THE APPLICATION OF *WARSSS* FOR A WATERSHED-BASED SEDIMENT BUDGET AND POST-FIRE STREAM RESTORATION: THE HAYMAN FIRE, TRAIL CREEK WATERSHED, COLORADO

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INTRODUCTION

The Hayman Fire started on June 8th, 2002, and burned over 138,000 acres and 133 homes. The burn area involved a large portion of the 186 mi^2 Horse Creek Watershed on the Pike National Forest, Colorado. Eight years following the fire, disproportionate sediment yields and river impairment were still prominent in the burn area. Thus a watershed assessment was conducted in 2010 and 2011 to ascertain erosional and depositional processes to identify the causes of impairment by specific location. The results of the watershed assessment were used to develop a master restoration plan to reduce the accelerated sediment yields in the areas affected by the burn.

The watershed assessment utilized the *Watershed Assessment of River Stability and Sediment Supply (WARSSS)* methodology (Rosgen, 2006b). *WARSSS* is a three-phase approach that assesses large watersheds with a practical, rapid screening component that integrates hillslope, hydrologic, and channel processes. It is designed to identify the location, nature, extent, and consequences of various past, existing, and proposed, land use impacts.

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 the 186 mi^2 Horse Creek Watershed (Rosgen and Rosgen, 2010). The *RLA* and the *RRISSC* assessments identified the Trail Creek Watershed within the Horse Creek Watershed as *High Risk* for disproportionate sediment supply and river impairment. Based on the results of *RLA* and *RRISSC*, the Trail Creek Watershed 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 and depositional processes that are disproportionately contributing sediment to Trail Creek
2. Quantify sediment loading by location, process, and land use
3. Develop a master plan for watershed restoration

The *PLA* methodology and results are summarized in this paper. These results were used to prioritize the locations within the Trail Creek Watershed for mitigation and restoration based on the magnitude of sediment sources for a variety of land uses. This paper also discusses design solutions for the identified areas with disproportionately high sediment yields throughout the watershed. The designs address typical sediment yield processes for hillslope and channel processes at representative or typical impaired stream type and landscape type locations.

THE *WARSSS* METHODOOGY: THE *PLA* RESULTS

The majority of the Trail Creek Watershed was burned during the Hayman Fire. The watershed involves nearly *16 mi^2* of drainage area within the South Platte River drainage in Colorado. The watershed is located in the Granitic geology associated with the Pikes Peak Batholith composed of erosive grussic granite soils. The confluence of Trail Creek is at West Creek near the community of West Creek. Ownership within the watershed is predominantly USDA Forest Service, Pike National Forest, with some private land inholdings in the upper watershed. The Trail Creek Watershed was delineated into 58 sub-watersheds, each given a unique number ID.

The *PLA* analysis identified and quantified annual sediment yields from hillslope, hydrology, and channel processes (Figure 1). Hillslope processes included assessments of the introduced sediment from surface erosion and roads and trails. Flow-related sediment was analyzed from a change in hydrology due to the fire. The assessment of channel processes included streambank erosion, degradation (bed erosion) due to headcuts and incising channels, and the combined sediment yield of the 58 sub-watersheds and the mainstem Trail Creek.

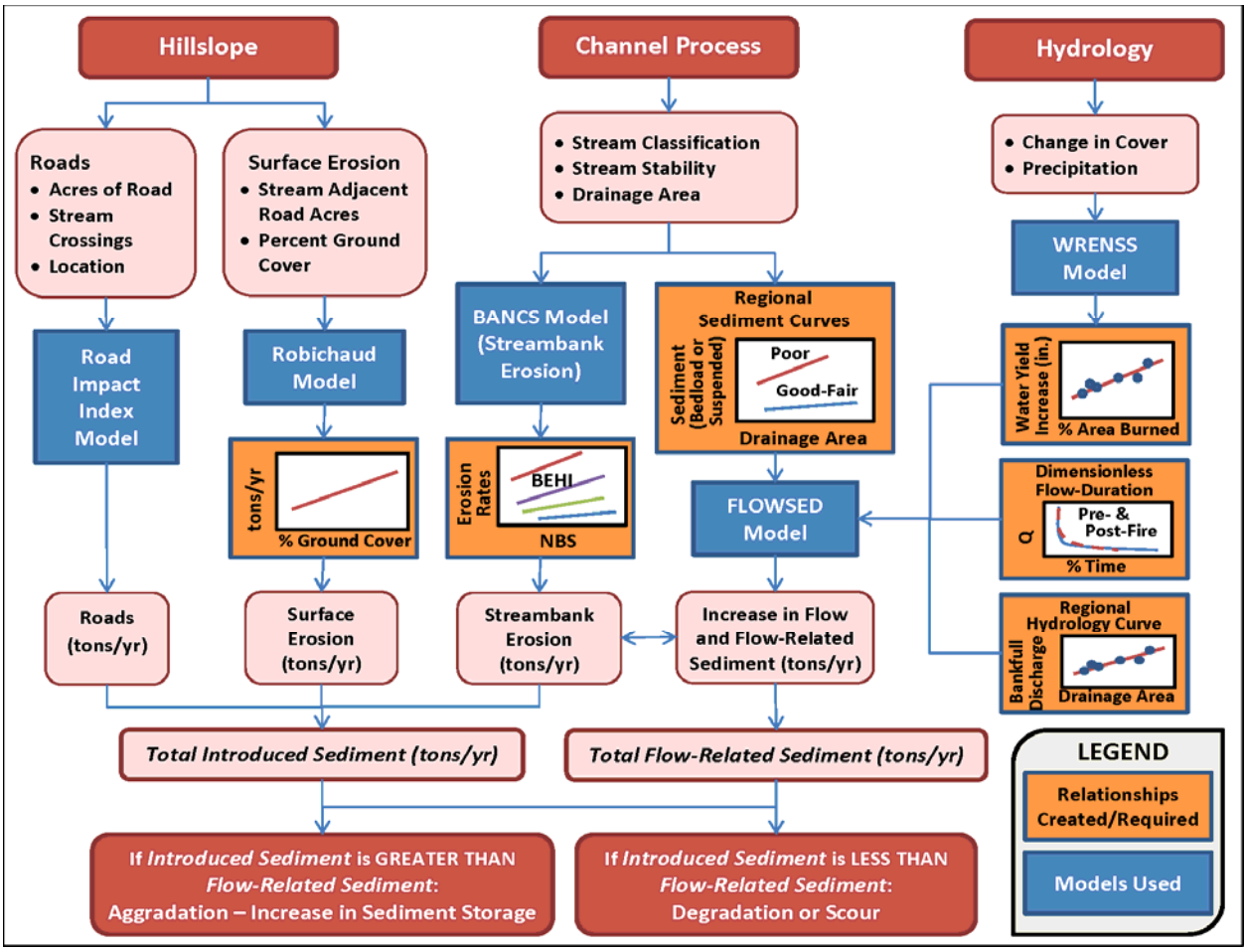

Figure 1 The procedure to quantify the sediment sources by major process (Rosgen, 2011a).

Hydrology

Increases in annual water yield following wildfires, although highly variable, can be expected (DeBano *et al*., 1998; Robichaud *et al*., 2000, 2002, 2003). Intense short duration storms 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; Robichaud *et al*., 2002). Continued frequent and high magnitude storms will generate excess sediment yields based on flow-related channel response for the Trail Creek Watershed and other tributaries involved in the Hayman fire. According to MacDonald (2009), the Hayman fire will continue to produce 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 Hayman fire are very poor due to the coarse-textured soils and low precipitation relative to potential evapotranspiration. Vegetative cover is not expected to increase much beyond the current levels in areas without coniferous trees. 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).

The hydrologic assessment for Trail Creek and its tributaries involved an application of the WRENSS water yield model (USEPA, 1980), completed by J. Nankervis, 2010, Blue Mountain Consultants. The water yield model simulates the increase in yield based on the percent of the stand that was burned for each sub-watershed to determine the inches of increased annual water yield due to the fire. The increase in flow is reflected in changes in a flow-duration curve, normalized for the flows of each sub-watershed and the mainstem Trail Creek. Changes in pre- and post-fire flow-duration curves were simulated as part of the flow-related sediment yield increase due to the wildfire for each sub-watershed and the entire Trail Creek Watershed.

The pre-fire water yield for the Trail Creek Watershed was predicted at *3,689 acre-ft* and the post-fire water yield at *6,560 acre-ft*. The total water yield increase from pre-fire to post-fire conditions was predicted to be *2,871 acre-ft*, representing a *44%* increase.

Bankfull Discharge

Bankfull discharge is the frequent peak flow that fills the channel to the incipient level of flooding. It often is associated with a return interval of 1 to 2 years and is coincident with the effective discharge or channel forming flows. Bankfull discharge was determined using the continuity equation ($Q = A * \bar{u}$) by estimating velocity ($\bar{u}$) and calculating the bankfull cross-sectional area (A). The calculated bankfull discharge was then compared to a regional curve developed for this project representing bankfull discharge *vs*. drainage area (see Rosgen, 2011b). This regional curve is based on calibrated, field-determined bankfull values at streamgage sites in the same hydro-physiographic province as Trail Creek. Velocity was estimated using a variety of methods, such as flow resistance to relative roughness and Manning's '*n*' by stream type (Rosgen, 1996, 2006b). The bankfull discharge at the mouth of each sub-watershed was determined from the regional curve relation of bankfull discharge *vs*. drainage area.

<u>Flow-Related Sediment Yields</u>

The flow-related sediment yield represents an integration of all introduced sources (including sediment supply from channel and hillslope processes) and the increased flow from flow-duration curves. The FLOWSED model (Rosgen, 2006a, 2006b) was applied to determine flow-related sediment yield increases due to the fire. The model uses dimensionless relations of the flow-duration curves from the WRENSS water yield analysis, along with dimensionless sediment rating curves. The normalization parameter to convert the dimensionless flow-duration curves to dimensional is the bankfull discharge determined from a regional curve of bankfull discharge *vs*. drainage area. Bankfull sediment values are used to convert the dimensionless sediment rating curves to dimensional curves. Flow-related sediment yield is then calculated based on routing the flow increase through sediment rating curves established by stream type and stability categories. This prediction assists in determining individual sub-watersheds that may be disproportionately contributing sediment based on their sediment supply, channel condition, and stream type related to the increases in post-wildfire peak flows and corresponding flow-related sediment.

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 by channel stability were developed for the batholith geology (Pikes Peak, grussic granite geology) for this assessment (see Rosgen, 2011b).

The FLOWSED model was run for each of the 58 sub-watersheds and for the entire Trail Creek Watershed. The flow-related sediment yield from the post-fire, existing condition is compared to the introduced sediment supply from roads, surface erosion, and streambanks. If the combined introduced sediment values exceed the existing annual sediment yield, then excess deposition (increased channel sediment storage) is indicated. If annual flow-related sediment yield values are greater than the combined introduced sediment supply, then channel scour (bed erosion) is indicated.

The flow-related increase in sediment for the Trail Creek Watershed due to changes in the flow-duration curves and the sediment rating curves from the FLOWSED model resulted in an increase from the pre-fire to post-fire total sediment yield of *1,250 tons/yr* to *20,838 tons/yr*, which represents an increase of *19,588 tons/yr*. The total yield is comprised of approximately 26% bedload sediment and 74% suspended sediment. Overall, for a 44% increase in water yield, there is a corresponding 94% increase in total sediment (based on flow-related increases) for the Trail Creek Watershed. The significance of the increased streamflow peaks cannot be overlooked based on the magnitude of the total sediment yield consequence. Annual sediment yields from the introduced supply of roads, trails, surface erosion, and streambank erosion compared to the flow-related sediment yields are helpful in identifying sediment sources to set priorities in restoration and stabilization proposals to reduce sediment.

Hillslope Processes

Surface Erosion

Sediment yields due to surface erosion following fires 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). MacDonald (2009) emphasizes that surface erosion rates are highly dependent on the amount of surface cover. According to the research reported by Robichaud and Wagenbrenner (2009), due to increasing ground cover in the Hayman fire burn area, a major reduction in sediment yield resulted between 2002 to 2008. 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. By 2008, although in the presence of high intense rainstorms, sediment yields are greatly reduced from the initial erosion and sedimentation rates. 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 a result of Robichaud and Wagenbrenner (2009) research, a negative exponential relationship of erosion rate (tons/acre) as a function of ground cover density (%) was developed for this analysis (see Rosgen, 2011b). The sediment delivery data was derived from surface erosion processes for relatively short slope lengths adjacent to ephemeral channels, and for 20–40% slopes based on ground cover density. The erosion rates represent delivered sediment within approximately 100 ft from the surface erosion source. Ground cover densities were determined for each 100 foot zone on both sides of each drainage to obtain the sediment yield from surface erosion in tons/acre/yr. Aerial photo interpretations from ground truth signatures contrasting roads as zero percent ground cover up to 90% were used to obtain ground cover percentage in these 100 foot, stream-adjacent slope zones. These variables were then used to determine the increase in sediment supply from surface erosion processes based on the surface erosion rate multiplied by the total acres for that condition. Although there is evident surface erosion on mid-to-upper slopes, the potential to provide for increased sediment supply is diminished as these locations are far removed from the stream-adjacent slopes. In cases where field observations (ground truthing) indicated lower ground cover than the aerial photo-interpretation, the following procedure was followed to obtain surface erosion contributions for each sub-watershed:

1. Determine the acres of burn intensity within the near-bank zone (100 feet each side of channel) using categories as previously mapped of *High*, *Moderate*, *Low*, and *Unburned* conditions
2. Calculate the percentage of area for each burn intensity condition
3. Determine the percent ground cover for each burn intensity condition using 30% ground cover for *High* intensity, 55% for *Moderate*, 75% for *Low*, and 85% for *Unburned*
4. Calculate the weighted percent ground cover for each burn intensity condition
5. Calculate the ground cover distribution for the sub-watershed
6. Calculate the corresponding erosion rate based on the relationship to the percentage of ground cover

The predictions of sediment yields related to surface erosion resulted in a total of *2,542 tons/yr* from the Trail Creek Watershed. The total surface erosion from individual sub-watersheds is estimated at *1,908 tons/yr*, and the surface erosion adjacent to the mainstem Trail Creek is estimated at *634 tons/yr*. Overall, surface erosion contributes approximately 12% of the total introduced sediment in the sub-watersheds, mainstem Trail Creek, and the Trail Creek Watershed.

Roads and ORV Trails

Over the long-term, studies by Colorado State University indicate that roads and ORV trails generate and deliver as much sediment to the stream channel network as high-severity wildfires (MacDonald, 2009). Sediment from stream encroachment, crossings, cut bank erosion, fill erosion, and poor drainage on the main Trail Creek road results in disproportionate sediment yields. Another source of sediment is from the encroachment of the road system on alluvial fans, which has over-steepened the channels causing headcuts and the routing of sediment from the fans directly into Trail Creek. The Trail Creek road parallels and crosses the stream channel multiple times throughout its length. The majority of the ORV road and trail systems follow in close proximity to the drainageways.

The Road Impact Index (RII) model (Rosgen, 2006b) was used to predict the delivered road erosion sediment from road cuts, surfaces, and fill slopes (RII = road density multiplied by the number of stream crossings). Reasonable

validation agreement of the measured road erosion rates from the Hayman fire research (Libohova, 2004) and the sediment yield prediction from roads using the RII suggests the RII is an appropriate model utilized for this assessment. The acres of road surfaces exposed were broken into three classes based on the type of road or trail, and the typical side-slope gradient. The acres of road divided by the sub-watershed acres multiplied by the number of stream crossings by slope position were used to determine the sediment yield (tons/acre/yr).

The total sediment yield of the Trail Creek Watershed from roads and trails (erosion delivered to stream channels) is *848 tons/yr* based on 8.9 miles of roads and trails. The total sediment from the sub-watersheds, separate from the main Trail Creek road, is *258.1 tons/yr* based on 4x4 and ORV trail systems involving less acres/road length. The main Trail Creek road contributes *589.9 tons/yr* due to its close proximity to the mainstem Trail Creek. Overall, the roads and trails contribute *approximately 11%* of the introduced sediment for the mainstem Trail Creek, *approximately 2%* of the introduced sediment for the sub-watersheds, and *approximately 4%* of the introduced sediment for the Trail Creek Watershed.

Channel Processes

According to MacDonald (2009), most of the sediment due to the fire is coming from rill, gully, and channel erosion rather than hillslopes. Large amounts of sediment are still generated seven years after the fire (MacDonald, 2009). This increase in sediment can be attributed to extreme storms where there is still sufficient surface runoff to cause further channel incision and streambank erosion. Increases in the headward expansion of the drainage network are evident and widespread due to the increased peak flows and decreased flow resistance from destroyed riparian vegetation following the fire. 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.

River Stability Analysis using Reference & Representative Reaches

Because there are 178 miles of stream channels within the Trail Creek Watershed, it was not practical to traverse each channel length, providing a detailed assessment of each channel. To characterize the major reaches in the watershed, the following procedure was utilized that allows for extrapolation of detailed stream channel process relations to other reaches of similar stream type and condition. Stream impairment and sediment supply are based on:

1. Development of typical, *representative reaches* that represent a range of stability and sediment supply conditions for the various stream types that occur within the Trail Creek Watershed
2. Departure of the representative reaches from the stable, *reference reach* condition for various stream types and landscape types with defined boundary conditions and controlling variables

River stability is evaluated for each reference and representative reach following the procedures in Rosgen (2006b). 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 conditions. Estimates of vertical stability, lateral stability, channel enlargement, and sediment supply are assessed, including streambank erosion, channel competence, and transport capacity evaluations. Streambank erosion is assessed using the *Bank Assessment for Non-point source Consequences of Sediment (BANCS)* model (Rosgen, 2001, 2006b). Competence is determined using the revised Shields relation for initiation of motion (Rosgen, 2006b); sediment transport capacity is evaluated using the POWERSED model (Rosgen, 2006a) as programmed in RIVERMorph™. The POWERSED model is also used to determine channel response (aggradation, degradation, or stable) for each representative reach as a departure from the reference condition. The river stability evaluation provides a quantitative expression of the stable form of stream types that may be potentially implemented as part of mitigation or restoration.

Overall, sixteen *representative reaches* and five *reference reaches* were obtained to document a range of stream types and conditions that occur within the Trail Creek Watershed. Data for each stream type and landscape type include the morphological characterization (dimensions, pattern, profile, and channel materials) to determine the departure of each representative reach from the potential, stable stream type (reference reach). If restoration designs are required, the reference reach data is also used to scale the morphological characteristics of the stable form to apply to the restoration reaches that have similar landscape types, boundary conditions, and controlling variables.

The data from the representative reaches were extrapolated to reaches with similar stream types and conditions within 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; see Rosgen, 1994, 1996 for stream type and valley type descriptions), unit erosion rates in tons/yr/ft of streambank erosion were obtained; these rates were extrapolated to other similar "Poor" stability, F4 reaches. The reaches that indicated *moderate* to *very high* sediment supply or channel instability were mapped in detail. Approximately 55 miles (31%) of the streams in the Trail Creek Watershed were traversed obtaining direct observations of stream types and associated stability. The remaining two-thirds 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 increases. 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.

Streambank Erosion

Streambank erosion is accelerated in the presence of aggradation, central bars, channel incision, increased peak flow magnitude and frequency, debris jams, and change in riparian vegetation that decreases frictional resistance. The BANCS model (Rosgen, 2001, 2006b) was used to predict streambank erosion rates on the reference reaches, representative reaches, sub-watersheds, and mainstem Trail Creek. 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.

The erosion rates for the reference reaches indicate baseline or geologic rates; whereas the erosion rates from the representative reaches indicate a potential departure from the reference condition, or an acceleration of this process. Stream reaches were mapped in each major sub-watershed and along the mainstem Trail Creek 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 sub-watershed and the mainstem Trail Creek. This allows the locations with very high sediment contributions to be identified within the sub-watersheds and their relative contribution to total sediment yield. Not all of the sediment, however, that is dislodged or entrained from the banks is routed out of the watershed. Much of the sediment from the streambank erosion process is stored temporarily in the channel. Sediment budgets for each sub-watershed, reference reach, and representative reach include the specific contributions from streambank erosion. Because streambank erosion can be mitigated or reduced through various streambank stabilization methods, this data is used to set priorities for restoration and stabilization recommendations.

Overall, streambank erosion contributes *14,087 tons/yr* of introduced sediment for the sub-watersheds, which represents *87%* of the total introduced sediment. The streambanks along the mainstem Trail Creek contribute *4,031 tons/yr* of introduced sediment, which represents *77%* of the total introduced sediment along the river corridor. Overall, for the entire Trail Creek Watershed, streambank erosion makes up *84%* of the introduced sediment and contributes *18,118 tons/yr* to the post-fire total sediment yield of *20,838 tons/yr*. These values indicate the significant contribution of streambank erosion to the introduced or accelerated sediment supply.

Stream Type Succession

Wildfire-induced changes in the boundary conditions (riparian vegetation and flow resistance) and the flow and sediment regimes promote changes in river morphology and stream type. Typical channel responses to the fire effects are generally increased streambank erosion, channel enlargement, aggradation, degradation, lateral migration, and channel avulsion. The extent, nature, and direction of change is dictated by the landscape 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 Trail Creek and its tributaries.

Stream type succession is used to interpret and predict the potential stable morphological state. Twelve stream succession scenarios and stream type shifts toward stable end points for each scenario are presented in Rosgen (2006b). 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. 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. The use of stream succession in design is dependent on the existing stream type and the stable, potential type based on a landscape type that matches the boundary conditions and the controlling variables. Based on the stream succession scenarios, Table 1 shows the typical, impaired stream types and their respective stable, potential stream types within specific landscape types.

Table 1 Existing, impaired stream types compared to the stable, potential stream types stratified by landscape types for the Trail Creek Watershed.

Existing, Impaired Stream Type	Existing Landscape Type	Stable, Potential Stream Type
A4	Short Alluvial Fan	B4a
A4	Long Alluvial Fan	D4
D4	Terraced Alluvial	C4
F4b	Colluvial	B4
F4b	Terraced Alluvial	B4
F4b	Short Alluvial Fan	B4
F4b	Long Alluvial Fan	D4
F4	Terraced Alluvial	C4
F4	Terraced Alluvial (confined)	B4c
G4	Terraced Alluvial	B4
G4	Short Alluvial Fan	B4
G4	Long Alluvial Fan	D4
B4 “Fair” or “Poor”	Terraced Alluvial	Stable B4
C4 “Fair” or “Poor”	Terraced Alluvial	Stable C4

Summary of Sediment Supply and Sub-Watershed Priorities

The contributions of the total introduced sediment supply to the total post-fire annual sediment yield for the Trail Creek Watershed are shown in Table 2. The total introduced sediment yield is higher than the flow-related annual sediment yield because not all of the sediment is routed out of the basin. Approximately *661 tons/yr* can potentially be related to excess sediment (channel storage) of the total flow-related increased sediment. The stored sediment in the channel is made available during subsequent stormflow runoff events and is reflected as an increase in flow-related channel source sediment.

The contributions of each erosional process for the 58 sub-watersheds are summarized in Rosgen (2011b). Priorities to address the sediment supply for the 58 sub-watershed were established based on a weighted sediment supply by area (see Rosgen, 2011b). The watershed master plan for restoration focuses on the high priority sub-watersheds to reduce the annual sediment supply based on the sediment sources.

Table 2 Relative contributions of erosional or depositional processes to total annual sediment yield for the Trail Creek Watershed.

Erosional or Depositional Processes	Total Annual Sediment Yield (tons/yr)	Percent of Total Introduced Sediment
Surface Erosion	2,542	12%
Roads & Trails	848	4%
Streambanks	18,109	84%
Total Introduced Sediment	21,499	100%
Erosional or Depositional Processes	**Total Annual Sediment Yield (tons/yr)**	**Sediment Deposition/ Increased Channel Storage (tons/yr)**
Post-Fire Flow-related Total Sediment Yield (FLOWSED)	20,838	661

THE WATERSHED MASTER PLAN FOR RESTORATION

The watershed and river restoration plan is based on the Natural Channel Design (NCD) methodology (Rosgen, 2007, 2011a). The watershed restoration master plan and design considers the stated objectives and offers a variety of solutions for a wide range of conditions. The following objectives help define the proposed watershed and river system restoration and sediment reduction plan:

1. Reduce sediment supply from disproportionate sources identified by erosional process, land use, and specific locations within the watershed
2. Quantify the sediment supply reduction by proposed restoration
3. Develop restoration scenarios that address the cause of impairment
4. Improve fish habitat diversity and function
5. Stabilize streambanks and streambeds
6. Utilize a natural channel design methodology that results in a natural appearance
7. Accelerate the recovery processes from the Hayman Fire
8. Re-establish a functional riparian corridor
9. Reduce road and trail maintenance
10. Provide for improved recreational opportunities
11. Provide ecological restoration (including habitats for birds, fish, mammals, and amphibians)
12. Reduce flood stage
13. Accommodate floods and reduce flooding impacts on adjacent road
14. Create cost-effective and low-risk restoration solutions
15. Be complimentary to the central tendency of natural systems
16. Provide a demonstration reach for extrapolation of similar applications
17. Provide an opportunity for research and restoration monitoring

Hydrologic Processes

The increase in peak flows due a reduction in evapo-transpiration will continue until a forested stand is re-established. Decades will be required to reach a full hydrologic utilization. Planting coniferous trees on the burned landscape will help accelerate the re-establishment of a forested stand for the potential long-term condition.

Restoration Plan for Hillslope Processes

Surface Erosion

Surface erosion reduction is planned within the *100 foot buffer* to existing streams because this zone has the highest probability of delivered sediment. The highest priorities are also set adjacent to perennial channels. The annual sediment contribution of approximately *2,542 tons/yr* makes this effort worthwhile. The following recommendations are designed to reduce this sediment source.

Because ground cover density is directly related to erosion rates and sediment supply, any sites with a ground cover density less than *40%* will need treatment. Treatment includes reseeding with a grass hay or straw mulch surface. Adding debris such as small logs, tops, and branches will also help reduce soil loss transport. The highest priorities for treatment are on slopes adjacent to perennial streams. The locations of the lowest ground cover density based on burn intensity for each sub-watershed are also zones of highest priority for surface erosion contributions.

Where sufficient space allows, constructing a bankfull bench against the toe of the slope is also recommended rather than allowing the sediment to be routed directly into the stream channel. The bench is most appropriate adjacent to B and C stream types. The materials for the entire bench width and length are generated from borrow sites. The borrow sites can also be used as a sediment detention basin. It is also necessary to establish vegetation on the bench to add as a potential sediment filter and sediment catch. Native bunchgrasses, such as big mountain brome, are appropriate species for the bench as these sites are not typically in wetland areas. The design requires approximately *89* yds^3 of fill per *100 ft* of constructed bench based on a bench width of *12 ft* and a mean depth of *2.0 ft*. Thus the borrow depression would be sufficiently deep and spaced to provide the needed fill. There is a net balance of cut and fill by design.

Overall, it is anticipated that at least *50%*, or *1,270 tons/yr*, can be reduced by increasing ground cover to above *65%* and by installing benches and establishing riparian vegetation on stream-adjacent slopes that are contributing to sediment delivery from surface erosion.

Roads & Trails

The *WARSSS* assessment indicated that the mainstem Trail Creek road contributes approximately *589.9 tons/yr* of delivered sediment compared to the total of *848 tons/yr* from the trails, off-road 4x4 roads systems, and the mainstem Trail Creek road. To reduce the delivered sediment and erosional debris from the Trail Creek road directly into Trail Creek, decreasing the *number* of stream crossings is recommended. Relocating the main Trail Creek road in two major locations will potentially reduce six crossings.

It is also recommended to reduce the fill erosion along many actively eroding road fill sites that are responsible for direct sediment contributions to Trail Creek; the following practices are recommended:

1. Relocate the channel away from the road fill slope to reduce the toe erosion from lateral channel migration
2. Place grass seed and native grass hay mulch or straw mulch over the seed on the fill slopes; native grass hay mulch is preferred as it is not as susceptible to wind transport as straw mulch and provides additional seed source
3. Move the localized road prism farther away from the channel without total relocation at locations where feasible
4. Stabilize channels cut through fills with step–pool grade control structures, side-slope reduction, and seeding and mulching
5. Place woody debris on fill slopes, including limbs, tops, branches and small logs, perpendicular to the slope; seed and mulch the slopes
6. Construct small terraces perpendicular to the slope to reduce rill erosion; seed and mulch the terraces
7. Construct a bankfull bench between the toe of fill slope and the channel where the channel impinges on fill
8. Install the toe wood structure with sod mats and willow transplants (or soil lifts with cuttings) on the bankfull bench to prevent Trail Creek from eroding the fill material

Also, reseeding and grading the road surface to reduce surface rills and maintain drainage features are recommended. Improving the road surface drainage is also advised as follows:

1. Out-slope the road to reduce concentration of water and sediment on the inside ditch line; this avoids the concentration of water from sub-surface interception and disperses the flow instead of concentrating such flows on the road and ditch-line surface
2. Place rolling "Kelly dips" on slope gradients greater than three percent
3. Construct sediment detention depressions at drainage outfalls or at drainage turnouts to encourage infiltration and sediment deposition

Headcut channels intercepted by the road should also be stabilized with step–pool grade control. This will help reduce the current high maintenance of sediment deposition on the road surface and will prevent over-steepening of the channel at the toe of the road.

It is anticipated that the aforementioned recommendations can effectively reduce the existing sediment yield from the Trail Creek road by approximately *413 tons/yr*, representing a *70%* sediment reduction.

In addition to the Trail Creek Road, numerous ORV roads and trails parallel and cross the channels in the Trail Creek Watershed; it is recommended to relocate the majority of these systems that are frequently introducing direct sediment away from the drainage proximities. Based on the immediate proximity of the ORV roads and trails to the adjacent channels and their steepness, it would be extremely difficult with a poor likelihood of success to institute sediment mitigation on these systems. The proposed ridge routes are available and feasible for these trails without changing their origin or destination sites (see Rosgen, 2011c). This recommendation can reduce nearly *200 tons/yr* of delivered sediment to Trail Creek.

Restoration Plan for Channel Processes

Due to high sediment yield results from flow-related increases, stream channel restoration and stabilization can be effective to reduce this accelerated sediment supply. The restoration work includes protecting streambeds and streambanks from the increased flows and re-establishing floodplain connectivity where possible. Creating a functioning riparian corridor is also recommended for the long-term stability of stream channels. Aquatic habitat will also be improved with such river restoration and stabilization work. The proposed restoration of the stream channels to reduce the accelerated sediment supply focuses on converting unstable stream types to stable stream types and reducing the streambank erosion.

Typical Design Scenarios

The *representative reaches* were established, measured, quantified, and evaluated in great detail to develop typical design scenarios that can be extrapolated to other locations in the Trail Creek Watershed where this level of detail was not obtained but is assumed to be similar. The reference reaches were established to provide the stable design criteria to develop the proposed design for the representative reaches. The nine design scenarios shown in Table 3 were developed to represent the range of stream types and stability conditions that require restoration within the Trail Creek Watershed. Each of the design scenarios is related to a specific location within the watershed for demonstration purposes. The appropriate scenario can then be extrapolated to other reaches of the same stream type, landscape type, and stability condition as the representative reach.

Table 3 The nine typical design scenarios developed to extrapolate to other locations in the Trail Creek Watershed for restoration.

Stream Type Conversions		
Existing, Impaired Stream Type	**Proposed Stream Type**	**Landscape Type**
1. D4 Poor	C4 Good	Terraced Alluvial
2. F4 Poor	B4 Good	Terraced Alluvial (confined)
3. G4 Poor	B4 Good	Terraced Alluvial
4. C4 Poor	C4 Good	Terraced Alluvial
5. F4b Poor Tributary	D4	Alluvial Fan
6. F4b Tributary	B4 Good	Alluvial Fan
7. A4a+ Poor	A4a+ Good	Colluvial
8. A4a+ Poor	D4	Alluvial Fan
9. A4a+ Poor	B4a Good	Alluvial Fan (short fan)

Each typical design scenario includes detailed descriptions of 1) General Description and Morphological Data; 2) Bankfull Discharge, Cross-Sectional Area, and Mean Velocity; 3) Plan View Alignment; 4) Cross-Section Dimensions; 5) Longitudinal Profile; 6) Structures; 7) Riparian Vegetation; 8) Cut and Fill Computations; 9) Streambank Erosion; 10) Flow-Related Sediment; and 11) Sediment Competence (see Rosgen, 2011c, for the detailed design scenarios).

The flow-related sediment and potential sediment reductions, including streambank erosion contributions, for the existing and proposed design reaches are documented in Rosgen (2011b). The majority of the design scenarios convert "Poor" condition stream types to "Good" stream types and unit sediment transport reductions are computed. However, the typical design scenarios 5 and 8 in Table 3 convert A4a+ and F4b stream types to the braided, D4 stream type with sediment detention basins and surface storage on alluvial fans. The typical designs for these scenarios store 100% of the sediment yield and are associated with a zero sediment transport to the mainstem Trail Creek.

The sediment reduction potential by implementing the proposed stream restoration design scenarios involving 3,025 ft of stream channels is approximately *1,600 tons/yr* for 7 of the 9 scenario locations. The remaining 2 scenarios associated with creating D4 stream types with sediment detention basins on alluvial fans result in reductions of

approximately *5,468 tons/yr* of sediment. In total, over *7,000 tons/yr* of sediment could be kept out of Trail Creek per year based on the implementation of the nine scenarios presented. This represents approximately *29%* of the total annual sediment yield in the Trail Creek Watershed. Extrapolating and implementing the design scenarios to appropriate locations will result in even greater sediment yield reductions.

Total Potential Sediment Reductions

The potential sediment reductions associated with implementing the nine typical design scenarios and the recommendations for hillslope processes are presented in Table 4. The total potential reduction is approximately *8,853 tons/yr*, representing approximately *37%* of the total annual sediment yield.

Table 4 The potential sediment reductions by implementing the recommendations for hillslope and channel processes.

Total Sediment Contribution Reductions	
Hillslope Processes	
Surface Erosion	*1,270 tons/yr*
Trail Creek Road	*413 tons/yr*
ORV Roads and Trails	*200 tons/yr*
Channel Processes	
The Nine Typical Design Scenarios	*7,000 tons/yr*
Total Potential Reduction	***8,853 tons/yr***

SUMMARY

The Trail Creek Watershed master plan for stream restoration and sediment reduction is the result of a detailed watershed assessment that has directed the proposed restoration to impaired streams. The assessment also identified the source of impairment including hillslope, hydrology, and channel processes. The master plan identified priorities of restoration based on disproportionate sediment supply contributions and the various sources, including streambed and streambank erosion from post-fire related streamflow increases, and direct introduction by surface erosion and roads and trails. These various erosional processes were identified and specific restoration scenarios were proposed to reduce the sediment supply and restore the physical and ecological function.

Each of the 17 specific, multiple objectives for the master restoration design for the Trail Creek Watershed are potentially met with the implementation of the various scenarios and locations proposed. Overall, the various restoration scenarios within the Trail Creek Watershed were developed to extrapolate general hydrology, sedimentological, and morphological relations and to create the dimensions, pattern, and profile of stable stream types scaled for individual reaches.

These subsequent designs are intended to accelerate the recovery of the Trail Creek Watershed from the adverse impacts of the Hayman fire. The proposed design scenarios and subsequent implementation will potentially direct the future of watershed restoration following large wildfires. The procedures can also be used for other watersheds that are currently impaired due to the Hayman fire in the South Platte Basin in a timely manner. Overall, the field assessment for the entire Horse Creek Watershed was completed in eight months and the assessment report and master restoration plan was completed in six months.

An individual 404 permit was issued for the master restoration plan for the entire Trail Creek Watershed to be implemented over 20 years, and project implementation began in 2011. The Forest Service (Pike and San Isabel National Forest) is monitoring the physical and biological response of the WARSSS-based restoration. The research and monitoring will document the benefits of restoration and watershed recovery.

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