Waldo Canyon Fire Watershed Assessment: The *WARSSS* Results




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Submitted to:

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Pike National Forest

Natural Resources Conservation Service

Colorado Water Conservation Board

Colorado Department of Transportation

The Navigators/Glen Eyrie

City of Colorado Springs

Colorado Springs Utilities

El Paso County

Colorado Water Resources and Power Development Authority

Coalition for the Upper South Platte

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Waldo Canyon Fire Watershed Assessment:

The *WARSSS* Results

Introduction

The Waldo Canyon Fire burned *18,247 acres* within the foothills and mountains of the Rampart Range immediately northwest of Colorado Springs, Colorado, in El Paso County. The fire perimeter and relative burn severity are displayed in **Figure 1**, which includes public and private lands. The fire started Saturday, June 23rd, 2012, and was fully contained Tuesday, July 10th, 2012, destroying 346 homes.

A watershed assessment was conducted for the Waldo Canyon Fire burn area using the *WARSSS* methodology: *Watershed Assessment of River Stability and Sediment Supply* (Rosgen, 2006/2009). *WARSSS* is a three-phase methodology that assesses large watersheds with a practical, rapid screening component that integrates hillslope, hydrologic, and channel processes. *WARSSS* is designed to identify the location, nature, extent, and consequences of land use impacts. Before changes in land use management and restoration are implemented, it is of utmost importance to first understand the cause of impairment.

The initial two phases of *WARSSS* involving the *Reconnaissance Level Assessment (RLA)* and the *Rapid Resource Inventory for Sediment and Stability Consequence (RRISSC)* levels were conducted on portions of the four major watersheds affected by the Waldo Canyon Fire (Camp Creek, Douglas Creek, Fountain Creek, and West Monument Creek). Using GIS, these four watersheds were delineated into sub-watersheds and given unique number ID's as identified in **Figures 2–6**. The *RLA* and the *RRISSC* assessments eliminated 24 of these sub-watersheds from a more detailed assessment due to low risk; the low risk was related to a stable channels and/or low burn severity. However, 89 sub-watersheds were identified as *High Risk* for disproportionate, post-fire sediment supply and river impairment, requiring further assessment.

The 89 *High Risk* sub-watersheds advanced to the third and most detailed phase of *WARSSS*, the *Prediction Level Assessment (PLA)*. The *PLA* phase was directed to:

1. Identify the erosional/depositional processes that are disproportionately contributing sediment
2. Quantify sediment loading by location, process, and land use
3. Provide the basis for development of a conceptual plan for watershed restoration

This assessment report is designed to:

1. Provide summaries of general principles related to watershed impacts from wildfires
2. Review ongoing research involving Colorado fires
3. Report the results of the *Prediction Level Assessment (PLA)*
4. Identify specific sub-watersheds that are disproportionately contributing excess sediment and the specific processes and locations responsible

Specific data collection, analysis, and interpretations are provided that document the state of the watershed condition related to hydrology, hillslope, and channel processes. This information will be used to develop a master plan for watershed and river restoration. The *WARSSS* textbook (Rosgen, 2006/2009) includes detailed descriptions of all the methodologies used in this report. All references to figures, worksheets, tables, and flowcharts beginning with "**5-**" are from the *WARSSS* textbook, Second Edition (Rosgen, 2006/2009), and were not changed for this report. Consecutively numbered figures, i.e., **Figure 1**, **Figure 2**, etc., are unique to the Waldo Canyon Fire assessment report.

Other Colorado fires, specifically the Hayman and Buffalo Creek Fires, were used as case studies for the Waldo Canyon Fire assessment. In the ten years since the Hayman Fire, extensive research and assessment have been conducted (including hydrology, surface erosion, roads and trails, and *WARSSS*). Research reviews including brief descriptions of the results are presented. A *WARSSS* study was previously conducted for the Horse Creek and Trail Creek Watersheds within the Hayman Fire burn area in 2010 (Rosgen and Rosgen, 2010; Rosgen, 2011). Portions of the *WARSSS* (*PLA*) data collected for the Trail Creek Watershed assessment are used for the Waldo Canyon Fire assessment because of the similar geology and hydrologic conditions.

Included with this report are digital copies of the maps created for the project and a collection of Google Earth KMZ files (see **Appendix D**). These maps provide detailed information on the data that was collected in the field and the results of the *WARSSS* analysis; the maps are provided in large format E-sized PDFs. The following are the maps and KMZ files included as digital copies:

Large Format PDF Files

- Waldo Canyon Fire Burn Area and Severity
- Hillslope-Delivered Sediment
- Stream Conditions
- Streambank Erosion Rates
- Total Introduced Sediment (tons/acre)
- Total Introduced Sediment (tons/yr)
- Valley Types
- WRENSS Change in Water Yield

Google Earth KMZ Files

- Waldo Canyon Fire Burn Area and Severity
- Waldo Canyon Fire Watershed Boundaries
- Stream Conditions
- Streambank Erosion Rates
- Hillslope-Delivered Sediment
- Photographs

Methods for the Sediment Budget & Stability Analysis

The following are the specific objectives of the *Prediction Level Assessment (PLA)*:

1. Quantify sediment yields as influenced by the Waldo Canyon Fire by individual erosional processes and by location
2. Identify and quantify the stable, reference reaches to analyze departure of the representative reaches from reference condition
3. Determine river stability and the degree of impairment for the representative reaches within the watershed
4. Understand time-trends of river morphology change
5. Identify stream succession scenarios to document the potential stable state of various stream types
6. Identify disproportionate sediment supply and river impairment by location, land use, and specific erosional or depositional process to develop a conceptual watershed and river restoration plan
7. Set priorities of specific sub-watersheds for restoration based on the magnitude and potential adverse consequences of sediment contributions and flood risks associated with the Waldo Canyon Fire

The procedure for the watershed assessment is summarized in **Flowchart 5-1** and **Flowchart 5-2** (Rosgen, 2006/2009). The organization of the data, models, and sediment budget analysis is shown in **Flowchart 1**. These flowcharts depict the assessment approach utilized to predict the total annual sediment yield and the associated erosional or depositional processes (roads, streambank erosion, surface erosion, and flow-related sediment increases) by specific location. The sediment yields for pre- and post-fire conditions for specific processes, land uses, and locations were determined by the methods explained in the following sections.

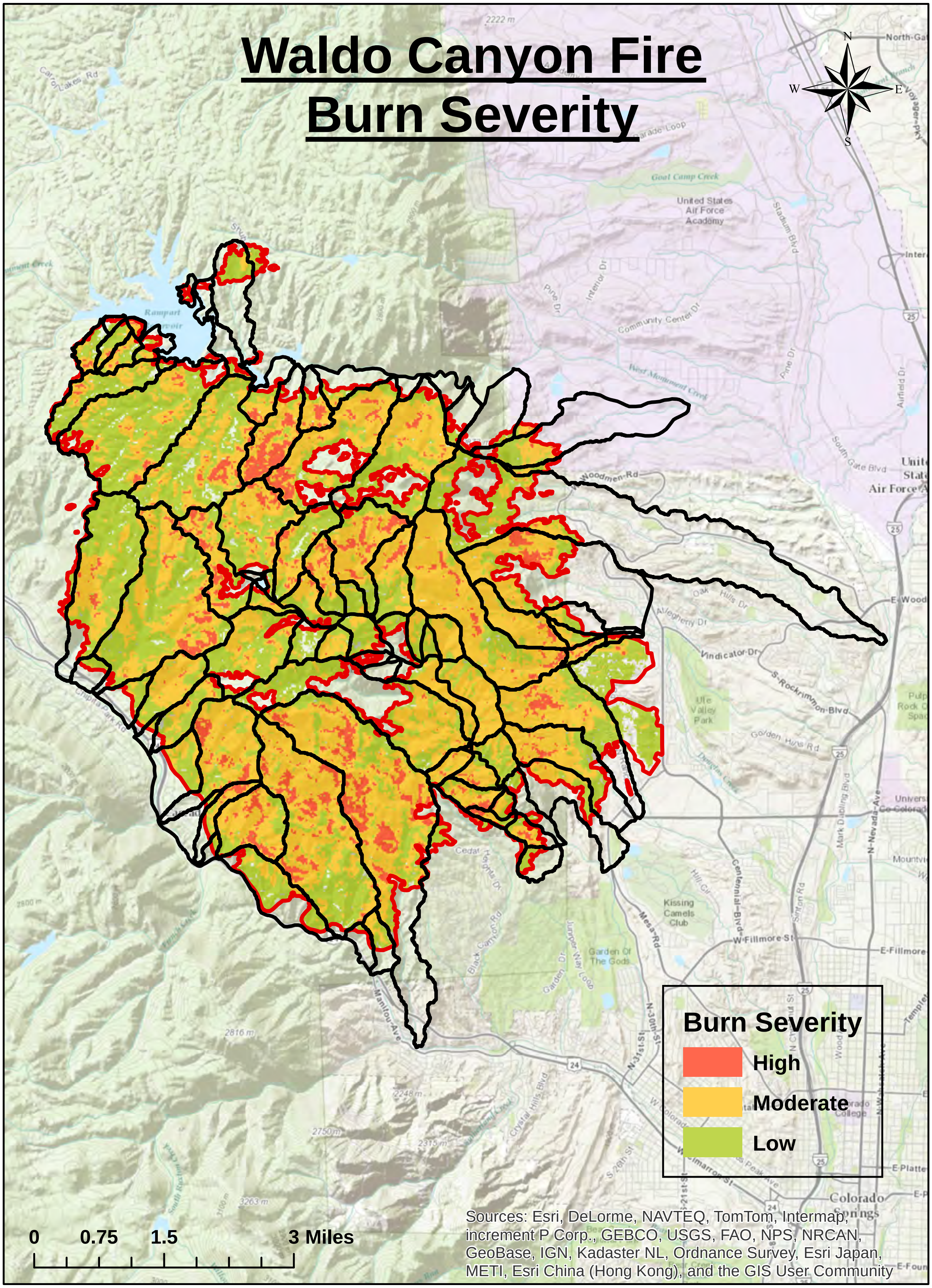

Figure 1. Waldo Fire burn severity and perimeter.

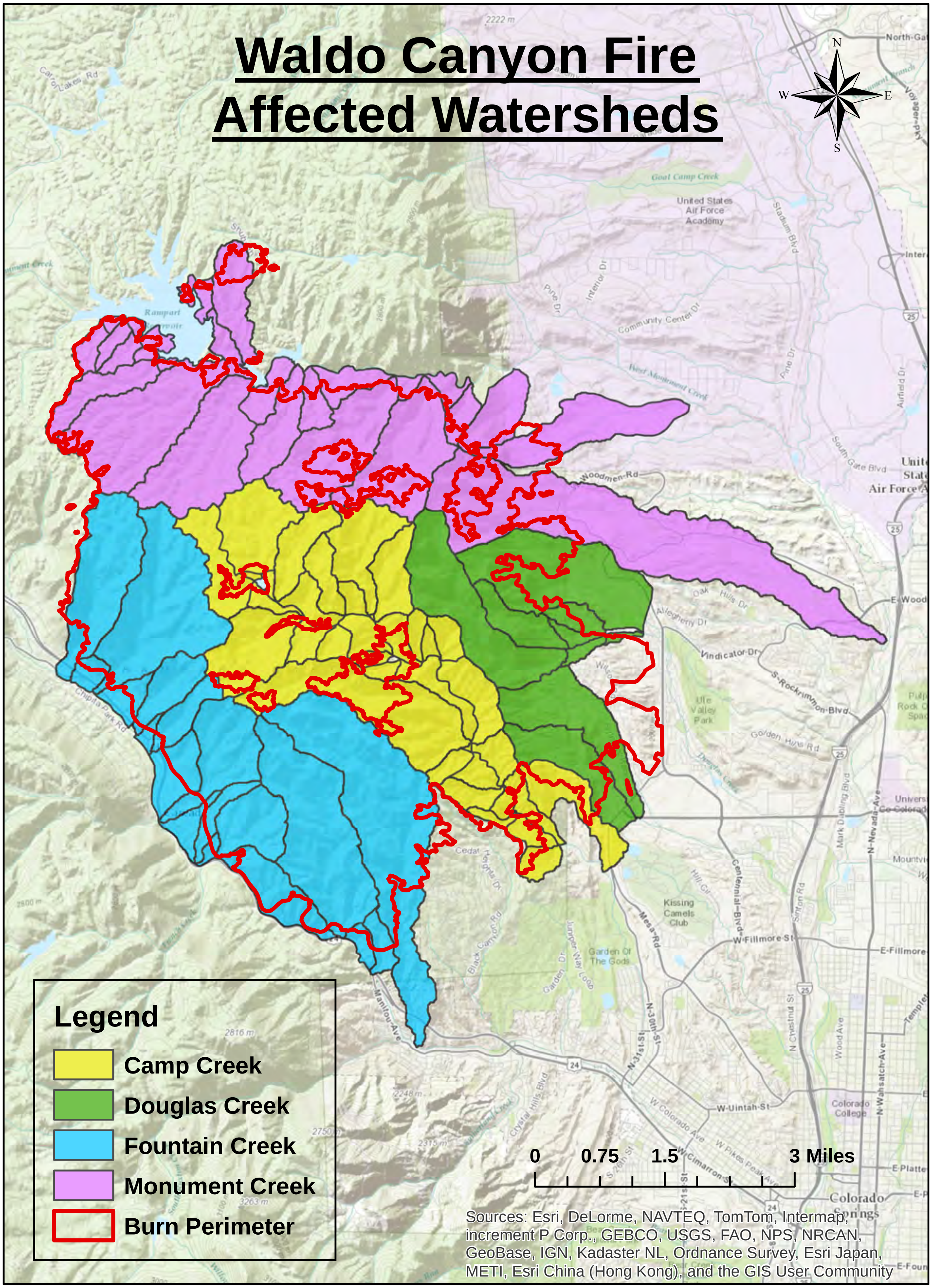

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Figure 2. Major watershed delineation of Camp Creek, Douglas Creek, Fountain Creek and West Monument Creek.

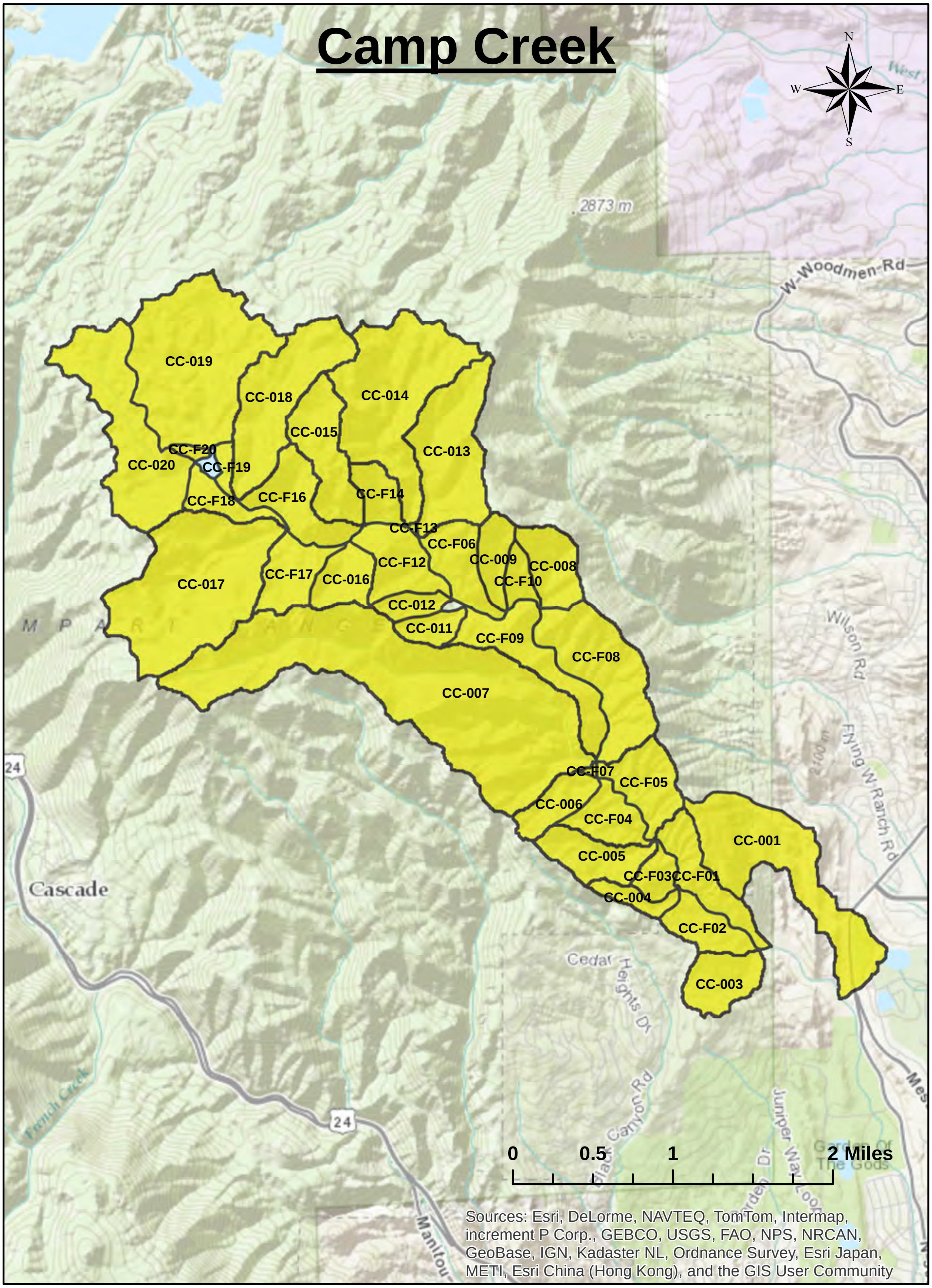

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Figure 3. Camp creek sub-watershed delineation.

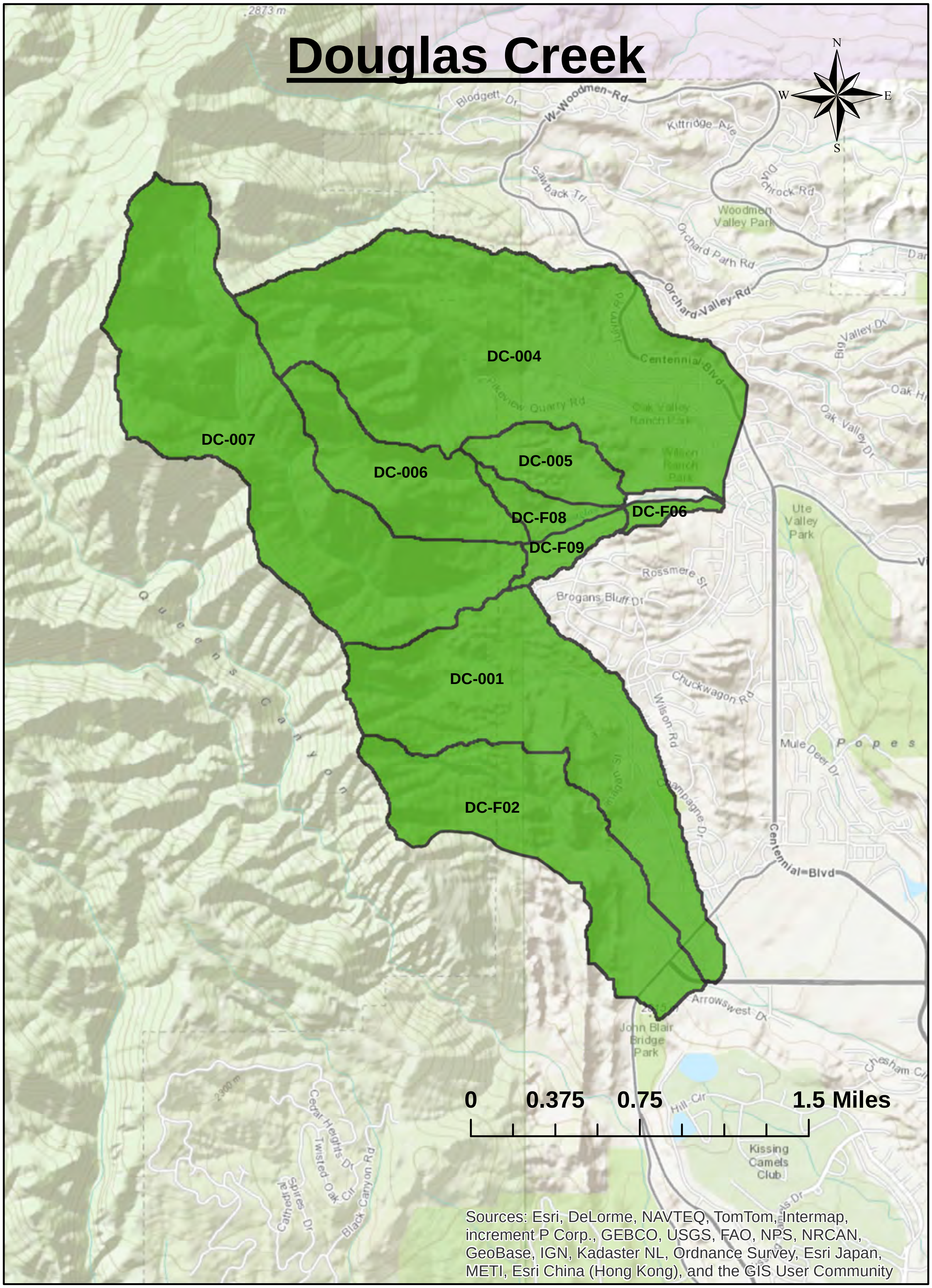
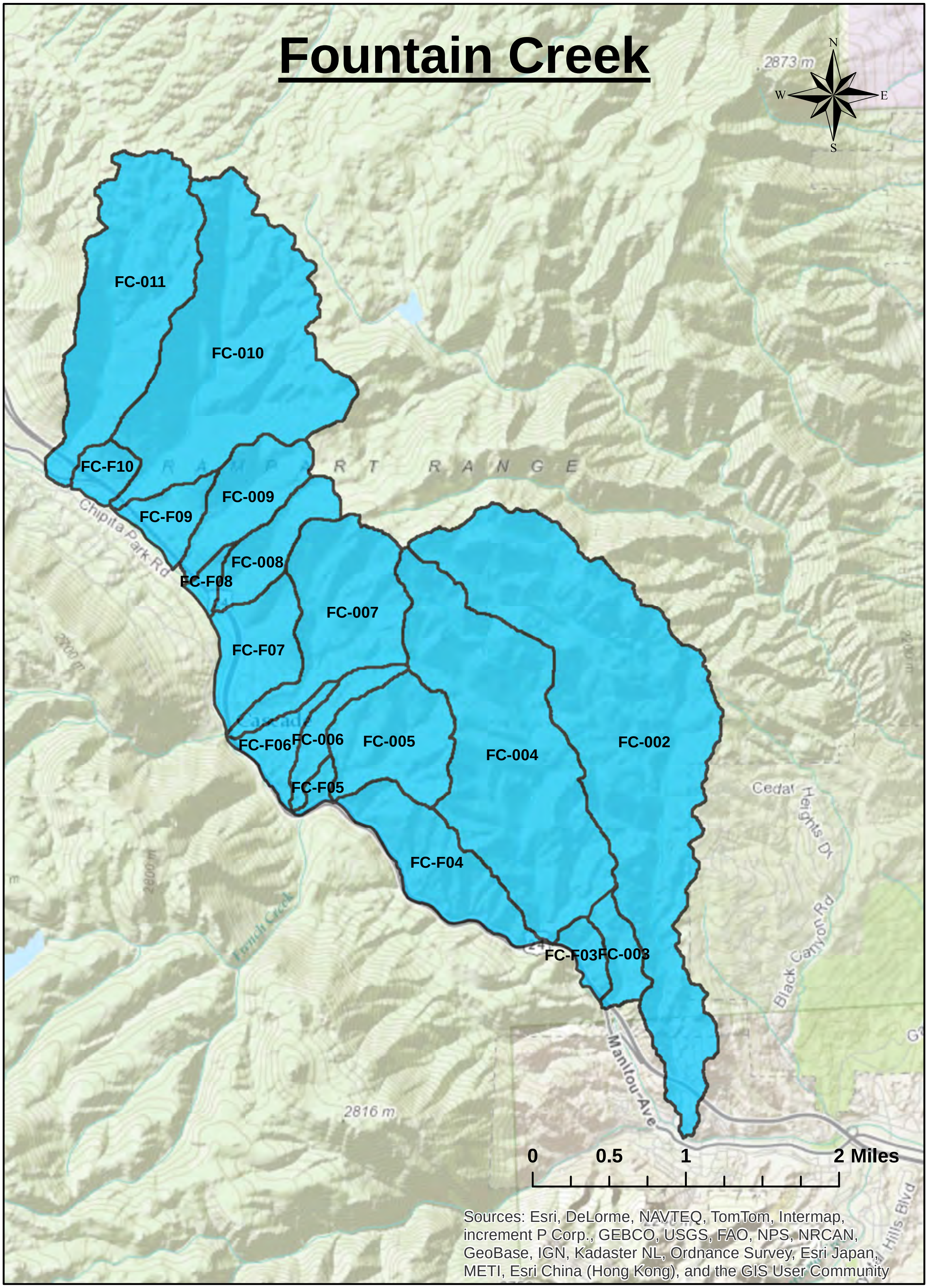


Figure 4. Douglas Creek sub-watershed delineation.



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), and the GIS User Community

Figure 5. Fountain Creek sub-watershed delineation.

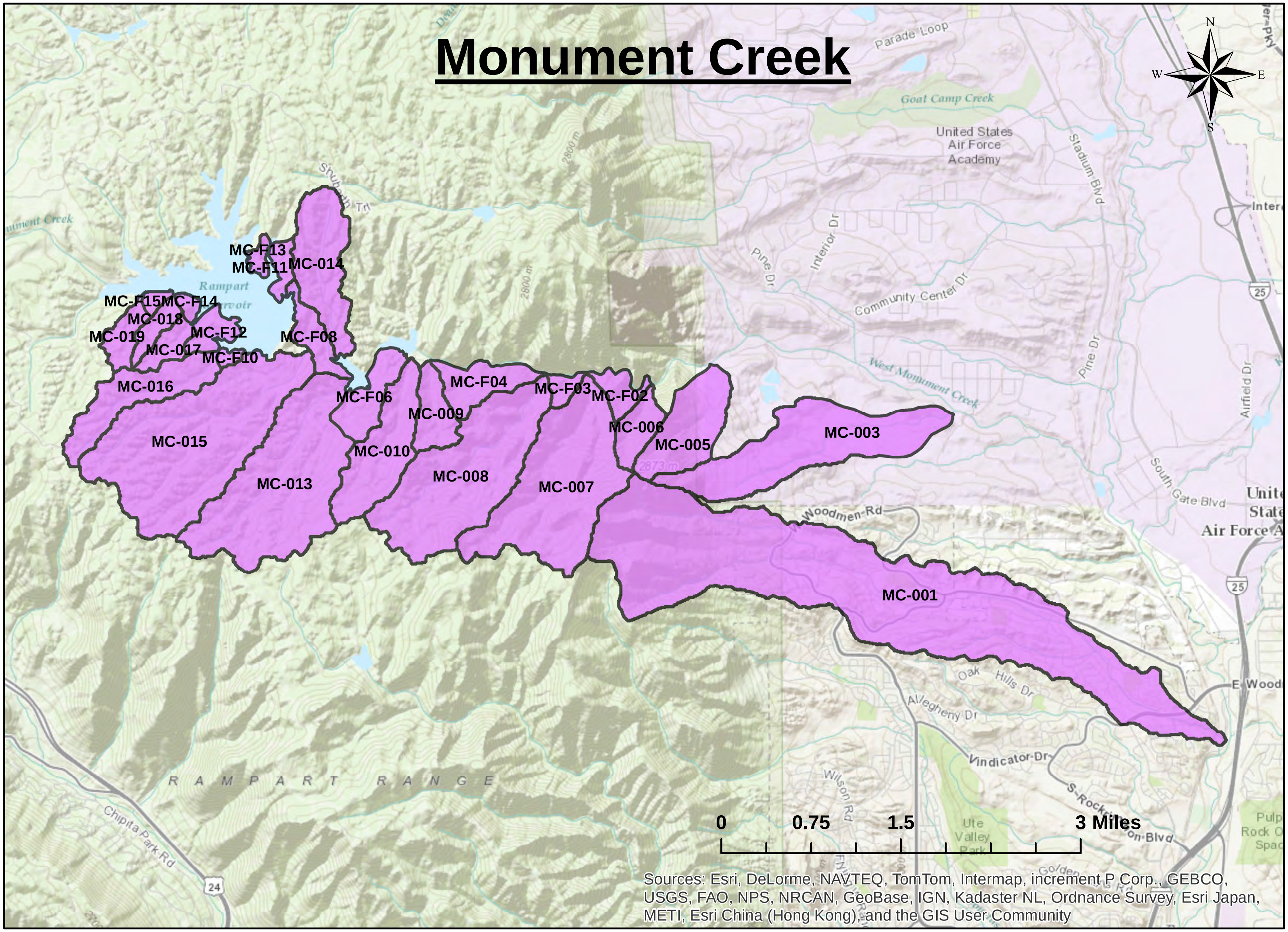


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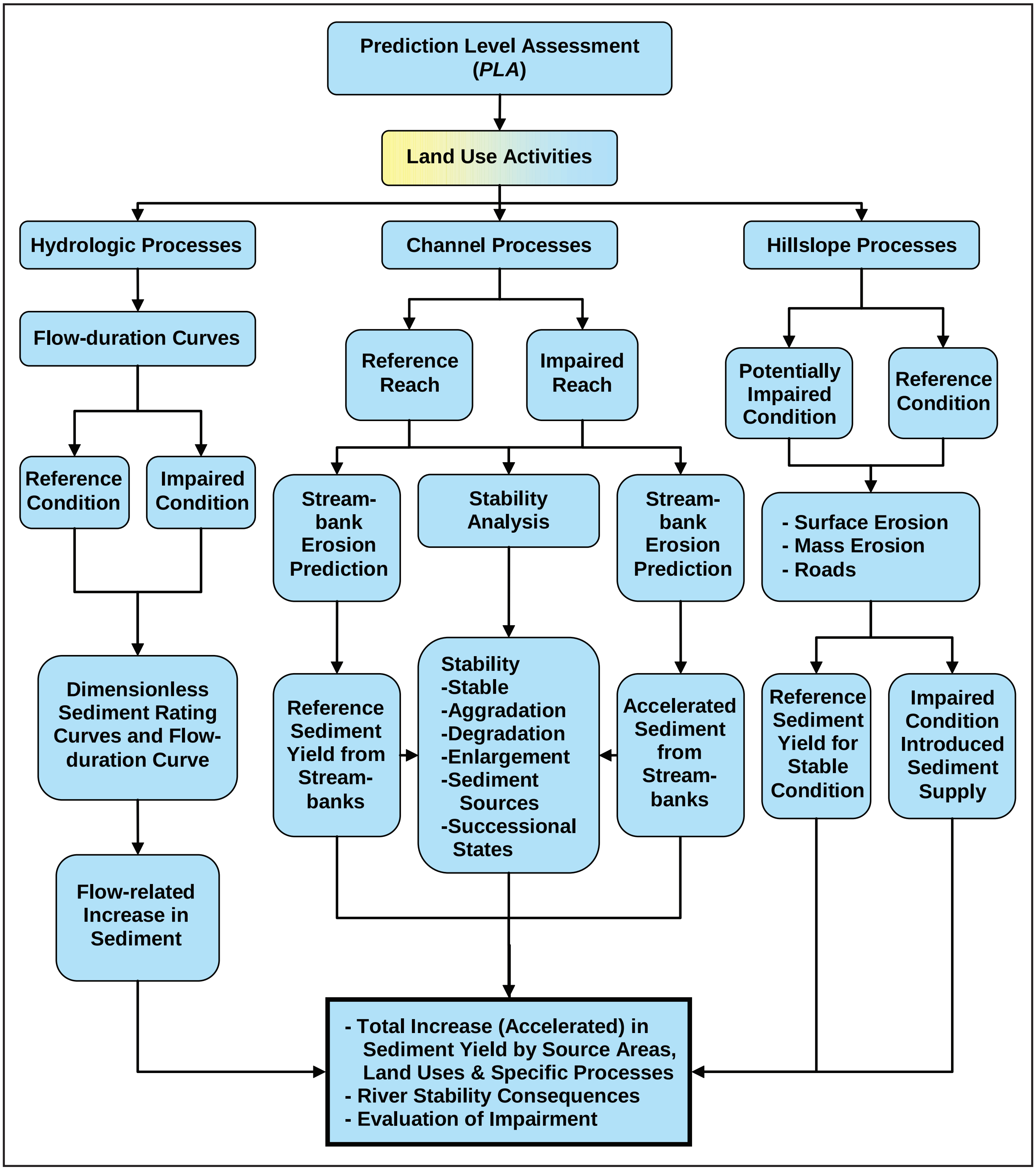
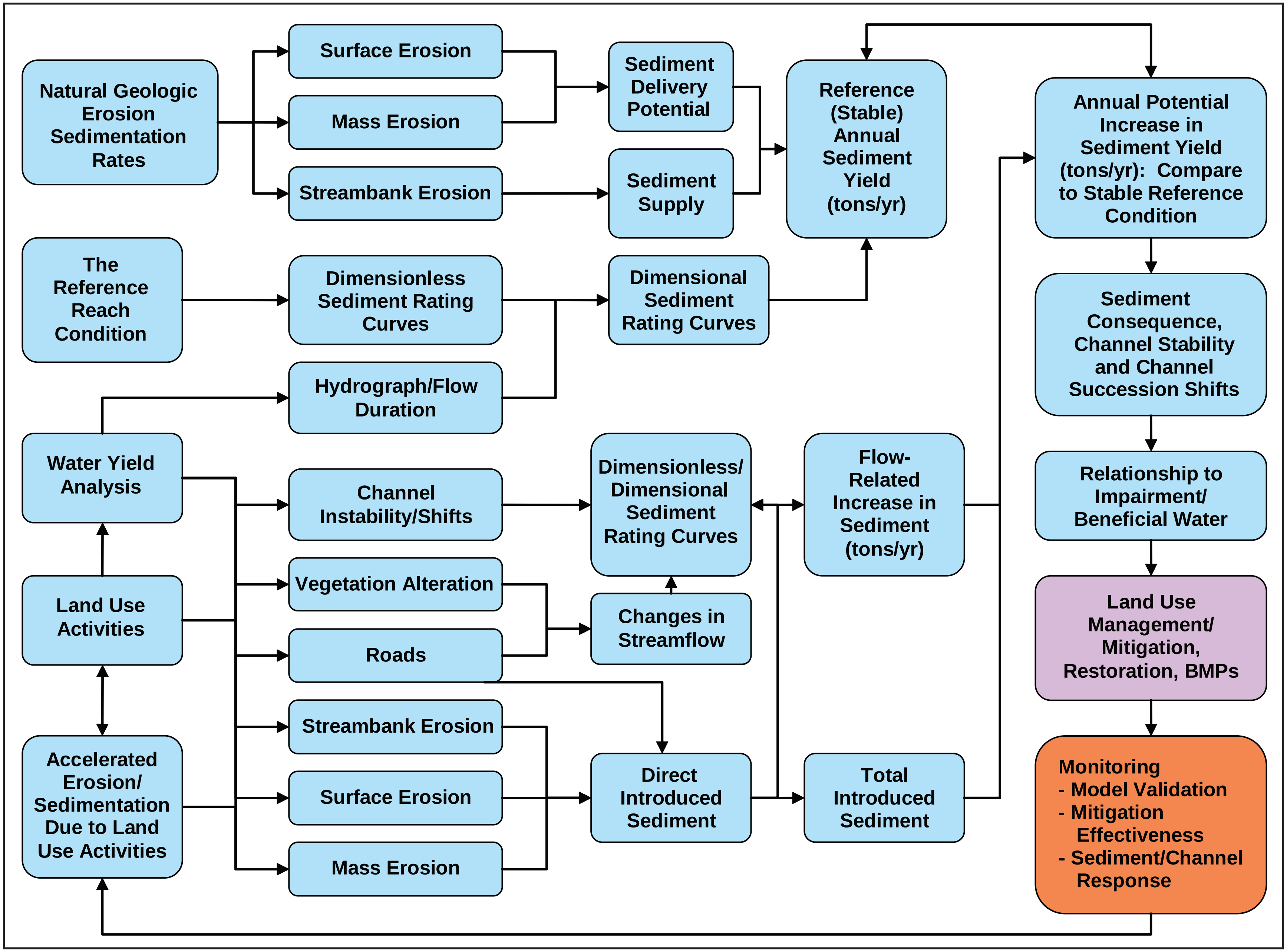
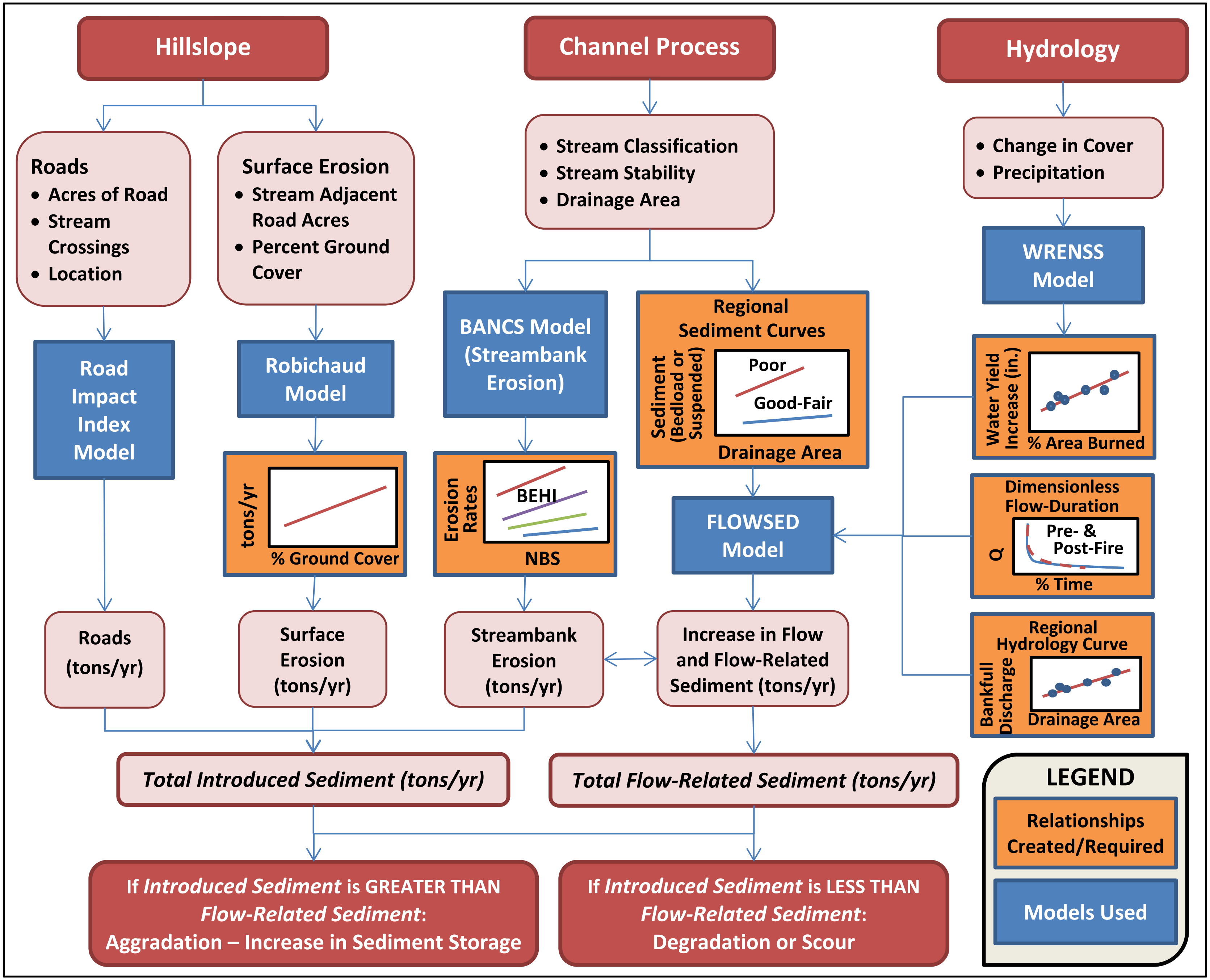
Figure 6. West Monument Creek sub-watershed delineation.



Flowchart 5-1. *PLA* comparative analysis of reference condition and impaired condition in parallel (Rosgen, 2006/2009).



Flowchart 5-2. The general organization of the procedural sequence for the *Prediction Level Assessment (PLA)* (Rosgen, 2006/2009).



Flowchart 1. Procedural flowchart of the quantification of sediment sources and channel response utilizing a variety of models.

Hydrology

Research Review

The following are excerpts from an interim report by Robichaud *et al*. (2002) that summarize the research pertaining to hydrology impacts after the Hayman Wildfire (refer to Robichaud *et al*., 2003, for the final report).

> "Increases in annual water yield (runoff from a specified watershed) after wildfires and prescribed fires are highly variable (DeBano *et al*., 1998; Robichaud *et al*., 2000). The increase in runoff rates after wildfires can be attributed to several factors. In coniferous forests and certain other vegetation types, such as chaparral, the volatilization of organic compounds from the litter and soil can result in a water repellent layer at or near the soil surface (DeBano, 2000). The net effect of this water repellent layer is to decrease infiltration, which causes a shift in runoff processes from subsurface lateral flow to overland flow (Campbell *et al*., 1977; Inbar *et al*., 1998). The loss of the forest litter layer can further reduce infiltration rates through rainsplash erosion and soil sealing (Inbar *et al*., 1998; DeBano, 2000). Loss of the protective litter layer and soil water repellency has occurred in the Hayman Fire area. These two factors combined will likely cause a large increase in runoff, which should diminish within two to five years as vegetation regrows.
>
> Flood peak flows produce some of the most profound watershed and riparian impacts that forest managers have to consider. The effects of fire disturbance on storm peak flows are highly variable and complex. Intense short duration storms that are characterized by high rainfall intensity and low volume have been associated with high stream peak flows and significant erosion events after fires (DeBano *et al*., 1998; Neary *et al*., 1999; Moody and Martin, 2001).
>
> In the Intermountain West, high-intensity, short duration rainfall is relatively common (Farmer and Fletcher, 1972). Unusual rainfall intensities are often associated with increased peak flows from recently burned areas (Croft and Marston, 1950). Moody and Martin (2001) measured rainfall intensities after the Buffalo Creek Fire in the Front Range of Colorado that was greater than 0.4 in/hr (10 mm/hr). Even in short bursts of 15 to 30 minutes, rainfall of such intensity will likely exceed the average infiltration. Water repellent soils and cover loss will cause flood peaks to arrive faster, rise to higher levels, and entrain significantly greater amounts of bedload and suspended sediments. The thunderstorms that produce these rainfall intensities may be quite limited in areal extent but will produce profound localized flooding effects. Observations to date indicate that flood peak flows after fires in the Western United States can range up to three orders of magnitude greater than pre-wildfire conditions. Although most flood peak flows are much less than this catastrophic upper figure, flood peak increases of even twice pre-fire conditions can produce substantial damage.
>
> The concepts of stormflow timing are well understood within the context of wildland hydrology. However, definitive conclusions have been difficult to draw from some studies because of combined changes in volume, peak and timing at different locations in the watershed, and the severity and size of the disturbance in relation to the size of watershed (Brooks *et al*., 1997). As a result of the Hayman Fire, peak flows within the watersheds covered by the burned area are expected to be higher and occur quickly, but specific amounts are difficult to predict."

Streamflows for Colorado Front Range data were documented by Jarrett (2009) where a 400% increase in post-fire peak flows was observed. Significantly large sediment yields from post-fire floods can be expected from the Hayman burn as a result of rain events ranging from *1.2 to 1.5 in/hr.* (Jarrett, 2009). Due to the severe microclimate extremes, droughty soils and low precipitation, a slow hydrologic recovery of these sites is anticipated.

An excellent summary of the hydrology impacts is summarized by the efforts of the USDA Forest Service research team and Colorado State University (Robichaud *et al*., 2003). According to Moody and Martin (2001), flood peak increases of 140% of background conditions occurred following wildfires in Colorado as determined from the Buffalo Creek Fire. A large flow-related measured sediment yield for the control (no surface ground cover treatment) between 2003 and 2005 generated *8.8 tons/acre* from a *1.7 inch/hr* storm, resulting in *650 csm* of runoff within the Hayman burn study plots (Robichaud & Wagenbrenner, 2006). In 2007, a *4.3 inch/hr* storm for 10 minutes generated a high peak flow of *1,064 csm* (Robichaud & Wagenbrenner, 2008). The sediment yield from this storm, however, was lower due to increased ground cover, yielding less than *1.5 tons/acre*, much less than the *8.8–10 tons/acre* immediately following the fire associated with a much lower magnitude storm. This research data reflects the surface erosion and hillslope process recovery of ground cover density five years following the fire (Robichaud & Wagenbrenner, 2008).

According to Jarrett (2009), there have been at least six rainstorms that have exceeded the 100-year event in the Hayman burn area in the Trail, West, Camp, Horse, Fourmile, and Sixmile Creek basins since the 2002 fire. The same report states "rainfall and flood data for unburned, forested areas in the Colorado Front Range indicates that rainfall amounts need to exceed 2.5 to 3.0 inches in one hour to produce any rainfall runoff" (Jarrett, 2009). Major flooding and sediment yields have been observed in the burn area with precipitation amounts half of these rates, indicating two factors: 1) that the basin enhances convectional stormflow amounts greater than the NOAA II 100-year storm probability estimates; and 2) that the influence of the fire in these steep watersheds promotes flooding with precipitation of *1.7 in/hr* rate rather than the *2.5–3.0 in/hr* rates for unburned, forested watersheds.

The USDA Forest Service Burned Area Emergency Response (BAER) team conducted a study on the runoff response in the area affected by the Waldo Canyon Fire (Moore and Park, 2012). The runoff response was calculated using WILDCAT5 (a unit hydrograph approach for hydrologic response) for storms of varying magnitude. Included in the report was Bob Jarrett's (2009) post-fire flood response for watersheds less than ten square miles from the Buffalo Creek, High Meadow, Bobcat Hayman, and Fourmile fires. Flood peak estimates for several Waldo Canyon Fire watersheds were predicted for relatively frequent storms. The peak flood-flow estimates utilized both the WILDCAT5 model (2 yr/1 hr storm) and Jarretts (USGS, based on a 1 inch rain in 1 hour) and was compared to the normal high flow (bankfull discharge), **Table 1**. As an example, Wellington Gulch, a 1.73 mi^2 drainage within the burn area with a bankfull discharge of *6.7 cfs* had predicted flood peak estimates of *740 cfs* with WILDCAT5 (for a 2 yr/1 hr storm) and *600 cfs* from Jarrett (for a 1 inch per hour storm). The WILDCAT5 model predicted close to observed values documented by Jarrett (2009); thus the WILDCAT5 model is utilized for the flood-flow predictions for the Waldo Canyon Fire. These flood estimates pose a significant risk for downstream flooding and stream impairment, depending on the extent of the fire within various watersheds.

Frequent, high magnitude storms will generate excess sediment yields based on flow-related channel response for the watersheds within the Waldo Canyon Fire Perimeter. According to MacDonald (2009), the areas affected by the fire in similar geology produced sediment from the more extreme storm events because of the limited recovery potential for revegetation to offset evapotranspiration and interception losses. The growing conditions on most of the Waldo Canyon Fire are very poor due to the coarse-textured soils and low precipitation relative to potential evapotranspiration. Using the Hayman Fire as an example, vegetative recovery rate will be slow. MacDonald (2009) observed for the Hayman Fire that if the amount of ground cover is not able to return to pre-fire levels, there will be a continuing susceptibility for a higher than normal streamflow "peak" response to high-intensity summer thunderstorms (MacDonald, 2009).

Table 1. Summary of peak flood flow *vs.* normal high flow (Moore and Park, 2012).

Sub-Watershed (Moore & Park, 2012)	*WARSSS* Sub-Watershed	Drainage Area (mi^2)	Bankfull (cfs)	Design Storm (2 year, 1 hour)	
				Jarrett Post-Fire (cfs)	Wildcat 5 (cfs)
A - Sand Gulch	FC-011	1.1	5.0	410	310
B - Wellington Gulch	FC-010	1.7	6.8	600	740
C - Unnamed (Mud across Hwy1)	FC-009	0.4	2.4	180	200
D - Unnamed (Mud across Hwy2)	FC-008	0.2	1.8	140	120
E - Unnamed (Cascade)	FC-007	0.8	4.0	320	400
F - Unnamed (Marygreen Pines)	FC-006	0.2	1.5	120	30
G - Unnamed	FC-005	0.5	3.1	240	310
H - Waldo Canyon	FC-004	1.8	6.8	620	590
I - Cavern Gulch	FC-003	0.2	1.3	100	20
K - Williams Canyon	FC-002	2.4	8.3	800	730
L - Camp Cr (Queens Canyon)	CC-All	8.1	18.6	1,900	1,590
M - Unnamed (Alpine)	DC-F02	0.4	2.4	190	170
N - S. Douglas Creek	DC-005*	2.0	7.4	690	590
O - N. Douglas Creek	DC-004	0.2	1.6	120	10
P - Dry Creek	MC-001	0.4	2.5	190	60
R - Unnamed (N. Blodgett Gulch)	MC-007	1.1	5.1	410	260
S - Unnamed (Devils Kitchen)	MC-008	1.1	5.0	400	320
T - Unnamed (Northfield Res)	MC-010	0.5	2.8	210	310
U - Unnamed (Nichols Res)	MC-013	1.2	5.3	450	370
V - Wildcat Gulch	MC-015	1.5	6.1	500	170
W - Unnamed (Rampart Res Shore 1)	MC-016	0.4	2.6	200	60
X - Unnamed (Rampart Res Shore 2)	MC-018	0.1	1.0	80	50
Y - Camp Creek above Eagle Camp 1	CC-020	0.5	2.9	220	210
Z - Camp Creek above Eagle Camp 2	CC-019	0.7	3.7	300	310

**Includes WARSSS sub-watershed DC-005, DC-006, DC-007, DC-F06, DC-F07, DC-F08, and DC-F09*

Processes and Methodology

Bankfull Discharge

Bankfull discharge is the frequent peak flow that fills the channel to the incipient level of flooding and when inundation of the floodplain or flood-prone area occurs. It often associated with a return interval of 1 to 2 years and is coincident with the effective discharge or channel forming flows. Bankfull (Q) was estimated using bankfull stage field indicators with the continuity equation ($Q = A * u$) by estimating mean velocity (u) and calculating the bankfull cross-sectional area (A). The calculated bankfull discharge was then compared to regional curves developed for this project representing bankfull discharge *vs*. drainage area. This regional curve is based on calibrated, field-determined bankfull values at USGS stream gages and other monitoring sites in the same hydro-physiographic province as the Waldo Canyon Fire. Velocity was estimated using a variety of methods, such as flow resistance to relative roughness and manning's "*n*" by stream type in detailed cross-sections. The bankfull discharge for each sub-watershed (at the mouth) was determined from the regional curve of bankfull discharge *vs*. drainage area (**Figure 7**).

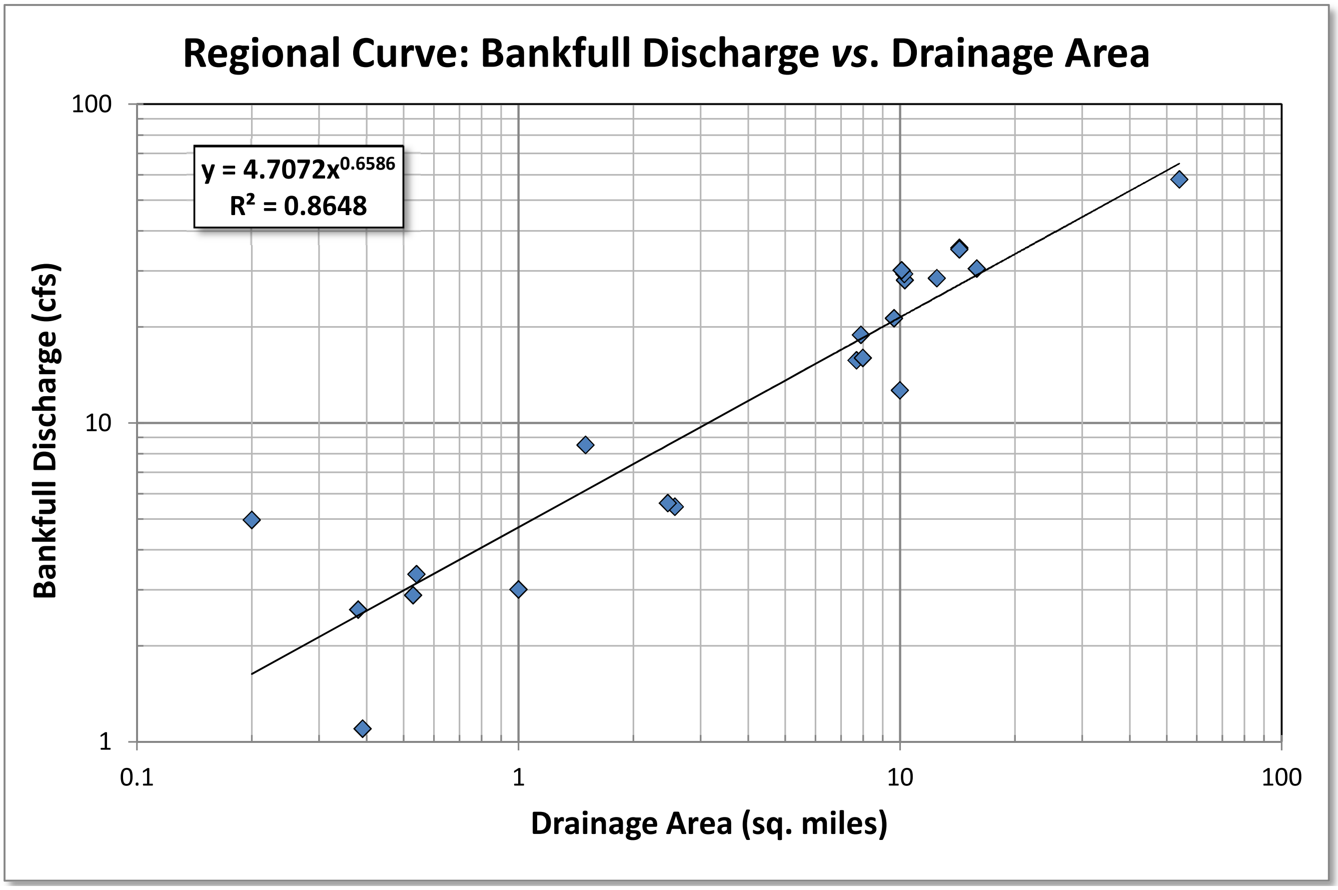


Figure 7. Bankfull discharge *vs*. drainage area relationship used for the Waldo Canyon Fire area.

WRENSS Water Yield Model

The reduction in forest vegetative cover (trees and gambel oak) following the Waldo Canyon Fire created a major reduction in evapo-transpiration leading to an increase in the magnitude and frequency of floods as a result of precipitation events. The assessment for Waldo Canyon Fire involves an application of the WRENSS water yield model (USEPA, 1980) completed by J. Nankervis, 2013, Blue Mountain Consultants. WRENSS simulates the increase in water yield based on reduction in forest cover. The forest stand data was provided by B. Banks, M. Purnell and E. Biery (USDA Forest Service). The model is run for homogenous units of vegetation conditions (species and density), area, aspect, and average monthly precipitation. The change in water yield is calculated based on the difference between pre- and post-fire vegetation condition. A linear regression was developed for each of the four watersheds correlating change in water yield as a function of percent reduction in cover (**Figure 8**). These regressions allow a reasonabe prediction of the changes in water yield for an infinite number of locations within each of the major watersheds. The incremental change in water yield for the four major watersheds is reported in **Table 2**, and the sub-watershed values can be observed in **Figure 9**. See **Appendix A** for a detailed description on the development of dimensionless flow-duration curves based on the change in water yield.

Table 2. Increased water yield for the four major watersheds as a result of the Waldo Canyon Fire.

Watershed	Area (acres)	Annual Precipitation (in)	Change in Water Yield (in)
Camp Creek	5,526	20.4	2.6
Douglas Creek	3,303	18.4	1.7
Fountain Creek	7,163	20.6	2.9
West Monument Creek	8,255	20.8	1.4

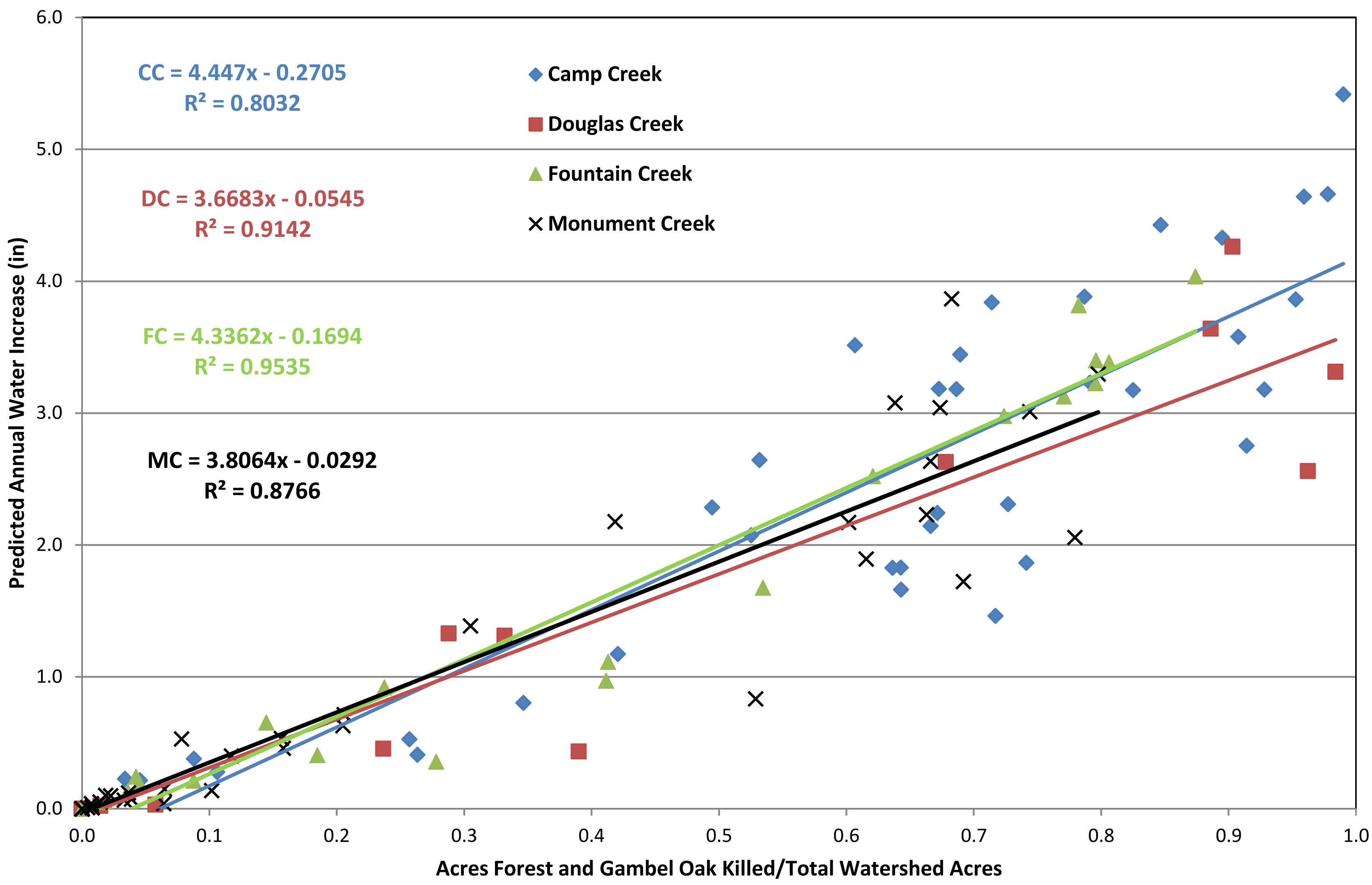
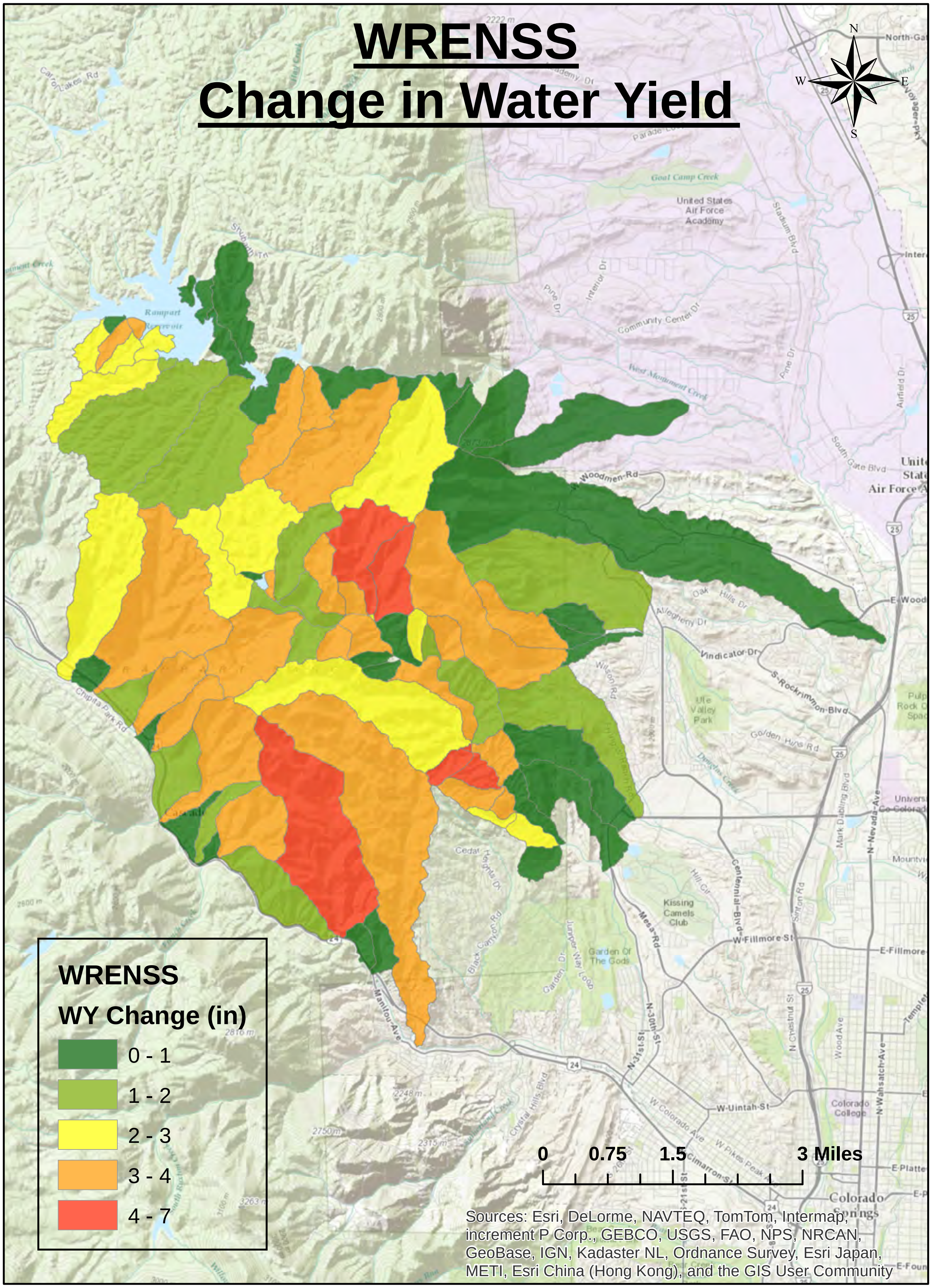


Figure 8. Predicted water yield increase as a function of percent reduction in cover by watershed.



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), and the GIS User Community

Figure 9. Map of increase in water yield for the sub-watersheds.

Flow-Duration Curves (Pre- and Post-Fire)

To evaluate the potential flow-related sediment yield increases, the water yield increase data from WRENSS must be converted to dimensionless flow-duration curves normalized by mean daily bankfull discharge. The dimensionless curves are converted to dimensional curves specific to a location. Dimensional flow-duration curves are developed for each watershed and sub-watershed for pre- and post-fire streamflow conditions. A dimensionless flow-duration curve for the major watersheds in the Waldo Canyon Fire is shown in **Figure 10**. The dimensionless flow-duration curve for the major watersheds reflects the burn area. In Camp Creek, Douglas Creek, and West Monument Creek, the watersheds affected by the burn represented a majority of the total area. Douglas Creek combines North and South Douglas Creeks. The water yield change in Fountain Creek is distributed over the entire watershed area where the burn only influences 63% of the watershed area resulting in a lower total annual water yield change (**Table 3**). This dimensionless curve was then converted to a dimensional flow-duration curve using mean daily bankfull discharge as shown in **Figures 11–14** for each major watershed. For the remainder of the analysis, the sum of the sub-watersheds influenced by the burn is used.

Table 3. Results of the water yield analysis for the four major watersheds within the Waldo Canyon Fire comparing the influence of the burned area on total water yield.

Watershed	Burned Sub-Watersheds		Entire Watershed Affected	
	Area (acres)	Change in Water Yield (in)	Area (acres)	Change in Water Yield (in)
Camp Creek	5,526	2.6	5,856	2.4
Douglas Creek	3,303	1.7	3,303	1.7
Fountain Creek	7,163	2.9	23,936	0.9
West Monument Creek	8,255	1.4	14,912	0.8

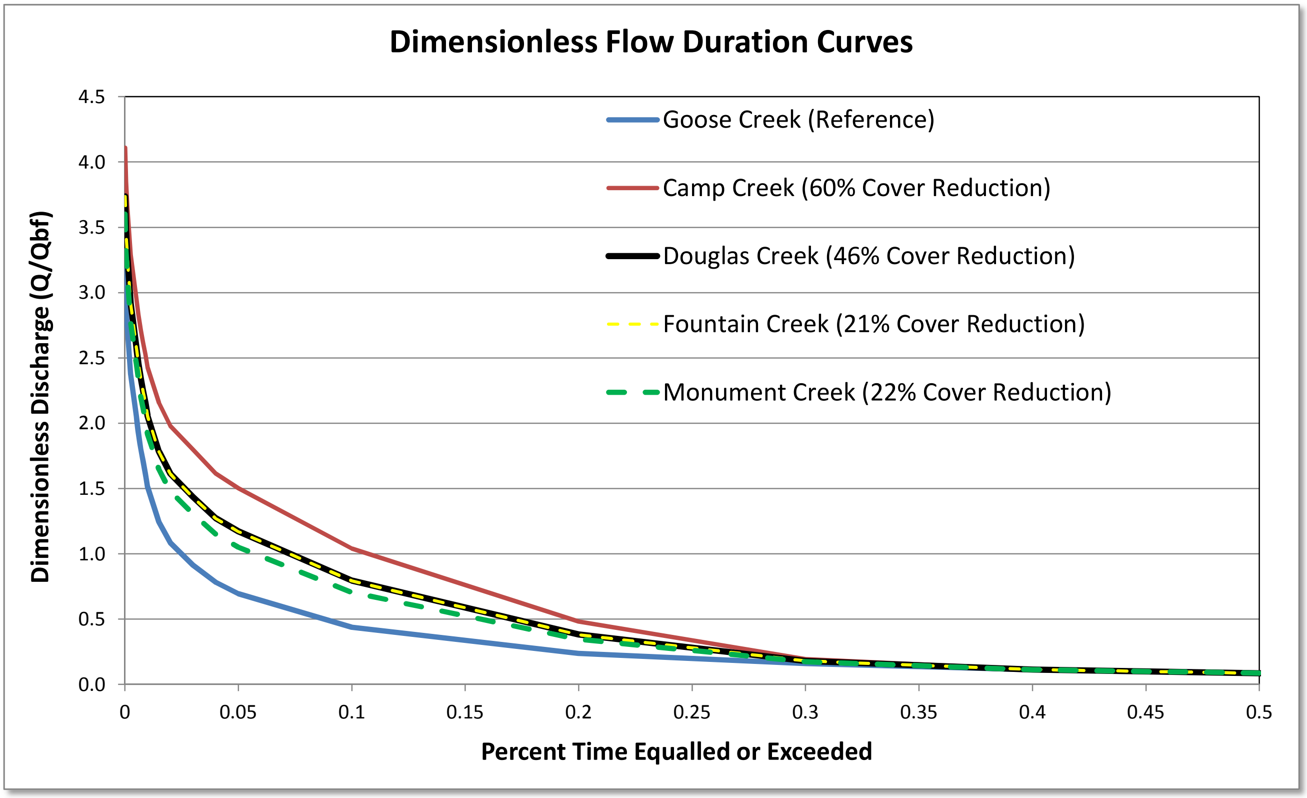


Figure 10. Dimensionless flow-duration curve for the four major watersheds in the Waldo Canyon Fire.

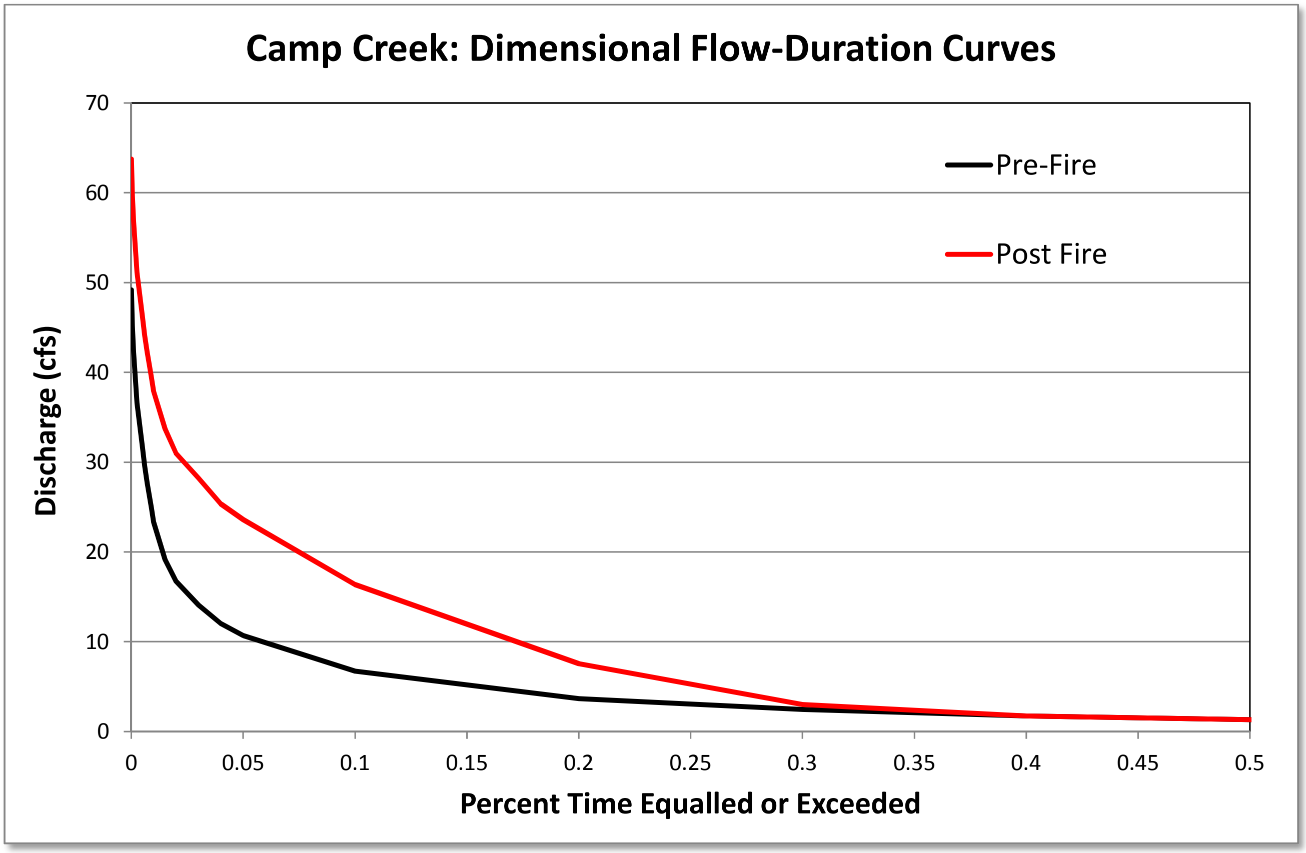


Figure 11. Dimensional flow-duration curve for the Camp Creek Watershed.

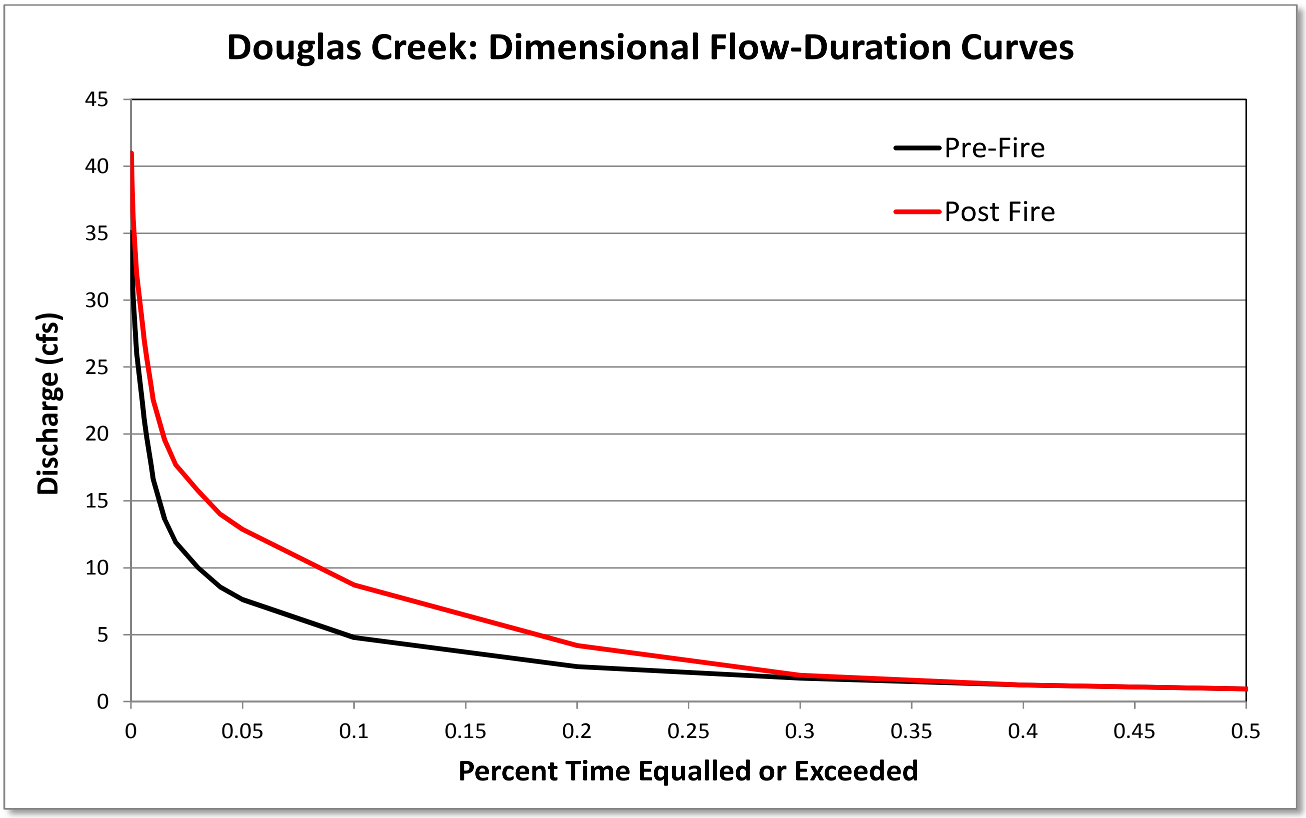


Figure 12. Dimensional flow-duration curve for the Douglas Creek Watershed.

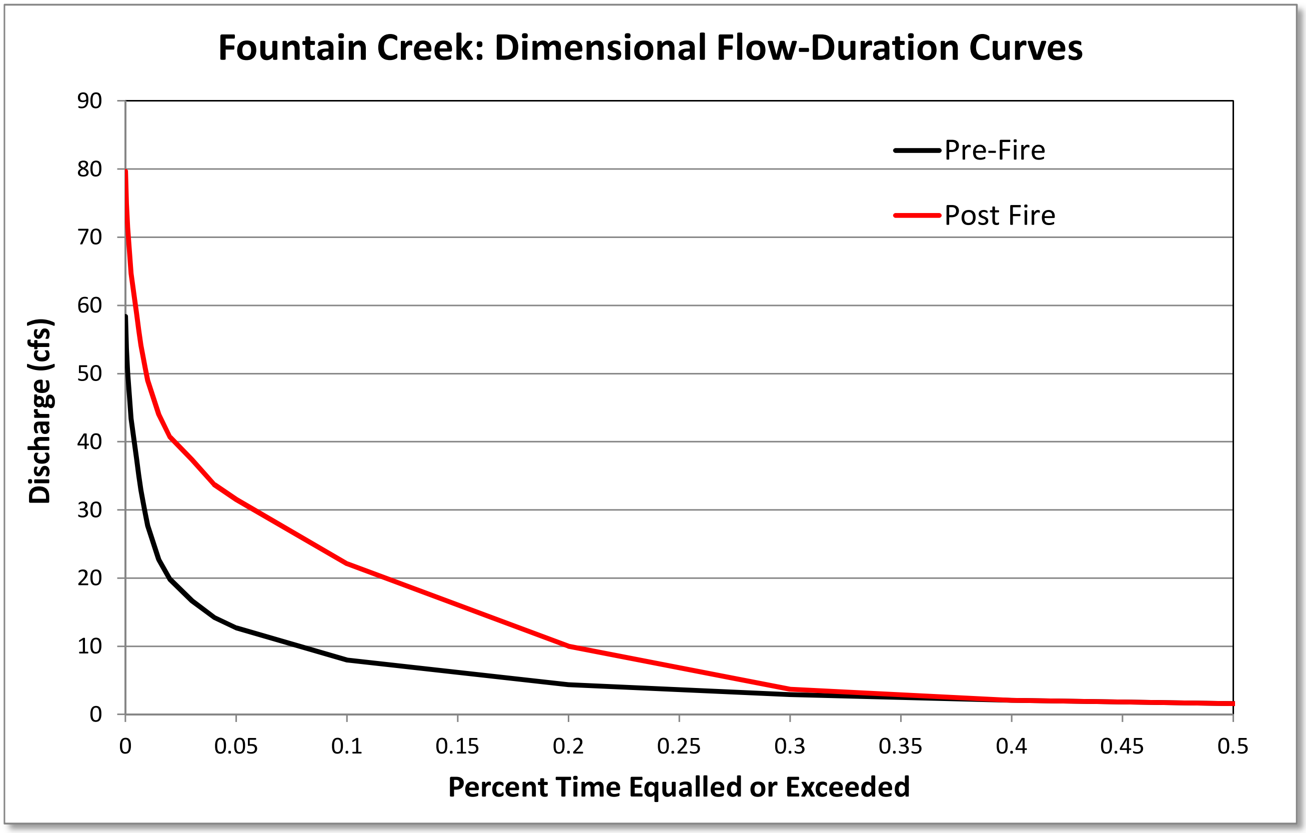


Figure 13. Dimensional flow-duration curve for the Fountain Creek Watershed.

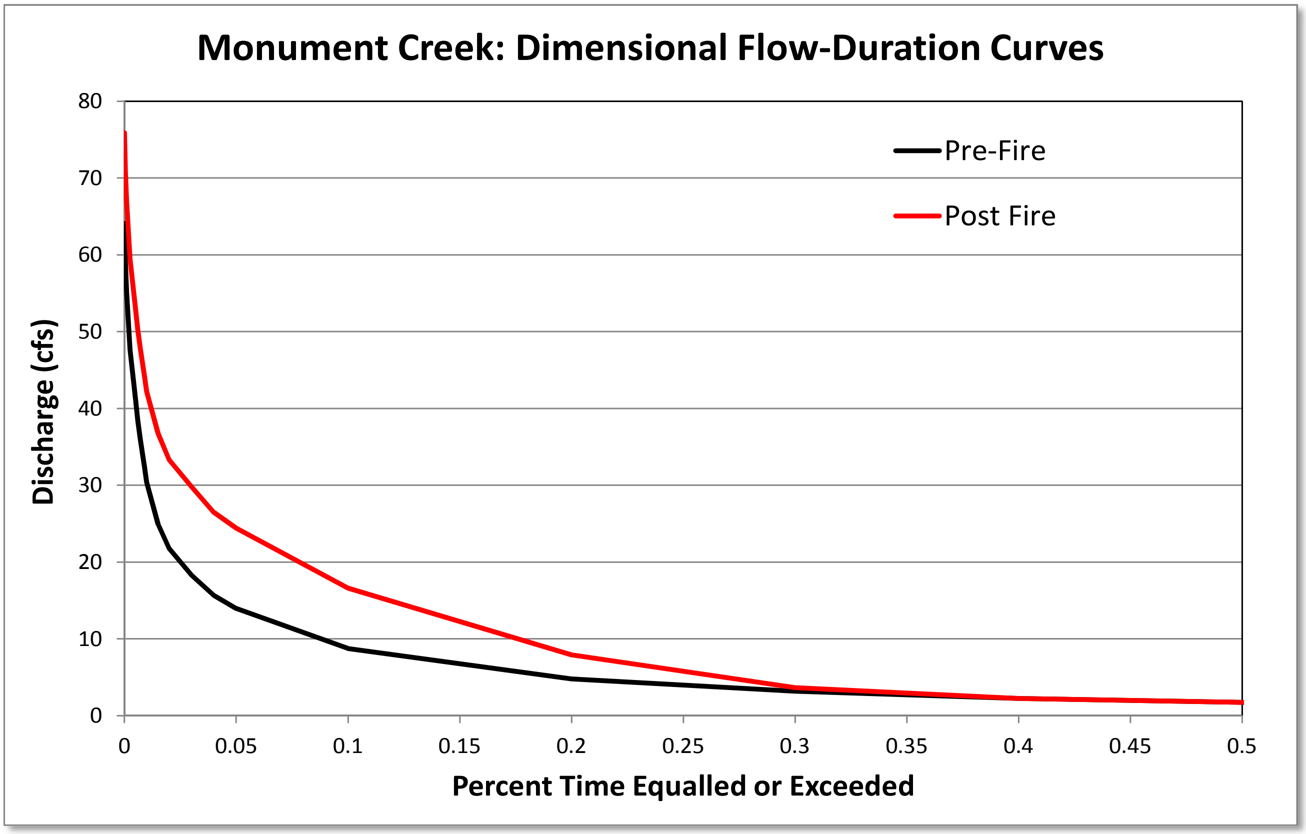


Figure 14. Dimensional flow-duration curve for the West Monument Creek Watershed.

The FLOWSED model (Rosgen, 2006/2009) uses the flow-duration curves and predicted sediment rating curves to compare increases in potential flow-related sediment yield based on increased streamflow from the Waldo Canyon Fire. The increased flows are routed through appropriate sediment rating curves (sediment *vs*. discharge) based on a sediment supply by stream channel type and stability condition (discussed in the following *Channel Processes* section). The pre-fire *vs*. post-fire water yields for the watersheds affected by the Waldo Canyon Fire are reported in **Table 4**. Water yield changes for the sub-watersheds are reported in **Appendix A**. Fountain Creek has the largest incremental water yield increase (2.9 in) (**Table 2**), resulting in a total water yield change of *2,322 acre-ft* in an average year (**Table 4**). Complete results for the increased water yield by major watershed and sub-watershed can be found in **Appendix D**. These increases in annual water yield indicate that there is significant additional available water to erode streambanks and streambeds and increase sediment transport. This analysis is separate from the flood peaks as the annual streamflow increases are related to very frequent events. A discussion of the sediment values associated with these streamflow increases are reflected in the FLOWSED model and are discussed in the *Flow-Related Sediment Yield* section.

Table 4. Summary of pre- and post-fire water yield by major watershed.

Watershed	Pre-Fire Water Yield (acre-ft)	Post-Fire Water Yield (acre-ft)	Increase Water Yield (acre-ft)
Camp Creek	2,115	3,702	1,587
Douglas Creek	1,511	2,156	645
Fountain Creek	2,500	4,822	2,322
West Monument Creek	2,747	4,035	1,288

Discussion

On July 30th, 2012, flood peaks were observed as a result of a 1.03 inch storm with a maximum hour intensity of 1.02 inch/hr and a maximum 30 minute intensity of 0.88 inches/30 min (USGS gage # 07103800). A storm of this magnitude is associated with an approximate 2-year return interval. As a result of the fire, this relatively frequent rainstorm produced an infrequent and rarely observed flood event on Northfield Gulch, a small tributary to West Monument Creek. This small drainage has a bankfull discharge of *4.0 cfs* but experienced approximately *180 cfs* from this 1.0 inch storm that generated a flood 45 times larger than the normal high flow. This storm resulted in extensive damage to West Monument Creek, buried water transmission lines, and damaged additional infrastructure of Colorado Springs Utilities. The predicted increases in water yield and higher magnitude, more frequent flood peaks will be long-term processes, but most pronounced in wetter years. Major changes in the post-fire hydrology drives the processes discussed later in this report. The increase in water yield is inversely proportional to the forest cover re-establishment, which may take decades for these watersheds.

Hillslope Processes: Surface Erosion

Research Review

Sediment yields primarily due to surface erosion from hillslopes can decrease by an order of magnitude following the first year, and by seven years, negligible erosion can result (Robichaud and Brown, 1999; Robichaud *et al*., 2002). In eastern Oregon, it took 7–14 years to return to the pre-fire condition (DeBano *et al*., 1998; Robichaud *et al*., 2002). For the Hayman burn area, MacDonald (2009) reports:

> “The amount of (surface) erosion is largely a function of the amount of ground cover. Prior to the fire there was less than 10% bare soil, as there was a nearly complete carpet of coniferous needles along with around 20–30% live vegetation. This ground cover, together with the high infiltration rates, created little to no overland flow or erosion on unburned slopes up to 50% even if the rainfall intensity was greater than two inches per hour. High severity post-fire areas had less than 10% surface cover (i.e., more than 90% bare soil and ash). Under these conditions a rainfall intensity of only one-third of an inch per hour generated substantial amounts of sediment. By summer 2004, erosion rates per unit rainfall intensity dropped to half of the values measured in 2002–2003, and by 2005–2006 most sites had more than 50% ground cover, and this was enough to greatly reduce hillslope erosion from most sites except from the most intense summer thunderstorms.
>
> Overall, post-fire erosion rates are highly dependent on the amount of surface cover. The importance of surface cover is further demonstrated by the fact that mulching was the most successful post-fire erosion treatment, as this immediately provided a protective ground cover. Treatments that disturb the soil surface, such as scarification, probably increase the hillslope erosion rate relative to untreated areas.”

Robichaud and Wagenbrenner (2009) reported that increasing ground cover led to a major reduction in surface erosion source sediment yield between 2002 and 2008 in the Hayman burn area (**Figure 15**). The result of the reduced sediment yield from surface erosion is shown by corresponding changes in the percent of ground cover (**Figure 16**). For slopes in the 15–40% range and for ground cover greater than 50%, limited sediment yields from surface erosion is anticipated based on data six years following the fire. Sediment yields were greatly reduced from the initial erosion and sedimentation rates by 2008, even in the presence of high intensity rainstorms. Based on the conducted research, it may be inferred that the highest potential for sediment yields from surface erosion are more likely to occur adjacent to stream systems on very steep slopes with less than 20% ground coverage. As stated by MacDonald (2009), hillslope processes (other than roads and ORV trails) do not contribute the bulk of the sediment yield from the Hayman Fire.

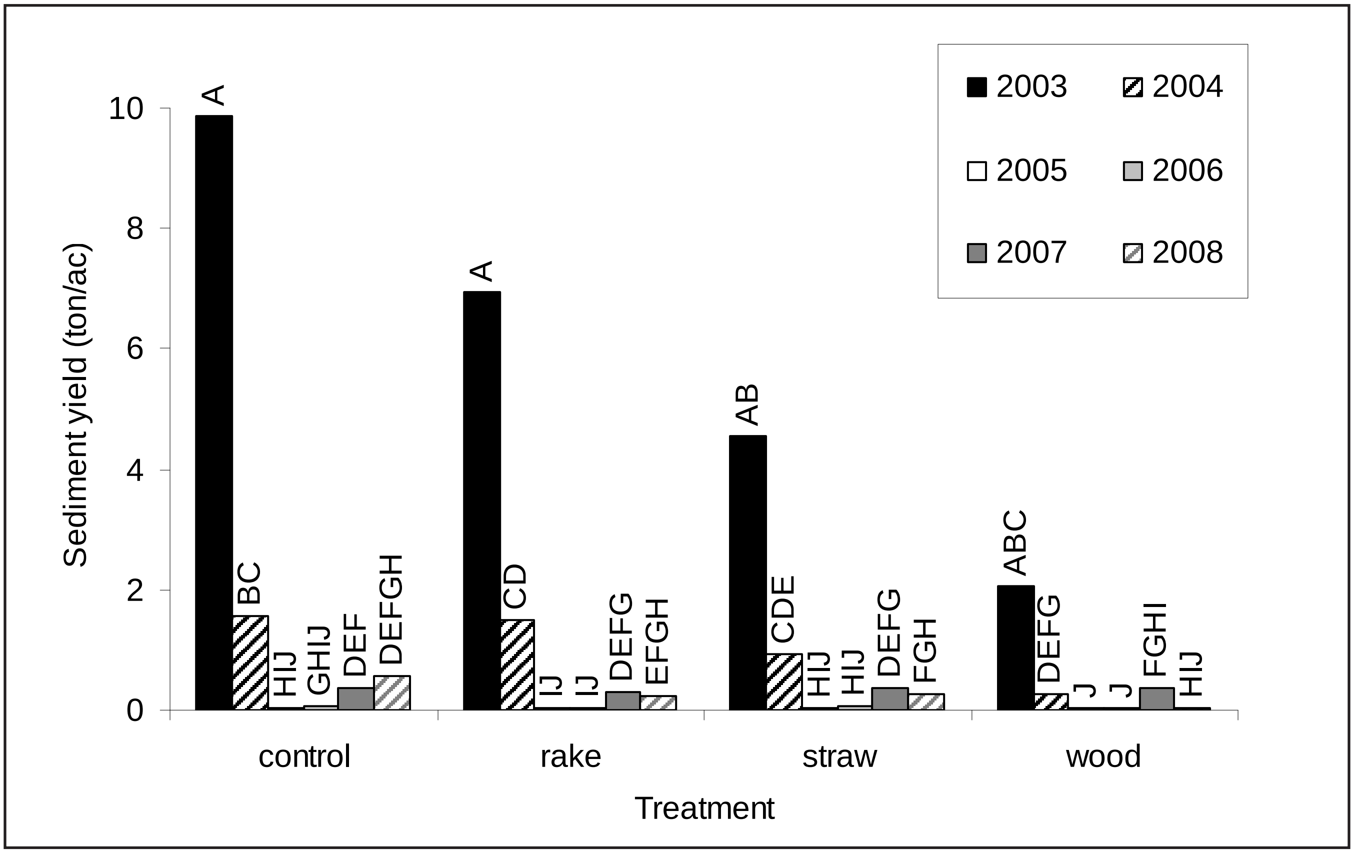


Figure 15. Sediment yield measurements (tons/acre/yr) over time from surface erosion study plots showing sediment reduction over time from 2002 to 2008, Hayman wildfire (reproduced from Robichaud & Wagenbrenner, 2009).

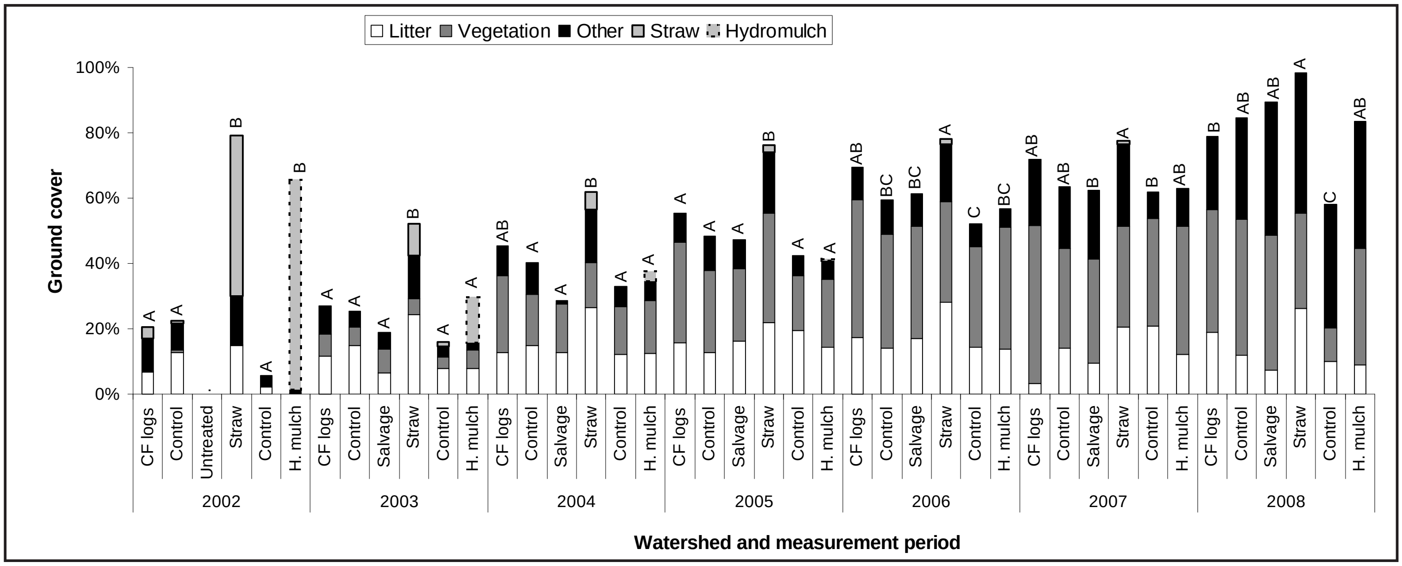


Figure 16. Ground cover recovery over time following the Hayman fire on research erosion study plots (reproduced from Robichaud & Wagenbrenner, 2009).

Processes and Methodology

The design of the surface erosion research conducted by the USDA Forest Service research station was to measure soil loss as exported to a weir that would represent delivered sediment for relatively short slope lengths and gradients between 20–40%. Variation in ground cover density and slope gradient was related to measured sediment yields. The research results by Robichaud and Wagenbrenner (2009), as depicted in **Figure 15** and **Figure 16**, show relations between ground cover and sediment yield over time. As a result of their data, a negative exponential relationship of erosion rate (tons/acre) as a function of ground cover density (%) was developed for this analysis (**Figure 17**). The research by Robichaud and Wagenbrenner showed "no significant" differences in erosion rate between 20% and 40% slopes. The "nonwettable" or hydrophobic soil condition that reduces infiltration is reduced after the first three years (Robichaud & Wagenbrenner, 2009). It was observed that hydrophobic soil conditions were discontinuous and not widespread throughout the Waldo Canyon Fire. As a result, surface erosion was not estimated as a function of hydrophobic soil conditions.

Ground cover densities were determined for small sections (polygons) within each sub-watershed to obtain the sediment yield from surface erosion in tons/acre/yr. The vegetation layer, provided by M. Purnell and B. Banks and E. Burry (USFS), was used to obtain ground cover percentage in these polygons. Because much of the area in the watershed was outside the range of Robichaud and Wagenbrenner's data, a delivery ratio was applied to the erosion rate using the Sediment Delivery Index (USEPA, 1980). The Sediment Delivery Index estimates the portion of surface erosion that is delivered to the stream systems.

The following variables were used to calculate delivered sediment from surface erosion:

- Percent Ground Cover
  - Total tree crown cover (TTCC)
  - Percent shrub
  - Percent forb
  - Percent grass
  - Percent barren
  - Percent water
- Satellite Burn Severity
- Treatments
  - Wood mulch
  - Straw mulch
- Presence of Rills (visual approximation from ground and aerial photos)
- Slope
- Slope Shape (concave *vs*. convex)
- Slope Length
- Soil Texture
- Available Water (using 1.0 inch/hr runoff)

The following procedure was followed to calculate delivered sediment for each sub-watershed:

1. Delineate polygons within sub-watersheds by similar physical attributes
2. Calculate variables (see above list) for each polygon
3. Calculate average delivery distance to nearest channel for each polygon
4. Calculate erosion rate for each polygon using the relationship derived from Robichaud and Wagenbrenner (2009) (**Figure 17**)
5. Calculate sediment delivery ratio for each polygon using the Stiff Diagram (USEPA, 1980)
6. Calculate delivered sediment for each polygon
7. Sum the delivered sediment for each sub-watershed (tons/yr)

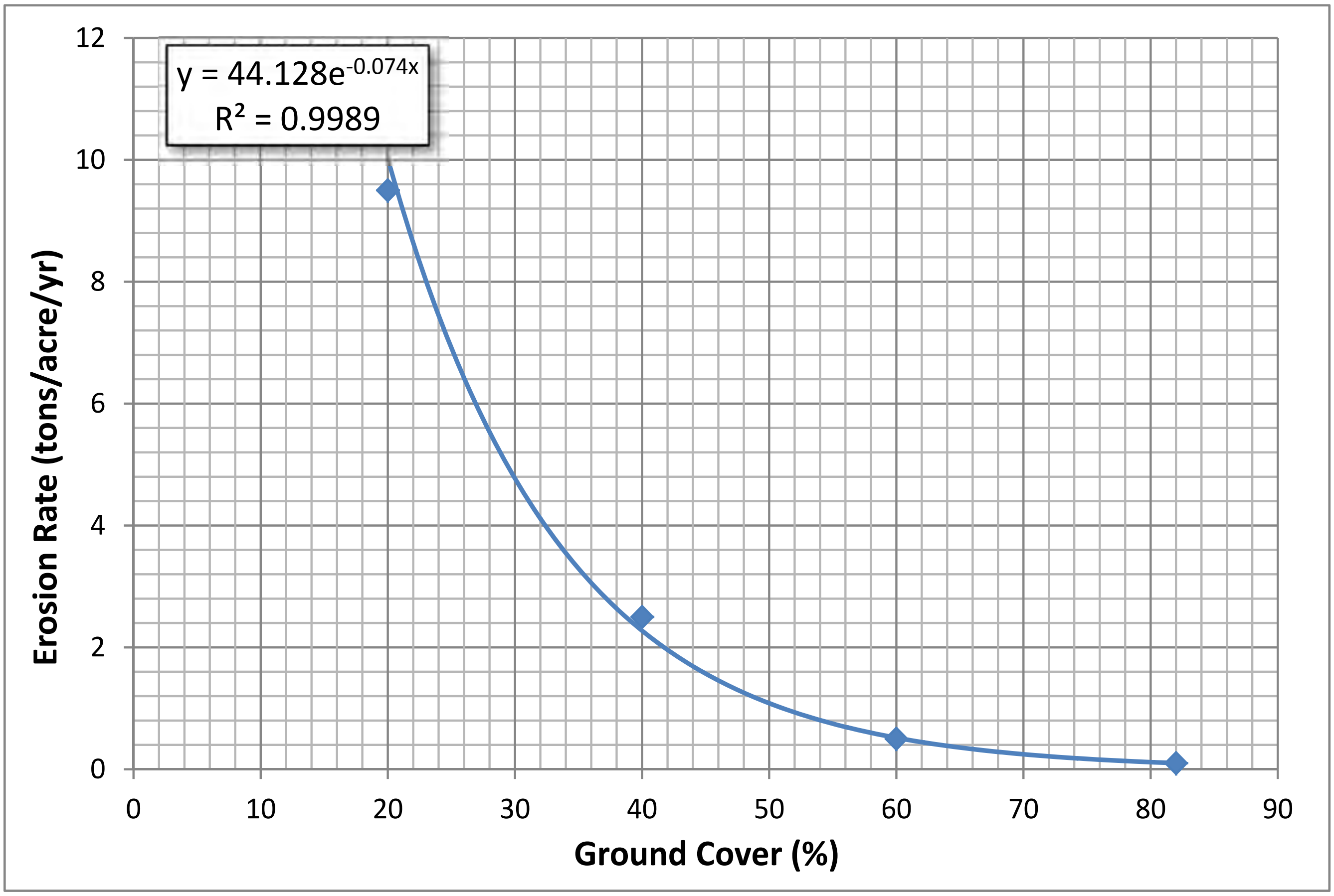


Figure 17. Surface erosion sediment yields by ground cover density for 20–40% slopes, as derived from Robichaud & Wagenbrenner (2009).

Hillslope erosion and associated sediment yield (tons/yr), average delivery ratios (percent of total surface erosion delivered as sediment), and sediment yield per unit of watershed (tons/acre/yr) are reported for the four major watersheds in **Table 5**. West Monument Creek had the lowest sediment yield (*2,532 tons/yr* and *0.30 tons/acre/yr*) and a sediment delivery rate of 7.7%, which is lower than the other major watersheds due to the lowest percentage of burn (48%) within the watershed. Camp Creek and Fountain Creek had comparable sediment delivery ratios, but Fountain Creek had nearly twice the estimated annual sediment yield delivered due to the larger watershed size. Camp Creek and Douglass Creek have similar delivered sediment yields but Douglas Creek had twice the delivered sediment per acre of *1.60 tons/acre/yr* compared to *0.80 tons/acre/yr* for Camp Creek.

Table 5. Surface erosion results for the four major watersheds.

Watershed	Hillslope Erosion (tons/yr)	Average Sediment Delivery	Delivered Sediment (tons/yr)	Delivered Sediment (tons/acre)
Camp Creek	42,809	9.8%	4,193	0.8
Douglas Creek	38,803	10.5%	4,057	1.6
Fountain Creek	74,549	9.8%	7,303	1.0
West Monument Creek	33,054	7.7%	2,532	0.3

The sediment yields, sediment delivery ratios, and unit area sediment yields for each of the sub-watersheds within each major watershed are included in **Appendix D**. These summaries will aid in identifying specific locations with disproportionate sediment source contributions from surface erosion processes to help direct restoration efforts.

For the Hayman Fire, Robichaud *et al*. (2005) indicated that hillslope processes of surface erosion due to the observed recovery were not the dominant contribution to the sediment supply, but rather were related to stream channels and gully erosion. It was noted that the sediment from active surface erosion processes and downslope transported sediment on stream adjacent slopes were effectively stored at the base of the slopes on benches with riparian vegetation adjacent to the channel (**Figures 18–21**). Significant reduction of sediment delivery from surface erosion processes was observed based on increasing ground cover density on stream adjacent slopes and the observations of benches at the toe of the slopes. This evidence suggests that the sediment delivery from surface erosion processes can be significantly reduced. Observations of such natural controls that prevent sediment yields will be used to provide additional mitigation recommendations documented in the restoration master plan. Because the sediment yield from surface erosion processes is directly related to ground cover density, and negligible sediment delivery ratios are associated with ground cover percentages greater than 65%, then revegetation and increased debris and sediment traps can greatly reduce this source of delivered sediment. Bankfull benches, floodplains, discontinuous slopes, dense riparian vegetation, alluvial fans, and slope debris have been effective at storing eroded surface erosion debris to prevent direct sediment introduction. These observations and interpretations will be included when considering conceptual designs to reduce surface erosion contributions to sediment yields.

Figure 18. Deposition of sediment from surface erosion behind logs and vegetation on slopes greater than 40% with high burn intensity, which provide low sediment delivery to stream channels.

Figure 19. Surface erosion on exposed slope adjacent to DC-007 showing rills and transported soils associated with a very low ground cover density.

Figure 20. Effective trap of eroded soil at the toe of an actively eroding slope due to a bankfull bench and riparian vegetation.

Figure 21. Close-up view of the effectiveness of the bankfull bench and riparian vegetation at preventing soil from entering stream.

Roads and Trails

Research Review

Over the long-term, studies by Colorado State University indicated that roads and motorized trails generate and deliver as much sediment to the stream channel network as high-severity wildfires (MacDonald, 2009). According to MacDonald (2009):

> "The estimated sediment production and delivery from roads and OHV trails was based on six years of road erosion monitoring, five years of post-fire erosion monitoring, nearly two years of monitoring sediment production from OHV trails, and extensive surveys of the connectivity of roads and OHV trails to streams.
>
> The exact balance between sediment from roads and OHV trails *vs*. high-severity wildfires depends on the assumed recurrence interval for high-severity wildfires. Charcoal dating, the extent of armoring on burned *vs*. unburned hillslopes, and the amount of accumulated sediment in channels all suggest that Hayman-type events are extremely rare. If this is true, then roads and OHV trails are quite possibly the dominant source of hillslope sediment because they produce large amounts of sediment from multiple storms every year."

Measured erosion rate values for roads resulted in *5.8 tons/acre* of road in the Hayman Fire (Libohova, 2004). The measured erosion rates are similar to sediment yields from roads if such roads are located adjacent to stream courses or drainage structures that drain directly into streams. Delivered sediment from roads was converted to the Road Impact Index (RII) (**Figure 22**, Rosgen, 2006/2009) based on USDA Forest Service research work on the Horse Creek Experimental area in Idaho and Fool Creek, Colorado (RII = road density multiplied by the number of stream crossings). Measured delivered sediment due to roads was related to the RII and stratified by lower *vs*. mid-to-upper slope position. Sediment rates for the lower 1/3 slope position of roads, with an RII of 0.1, resulted in delivered sediment to weir ponds of *5.7 tons/acre* of road (similar to the measurements by Libohova, 2004). However, up to *17.6 tons/acre* could potentially be delivered for RII values of 0.4 using the relationship for the lower 1/3 slope position of roads in **Figure 22**. For mid-to-upper slope positions, delivered sediment rates could potentially generate *0.15 tons/acre* for RII values of 0.1, and *1.1 tons/acre* for RII values of 0.4. Agreement between the measured road erosion rates from the Hayman Fire research (Libohova, 2004) and the sediment yield prediction from roads using the RII (Rosgen, 2006/2009) suggests the Road Impact Index is an appropriate model utilized for this assessment.

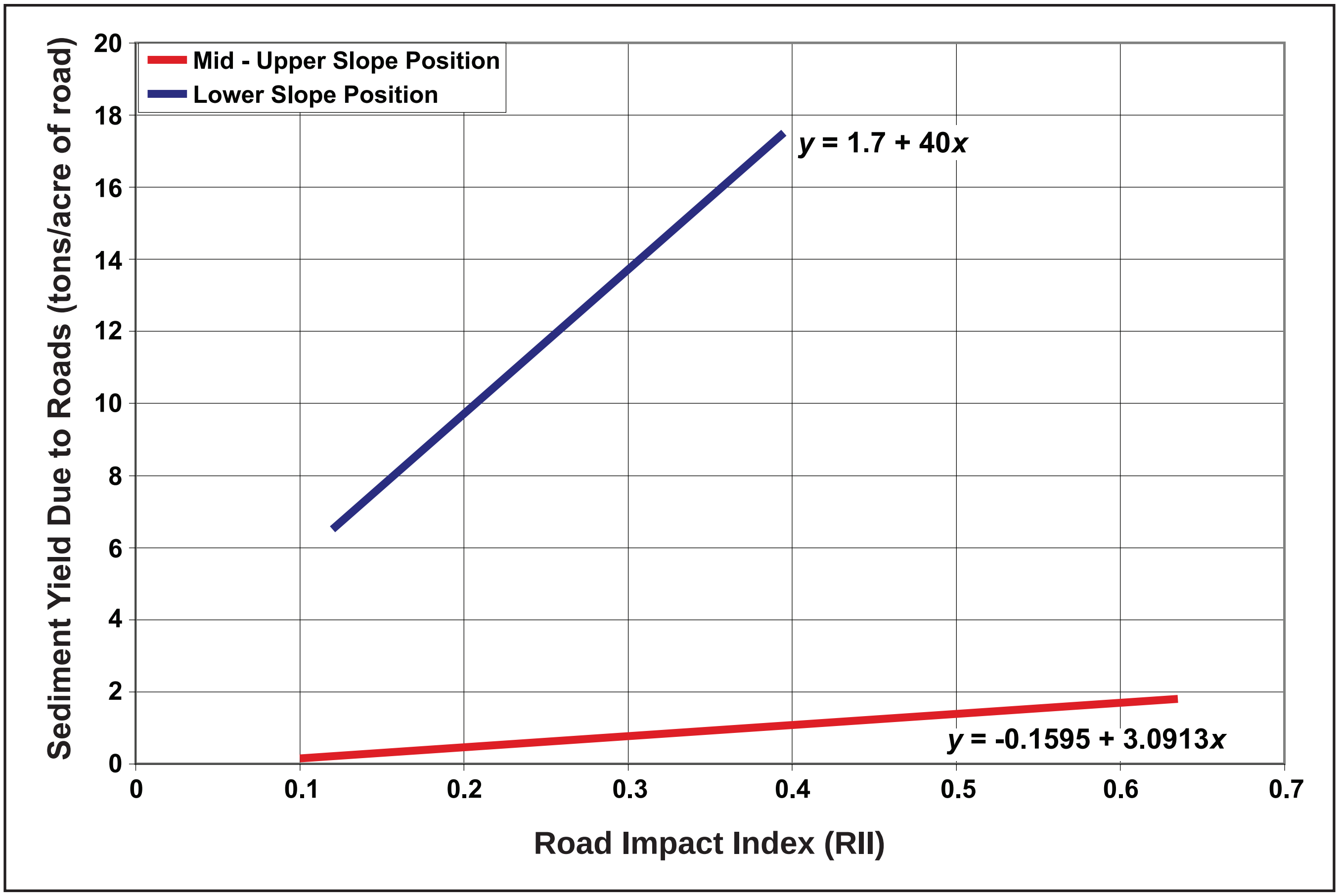


Figure 22. Sediment yield from roads based on the Road Impact Index (RII) stratified by slope position (WARSSS, Rosgen, 2006/2009).

Processes and Methodology

Stream encroachment, crossings, cut bank erosion, fill erosion, and poor drainage structure design (**Figure 23**) frequently result in disproportionate sediment yields. Another source of sediment is from the encroachment of the road system on stream channels that cut into the toe of alluvial fans (**Figure 24**); this over-steepens the channels causing headcuts and the routing of sediment from the fans directly into trunk streams. Also, routing ditch-line water and sediment from in-sloped roads leads to over-steepened A4 and G4 stream types, causing accelerated sediment delivery (**Figure 25** and **Figure 26**) (see **Appendix B** for stream type descriptions). These activities have caused maintenance problems in addition to delivered sediment.

The delivered sediment from roads and trails in the Waldo Canyon Fire is determined by use of the Road Impact Index (RII) as discussed in the previous section. The RII is implemented by calculating the total acres of sub-watershed, the total acres of road, the number of stream crossings (including ephemeral channels), and the dominant slope position (lower slope position *vs*. mid-to-upper slope position). The corresponding sediment yields are determined using **Figure 22** for each major watershed and sub-watershed. The total amount of sediment attributed to roads and trails in the four major watersheds is *2,035 tons/yr* (**Table 6**). Values for road-related sediment yields are included for each individual sub-watershed in **Appendix D** (**Note:** *These values are conservative as the Road Impact Index model does not necessarily reflect the increased flows that expose many roads and trails to accelerated sediment yield impacts from increased peak flows; thus these values are compared to sediment yield for pre-fire conditions*).

The sediment yield from roads and trails can be effectively controlled by improving road drainage, implementing closer-spaced cross drains, out-sloping the road, relocating site-specific roads, routing the channel away from the road fills, stabilizing tributaries above and below the road, and other related best management practices to mitigate this sediment source. Recommendations for sediment mitigation for roads and trails will be made in the master design plan for restoration.

Table 6. Summary of sediment derived from roads and trails.

Watershed	Roads and Trails			
	Total Acres of Road	Number of Stream Crossings	Sediment Delivered (tons/yr)	Percent of Total Introduced Sediment
Camp Creek	73.9	32	750.8	6.4%
Douglas Creek	68.1	31	236.1	2.3%
Fountain Creek	168.2	78	619.4	3.2%
West Monument Creek	124.9	36	428.7	4.2%

Figure 23. Cleaning out drainage structures continues to cut through depositional surfaces and cause headcut migration.

Figure 24. Road with a cut off fan accelerating erosion.

Figure 25. Road ditch with berm delivering sediment into stream channel.

Figure 26. Headcut from poor drainage causing excess erosion below road.

Channel Processes

Research Review

MacDonald (2009) reports the following related to channel processes for the Hayman burn area:

> "Most of the post-fire sediment is coming from rill, gully, and channel erosion rather than hillslopes. Almost all of the erosion occurs as a result of high-intensity summer thunderstorms, and the hillslopes play a critical role in terms of generating the surface runoff that then is concentrated into channels and induces flow-related erosion.
>
> Much of the sediment that is being generated from rills, gullies, and channels is then deposited in lower-gradient reaches. In ephemeral channels much of the sediment enters into storage, and is delivered to downstream reaches during larger storm events. In perennial channels there also is extensive sediment storage, but the accumulated sediment is primarily fine gravel and smaller. This means that the streams are able to transport this sediment into the downstream reaches at both high and low flows, and over time, much of the post-fire sediment will be excavated and delivered downstream.
>
> In-channel treatments, such as straw bale check dams, were primarily applied by the Denver Water Board, and there was no systematic monitoring of the effectiveness of these in-channel treatments."

Large amounts of sediment were still generated seven years after the Hayman Fire (MacDonald, 2009). Seven years after the Hayman fire, the Trail Creek Watershed study determined that 83% of the total sediment in the watershed was attributed to channel source sediment from increased runoff and unstable stream channels. This increase in sediment can be attributed to extreme storms where there is still sufficient runoff to cause further channel incision and streambank erosion (MacDonald, 2009).

Channel Source Sediment

There exists a high likelihood of debris flows/debris avalanche processes due to flood-related stormflow response and unstable channels in highly erodible grussic granite material. The prediction of such processes is extremely difficult. The USGS estimated thousands of tons of erosional debris from this process for 21 sub-basins as shown in **Table 7** (Verdin *et al*., 2012). On-site mitigation for such processes is nearly impossible; thus channel reconnection and functional use of alluvial fans become critical geomorphic components that should be considered for the restoration design phase.

The function of alluvial fans are to naturally store sediment directly below high sediment supply and high transport stream types, such as A3a+, A4a+, A5a+, A3–A5, F3–F5, and G3–G5 stream types (see **Appendix B** for stream type descriptions). The stable stream type for actively building, alluvial fans are the braided, D3–D5 stream types. The braided channel types disperse flow by convergence/divergence bed feature processes and induce sediment deposition over the width and length of the fan. Small to large alluvial fans are shown in **Figures 27–32** depicting the sediment deposited from upstream, high sediment supply stream types onto the extensive fan surface associated with braided, D4 stream types.

Table 7. Summary of USGS estimated erosion from debris flows by sub-watershed.

Watershed			2-year/ 1-hour Precipitation 29mm (1.1in)			10-year/ 1-hour Precipitation 42mm (1.7in)			25-year/ 1-hour Precipitation 48mm (1.9in)		
Basin	*WARSSS*	Drainage Area (mi^2)	Probability %	Tons	Volume (m^3)	Probability %	Tons	Volume (m^3)	Probability %	Tons	Volume (m^3)
1	MC-018/019, F15	0.3	0	5,000	2,400	1	6,100	2,900	2	6,700	3,200
2	MC-017	0.1	1	3,100	1,500	1	3,800	1,800	2	4,200	2,000
3	MC-016	0.4	0	5,700	2,700	0	6,900	3,300	0	7,500	3,600
4	MC-015	1.5	0	13,000	6,200	0	16,100	7,700	1	17,600	8,400
5	MC-016	1.3	3	33,500	16,000	8	41,900	20,000	12	46,000	22,000
6	MC-010	0.5	10	16,700	8,000	21	20,700	9,900	29	23,000	11,000
7	MC-008	1.1	5	35,600	17,000	12	43,900	21,000	18	48,100	23,000
8	MC-007	1.2	3	33,500	16,000	7	41,900	20,000	10	46,000	22,000
9	MC-001	1.4	2	33,500	16,000	4	41,900	20,000	6	46,000	22,000
10	DC-005**	2.1	22	96,300	46,000	41	119,000	57,000	51	129,700	62,000
11	DC-001, F02	1.3	13	41,900	20,000	27	52,300	25,000	36	56,500	27,000
12	CC-All	8.0	24	>209,000	>100,000	45	>209,000	>100,000	55	>209,000	>100,000
13	FC-002	2.6	32	129,700	62,000	54	161,100	77,000	64	176,000	84,000
14	FC-004	1.8	31	81,600	39,000	53	100,400	48,000	63	110,900	53,000
15	FC-005	0.5	54	23,000	11,000	74	29,300	14,000	82	33,500	16,000
16	FC-006	0.2	1	3,800	1,800	2	4,600	2,200	3	5,200	2,500
17	FC-007	0.8	54	35,600	17,000	74	43,900	21,000	82	48,100	23,000
18	FC-F07	0.1	15	6,100	2,900	30	7,500	3,600	40	8,500	3,900
19	FC-008	0.3	33	13,000	6,200	55	16,100	7,700	65	17,800	8,500
20	FC-009	0.3	45	17,000	8,100	67	20,900	10,000	76	23,000	11,000
21	FC-010	1.7	48	85,800	41,000	69	108,800	52,000	78	117,000	56,000
22	FC-011	1.1	6	33,500	16,000	13	41,900	20,000	18	46,000	22,000

Figure 27. Small alluvial fan deposit showing stable, functioning fan and a D4 stream type at the toe of a slope as the deposit is spread onto floodplain surface preventing direct introduction of sediment.

Figure 28. A stable, functioning, braided, D4 stream type on an alluvial fan (Valley Type IIIb), Douglas Creek.

Figure 29. Vegetated alluvial fan that is effectively trapping sediment from an ephemeral D4 stream type, Northfield Gulch.

Figure 30. A functioning, braided, D4 stream type on an alluvial fan that is depositing sediment rather than the sediment being routed into Northfield Gulch.

Figure 31. A large tributary and functioning alluvial fan with a D4 stream type that is depositing excess sediment onto the active fan surface.

Figure 32. A braided, D4 stream type that is depositing sediment onto a fan rather than effectively routing sediment into trunk stream.

Processes & Methodology

Stream inventories conducted in the burn area from Waldo Canyon Fire document existing valley types, stream types, and conditions to locate and quantify disproportionate sediment sources (see **Appendix B** for stream type and valley type descriptions). Because there are 237 miles of stream channels within the watersheds affected by the Waldo Canyon Fire, it was not practical to traverse each channel length, providing a detailed assessment of each. To characterize the major reaches in the watershed, the following procedures were utilized that allow for extrapolation of observed, detailed channel process relations to other reaches of similar stream type and condition. Stream impairment and sediment supply estimates were developed in a two-phase process:

Phase I

- Development of typical, *representative reaches* that represent a range of stability and sediment supply conditions for the various stream types that occur within the Waldo Canyon Fire Watershed
- Departure of the representative reaches from the stable, *reference reach* condition for various stream types and valley types with defined boundary conditions and controlling variables

Phase II

- Map stream types and conditions within the watersheds affected by the burn
- Extrapolate variables from the representative reaches to the mapped streams

A series of models are used to simulate channel response for a variety of erosional and depositional processes for the reference and representative reaches, and for each major watershed and sub-watershed. The following sections describe the assessment methodology implemented to characterize the sediment loads attributed to channel processes.

Phase I

Wildfire-induced changes in the boundary conditions (riparian vegetation and flow resistance) and the flow and sediment regimes promote changes in river morphology (stream type and stability). Typical channel responses to the fire effects include increased streambank erosion, channel enlargement, aggradation, degradation, lateral migration, and channel avulsion. The extent, nature and direction of change is dictated by the valley type and stream type associated with a given stream reach and its condition prior to the fire. Recognizing disequilibrium or unstable reaches and understanding what the stable form should be is instrumental to this effort on the watersheds affected by the Waldo Canyon Fire.

Stream type succession is used to interpret and predict the potential stable morphological state. Sixteen stream succession scenarios and stream type shifts toward stable end points for each scenario are presented in **Figure 33** (Rosgen, 2006/2009). These scenarios represent various sequences from actual rivers and are used to assist in predicting a river's behavior based on documentation of similar response from similar types for imposed conditions. Note that more scenarios exist than the sixteen depicted. It is important to select the appropriate scenario and current stage of stream succession to assist in selecting the stable, end-point stream type for restoration. Scenario #3, associated with the C4 to D4 to G4 to F4 to C4 stream type succession (**Figure 33**), is occurring in Northfield Gulch as depicted in **Figure 34** (D4 stream type), **Figure 35** (G4 stream type), and **Figure 36** (F4 stream type). The stable end-point, meandering, C4 stream type is depicted in **Figure 37**.

In several scenarios, a C4 stream type is shifted to a G4 stream type (e.g., Scenarios #1, #4, #8, #9 and #12 in **Figure 33**). The C4 to G4 stream type shift is due to either widening or an avulsion that then headcuts back into the previous, over-wide C4 stream type creating a G4 stream type. Another process leading to a C4 to G4 stream type conversion is a local lowering of base level where the bed elevation of the receiving stream is lowered. This process is termed *tributary rejuvenation or over-steepening headward*. Another cause can be the presence of debris jams or beaver dams; the aggradation caused by high sediment supply raises the local base level above the dam, and then over-steepens the slope causing lateral migration around the channel blockage resulting in a channel headcut or G4 stream type. The sediment consequence from channel incision when G4 channels are created is accelerated streambed and streambank erosion rates (**Figure 38**). In certain situations, the restoration direction is to convert the G4 stream type to a B4 stream type. This is appropriate where the meander width ratios (channel belt width divided by bankfull width that represents the degree of confinement) and entrenchment ratios (width of the flood-prone area divided by bankfull width that represents the degree of entrenchment) are both less than 3.0. The natural stream adjustment process associated with G4 stream types, as shown in **Figure 38**, is the G4 to F4 stream type shift, which involves extensive streambank erosion on both streambanks and bed lowering.

The tributary in **Figure 39** has downcut from a D4 stream type to a G4 stream type, and at the lower end has laterally eroded to an F4 stream type. These stream type shifts are associated with a very high sediment supply as the stream is adjusting to reach a stable end point. A B4 stream type is anticipated as the stable form in this situation due to the low meander width ratio and entrenchment ratio.

Stream successional scenarios #13 and #16 (**Figure 33**) are potentially appropriate for application on active alluvial fans (Valley Type IIIa, see **Appendix B**). Previously, headcut channels (fan-head trench channels) have been incised in the fan deposit causing loss of fan function. Subsequent flows and sediment are rapidly routed downstream with resultant streambed and streambank erosion. The modification to scenarios #13 and #16 would be to raise the level of the eventual braided, D channel back up to the original fan surface to restore the fan function by dispersing flow energy and storing sediment. Overall, the use of stream succession in design is dependent on the existing stream type and the stable potential type based on a valley type that matches the boundary conditions and the controlling variables.

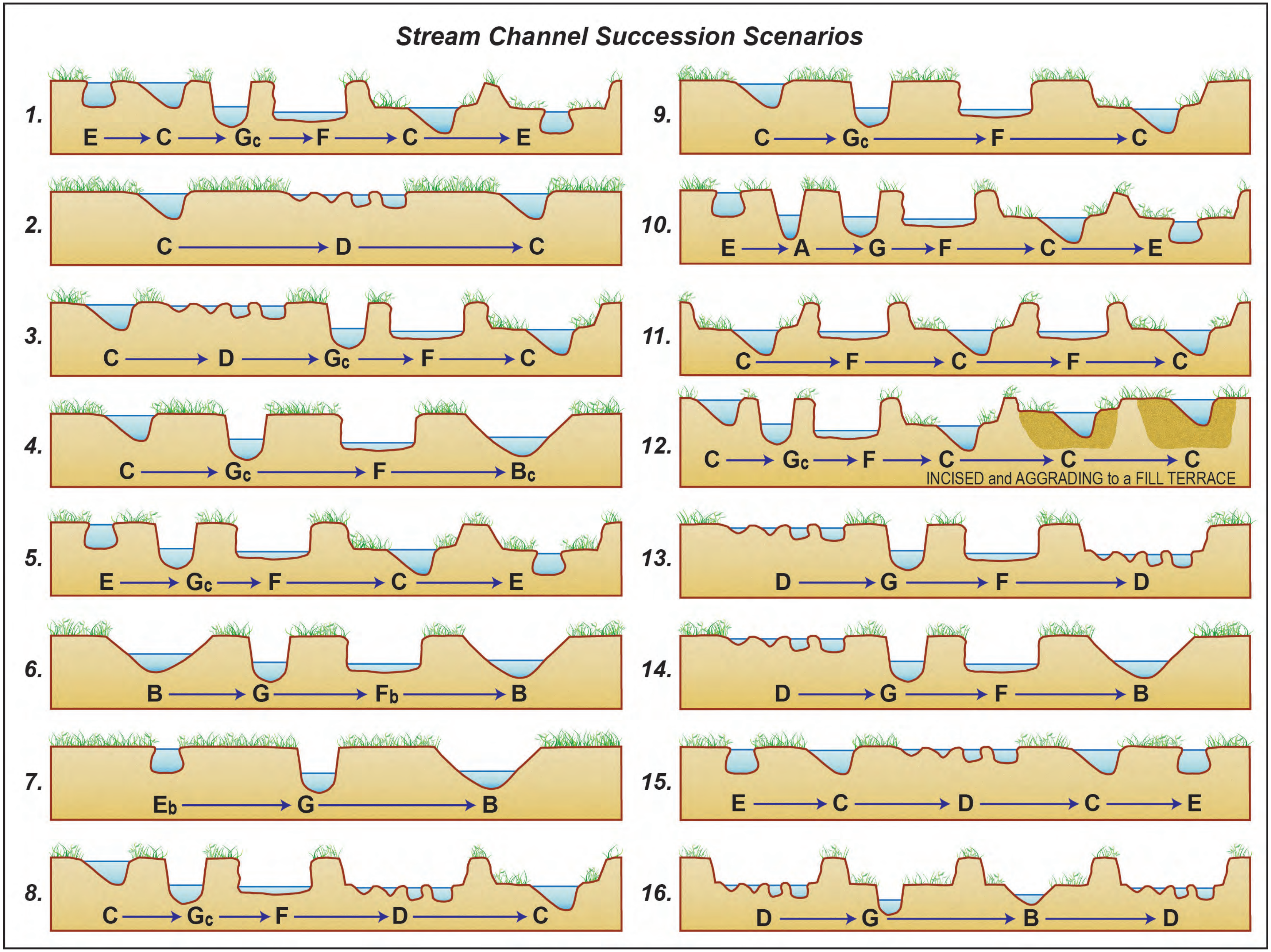


Figure 33. Various stream succession scenarios and corresponding stages of adjustment (Rosgen, 2006/2009).

Figure 34. A gravel-bed, braided, D4 stream type showing a very high width/depth ratio and excess bar deposition on Northfield Gulch.

Figure 35. An entrenched and actively incising gravel-bed gully, G4 stream type, downcut in previously deposited material in Northfield Gulch. Note the very high sediment supply from both streambed and banks.

Figure 36. An entrenched and actively enlarging F4 stream type with a high width/depth ratio, bar deposition and accelerated streambank erosion, Northfield Gulch.

Figure 37. A meandering, gravel-bed, C4 stream type, developing a new floodplain on an abandoned bed surface of a D4 stream type, Camp Creek.

Figure 38. An entrenched and actively incising gravel-bed gully, G4 stream type, downcut in previously deposited material, Northfield Gulch (MC-010). Note the very high sediment supply from streambed and banks.

Figure 39. An actively incising and widening gully G4 stream type, Sand Gulch (FC-011). Increases in streamflow peaks show unlimited, high sediment supply from channel erosion processes.

River Stability & Sediment Supply Evaluation

River stability is evaluated for each reference and representative reach. The evaluation is conducted on the reference reaches to validate a "Good" overall stability, and the data is used in the departure analysis of the representative reaches compared to reference condition. The stable reference reach data and the representative reach characterizations are stratified by stream type. The stream classification system is summarized in **Appendix B**. The variety of reference and representative stream types and their existing morphological, hydraulic, and sedimentological characteristics that occur within the Waldo Canyon Fire are summarized in **Appendix C**. Stratifying by stream type is necessary to extrapolate the established relationships elsewhere in the watershed based on similarity. Stream types are also stratified by valley types (Rosgen, 1994, 1996, 2006/2009, **Appendix B**) that integrate the boundary conditions and controlling variables responsible for a unique channel morphology and condition. A departure analysis of the representative reaches from their potential stable, reference reach condition is important in this assessment. The various stream types are mapped by the four major watersheds and sub-watersheds, and their corresponding stability and sediment relations are included in **Appendix D**.

Numerous models are used in the river stability evaluation and departure analysis of the representative reaches from their potential reference reach condition. Estimates of vertical and lateral stability, channel enlargement, and sediment supply are assessed, including channel competence and capacity evaluations. The BANCS model (*Bank Assessment for Non-point source Consequences of Sediment*, Rosgen, 2001, 2006/2009) is used to predict streambank erosion (tons/yr) and erosion rates (tons/yr/ft) for the reference reaches, representative reaches, major watersheds, and sub-watersheds. The BANCS model utilizes two tools to predict streambank erosion: 1) The Bank Erosion Hazard Index (BEHI), and 2) Near-Bank Stress (NBS). The BANCS model evaluates the bank characteristics and flow distribution along river reaches and maps BEHI and NBS risk ratings commensurate with streambank and channel changes. Annual erosion rates are estimated using the BEHI and NBS ratings, and then are multiplied by the bank height and corresponding bank length of a similar condition to estimate the tons of sediment per year.

Competence is determined using the revised Shields relation for initiation of motion (Rosgen, 2006/2009). The FLOWSED and POWERSED models (as programmed in RIVERMorph™) are used to analyze sediment yield and transport capacity to determine the bed stability (stable, aggradation or degradation) compared to the upstream sediment supply; the bed stability determination is based on the percentage of change between the upstream sediment supply and the sediment transport capacity of the existing condition. The POWERED model uses only the suspended sand concentration, which is the hydraulically-controlled sediment transport, rather than total suspended sediment as used in FLOWSED. POWERSED was not run on the A stream types; the A4a+ stream types are at their potential stream type, and will always show excess energy due to their steep slopes and characteristic high sediment transport.

The following are the worksheets from the WARSSS textbook (Rosgen, 2006/2009) utilized to determine the river stability and sediment supply for the reference and representative reaches:

- **Worksheet 5-2.** Computations of velocity and bankfull discharge, *WARSSS* page 5-24
- **Worksheet 5-3.** Level II stream classification, *WARSSS* page 5-32
- **Worksheet 5-4.** Morphological relations, modified from WARSSS page 5-34
- **Worksheet 5-6.** Riparian vegetation, *WARSSS* page 5-40
- **Worksheet 5-7.** Flow regime, *WARSSS* page 5-41
- **Worksheet 5-8.** Stream order and stream size, *WARSSS* page 5-42
- **Worksheet 5-9.** Meander patterns, *WARSSS* page 5-43
- **Worksheet 5-10.** Depositional patterns, *WARSSS* page 5-44
- **Worksheet 5-11.** Channel blockages, *WARSSS* page 5-45
- **Worksheet 5-12.** Degree of channel incision, *WARSSS* page 5-48
- **Worksheet 5-13.** Width/depth ratio state, *WARSSS* page 5-50
- **Worksheet 5-14.** Degree of channel confinement (lateral containment), *WARSSS* page 5-52
- **Worksheet 5-15.** Pfankuch channel stability rating, *WARSSS* page 5-54
- **Worksheet 5-16.** Bank Erosion Hazard Index (BEHI) rating, *WARSSS* page 5-59
- **Worksheet 5-17.** Near-Bank Stress (NBS) rating, *WARSSS* page 5-69
- **Worksheet 5-18.** Annual streambank erosion estimates, *WARSSS* page 5-84
- **Worksheet 5-19.** Total annual sediment yield prediction, *WARSSS* page 5-91
- **Worksheet 5-20a.** The upstream sediment transport prediction, *WARSSS* page 5-111
- **Worksheet 5-20b.** Sediment transport for the representative reach, *WARSSS* page 5-122
- **Worksheet 5-22.** Sediment competence calculations, *WARSSS* page 5-136
- **Worksheet 5-24.** Successional stage shifts, *WARSSS* page 5-148
- **Worksheet 5-25.** Lateral stability, *WARSSS* page 5-151
- **Worksheet 5-26.** Vertical stability – aggradation, *WARSSS* page 5-153
- **Worksheet 5-27.** Vertical stability – degradation, *WARSSS* page 5-154
- **Worksheet 5-28.** Channel enlargement, *WARSSS* page 5-155
- **Worksheet 5-29.** Overall sediment supply, *WARSSS* page 5-158
- **Worksheet 5-32.** Summary of stability condition categories, *WARSSS* page 5-166

The overall stability and sediment supply condition categories are summarized in **Worksheet 5-32** (Rosgen 2006/2009) for a range of stability indices. The completed worksheets and stability summaries are included in **Appendix C** for the reference and representative reaches.

Worksheet 5-32. Summary of the stability condition categories (Rosgen, 2006/2009).

Stream:					Location:					
Observers:				Date:		Stream Type:			Valley Type:	
Channel Dimension	Mean Bankfull Depth (ft):		Mean Bankfull Width (ft):		Cross-Section Area (ft^2):		Width of Flood-Prone Area (ft):		Entrenchment Ratio:	
Channel Pattern	Mean: Range:	MWR:		L_m/W_{bkf}:		R_c/W_{bkf}:			Sinuosity:	
River Profile and Bed Features	Check ✓: ☐ Riffle/Pool ☐ Step/Pool ☐ Plane Bed ☐ Convergence/Divergence ☐ Dunes/Antidunes/Smooth Bed									
	Max Bankfull Depth (ft):	Riffle	Pool	Depth Ratio (Max/Mean):	Riffle	Pool	Pool to Pool Spacing:	Ratio	Slope	
									Valley:	Average Bankfull:
Level III Stream Stability Indices	Riparian Vegetation	Current Composition/Density:		Potential Composition/Density:		Condition, Vigor and/or Usage of Existing Reach:				
	Flow Regime:	Stream Size and Order:		Meander Pattern(s):		Depositional Pattern(s):		Debris/Channel Blockage(s):		
	Degree of Incision (Bank-Height Ratio):		Degree of Incision Stability Rating:			Modified Pfankuch Stability Rating (Numeric and Adjective Rating):				
	Width/depth Ratio (W/d):	Reference W/d Ratio (W/d_{ref}):		Width/Depth Ratio State (W/d) / (W/d_{ref}):			W/d Ratio State Stability Rating:			
	Meander Width Ratio (MWR):	Reference MWR_{ref}:		Degree of Confinement (MWR / MWR_{ref}):			MWR / MWR_{ref} Stability Rating:			
Bank Erosion Summary	Length of Reach Studied (ft):	Annual Streambank Erosion Rate: (tons/yr)	(tons/yr/ft)	Curve Used:	Remarks:					
Sediment Capacity (POWERSED)	☐ Sufficient Capacity	☐ Insufficient Capacity	☐ Excess Capacity	Remarks:						
Entrainment/ Competence	Largest Particle from Bar Sample (mm):	$\tau =$	$\tau^* =$	Existing $Depth_{bkf}$:	Required $Depth_{bkf}$:	Existing $Slope_{bkf}$:	Required $Slope_{bkf}$:			
Successional Stage Shift	→ → → → →				Existing Stream State (Type):	Potential Stream State (Type):				
Lateral Stability	☐ Stable	☐ Mod. Unstable	☐ Unstable	☐ Highly Unstable	Remarks/Causes:					
Vertical Stability (Aggradation)	☐ No Deposition	☐ Mod. Deposition	☐ Ex. Deposition	☐ Aggradation	Remarks/Causes:					
Vertical Stability (Degradation)	☐ Not Incised	☐ Slightly Incised	☐ Mod. Incised	☐ Degradation	Remarks/Causes:					
Channel Enlargement	☐ No Increase	☐ Slight Increase	☐ Mod. Increase	☐ Extensive	Remarks/Causes:					
Sediment Supply (Channel Source)	☐ Low	☐ Moderate	☐ High	☐ Very High	Remarks/Causes:					

The Representative & Reference Reaches

The most detailed assessment of individual reach stability was conducted on the representative, or typical, stream types that occur within the various watersheds in the Waldo Fire area. The results of this analysis were extrapolated to other similar reaches within the watershed. Data for each stream type and valley type include the morphological characterization (dimension, pattern, profile, and channel materials) to determine the departure of each representative reach from the potential, stable stream type (reference reach).

Fifteen representative reaches were obtained:

1. A4/1a+ Fair Stability Reach
2. A4a+ Poor Stability Reach
3. A4a+ Poor Stability South Reach
4. A4a+ Poor Stability Downstream Reach
5. B4 Fair Stability Reach
6. C4 Fair Reach
7. C4 Poor Reach
8. D4a+ Poor Reach
9. E4 Good Stability HWD
10. F4 Fair Stability Reach
11. F4b Fair-Poor Stability Reach
12. F4b Poor Stability Reach
13. F4b Poor Stability Mainstem Reach
14. F4b Poor Stability Trib. Reach
15. G4 Poor Stability Reach

Three of the representative reaches (the A4a+ Poor Stability Reach, the F4 Fair Stability Reach, and the F4b Poor Stability Reach) are located in the West Monument Creek Watershed (**Figure 40**); the remaining reaches are located within the nearby Trail Creek Watershed as depicted in **Figure 41**. In addition to the stream type characterization, the reach identifiers also include the overall stability condition. These conditions were initially determined in the field and later verified using all the stability indices to determine an overall sediment supply rating. The overall stability conditions are based on the summary ratings from **Worksheet 5-29** (Rosgen, 2006/2009) that are derived from five individual stability rating categories (**Table 8**). The *WARSSS* worksheets that were used to characterize the representative reaches are completed in **Appendix C**.

Seven reference reaches were established to document a range of stream types and their associated stable dimensions, pattern, profile, and materials. Stability ratings for each reference reach were also obtained to document the existing, stable state. These data are used to extrapolate the dimensionless relations of the reference reach morphology for departure analysis when compared to unstable stream types. Thus, the same analysis that is completed for the representative, unstable reaches is completed for the reference reaches. If restoration designs are required, the reference reach data is used to scale the morphological characteristics of the stable form to apply to the restoration reaches that have similar valley types, boundary conditions, and controlling variables.

Seven reference reaches were surveyed for departure analysis and restoration design purposes:

1. A4a+ Reference Reach
2. A4/2 Reference Reach
3. B4 Reference Reach
4. B4/2c Reference Reach
5. C4 Reference Reach
6. D4a Reference Reach
7. E4 Reference Reach

The A4/2, B4/2c, and D4a reference reaches are from the West Monument Creek Watershed in the Waldo Canyon Fire burn perimeter as indicated in **Figure 40**. The C4 reference reach is Trout Creek located near the Manitou Experimental Forest Station in the nearby Trout Creek Watershed. The A4a+, B4, and E4 reference reaches are located within the nearby Trail Creek Watershed (**Figure 41**).

The summary of the dimension, pattern, and profile data for each representative and reference reach is shown in **Table 9**. The RIVERMorph™ software program was used to organize all the morphological data and the output graphs are shown in **Appendix C**. The summary of the stability rating categories for the reaches are presented in **Table 10**. The BANCS model was also conducted on the reference reaches to observe the natural (acceptable), stable streambank erosion rates to help understand the geologic rates that can be expected. The streambank erosion, sediment competence, and the individual stability processes are summarized in **Table 11**. The basic data summarized in **Tables 9–11** were used to determine the departure of the representative reaches from the naturally stable, reference reaches and to apply the dimensionless relations of the stable morphology for restoration purposes.

Table 8. Overall stability condition categories for the representative reaches based on the points from **Worksheet 5-29** (Rosgen, 2006/2009) that are derived from five individual stability rating categories.

Overall Stability Condition ***Based on Points from Worksheet 5-29***				
5 Points **"GOOD"**	**6 – 8 Points** **"GOOD-FAIR"**	**9 – 11 Points** **"FAIR"**	**12 – 13 Points** **"FAIR-POOR"**	**> 13 Points** **"POOR"**

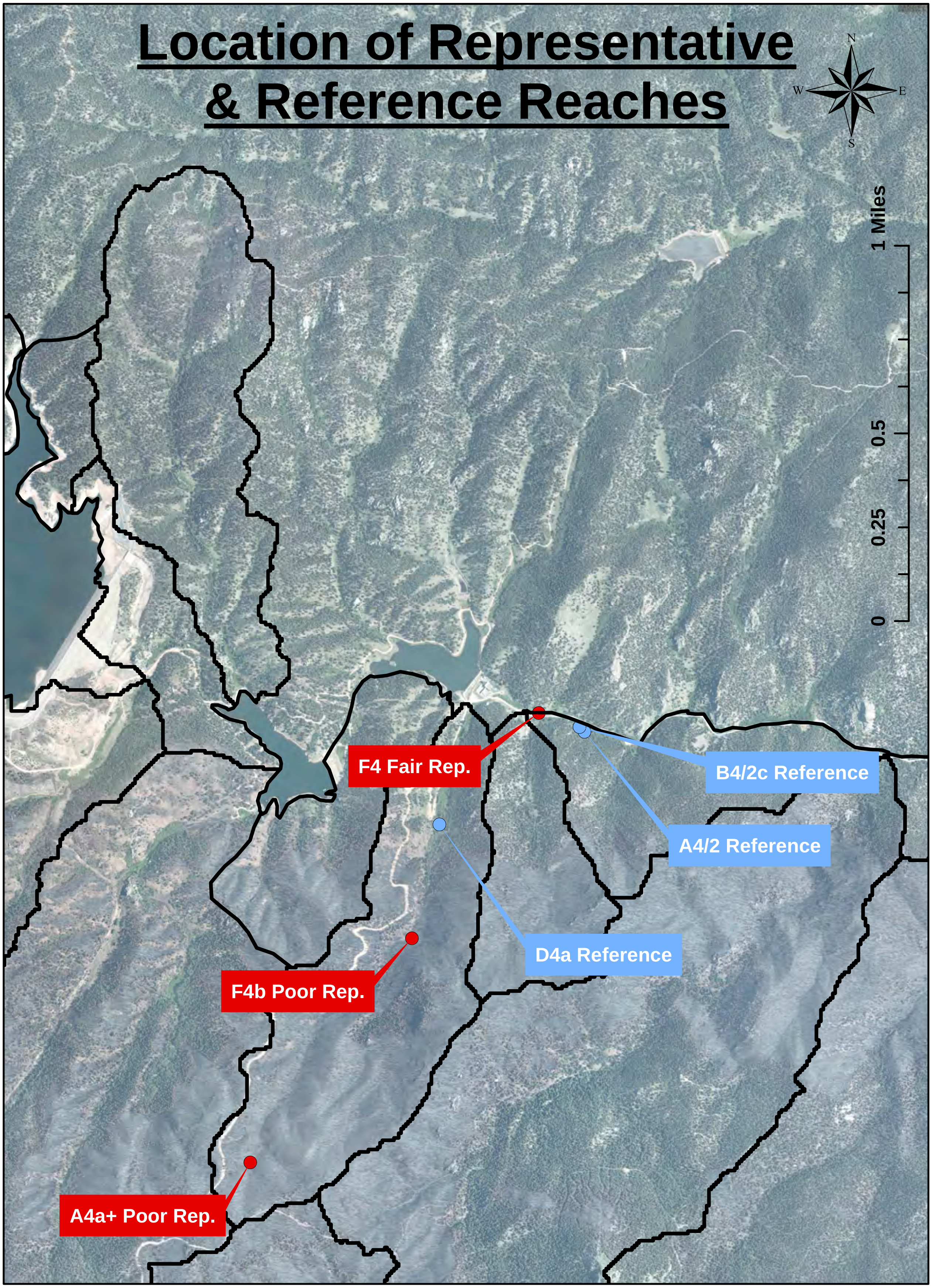


Figure 40. Location of the Waldo Canyon Fire representative and reference reaches, as summarized in **Appendix C**.

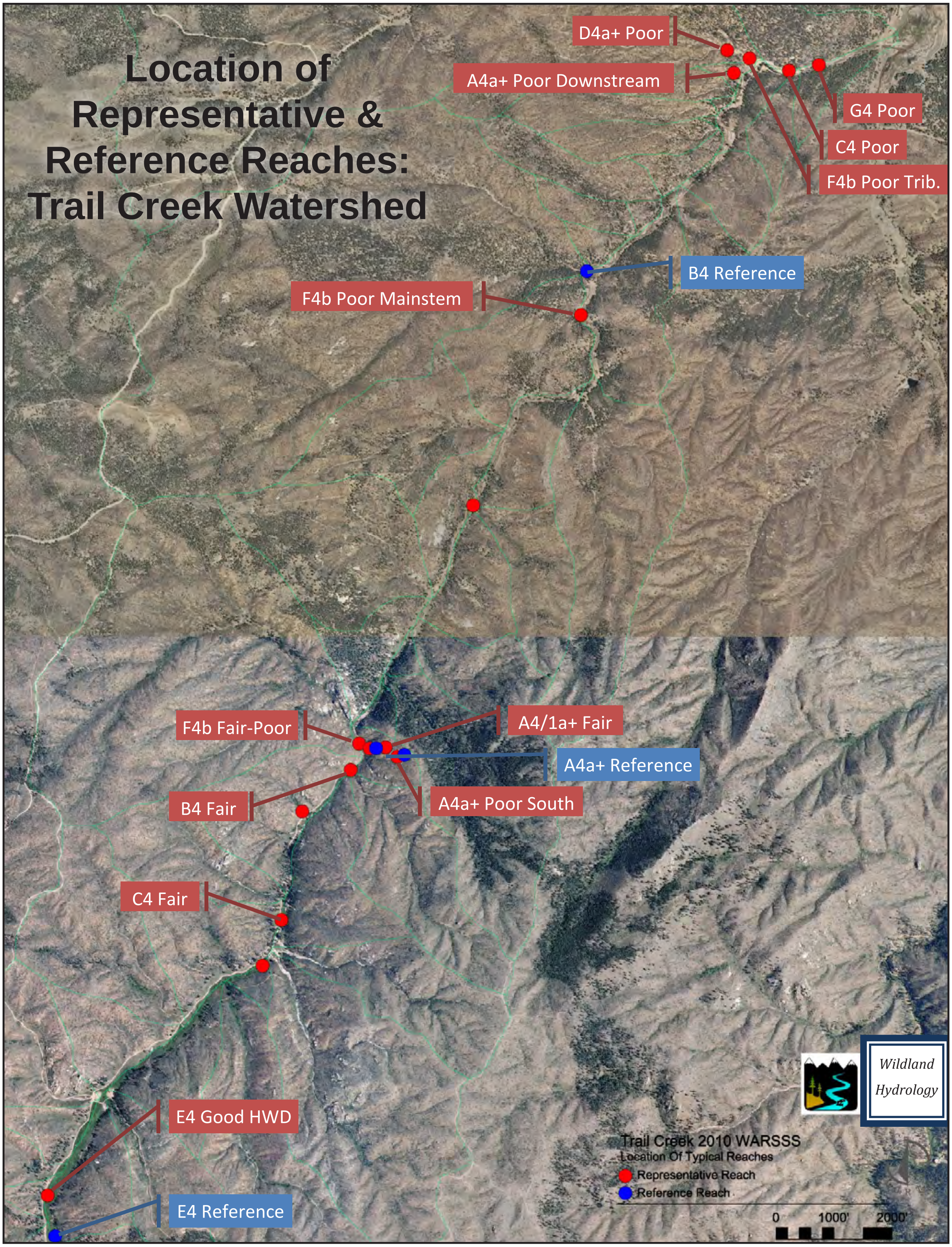


Figure 41. Location of the reference and representative reaches within the Trail Creek Watershed, as summarized in **Appendix C**.

Worksheet 5-29. Overall sediment supply rating (Rosgen, 2006/2009); the points from this worksheet are used to determine an overall stability rating for each reach.

Stream:	Stream Type:
Location:	Valley Type:
Observers:	Date:

Overall Sediment Supply Prediction Criteria (choose corresponding points for each criterion 1–5)	**Stability Rating**	**Points**	**Selected Points**
1 Lateral Stability (Worksheet 5-25)	Stable	1	
	Mod. Unstable	2	
	Unstable	3	
	Highly Unstable	4	
2 Vertical Stability Excess Deposition/ Aggradation (Worksheet 5-26)	No Deposition	1	
	Mod. Deposition	2	
	Excess Deposition	3	
	Aggradation	4	
3 Vertical Stability Channel Incision/ Degradation (Worksheet 5-27)	Not Incised	1	
	Slightly Incised	2	
	Mod. Incised	3	
	Degradation	4	
4 Channel Enlargement Prediction (Worksheet 5-28)	No Increase	1	
	Slight Increase	2	
	Mod. Increase	3	
	Extensive	4	
5 Pfankuch Channel Stability Rating (Worksheet 5-15)	Good: Stable	1	
	Fair: Mod Unstable	2	
	Poor: Unstable	4	
		Total Points	

	Category Point Range			
Overall Sediment Supply Rating (use total points and check ✓ stability rating)	Low 5 ☐	Moderate 6 – 10 ☐	High 11 – 15 ☐	Very High 16 – 20 ☐

Table 9. Dimension, pattern and profile data summarized for the reference and representative reaches; the morphology for each reach is provided in **Appendix C**.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Sub-watershed or Reach Location	Dimension							Pattern					Profile	
	Representative Cross-Section for Dimensions	Bankfull Mean Depth (d_{bkf})	Bankfull Width (W_{bkf})	Cross-Sectional Area (A_{bkf})	Width/ Depth Ratio (W/d)	Bankfull Maximum Depth (d_{max})	Entrench-ment Ratio (ER)	Linear Wavelenth to Bankfull Width (λ/W_{bkf}) (mean & range)	Stream Meander Length to Width (L_m/W_{bkf}) (mean & range)	Radius of Curvature to Width (R_c/W_{bkf}) (mean & range)	Meander Width Ratio (W_{blt}/W_{bkf}) (mean & range)	Sinuosity (k)	Average Water Surface Slope (S)	Valley Slope (S_{val})
1. **A4/1a+ Fair**	**XS 0+25.2**	**0.25**	**1.79**	**0.45**	**7.16**	**0.37**	**1.31**	**N/A**	**N/A**	**N/A**	**1.5**	**1.1**	**0.243**	**0.2673**
2. **A4a+ poor**	**XS 2+83**	**0.72**	**7.03**	**5.04**	**9.76**	**1.39**	**2.37**	**N/A**	**N/A**	**N/A**	**2.51, 3.18-3.15**	**1.23**	**0.081**	**0.085**
3. **A4a+ Poor South**	**XS 0+99.1**	**0.22**	**1.98**	**0.44**	**9.00**	**0.43**	**1.47**	**N/A**	**N/A**	**N/A**	**N/A**	**1.01**	**0.128**	**0.129**
4. **A4a+ Poor Downstream**	**XS 0+9.84**	**0.24**	**2.2**	**0.53**	**9.17**	**0.4**	**1.25**	**N/A**	**N/A**	**N/A**	**5.4**	**1.09**	**0.1236**	**0.1347**
5. **B4 Fair**	**XS 2+74**	**0.57**	**12.59**	**7.19**	**22.09**	**1.1**	**1.46**	**7.16**	**N/A**	**N/A**	**2.97**	**1.2**	**0.024**	**0.029**
6. **C4 Fair**	**Riffle XS 3+76**	**0.58**	**14.2**	**8.15**	**24.48**	**1.03**	**2.52**	**7.48, 4.04–9.89**	**8.03, 5.75–9.95**	**3.48, 1.71–5.27**	**1.45, 1.37–1.57**	**1.05**	**0.018**	**0.0189**
7. **C4 Poor**	**Riffle XS 0+22.7**	**0.48**	**29.02**	**13.95**	**60.46**	**1.12**	**2.03**	**N/A**	**N/A**	**1.18, 0.67–1.91**	**1.38, 0.83–1.66**	**1.08**	**0.014**	**0.0148**
8. **D4a+ Poor**	**Riffle XS 1+07.5**	**0.15**	**7.8**	**1.18**	**52.00**	**0.46**	**5.55**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0.123**	**0.1267**
9. **E4 Good HWD**	**Riffle XS 1+13**	**0.61**	**5.93**	**3.63**	**9.72**	**1.03**	**5.44**	**5.99, 4.3–8.26**	**8.03, 5.15–11.2**	**1.25, 0.75–1.75**	**3.86, 2.75–5.33**	**1.46**	**0.008**	**0.0117**
10. **F4 Fair**	**XS 0+24**	**0.53**	**7.68**	**4.06**	**14.49**	**0.8**	**1.38**	**6.91, 6.63-7.19**	**7.88, 7.29-8.46**	**1.60, 1.15-3.26**	**3.44**	**1.09**	**0.016**	**0.018**
11. **F4b Fair-Poor**	**Rifle XS 0+40**	**0.53**	**19.9**	**10.6**	**37.55**	**1.13**	**1.32**	**N/A**	**N/A**	**N/A**	**1.18**	**1.03**	**0.021**	**0.0215**
12. **F4b Poor**	**XS 1+22**	**0.26**	**5.8**	**1.53**	**22.31**	**0.53**	**1.06**	**12.12**	**13.08**	**6.63, 6.15-7.12**	**10.45, 5.94-18.51**	**1.05**	**0.036**	**0.037**
13. **F4b Poor Mainstem**	**Riffle XS 3+75**	**0.53**	**17.15**	**9.17**	**32.36**	**1.05**	**1.4**	**9.9, 7.9–12.8**	**10.7, 7.9–12.8**	**2.75, 2.2–3.5**	**1.99, 1.17–2.82**	**1.25**	**0.028**	**0.035**
14. **F4b Poor Trib.**	**XS 2+80**	**0.24**	**11.35**	**2.67**	**47.29**	**0.41**	**1.17**	**N/A**	**N/A**	**N/A**	**1.43, 1.09–2.14**	**1.04**	**0.041**	**0.0425**
15. **G4 Poor**	**Riffle XS 2+31**	**0.89**	**9.75**	**8.68**	**10.96**	**1.17**	**1.27**	**N/A**	**N/A**	**N/A**	**1.82**	**1.05**	**0.0259**	**0.027**
16. **A4a+ Reference**	**XS 0+15.62**	**0.21**	**2.3**	**0.48**	**10.95**	**0.27**	**1.59**	**N/A**	**N/A**	**N/A**	**1.52**	**11.1**	**0.198**	**0.220**
17. **A4/2 Reference**	**XS 2+83**	**0.72**	**7.03**	**5.04**	**9.76**	**1.39**	**2.37**	**N/A**	**N/A**	**N/A**	**2.51, 2.18-3.15**	**1.23**	**0.081**	**0.085**
18. **B4 Reference**	**XS 0+18.5**	**0.74**	**9.31**	**6.91**	**12.58**	**1.18**	**1.99**	**10.4, 8.7–12.9**	**11.2, 9.4–13.5**	**5.4, 3.4-7.0**	**2.7, 1.5–6.0**	**1.13**	**0.0242**	**0.02735**
19. **B4/2c Reference**	**XS 0+80**	**0.81**	**7.7**	**6.21**	**9.51**	**1.47**	**2.54**	**6.34, 5.35-7.34**	**6.84, 6.22-7.46**	**2.89, 1.95-4.42**	**10.45, 5.94-18.51**	**1.06**	**0.013**	**0.014**
20. **C4 Reference**	**XS 0+67**	**0.89**	**19.37**	**17.32**	**21.76**	**1.4**	**2.16**	**4.67, 3.43–6.33**	**5.79, 4.02–8.9**	**2.31, 1.68-3.51**	**3.66, 2.37–4.58**	**1.38**	**0.0044**	**0.0061**
21. **D4a Reference**	**XS 0+12**	**0.16**	**17.92**	**2.81**	**112.00**	**0.78**	**4.83**	**N/A**	**N/A**	**N/A**	**N/A**	**1**	**0.072**	**0.078**
22. **E4 Reference**	**XS 2+42.5**	**0.73**	**5.73**	**4.17**	**7.85**	**0.95**	**6.24**	**5.4, 4.99–6.27**	**6.08, 5.09–7.27**	**3.09, 1.76–4.8**	**3.3, 2.76–3.8**	**1.23**	**0.0101**	**0.0124**

Table 10. Summary of the stability indices for the reference and representative reaches modified from **Worksheet 5-5** of *WARSSS* (Rosgen, 2006/2009). The detailed stability indices are included in **Appendix C** for each reach.

	(1)	(2)	(3)		(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Reach Location	Stream Type **(Worksheet 5-3)**	**a.** Riparian Vegetation **(Worksheet 5-6)**		**b.** Flow Regime **(Worksheet 5-7)**	**c.** Stream Order/Size **(Worksheet 5-8)**	**d.** Meander Patterns **(Worksheet 5-9)**	**e.** Deposi-tional Patterns **(Worksheet 5-10)**	**f.** Channel Blockages **(Worksheet 5-11)**	**g.** Degree of Channel Incision **(Worksheet 5-12)**	**h.** Width/ Depth Ratio State **(Worksheet 5-13)**	**i.** Degree of Channel Confinement **(Worksheet 5-14)**	**j.** Pfankuch Channel Stability Rating **(Worksheet 5-15)**
			Existing Species Composition	Potential Species Composition									
1	**A4/1a+ Fair**	**A4/1a+**	**Aspen/Shrubs/Grass**	**Aspen/P.Pine/Shrubs**	**E1, E2, E8**	**S-2(2)**	**M1**	**B2**	**D3 (Moderate)**	**1.5 (Mod. Incised)**	**0.66 (Mod. Unstable)**	**0.99 (No Departure)**	**97 (Fair)**
2	**A4a+ Poor**	**A4a+**	**Burnt Trees, Young Aspen**	**Aspen/Conifers**	**E1, E2, E8**	**S-2(1)**	**N/A**	**N/A**	**D2 (Infrequent)**	**3.7 (Deeply Incised)**	**0.74 (Moderately Unstable)**	**7.0 (Unconfined)**	**104 (Poor)**
3	**A4a+ Poor South**	**A4a+**	**Aspen, Raspberry**	**Aspen, P. Pine**	**E1, E2, E8**	**S-2(1)**	**M1**	**B4, B5**	**D1 (None)**	**4.7 (Deeply Incised)**	**0.82 (Stable)**	**1.0 (No Departure)**	**133 (Poor)**
4	**A4a+ Poor Downstream**	**A4a+**	**P.Pine Seeds, Grass/Forb**	**Mature Pine/Shrubs**	**E1, E2, E8**	**S-2(2)**	**M1**	**B3, B4, B5**	**D2 (Infrequent)**	**5.1 (Deeply Incised)**	**0.84 (Stable)**	**3.6 (Unconfined)**	**140 (Poor)**
5	**B4 Fair**	**B4**	**Willow, Aspen, Grass**	**Same but w/o Invasives**	**P1, P2, P8**	**S-3(3)**	**M1**	**B4, B8**	**D2 (Infrequent)**	**1.0 (Stable)**	**1.75 (Highly Unstable)**	**1.1 (Unconfined)**	**70 (Fair)**
6	**C4 Fair**	**C4**	**Willow, Pine, Spruce, Carex**	**Same but w/o Invasives**	**P1, P2, P8**	**S-3(4)**	**M3**	**B1, B4, B7**	**D1 (None)**	**1.0 (Stable)**	**1.28 (Mod. Unstable)**	**0.32 (Mod. Confined)**	**94 (Fair)**
7	**C4 Poor**	**C4**	**Spruce, Willow, Shrubs, Grass**	**Higher Density w/o Invasives**	**P2, P8**	**S-4(4)**	**M3**	**B1, B2, B4**	**D2 (Infrequent)**	**1.0 (Stable)**	**4.38 (Highly Unstable)**	**0.31 (Mod. Confined)**	**133 (Poor)**
8	**D4a+ Poor**	**D4a+**	**< 5% Annual Grass/Forb**	**Willow, Alder, Brass, Aspen**	**E2, E8, S2, S8**	**S-3(2)**	**None**	**B5, B6, B7**	**D4 (Numerous)**	**1.0 (Stable)**	**4.14 (Highly Unstable)**	**0.76 (Slight Departure)**	**146 (Poor)**
9	**E4 Good HWD**	**E4**	**Willow, Cares, Thistle, Grass**	**Same but w/o Invasives**	**P1, P2, P8**	**S-3(3)**	**M3**	**B1, B4**	**D1 (None)**	**1.0 (Stable)**	**1.25 (Mod. Unstable)**	**1.2 (Unconfined)**	**56 (Good)**
10	**F4 Fair**	**F4**	**Willow, Aspen**	**At Potential**	**P1, P2, P7, P8**	**S-3(4)**	**M3**	**B2, B5**	**D3 (Moderate)**	**2.2 (Deeply Incised)**	**0.91 (Stable)**	**0.93 (Unconfined)**	**97 (Poor)**
11	**F4b Fair-Poor**	**F4b**	**Willow, Aspen, Grass, Forb**	**Same but w/ Mature Species**	**P1, P2, P8**	**S-4(4)**	**M1**	**B3, B4**	**D1 (None)**	**1.0 (Stable)**	**2.99 (Highly Unstable)**	**0.44 (Mod. Confined)**	**103 (Fair-Poor)**
12	**F4b Poor**	**F4b**	**Burnt Trees, Young Aspen**	**Aspen, Confifers**	**P1, P2, P8**	**S-3(3)**	**M3**	**B5, B6, B7**	**D2 (Infrequent)**	**8.7 (Deeply Incised)**	**1.39 (Mod. Unstable)**	**1.20 (Unconfined)**	**143 (Poor)**
13	**F4b Poor Mainstem**	**F4b**	**Alder, Willow, Forbs**	**Willow, Carex/Juncus**	**P1, P2, P8**	**S-4(3)**	**M3**	**B4**	**D3 (Moderate)**	**1.0 (Stable)**	**2.57 (Highly Unstable)**	**0.8 (Unconfined)**	**134 (Poor)**
14	**F4b Poor Trib.**	**F4b**	**5% P. Pine, Grasses**	**Willow, Alder, Grass, Aspen**	**E2, E8, S2, S8**	**S-3(4)**	**M1**	**B5, B7**	**D2 (Infrequent)**	**1.0 (Stable)**	**3.76 (Highly Unstable)**	**0.53 (Mod. Confined)**	**144 (Poor)**
15	**G4 Poor**	**G4**	**Willow 100%**	**Salix, Alder**	**P1, P2, P8**	**S-3(4)**	**M3, M4**	**B6, B7**	**D3 (Moderate)**	**1.7 (Deeply Incised)**	**0.48 (Unstable)**	**0.52 (Mod. Confined)**	**138 (Poor)**
16	**A4a+ Reference**	**A4a+**	**Aspen, Forbs, Grasses**	**Same w/o Invasives**	**E1, E2, E8**	**S-2(1)**	**M1**	**None**	**D2 (Infrequent)**	**3.0 (Deeply Incised)**	**1.0 (Stable)**	**1.0 (No Departure)**	**89 (Good)**
17	**A4/2 Reference**	**A4/2**	**Aspen, Spruce, Ponderosa pine, Willow, Choke**	**At Potential**	**P1, P2, P7, P8**	**S-3(4)**	**N/A**	**N/A**	**D3 (Moderate)**	**1.2 (Slightly Incised)**	**1.0 (Stable)**	**1.0 (Unconfined)**	**74 (Good)**
18	**B4 Reference**	**B4**	**Aspen, Willow**	**Aspen, Willow**	**P1, P2, P8**	**S-3(3)**	**M1, M3**	**B4**	**D2 (Infrequent)**	**1.0 (Stable)**	**1.0 (Stable)**	**1.0 (Unconfined)**	**60 (Good)**
19	**B4/2c Reference**	**B4/2c**	**Spruce, Aspen, Willows, Grass**	**At Potential**	**P1, P2, P7, P8**	**S-3(4)**	**M3**	**N/A**	**D3 (Moderate)**	**1.0 (Stable)**	**1.0 (Stable)**	**1.0 (Unconfined)**	**54 (Good)**
20	**C4 Reference**	**C4**	**Willow, Redtop, Carex/Juncus**	**Same w/o Invasives**	**P1, P2, P8**	**S-4(4)**	**M1, M3**	**B1, B2**	**D1 (None)**	**1.0 (Stable)**	**1.0 (Stable)**	**1.0 (Unconfined)**	**73 (Good)**
21	**D4a Reference**	**D4a**	**Mixed Conifer, Aspen, Willow**	**At Potential**	**E1, E2, E7, E8**	**S-4(3)**	**N/A**	**B6**	**D2 (Infrequent)**	**1.0 (Stable)**	**1.0 (Stable)**	**N/A**	**40 (Good)**
22	**E4 Reference**	**E4**	**Willow, Carex, Conifers**	**Same as Existing**	**P1, P2, P8**	**S-3(3)**	**M3**	**B2**	**D1 (None)**	**1.0 (Stable)**	**1.0 (Stable)**	**1.0 (Unconfined)**	**60 (Good)**

Table 11. Summary of the sediment from streambank erosion and the channel stability ratings for the reference and representative reaches using a modified **Worksheet 5-30** from *WARSSS* (Rosgen, 2006/2009). The detailed stability ratings are included in **Appendix C** for each reach.

(1)	(2)		(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Sub-watershed or Reach Location	**Step 9:** Streambank Erosion (**Worksheet 5-18**)		**Step 19:** Sediment Transport Capacity Stability Rating **(Worksheet 5 20b)**	**Step 22:** Sediment Competence/ Entrainment **(Worksheet 5-22)**	**Step 23:** Overall Channel Response due to Sediment Competence and Capacity	**Step 24:** Successional Stage Shifts Stability Rating **(Worksheet 5-24)**	**Step 25:** Lateral Stability Rating **(Worksheet 5-25)**	**Step 26:** Vertical Stability Rating - Aggradation **(Worksheet 5-26)**	**Step 26:** Vertical Stability Rating - Degradation **(Worksheet 5-27)**	**Step 27:** Channel Enlargement Rating **(Worksheet 5-28)**	**Step 28:** Overall Channel Source Sediment Supply Rating & Associated Points **(Worksheet 5-29)**	Overall Stability Condition Associated with Points from **Worksheet 5-29**
	(tons/yr)	(tons/yr/ft)	Stable/ Aggrading/ Degrading	Stable/ Aggrading/ Degrading	Stable/ Aggradation/ Degradation	Stable/ Mod. Unstable/ Unstable/ Highly Unstable	Stable/ Mod. Unstable/ Unstable/ Highly Unstable	No Deposition/ Mod. Dep. / Excess Dep. / Aggradation	Not Incised/ Slightly Incised/ Mod. Incised/ Degradation	No Increase/ Slight Increase/ Mod. Increase/ Extensive	Low/ Moderate/ High/ Very High	Good/ Good-Fair/ Fair/ Fair-Poor/ Poor
1 **A4/1a+ Fair**	**0.43**	**0.0055**	**Degrading**	**Degrading**	**Degradation**	**Stable**	**Stable**	**No Deposition**	**Moderately Incised**	**Slight Increase**	**Moderate (9)**	**Fair**
2 **A4a+ Poor**	**11.73**	**0.0617**	**Degrading**	**Degrading**	**Degradation**	**Stable**	**Moderately Unstable**	**No Deposition**	**Slightly Incised**	**Moderate Increase**	**High (15)**	**Poor**
3 **A4a+ Poor South**	**2.73**	**0.0355**	**Degrading**	**Degrading**	**Degradation**	**Stable**	**Unstable**	**No Deposition**	**Degradation**	**Moderate Increase**	**High (15)**	**Poor**
4 **A4a+ Poor Downstream**	**4.55**	**0.0785**	**Degrading**	**Degrading**	**Degradation**	**Stable**	**Unstable**	**No Deposition**	**Degradation**	**Moderate Increase**	**High (15)**	**Poor**
5 **B4 Fair**	**33.08**	**0.0973**	**Aggrading**	**Stable**	**Aggradation**	**Stable**	**Unstable**	**Excess Deposition**	**Not Incised**	**Slight Increase**	**High (11)**	**Fair**
6 **C4 Fair**	**4.67**	**0.0217**	**Aggrading**	**Stable**	**Aggradation**	**Moderately Unstable**	**Moderately Unstable**	**Excess Deposition**	**Not Incised**	**Slight Increase**	**Moderate (10)**	**Fair**
7 **C4 Poor**	**7.55**	**0.0472**	**Aggrading**	**Aggrading**	**Aggradation**	**Moderately Unstable**	**Unstable**	**Aggradation**	**Not Incised**	**Moderate Increase**	**High (15)**	**Poor**
8 **D4a+ Poor**	**215.58**	**0.7183**	**Aggrading**	**Aggrading**	**Aggradation**	**Highly Unstable**	**Highly Unstable**	**Aggradation**	**Slightly Incised**	**Extensive**	**Very High (18)**	**Poor**
9 **E4 Good HWD**	**0.63**	**0.007**	**Stable**	**Stable**	**Stable**	**Stable**	**Moderately Unstable**	**No Deposition**	**Not Incised**	**No Increase**	**Moderate (6)**	**Good-Fair**
10 **F4 Fair**	**7.07**	**0.0589**	**Degrading**	**Stable**	**Stable**	**Unstable**	**Unstable**	**Moderate Deposition**	**Slightly Incised**	**Moderate Increase**	**High (12)**	**Fair**
11 **F4b Fair-Poor**	**5.31**	**0.024**	**Aggrading**	**Stable**	**Aggradation**	**Unstable**	**Unstable**	**Excess Deposition**	**Not Incised**	**Moderate Increase**	**High (13)**	**Fair-Poor**
12 **F4b Poor**	**45.08**	**0.27**	**Aggrading**	**Aggrading**	**Aggrading**	**Unstable**	**Unstable**	**Excess Deposition**	**Slightly Incised**	**Moderate Increase**	**High (15)**	**Poor**
13 **F4b Poor Mainstem**	**152**	**0.4721**	**Aggrading**	**Stable**	**Aggradation**	**Unstable**	**Unstable**	**Excess Deposition**	**Not Incised**	**Moderate Increase**	**High (14)**	**Poor**
14 **F4b Poor Trib.**	**132.39**	**0.39**	**Aggrading**	**Degrading**	**Aggradation**	**Unstable**	**Highly Unstable**	**Excess Deposition**	**Slightly Incised**	**Extensive**	**Very High (17)**	**Poor**
15 **G4 Poor**	**121.15**	**0.6584**	**Degrading**	**Degrading**	**Degradation**	**Highly Unstable**	**Unstable**	**No Deposition**	**Degradation**	**Extensive**	**Very High (16)**	**Poor**
16 **A4a+ Reference**	**0.12**	**0.0017**	**Stable**	**Stable**	**Stable**	**Stable**	**Stable**	**No Deposition**	**Slightly Incised**	**No Increase**	**Moderate (6)**	**Good-Fair**
17 **A4/2 Reference**	**1.33**	**0.0076**	**Stable**	**Stable**	**Stable**	**Stable**	**Stable**	**No Deposition**	**Not Incised**	**No Increase**	**Low**	**Good**
18 **B4 Reference**	**1.96**	**0.0048**	**Stable**	**Stable**	**Stable**	**Stable**	**Stable**	**No Deposition**	**Not Incised**	**No Increase**	**Low (5)**	**Good**
19 **B4/2c Reference**	**0.58**	**0.0050**	**Stable**	**Stable**	**Stable**	**Stable**	**Stable**	**No Deposition**	**Not Incised**	**No Increase**	**Low (5)**	**Good**
20 **C4 Reference**	**2.94**	**0.0063**	**Stable**	**Stable**	**Stable**	**Stable**	**Stable**	**No Deposition**	**Not Incised**	**No Increase**	**Low (5)**	**Good**
21 **D4a Reference**	**N/A**	**N/A**	**Aggrading**	**Stable**	**Stable**	**Stable**	**Stable**	**Excess Deposition**	**Not Incised**	**Slight Increase**	**Moderate (6)**	**Good**
22 **E4 Reference**	**0.42**	**0.0017**	**Stable**	**Stable**	**Stable**	**Stable**	**Stable**	**No Deposition**	**Not Incised**	**No Increase**	**Low (5)**	**Good**

Phase II

Site-specific data and analysis were extrapolated from the representative reaches to reaches of apparent similar type and condition. Once specific relations were established, this information was utilized for model application and interpretations for similar stream types and conditions elsewhere in the watershed. For example, for the typical "Poor" stability, F4 stream types (entrenched channels with high width/depth ratios and high banks on both sides), annual streambank erosion rates were predicted in tons/yr/ft using BEHI and NBS ratings with the corresponding bank height and stream lengths. These values are extrapolated to other similar ("Poor" stability) F4 reaches as unit erosion rates. Approximately 117 miles (about 50%) of the streams in the watersheds affected by Waldo Canyon Fire were traversed obtaining direct observations of stream types, streambank erosion rates, and associated stability. The remaining 50% of the reaches utilized extrapolated relations due to similar boundary conditions and controlling variables.

Based on stable, low sediment supply indicators at the mouth of several small watersheds, values of "Good" were used to predict the potential flow-related sediment increase. Because of the distinctly evident stable conditions, more detailed site investigations were not warranted; thus these small watersheds were not mapped in the same detail (streambank erosion rates, stream type and condition) as the "Fair" and "Poor" condition sub-watersheds. The reaches that indicated *Moderate* to *Very High* sediment supply or channel instability were mapped in detail as shown in **Appendix D**.

Stream reaches are mapped in each major watershed and sub-watershed to spatially locate disproportionate accelerated sediment supply from streambank erosion. The total tons of sediment from streambank erosion are weighted by the length and condition for each major and sub-watershed. This allows the locations with very high sediment contributions to be identified within the sub-watersheds and their relative contribution to total sediment yield.

The final streambank erosion rates are summarized for each sub-watershed in total tons and mapped in tons/yr/ft to identify specific locations of particularly high rates in **Appendix D**. Not all of the soil from streambank erosion is routed out of the basin, but the erosion reflects the supply entered into a stream channel, some of which contributes to sediment storage within the channel cross-section. The sediment supply from streambank erosion is summarized in **Table 12**. Streambank erosion contributes *31,480 tons/yr* of sediment within the watersheds affected by the Waldo Canyon Fire. The erosion rates for the reference reaches reflect the natural geologic rates compared to the accelerated rates of the impaired, representative reaches as shown in **Table 11**.

The streambank erosion data is compared to erosion rates from roads, surface erosion, and flow-related increases in sediment. Streambank erosion can be mitigated or reduced through various streambank stabilization methods; this data will be used to set priorities for restoration and stabilization recommendations.

Table 12. Summary of streambank erosion by major watershed.

Watershed	Streambank Erosion (tons/yr)
Camp Creek	6,750
Douglas Creek	6,108
Fountain Creek	11,318
West Monument Creek	7,183

Flow-Related Sediment Yield

Increases in post-fire streamflows following wildfires are significant and long-lasting until vegetative cover is reestablished. The consequences of the increased magnitude, frequency, and duration of streamflows can generate a corresponding exponential increase in sediment. The rate of increase in sediment for a corresponding increase in streamflow (sediment rating curve) is dependent on the overall stability rating and the corresponding stream type. Stream types that are vertically contained (entrenchment ratios < 1.4), such as A, G and F stream types, and stream types that are actively incising (bank-height ratios > 1.2; bank-height ratio is the quantitative expression for degree of channel incision, equal to the study bank height divided by bankfull height; Rosgen, 2006/2009) are susceptible to continued degradation, lateral erosion, and channel enlargement processes.

Following the application of the WRENSS water yield model (**Appendix A**), the increased water yield for pre- and post-fire conditions are reflected in the form of a changed flow-duration curve (see **Figures 11–14**). The increased water yield is routed through dimensionless bedload and suspended sediment rating curves by stream stability for both pre- and post-fire hydrologic conditions. Dimensionless bedload and suspended sediment rating curves for “Good” or “Fair” stability streams are shown in **Figure 42** and **Figure 43**. Similar dimensionless bedload and suspended sediment rating curves for “Poor” stability streams with a high sediment supply are shown in **Figure 44** and **Figure 45**. This aspect of the flow-related sediment increase involves the use of the FLOWSED model (Rosgen, 2006/2009). Dimensionless bedload and suspended sediment rating curves are converted to actual, dimensional curves scaled for an individual river for a given condition by multiplying by the bankfull discharge and the bankfull sediment values. When the dimensional sediment rating curves are combined with the change in the flow-duration curves, flow-related sediment can be computed.

The bankfull discharge, as discussed previously, is determined from a regional curve of bankfull discharge *vs*. drainage area (see **Figure 7**). In the absence of measured bankfull sediment data, similar to the approach used to estimate bankfull discharge, bankfull bedload and suspended sediment data by drainage area can be developed for a given geological region by stability. Regional sediment curves were developed by stability for the batholith geology (Pikes Peak, grussic granite geology) for this assessment as shown in **Figure 46** and **Figure 47**. The bankfull sediment values from the regional curves can then be used to convert the dimensionless sediment rating curves to dimensional curves that are unique and scaled for each sub-watershed.

To validate the sediment curves used for the Waldo Canyon Fire watersheds, sediment rating curves developed from bedload and suspended sediment in 1984 were compared with 2010 measured bedload and suspended sediment in the nearby Trail Creek Watershed (**Figure 48** and **Figure 49**). The increased sediment values for the same discharge reflect the post-fire sediment supply increase for bedload and suspended sediment.

The increase in water yield and flow-related sediment supply using the FLOWSED model comparing the pre- and post-fire conditions are reported in **Table 13** for the major watersheds. Values for all individual sub-watersheds are reported in **Appendix D**. The increased flood peaks and duration of bankfull discharges are reflected in the exponential increase in corresponding sediment yields: *16,826 tons/yr* for the Camp Creek Watershed, *7,787 tons/yr* for the Douglas Creek Watershed, *24,985 tons/yr* for the Fountain Creek Watershed, and *7,385 tons/yr* for the West Monument Creek Watershed (**Table 13**). Total post-fire average annual sediment production is greatest in Fountain Creek (*25,075 tons/yr*) but Douglas Creek delivers the most sediment per unit area (*3.07 tons/acre/yr*). Based on recent experience with the Hayman Fire, it is anticipated that hydrologic recovery will be slow and increases in magnitude and duration of streamflow and accelerated flood peaks could persist for many years to come.

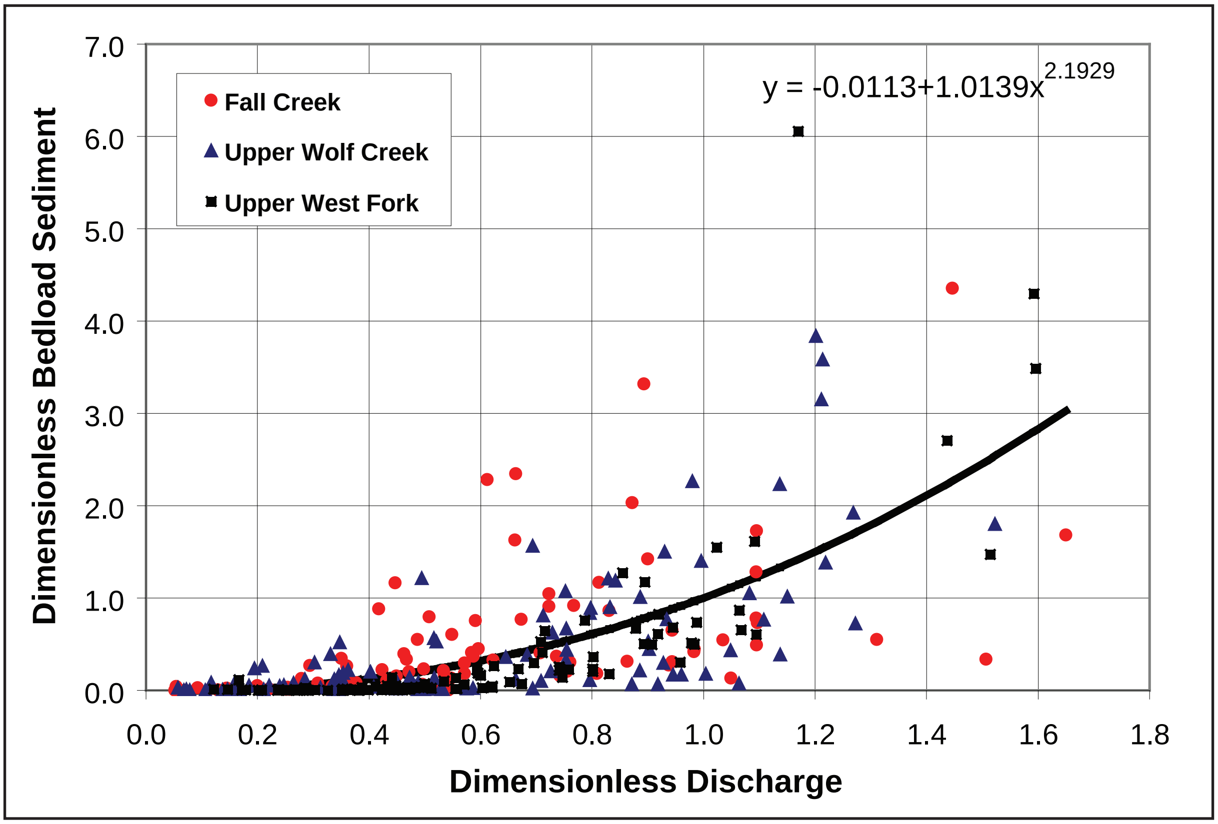


Figure 42. Dimensionless bedload sediment rating curves for "Good" and "Fair" stability streams derived from three streams in Pagosa Springs, Colorado.

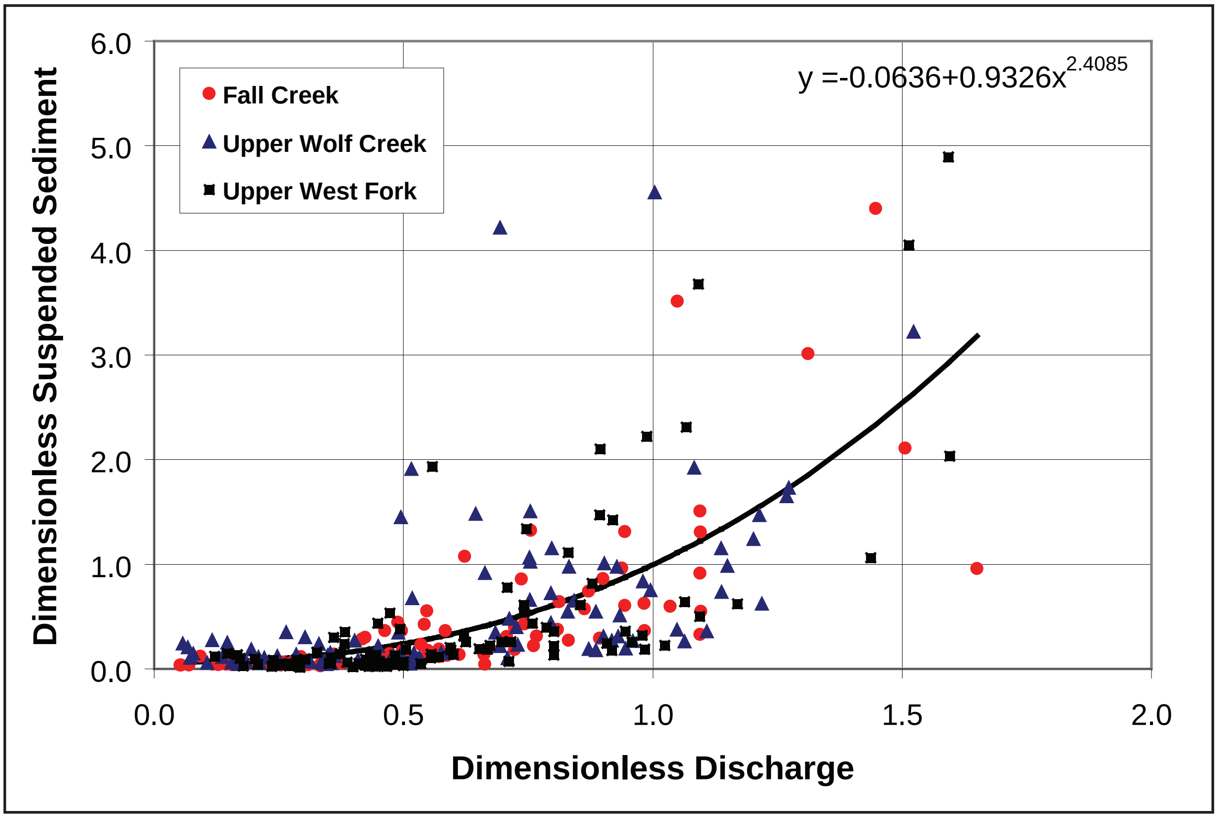


Figure 43. Dimensionless suspended sediment rating curves for "Good" and "Fair" stability streams derived from three streams in Pagosa Springs, Colorado.

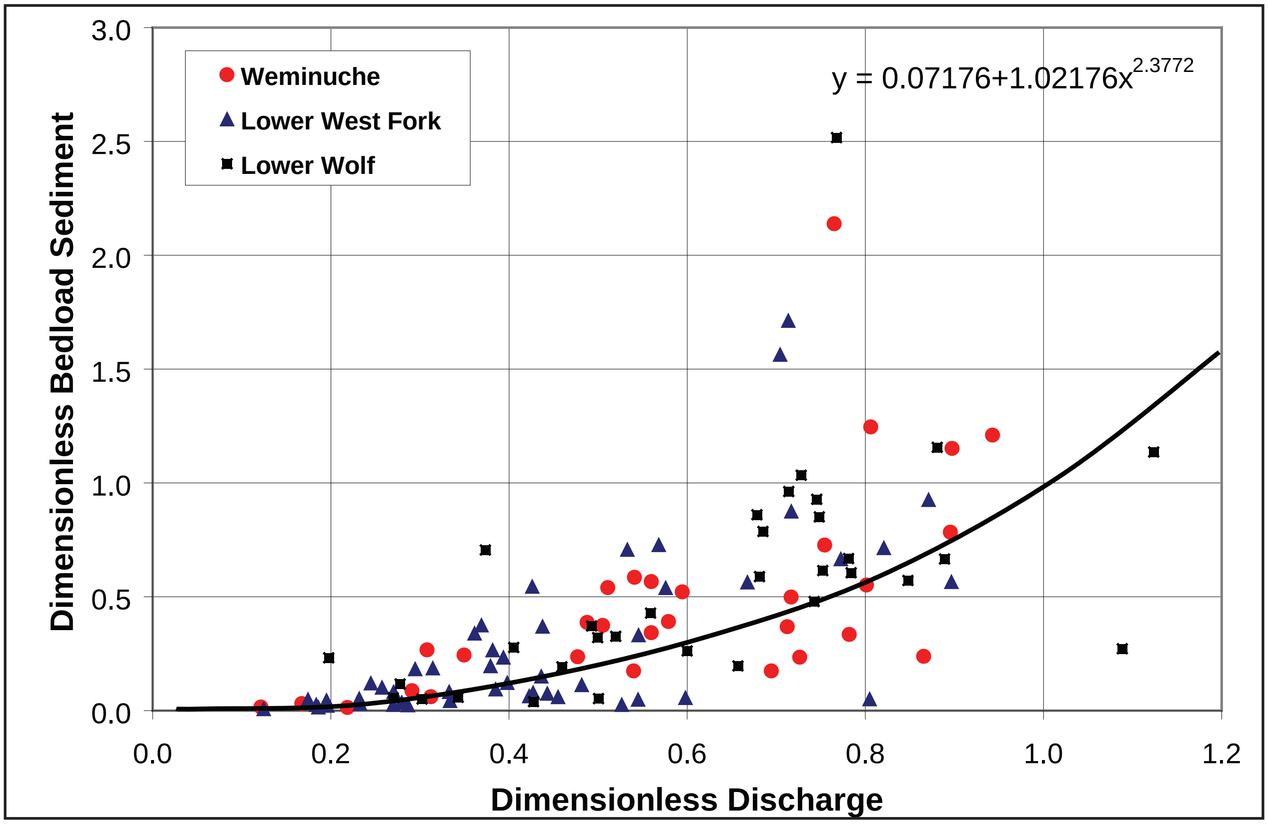


Figure 44. Dimensionless bedload sediment rating curves for "Poor" stability streams derived from three streams in Pagosa Springs, Colorado.

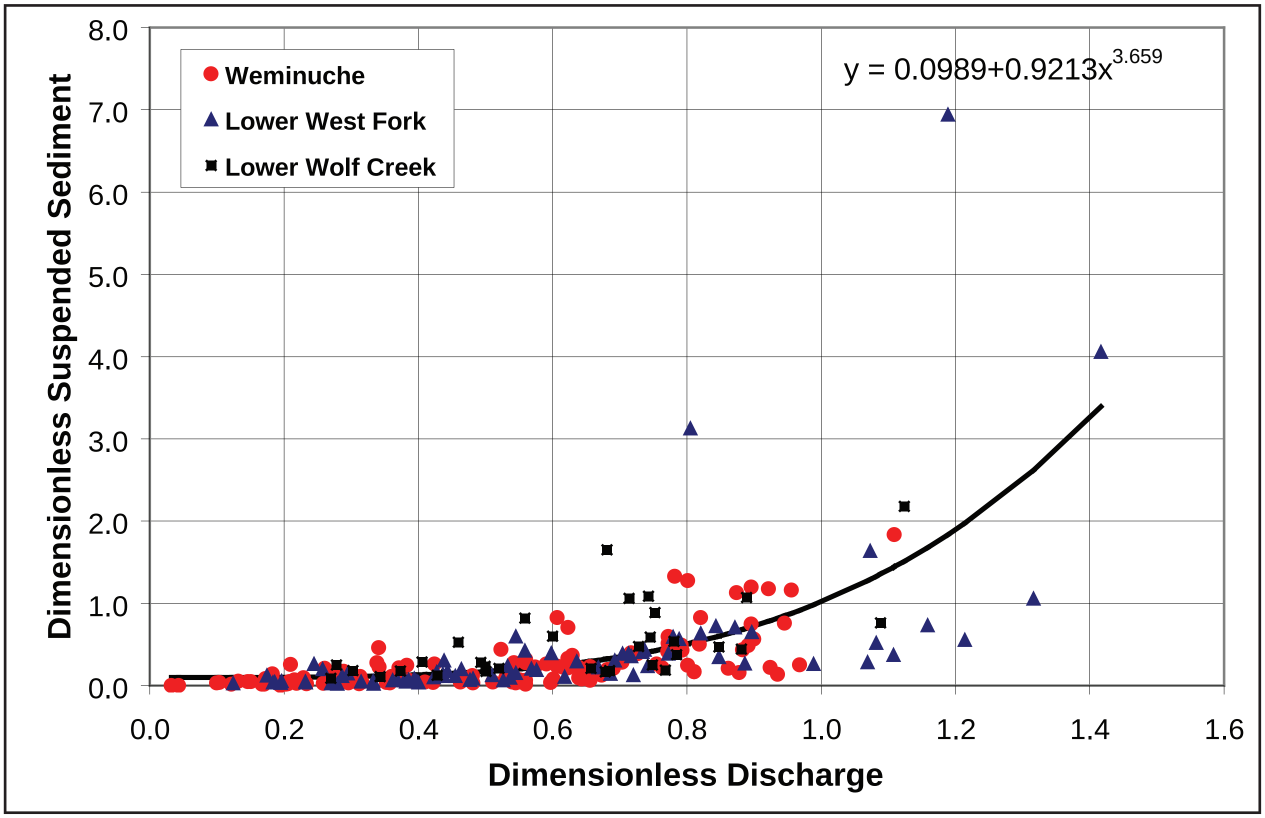


Figure 45. Dimensionless suspended sediment rating curves for "Poor" stability streams derived from three streams in Pagosa Springs, Colorado.

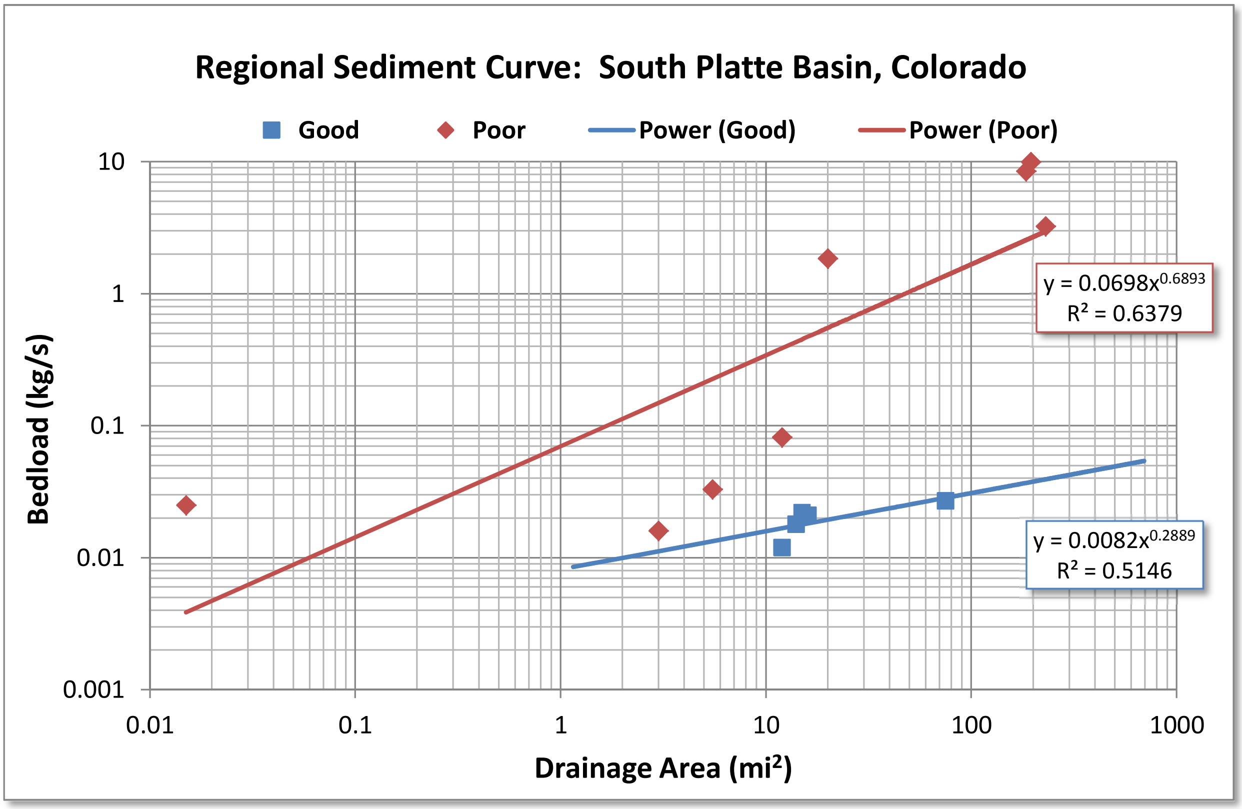


Figure 46. Regional bedload sediment curve: South Platte Basin, Colorado.

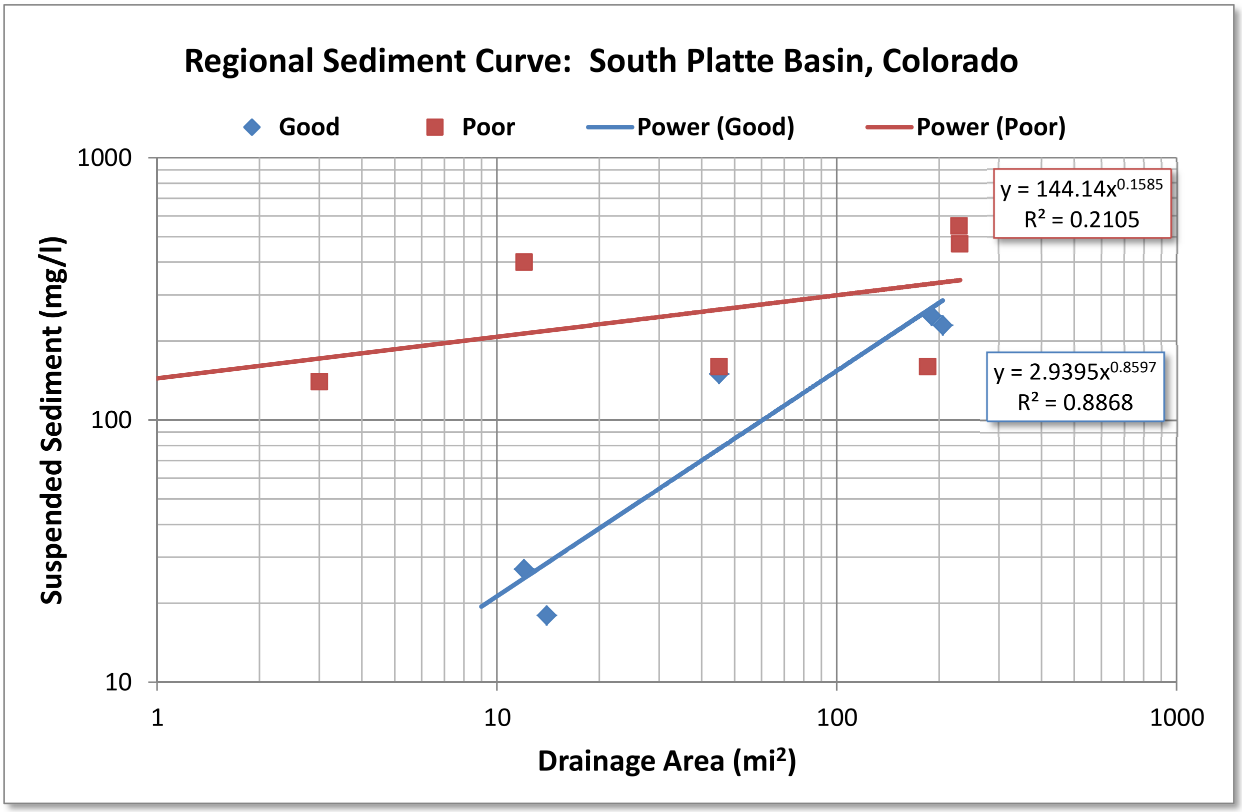


Figure 47. Regional suspended sediment curve: South Platte Basin, Colorado.

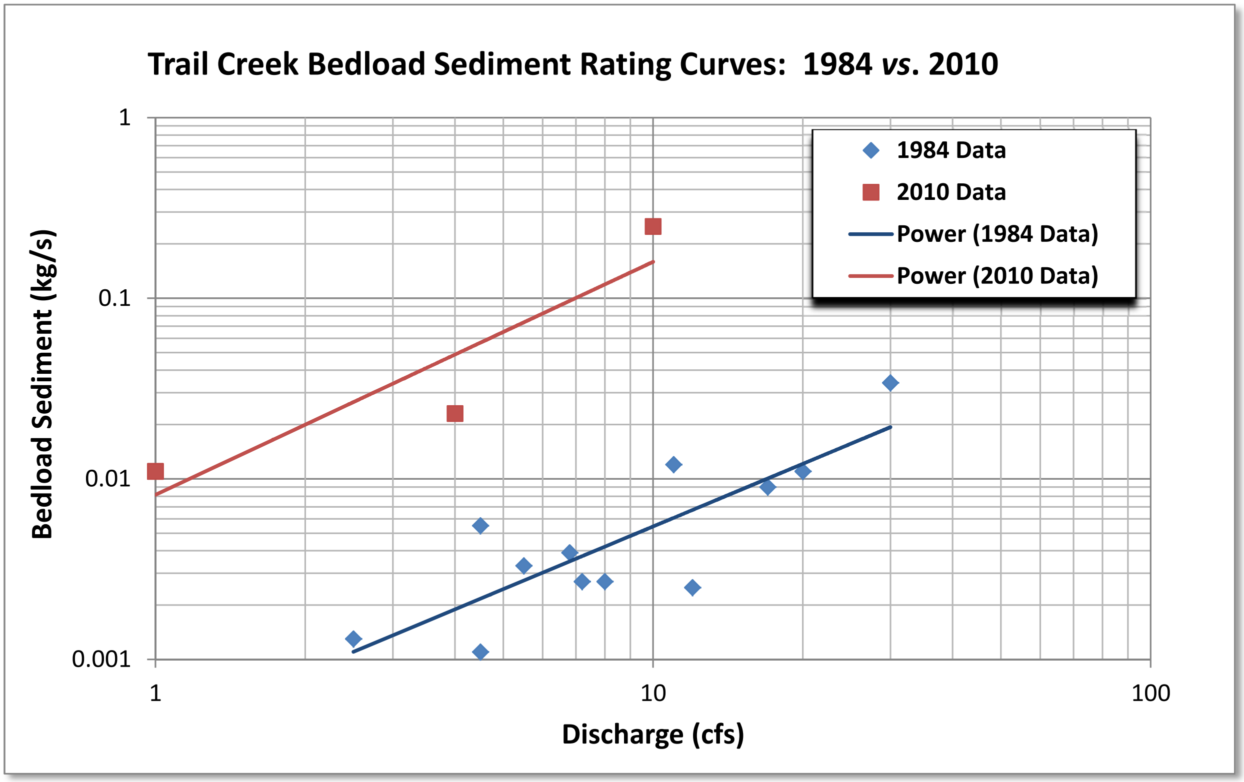


Figure 48. Bedload sediment rating curve from 1984 data compared to 2010 data reflecting the post-fire increase in sediment supply.

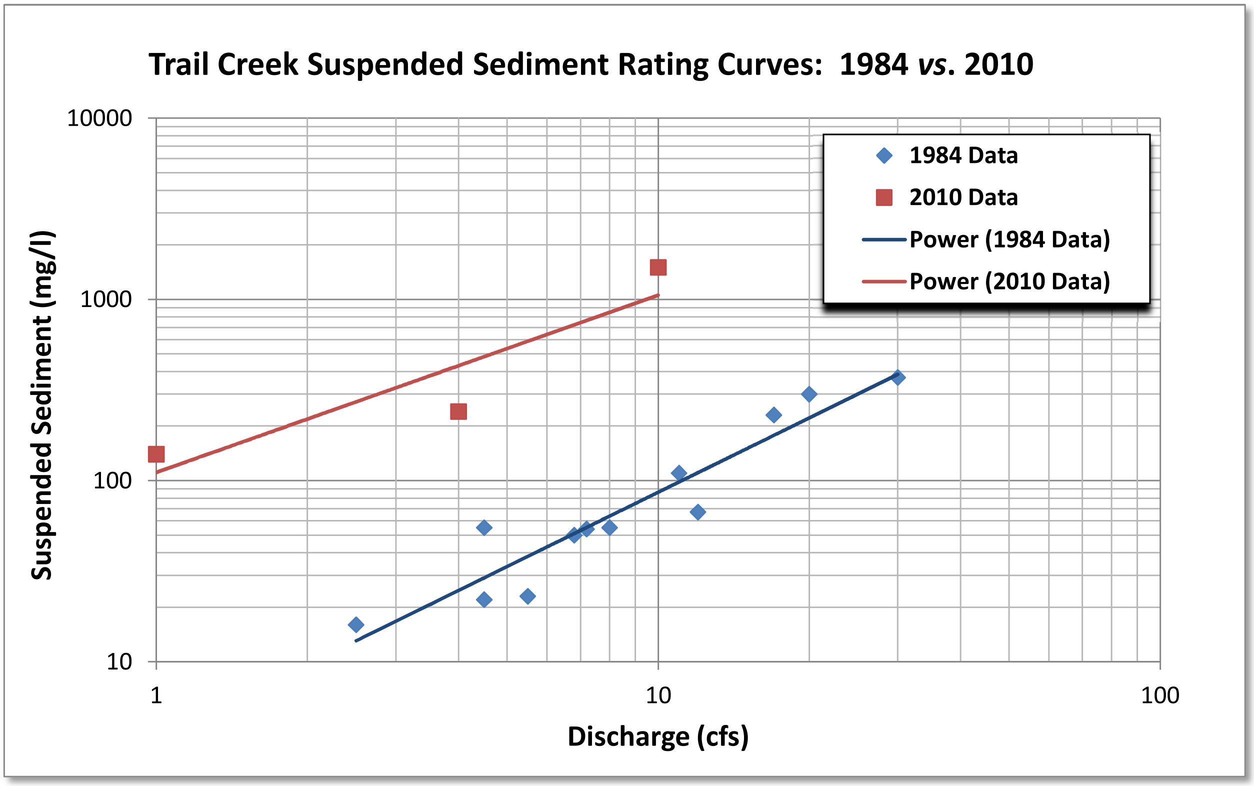


Figure 49. Suspended sediment rating curve from 1984 data compared to 2010 data reflecting the post-fire increase in sediment supply.

Table 13. Summary of pre- and post-fire water and flow-related sediment yields by major watershed.

Watershed	Pre-Fire		Post-Fire		Increase		Total Sediment per Unit Area (Post-Fire)
	Water Yield	Total Sediment	Water Yield	Total Sediment	Water Yield Increase	Total Sediment Increase	
	(acre-ft)	(tons/yr)	(acre-ft)	(tons/yr)	(acre-ft)	(tons/yr)	(tons/acre/yr)
Camp Creek	2,115	71	3,702	16,897	1,587	16,826	2.12
Douglas Creek	1,511	47	2,156	7,834	646	7,787	3.07
Fountain Creek	2,500	90	4,822	25,075	2,322	24,985	2.69
West Monument Creek	2,747	104	4,035	7,489	1,288	7,385	1.23

Sediment Summary

The four major watersheds affected by the Waldo Canyon Fire were sub-divided into 113 uniquely identified sub-watersheds (33,534 acres). Through the *RLA* and *RRISSC* assessments, 24 sub-watersheds were eliminated from further evaluation. Based on the remaining 89 sub-watersheds (24,248 acres), the *PLA* phase was used to quantify the sediment sources within the four major watersheds and each sub-watershed. Within the Waldo Canyon Fire, 61% of the introduced sediment is derived from streambank erosion, 35% from hillslopes, and 4% from roads (**Table 14**). This general trend was consistent for all four basins.

Flow-related sediment yield represents an integration of all introduced sediment sources (hillslope, roads, and channel processes) with the flow-duration curve. One process that cannot be accounted for in the field is the net change in streambed elevation or base level shift. The flow-related sediment value output from FLOWSED accounts for this process. The difference in the flow-related sediment and the total field-estimated sediment by process (hillslope, roads, and streambank erosion) is the net stream bed elevation shift (aggradation/degradation). For example, Camp Creek has less introduced sediment (*11,694 tons/yr*) than flow-related sediment (*16,897 tons/yr*) yielding *5,203 tons/yr* scoured from the streambed, or net degradation (**Table 14**). Total sediment contribution by process for the four major watersheds is presented in **Figure 50** where Camp and Fountain Creeks show net degradation (streambed scour) and Douglas and West Monument Creeks show net aggradation (increased channel sediment storage). Degradation occurs where energy exceeds supply; however, it is often observed that high streamflows following a previous aggrading event (excess supply/energy limited) create headcuts through previously deposited material.

As a result of the increased peak flows and decreased flow resistance from destroyed riparian vegetation following the fire, an increase in the headward expansion of the drainage network is widespread. Headcuts result in an over-steepening of the energy slope and corresponding channel bed degradation. Consequently, slope rejuvenation occurs, leading to a corresponding accelerated increase in bed and bank erosion rates with increased sediment supply. Another cause of headcutting is the excess sediment deposition followed by the reworking of the sediment headward as shown in **Figure 51**. Another process leading to headcuts is the lowering of the base level of a main trunk or receiving stream (**Figure 52**). In addition to incision processes, channel enlargement and accelerated streambank erosion are also associated with headcuts (**Figure 51** and **Figure 52**).

Table 14. Post-fire introduced sediment and flow-related sediment supply for the major watersheds.

	Streambank Erosion		Roads and Trails		Hillslope		Total Introduced Sediment (tons/yr)	Flow-Related Sediment (tons/yr)	Aggrade or Degrade (tons/yr)
Watershed	Streambank Erosion (tons/yr)	% of Total Introduced Sediment	Total Tons per Year	% of Total Introduced Sediment	Hillslope Sediment	% of Total Introduced Sediment			
Camp Creek	6,750	58%	751	6%	4,193	36%	11,694	16,897	5,203 (Degrade)
Douglas Creek	6,108	59%	236	2%	4,057	39%	10,401	7,834	-2,567 (Aggrade)
Fountain Creek	11,318	59%	619	3%	7,303	38%	19,241	25,075	5,834 (Degrade)
West Monument Creek	7,183	71%	429	4%	2,532	25%	10,143	7,489	-2,654 (Aggrade)
Totals	31,359	61%	2,035	4%	18,085	35%	51,479	57,295	5,816

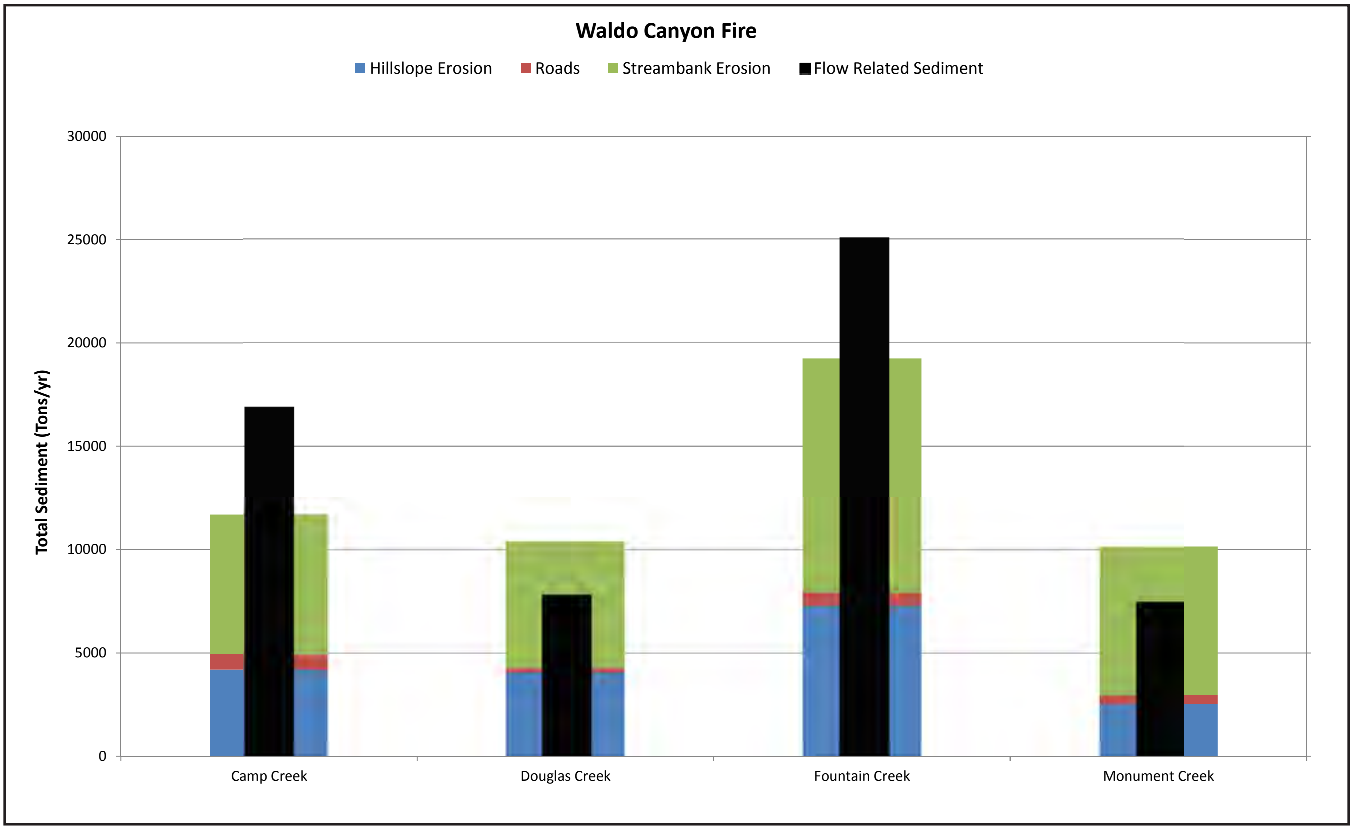


Figure 50. Relative amount of sediment contribution by process for the four major watersheds.

Figure 51. A headward-advancing G4 stream type in the Douglas Creek Watershed (DC-007) shifting to an F4 stream type due to excessive deposition and the easily-mobilized bed material (grussic granite).

Figure 52. The lowering of a stream in the Douglas Creek Watershed (DC-007) caused by a base-level drop that accelerated the headward advancement (incision process) of a tributary on an alluvial fan.

Excess sediment deposition results from a sediment supply greater than the transport capacity of the channel and generally relates to high width/depth ratio channels that encourage sediment deposition and aggradation processes. A high width/depth ratio, F4b stream type with fresh sediment deposition and corresponding accelerated streambank erosion is shown in **Figure 53**. Sediment storage is available for increased sediment transport during high flows as shown in **Figure 54**. Reworking of previously deposited sediment is shown in the G4 stream type in **Figure 55**. If high flows were to "flush out" the stored sediment, then the subsequent high flows that have occurred since the fire would have reduced the stored sediment. However, such observations indicate that high flows have not reduced sediment storage, but rather have contributed to increased sediment storage. Because the increased flows are generally directed to the streambanks and not the beds on these high width/depth ratio channels, increased flows generate increased streambank erosion rates that add to the sediment supply.

Reducing potential sediment from flow-related sediment increases is related to establishing stream types that are associated with a "Good" stability condition and low sediment supply rather than a "Poor" stability condition. For example, G4 stream types with a "Poor" stability condition in many instances can be converted to B4 stream types that reflect a "Good" stability and associated low sediment supply. Converting F4 stream types to C4 stream types is a natural stream succession direction associated with sediment supplies that are orders of magnitude less for the same discharge. Also, converting A4 stream types to braided, D4 stream types by directing the D4 stream types onto alluvial fans provides a natural sediment detention and storage condition. Even with increased streamflows, the corresponding accelerated sediment yields can be significantly reduced by shifting to stable stream types and distributing transported sediment onto alluvial fans for storage. Overall, the greatest source of total sediment yield increases is associated with streambank erosion processes.

Figure 53. A very high sediment supply, high energy F4b stream type in Fountain Creek with evident streambank and streambed instability.

Figure 54. Excessive channel downcutting, which provides an unlimited sediment supply, Sand Gulch in the Fountain Creek Watershed (FC-011).

Figure 55. A downcutting G4 stream type in West Monument Creek (MC-010).

Sediment Summaries by Major Watershed

A summary of the various sources of sediment is discussed within each major watershed assessed. To locate individual sub-watersheds within each major watershed, a referenced alpha-numeric code is used to locate the area in the sub-watershed maps shown in **Figures 2–6**. The changes in streamflow, flow-related sediment, and introduced sediment sources are summarized in the following sections. Refer to **Appendix D** for all sub-watershed summaries.

Camp Creek Sub-Watersheds

In Camp Creek, 36 sub-watersheds (5,526 acres) were evaluated. Of the total watershed area, 78% burned (36% low intensity, 37% moderate intensity, and 5% high intensity) resulting in an average annual change in water yield of *2.6 inches*, the second greatest change in water yield (**Table 3** and **Appendix A1**). For a detailed description of the burn effects on vegetative cover, see **Appendix A2**. The total amount of estimated introduced sediment from Camp Creek is *11,694 tons/yr*, the second highest producer of the four major watersheds, with 58% from streambank erosion, 36% from hillslopes, and 6% from roads (**Table 14**). The FLOWSED model predicts *16,897 tons/yr* of flow-related sediment, resulting in a potential net degradation (scour) of *5,203 tons/yr* (**Table 13** and **Table 14**), equivalent to *3,251* yds^3*/yr*, or *325 10-yard, end-dump truck loads per year*. This value represents the average condition over the 36 sub-watersheds but does not imply that degradation occurs uniformly within the watershed or for every stream reach within the watershed. In fact, three of the 36 sub-drainages show a net potential aggradation, but Camp Creek is dominated by the 21 degrading sub-watersheds (**Figure 56**). The sub-watersheds on the left side in **Figure 56** show net aggradation (plotted in descending order of total introduced sediment), the sub-watersheds on the right side show net degradation (plotted in ascending order of total introduced sediment), and those in the middle are face drainages where the FLOWSED model was not applied. Sub-watershed CC-007 is the highest sediment producer and shows the most degradation at *1,901 tons/yr*. Sub-watersheds CC-F06, CC-011, and CC-012 show a net aggradation of *16 tons/yr*, cumulatively. Streambank erosion is the dominant sediment delivery process in most sub-watersheds. Road and trail sediment processes dominate in two sub-watersheds (CC-001 and CC-003) with significant contributions in just two others, CC-020 and CC-019. Hillslope erosion is the major process delivering sediment to just six of the 36 sub-watersheds. Sub-watersheds CC-F04 and CC-006 have the highest estimates of introduced sediment per unit area in the Camp Creek drainage at *4.5 and 4.3 tons/acre/yr*, respectively.

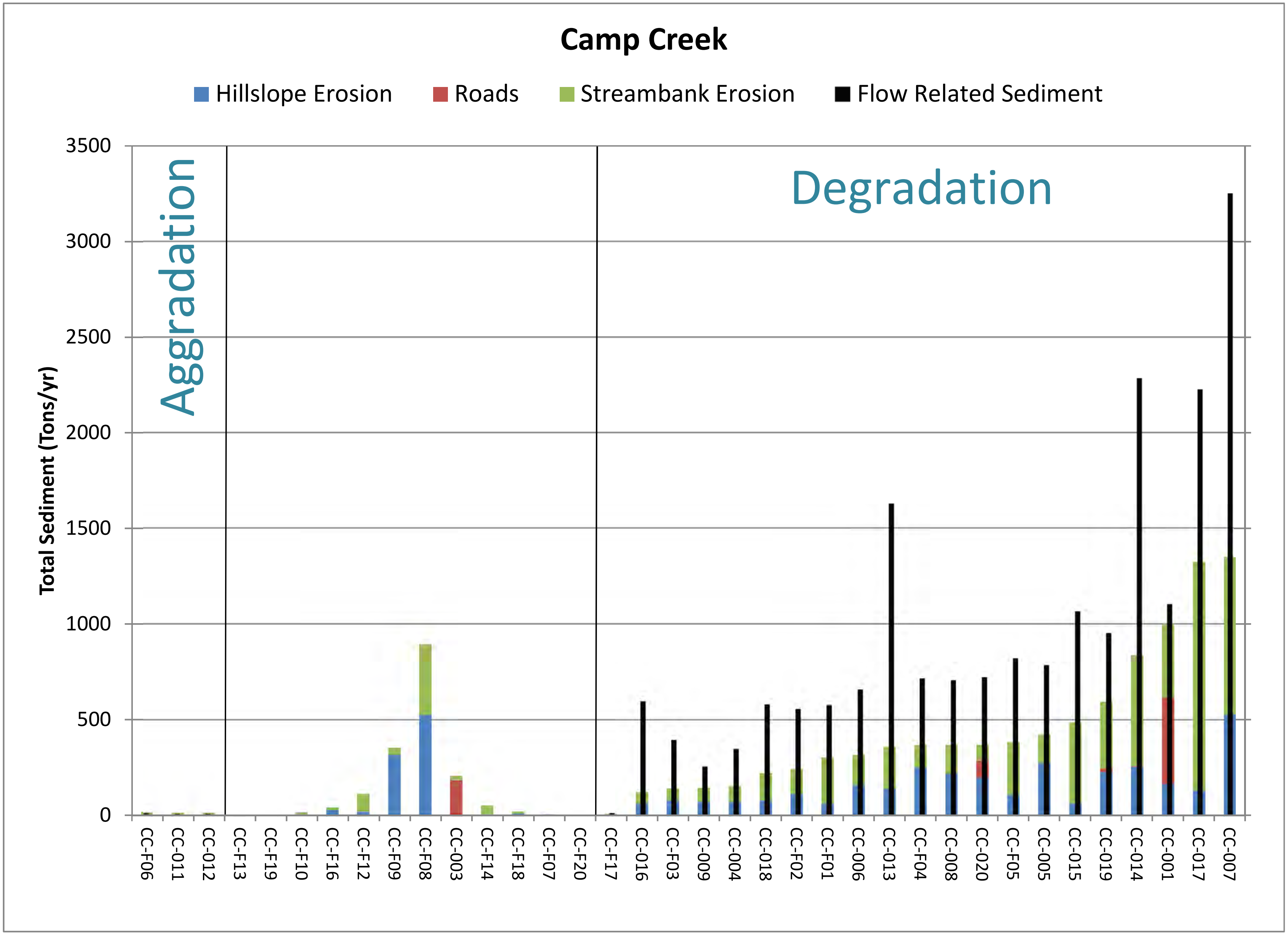


Figure 56. The potential of the Camp Creek sub-watersheds for aggradation / degradation.

Douglas Creek Sub-Watersheds

In Douglas Creek, nine sub-watersheds (3,303 acres) were evaluated. Of the total watershed area, 59% burned (21% low intensity, 30% moderate intensity, and 6% high intensity) resulting in an average annual change in water yield of *1.7 inches* (**Table 3** and **Appendix A1**). For a detailed description of the burn effects on vegetative cover, see **Appendix A2**. The total amount of estimated introduced sediment from Douglas Creek is *10,401 tons/yr*, similar to West Monument Creek that yielded *10,144 tons/yr* (**Table 14**). The various source contributions from North and South Douglas Creeks are 59% from streambank erosion, 39% from hillslopes, and 2% from roads (**Table 14**). The FLOWSED model predicted *7,834 tons/yr* of flow-related sediment from North and South Douglas Creeks, resulting in a net aggradation of *2,567 tons/yr* (**Table 13** and **Table 14**). This value represents the average condition over the Douglas Creek sub-watersheds even though six of the nine sub-watersheds show net degradation (**Figure 57**). Sub-watershed DC-007 is the highest sediment producer of all eighty nine sub-watersheds evaluated and shows a net aggradation potential of *1,913 tons/yr*, which exceeds the total introduced sediment (*1,613 tons/yr*) of the next highest producing sub-watershed, DC-001. DC-F02 is the fourth highest sediment producer of the six degrading sub-watersheds but exhibits the most degradation (*611 tons/yr*). In five of the nine sub-watersheds, sediment delivery processes are dominated by streambank erosion, while road and trail processes contribute significantly in just one sub-watershed, DC-001, but dominate in none. Hillslope processes are the dominant sediment contributors in the other four sub-watersheds. Sub-watersheds DC-007 and DC-006 show the highest introduced sediment per unit area of *6.7 and 5.7 tons/acre/yr*, respectively.

Fountain Creek Sub-Watersheds

In the Fountain Creek Watershed, 18 sub-watersheds (7,163 acres) were evaluated. Of the total watershed area, 63% burned (29% low intensity, 30% moderate intensity, and 5% high intensity) resulting in an average annual change in water yield of *2.9 inches* (**Table 3** and **Appendix A1**), the highest change in water yield seen in the Waldo Canyon Fire. For a detailed description of the burn effects on vegetative cover, see **Appendix A2**. The total amount of estimated introduced sediment from Fountain Creek is *19,241 tons/yr*, the largest producer of the four major watersheds, with 59% from streambank erosion, 38% from hillslopes, and 3.0% from roads (**Table 14**). The FLOWSED model predicts *25,075 tons/yr* of flow-related sediment, resulting in a net degradation of *5,835 tons/yr* (**Table 13** and **Table 14**). Nine of the 18 sub-watersheds show degradation while just one (FC-006) shows aggradation (**Figure 58**). Flow-related sediment (FLOWSED) for the eight remaining sub-watersheds (all face drainages) was not calculated. Sub-watershed FC-002 is the highest sediment producer at *5,111 tons/yr*, while sub-watershed FC-004 exhibits the greatest degradation (*2,968 tons/yr*). With the exception FC-002 and FC-007 where hillslopes are the major sediment delivery process, all of the degrading sub-watersheds are dominated by streambank erosion processes. Road and trail processes do not dominate in any sub-watershed and only make a significant contribution to total sediment delivered in FC-010, with minor contributions to total sediment in FC-004, FC-007, and FC-F06. Hillslope processes dominate in the only aggrading sub-watershed (FC-006), the two degrading sub-watersheds mentioned above, and in FC-F06, FC-F09, and FC-F10. Sub-watersheds FC-005 and FC-009 showed the highest introduced sediment per acre of *5.2 and 5.1 ton/acre/yr*, respectively.

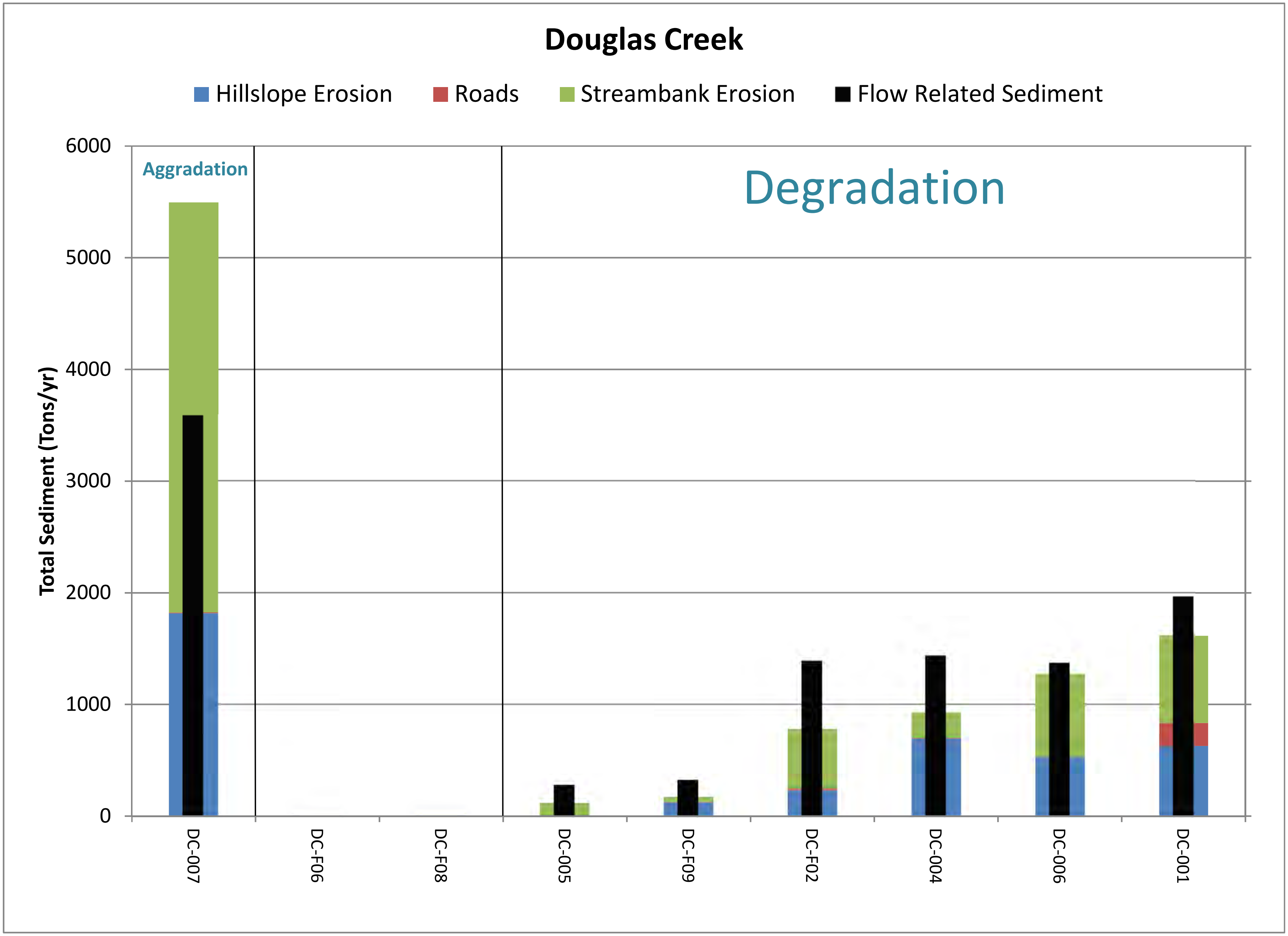


Figure 57. The potential of the Douglas Creek sub-watersheds for aggradation / degradation.

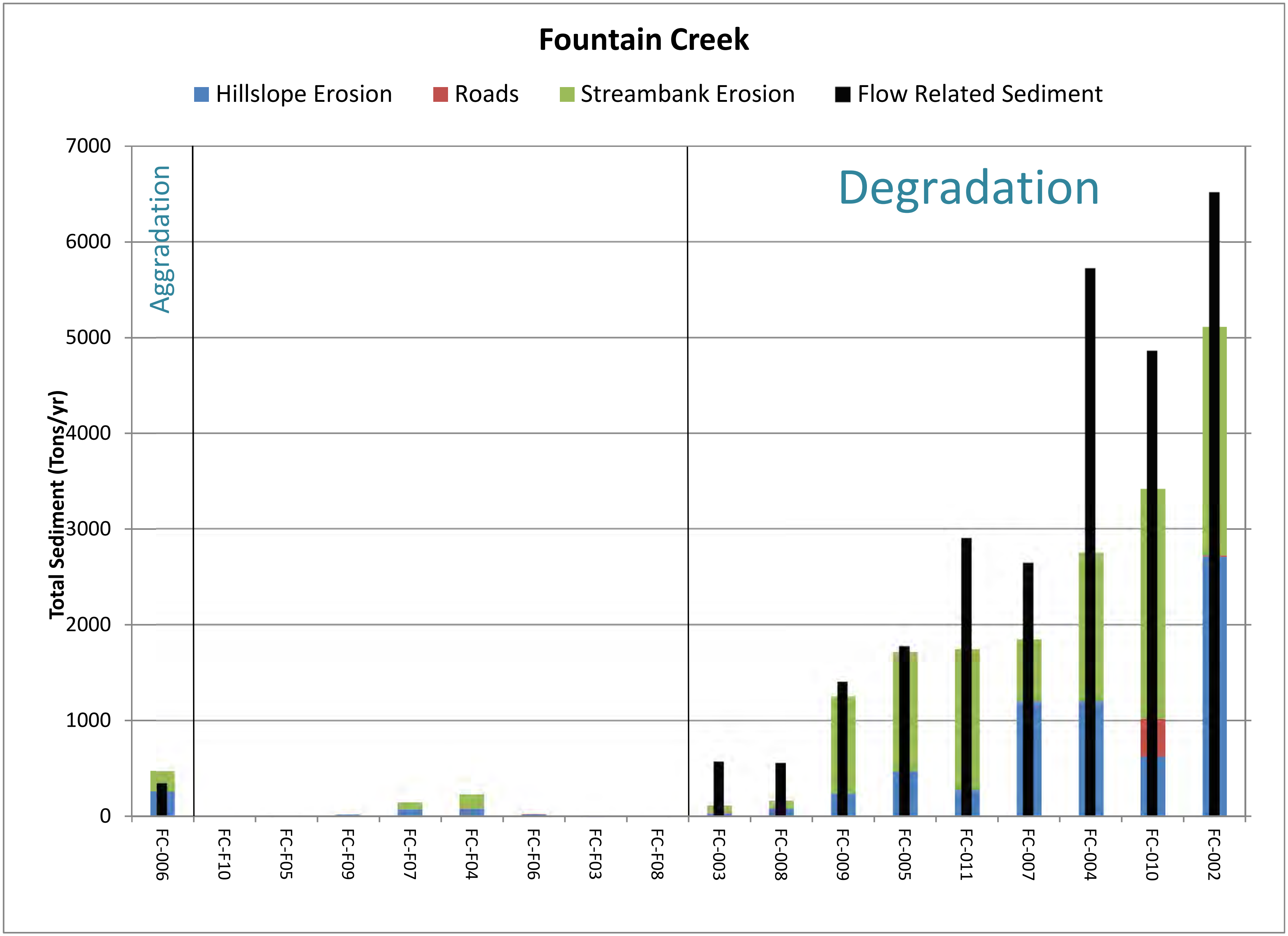


Figure 58. The potential of the Fountain Creek sub-watersheds for aggradation / degradation.

West Monument Sub-Watersheds

In West Monument Creek, 26 sub-watersheds (8,255 acres) were evaluated. Of the total watershed area, 48% burned (26% low intensity, 19% moderate intensity, and 4% high intensity), resulting in an average annual change in water yield of *1.4 inches* (**Table 3** and **Appendix A1**), the lowest change in water yield seen in the Waldo Canyon Fire. For a detailed description of the burn effects on vegetative cover, see **Appendix A2**. The total amount of estimated introduced sediment from West Monument Creek is *10,143 tons/yr*, the lowest producer of the four major watersheds, with 71% from streambank erosion, 25% from hillslopes, and 4% from roads (**Table 14**). West Monument Creek is also the lowest sediment producer per acre of the four major watersheds (**Table 13**). The FLOWSED model predicts *7,489 tons/yr* of flow-related sediment, resulting in a net aggradation of *2,654 tons/yr* (**Table 13** and **Table 14**). Ten of the 26 sub-watersheds show net aggradation and six sub-watersheds show net degradation (**Figure 59**). There are ten sub-watersheds where FLOWSED was not applied. Sub-watershed MC-010 is the highest sediment producer at *2,289 tons/yr* and exhibits the greatest potential aggradation (*608 tons/yr*). Sub-watershed MC-007 produces the most total sediment of the degrading sub-watersheds (*2,104 tons/yr*), while MC-008 has the most degradation (*1,474 tons/yr*). Streambank erosion processes dominate the top 11 sediment producing sub-watersheds in West Monument Creek, while hillslope processes dominate sediment delivery in nine of the 26 sub-watersheds (all relatively low sediment producers). Road and trail processes dominate sediment delivery in MC-F10 (*0.02 tons/yr*) and only contribute significantly in MC-010 and MC-013, with smaller contributions in four other low sediment-producing sub-watersheds. Sub-watersheds MC-010 and MC-017 show the highest introduced sediment per unit area within the entire burn perimeter, at *7.4 and 6.9 ton/acre/yr*, respectively.

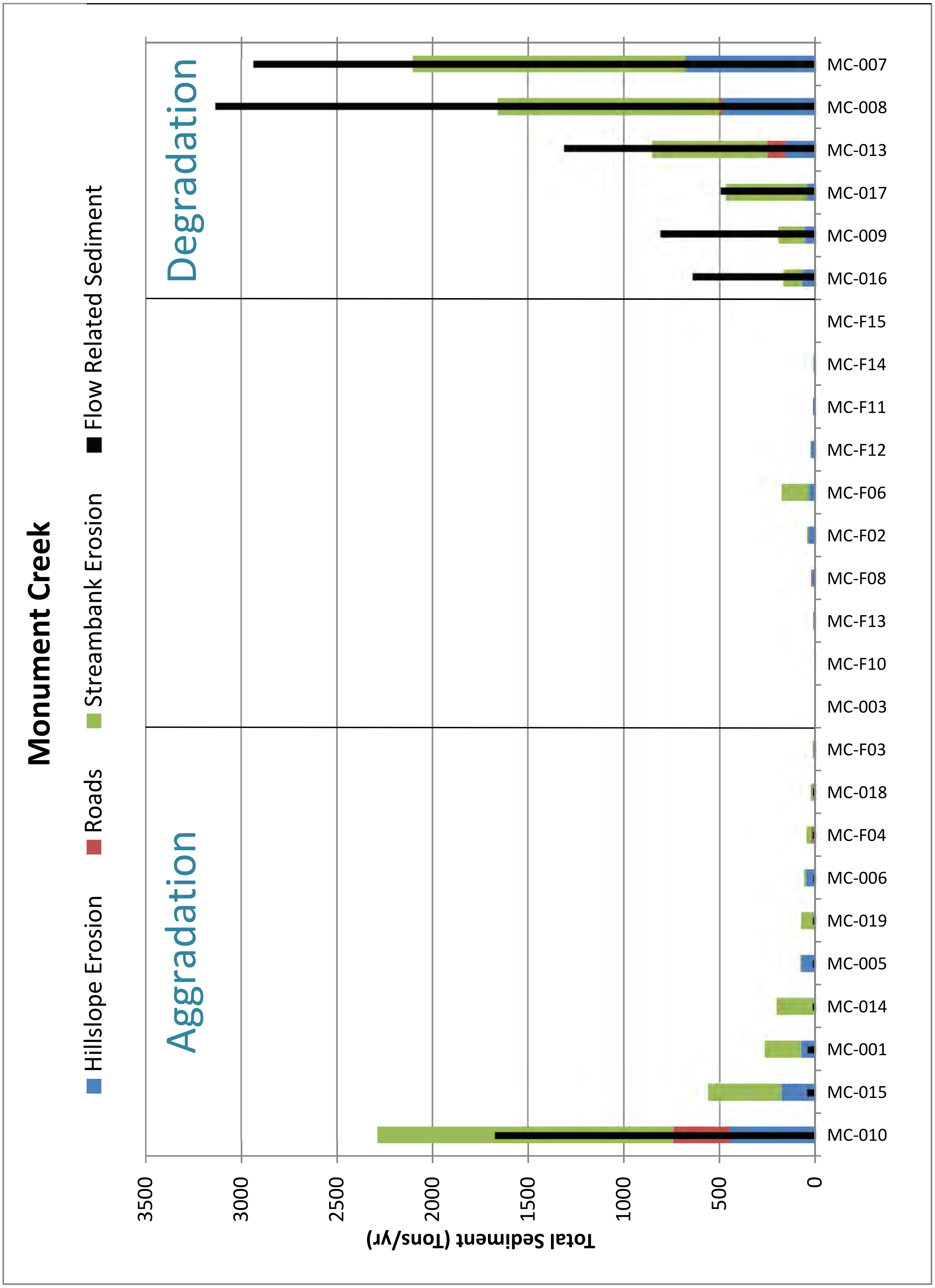


Figure 59. The potential of the West Monument Creek sub-watersheds for aggradation / degradation.

Mitigation & Restoration Priorities

This cumulative watershed effects analysis provides a basis for setting mitigation and restoration priorities linked to land uses, locations, processes, disproportionate sediment yields, and associated river impairments. Priorities were developed based on the total sediment supply from hillslopes, roads, and streambanks as determined by the *WARSSS* methodology (**Table 15** and **Figure 60**). Six of the top ten priority sub-watersheds are located in the Fountain Creek Watershed, three of the top ten are within the West Monument Creek Watershed, and one, DC-007, in the Douglas Creek Watershed is the highest overall priority. These priorities are based on the assessment of the individual sub-watersheds and do not account for the cumulative effects of the major watersheds. While no individual sub-watersheds in Camp Creek rank in the top ten priorities, the aggregate of the 36 Camp Creek sub-watersheds rank second in total introduced sediment for the major watersheds. By separating sub-watersheds and reaches from the major watersheds, we can identify and locate disproportionate sources of sediment supply.

When the sediment budget analysis shows a greater sediment supply than the post-fire increase in sediment transport capacity, deposition will occur in certain stream types of lower gradient. What was observed in Trail Creek from the Hayman Fire was that this initial deposition was followed by channel incision within the deposit, working headward. Channel incision and headcuts will continue in the presence of the in-channel deposition as a function of the chronic increase in streamflows. These widespread processes extended the recovery time and increased sediment yields for over ten years following the Hayman Fire and are expected within the watersheds affected by the Waldo Canyon Fire. Stream types that have floodplains or connected alluvial fans have less adverse consequences than the incised and entrenched channels. Maintenance and establishment of floodplains and alluvial fan connectivity are major considerations for the restoration phase of this effort.

Table 15. The sub-watershed priorities for mitigation and restoration based on the total sediment supply from hillslopes, roads, and streambanks.

Priority	Watershed	Priority	Watershed	Priority	Watershed	Priority	Watershed
1	DC-007	**23**	MC-015	**45**	MC-016	**67**	FC-F09
2	FC-002	**24**	CC-015	**46**	FC-008	**68**	CC-F10
3	FC-010	**25**	FC-006	**47**	CC-004	**69**	CC-F06
4	FC-004	**26**	MC-017	**48**	FC-F07	**70**	CC-011
5	MC-010	**27**	CC-005	**49**	CC-009	**71**	MC-F03
6	MC-007	**28**	CC-F05	**50**	CC-F03	**72**	CC-012
7	FC-007	**29**	CC-020	**51**	DC-005	**73**	MC-F11
8	FC-011	**30**	CC-008	**52**	CC-016	**74**	MC-F13
9	FC-005	**31**	CC-F04	**53**	FC-003	**75**	MC-F14
10	MC-008	**32**	CC-013	**54**	CC-F12	**76**	CC-F17
11	DC-001	**33**	CC-F09	**55**	MC-005	**77**	FC-F03
12	CC-007	**34**	CC-006	**56**	MC-019	**78**	DC-F08
13	CC-017	**35**	CC-F01	**57**	MC-006	**79**	DC-F06
14	DC-006	**36**	MC-001	**58**	CC-F14	**80**	CC-F07
15	FC-009	**37**	CC-F02	**59**	MC-F04	**81**	FC-F05
16	CC-001	**38**	FC-F04	**60**	MC-F02	**82**	FC-F08
17	DC-004	**39**	CC-018	**61**	CC-F16	**83**	MC-F10
18	CC-F08	**40**	CC-003	**62**	MC-F12	**84**	FC-F10
19	MC-013	**41**	MC-014	**63**	MC-018	**85**	CC-F19
20	CC-014	**42**	MC-009	**64**	MC-F08	**86**	CC-F20
21	DC-F02	**43**	MC-F06	**65**	CC-F18	**87**	MC-F15
22	CC-019	**44**	DC-F09	**66**	FC-F06	**88**	CC-F13
						89	MC-003

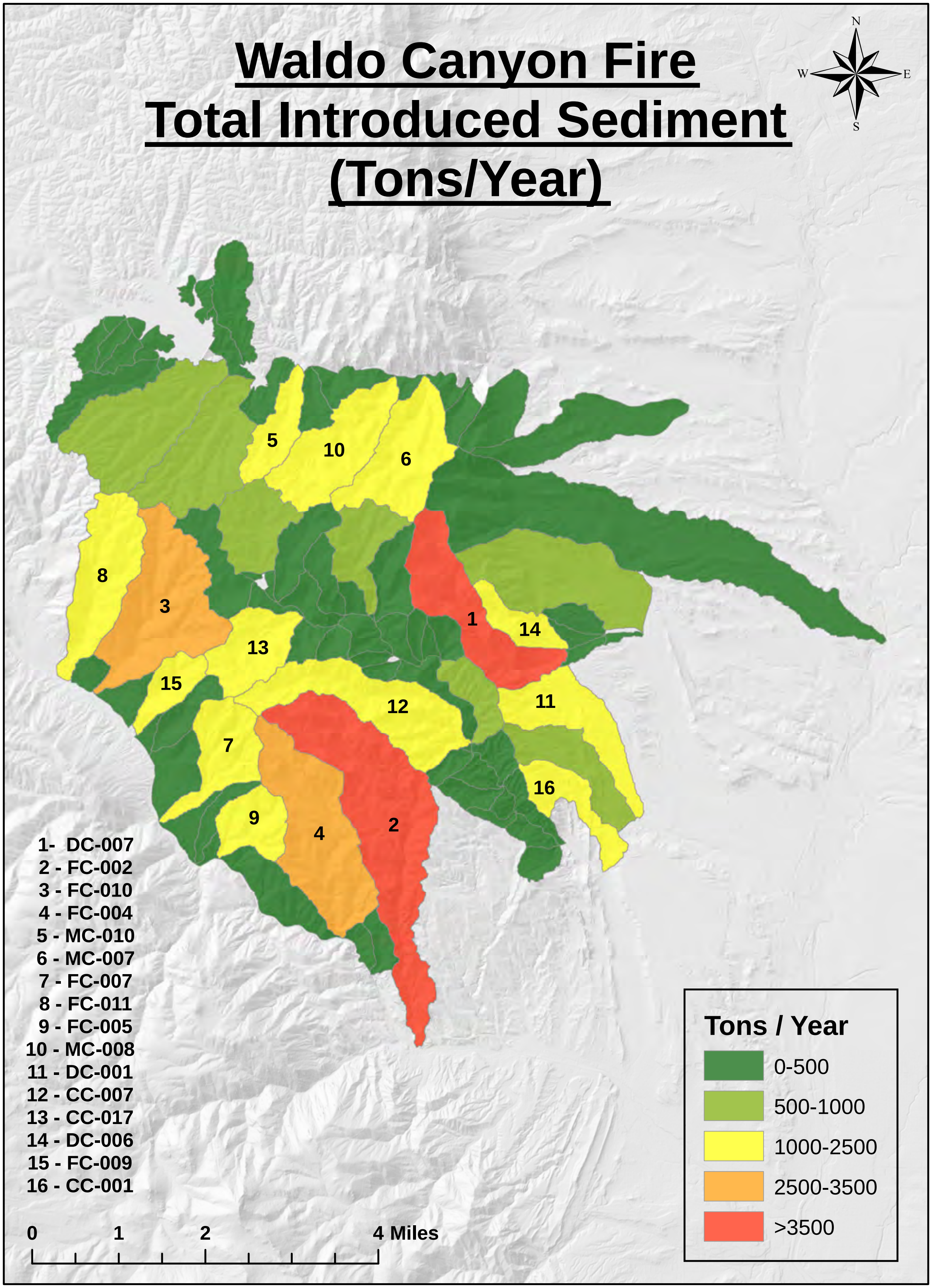


Figure 60. The top priorities for mitigation and restoration based on the disproportionate supply of introduced sediment.

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