# RESTORING ALLUVIAL FAN CONNECTIVITY FOR POST-FIRE FLOOD ALLEVIATION AND SEDIMENT REDUCTION

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## 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 started Saturday, June 23rd, 2012, and was fully contained Tuesday, July 10th, 2012, after destroying 346 homes. The four major watersheds affected by the Waldo Canyon Fire were Camp Creek, Douglas Creek, Fountain Creek, and West Monument Creek. Using GIS, these four watersheds were delineated into 89 sub-watersheds.

A post-fire *Watershed Assessment for River Stability and Sediment Supply (WARSSS)* study was conducted within the four watersheds impacted by the Waldo Canyon Fire in the fall of 2012 and completed in April, 2013 (Rosgen, 2006; Rosgen *et al*., 2013a). The *WARSSS* study is a cumulative watershed effects analysis that quantifies changes in water yield, hillslope erosional processes, and stream channel impacts, including streambank erosion due to disturbance. The assessment found that the prevailing consequences of the Waldo Canyon Fire included: 1) an increased magnitude and frequency of peak flows; 2) accelerated sediment yield from hillslope erosional processes, including rill, gully, and debris flow/debris torrents; 3) streambank erosion and channel enlargement due to destruction of riparian vegetation and increased flows; and 4) channel incision and subsequent abandonment of fluvial features, including alluvial fans.

The results of the *WARSSS* study form the foundation for a multi-watershed master plan to direct restoration efforts to reduce delivered sediment, restore the stability and function of the stream and riparian systems, and accelerate the watershed recovery processes (Rosgen *et al*., 2013b). The results were used to develop design scenarios for post-fire restoration priorities directly related to individual erosional processes by specific sub-watershed location.

This paper focuses on one of the restoration design scenarios related to restoring alluvial fan functions to meet the primary restoration objectives. Ephemeral, fan-head trenches (gullies) within alluvial fans were raised to reconnect to the original fan surface to reduce the flood and debris flows that were directly routed into the trunk stream. Once connectivity of the fan was restored, flood flows were dispersed and sediment was stored. Fill material for the gully was obtained from excavating sediment detention basins at the start, middle, and lower sections of the fan, and braided channels were constructed on the fan surface to match the natural channel form. Log crib walls were constructed for grade control on the upslope end of the sediment detention basins with log sills buried flush on the fan surface to prevent channel incision. An example is presented on the flow and sediment response of restoring alluvial fan function.

## IMPACTS OF THE WALDO CANYON FIRE

Rill and gully erosion is common within the fire-scarred landscape associated with soils comprised of highly-weathered grussic granite from Pikes Peak Batholith (Figure 1). Such rills and gullies increase the time of concentration of flows that lead to increased peak flows and associated debris flows.

The post-fire floods and debris flows resulted in major destruction to property and loss of lives. Damage to water transmission lines caused millions of dollars of damage to infrastructure to the Colorado Springs Utilities (Figure 2). A fatality occurred due to debris flows similar to the one shown in Figure 3 that occurred on Highway 24 following a post-fire storm in August, 2013. Furthermore, a 1.0-inch in 30 minute precipitation event created a 1,100 cfs debris flow in Williams Canyon (2.69 $mi^2$ drainage area with a bankfull discharge of 9.0 cfs) (Figure 4). The sediment supply from debris flows overwhelmed multiple receiving streams and induced stream aggradation (Figure 5). The erosional debris accumulated in downstream channels (Figure 6) and reservoirs (Figure 7).

High rates of sediment are also delivered downstream with subsequent flows when streams become incised in the erosional debris. The incised gullies increase sediment transport capacity due to the increased slope and decreased

width/depth ratio (Figure 8). Further channel aggradation was evident in the receiving streams due to the very high sediment supply delivered from upstream.

Figure 1 Rill and gully development from a recent storm on a fire-scarred landscape of the Waldo Canyon Fire.

Figure 2 Damage to water transmission lines, North Monument Creek.

Figure 3 An alluvial fan being formed on Highway 24 following a post-fire flood. The flooding resulted in a fatality due to debris flows onto the highway.

Figure 4 Destruction of homes following a post-fire flood and debris flow in Williams Gulch associated with the Waldo Canyon Fire.

Figure 5 Stream aggradation due to excess sediment deposition, North Monument Creek.

Figure 6 Erosional debris following a post-fire flood in Waldo Canyon.

Figure 7 Loss of reservoir storage due to excess sediment deposition following the Waldo Canyon fire in the Monument Creek drainage.

Figure 8 Erosional debris in a 3rd order stream following post-fire flooding in Chuckwagon Creek; note the new deposition and subsequent channel incision and headward advancement of the gully.

**Hydrology Impacts:** The effects of wildfire on increased peak flows and associated channel source sediment are well-documented (Moody, 2001; Kunze and Stednick, 2006; Moody and Martin, 2009). Relatively frequent precipitation events associated with high intensity, short duration storms are related to unusually large flood peaks (Neary *et al*., 2005; Moody and Martin, 2001a). Jarrett (2013) demonstrated that relatively frequent precipitation events following wildfires result in extremely rare, infrequent flood magnitudes; the predicted peak flows for a given precipitation by drainage area are shown in Figure 9 (Jarrett, 2013). A post-flood, 1.0-inch in 30 minute storm (frequent return period) generated 1,100 cfs (a rare flood) in Waldo Canyon associated with a 1.7 $mi^2$ drainage area and a bankfull peak flow discharge of 10 cfs. In Northfield Gulch (associated with a drainage area of 0.5 $mi^2$ and a bankfull discharge of 3.0 cfs), a 1.0-inch per hour storm predicted a flood peak of 210 cfs, where the observed value was 180 cfs (Figure 10).

Stednick and Webb (2014) indicated that post-fire floods can be up to three orders of magnitude greater than pre-flood conditions. Post-fire peak flows have been reported on the Hayman fire in Colorado on small drainage basins that can vary from 600 csm ($ft^3/sec/mi^2$) to over 1,064 csm from a 4.3-inch storm (Robichaud and Wagenbrenner, 2009). Post-fire peak flows have increased from 3.7 csm to over 600 csm on North Douglas Creek on the northern end of the Waldo Canyon Fire.

Moody and Martin (2001b) state that high sediment yields may persist for four to seven years following wildfires. However, hydrologic recovery in certain landscapes is much longer than anticipated; for example, the Hayman fire that burned 12 years ago is still producing high peak flows and disproportionately high sediment yields compared to pre-fire conditions (Rosgen *et al*., 2013a; Stednick and Webb, 2014). Sediment supply recovery from debris flows and associated channel source sediment related to peak flows is not rapid.

The influence of the loss of vegetative cover on streamflow response following wildfires is critical in addressing restoration strategies for recovery (Beanvides-Solorio *et al*., 2005). Hydrologic recovery and decreasing flow-related, channel source sediment is a long-term proposition related to re-establishing the riparian community following wildfires in Colorado. However, decades will be required to reach a full hydrologic utilization due to the cold climate, relatively low precipitation, steep slopes, shallow soils, high elevations, and short growing seasons.

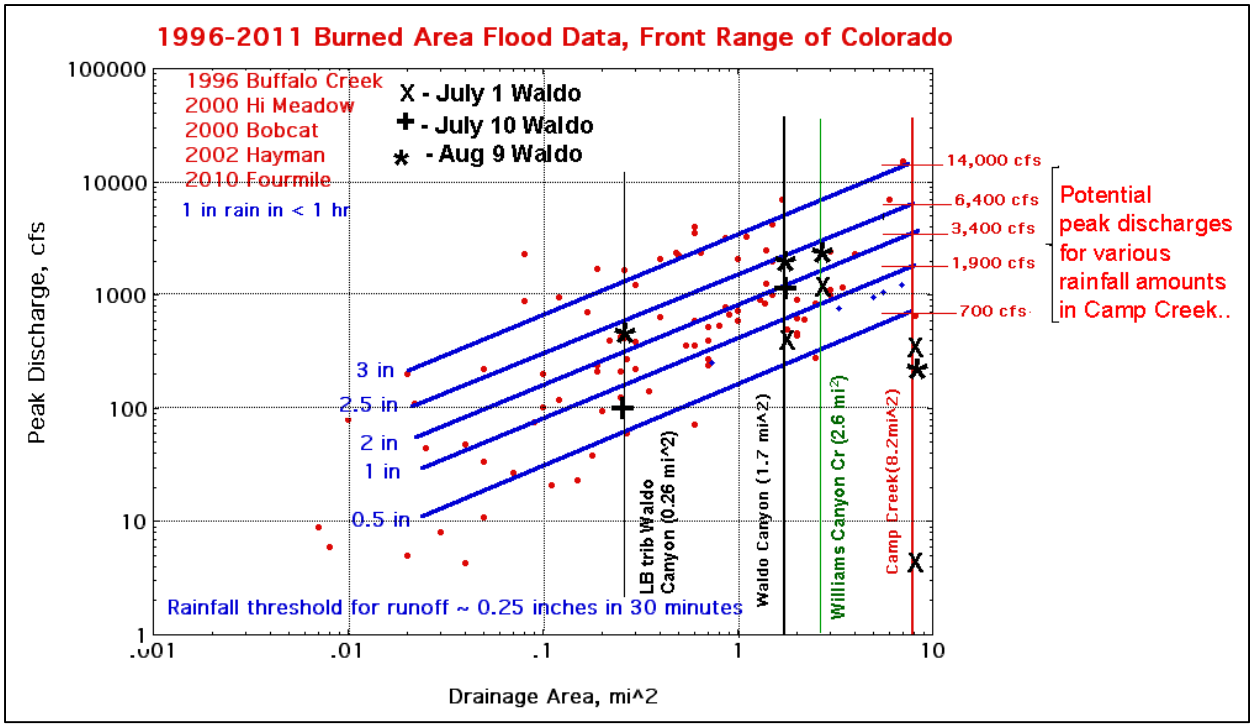


Figure 9 Peak flow data for various precipitation rates by drainage area for various burned watersheds on the Front Range of Colorado (Jarrett, 2013).

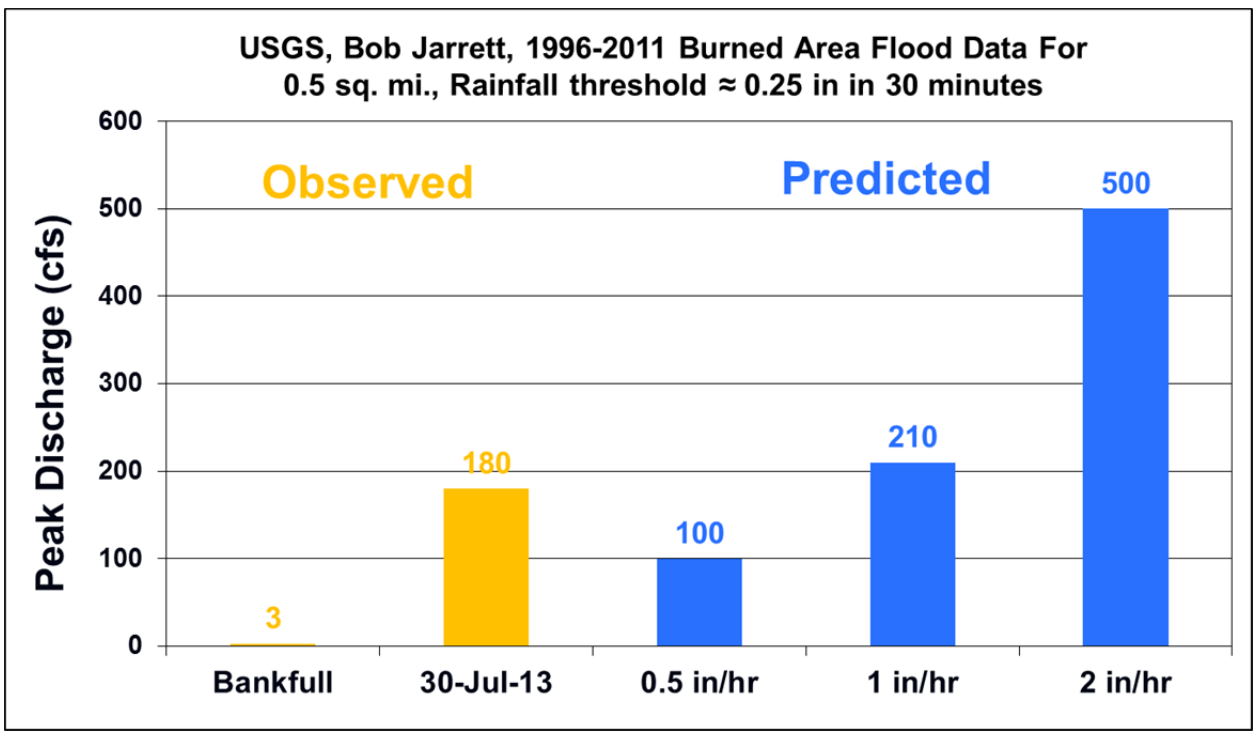


Figure 10 Predicted versus observed post-fire peak discharge for Northfield Gulch by storm intensity rates (Jarrett, 2013).

## POST-FIRE ASSESSMENT AND MASTER RESTORATION PLAN

In total, 89 sub-watersheds and 237 miles of stream channel were evaluated within the four major watersheds impacted by the Waldo Canyon Fire to quantify the sediment supply from hillslope, hydrology, and channel processes (Rosgen *et al*., 2013a). The sediment supply was evaluated for each sub-watershed and was totaled for the entire fire area. The total introduced sediment from the Waldo Canyon Fire is estimated to be *51,479 tons/yr*.

The surface erosion from hillslope processes accounted for approximately *18,085 tons/yr*, or 35% of the total introduced sediment. Contributions from roads and trails accounted for approximately *2,035 tons/yr*, or 4% of the total introduced sediment.

Channel processes were evaluated for each stream reach by sub-watershed using the stability methods in *WARSSS* (Rosgen, 2006). The FLOWSED/POWERSED model was used to evaluate sediment transport capacity, and streambank erosion rates were estimated using the BANCS model. Overall, the sediment yield from streambank erosion accounted for *31,480 tons/yr*, or 61% of the total sediment yield (Rosgen *et al*., 2013a). Moody and Martin (2001b) predicted that 80% of introduced sediment from wildfires was from channel sources and 20% was from hillslopes based on the assessment of other fires on the Colorado Front Range.

Changes in hydrology were evaluated using the WRENNS model (USEPA, 1980); post-fire changes in water yield and peak flows were estimated based on the severity of the burn, the percentage of the watershed burned, pre-existing stand composition, and precipitation by elevation/aspect zone. The results from WRENNS were used to determine the flow-related increases in sediment yield using the FLOWSED model.

The results of the *WARSSS* study were used to direct a multi-watershed mater restoration plan (Rosgen *et al*., 2013b). Priority areas for restoration were established for each sub-watershed based on the highest risk and highest sediment producers from the *WARSSS* analysis. Design scenarios were developed to represent the range of stream types and stability conditions that require restoration within the watersheds using representative and reference reaches. The appropriate scenario can then be extrapolated to other reaches of the same stream type, landscape type, and stability condition.

Post-fire rehabilitation often focuses on hillslope processes because of the fast recovery rates; remediation to reduce surface erosion often includes aerial seeding, mulching, planting trees, placing contour logs on burned slopes, and contour trenching. The majority of the work completed by the USDA Forest Service BAER (Burned Area Emergency Rehabilitation) teams focused on surface erosion processes. Although it is important to maintain surface soils and revegetate as soon as possible, the restoration designs must also account for channel source sediment, which contributed 61% of the total sediment yield. The recovery of channel processes is often slow due to the long-term, peak flow increases and associated debris flows, especially in incised and entrenched stream systems. The remainder of this paper focuses on one of the restoration scenarios that accounts for excess channel source sediment related to incised and entrenched stream systems within alluvial fan landscapes.

## RESTORING ALLUVIAL FAN CONNECTIVITY

Active alluvial fans and associated braided channels are the natural solution to sediment detention of the erosional material delivered from upper slopes to prevent direct sediment introduction into main trunk streams. The braided, D stream types are the natural, functioning channels on active alluvial fan surfaces that deposit sediment, decrease velocity, increase infiltration, and attenuate flood peaks (see Rosgen, 1994, 1996, for stream type descriptions).

A functioning alluvial fan as displayed in Figure 11 was enlarged following the major 1982 Lawn Lake Flood in Rocky Mountain National Park, Colorado. The Lawn Lake Flood was estimated to be the largest flood since the end of the last glacial retreat at the start of the Holocene period, 10,000 years ago (Jarrett and Costa, 1986). Extensive debris flows were deposited on the fan surface from the upstream lake breach and the associated high energy/high sediment supply from A3a+ stream types that cut into unconsolidated, glacial till with lateral moraine deposits of boulders, cobble, gravel, and sand. The natural grading of the fan deposited the coarser, boulder material at the apex and decreased the surface grain size to sand at the lower lobe. The fan prevented the bulk of the coarse, erosional debris from reaching Fall River, located immediately below the fan, as shown three days following the flood in

Figure 12. Regardless of the magnitude of the flood, the Fall River retained its naturally stable morphology due to its stable riparian corridor and floodplain connectivity.

Figure 11 Alluvial fan and braided, D stream type on the Roaring River in Rocky Mountain Park following the 1982 Lawn Lake flood.

Figure 12 Fall River in Rocky Mountain National Park, one-quarter mile below the alluvial fan of the Lawn Lake Flood. This photo was taken three days following the flood that was estimated at approximately 14,000 cfs.

Fan head trenches, or incised channels associated with A, F, and G stream types, often form due to the increased post-fire stormflow peaks (Figure 13). When stream channels abandon the fan surface and become incised in alluvial fans, they become high supply and high transport systems; thus the sediment yield is not only routed from farther upstream but is cut through portions of the fan deposit as well. The incised streams have increased velocity, stream power, and sediment transport capacity, thereby delivering excess sediment to the receiving streams. Under this scenario, the alluvial fan ceases to properly function.

Figure 13 A fan-head trench, an F4 stream type, incised in grussic granite soils within an alluvial fan on a tributary to Trail Creek following the Hayman Fire of 2002 in the South Platte River basin, Colorado.

An example of the fan head trench scenario occurred on North Douglas Creek within the Waldo Canyon Fire area. Deposition from debris flows on a fan surface is shown in Figure 14 following a storm; within one month following the deposit, an 8.0 ft headcut gully developed at the same location (Figure 15).

Figure 14 Erosional debris deposited on North Douglas (note the curved tree).

Figure 15 Channel incision (G4 to F4 stream type) at the same location as shown in Figure 14 (note the arrow directed to the same curved tree).

**Restoration Design:** To reduce the sediment delivered to mainstem stream systems from anticipated debris flows, the fan head trenches associated with incised A, G, and F stream types were reconnected to the alluvial fan surface with fill material to naturally create a braided, D4 stream type. Sediment debris basins were excavated to obtain the material to reconnect the incised channels with the original fan surface and to provide for sediment storage and help attenuate flood peaks. Once the basins are filled, the flood debris is designed to spread onto the fan surface with a braided channel system that will persist as long as there is a high sediment supply.

The restoration design is shown in Figure 16, featuring an interlocked crib wall to prevent headcutting during runoff events. Additional log or rock sills are located within the gully fill on the fan surface to prevent future channel incision and maintain fan function (Figure 16).

If the basins are cleaned out on a frequent basis and clear water discharge results, then a single-thread, B stream type can be constructed at the lowest basin on the fan lobe to direct streamflows to a receiving stream that overtop the basin. The B stream types are stable stream types found on inactive alluvial fans or when the incised channels become stabilized through stream succession processes in confined fluvial landscapes (Rosgen, 1996).

Where possible, restoring active fan function is the top priority for all ephemeral, 2nd and 3rd order streams affected by the Waldo Canyon Fire. The following is a summary of the specific objectives of this design scenario:

- Store sediment before it is delivered to downstream channels
- Reduce the accelerated streambank erosion rates
- Eliminate any advancing or future headcuts
- Develop sediment detention storage basins
- Attenuate flood peaks

**Case Example: North Douglas Creek:** Based on the *WARSSS* assessment, North Douglas was identified as a high priority sub-watershed due to the high probability of debris flows and flow-related sediment increases located immediately above thousands of homes in Colorado Springs. An incised, F4 gully over 6.0 ft deep was cut into a large alluvial fan in the sub-watershed. Although the drainage area is only 1.7 $mi^2$ with approximately 12.0 cfs bankfull discharge, the *WARSSS* assessment predicted approximately *10,000 tons/yr* of sediment from post-fire storms (Rosgen *et al*., 2013a).

Five sediment basins were constructed along the large alluvial fan to obtain sufficient material to fill the incised channel and to accommodate the predicted sediment yield (Figure 16 and Figure 17). The Water Resources Department at Colorado State University monitored the flows and sediment in North Douglas Creek to obtain detailed data on reactivating alluvial fans and creating sediment basins (Stednick and Webb, 2014). Streamflow measurements were obtained above the first basin, and each basin was monitored following storm events.

Following a July 1, 2013 storm, *2,751 tons* were stored in the first basin with a flow of 120 cfs (an order of magnitude higher than bankfull discharge). The constructed basin (Figure 18) is compared to the post-fire storm results depicting a completely filled basin (Figure 19). By the end of the storm season following eight, individual storms, all five basins were filled with an estimated *10,000 tons* of sediment (Stednick and Webb, 2014); additionally, one foot of sediment deposited on the fan surface, and a braided, D4 stream type was created naturally (Figure 19). In all but the last storm, no flows or sediment were delivered downstream of the last basin on the fan; the last storm on September 23, 2013, associated with over 773 cfs from a 7.0-inch rainstorm, filled the sediment basins and resulted in minor flows and sediment delivered downstream without incident or reported damage.

The relationship between the sediment captured in cubic yards versus peak flow discharge is shown in Figure 20 as developed by Stednick and Webb (2014). This relationship does not include the last storm that produced 773 cfs and the sediment that overfilled the basins and deposited on the fan surface.

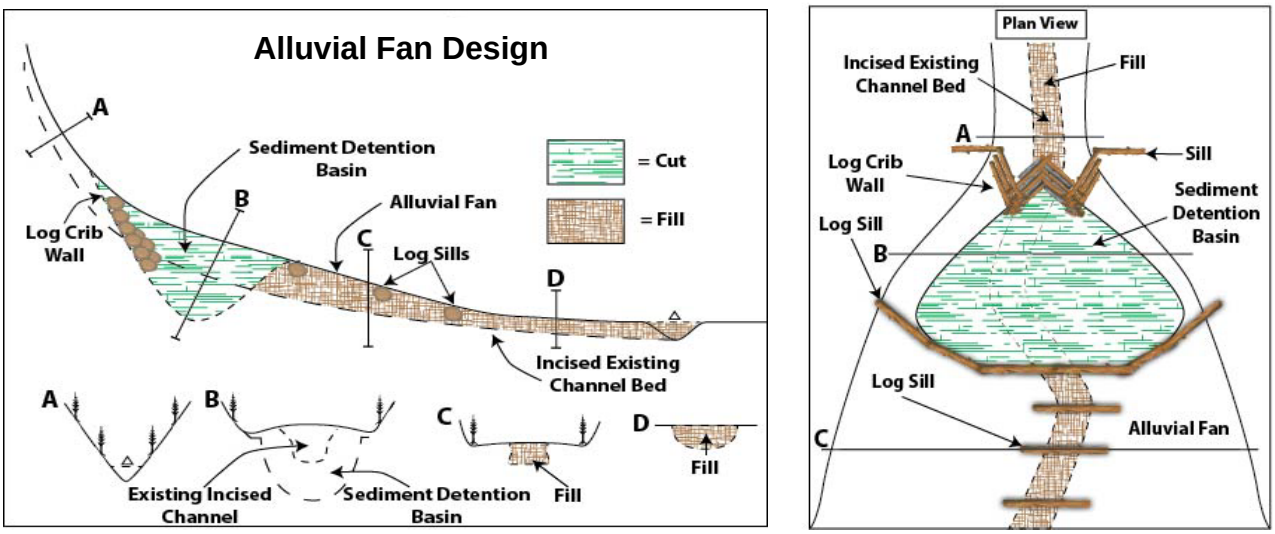


Figure 16 The design to reactivate alluvial fans and create braided, D stream types featuring a proposed debris basin with a crib wall and log sills (Rosgen, 2013b).

Figure 17 Post-construction of the five debris basins installed on North Douglas Creek on an alluvial fan.

Figure 18 Newly constructed debris basin and crib wall on North Douglas Creek where the excavated material was used to fill the deep and wide gullies (note the arrow indicating the location of the rock and exposed root wad).

Figure 19 The debris basin completely filled with sediment and ash deposits, looking downstream on fan surface, North Douglas Creek (note the same exposed root wad and rock as shown in Figure 18).

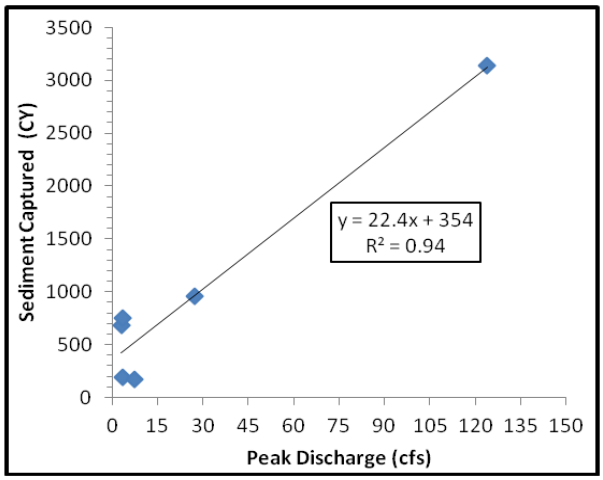


Figure 20 Relation of sediment storage by flow discharge; this does not include the 773 cfs streamflow that filled the basins and deposited one foot of sediment on the fan surface (from Stednick and Webb, 2014).

**Discussion:** The estimated design, oversight, and implementation costs of the debris basins vary between $4.00−$10.00 per ton of sediment saved. The costs per ton to dredge sediment from downstream reservoirs for water storage varies between $90.00−$120.00 per ton; thus it is much more cost effective to retain the sediment within the watershed. The reduced risk to downstream homeowners and the mitigation of potential adverse ecological impacts associated with sediment deposition in stream channels also provide strong motivation for implementing this approach.

Overall, restoring the alluvial fan connectivity with detention basins has saved thousands of tons of sediment from being directly delivered to the urban development immediately below the Waldo Canyon Fire perimeter. Over 40 sediment basins were constructed in 2013 on many of the high risk tributaries and all were successful at reducing delivered sediment. Due to the efficiency of the sediment detention basins, the City of Colorado Springs has since established a permanent basin at the end of the chain of basins on North Douglas Creek to reduce future flooding and sediment problems above adjacent subdivisions; the basin will be cleaned out when filled with sediment from future storms. Furthermore, the Forest Service BAER team recently approved the debris basin approach to be considered in their arsenal of recommended treatments nationwide.

Restoring alluvial fan connectivity with sediment detention basins was also successfully implemented in 2012 on numerous tributaries within the Trail Creek Watershed affected by the Hayman Fire of 2002 (Rosgen, 2011). The performance of these basins following post-fire storms promoted the application on the Waldo Canyon Fire and elsewhere. The approach was subsequently implemented within the Shultz Fire Burn Area in Flagstaff, Arizona (Natural Channel Design, Inc., 2012), saving thousands of tons of sediment from damaging downstream subdivisions.

## SUMMARY

The erosional and depositional processes must be understood following wildfires to appropriately prescribe treatments that address the impairment. Restoration priorities by process and locations are always challenging when faced with limited budgets and time constraints. The challenge presented to managers is to have the most effective measures available that properly address the erosional processes when faced with post-fire rehabilitation prescriptions, which must be cost-effective, low risk, and meet specific objectives. The recent application and positive performance of reactivating alluvial fans for extensive sediment reduction and flood attenuation due to post-fire impacts shows excellent promise to assist in future flood restoration/rehabilitation efforts.

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