatively short
duration monsoonal rain events, a 1-hour storm duration was implemented. Rainfall
depths were extracted from NOAA Atlas 2, Volume 3 (Miller et al. 1973) for the 2-, 10-, 25-, 50- and 100-year rainfall events. The rainfall duration and distribution was identical
to that used in the BAER modeling (BAER 2012), and is provided in the project report (Yochum 2012b). For catchments with drainages areas ≥ 6 square miles, an areal
reduction factor was applied as detailed in Miller et al. (1973). Reduction varied from 0.95 to 0.78. When applied, this area reduction was implemented in all catchments; flow may be underpredicted in the smaller, upper catchments of such drainages.

Lag Time
Lag time \( L \) was computed using the watershed lag method (USDA-NRCS 2010). This equation is:
\[
L = \frac{l^{0.8}(S + 1)^{0.7}}{1900Y^{0.5}}
\]  
(eq. CS1-1)

where \( l \) is flow length (ft), \( Y \) is average watershed land slope (%), and \( S \) is maximum potential retention (in). \( S \) may be calculated from equation CS1-2:
\[
S = \frac{1000}{cn'} - 10
\]  
(eq. CS1-2)

where \( cn' \) is the retardance factor and is approximately equal to the \( CN \). This method allows the computation of differing lag times for pre- and post-fire simulations, reflecting the actual physical mechanism of more rapid flow response during post-fire conditions. The method was developed under a wide range of conditions, including steep, heavily forested watersheds (USDA-NRCS 2010). Note that equation CS1-1 is equivalent to the time of concentration equation in the Technical Note main body (equation 1) since lag is considered to be 0.6 of the time of concentration.
Flow Routing

A Muskingum-Cunge procedure was used to route flow from upper catchments to stream outlets, along the modeled stream reaches (figure CS1-3). This 1-dimensional method simulates flow attenuation but does not provide a numerical solution of the full unsteady flow routing equations, as provided in such computational models as HEC-RAS. Instead, in each reach flow routing was estimated using a single simplified cross section, channel slope, and Manning’s $n$ estimate. Photographic guidance (Yochum and Bledsoe 2010) was used to help select flow resistance coefficients, and these values were checked by inspecting the model solutions to verify that the selected Manning’s $n$ values resulted in subcritical or approximately critical flow velocity. Hence, it was assumed that bedform development prevents reach-average supercritical flow in these alluvial channels.

Sediment Bulking

A simple multiplication factor was applied to the post-fire flood predictions to account for sediment bulking in the debris flows. For burned catchments, this multiplication factor was assumed to be 1.25 if the (severe + moderate) soil burn severity aerial extent was greater than 50%, and 1.1 for catchments with between 10 and 50 % (severe + moderate) soil burn severity.

StreamStats

The regional USGS regression equations for peak flow prediction (Capesius and Stephens 2009), embedded in Streamstats, were used to assess the reasonableness of pre-fire peak flow predictions. The predictions use input of drainage area and the 6-hour, 100-year precipitation depth to provide expected runoff from rain events, reflecting the expectation that floods result from summer monsoons. The error bars associated with these predictions are substantial – typically about 140 percent.

These predictions are based on streamgage data and, hence, provide a level of ground truthing, but this method accounts for only drainage area and precipitation regime. Other physical characteristics and processes that are relevant in runoff processes, such as infiltration capacity, vegetative type, ground cover condition, watershed shape, and flow
Results and Discussion

Hydrologic modeling was performed to develop estimates of increased flood hazard and potential threats to life and property along streams draining the High Park Fire. For several key catchments, at locations of threats to residences, example hydrographs (figure CS1-4) show the expected response to a 10-year rainfall depth over each entire catchment. Substantially increased flow peaks and runoff volumes were estimated. The simplicity of a map presentation style (figure CS1-5) facilitated use by planners, designers, and emergency response officials. Results were provided at 96 computation points over the fire extent and also provided as attributes in ArcGIS shapefiles. In addition to simulated flood peaks, time-to-peak estimates were provided to give emergency response personnel estimates of the expected flood response times. For detailed results, refer to Appendix A of the project report (Yochum 2012b) and the accompanying poster (Yochum 2012a).

Substantially higher peak flows and flood volumes are predicted for post-fire conditions. In many catchments, post fire conditions were predicted to cause a 50- or 100-year flood (pre-fire recurrence) to result from a 10-year rain event on burned landscapes, similar to measured fire runoff responses (Conedera et al. 2003). If it is estimated that the fire impacts on runoff in each of these catchments will be substantial for at least 5 years, the risk of a 10-year rainfall event over each point in these catchments over those 5 years of destabilization is 41 percent, with resulting 50- to 100-year floods (pre-fire recurrence). If a ten year recovery period is assumed, the risk increases to 65 percent. However, the expected severity of flooding lowers with increasing catchment size, due to the small spatial extent of typical convective storms.

Due to their simplicity, peak flow enhancement ratios \( Q_{\text{post}} / Q_{\text{pre}} \) can be a preferred method for communicating flood enhancement predictions. Predicted ratios for the 25-
year rain event are provided (figure CS1-6). Peak flow enhancement ratios are higher for more frequent rain events (2- and 10-year storms) and lower for less frequent events (50- and 100-year storms), with this same pattern observed with field-collected data (Moody and Martin 2001). This method only provides meaningful results where the pre-fire peak flow is greater than zero for the rainfall event of interest.

Figure CS1-4. Example estimated pre- and post-fire hydrographs for the 10-year rain event.
DRAFT Technical Note  Hydrologic Analyses of Post-Wildfire Conditions  

Case Study 1: High Park Fire Colorado

Figure CS1-5. Example map with pre- and post-fire flood prediction estimates for the Poudre Park area.

Figure CS1-6. Estimated 25-year peak flow enhancement ratios for the High Park Fire.

Comparison with Regression Predictions

Table CS1-2 illustrates USGS regression modeling results (from Streamstats) compared to CN modeling results at a number of locations, for the 10- and 25-year events.

Considering the large expected prediction errors of the USGS regression equations in this...
area (typically 140%), the results are reasonably comparable. The greatest differences in
prediction are typically in the largest catchments. Differences in the results are likely due
to limited data available for selecting CN values for post-fire conditions, questionable CN
model appropriateness in forested watersheds, and possible inaccurate rainfall depths and
aerial reduction factors. Additionally, the regression technique does not account for
relevant hydrologic processes, such as variable soil infiltration capacity, vegetative type,
ground cover condition, and stream flow attenuation.

Table CS1-2. Comparison of CN modeling with USGS regression results from StreamStats.

<table>
<thead>
<tr>
<th>Point</th>
<th>Area (mi²)</th>
<th>10-yr flow (cfs)</th>
<th>25-yr flow (cfs)</th>
<th>10-yr flow (cfs)</th>
<th>25-yr flow (cfs)</th>
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<tbody>
<tr>
<td>MC-2</td>
<td>3.33</td>
<td>119</td>
<td>212</td>
<td>249</td>
<td>360</td>
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<tr>
<td>MC-5</td>
<td>6.61</td>
<td>272</td>
<td>335</td>
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<td>574</td>
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<tr>
<td>BC-8</td>
<td>23.2</td>
<td>44</td>
<td>407</td>
<td>119</td>
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<td>BC-13</td>
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<td>741</td>
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<tr>
<td>HlG-3</td>
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<td>248</td>
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<tr>
<td>HlG-5</td>
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<td>210</td>
<td>348</td>
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<tr>
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<td>23</td>
<td>96</td>
<td>60</td>
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<td>LC-4</td>
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<td>89</td>
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<td>RdC-5</td>
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Accuracy and Limitations

As with all hydrologic modeling, the results provided by these simulations are
approximate. Comparisons with flood peaks estimated using the USGS regression
equations (table 2) indicate that the pre-fire runoff simulations are more-or-less
reasonable overall, but that the modeling often provides estimates that may be inaccurate,
especially as catchment size increases. Post-fire runoff prediction using the CN technique
is hampered by the very little available field data to enable reliable selection of CN
values from measured rainfall and runoff in burned catchments. Additionally, the use of
dated rainfall depths and areal reduction factors (Miller et al. 1973) in orographic-forced
mountainous watersheds adds an additional layer of uncertainty to the estimates.

Additionally, greater infiltration is indicated by the USFS soil survey than the adjacent
NRCS survey, with infiltration commonly increasing by a step at the survey boundary
and a large area with HSG A indicated. In the most problematic areas zero runoff is predicted for pre-fire conditions in some catchments during the 10- and 25-year rain events. This problem may be due to shallow, permeable soils over bedrock dominating the USFS soil survey classification methodology, but the true reason for this inconsistency is unknown. As a result, the modeling may be underpredicting runoff and overestimating flood response ratios in catchments draining the Arapaho-Roosevelt soil survey area, especially for more frequent (shallower) rainfall events.

More fundamentally, the reliability of the CN method for predicting peak flow from forested, mountainous watersheds is questionable, due to doubtful appropriateness of the CN method and shifting streamflow generation processes between and pre- and post-fire conditions. This issue is discussed in the main body of this technical note under the section Limitations of the CN Method.

Despite these shortcomings, due to its relative simplicity and achievable data requirements for large scales, the CN method is a preferred tool for predicting flood responses of wildfire areas. The modeling performed for the High Park Fire has substantial value for identifying areas of greatest threat to life, property and infrastructure. Peak flow ratios provide an excellent tool for communicating expected increases in runoff with agencies, first responders, and the public. And peak flow and runoff volume estimates are still required for sizing infrastructure improvements. The unknown extent of uncertainty in the estimates needs to be effectively communicated to provide assurances that involved parties use the estimates with caution. Research and technical guidance is needed to develop and communicate more robust methods for flood prediction from wildfire-impacted landscapes.

**Conclusions**

Using the NRCS Curve Number method, peak flow predictions were made for streams draining the High Park Fire area, for both pre-fire and post-fire conditions. Watershed maps for each modeled catchment were developed, illustrating computation points, peak discharges, peak flow enhancement ratios, soil burn severity, and stream outlet
hydrographs. While many relevant hydrologic mechanisms were simulated, including rainfall depth and spatial extent, variation in runoff by soil burn severity, vegetation type and soil conductivity, variable lag times, and stream attenuation, the questionable reliability of the CN method in forested watersheds, for both post- and pre-fire conditions, adds varying uncertainty to the estimates. Research is needed to address this uncertainty, especially since lives are often at risk. In the meantime, wildfires will occur and methods need to be available to predict the expected flood response from burned watersheds. This case study provides an example of one such approach.

Acknowledgements

Appreciation is expressed to High Park Fire BAER team, for their initial analyses, Brandon Stone and Colorado State University for the utilized BARC soil burn severity interpretation, and Randy McKinley of the USGS and Eric Schroder of the USFS for the presented soil burn severity interpretation. Appreciation is also expressed to John Andrews for his contributions to the post-fire CN assignment compilation, John Norman for GIS analysis assistance and soils expertise, and Kari Sever and Sam Streeter for field data collection.

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Hawkins, R.H., Greenberg, R.J. 1990 WILDCAT4 Flow Model. School of Renewable Natural Resources, University of Arizona, Tucson, AZ. BLM contact: Dan Muller, Denver, CO.


Case Study 1: High Park Fire Colorado


Case Study 1: High Park Fire Colorado


Case Study 2: Bitterroot Wildfires, Montana

Background

Southwestern Montana in the year 2000 endured severe climatic drought conditions. Late that summer wildfires raged through the area, with the Bitterroot National Forest hit particularly hard. See figures CS2-1 through CS1-3 for location and fire severity mapping.

Figure CS2-1. State of Montana, with inset of Bitterroot River valley

Figure CS2-2. Bitterroot River Watershed with inset of area of the wildfires in the year 2000.
These fires were largely started by lightning strikes, as shown in figure CS2-4. The damaged area included 244,000 acres on USDA National Forest lands and 49,000 acres of state-owned and private land. The severity of the fires ranged from low (some understory destroyed, minimal impact on tree canopy) to high (complete destruction of all living plant material). See figure CS2-3 for fire severity and figure CS2-5 for photo of fire in progress.
After the fires, specialists from the USDA Forest Service and Natural Resources Conservation Service (NRCS) evaluated potential hydrologic impacts to area residents and infrastructure. The NRCS effort included the Emergency Watershed Protection Program (EWP). (For more detail on EWP, see the technical note section “The role of NRCS in post-fire assessments and modeling.”) For the Bitterroot fires of 2000 an
immediate technical challenge arose because traditional agency hydrologic methods were not designed to address post-wildfire conditions. A literature search for existing procedures yielded none that could be expeditiously applied. As a result, the NRCS Montana office developed a simple but accurate hydrologic evaluation method which would be more broadly applicable to post-wildfire watershed protection projects. The spreadsheet tool FIRE HYDRO (Cerrelli, 2005) resulted from this effort.

A key factor which made apparent the need for such a tool was the lack, in existing NRCS engineering handbooks, of guidance specifically related to post-wildfire conditions. The runoff curve number (RCN) methodology is described in NRCS National Engineering Handbook (NEH), Part 630, Hydrology, Chapter 9, Hydrologic soil-cover complexes (2004a), and Chapter 10, Estimation of direct runoff from storm rainfall (2004b). The new spreadsheet tool was to retain this guidance, given its familiarity to most NRCS engineers. However, the challenge was to provide correct CNs for the various land covers burned by wildfires of differing severities. Additionally, the analysis used to determine times of concentration for the burned areas needed to be examined for post-fire effects. As the FIRE HYDRO spreadsheet has been used by both NRCS and Forest Service personnel after numerous wildfires since the year 2000, and in other states besides Montana, this case study will discuss its original development and use for evaluating the Bitterroot fires.

Methods

The envisioned goal of the spreadsheet tool was to provide a simplistic method, readily familiar to USDA field engineers that could be run on laptop computers at remote locations. In evaluating a wildfire, NRCS field engineers must quickly determine appropriate conservation practices and areal extents, which could be applied to reduce the impact of runoff and debris coming from the burn areas. The Emergency Watershed Protection program (EWP) and the Burn Area Emergency Rehabilitation program (BAER) are administered for recovery work and typically activated quickly, during and shortly after an event. (See the technical note for more information on both EWP and
Within these programs, projects must be evaluated, designed, contracted, and constructed quickly or they will not be considered for agency funding.

The hydrologic principles found in the NRCS Engineering Field Handbook, Chapter 2, Estimating Runoff (USDA-NRCS 1989) were considered appropriate to meet the needs for this simple but accurate analysis of the wildfire areas. These procedures are abbreviated EFH-2.

At the time of this study (2000), EFH-2 was only available as a manual method that required the user to look to the tabular and graphical listings within the guidance to determine the runoff volume for the singular watershed under investigation. The EFH-2 peak discharge analysis requires the user to specify the design rainfall distribution type (defined by NRCS into four categories nationwide) that is appropriate for the project area under investigation. The NRCS Montana office has its own criteria for determining the appropriate selection of design rainfall distribution based on the project area’s ratio of the 6-hour to 24-hour rainfall amounts for the desired recurrence event. The spreadsheet methodology was created in Microsoft Excel and named FIRE HYDRO, incorporating NRCS RCN technology and EFH-2 peak discharge graphical solution in conjunction with the NRCS Montana design rainfall selection criterion.

EFH-2 provides a set of curves for each rainfall distribution region in the US. Each curve pertains to an $I_a/P$ ratio (where $I_a$ refers to the CN runoff initial abstraction and $P$ is total rainfall, both units in inches). To obtain peak discharge, one selects the correct curve, given $I_a/P$, then enters the x-axis with time of concentration, and reads unit peak discharge on the y-axis. For FIRE HYDRO an algebraic function was derived for each of these curves and provided in the Excel file to solve for predicted peak discharge.

Among the technical issues that needed to be addressed in the creation of FIRE HYDRO were proper selection of burn area runoff curve numbers and times of concentration, and
soil hydrophobicity. These issues will be discussed in greater detail below. The FIRE HYDRO methodology analyzes four different watershed conditions. They are as follows:

- Pre-Fire (watershed significantly healed from any previous fires)
- Post-Fire 1 (Immediately after the event, including consideration of hydrophobic soil)
- Post-Fire 2 (After some emergence of vegetation and breakdown of hydrophobicity)
- Post-Fire 3 (After estimated or expected vegetation recovery in next growing season)

These four conditions were evaluated to give the designer a greater feel for the range of runoff conditions that were, are, and will be present for the watershed being investigated. This information helps the designer better understand the change in relative risk over time on various alternative hydrologic control measures considered for installation, including the “do nothing” alternative.

For the Bitterroot fires, conditions were monitored for both immediately post-fire conditions and later post-fire conditions. Figure CS2-6 shows how runoff shortly after the burn eroded the soil surface and was retarded by the conservation practice of silt fencing.
Figure CS2-6. Fully loaded silt fence placed in the aftermath of the 2000 Bitterroot Valley Complex wildfire.

Figure CS2-7 shows a watershed in the early stages of recovery. Figures CS2-8 through CS2-10 show Bitterroot watersheds after several years of recovery.

Figure CS2-7. Laird Creek in 2001 within what was the Bitterroot Fire Valley Complex.

Figure CS2-8. Sheafman Point in October 2008.
Runoff Curve Number (RCN) Estimation for Burn Areas

The FIRE HYDRO method is used to evaluate individual watersheds by treating all land use/soil conditions as a composite homogeneous collection. This assumption contains inherent problems when widely varying runoff conditions exist in the watershed being modeled. A literature search for recommended RCNs for wildfire burn areas specifically related to climate and vegetation types of southwestern Montana yielded nothing.
Consequently, select NRCS Montana engineers created the following guidance for selection of RCN based on burn severity and hydrologic soil grouping (HSG) specific to the Bitterroot wildfire vicinity (Tables CS2-1 through CS2-4.)

**Table CS2-1. Runoff curve numbers for high severity burned areas of southwest Montana**

<table>
<thead>
<tr>
<th>Hydrologic soil group</th>
<th>High burn severity CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>64</td>
</tr>
<tr>
<td>B</td>
<td>78</td>
</tr>
<tr>
<td>C</td>
<td>85</td>
</tr>
<tr>
<td>D</td>
<td>88</td>
</tr>
</tbody>
</table>

*High Severity Burn Areas assumed to have attained a minimum of 30% ground cover consisting of vegetation, duff, thick ash, or woody debris by June of the following year.

**Table CS2-2. Recommended runoff curve numbers for moderate severity burned areas**

<table>
<thead>
<tr>
<th>Cover type</th>
<th>RCN for given hydrologic soil group&lt;sup&gt;+&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Herbaceous mixture of grass, weeds, and low-growing brush, with brush the minor element</td>
<td>71</td>
</tr>
<tr>
<td>Oak-aspen mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple</td>
<td>48</td>
</tr>
<tr>
<td>Pinyon-juniper pinyon, juniper or both, grass understory</td>
<td>58</td>
</tr>
<tr>
<td>Sagebrush grass understory</td>
<td>51</td>
</tr>
<tr>
<td>Desert shrub major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.</td>
<td>55</td>
</tr>
</tbody>
</table>

<sup>+</sup>Moderate burn area RCNs are for cover types in Fair condition. This table is from EFH-2, for arid & semiarid rangelands, which stated that curve numbers for HSG A were developed only for desert shrub cover type.
Table CS2-3. Recommended RCNs for low severity burned and unburned areas with north and east facing slopes.

<table>
<thead>
<tr>
<th>Cover type</th>
<th>RCN for given hydrologic soil group*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td><strong>Herbaceous</strong></td>
<td></td>
</tr>
<tr>
<td>mixture of grass, weeds, and low-growing brush, with brush the minor element</td>
<td>62</td>
</tr>
<tr>
<td><strong>Oak-aspen</strong></td>
<td></td>
</tr>
<tr>
<td>mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple</td>
<td>30</td>
</tr>
<tr>
<td><strong>Pinyon-juniper</strong></td>
<td></td>
</tr>
<tr>
<td>pinyon, juniper or both, grass understory</td>
<td>41</td>
</tr>
<tr>
<td><strong>Sagebrush</strong></td>
<td></td>
</tr>
<tr>
<td>grass understory</td>
<td>35</td>
</tr>
<tr>
<td><strong>Desert shrub</strong></td>
<td></td>
</tr>
<tr>
<td>major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.</td>
<td>49</td>
</tr>
</tbody>
</table>

*Moderate burn area RCNs are for cover types in Fair condition. This table is from EFH-2, for arid & semiarid rangelands, which stated that curve numbers for HSG A were developed only for desert shrub cover type.
Case Study 2: Bitterroot Wildfires, Montana

<table>
<thead>
<tr>
<th>Cover type</th>
<th>RCN for given hydrologic soil group*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbaceous</td>
<td>A</td>
</tr>
<tr>
<td>mixture of grass, weeds, and low-growing brush, with brush the minor element</td>
<td>67</td>
</tr>
<tr>
<td>Oak-aspen</td>
<td>A</td>
</tr>
<tr>
<td>mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple</td>
<td>39</td>
</tr>
<tr>
<td>Pinyon-juniper</td>
<td>A</td>
</tr>
<tr>
<td>pinyon, juniper or both, grass understory</td>
<td>50</td>
</tr>
<tr>
<td>Sagebrush</td>
<td>A</td>
</tr>
<tr>
<td>grass understory</td>
<td>43</td>
</tr>
<tr>
<td>Desert shrub</td>
<td>A</td>
</tr>
<tr>
<td>major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.</td>
<td>52</td>
</tr>
</tbody>
</table>

*Low burn and unburned area RCNs are for cover types between Fair and Good condition, with values averaged from tables CS2-2 and CS2-3.

These recommended RCNs (for all burn severity types listed) were arrived at by consensus amongst three NRCS Montana engineers with hydrologic evaluation experience. See figures CS2-11 and CS2-12 for examples of data available for the Bitterroot fires that used in establishing the areal extent of different burn severities. The basic premise of the three NRCS Montana engineers was to establish a logical fit for burn area RCN values within the existing accepted NRCS RCN/land use table. There was no time between the fire occurrence and the need for installation of exigency runoff protection work for gauging or other verification procedures. Storms that occurred the following spring and summer, events of approximately 2-year to 5-year recurrence, 24-hour duration, did not produce runoff which led to the failure of any protection practices installed using these RCN values.
Figure CS2-11. Satellite imagery used to detail burn severity of the 2000 Bitterroot Valley Complex wildfire.

Figure CS2-12. Burn severity map and rain gage data for a rain event that happened a year after the 2000 Bitterroot Valley Complex wildfire.
Hydrophobic Soils

Hydrophobicity in soils can be induced by wildfire. It requires certain soil textures and certain plant types to be burned in order to create this condition of significant water repellency. In brief, the condition can be found in more moderately coarse soils that have a deep plant litter mat and experience a severe burn. The resulting “waxy gas” that is created then permeates and coats the upper soil layer making it water repellent. More detail on soil hydrophobicity is provided in the technical note sections “Hydrophobicity” and “Assessment of post-fire soil hydrophobic conditions.”

Runoff rates and volumes from hydrophobic soils can become extremely high. The engineer must make best estimates as to how widespread and persistent hydrophobicity exists after a fire. Assigning a design RCN to account for hydrophobicity also depends on the expected duration of this changed runoff condition. For example, the timing of next normal rain season compared to hydrophobic abatement recovery time should be considered. Field-testing is called for, which involves applying water to the mineral soil (below the ash layer) and checking for infiltration with time. See also the technical note section “Accounting for hydrophobicity with infiltration parameters.” In addition, Tables 7 and 8 of the technical note show Forest Service derived curve numbers in relation to soil hydrophobicity.

For the Bitterroot fires of 2000 the NRCS Montana engineers gave all hydrophobic soils a runoff curve number of 94. It is important to consider the window of time to which hydrophobic conditions are expected to occur. Soil hydrophobicity tends to breakdown over time as the water repellent layer is fractured through either plant growth activity or water action (freeze/thaw or dew and desiccation). These two processes occur very typically in Montana but may not be so prominent in other states.

Experience gained from the Bitterroot EWP effort, while considering hydrophobic soil properties for effective RCN assignment, yielded some interesting findings. Significant
field reconnaissance, largely by Forest Service personnel, was dedicated to evaluating the water-repellent properties of soils in the fire-affected watersheds. These investigations in the Bitterroot burn found areas with enough hydrophobicity to repel 50-70% of incoming water. It should be noted that even unburned forest soils can exhibit hydrophobicity. Tests in the Bitterroot fire area of adjacent unburned areas found that the soils would repel 40-60% of incoming water. It was thought that the drought that had been prevalent throughout the area in the summer of 2000 created a “tightening effect” of drought-affected soils, which created some water-repellency within the soil. Since the burned and unburned rates of water repellency seemed so similar it was determined that the fire had not induced a significant increase in hydrophobicity. Therefore, the analysis of the Bitterroot fires using FIRE HYDRO shortly after the event did not use CNs that attempted to account for hydrophobic conditions. Observations of subsequent rainfall events tended to support the earlier suspicions, as large increases in runoff that might be expected from significantly hydrophobic areas was generally not in evidence.

Time of Concentration (Tc) and Assumed Watershed Shape

The engineers and technicians assigned to perform the watershed hydrologic evaluations of the Bitterroot wildfire area were not provided detailed topographic mapping of the site. They were provided GIS data that included total watershed area as well as percentages of which experienced low, moderate, or high severity burns along with soils data that included land slopes within the dominant soil classes found. It should be noted that, although today’s engineers are often skilled GIS users, the rapid turn-around time for the Bitterroot fires of 2000 and the skill set of the engineers who happened to be available at the time, precluded use of GIS to determine the longest flowpath lengths of subareas of the fire directly. Thus, an assumption was needed that would provide an estimate of watershed longest flow path based on drainage area. An assumed rectangular shape watershed with dimensions of one unit wide by two units long was made to produce the area stated for the watershed in the GIS data report. The longest flow path was taken as the longitudinal line down the center of this rectangle with a bend towards a corner at the upper third. The Tc was
calculated using the Lag Method found in EFM-2. (See also the technical note section “Watershed lag method.” This method used RCN, flow length, and average watershed slope (based on values from the soils data in the GIS data) as its basis. The post-fire $T_c$ was assumed to stay equal to the pre-fire $T_c$ even though there was a reduction in plant cover (therefore reduced flow friction leading to higher flow velocities) after the fire that should logically allow a faster $T_c$ to develop. The assumption here though was that the excessive amount of available debris after the fire would cause blockages in the flowpath, a kind of debris dam, which would serve to attenuate the flows. The degree of flow attenuation after a fire may vary tremendously from one area to another or one watershed to another, but it was felt that a reasonable estimate would be to use the same time of concentration for both pre-fire and post-fire conditions.

Results and Discussion

The FIRE HYDRO spreadsheet was much utilized by engineers and technicians involved with the 2000 Bitterroot Wildfire recovery operations. NRCS personnel designed many runoff diversion practices to protect homes from the anticipated increased rainfall runoff brought about by changes in watershed conditions due to the wildfires. Forest Service personnel used FIRE HYDRO to design for the enlargement of culverts to provide capacity for the anticipated increase in runoff and also to allow for fish passage. All of the practices designed using FIRE HYDRO were able to satisfactorily withstand rainfall-runoff events in the following years without any notable failures being reported.

It should be noted that many homes which benefitted from conservation practices after this event happened to be situated on the only reasonably flat land around, that being surrounded by steep mountainous land. Such land was near level because of being located on an alluvial fan created by deposition of sediments from previous historic wildfires. So in effect, the homes were prime targets for heavy post fire sediment and debris deposition, if not for the successful functioning of diversion practices (most typically in the form of concrete highway dividers placed slightly down the slope and above the area of interest).
One key feature that should be considered in establishing the proper design RCN for post-wildfire hydrologic evaluations is the anticipated recovery time of the watershed towards its pre-fire condition. RCN increases as burn severity worsens. This leads to higher estimated runoff from the various design rainfalls used for sizing runoff control practices. These, in turn, lead to higher project costs. Nevertheless, in the seasons that follow the wildfire landscape recovery tends to return hydrologic processes toward pre-fire conditions. The longer the healing time, the less the design RCN should diverge from that used immediately after the fire. It is incumbent upon the engineer in charge of assigning the recommended design RCNs for various land covers and burn severities to consider both the risk of failure versus storm frequency. Design RCNs based on recovery of the land cover can vary greatly in the seasons following a wildfire.

The Bitterroot fires of 2000 and the use of FIRE HYDRO to design conservation practices happened to coincide with disagreements among engineers about proper post-fire design storm recurrence intervals. The concern stemmed from the idea that the notable increase in RCN value as the result of a fire would be short-lived and ground cover recovery would decrease the RCN in the seasons following the wildfire. The EFH-2 method that FIRE HYDRO is based on is very sensitive to the selected design RCN. It was thought that if all designs, including those for low hazard structures, were based on the accepted storm recurrence interval (25-yr for most practices) overly conservative and costly designs would result, since the watersheds would heal significantly in the early post-fire years. The NRCS Montana State Conservation Engineer issued a guidance letter to all EWP engineers and technicians relating to the selection of recurrence interval design storms to be used for the statewide EWP effort. Low hazard scenarios were to be designed for non-damaging passage of flows of the 25-year pre-fire peak discharge or post-fire 10-year peak, whichever was greater. High hazard scenarios were to be dealt with on a case-by-case basis, in consultation with the state engineer.
The assumption for using the same $T_c$ both pre-fire and post-fire should be more thoroughly investigated to determine its validity. As previously mentioned, this assumption was based on the idea that the added debris and sediment load from the burn would create increased opportunity for flow blockages to occur thereby slowing the runoff process from what might initially be expected from a higher RCN value.

Improvements to post-fire hydrologic methods such as FIRE HYDRO would benefit from research in this area. Onsite inspection of the burn area during a prominent runoff event should provide evidence of the validity of the assumption that post-fire debris offsets the loss of vegetation in runoff speed. Evidence of flow blockages may exist and their potential to eventually breach after a storm. The ideal investigation would gage rainfall and runoff both before and after a wildfire. This would provide the most accurate assessment of wildfire influence to $T_c$ and storm runoff volume and rate.

Complex issues should be acknowledged when attempting to model post wildfire hydrology. One of the most impactful is the time variance of RCN value. Clearly, the effective RCN for burned watersheds will have increased drastically. As the watershed heals, however, the RCN reduces toward the pre-fire condition. But at what rate? It might not be economically proper to assume the worst case RCN (immediately after the fire) for all hydrologic modeling related to design of runoff control practices in these areas. An accurate assessment of RCN change with time would help decision makers develop a sensible strategy for setting proper design parameters. Peter Robichaud, USDA Forest Service, has spent considerable time investigating and monitoring post wildfire watersheds. His findings indicate a tremendous increase in sheet erosion taking place on the landscape the year following the fire but then cutting back drastically each year thereafter. Evidently, growth of grass on the bare ground provides abatement to raindrop impact on the soil thereby stemming erosion about a year or two after the fire.

The technical note references Robichaud’s work in three articles, (Foltz et al. 2009, Hudak et al. 2004, and Robichaud et al. 2008). The question remains as to whether the runoff amount has also significantly decreased in this timeframe. (The dominant driving mechanism of curve number change over time may not be raindrop impact).
Determining the reduction of post-wildfire RCNs over time to their pre-fire values may best be investigated by gaging the watershed runoff or possibly by documenting field indicators of stream flow levels along stream banks from various rainfall events. Optimally, these post-fire gage records would be compared to those kept from the same area prior to the fire.

One convenient option might be to gage watersheds for which good quality USGS predictive regression equations (for, say, peak discharge) exist, and that have also experienced wildfire. These areas could then be similarly analyzed for newly developed equations to reveal what trends have become apparent. RCNs could perhaps then be assigned within the NRCS hydrology models that produce results in line with the USGS gaged watersheds.

**Limitations**

Sound hydrologic judgment is called for in utilizing FIRE HYDRO. It is based on the NRCS curve number runoff equation and subject to all of the assumptions pertaining to that method. The selection of appropriate (and likely weighted) RCN should be based on the best information available (pre-fire land cover/condition and fire severity distribution in the watershed being evaluated). The predicted peak discharges from this model are quite sensitive to the RCN used. The RCNs listed in this paper were refined from existing tables in EFM-2 and altered by the judgment of NRCS Montana engineers to address the conditions found in western Montana. Other areas may require similar scrutiny to best define appropriate RCN usage. The decision of whether or not it is appropriate to weight the various RCN attributed sub-areas and treat them as one homogeneous area is left to the designer. A more refined modeling approach might be to use WinTR-20 (USDA-NRCS 2004c) or one of the hydrologic models discussed in the other case studies of this technical note. Consultation with experienced users of these programs is warranted to assure accurate assessments.
Another way to handle non-homogeneous watersheds with FIRE HYDRO would be to
determine peak flowrates per unit area for various pre and post burn curve numbers for
each of the various recurrence events. Watersheds that do not vary too widely could
benefit by this procedure. For example, the watershed would be modeled in pre-fire
condition and a pre-fire flowrate per unit area determined. Then only the area of the
portion burned severely could be analyzed and a severe burn flowrate per unit area
determined. If the burned area of this hypothetical watershed burn was severe only, then
the total predicted peak would be the severe burn area times the severe flowrate per unit
area, plus the unburned area times the unburned flowrate per unit area. Watersheds with a
wide mosaic of burns (and resultant varying RCNs) would not be handled in this way,
since they would not fit the homogenous assumption that the spreadsheet utilizes. Again,
sound judgment is called for, by the designer, to ensure that accurate modeling
procedures are followed.

Though the drainage area is limited to 2000 acres by the parent method (EFM-2) of FIRE
HYDRO, some of the burn areas are much larger than this. The results of FIRE HYDRO
were compared to those from a more detailed method (TR-20) and found to be reasonably
close for watersheds in the 5-10 square mile range. Consequently, no limit on drainage
area was imposed on FIRE HYDRO. The user is cautioned to exercise judgment in the
appropriate use of FIRE HYDRO to make sure that sound principles of hydrology are
being modeled properly for the conditions present in the watershed. The assumption of
rectangular watershed shape, used in the $T_c$ computation, should no longer be necessary,
since today’s widely available GIS programs generally produce longest flowpaths easily.

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Case Study 2: Bitterroot Wildfires, Montana


Case Study 3: West Fork Complex Fire, Colorado

Background

The West Fork Complex Wildfire, in the San Juan Mountains west of the community of South Fork, burned more than 109,000 acres between June 9th and July 12th, 2013. See figure CS3-1 for the general location and figure CS3-2 for the area of the West Fork Complex fire.

Figure CS3-1. State of Colorado with zoom into the upper Rio Grande watershed

Figure CS3-2. Area of the West Fork Complex wildfire, west of South Fork CO.

The fire area was composed of three separate fires: the Papoose Fire in the Rio Grande watershed, the West Fork Fire in the Rio Grande and San Juan watersheds, and the Windy Pass Fire in the San Juan watershed. Together, these three fires are known as the West Fork Complex fire. See figure CS3-3 for the individual fire perimeters of the West Fork Complex.
Wildfires cause hydrologic shifts for a number of years. Substantially increased runoff and sediment production result from the loss of vegetation and soil cover, as well as from soil hydrophobicity. Lack of interception by vegetation, reduced soil infiltration, loss of surface roughness and ground litter, and increased hydrophobicity, all combine to shift the rainfall response from infiltration-dominated to surface runoff-dominated processes. For example, watershed impacts due to recent wildfire caused a Swiss catchment to produce runoff in the range of 100-year to 200-year recurrence interval from a 10-year rainfall event. This extreme runoff increase was due to changes in infiltration capacity (Conedera et al. 2003). It should be noted that this phenomenon may have some scale dependency, with greater runoff enhancement in smaller catchments and tendencies towards overestimation in larger catchments (Stoof et al. 2011).
Hydrophobicity, which tends to be more prevalent with increased sand content and lower soil water content, has been found to weaken within a few months of a fire but persist for at least 22 months in ponderosa and lodgepole pine forests of the Colorado Front Range (Huffman et al. 2001). Post-fire sediment yield is most dependent on ground cover, with percent ground cover explaining more than 80 percent of the variability in sediment yield (Benavides-Solorio and MacDonald 2001). Accounting for soil burn severity is hence fundamental for predicting sediment yield increases.

The West Fork Complex Wildfire Burned Area Emergency Response (BAER) report presented an initial hydrologic analysis of flood increases to be expected from the fire. However, this assessment was performed with a number of simplifications to meet the aggressive timeline dictated by the BAER process. A more detailed peak flow analysis was performed to assess the variation and magnitude of increased flooding to be expected from the burned catchments. This analysis implemented the NRCS curve number (CN) runoff methodology.

Additionally, estimates of increased post-fire sediment yield help prioritize locations where hillslope and riparian mitigation may be needed. Such conservation practices minimize impacts of wildfire on such sensitive infrastructure as municipal water supply, irrigation diversions, and culvert conveyance. Predictions of post-fire sediment yield rely on mathematical models such as Revised Universal Soil Loss Equation RUSLE (Renard et al., 1997), Water Erosion Prediction Project WEPP (Elliot, 2004) and GeoWEPP (Renschler, 2003), as well as professional judgment (Robichaud et al., 2000). These methods have varying advantages and disadvantages for estimating the spatial distribution of post-fire soil loss, but all methods can require large amounts of time and energy to estimate soil loss and its associated risks over large spatial extents. With wildfires becoming more pronounced in the wildland/urban interface, rapid watershed management actions to protect sociological concerns, water quality, and ecosystem health are needed. This need for a rapid response to evaluate and manage post fire soil loss has increased the interest in using Geographic Information System (GIS) technology to
spatially model post fire sediment yields. Many toolsets have been produced that use the
above models as engines to spatially estimate soil loss rates.

This case study details hydrologic analyses performed within the Rio Grande basin to
assess the expected magnitude of flood increases in populated areas at risk of loss of life
and property. Additionally, erosion modeling was performed to evaluate the expected
increase in sediment expected from the burn areas. These results were provided to
stakeholders to assist with planning and prioritizing recovery efforts.

Methods
Rainfall-runoff modeling was performed to simulate the expected flood response of the
streams draining the wildfire areas. Additionally, predictions of post-fire sediment yield
were also developed. The methods implemented to provide these predictions are
presented below.

Hydrologic modeling for the West Fork Complex Fire was performed using the program
HEC-HMS from the U.S. Army Corps of Engineers Hydrologic Engineering Center. The
NRCS curve number (CN) technique for estimating direct runoff from rain events,
combined with the NRCS dimensionless unit hydrograph method, was used in this
analysis. Catchments, modeled stream channels, and pour points are presented in figure
CS3-4. The average modeled catchment size is 2.4 square miles.

The CN is a simple catchment-scale method that gives simplified results at a stream
outlet, with more accurate results expected for larger, higher-intensity rain events. The
method is documented in the NRCS National Engineering Handbook, Section 4,
Hydrology, Chapters 9 and 10 (USDA-NRCS 2004a, USDA-NRCS 2004b), in Rallison
(1980), as well as in numerous other publications. However, little quantitative
information has been published of the database on which it was developed (Maidment
1992). In general, the method was developed for rural watersheds in various parts of the
United States, within 24 states, was developed for single storms (not continuous or partial
The initial abstraction ($I_a$) of the CN method has been traditionally assumed to be 0.2 of the storage coefficient, $S$. (For more on the CN method see the technical note section Runoff curve numbers.) To reflect the decreased storage of a fire impacted soil surface (due to a reduction of depression storage from the elimination of soil litter), the initial abstraction was assumed to be 0.1$S$ for post wildfire conditions in catchments that were substantially burned (>50% moderate + severe soil burn severity). Catchments that were not substantially burned were modeled with the standard $I_a$ of 0.2$S$. For the high CN post-wildfire conditions the impact on CNs of the $I_a$ adjustment was ignored, since smaller shifts in CN due to changes in $I_a$ can be expected (Woodward et al. 2003).
Runoff Curve Number (CN) Estimation

CNs were assigned throughout the modeled catchments according to hydrologic soil group, vegetative type, and soil burn severity. Soil burn severity is a dominant factor in CN assignments in burned areas. (See the technical note.) Hydrophobicity was assumed to be minimal, since the next substantial rain events (after this analysis was performed) would likely occur a year after the fire. The average catchment CN was computed using an aerial averaging methodology. Hence, catchment size was limited to areas with similar runoff characteristics, to provide the most reliable results. As catchment size increased, CNs were computed for adjacent and serial catchments, and flows were routed downstream and combined with lower catchments to predict flow at downstream points of interest. This was necessary due to the larger basins draining the fire areas, as well as to account for catchment shape and stream channel attenuation.

Soil burn severity is the principle driver for increasing flow in runoff predictions. For this modeling, soil burn severity was measured using the BARC process from satellite data collected on 7/18/2013 (figure CS3-4). BARC uses reflectance recorded in satellite images to quantify soil burn severity. For defining soil burn severity, BARC images have the advantage of being comprehensive and relatively-rapidly developable. (See the technical note for more information on both BARC and soil burn severity.) However, comparison with field-collected data has indicated that this remotely-sensed product can be more indicative of post-fire vegetative condition than soil condition, especially in low to moderately burned areas (Hudak et al. 2004).

Hydrologic soil group (HSG) classification was selected using soils data published in the NRCS SSURGO (Soil Survey Geographic) database. Using this method, soil are classified as being either A, B, C, or D type, where A allows the most infiltration and least runoff and D allows the least infiltration and greatest runoff. Type A soils are prevalent in many areas of the fire. Dual hydrologic groups (i.e. A/D, B/D) are indicated in portions of the catchments. These dual classifications are for certain wet soils that could be adequately drained, with the first letter indicating the wet condition and the
second indicating the undrained condition. In these cases, an undrained condition was assumed.

Vegetation type, from SWReGAP (Southwest Regional Gap Analysis Project) land cover mapping, was included in the assignment of CNs used for the modeling. The dominant vegetation types within the stream drainages of the fire areas were spruce-fir, aspen, and alpine meadow and tundra.

Curve numbers were assigned by polygons that had unique values of hydrologic soil group, vegetation type, and soil burn severity. Using primarily a compilation modified from the values used in the High Park (Case Study 1 of this technical note) and Black Forest Wildfire analyses, the implemented CN values are provided in table CS3-1. A fair ground cover condition was generally assumed for the unburned values abstracted from USDA-NRCS (2004a), though a good ground condition was assumed for herbaceous/grassland. The CN values for burned conditions were primarily compiled from various grey literature and unpublished sources; they should be considered approximate.

Table CS3-1. CN assignments implemented in West Fork Complex Fire hydrologic modeling.

<table>
<thead>
<tr>
<th>Cover Description</th>
<th>A HSG Unburned</th>
<th>B HSG Unburned</th>
<th>C HSG Unburned</th>
<th>D HSG Unburned</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Herbaceous, Pasture, Alpine Meadow, Park</td>
<td>49</td>
<td>55</td>
<td>67</td>
<td>77</td>
</tr>
<tr>
<td>Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush</td>
<td>45</td>
<td>52</td>
<td>65</td>
<td>77</td>
</tr>
<tr>
<td>Ponderosa pine-juniper (grass understory)</td>
<td>49</td>
<td>57</td>
<td>65</td>
<td>77</td>
</tr>
<tr>
<td>Sagebrush (grass understory)</td>
<td>46</td>
<td>54</td>
<td>65</td>
<td>77</td>
</tr>
<tr>
<td>Lodgepole Pine Forest</td>
<td>49</td>
<td>57</td>
<td>65</td>
<td>77</td>
</tr>
<tr>
<td>Bare soil</td>
<td>77</td>
<td>77</td>
<td>77</td>
<td>77</td>
</tr>
<tr>
<td>Wetland</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
</tbody>
</table>

Rainfall

Rainfall depths used in the modeling were extracted from NOAA Atlas 14, Vol 8 (Perica et al. 2013). 6-hour rainfall durations and NRCS Type II rainfall distributions were
assumed. Three rainfall depths were used in the analysis, reflecting the variable spatial
and elevation extent of the catchments draining the fire area. However, for each specific
watershed analyzed, identical rainfall depths were used for all catchments. The specific
rainfall depths for the 10-, 25-, 50- and 100-year floods are provided in table CS3-2. The
implemented rainfall distributions for the 25-year event are shown in figure CS3-5. Note
that the majority of the rainfall is assumed to fall within a half hour of the 6-hour duration
event.

Table CS3-2. Rainfall depths (inches) implemented in the modeling.

<table>
<thead>
<tr>
<th>Return Interval</th>
<th>10-year</th>
<th>25-year</th>
<th>50-year</th>
<th>100-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone A</td>
<td>2.17</td>
<td>2.59</td>
<td>2.93</td>
<td>3.28</td>
</tr>
<tr>
<td>Zone B</td>
<td>1.79</td>
<td>2.18</td>
<td>2.48</td>
<td>2.77</td>
</tr>
<tr>
<td>Zone C</td>
<td>1.99</td>
<td>2.48</td>
<td>2.91</td>
<td>3.40</td>
</tr>
</tbody>
</table>

Figure CS3-5. 25-year cumulative rainfall distributions used in modeling.

For catchments with drainages areas greater than 11 square miles (≤ 0.98 reduction), an
areal reduction factor was applied as detailed in Miller et al. 1973. Reduction varied from
0.98 (Elk Creek) to 0.94 (Trout Creek). When applied, this area reduction was
implemented in all catchments; flow may be underpredicted in the smaller, upper
catchments of such drainages.

Lag Time
Lag time ($L$), which is required to generate a hydrograph using the NRCS unit
hydrograph methodology, was computed using the watershed lag method (USDA-NRCS
2010). This equation is:

\[
L = \frac{l^{0.8} (S + 1)^{0.7}}{1900Y^{0.5}}
\]  
(eq. CS3-1)

where $l$ is flow length (ft), $Y$ is average watershed land slope (%), and $S$ is maximum
potential retention (in). $S$ may be calculated from equation CS1-2:

\[
S = \frac{1000}{cn'} - 10
\]  
(eq. CS3-2)

where $cn'$ is the retardance factor and is approximately equal to the CN. This method
allows the computation of differing lag times for pre- and post-fire conditions, reflecting
the actual physical mechanism of more rapid flow response during post-fire conditions.
Note that equation CS3-1 is equivalent to the time of concentration equation in the
Technical Note main body (equation 1) since lag is considered to be 0.6 of the time of
concentration.

Flow Routing
A Muskingum-Cunge procedure was used to route flow from upper catchments to the
stream outlets. This 1-dimensional method, embedded in HEC-HMS, allows for flow
attenuation in the computations but does not provide a numerical solution of the full
unsteady flow routing equations, as provided in such computational models as HEC-
RAS. In each reach, flow routing was estimated using a single simplified cross section,
channel slope, and Manning’s $n$ roughness estimates. Manning’s $n$ was selected using a
visual estimation procedure, with a quality control step to assure that subcritical or
approximately critical velocity was maintained, reflecting an assumption that existing or new channel bedform development prevents reach-average supercritical flow.

Sediment Bulking

A simple multiplication factor was applied to the post-fire flood predictions to account for sediment bulking in the wildfire-induced floods. For burned catchments, this multiplication factor was assumed to be 1.25 if the severe + moderate soil burn severity aerial extent was greater than 50%, and 1.1 for catchments with between 15 and 50% soil burn severity.

Erosion Modeling

The RUSLE (Revised Universal Soil Loss Equation) model was chosen to estimate pre- and post-fire sediment related issues for the burn area because it is widely used, can be quick to execute with straightforward factors and has a large amount of supporting documentation. The RUSLE models (pre- and post-fire) are based on a spatial version of RUSLE outlined in the Assessment of Threats to Riparian Ecosystems in the Western U.S. [Theobald et al., 2010] report. More recently, Litschert et al. 2014 used similar methods to investigate climate change effects on wildfire frequency and soil loss in the Southern Rockies Ecoregion. The ATREW methods entail calculating RUSLE (Equation CS3-3) the standard way, using widely available fine resolution spatial datasets to approximate the six RUSLE factors. The ATREW report also provides guidance on parameterizing the RUSLE C and P factors based on commonly used landcover datasets (e.g., USGS National Landcover Dataset and USFS Existing Vegetation Dataset), as well as equations that scale GIS based terrain analysis for the L and S factors.

\[ A = R \cdot K \cdot L \cdot S \cdot C \cdot P \]  

(eq. CS3-3)  

where:

\[ A = \text{average annual unit-area (tons/ha/yr)} \]

\[ R = \text{rain erosivity factor (MJ mm/(ha h yr))} \]

\[ K = \text{soil erosivity factor (tons ha h/(ha MJ mm))} \]
The advantages of the ATREW approach are:

- the simple model parameterization uses nationwide spatial datasets
- the sedimentation rate raster allows better spatial resolution of erosion estimation
- spatial evaluation of sediment yield helps prioritize soil treatment zones and emergency resource allocation

The sediment modeling entailed four general steps:

1) collection of geospatial dataset for the greater burn area (table CS3-3)
2) development of spatial RUSLE factors for pre- and post-fire conditions
3) calculation of RUSLE for pre- and post-fire scenarios (using ArcGIS Raster Calculator)
4) attribution of computation points and values at risk with pre- and post-fire sedimentation rates.

Pre-fire and post-fire sedimentation rate estimates were executed in GIS using terrain analysis tools to calculate slope length (L) and steepness (S) factors with simple map algebra statements. Computation of rainfall erosivity (R), soil erodibility (K) and cover management (C) factors used ancillary spatial datasets. The soil/cover management (P) factor was not incorporated into the analysis due to a lack of spatial information on management activity in the burn area. For each of the five RUSLE factors used, a 10-meter resolution raster dataset was generated. The five RUSLE factor rasters where multiplied together to calculate the local (cell level) sedimentation rate. These local rate values were accumulated downslope via a flow direction raster (figure CS3-6) and averaged by the contributing area above each raster cell. This results in the final sedimentation rate raster with values representing the average cumulative sedimentation rate in tons per year over 30 years for each scenario.
Table CS3-3. Spatial datasets used for the six RUSLE factors.

<table>
<thead>
<tr>
<th>RUSLE factor</th>
<th>Website</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td><a href="http://www.epa.gov/esd/land-sci/emap_west_browser/pages/wemap_mm_sl_table.htm#mapnav">http://www.epa.gov/esd/land-sci/emap_west_browser/pages/wemap_mm_sl_table.htm#mapnav</a></td>
<td>EPA EMAP RUSLE factors summarized to HUC 8 units for the Western United States.</td>
</tr>
<tr>
<td>$L$ and $S$</td>
<td><a href="http://viewer.nationalmap.gov/viewer">http://viewer.nationalmap.gov/viewer</a></td>
<td>10x10 meter elevation model downloaded for HUC 8 areas associated with the burn area</td>
</tr>
<tr>
<td>$C$</td>
<td><a href="http://earth.gis.usu.edu/swgap/landcover.html">http://earth.gis.usu.edu/swgap/landcover.html</a></td>
<td>30x30 meter landcover dataset for NV, AZ, UT and CO</td>
</tr>
<tr>
<td>$P$</td>
<td>Parameter not used in analysis due to lack of good spatial data</td>
<td></td>
</tr>
</tbody>
</table>

Figure CS3-6. Flow direction raster cell example*

A. shows the eight directions of flow from center cell.
B. shows the possible flow direction raster values.
C. shows an example cell with a north flow direction.
D. shows the flow direction raster value of the cell in C.
E. shows a flow direction grid with the color scheme of A.
F. shows a flow accumulation raster, with each cell encoding the number of cells that drain to it.
The rain erosivity ($R$) factor raster was generated by converting an EPA EMAP HUC 8 polygon shapefile to a raster containing $R$ factor values. Due to a lack of information about how wildfire changes rain erosivity values and the $R$ factor raster was held constant between the pre- and post-fire scenarios. In addition, the EPA EMAP values are based on 30-year averages.

The development of soil erodibility ($K$) factor raster entailed summarizing KFFACT (SSURGO table attribute) to NRCS SSURGO map units and then rasterizing the map units in the same manner as the $R$ factor. KFFACT (property of a soil horizon) was summarized to map unit delineations by calculating a depth/area weighted average based on horizon depths up to 15 centimeters and the component percent within a map unit. This was accomplished through queries developed in the SSURGO database downloaded from the USDA Geospatial Data Gateway website (see table CS3-3). The $K$ factor raster was held constant for both pre- and post-fire scenarios even though burn severity alters soil erodibility. Altering soil erodibility based on burn severity between scenarios could be incorporated in future models but would require additional research and parameterization.

The $L$ and $S$ factors were calculated jointly ($LS$) using basic terrain analysis methods outlined in Theobald et al. (2010) using a 10 meter elevation model. These methods include calculating a percent slope, aspect (radians) and accumulated upslope length. The accumulated upslope length process entailed accumulating number of contributing raster cells to a given cell based on the overland flow paths from the flow direction raster (figure CS3-6). The resulting slope, aspect, and upslope length rasters were transformed using equations developed by Winchell et al. (2008), given herein as equation CS3-4, and Nearing (1997), given herein as equation CS3-6. These equations scale the values derived from the above terrain analysis to better fit within the framework of the RUSLE equation and ensure that the units are correct.

$$LS = S \left[ \left( \frac{A + D^2}{m+1} \right)^{m+1} - A^{m+1} \right]$$

(eq. CS3-4)
where: $L =$ transformed slope length at the given raster cell, $S =$ RUSLE slope factor of the cell

$A =$ contributing drainage area to the cell (m$^2$), $D =$ raster cell size (10m)

$x =$ aspect transformation (equation CS3-5)

$m =$ percent slope transformation (equation CS3-6)

$$x = \sin \alpha + \cos \alpha$$  \hspace{1cm} (eq. CS3-5)

where: $\alpha =$ land aspect of the raster cell in radians, clockwise from north

$$m = \frac{\beta}{1 + \beta}$$  \hspace{1cm} \text{where:} \hspace{1cm} \beta = \frac{11.16 \sin \theta}{3 \sin \theta + 1.68}$$  \hspace{1cm} (eq. CS3-6)

and where $\theta =$ land slope (in percent)

The raster of the slope length ($LS$) factor was developed using the Nearing (1997) equation (given herein as equation CS3-7) in conjunction with equations CS3-5 and CS3-6, which use aspect and slope dynamics to adjust for inaccuracies caused by scale. This is necessary because the raster values of the area draining to each cell ($A$, in square meters) can get very large and inflate sedimentation estimates. The raster for $S$ factor was developed by transforming percent slope using equation CS3-7. That equation scales slope values to reduce inflated soil loss calculations, especially for slopes greater than 50%. The $L$ and $S$ factor rasters where multiplied together to using ArcGIS Raster Calculator to create the raster for $LS$ factor. As with the $R$ and $K$ factors the $L$ and $S$ factors were held constant between the pre- and post-fire models.

$$S = 1.5 + \frac{17}{1 + e^{(2.3-6.1 \sin \theta)}}$$  \hspace{1cm} (eq. CS3-7)

where $\theta =$ land slope (in percent)
The $C$ factor parameterization for the pre- and post-fire scenarios was developed using various source tables from different documents related to RUSLE. The pre-fire scenario parameterization involved developing a lookup table that assigns the existing landcover types (Southwest ReGAP) within the greater burn area to their associated $C$ factors. (See table CS3-4). The table was compiled by Theobald et al. (2010) for the ATERW report and provides a broad spectrum of landcovers found in most landcover datasets and can be modified based on local knowledge. The post-fire $C$ factor parameterization entailed modifying the pre-burn $C$ factor raster based on burn severity classes derived from the Burned Area Reflectance Classification (BARC) image. This process consisted of assigning the BARC burn severity classes $C$ factor values (low burn = 1.03, moderate burn = 2.25 and high burn 3.75) (Larsen et al., 2007) that were then used to modify the pre-fire $C$ factors by summing the two rasters together. Larsen et al. (2007) estimated that high burn severity area $C$ factors changed by four hundred percent but didn’t estimate moderate and low burn severity changes. For these, $C$ factors changes where estimated using professional judgment.
Table CS3-4. C factors for common land covers (Theobald et al. 2010)

<table>
<thead>
<tr>
<th>Land cover</th>
<th>C Factor</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barren</td>
<td>1.0000</td>
<td>Toy and Foster 1998</td>
</tr>
<tr>
<td>Coniferous Forest</td>
<td>0.0020</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>0.0010</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Deciduous Shrubland</td>
<td>0.0250</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Dense Grassland</td>
<td>0.0800</td>
<td>Dawen et al. 2003</td>
</tr>
<tr>
<td>Floodplain Forest</td>
<td>0.0100</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Lowland Coniferous Forest</td>
<td>0.0025</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Lowland Deciduous Forest</td>
<td>0.0015</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Marsh/Riparian/Wetland</td>
<td>0.0010</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Medium-tall grassland</td>
<td>0.0120</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>0.0010</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Mixed Forest woodland</td>
<td>0.0020</td>
<td>Breiby 2006</td>
</tr>
<tr>
<td>Open Water/Exposed Rock</td>
<td>0.0000</td>
<td>Breiby 2006; McCuen 1998</td>
</tr>
<tr>
<td>Shrubland Other</td>
<td>0.0290</td>
<td>McQuen 1998</td>
</tr>
<tr>
<td>Snow field</td>
<td>0.0010</td>
<td>Dawen et al. 2003</td>
</tr>
<tr>
<td>Sparse Grassland</td>
<td>0.2000</td>
<td>Dawen et al. 2003</td>
</tr>
<tr>
<td>Aggregate mining</td>
<td>1.0000</td>
<td>Guobin et al. 2006</td>
</tr>
<tr>
<td>Asphalt</td>
<td>0.0001</td>
<td>Toy and Foster, 1998</td>
</tr>
<tr>
<td>Cultivated Crops Irrigated</td>
<td>0.2400</td>
<td>McCuen, 1998</td>
</tr>
<tr>
<td>Developed General</td>
<td>0.0030</td>
<td>Guobin et al. 2006</td>
</tr>
<tr>
<td>Developed Suburban</td>
<td>0.0020</td>
<td>Guobin et al. 2006</td>
</tr>
<tr>
<td>Developed Urban</td>
<td>0.0010</td>
<td>Guobin et al. 2006</td>
</tr>
<tr>
<td>Fallow</td>
<td>1.0000</td>
<td>McCuen, 1998</td>
</tr>
<tr>
<td>General Cropland</td>
<td>0.5000</td>
<td>Dawen et al., 2003</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.2000</td>
<td>Toy and Foster, 1998</td>
</tr>
<tr>
<td>Industrial</td>
<td>0.0050</td>
<td>Guobin et al. 2006</td>
</tr>
<tr>
<td>Mixed Urban</td>
<td>0.0040</td>
<td>Guobin et al. 2006</td>
</tr>
<tr>
<td>Paddy field</td>
<td>0.1000</td>
<td>Dawen et al., 2003</td>
</tr>
<tr>
<td>Pasture Hay</td>
<td>0.1400</td>
<td>McCuen, 1998</td>
</tr>
<tr>
<td>Recreational Grasses</td>
<td>0.0080</td>
<td>McCuen, 1998</td>
</tr>
<tr>
<td>Small Grains</td>
<td>0.2300</td>
<td>McCuen, 1998</td>
</tr>
</tbody>
</table>

The final estimates of sedimentation rate for the pre- and post-fire scenarios were generated by multiplying the 5 factors, accumulating the those values downslope via the flow direction raster, and calculating an area-weighted sedimentation rate. The latter is determined by dividing the accumulated sedimentation rate by the total accumulated drainage area. Figures CS3-7 shows how sediment yield varies in different zones on a hillslope. The transport of sediment from areas where it originates (steep slopes or burned
areas) dampens with decrease in slope, increase in flow distance, or interruption by unburned areas. Figure CS3-8 is an example of an area-weighted sediment yield raster, showing that the high loss areas (red) dampened with flattening slope and distance.

**Figure CS3-7. Conceptual diagram of sediment yield estimation on hillslope zone breaks**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Accumulated RUSLE (tons/yr)</th>
<th>Accumulated Area (ha)</th>
<th>Average RUSLE (tons/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12000</td>
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<tr>
<td>B</td>
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<td>225</td>
<td>75</td>
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<tr>
<td>C</td>
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<td>600</td>
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<tr>
<td>D</td>
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</tr>
<tr>
<td>E</td>
<td>22000</td>
<td>1000</td>
<td>22</td>
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</tbody>
</table>
Results and Discussion

Hydrologic modeling was performed to develop estimates of increased flood hazard and erosion potential for streams draining the West Fork Complex Wildfire. For several key catchments, at locations where there are threats to residences, hydrographs such as in figure CS3-9 show the expected response to a 25-year rainfall depth over each entire catchment. Substantially increased flow peaks, runoff volumes, and sediment were estimated. Using a map presentation style (figures CS3-10) that is simple for planners, designers, and emergency response officials to utilize, results were provided at pour points throughout and downstream of the fire extents. Results were also provided as attributes in ArcGIS shapefiles. For detailed results, refer to the project report (Yochum and Norman 2014).
Figure CS3- 9. Example of estimated pre- and post-fire hydrographs for the 25-year event.

Figure CS3- 10. Example map providing pre- and post-fire flood predictions for the S. F. of the Rio Grande.
**Runoff Modeling Results**

In many catchments, post-fire conditions are predicted to cause a 50- or 100-year (pre-fire) flood to result from a 10-year rain event on burned landscapes, similar to actual measured fire runoff responses (Conedera et al. 2003). Peak flow magnification ratios for the 25-year rainfall event are provided (figure CS3-11). These ratios are computed as the post-fire peak flow divided by the pre-fire peak flow; a value of 3 indicates that 3 times the peak flow is predicted from the burned landscape for the identical rain event.

**Figure CS3-11. Peak flow magnification ratios for the West Fork Complex wildfire.**

The fire results in a 41 percent risk that a 10-year rain event will cause runoff that, pre-fire, would have been 50- to 100-year in recurrence. These substantial fire impacts on runoff may persist for at least 5 years. However, as catchment size increases the small spatial extent of typical convective storms will reduce the severity of the flood effects from these storms.
**Sediment Modeling Results**

Sediment modeling was intended to provide estimated sediment magnification ratios at hydrologic pour points, as well as approximations of sediment yield. Sediment magnification ratios were calculated by taking the ratio between the predicted post- and pre-fire sediment flux values (tons/yr) to compute the magnitude of change. The true magnification ratios and quantities for the pre- and post-fire scenarios are unknown, and these estimates are based on a lumped modeling approach (RUSLE) that provides values with substantial expected error. However, the results do provide a reasonable framework for making management decisions. An overview of the sediment magnification ratios is provided in figure CS3-12.

**Figure CS3-12.** Sediment magnification ratios for the West Fork Complex wildfire.

The sedimentation analysis for the entire West Fork Complex Wildfire predicts that the Upper Rio Grande River will experience on average 130 times more sediment annually above pre-fire conditions (approximately 1,030,000 tons/yr). This is based on sediment rates estimated for the 27 outlet pour points that are hydrologically connected to the burn.
These pour point estimates account for all sediment production and transport that occurs upstream of them. The Papoose Wildfire accounts for 65% of the total sediment yields in the West Fork Complex with 70% of its outlets having sediment magnification ratios greater than 100. The West Fork Wildfire area has lower sediment magnification ratios with 50% of its outlets having ratios higher than 100, but it has the highest yielding catchment (Hope Creek HC) which accounts for about 18% of the total sediment yield of the entire West Fork Fire Complex area.

The majority of sediment produced by the Papoose Wildfire area is from two large catchments (Little Squaw Creek and Trout Creek) which together account for about 50% of its total sediment yield. The other 17 outlet pour points do not account for as much sediment on an individual basis, but several (CIC-1, PC-1, UN-1, UN-2 and WC-1 in figure CS3-4) have sedimentation magnification rates that exceed 500 times pre-fire conditions. These catchments are small, but have steep slopes with high proportions of moderate and high burn severities which could pose a mass movement risk. The pour points that make up Trout Creek all have sediment magnification ratios greater than 100 with TC-6 (figure CS3-4) having the highest sedimentation rate. The Little Squaw Creek catchment of the Upper Rio Grande has magnification ratios that increase dramatically downstream with a large bump in sediment yield at the outlet point (LSC-4). The Texas Creek catchment has magnification ratios that increase up to the midpoint of the catchment (TxC-3) and then decreases to the outlet point with sediment yields still increasing steadily downstream.

The majority of sediment produced by the West Fork Wildfire is dominated by two catchments (Goose Creek, and Hope Creek) that together produce 75% of the its total sediment yield. The analysis for Hope Creek predicts sediment magnification ratios greater than 400 with a peak ratio of 605 at HC-2, dropping back to 483 at the outlet. This catchment along with LF-4, CbC-1, and DC-3 (figure CS3-4) connect to the South Fork of the Rio Grande River which will increase its sediment yield by approximately 250,000 tons annually. The Goose Creek analysis predicts that sediment magnification ratios and yields increase dramatically to pour point GC-4 and then decrease by half at the outlet.
Case Study 3: West Fork Complex Fire, Colorado

Pour point at Lake Humphreys, where a post-fire sediment yield of approximately 85,400 tons/year was simulated. The other four outlets DC-3, TCE-3, EC-3 and Lec-5 have moderately low sediment magnification ratios, with a total yield of approximately 390,000 tons/year.

Modelling Limitations

As with all hydrologic modeling, the results provided by these rainfall-runoff and sediment models are approximate. The best use of these results is on a comparative basis, to help identify points of concern and develop mitigation priorities. Absolute values of runoff and sediment yield are approximate and use of these values for infrastructure sizing and estimating reservoir sedimentation rates should be done with caution. Specific limitations in the modeling methods are discussed below.

Rainfall-Runoff Modeling Limitations

Post-fire runoff prediction using the CN technique is hampered by the very little available field data available to reliably select CN values from measured rainfall and runoff in burned catchments. With CN values for burned conditions primarily compiled from various grey literature and unpublished sources, they should be considered approximate. As a result, consistent application of these values result in model results that are more dependable in a comparative manner. Catchment-scale research of wildfire-impacted areas is needed to develop more robust post-wildfire CN estimates.

An additional complication arises from the peak rate factor imbedded in the NRCS dimensionless unit hydrograph method. Within HEC-HMS, this peak rate factor cannot be altered from the default value, despite an understanding that this factor tends to increase with steeper watersheds. The ability to adjust the peak rate factor (an option in WinTR-20) would be a valuable addition to HEC-HMS. For more information, see the technical note section “NRCS dimensionless unit hydrograph.”

Most fundamentally, the reliability of the CN method for predicting peak flow from forested, mountainous watersheds is questionable. Forested watersheds in unburned
conditions may be dominated by saturation-excess overland flow (figure CS3-13), where runoff is produced from relatively small and variable portions of a catchment when rainfall depths exceed the soil capacity to retain water. Newly burned catchments, on the other hand, may be dominated by infiltration-excess (Hortonian) overland flow, where surface runoff is generated when rainfall intensity is greater than soil infiltration capacity, and flow runs down the hillslope surface. Evidence of this surface runoff is provided by such features as surface rilling on freshly-burned hillslopes. Rainfall-runoff modeling performed in the San Dimas Experimental Forest (Chen et al. 2013) found that pre-fire runoff predictions were more accurate using the CN method, while KINEROS2 performed better for post-fire conditions. These results suggest fundamental shifts in runoff mechanisms between pre- and post-fire conditions, complicating modeling strategies.

Despite this shortcoming, due to its relative simplicity and achievable data requirements on large scales, as well as reasonable results when qualitatively compared to actual post-fire runoff events, the CN method is often considered a preferred tool for predicting flow response of wildfire areas. Alternatives approaches can be problematic, due to the need to quantify infiltration rates, the effects of soil litter and hydrophobicity on retention and infiltration for pre- and post-fire conditions, as well as vegetation canopy rainfall interception. This accounting would need to be performed at a spatial resolution.
appropriate for obtaining the needed flood predictions throughout the entire wildfire extent, which can be a very challenging task with the limited time and resources allotted to practitioners for prediction.

Sediment Modeling Limitations

The ATREW method used to estimate pre- and post-fire sediment yields was originally developed to estimate sedimentation rates to riparian areas based on different landuse and climate change scenarios for the Western U.S. (See Theobald et al. 2010.) This scaling issue along with limited information on parameterizing $C$ factors for burned vegetation, inherent errors associated with the spatial data and the lumped approach of the RUSLE equation makes predicted sedimentation rates unreliable. This was evident when Larsen et al. (2007) evaluated spatial versions of RUSLE and WEPP performance using established plots for fires on the Front Range of Colorado and found that the models performed poorly due to unaccountable variability not incorporated into the models. To address this weakness, it is preferred that sediment yield modeling focus on the magnitude of change in soil loss and not just to amount produced post-fire. The magnitude values are based on an annual average increase in sediment yields for 30 years. This means that actual sediment yields for a given year will fluctuate around the predicted value, but over 30 years may be close to the predicted annual increase in sediment. Nevertheless, the ATREW method, used to estimate pre- and post-fire sedimentation rates and the magnitude of sedimentation post-fire, provides a robust framework for managers to help prioritize and guide timely post-fire mitigation activities.

Conclusions

Using the Curve Number and RUSLE methods, peak flow and erosion potential predictions were made for streams draining the West Fork Complex wildfire area, for both pre- and post-wildfire conditions. Watershed maps for each modeled watershed were developed, illustrating pour points, peak discharges, peak flow and sediment magnification ratios, soil burn severity, and stream outlet hydrographs. While many relevant hydrologic mechanisms were simulated in the rainfall-runoff modeling, including rainfall depth and spatial extent; variation in runoff by soil burn severity,
vegetation type and soil conductivity; variable lag times; and stream attenuation, the
questionable reliability of the CN method in forested watersheds, for both post- and pre-
fire conditions, adds a level of undefined uncertainty to the estimates.

The pre- and post-fire sedimentation analysis used landcover solely as a proxy for
changes in soil erodibility, rainfall erosivity and cover post-fire. This allows for a rapid
response in estimating sediment related issues post-fire, but could be enhanced if soil
erodibility and rainfall erosivity were incorporated. Additional research is needed to
address these uncertainties, especially since lives are often at risk. In the meantime,
wildfires will occur and methods need to be available to predict the expected flood
response and sediment release from burned watersheds. This case study provides
examples for simulation approaches that can be relatively-rapidly deployed after a
wildfire.

Acknowledgements

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field data collection activities documenting channel condition for the modeled streams.
Additionally, the U.S. Forest Service is appreciated for providing heat perimeter and soil
burn severity mapping data.

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Case Study 3: West Fork Complex Fire, Colorado


NRCS National Engineering Handbook, Part 630 Hydrology, Chapter 9, Hydrologic Soil Cover Complexes.


Case Study 4: Whitewater Creek, Gila Wilderness, New Mexico

Background

Lightning sparked several outbreaks of wildfire in May 2012 that joined to become the largest in New Mexico recorded history. Lack of road access and the steep terrain of the Gila Wilderness hampered containment efforts, allowing the individual fires to grow rapidly. By the end of May, they had become one large wildfire known as the Whitewater-Baldy Complex.

The rugged landscape was not the only reason these fires escaped control. The watershed had already been under extreme drought conditions, with the two previous winters recording very low snowfall. Air temperatures at the time of the outbreak were well above average, and high winds contributed to the merging of the fires. In early June the Whitewater-Baldy Complex was only about 18 percent contained. By mid-June containment increased to 56%. For about three months the wildfire burned Ponderosa, Pinon/Juniper, and mixed conifer forests with relatively low burn temperatures. Rainfall in mid-July finally helped fire fighters gain momentum, with 95% containment attained in late July.

The wildfire had burned about 465 square miles. The USDA Forest Service estimated the final burn severity for the area within the fire perimeter to be 14% high, 12% moderate, 55% low or unburned, and 20% unknown (due to inadequate satellite imagery).

This case study presents a hydrologic analysis of the flood potential of Whitewater Creek and possible hazard to the community of Glenwood NM. As shown in figure CS4-4, Glenwood is located near the confluence of Whitewater Creek and the San Francisco River. Considering the drainage area upstream of Glenwood, the percent of the watershed burned was 34% high severity, 21% medium severity, and 13% low severity.
Case Study 4: Whitewater Creek, Gila Wilderness, New Mexico

Figure CS4-1. Location of concern: State of New Mexico with county boundaries, USFS Gila National Forest in green, Gila Wilderness area in yellow.

Inset shown in figure CS4-2

Figure CS4-2. Location of concern, with Whitewater-Baldy Complex Fire location in red.

Inset shown in figure CS4-3

Figure CS4-3.
Figure CS4-3. Location of concern, showing fire location in red, nearby communities and highways.

Map provided by the USGS Gila National Forest.

Figure CS4-4. Whitewater Creek watershed and the community of Glenwood NM.

Glenwood NM
San Francisco River
Whitewater Creek
NRCS Involvement

The NRCS Emergency Watershed Protection (EWP) program was implemented for the installation of monitoring gages in the Whitewater-Baldy Complex burn area, to provide early warning to downstream communities of flood potential. The intensity of the wildfire and its large area prompted the USDA Forest Service, in cooperation with the United States Geological Survey (USGS), to seek EWP funding from NRCS. The NRCS New Mexico State office worked with the New Mexico Department of Homeland Security & Emergency Management, which acted as the EWP local sponsor. USGS installed a streamflow gage on Whitewater Creek, near the Catwalk Recreational Area (figure CS4-5). That station also received a precipitation gage. The existing NRCS Snotel site is shown in figure CS4-5, along with additional newly installed gages.

Figure CS4-5. Gages in the vicinity of Whitewater Creek.
NRCS performed a hydrologic analysis to assess flood potential for the community of Glenwood. In recent years, New Mexico residents had witnessed flash flooding after wildfire. The watersheds of the 2011 Las Conchas fire near Los Alamos experienced monsoon rains within weeks of the end of the fire, which sent floodwater, sediment, and debris rapidly downstream. That wildfire burned 245 square miles and held the record for the largest in recorded New Mexico history, until eclipsed by the Whitewater-Baldy Complex wildfire, almost twice as large.

The USDA Forest Service, through the BAER team process, also provided a hydrologic assessment. In addition, the USGS held a workshop in early July 2012 for Glenwood residents to learn how to access the early warning data from the new gages. The data are on the web at: http://nm.water.usgs.gov/wildfire/.

The NRCS hydrologic modeling effort, documented in this case study, examined pre-fire floods and post-fire floods, both immediately after the fire and one year later. Data from the newly installed precipitation and streamflow gages was used to verify that the hydrologic model produced reasonable results.

Figure CS4-6. Burned trees near Hummingbird Saddle, Gila National Forest,
Methods and Application

As an alternative to the often used runoff curve number (CN) method, this case study modeled infiltration of rainfall by the process-based Green & Ampt (GA) method. Both the CN and GA methods are discussed in the main body of this Technical Note. It should be noted that CN runoff is not directly comparable to GA infiltration, in that the CN runoff equation accounts for more phenomena than infiltration. These include losses due to transpiration and surface ponding, which, if using GA, must be modeled separately.

In this case study, runoff transformation was also performed differently than the NRCS dimensionless unit hydrograph (UH). The standard NRCS UH peak rate factor of 484, determined with Technical Note equation 9, is usually too low for mountain streams. The NRCS National Engineering Manual hydrology chapter 15 (USDA-NRCS 2010) provides dimensionless unit hydrographs for peak factors up to 600, which may be used in the hydrology program WinTR-20. However, even a peak factor of 600 is often too low for mountain streams in the unburned condition, and the effect of wildfire is to raise it further. Technical Note figure 17 shows the pre-fire and post-fire unit hydrographs for one sub-basin of Whitewater Creek (this case study), demonstrating that the peak factor is raised by the fire event from 720 to 769.

Although runoff transformation for Whitewater Creek also used the unit hydrograph technique, the shape and peak of the UH were determined with time-area histograms. Neither peak factor nor time of concentration were needed. The hydrology model HEC-HMS (USCOE-HEC 2013) accepts input of user-derived unit hydrographs, as well as the GA infiltration method. The following list summarizes the modeling options used in this case study:

- choice of hydrologic computer model: HEC-HMS (USCOE-HEC 2013)
- runoff transformation: synthetic UH derived by GIS analysis of time-area histograms
- infiltration loss method: Green & Ampt equation
• initial abstraction, ponding: estimates of loss due to vegetation canopy, surface detention
• baseflow: pre-flood estimates based on subarea size, post-flood estimates based on exponential recession curve.
• rainfall events examined: 2-year, 25-year, and 100-year, under three scenarios (pre-fire, post-fire immediately, and post-fire one year later).
• sediment bulking estimated

Choice of hydrologic computer model: HEC-HMS

The model HEC-HMS (USCOE 2013) features many options for estimating flood hydrographs. The runoff transformation options include the NRCS dimensionless UH, but without optional peak factors other than the standard 484. Additional synthetic UH options are the Snyder and Clark UHs, which require some form of peaking factor estimation. This case study demonstrates a user-derived synthetic unit hydrograph, in the S curve format. (See figure CS4-7 for the HEC-HMS input window which summarizes the modeling options.)
The Whitewater Creek watershed upstream of Glenwood NM is shown in figure CS4-8. For each of the forty-one subareas shown a GIS time-area analysis was performed. More detail is provided for a single sub-basin (figure CS4-9, the red inset of figure CS4-8).
Figure CS4-9. Upper Whitewater subarea (called “Baldy Fork”)

Time-area histogram and synthetic UH Estimation

Determining runoff depth over time at the outlet of a given subarea requires an estimate of flow travel time from every part of the drainage area. Even small subareas vary considerably in flow slopes, flow cross-sectional areas, and surface roughnesses. Travel time computation requires spatial accounting of these variables as they affect flow velocity, and then the accumulation of time as flows with these varying velocities traverse the distances to the outlet.

Given the three standard flow segment types (overland, shallow-concentrated, and stream channel), equations and tables from the Technical Note on the Velocity Method may be used. A time-area histogram, however, requires not merely time of concentration, but flow time estimation from many subdivisions of the drainage area. Such an analysis is greatly facilitated by the use of GIS.
To develop a time-area histogram for Baldy Fork (figure CS4-9) using GIS, the flow time from each GIS raster cell in the subarea to the outlet was determined. The cells were grouped into five minute time bands. Flow velocity in each cell depended on whether the flow segment type was primarily overland, shallow-concentrated, or stream channel. Within these segment types, surface roughness was specified. To create a unit hydrograph the time band GIS attribute data was copied into a spreadsheet, as will be detailed below.

**Roughness in GIS**

The land roughness was determined, given pre-fire land cover and post-fire burn severity, as shown in Tables CS4-1 through CS4-3. For typical overland and shallow-concentrated flow roughness values, see Technical Note Tables 10 and 11, respectively. Three roughness rasters were created, one for each fire condition. The raster grid sizes, based on the available digital elevation model (DEM) were ten meters square.

**Table CS4-1. Pre-fire roughness assumptions.**

<table>
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<tr>
<th>Flow segment</th>
<th>Land use assumptions</th>
<th>n value</th>
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</thead>
<tbody>
<tr>
<td>Overland</td>
<td>Grass, short-grass prairie</td>
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</tr>
<tr>
<td>Shallow-concentrated</td>
<td>Steep, rocky, less depth flow</td>
<td>0.08</td>
</tr>
<tr>
<td>Channel</td>
<td>Steep, rocky, less debris</td>
<td>0.045</td>
</tr>
</tbody>
</table>

**Table CS4-2. Post-fire (immediately) roughness assumptions.**

<table>
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<th>Land use assumptions</th>
<th>n value</th>
</tr>
</thead>
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<tr>
<td>Overland</td>
<td>Bare ground (severe, moderate burn)</td>
<td>0.011</td>
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<tr>
<td></td>
<td>Bare ground (low burn)</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Bare ground (no burn)</td>
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</tr>
<tr>
<td>Shallow-concentrated</td>
<td>Steep, rocky, more depth flow</td>
<td>0.06</td>
</tr>
<tr>
<td>Channel</td>
<td>Steep, rocky, more debris</td>
<td>0.05</td>
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</table>
Table CS4-3. Post-fire (1 year) roughness assumptions.

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<th>Land assumptions</th>
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<tbody>
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</tr>
<tr>
<td></td>
<td>Bare ground (low burn)</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Bare ground (no burn)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

To set the flow segment type of each raster cell, the typical GIS hydrologic function flow accumulation was used. In GIS, the flow accumulation value of each cell is the number of cells upstream of it (which therefore drain to it). The flow segment type for each ten meter square cell was determined using the following assumptions:

- Overland flow extends for about the first 100 feet of drainage (three cells).
- Shallow-concentrated flow extends for the next 1000 feet (thirty cells).
- Channel flow is assumed for any flow accumulation of more than thirty-three cells.

These GIS operations are performed with the raster calculator in ArcMap (ESRI 2010). An example of a raster calculator command is shown in figure CS4-10, circled in red. Note that the function Con is short for Conditional (an if statement). Given the flow accumulation layer flowAcc, the command may be translated into plain English, as follows. “If flowAcc is less than or equal to three (an overland flow segment) then set the roughness to 0.15. Otherwise, if flowAcc is less than or equal to 33 (a shallow-concentrated flow segment), set roughness to 0.08. If neither of those two conditions exists (flowAcc is greater than 33, a channel flow segment), then set the roughness to 0.045. Note in figure CS4-10 that the output raster is named “roughPreFire”.
To assess the burn condition of each raster cell, the burn severity shape file provided by USDA Forest Service was transformed into a raster layer within GIS. In that layer, (figure CS4-11) each cell with a high severity is assigned the number 4, medium 3, low 2, and unburned 1. For the pre-fire condition, using the data in Table CS4-1, the ArcMap Raster command is shown in Figure CS4-10. Note that the roughness layers may be created for the entire watershed, not each subarea separately.

For the condition immediately post-fire, using Table CS4-2, the raster command slightly more complicated:

\[
\text{Con}(\text{"rufPreFire"} == 0.08, 0.06, \text{Con}(\text{"rufPreFire"} == 0.045, 0.05, \text{Con}(\text{"burnRaster"} \geq 3, 0.011, \text{Con}(\text{"burnRaster"} == 2, 0.08, \text{"rufPreFire"}))))
\]

In plain English, this command says, “If the roughPreFire cell is 0.08 (i.e., a shallow-concentrated flow cell) then set the roughness to 0.06, otherwise, if the cell in roughPreFire is 0.045 (i.e., a channel cell) then set the roughness to 0.05. If neither of those conditions is true, then if the burn raster cell is greater than or equal to 3 (moderate or severe) then set the roughness to 0.011, otherwise if the burn raster cell is 2 then set the roughness to 0.08.
Finally, if none of those conditions is true, then set the new raster value to the same as the old raster value (unburned overland flow cells).

Figure CS4-11. Burn raster (red = high, orange = medium, yellow = low, green = no burn).

Flow slope in GIS

ArcMap (ESRI 2010) has a surface slope function that does not produce flow slope because it uses average elevations in a raster cell neighborhood. To obtain flow slope for each cell, the required information is elevation drop from that cell to the lowest neighbor, and the flow length between the two cells. Since flow in a three by three neighborhood of cells (figure CS4-12) may be either straight or diagonal, the flow length is one of two values. To create a flow distance raster in feet, given a 10 meter DEM, the two length values are either 46.40 feet (diagonal) or 32.81 feet. Figure CS4-12 shows the cell values created by the hydrology command flow direction. The following raster command to obtain flow length examines the flow direction raster for whether the flow is straight or diagonal:
To obtain elevation difference, the ArcToolbox function “Focal Statistics” may be used. Among the available statistics is the elevation drop to the lowest neighbor. Then a flow slope raster is obtained with a raster calculation dividing that elevation difference by the flow length. One final procedure is to prevent zero slopes by evaluating the flow slope raster and setting any zeroes to some minimum value.

*Velocity relationship derivations*

In addition to the velocity methods discussed in the Technical Note, other references such as USCOE (2013) and MacArthur and DeVries (1993) discuss flow velocity calculations for different channel segment types. Falling under the general category of *kinematic wave routing*, these techniques transform Manning’s equation into the general form shown in equation 1, where

\[ Q = ay^{5/3} \]

where:

\[ a = \frac{1.486\sqrt{S}}{n} \]  

(eq. CS4-1)

Given possible flow areas, often estimated by assuming a flow width, equation CS4-1 can, for overland flow, be formulated as equation CS4-2:

\[ V_{\text{overland}} = \frac{\phi\sqrt{S}}{n} \]

\[ \phi = \frac{1.486y^{2/3}}{w} \]
Note that the velocity equations in Technical Note Table 11 are also given in this form. Table CS4-4 shows the range of phi values for overland flow.

Table CS4-4. Values of $\phi$, given assumptions of overland flow width and depth.

<table>
<thead>
<tr>
<th>$y$ (in)</th>
<th>$W$ (ft)</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>2.0</td>
<td>0.056</td>
</tr>
<tr>
<td>0.25</td>
<td>2.5</td>
<td>0.045</td>
</tr>
<tr>
<td>0.25</td>
<td>3.0</td>
<td>0.038</td>
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<tr>
<td>0.25</td>
<td>3.5</td>
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<td>0.25</td>
<td>4.0</td>
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<tr>
<td>0.50</td>
<td>2.0</td>
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</tr>
<tr>
<td>0.50</td>
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<td>0.50</td>
<td>3.0</td>
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<td>0.50</td>
<td>3.5</td>
<td>0.0451</td>
</tr>
<tr>
<td>0.50</td>
<td>4.0</td>
<td>0.045</td>
</tr>
</tbody>
</table>

For shallow-concentrated flow (collector channels), assuming a triangular channel shape, MacArthur and DeVries (1993) develop an equation in the same form (equation CS4-3). Table CS4-5 shows the range of phi values for shallow-concentrated flow, given side-slope $z$ in length horizontal divided by length vertical.

$$V_{\text{shallow}} = \frac{\phi \sqrt{S}}{n}$$

where:

$$\phi = 0.94 A^{1/3} \left( \frac{z}{1 + z^2} \right)^{1/3}$$
For channel flow segments, assuming a trapezoidal shape, MacArthur and DeVries (1993) developed an equation of similar form, but more complicated because trapezoidal flow area is dependent on both channel bottom width and side slopes, in addition to depth. In a watershed, the equation also varies considerably with the drainage area. In other words, the flow area varies directly with drainage area. In kinematic wave routing models, the flow depth and area are computed along the channel, with a time-step change in flow depth. For a time-area histogram, an overall velocity for each cell is needed, regardless of what time during a storm. (Recall the UH assumption that the time is independent of the depth of direct runoff.)

One way to estimate flow area for any given GIS raster cell is to use regional regression equations, if available. For many areas of the country equations which relate bankfull flow area to watershed area have been developed. For the Gila Wilderness region Moody, Wirtanen, and Yard (2003) derived the following:

\[ A = 4.78B^{0.512} \quad r^2 = 0.9163 \quad \text{(eq. CS4-4)} \]

where: \( A = \) flow cross-sectional area (ft²)
\( B = \) watershed area (mi²)
Although the equation has a relatively high correlation, the authors included their data, which shows that many much larger watersheds were used than the subarea sizes within Whitewater Creek. To obtain a more applicable equation for such small subareas the authors’ data was culled for only the small watershed sizes, 23 total, and the following equation derived, for use in Whitewater Creek (where \( A \) and \( B \) are as defined above):

\[
A = \exp(0.5036 \ln B + 1.595) \quad r^2 = 0.88 \quad \text{(eq. CS4-5)}
\]

To obtain channel flow velocity, based on a trapezoidal channel shape (figure CS4-13), the following equation was used:

\[
V_{\text{channel}} = \frac{\phi \sqrt{S}}{n} \quad \text{where:} \quad \phi = 1.486 A^{1/3} \mu \quad \text{(eq. CS4-6)}
\]

**Figure CS4-13. Trapezoidal channel dimensions.**

The \( \mu \) in equation CS4-5 is derived from the choice of trapezoidal side slopes and the relationship between bottom width and depth, with a range of values shown in table CS4-6:
Table CS4-6. Trapezoidal channel parameters.

<table>
<thead>
<tr>
<th>z</th>
<th>w/y</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>0.457</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.447</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>0.437</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0.416</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0.410</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.403</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0.385</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0.381</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>0.376</td>
</tr>
</tbody>
</table>

Velocity relationships used in Whitewater Creek

Tables CS4-4, CS4-5, and CS4-6 show that variations in estimated flow depth have a relatively minor effect on velocity, especially in comparison to the effect of roughness. For Whitewater Creek, overland flow depth was assumed 0.25 inches, width 3 feet. With these assumptions, equation CS4-2 becomes equation CS4-7 below.

\[
V_{\text{overland}} = \frac{0.038S^{0.5}}{n} \tag{eq. CS4-7}
\]

For the shallow-concentrated flow segments, depth was assumed to be 0.5 feet and \( z \) was assumed to be 4, which yields (from equation CS4-3 and Table CS4-5) equation CS4-8:

\[
V_{\text{collector}} = \frac{0.58\sqrt{S}}{n} \tag{eq. CS4-8}
\]

For the channel flow segments, a separate raster layer for flow cross-sectional area was obtained using equation CS4-5. Then, assuming a trapezoidal channel, two different relationships were derived depending on slope. For a flow slope greater than or equal to 0.05, width-depth ratio was assumed 3 and \( z = 2 \). For flow slope less than 0.05, width-depth ratio was assumed 5 and \( z = 3 \). Then, using equation CS4-6 and Table CS4-6, the following equations were derived:
When creating the velocity rasters, the possibility exists that velocity will come out unreasonably high due to very steep slopes, such as vertical drops, or zero due to flat slopes. A better travel time estimate was obtained for Whitewater Creek by restricting the maximum and minimum velocities to 15 and 0.10 feet per second, respectively.

**Travel time in GIS**

In ArcGIS, the hydrology tool *Flow Length* is used to obtain the flow travel time of any cell to its outlet. This is possible because the tool can apply an optional *weight* raster, which may contain such parameters as unit conversions and channel sinuosity, as shown in equation CS4-11. The time in minutes is obtained using a weight raster that includes a sinuosity of 1.1, a conversion of meters to feet (since the tool is using the 10m DEM), and from seconds to minutes.

\[
\text{time} = \text{flowLength} \times \text{weight} \quad \text{where:} \quad \text{weight} = \frac{1.1 \times 3.28083}{\text{flowVelocity} \times 60} \quad (\text{eq. CS4-11})
\]

The resulting time raster can then be reallocated to group the cells into time bands of, say, five minutes. The 5-minute time band raster for Baldy Fork subarea is shown in Figure CS4-14.
The Attribute Table shows the number of cells in each of 21 time bands in Baldy Fork. Since there are 21 five-minute bands the longest drainage time (or time of concentration) may be estimated at 1 hour and 45 minutes. However, the hydrologist can note the number of cells in those later time bands. Sometimes they become so few that a better estimate of time of concentration is taken to be earlier. For Baldy Fork, one might select timeband 18, or 90 minutes, because later time bands have only a total of 61 cells among them. Note that a separate travel time raster is produced for the three scenarios, pre-fire, post-fire immediately, and post-fire after one year.

Spreadsheet derivation of time-area histogram and unit hydrograph

To obtain a time-area histogram the five-minute time band attribute table is copied into a spreadsheet. This procedure is described in many hydrology textbooks, including Bedient, Huber, and Vieux (2012). Since the cells are 100 square meters each, the area drained by each time band can be converted to any convenient unit, such as acres, in the
spreadsheet. The resulting time-area histogram for Baldy Fork pre-fire is shown in figure CS4-15. To obtain a unit hydrograph, a duration must be chosen and one inch of effective rainfall applied within that timeframe. The runoff from each time band is computed, lagged, and summed.

A screenshot of the spreadsheet is shown in figure CS4-16. The flow values in column G, in acre-inches, are obtained by summing the lagged flow values in columns K through P. Those flow values are obtained by multiplying the 5-minute increment of effective rainfall (0.167 inches) by the area in acres of each time band (from the GIS attribute table, column B). Then, in column H, the flow is converted to cfs. The 30 minute unit hydrograph peak (cell H14) is 1817 cfs, the peak that would be expected from Baldy Fork if one inch of effective rainfall was evenly distributed over the subarea in thirty minutes. Figure CS4-17 shows the thirty minute unit hydgrpahs for Baldy Fork under the three scenarios.
The 30-minute unit hydrograph is applicable when the duration of excess rainfall from a given event is thirty minutes long. To enable a unit hydrograph compilation to apply for any duration of excess rainfall, a so-called S-curve is derived by lagging the 30-minute unit hydrographs in successive 30-minute periods, as shown in figure CS4-18.
The maximum of the S-curve is the unit flow for the subarea—the amount of runoff if a full inch of effective rainfall runs off the entire watershed area in thirty minutes. In the case of Baldy Fork, since the total area is 57,124,070 square feet the unit flow is:

\[
\frac{57,124,070 \text{ ft}^2 \times 1 \text{ in}}{30 \text{ min}} \times \frac{1 \text{ ft}}{12 \text{ in}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 2,644 \text{ cfs}
\]

The hydrology model HEC-HMS requires the S-curve to be given as a percent of lag versus percent of unit flow. Watershed lag is the time from the center of the effective rainfall duration to the runoff peak. The lag for Baldy Fork can be seen from the 30-minute unit hydrograph, figure CS4-17, to go from 15 minutes (center of rainfall) to 45 minutes (peak) or 30 minutes. The S-Curve, reformulated for input into HEC-HMS is shown in figure CS4-19. The values along the x-axis come from the times of figure CS4-18 divided by the lag time, and the values of the y-axis come from the flow values of figure CS4-18 divided by the unit flow.
This section has shown the development of the UH S-curve input to HecHMS for one subarea in the Whitewater Creek watershed. The same procedures were followed to produce S-curves for every subarea in the model for the three scenarios.

**Figure CS4-19. Baldy Fork S-curves for HecHMS, three scenarios**

**Infiltration Loss Method: Green & Ampt Equation**

The process-based Green & Ampt method of infiltration uses soil properties to model progressive loss of surface water into the soil and the change in soil moisture capacity. Although GA is a point-model, the more spatially homogeneous the soil in a given subarea the more applicable this method. HEC-HMS does have the ability to do a grid-based Green & Ampt infiltration, modeling from cell to cell within a subarea, but this requires more data than is available for the Whitewater Creek basin. Being within the Gila Wilderness, spatially distributed soil data is not available. For the entire watershed, the Green & Ampt parameters were estimated based on soil type and using the Technical Note Table 12. The assumed soil texture was “loamy sand” with porosity of 0.42 cubic inches of pore space per cubic inch of soil. The initial moisture content was assumed to be near “field capacity” or 15 percent of the porosity. Converting from the metric units of Table 12, the wetting front suction was estimated at 2.4 inches and the hydraulic conductivity 1.6 inches per hour.
A final specification for this method is the percent impervious surface of the subarea. This was set at zero for the pre-fire condition. For post-wildfire conditions, the percent imperviousness was used as a way to account for soil hydrophobicity. However, water-repellent soil is not the same as a parking lot pavement. It is consistent in neither spatial extent, nor depth or layer thickness. In addition, higher rainfall rates can sometimes penetrate hydrophobic soils and infiltrate more than lower rainfall rates. The hydrophobicity will then generally return upon drying. Finally, high soil burn severity is not a fool-proof predictor of the location of hydrophobic soil.

For modeling soil hydrophobicity in the Whitewater Creek watershed, the percent imperviousness for the immediately post-fire condition for each subarea was set to 65% of the high soil burn severity area for the 25-year and more frequent rainfall events. For the 100-year rainfall event, the imperviousness was set to 30% of the high burn severity area. For the post-fire 1-year later condition, the imperviousness was set to 45% of the high burn severity for the 25-year rainfall and more frequent events. For the 100-year rainfall event, the imperviousness was set to 15% of the high burn severity.

Initial Abstraction, Surface Ponding, Canopy Loss

The CN method includes an initial abstraction which is considered to represent interception by vegetation, surface storage, and infiltration prior to runoff. This initial abstraction is not changeable by the user and is a function of the potential maximum loss to infiltration, ultimately a fraction of the user choice of curve number. While the CN method is provided as an option by HEC-HMS, the program also provides explicit canopy loss and surface loss methods. Since the Green & Ampt loss method was chosen for the Whitewater Creek analysis, further losses due to vegetation and surface depressions needed to be modeled.

The options for these losses are not highly sophisticated in HEC-HMS. A maximum retention is specified by the user and an initial condition. The HEC-HMS user manual (USCOE-HEC 2013) states that use of a canopy method is generally not necessary for
storm events, whereas continuous simulation modeling would take into account the evaporation of intercepted moisture between storms. However, forest canopy is not an insignificant moisture interceptor. The flashiness of Southwestern US storm events contributes to raising the significance of canopy. In addition, for wildfire events in forests the near total loss of canopy represents a widespread landscape change. For Whitewater Creek pre-fire conditions the canopy initial storage was set to zero and the maximum storage set to 0.05 inches. For post-wildfire conditions the canopy interception was set to none.  

Surface storage is a separate option in HEC-HMS, represents loss of incoming rainfall to surface depressions, and may be used to represent the retention of moisture in the forest litter or duff layer. For Whitewater Creek pre-fire condition the initial storage was set to zero and maximum loss set to 0.03 inches. For post-fire conditions the maximum loss was set to 0.01 inches.  

**Baseflow**

HEC-HMS provides several options for modeling baseflow. The recession method is common for flood simulations, by which the initial baseflow is specified, along with a constant to modify the rate of exponential recession, and a threshold at which the baseflow is reset after the event. In the arid Southwest US baseflow is generally less significant when the concern is storm-event flood peaks. However, the Whitewater Creek analysis included the recession baseflow option, with the initial baseflow set to 0.25 cfs per square mile of subbasin drainage area.  

**Rainfall events examined**

The NOAA National Weather Service Precipitation Frequency Data Server (NOAA 2013) was recently updated for New Mexico. The website (see reference) allows the user to select a given precise location on a map and provides the total storm values for various recurrence intervals and durations. Often the 24-hour duration values are used. In the flashy thunderstorm prone Southwestern US, a shorter duration may be more applicable.
Since the BAER hydrologic analysis for the Gila Wilderness used a 6-hour duration, this was selected for the current analysis.

The total rainfall values shown in Table CS4-7 show that there is some orographic effect within the watershed, lowering rainfall values with descending elevation toward the outlet. The first flood hydrograph analysis of this case study assumed that these rainfall amounts would fall on all subareas at the same time. This is unrealistic but provides conservatively high peaks and larger volume hydrographs.

Table CS4-7. Whitewater Creek watershed 6-hour duration storm totals.

<table>
<thead>
<tr>
<th>Watershed area</th>
<th>2-year (in)</th>
<th>25-year (in)</th>
<th>100-year (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Whitewater</td>
<td>1.54</td>
<td>2.73</td>
<td>3.49</td>
</tr>
<tr>
<td>SF Whitewater</td>
<td>1.42</td>
<td>2.49</td>
<td>3.39</td>
</tr>
<tr>
<td>Lower Whitewater</td>
<td>1.20</td>
<td>2.12</td>
<td>2.39</td>
</tr>
</tbody>
</table>

A second and third set of flood hydrograph analyses considered the three recurrence interval 6-hour rainfalls from Table CS4-7 with an areal reduction factor obtained from figure CS4-21. The second set of analyses centered the storms over the upper Whitewater Creek portion of the watershed and the third set centered the storms over the SF Whitewater sub-watershed. For these areally reduced analyses, each basin received a rainfall rate lowered in proportion to their distance from the assumed center of the storm.

Figure CS4-20, developed for Walnet Gulch AZ, is assumed applicable to Whitewater Creek, in the same geographic region, about 180 miles away. As Whitewater Creek is about 23 km wide, east to west, the areal reduction from figure CS4-20 is significant. The largest area on the graph is 300 square kilometers, which corresponds to a radius of about 10 kilometers. Therefore, many of the sub-basins of Whitewater Creek will be farther away from the storm center than can be analyzed with the figure. Rather than reduce the rainfall of more remote subareas to zero, the analyses applied minimum values
The selected storm centerings for the areally reduced analyses are shown in figure CS4-21. The red star marks the upper Whitewater centering and the red circular line shows the 10km radius for that storm. The blue star marks the storm centering in the SF Whitewater sub-basin, with blue circular line showing the 10km radius from that point.

Figure CS4-20. Areal reduction factors developed for 6-hour duration storms at Walnut Gulch AZ Experimental Watershed (modified, from Osborn, Lane, and Myers 1980).

To distribute the rainfall totals over time, the standard SCS Type II rainfall distribution, considered applicable in New Mexico, was used. Although the standard distribution pertains to a 24-hour duration, it is easily modified by proportioning for shorter durations, including the 6-hour.
Sediment Bulking

This analysis did not attempt to model sedimentation. As discussed in the main body of the Technical Note, the maximum sediment concentration short of “debris flow” is considered about twenty percent. A USGS report specifically concerning the Whitewater Baldy Complex wildfire (Tillery, Matherne, and Verdin, 2012) estimated high probabilities in Whitewater Creek of debris flows from 30-minute duration rainfall events for recurrence intervals of 2-year, 10-year, and 25-year. A shorter duration storm of higher intensity is generally required to generate debris flow.

Figure CS4-22 is a screenshot from Plate 3 of Tillery, Matherne, and Verdin (2012) which shows their overall debris flow hazard findings for Whitewater Creek. Notice the main channel of Whitewater Creek in blue and the community of Glenwood at the downstream end circled in red. Sub-basins labeled 92 and 93 are the upper Whitewater, sub-basin 91 is the SF Whitewater, and sub-basin 90 is the upper Little Whitewater. These of brown color are the highest hazard for debris flow in response to a 25-year 30-minute rainfall event (a total storm rainfall of about 1.54 inches).
As a conservative estimate of possible sediment bulking for the events examined in this analysis, with six-hour duration, the sub-basins in brown from figure CS4-23 were considered 20 percent bulked and the sub-basins in yellow, 10 percent bulked.

**Results and Discussion**

Figure CS4-23 shows the four locations for which modeling data is reported herein. The model user can receive results for the outlet of any sub-basin (shown in the figure by different pastel colors). The output is reported for three recurrence intervals, 2-year, 25-year, and 100-year, for the three scenarios, pre-fire, post-fire immediately, and post-fire one year later. In addition, three types of storm centerings were considered. One for which no areal reduction is applied and the rainfall values of Table CS4-7 are applied at the same time over the entire watershed. The second and third centerings are as shown in figure CS4-21, over the upper Whitewater subarea or over the SF Whitewater, with areal reductions determined from the curves of figure CS4-20.
Figure CS4-23. Locations of reported HEC-HMS modeling output.

1 = Whitewater Creek outlet at Glenwood NM
2 = USGS gage “Whitewater Creek at Catwalk” (installed 2012)
3 = Upper Whitewater Creek just above the confluence of SF Whitewater
4 = SF Whitewater just above the confluence of the Whitewater.

Table CS4-8 shows HEC-HMS modeling results for the rainfall events with no areal reduction. (These runs include the slight reduction, shown in Table CS4-7, due to the fact that the data provided by NOAA, for three general areas of the watershed, lessens for each recurrence interval as location changes toward the west.)
These peaks are considered conservatively high, since no areal reduction was applied and the nature of storms in the Gila Wilderness area is more localized convective thunderstorms. In addition, although the unit hydrographs did change between the two post-fire scenarios, due to the consideration of some vegetation regrowth, the majority of the drop in the peak for the one year later condition came from assumptions about the reduction in hydrophobic soils. No field verification was completed for this analysis and the BAER report (USDA Forest Service, 2012) did not discuss the extent of hydrophobic soil. Estimates for this analysis were made using the soil burn severity GIS shapefiles and from the findings of Tillery, Matherne, and Verdin (2012). Figure CS4-24 shows the full hydrographs for the 100-year no areal reduction scenario at the Whitewater Creek outlet, near Glenwood.
The areal reductions, as discussed above came from Osborn, Lane, and Myers, (1980), in particular their examination of Walnut Gulch AZ. That paper also examined a watershed near Alamogordo NM, which showed less areal reduction than Walnut Gulch. However, the Gila Wilderness area is considered closer geographically to Walnut Gulch than to Alamogordo. Nevertheless, the areal reductions may be less at Whitewater Creek than what were applied for the results reported in Table CS4-9. Note that the 100-year pre-fire peak at Glenwood between Tables CS4-8 and CS4-9 drops from 14,304 cfs to 2,904 cfs. The post-fire reductions in peak are less dramatic, with the post-fire immediately peak at Glenwood dropping from 20,970 cfs to 11,826 cfs.
Table CS4-9. HecHMS output: hydrograph peaks at four locations (areal reductions applied, with centerings as shown in figure CS4-22).

<table>
<thead>
<tr>
<th>Storm</th>
<th>Location</th>
<th>Upper Whitewater centering</th>
<th>SF Whitewater centering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pre-fire peak discharge (cfs)</td>
<td>Post-fire peak (immediately following fire) (cfs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3,126</td>
<td>10,708</td>
</tr>
<tr>
<td>100-yr</td>
<td>abv SF</td>
<td>3</td>
<td>1,534</td>
</tr>
<tr>
<td>100-yr</td>
<td>SF at mouth</td>
<td>3</td>
<td>1,534</td>
</tr>
<tr>
<td></td>
<td>gage</td>
<td>3,118</td>
<td>11,785</td>
</tr>
<tr>
<td>100-yr</td>
<td>Glenwood</td>
<td>2,904</td>
<td>11,826</td>
</tr>
<tr>
<td>25-yr</td>
<td>abv SF</td>
<td>763</td>
<td>7,274</td>
</tr>
<tr>
<td>25-yr</td>
<td>SF at mouth</td>
<td>3</td>
<td>1,338</td>
</tr>
<tr>
<td>25-yr</td>
<td>gage</td>
<td>753</td>
<td>8,247</td>
</tr>
<tr>
<td>25-yr</td>
<td>Glenwood</td>
<td>682</td>
<td>8,355</td>
</tr>
</tbody>
</table>
Comparing the results in Table CS-9 between the two storm centerings varies depending on recurrence interval. For the 100-year flood, the pre-fire peak at Glenwood is 22% less if the same storm is centered over the SF Whitewater rather than the upper Whitewater, but the post-fire immediately results show a 1% greater peak at Glenwood if the storm is centered over the SF Whitewater. This is a direct result of the burn severity between the two sub-basins. As the sub-basins heal, the results show that the Glenwood 100-year peak moves toward being greater if the storm is centered over the upper Whitewater. Figure CS4-26 shows the post-fire results for the 100-year peaks at Glenwood under both centering conditions. Figure CS4-27 shows the same results for the 25-year recurrence interval. Note that storms centered over the SF Whitewater sub-basin peak at Glenwood about 15 minutes earlier than if they were centered over the upper Whitewater.
Figure CS4-26. 100-year post-fire hydrographs at Glenwood between storm centerings in the upper Whitewater sub-basin and the SF Whitewater sub-basin.

Figure CS4-27. 25-year post-fire hydrographs at Glenwood between storm centerings in the upper Whitewater sub-basin and the SF Whitewater sub-basin.
Sediment bulked peak flows have been computed as mentioned above, with the upstream end (about one third) of the Upper Whitewater sub-basin contributing a 20 percent sediment discharge, the lower end 10 percent, and the entire SF Whitewater sub-basin contributing 20 percent. These results are shown in Table CS4-10.

Table CS4-10. Sediment bulked flows for Whitewater Creek.

<table>
<thead>
<tr>
<th>Storm</th>
<th>Location</th>
<th>Upper centering</th>
<th>SF centering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Post-fire peak (immediately following fire) (cfs)</td>
<td>Post-fire peak discharge (One year later) (cfs)</td>
</tr>
<tr>
<td>100-yr</td>
<td>abv SF</td>
<td>11,848</td>
<td>8,272</td>
</tr>
<tr>
<td>100-yr</td>
<td>SF at mouth</td>
<td>1,534</td>
<td>1,052</td>
</tr>
<tr>
<td>100-yr</td>
<td>gage</td>
<td>13,591</td>
<td>10,236</td>
</tr>
<tr>
<td>100-yr</td>
<td>Glenwood</td>
<td>13,632</td>
<td>10,158</td>
</tr>
<tr>
<td>25-yr</td>
<td>abv SF</td>
<td>7,975</td>
<td>5,011</td>
</tr>
<tr>
<td>25-yr</td>
<td>SF at mouth</td>
<td>1,534</td>
<td>1,052</td>
</tr>
<tr>
<td>25-yr</td>
<td>gage</td>
<td>9,532</td>
<td>6,518</td>
</tr>
<tr>
<td>25-yr</td>
<td>Glenwood</td>
<td>9,641</td>
<td>6,529</td>
</tr>
</tbody>
</table>

Modeling observed data

September 2013 brought heavy rainfall to the Rockies from Wyoming to New Mexico. The extensive damage in and around Boulder, Lyons, and Estes Park Colorado grabbed national headlines. But storms of similar magnitude also visited the Gila Wilderness watersheds that had been previously damaged by the Whitewater-Baldy Complex fire.
The largest rainfall totals in the Whitewater Creek watershed were recorded between 14 and 15 September 2013. The NOAA Precipitation-Frequency data server (NOAA 2013) data for a storm centering over the confluence of the SF Whitewater is shown in Table CS4-11, along with the rainfall totals (in blue) for the event recorded at the Catwalk gage.

Table CS4-11. NOAA Precip-Frequency values and Sep 2013 rainfall event from Catwalk gage

<table>
<thead>
<tr>
<th>Duration</th>
<th>Recurrence--&gt;</th>
<th>50-year</th>
<th>100-year</th>
<th>200-year</th>
<th>500-year</th>
<th>1000-year</th>
<th>gage</th>
<th>14-15 Sep 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-hour</td>
<td></td>
<td>1.83</td>
<td>2.04</td>
<td>2.24</td>
<td>2.5</td>
<td>2.71</td>
<td>3.01</td>
<td>9-10 pm</td>
</tr>
<tr>
<td>2-hour</td>
<td></td>
<td>2.02</td>
<td>2.27</td>
<td>2.52</td>
<td>2.86</td>
<td>3.14</td>
<td>4.09</td>
<td>9-11 pm</td>
</tr>
<tr>
<td>3-hour</td>
<td></td>
<td>2.12</td>
<td>2.38</td>
<td>2.66</td>
<td>3.04</td>
<td>3.35</td>
<td>6.10</td>
<td>9-midnight</td>
</tr>
<tr>
<td>6-hour</td>
<td></td>
<td>2.48</td>
<td>2.8</td>
<td>3.14</td>
<td>3.61</td>
<td>3.99</td>
<td>6.85</td>
<td>9pm-3am</td>
</tr>
</tbody>
</table>

For all four durations shown in the table the event was more rare than a 1,000 year recurrence. Evidence of storm areal extent is provided by the fact that the Hummingbird Saddle gage during this event received minimal precipitation. Between 9 pm and midnight, while the Catwalk gage was recording 6.10 inches of rainfall, the Hummingbird Saddle gage received zero. For the three hours after midnight, rainfall at Calwalk dropped off considerably (0.75 inches, total) and Hummingbird Saddle recorded a similar total (0.93 inches). Figure CS4-28 shows the storm event for which modeling results are presented below.
To have two gages in a post-wildfire watershed may be considered a great luxury, but the data will be far from adequate to calibrate a hydrologic model. However, such data can be used to show whether the hydrologic model is reasonable. For example, three runs with different assumed storm centerings were made for this event. The same areal reduction factors as shown in figure CS4-21 were used (although the rarest event on that graph is 100-year, compared to the observed event, more rare than a 1000-year recurrence). The areal reduction for the observed event could be expected to show a steeper drop off than the 100-year event in the figure. This is not contradicted by the concurrent rainfall at Hummingbird Saddle. To estimate sediment bulking, the extreme rarity and magnitude of the event was considered to justify a 20% estimate for both brown and yellow sub-watersheds from figure CS4-23. The event occurred about a year after the wildfire, so some healing could have occurred. However, this event could have produced debris flow, and uncertainty of sediment transport may be considered significant for this observed event. To create sediment hydrographs, the Data Storage System (DSS) functionality of HEC-HMS was employed. A separate program HEC-DSSVue provides hydrograph manipulation tools, with which sediment hydrographs were made by multiplying individual sub-basin flow hydrographs by 20%. The database preserves the timing, so that the sub-basin bulked hydrographs can be summed for an
outlet such as the Catwalk gage. Only two subwatershed sediment hydrographs were required (as can be seen by examining figure CS4-23). One for the upper Whitewater and one for the entire SF Whitewater. These were combined to create a total sediment hydrograph at the gage. Figure CS4-29 shows modeled versus observed flows.

Figure CS4-29. Whitewater Creek flood 14-15 Sep 2013, observed and modeled

Conclusions
The post-fire hydrograph results are highly dependent on the amount of hydrophobic soil and the timing of its breakdown and return to pre-fire conditions. This is impossible to predict accurately without extensive field investigation. The burn severity mapping can be considered to at least rule out hydrophobicity in unburned and low burned areas. The extent to which hydrophobicity truly excludes infiltration in highly burned areas should be investigated. Although the findings of the research literature indicate that post-wildfire hydrophobic soils can persist for over five years, critical questions remain for hydrologic modeling. For example, does hydrophobicity immediately post-fire completely cover a landscape or only partially? And does the breakdown of hydrophobic effects on runoff occur more rapidly than the complete disappearance of the phenomenon because of the non-homogeneity on a landscape?
The second major issue for hydrologic modeling, particularly in the arid Southwestern US, is the extent of areal reduction in any given area. A literature search for this analysis turned up very little, and studies by NOAA that were scheduled to be underway by 2006 apparently have not been completed.

In considering the methodology differences between this case study and others, which use NRCS Curve Number and dimensionless unit hydrographs, a number of salient points arise. Practitioners accounting for high burn severity and/or hydrophobicity have found that CN values should be set very high, usually around 95. See tables 5, 7, 8, and 9 in this document. This need to approach the very upper limit of CNs may have been necessary not only because hydrophobicity does, indeed, somewhat mimic a pavement, but also because the standard NRCS peak factor was not adjusted. The standard peak factor is usually too low for steep mountain streams. However, the practice of running up the CN to account for hydrophobicity has no less scientific merit than setting sub-basin percents of imperviousness, as was done in this case study. The need for some way to rapidly assess hydrophobic effects becomes apparent.

Although the time-area histogram methodology demonstrated in this case study precludes the need to determine peak factors, the GIS manipulations require analysis time, which can be a function of the GIS experience of the hydrologist. Perhaps scripts could be written to speed up the process, but the greater the number of sub-areas the more analysis time needed to create time-area based UHs. However, the numerous GIS layers available for use in post-wildfire analyses, especially regarding soil burn severity, should encourage the hydrologist to increase GIS proficiency.

References

Case Study 4: Whitewater Creek, Gila Wilderness, New Mexico


Case Study 5: Saratoga Springs, UT

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 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 CS5-1 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 countermeasures 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 CS5-4. 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 CS5-5 and CS5-6). 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 CS5-1. State of Utah and fire location, about 40 miles south of Salt Lake City.

Figure CS5-2. Burning watershed from Eagle Mountain, UT, 21 June 2012.
Photo by Cindi Braby, Eagle Mountain, UT
Figure CS5-3. Burning watershed from Eagle Mountain, UT, 22 June 2012.

Photo by Cindi Braby, Eagle Mountain, UT.

Figure CS5-4. Burned watershed flow direction into Saratoga Springs, UT from 1 September 2012 event.
Figure CS5- 5. Sediment laden flow through residential neighborhood.

Photo courtesy of Utah County.

Figure CS5- 6. Typical sediment composition in residential area.

Photo courtesy of 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 CS5-1 and are shown on the Figure CS5-7 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 CS5-8).

**Table CS5- 1. Six stream gages near Saratoga Springs, UT**

<table>
<thead>
<tr>
<th># on fig. CS5-8</th>
<th>USGS #</th>
<th>Drainage (sq. mi.)</th>
<th>gage name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10172790</td>
<td>5.77</td>
<td>Settlement Canyon nr Tooele UT</td>
</tr>
<tr>
<td>2</td>
<td>10172805</td>
<td>5.38</td>
<td>N. Willow Creek nr Grantsville UT</td>
</tr>
<tr>
<td>3</td>
<td>10172800</td>
<td>4.19</td>
<td>S. Willow Creek nr Grantsville UT</td>
</tr>
<tr>
<td>4</td>
<td>10166430</td>
<td>26.5</td>
<td>W. Canyon Creek nr Cedar Fort UT</td>
</tr>
<tr>
<td>5</td>
<td>10172765</td>
<td>6.7</td>
<td>Clover Creek abv Big Hollow nr Clover UT</td>
</tr>
<tr>
<td>6</td>
<td>10172910</td>
<td>16.8</td>
<td>Settlement Creek abv Resvr nr Tooele UT</td>
</tr>
</tbody>
</table>
Of the six nearby gaged watersheds, numbers 1 through 3 (Table CS5-1) 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 CS5-8, the graphs of those three gages are the higher ones: blue, green, and violet.

**Tc 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 CS5-9. Subareas 1 and 2 converge and provide outlet to the Saratoga Springs residential areas shown in Figures CS5-4 through CS5-6. Subarea 1 is known as Israel Canyon. See Tables CS5-2 and CS5-3 for WinTR-20 basic input related to these subareas, including selected pre-fire and post-fire CN.
Table CS5-2. Burned watershed subarea input to WinTr-20.

<table>
<thead>
<tr>
<th>Subarea</th>
<th>Drainage (sq. mil)</th>
<th>CN (Pre-fire)</th>
<th>CN (Post-fire)</th>
<th>$T_c$ (Pre-fire) (hrs)</th>
<th>$T_c$ (Post-fire) (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.81</td>
<td>62</td>
<td>74</td>
<td>0.92</td>
<td>0.85</td>
</tr>
<tr>
<td>2</td>
<td>0.60</td>
<td>74</td>
<td>80</td>
<td>0.40</td>
<td>0.37</td>
</tr>
<tr>
<td>1 + 2</td>
<td>2.50</td>
<td>65</td>
<td>75</td>
<td>1.00</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Figure CS5-9. 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 CS5-10. Curve number from cover, for hydrologic soil groups (Goodrich et al. 2005)

Table CS5-3 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>
<thead>
<tr>
<th>Burn severity</th>
<th>NLCD</th>
<th>Cover name</th>
<th>HSG A</th>
<th>HSG B</th>
<th>HSG C</th>
<th>HSG D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>41</td>
<td>Deciduous Forest</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>Evergreen Forest</td>
<td>4</td>
<td>16</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>Mixed Forest</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>Shrubland</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Moderate</td>
<td>41</td>
<td>Deciduous Forest</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>Evergreen Forest</td>
<td>10</td>
<td>21</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>Mixed Forest</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>Shrubland</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>High</td>
<td>41</td>
<td>Deciduous Forest</td>
<td>15</td>
<td>16</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>Evergreen Forest</td>
<td>15</td>
<td>27</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>Mixed Forest</td>
<td>15</td>
<td>16</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>Shrubland</td>
<td>10</td>
<td>11</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

Time of concentration post-fire modification

Tc 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 CS5-11). 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.

*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 CS5-4. Output variables available in AGWA.**

<table>
<thead>
<tr>
<th>KINEROS</th>
<th>SWAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration (mm; m$^3$/km)</td>
<td>Channel Discharge (m$^3$/day)</td>
</tr>
<tr>
<td>Infiltration (in; ac-ft/mi)</td>
<td>ET (mm)</td>
</tr>
<tr>
<td>Runoff (mm)</td>
<td>Percolation (mm)</td>
</tr>
<tr>
<td>Runoff (m$^3$)</td>
<td>Surface runoff (mm)</td>
</tr>
<tr>
<td>Sediment yield (kg/ha)</td>
<td>Transmission loss (mm)</td>
</tr>
<tr>
<td>Peak flow (m$^3$/s), Peak flow (mm/hr)</td>
<td>Water yield (mm)</td>
</tr>
<tr>
<td>Sediment discharge (kg/s)</td>
<td>Sediment yield (t/ha)</td>
</tr>
<tr>
<td>■</td>
<td>■</td>
</tr>
</tbody>
</table>

### 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.

\[
\ln V = 0.59(\ln S) + 0.65B^{1/2} + 0.18R^{1/2} + 7.21 \quad \text{(eq. CS5-1)}
\]

where:  
- \(V\) = 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 CS5-12 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 CS5-12 were considered.
Figure CS5-12. Comparison of observed and simulated pre-and post-fire peak discharges per unit drainage basin area in New Mexico. (McLan 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.

\[ Q_p = 17.4 A_b^{0.4} \]
\[ R^2 = 0.42 \]  
(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 CS5-13. 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 CS5-5 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 CS5-6 reflects the pre- and post-fire peak discharges.
Table CS5-5. Cubic feet per second per square mile (CSM) from WinTR-20 pre-fire results and selected stream gages.

<table>
<thead>
<tr>
<th></th>
<th>2-year (50%-chance) (CSM)</th>
<th>5-year (20%-chance) (CSM)</th>
<th>10-year (10%-chance) (CSM)</th>
<th>25-year (4%-chance) (CSM)</th>
<th>50-year (2%-chance) (CSM)</th>
<th>100-year (1%-chance) (CSM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WinTR-20 Pre-fire</td>
<td>0</td>
<td>2.5</td>
<td>6.8</td>
<td>28.4</td>
<td>58</td>
<td>100.8</td>
</tr>
<tr>
<td>Observed CSM from Figure 8</td>
<td>~5</td>
<td>12</td>
<td>&lt;20</td>
<td>30</td>
<td>45</td>
<td>60</td>
</tr>
</tbody>
</table>

Table CS5-6. Burned watershed pre-fire and post-fire peak flow output from WinTR-20.

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

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 CS5-7) 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 CS5-14. Burned watershed pre-fire and post-fire hydrographs from WinTR-20.

Table CS5-7. Storm totals runoff for various recurrence intervals, input to WinTR-20 and post-fire runoff values for Subarea 1+2.

<table>
<thead>
<tr>
<th>Percent Chance</th>
<th>2-year (50%-chance)</th>
<th>5-yr (25%-chance)</th>
<th>10-yr (10%-chance)</th>
<th>25-yr (4%-chance)</th>
<th>50-yr (2%-chance)</th>
<th>100-yr (1%-chance)</th>
<th>200-yr (0.5%-chance)</th>
<th>500-yr (0.2%-chance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Fire runoff (inches) Subarea 1+2</td>
<td>0.01</td>
<td>0.03</td>
<td>0.07</td>
<td>0.13</td>
<td>0.19</td>
<td>0.27</td>
<td>0.35</td>
<td>0.48</td>
</tr>
<tr>
<td>Post Fire runoff (inches) Subarea 1+2</td>
<td>0.09</td>
<td>0.17</td>
<td>0.25</td>
<td>0.38</td>
<td>0.48</td>
<td>0.60</td>
<td>0.73</td>
<td>0.92</td>
</tr>
<tr>
<td>Pre Fire - Runoff in acre feet over 2.5 sq.mi</td>
<td>1</td>
<td>4</td>
<td>9</td>
<td>17</td>
<td>25</td>
<td>36</td>
<td>47</td>
<td>64</td>
</tr>
<tr>
<td>Post Fire - Runoff in acre feet over 2.5 sq.mi</td>
<td>12</td>
<td>23</td>
<td>33</td>
<td>51</td>
<td>64</td>
<td>80</td>
<td>97</td>
<td>123</td>
</tr>
</tbody>
</table>
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 CS5-8 was derived by taking the post-fire clear flow hydrographs of Figure CS5-14, 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 CS5-8.

Table CS5-8. Burned watershed post-fire event total sediment runoff in tons.

<table>
<thead>
<tr>
<th>Event totals</th>
<th>25-yr (4% chance) (tons)</th>
<th>50-yr (2% chance) (tons)</th>
<th>100-yr (1% chance) (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment</td>
<td>23,705</td>
<td>29,943</td>
<td>37,429</td>
</tr>
</tbody>
</table>

**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 CS5-9 shows the WinTR-20 pre-fire and post-fire peaks (in cfs per square mile) for comparison with Figure CS5-12. 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 CS5-9. Saratoga Springs burned watershed pre-fire and post-fire peaks (CSM) from WinTR-20.

<table>
<thead>
<tr>
<th>Flood</th>
<th>25-year (4% chance)</th>
<th>50-year (2% chance)</th>
<th>100-year (1% chance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-fire (CSM)</td>
<td>28.4</td>
<td>58</td>
<td>100.8</td>
</tr>
<tr>
<td>Post-fire (CSM)</td>
<td>136.8</td>
<td>206.4</td>
<td>291.2</td>
</tr>
</tbody>
</table>

**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 WinTR-20 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 $T_c$. 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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