ESTIMATION OF POTENTIAL DEBRIS-FLOW VOLUMES FOR CENTERVILLE CANYON, DAVIS COUNTY, UTAH

by Richard E. Giraud and Jessica J. Castleton

REPORT OF INVESTIGATION 267
UTAH GEOLOGICAL SURVEY
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Cover photo: *Looking down Centerville Canyon towards Centerville City.*

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ESTIMATION OF POTENTIAL DEBRIS-FLOW VOLUMES FOR CENTERVILLE CANYON, DAVIS COUNTY, UTAH

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ABSTRACT

Centerville Canyon in Davis County, Utah, has a high debris-flow hazard due to the volume of sediment stored in the canyon, the lack of historical debris flows to reduce the volume of stored sediment, and the lack of mitigation structures to reduce the hazard from a large-volume debris flow. We estimated fire-related and rainfall and snowmelt debris-flow volumes for Centerville Canyon to aid in sizing a debris basin to reduce the hazard. Our fire-related debris-flow volumes estimated using the empirical Western U.S. regression model are significantly less than historical debris-flow volumes produced from overgrazed and fire-damaged watersheds. The model volumes are likely smaller because the model does not account for the bulking of water and sediment from the long perennial channels in the canyons that produced historical debris flows. Rainfall and snowmelt debris-flow volumes were estimated using the unit-volume analysis method to estimate the volume of channel sediment bulked by debris flows. Topographic cross-channel profiles were used to estimate the volume of stored channel sediment. The stored-channel volume estimates and the maximum historical bulking rate were used to estimate likely rainfall and snowmelt debris-flow volumes. Uncertainties in our volume estimates are difficult to quantify. We use historical debris flow volumes from other canyons as a check of our volume estimates. The rainfall and snowmelt volume estimate of 196,000 cubic yards (149,900 m^3) for a debris flow initiating in the upper canyon compares favorably with the largest historical debris-flow volumes from other Davis County canyons with similar bulked channel lengths.

Formal debris-basin volume design guidance based on return periods similar to those used for earthquake and flood hazards is not available. Consideration of historical debris-flow volumes produced in other Davis County canyons is likely the best approach for sizing debris-basin volume. Because the 196,000 cubic yards (149,900 m^3) volume compares favorably with nearby historical debris-flow volumes, this volume is likely the most appropriate volume to consider when sizing a debris basin to accommodate a large-volume debris flow from Centerville Canyon. This study and previous studies show that Centerville Canyon has a high debris-flow hazard, and a large-volume debris flow will cause significant damage to development on the alluvial fan below the canyon. An appropriately sized debris basin will significantly reduce the debris-flow hazard and provide protection for the developed residential area on the alluvial fan in Centerville.

INTRODUCTION

Centerville Canyon presents a serious debris-flow hazard because the canyon has not discharged a historical debris flow, contains abundant sediment that will likely be bulked into future debris flows, and therefore has a high potential for producing a large-volume debris flow. The hazard severity was recognized by Williams and Lowe (1990) in their study of debris-flow-producing canyons in Davis County. Debris flows are a hazard on the alluvial fan below the canyon (figure 1) where they deposit sediment. Development on the alluvial fan in Centerville City will likely be damaged by future debris flows. Debris flows on alluvial fans elsewhere in Davis County have caused damage to several communities since the area was first settled in 1847 (Keate, 1991).

Debris flows are fast-moving flow-type landslides composed of a slurry of rock, mud, organic matter, and water that move down drainage-basin channels onto alluvial fans. Debris flows generally initiate on steep slopes or in channels by the addition of water from intense rainfall or rapid snowmelt. As flows travel downchannel, the channel bed is typically destabilized and eroded, and sediment and vegetation are entrained into the flowing mass increasing the flow volume. When flows reach the alluvial fan and lose channel confinement, they spread laterally and deposit the entrained sediment. Debris flows typically exhibit a surging behavior as they flow down channels and onto alluvial fans.

Debris flows pose a hazard very different from other types of landslides and floods due to their rapid movement and destructive power. Debris flows can occur with little warning. Fifteen people have been killed by debris flows in Utah. Thirteen of those people died in two different events at night as fast-moving debris flows allowed little chance of escape. Six of the 13 victims were campers in Farmington Canyon who died in an August 13, 1923, debris flow (Keate, 1991). In ad-

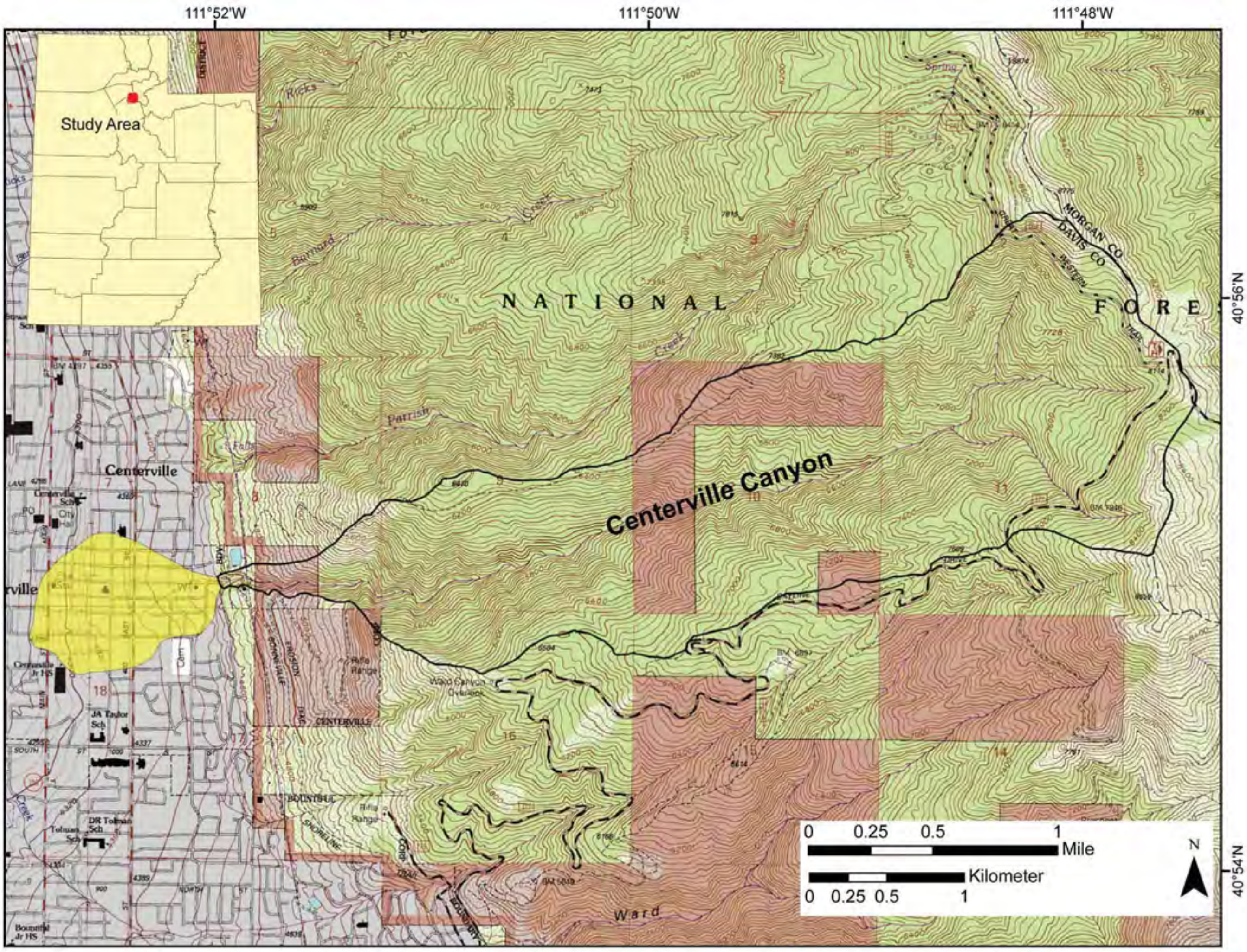


Figure 1. *Map showing Centerville Canyon, drainage basin boundary (solid black line), and alluvial fan (yellow); modified from Lowe (1988a) and Nelson and Personius (1993). Base map from U.S. Geological Survey (USGS) 7.5-minute Farmington and Bountiful Peak quadrangles.*

dition to threatening lives, debris flows can damage buildings and infrastructure by sediment burial, erosion, direct impact, and associated water flooding.

At the request of Davis County and Centerville City, the Utah Geological Survey estimated likely debris-flow volumes that could be produced from Centerville Canyon to aid in sizing a debris basin for hazard reduction. Debris-flow investigations typically involve investigation of both the drainage basin and alluvial fan to estimate and compare potential debris-flow volumes (Giraud, 2005; Jakob, 2005). Because the Centerville Canyon alluvial fan is developed, an alluvial-fan evaluation to determine past debris-flow volumes is not practical. Therefore, we investigated the drainage basin and channels in the drainage basin to estimate likely debris-flow volumes that will reach the alluvial fan, and compared our estimated volumes with historical debris-flow volumes from nearby canyons. Our volume estimates include debris flows triggered by rainfall following wildfires and debris flows triggered solely by intense rainfall or rapid snowmelt.

Parrish Creek, Barnard Creek, Ford Canyon (Ricks Creek), and Lone Pine Canyon east of Centerville also produce debris flows. However, these creeks and canyons have engineered debris basins in place to reduce the debris-flow hazard. Centerville Canyon has a small 4450 cubic yard (3400 m^3) basin (Keaton and Lowe, 1998) designed for removing fine sediment to reduce sediment deposition farther downstream (Fred Campbell, Centerville City, verbal communication, 2009); however, the basin is too small to reduce the debris-flow hazard.

Davis County Debris-Flow History

From a historical perspective, potential stream-flooding, alluvial-fan-flooding, and debris-flow hazards are the most frequent and destructive geologic hazards affecting Centerville and other Davis County communities. Davis County has sustained more loss of life and property damage from flash floods and debris flows than any other county along the Wasatch Front. The majority of these floods and debris flows were produced by intense thunderstorm rainfall (Woolley, 1946; Croft, 1967; Butler and Marsell, 1972; Pack, 1985). Debris flows were also triggered by rapid snowmelt in the Shepard, Farmington, Rudd, and Steed drainages in 1983 and 1984 (Keaton and Lowe, 1998). The 1983 Rudd Canyon debris flow in Farmington deposited approximately 84,000 cubic yards (64,000 m^3) of sediment on the alluvial fan, damaged 35 houses, and caused an estimated $3 million in property damage (Deng and others, 1992). Flood water from Centerville Canyon in 1983 produced a small sediment volume of 2600 cubic yards (1990 m^3) (Williams and others, 1989).

Historical accounts of debris flows in Davis County date back to 1878 when debris flows were triggered by thunderstorm rainfall in Farmington and Davis Canyons (Keate, 1991). Keaton and Lowe (1998) provided a historical summary of debris flows in Davis County. They show 78 alluvial-fan flooding and debris-flow events and include sediment volume estimates for 56 events. Forty of these events were triggered by thunderstorm rainfall and 16 by rapid snowmelt. Many of these events are the result of natural geological and meteorological processes, but most events in the 1920s and in1930 are attributed to denuded canyon slopes, due to overgrazing and wildfire (Cannon, 1931).

To reduce the hazard and minimize future damage from debris flows and alluvial-fan flooding events, debris basins have been constructed for many Davis County canyons. Debris basins were typically constructed for canyons that had discharged debris flows rather than canyons that had not generated a historical debris flow (Keaton and Lowe, 1998). However, Williams and Lowe (1990) suggest that the canyons most capable of producing future large debris flows are those canyons that have not discharged historical debris flows, such as Centerville Canyon.

Previous Work

Many researchers have studied Davis County debris flows, but the primary researchers using geologic methods to study historical and potential debris-flow volumes were Williams and others (1989) and Williams and Lowe (1990). Their research objective was to estimate potential debris-flow volumes in Davis County for the Davis County Planning and Flood Control Departments. For historical debris flows, they compared eroded channel lengths with debris-flow volumes deposited on alluvial fans to derive a channel sediment-bulking rate. For historical debris flows triggered by intense rainfall and rapid snowmelt in canyons with perennial streams, they estimated an average bulking rate of 12 cubic yards per linear foot (yd^3/ft; 36 cubic yards per yard [yd^3/yd]; 30 cubic meters per meter [m^3/m]). They used this bulking rate to estimate debris-flow volumes for canyons with perennial streams in Davis County that had not discharged a historical debris flow.

Bulking rates for ephemeral streams are generally lower than those for perennial streams. For the thunderstorm-rainfall-triggered 1991 Cameron Cove debris flow in northern Weber County, Mulvey and Lowe (1992) estimated a bulking rate of 15 yd^3/yd (12.6 m^3/m). Fire-related debris flows in northern Utah typically have measured bulking rates of 6 yd^3/yd (4.6 m^3/m) or less (Giraud and McDonald, 2007). Bulking rates along dry channels are generally lower because water in the passing debris flow is needed to saturate, erode, and entrain sediment from the dry channel bed. Bulking rates along perennial streams are generally higher because they have saturated channel beds, and channel sediment and channel water are more easily entrained into the passing debris flow, resulting in a higher bulking rate.

Evanstad and Rasely (1995) estimated fire-related hillslope sediment yield for Wasatch Front drainages in Davis County. However, their sediment volume estimates are for annual post-burn hillslope sediment yields only and do not include the channel sediment bulking that must be considered when estimating total debris-flow volumes.

The U.S. Army Corps of Engineers (USACE, 1998) Centerville Canyon flood hazard study included a debris-flow hazard evaluation. They simulated deposition of debris-flow sediment on the Centerville Canyon alluvial fan by routing debris-flow volumes of 153,000 cubic yards (117,000 m^3) and 193,000 cubic yards (147,600 m^3) using the computer program FLO-2D. The computer simulations show a large area of the alluvial fan buried by debris-flow sediment, which would result in substantial damage to existing and future development on the alluvial fan.

Methods

Sediment supply, erosion conditions, drainage basin morphology, and hydrologic conditions in the canyon control the debris-flow volumes that reach the alluvial fan. In addition to the volume of runoff water, debris-flow volume is a function of initiating landslide volume (where applicable), the sediment volume bulked along the channel, and the volumes deposited along the channel. Our fire-related debris-flow volumes consider rainfall, runoff water, and basin characteristics. Our rainfall and snowmelt debris-flow volumes use an initiating landslide volume and sediment volume entrained by a debris flow traveling down the channel. We do not reduce our volumes for sediment deposited along the channel because observed debris-flow levees are relatively small.

To estimate fire-related debris-flow volumes we used the Western U.S. regression model by Gartner and others (2008). The model uses drainage basin area, slope steepness, burn characteristics, and total rainfall to estimate a potential debris-flow volume. The model is calibrated with historical fire-related debris-flow volumes from the Rocky Mountains, including September 12, 2002, flows in Santaquin and April 6, 2004, flows in Farmington (Giraud and McDonald, 2007).

To estimate rainfall and snowmelt debris-flow volumes, we use the unit-volume analysis method that involves measuring and estimating the stored erodible sediment in the channel, generally expressed in cubic yards per linear yard of channel (Hungr and others, 1984, 2005; VanDine, 1985; Williams and Lowe, 1990). Estimating the channel sediment volume available for debris-flow entrainment or bulking is critical because study of historical debris flows in Davis County indicates 80 to 90% of the debris-flow volume comes from the channel (Croft, 1967; Santi, 1988; Keaton and Lowe, 1998). Williams and others (1989) and Williams and Lowe (1990) measured three cross-channel profiles in Centerville Canyon from which they estimated a potential debris-flow volume of 216,000 cubic yards (165,100 m^3) for the first event from the canyon using a channel length of 18,000 feet (5486 m). We provide an independent check of their work and further refine their bulking rates.

To estimate the sediment volume bulked along the channel, we measured topographic cross-channel profiles and inspected sediment-supply conditions on the main and tributary channels. We also measured the length of channel floored by bedrock, where stored sediment is absent. Using our measured profiles and sediment supply observations, we estimated the volume of erodible sediment stored along individual, relatively homogeneous channel reaches and summed the individual reaches to obtain a total volume. We checked our estimated debris-flow volumes by comparing them with historical debris-flow volumes from nearby canyons. We include a 10,000 cubic yards (7600 m^3) landslide volume to account for a possible landslide-initiated debris flow. We believe this is a conservative volume, because mapped landslides in the canyon (Lowe, 1988a) that have initiated debris flows are smaller in volume. For Centerville Canyon, where long channel distances exist above the alluvial fan, the initial landslide volume is small compared to the bulked channel volume. We round our volume estimates to the nearest 1000 cubic yards.

The most subjective factor in the unit-volume analysis method is estimating the depth of erodible sediment stored in the channel. Along some channel reaches, bedrock outcrops line the stream banks and stored sediment is only a few feet thick. However, in the absence of bedrock exposures along channel banks and the longitudinal channel axis, geologic judgment is necessary to estimate erodible sediment depth. Our depth estimates are similar to eroded depths shown in historical debris-flow photographs (Bailey and others, 1947; Copeland, 1960; Croft, 1962, 1967) and measured depths of Williams and Lowe (1990) in other Davis County canyons. We used a maximum eroded depth of 10 feet (3 m) to estimate our stored sediment volumes.

We used a Geographic Information System (GIS) to store, organize, and analyze data used to estimate debris-flow volumes. We used U.S. Geological Survey (USGS) 1997 orthophotography at various scales (Utah Automated Geographic Reference Center [AGRC], 2009a), and 2004 and 2006 National Agriculture Imagery Program (NAIP) orthophotography at various scales (Utah AGRC, 2009b), as well as 1985, 1:24,000-scale and 2001, 1:17,000-scale stereo aerial photographs. We used a 2-meter (6-feet) Digital Elevation Model (DEM) derived from 2006 Light Detection and Ranging (LiDAR) data (Utah AGRC, 2009c) to generate two shaded relief (hillshade) maps, slope maps, and a detailed topographic map with 10-foot contour intervals. The hillshade maps and aerial photography were used to estimate potential debris-flow-initiating landslide volumes for landslides shown on the landslide-inventory map (Lowe, 1988a). The topographic map and field measurements were used for subdividing individual channel reaches.

PHYSOGRAPHIC AND GEOLOGIC SETTING

Centerville Canyon (figure 1) is in north-central Utah at the southern end of Davis County. The creek in Centerville Canyon is locally called Deuel Creek, named after William Deuel, one of the original Centerville City settlers. After settlement in 1848, water from Centerville Canyon was diverted for irrigation and other uses. In 1854, a grist mill was built on Deuel Creek (Utah State History, 2009). Centerville Canyon is the only canyon east of Centerville that was not overgrazed (Bailey and others, 1947), and this may partially explain why the canyon has not discharged a historical debris flow. Most overgrazed canyons in Davis County have discharged historical debris flows.

Centerville Canyon has a basin area of 3.1 square miles (8.0 km^2). The mouth of Centerville Canyon is located near 100 South Island View Drive at an elevation of 4560 feet (1390 m). The Wasatch Range east of Centerville rises to elevations of over 8775 feet (2674 m) (figure 2A). The main channel has a length of 17,906 feet (5458 m) to the confluence with upper tributary channels. Channel gradient ranges from about 7% (4º) near the mouth to nearly 52% (28º) in the upper canyon; the average gradient is 19% (11º). Channel bedrock reaches have gradients up to 66% (33º). The upper canyon (figure 2A, 2B) and higher elevation north-facing slopes are covered with mixed conifer and aspen forest. The south-facing slopes and lower canyon elevations (figure 2C, 2D) are covered with gamble oak and other mountain shrubs that transition into grass and sagebrush-covered slopes in the lowest canyon elevations. Most of Centerville Canyon is within the Uinta-Wasatch-Cache National Forest. Forest Service roads Ward Canyon (117) and Skyline Drive (008) pass through the upper canyon.

Centerville Canyon is at the eastern edge of the Basin and Range Province, where the Wasatch Range has been uplifted by movement on the Wasatch fault. The Weber segment of the Wasatch fault lies at the base of the range. The Great Salt Lake Basin lies west of the Wasatch Range and is filled with lacustrine and alluvial sediments. Bedrock in the canyon is part of the Precambrian Farmington Canyon Complex (Bryant, 1988) and is predominantly quartzite, schist, and gneiss.

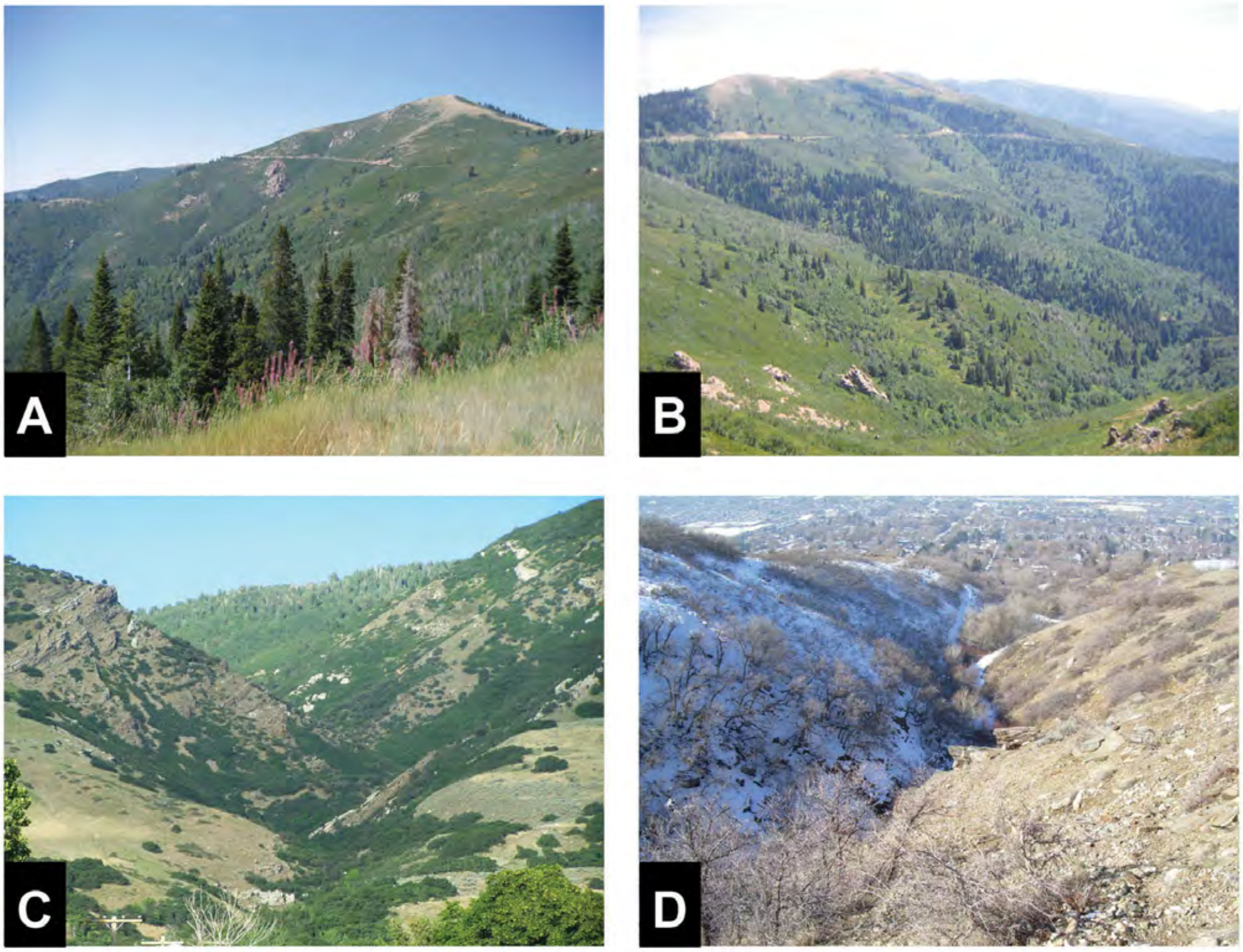


Figure 2. *Photos showing physiographic character of Centerville Canyon.* ***A****. View to the north of the upper canyon covered by conifers and aspen forests. The elevation of the unnamed peak is 8775 feet. Skyline Drive is evident below the peak.* ***B.*** *View to the south of the upper canyon. Ward Canyon Road cuts across steep upper canyon slopes.* ***C.*** *View to the east up canyon from Centerville City. Discontinuous bedrock outcrops are present along the lower canyon channel.* ***D****. View to the southwest showing discontinuous bedrock exposures along the lowermost canyon above Centerville City.*

The bedrock is highly fractured and weathers into colluvium that mantles the drainage basin slopes. Steep slopes covered with colluvium are prone to landsliding, and numerous debris slides occurred during rapid snowmelt in 1983 (Wieczorek and others, 1983; Pack, 1985) in Centerville and other Davis County canyons. Colluvium is transported down steep tributary channels and deposited as alluvium in the main channel. Large volumes of sediment are stored along the main channel. From a debris-flow-potential perspective, Centerville Canyon is classified as a supply-unlimited canyon (Bovis and Jakob, 1999) where the sediment supply is not a limiting condition for a debris flow.

A large alluvial fan is mapped by Lowe (1988a) and Nelson and Personius (1993) below the mouth of Centerville Canyon (figure 1). The alluvial fan formed as Lake Bonneville receded from the Provo shoreline after 14,400 years ago (Godsey and others, 2005) to the present level of Great Salt Lake. A post-Lake Bonneville alluvial fan of this size is indicative of active debris-flow deposition on the fan. The fan is considered active from a debris-flow-hazard perspective, and developed residential subdivisions on the fan are within an area where debris flows runout onto the fan and deposit sediment (Lowe, 1988b).

FIRE-RELATED DEBRIS-FLOW VOLUMES

The debris-flow hazard potential increases following a wildfire because fires typically remove the rainfall-intercepting vegetation, organic litter, and duff that effectively reduce runoff and overland flow. Post-fire debris flows are most frequently initiated by high-intensity rainfall during short-duration storms. Typically, fire-related debris flows in Utah are generated by erosion and progressive sediment bulking of runoff water rather than landsliding. Fire-related debris flows are fairly common in northern Utah, and seven wildfire areas produced 26 debris flows between 2000 and 2004 (Giraud and McDonald, 2007). These debris flows were triggered by short-duration, intense thunderstorm rainfall. Some of the triggering rainfall has recurrence intervals of two years or less. Williams and Lowe (1990) state that the most significant debris-flow threat exists from thunderstorm rainfall over a burned canyon, and that the most dangerous canyons are those that have not discharged a historical debris flow and have no engineered debris-flow protection (conditions that apply to Centerville Canyon). Centerville Canyon will likely experience wildfires at some future time; therefore, we estimate fire-related debris-flow volumes.

Regression Model

We used Gartner and others' (2008) empirical Western U.S. regression model to estimate fire-related debris-flow volumes. The model estimates debris-flow volume as:

$$\ln V = 0.59(\ln S) + 0.65(B)^{1/2} + 0.18(R)^{1/2} + 7.21$$

where:

V = volume (cubic meters),

S = basin area with slopes greater than or equal to 30% (square kilometers),

B = basin area burned at moderate and high severity (square kilometers), and

R = total storm rainfall (millimeters).

We convert from metric to English units for our primary use of English units. Burned slopes steeper than 30% (17º) are highly susceptible to erosion (Gartner and others, 2008), and the area with slopes steeper than 30% (17º) in Centerville Canyon is 2.7 square miles (7 km^2), or 85% of the total basin area. To consider wildfires that partially burn the canyon, we estimated volumes for four different burn areas shown on figure 3. Burn severity is rated as high, moderate, or low (Miller, 2001) depending on burn characteristics and soil heating. Cannon and Gartner (2005) concluded that moderate and high burn severities strongly influence debris-flow occurrence. To provide conservative volume estimates, we considered all slopes steeper than 30% (17º) to be burned at moderate and high severity.

We used two different rainfall totals in our volume estimates (table 1). We used a 60-minute rainfall total with an average five-year return interval from the National Oceanic and Atmospheric Administration (NOAA) precipitation frequency atlas (NOAA, 2009). The five-year return interval accounts for rainfall on a burn area before significant post-fire vegetation growth that inhibits initiation of fire-related debris flows. The total rainfall values did not change significantly (0.92 to 0.94 inch; 23 to 24 mm) for the upper elevations of our four burn areas, so we used the larger (conservative) 0.94 inch (24 mm) value. We also consider measured thunderstorm rainfall totals of 1.14 inch (29 mm) on July 10, 1936, and 0.7 inch (18 mm) on July 10, 1950, in Parrish Creek north of Centerville Canyon (Marston, 1958). We use both the estimated precipitation frequency atlas value (0.94 inch [24 mm]) and measured value (1.14 inch [29 mm]) in our volume estimates.

Our estimated fire-related debris-flow volumes for the different burn areas are shown in table 1. The larger rainfall total yields larger (more conservative) volume estimates for all of the burn areas. The total basin burn area produces an estimated debris-flow volume of 91,000 cubic yards (69,600 m^3).

Fire-Related Volume Limitations

Empirical models can only predict within certain margins of error, and a degree of uncertainty is inherent in our estimates. The Western U.S. regression model has a correlation coefficient of 0.83 and a residual standard error of 0.79. When the model was applied to fire-related debris flows that occurred in northern Utah from 2000 to 2004 (Giraud and McDonald, 2007), the model underestimated the deposit volumes measured on alluvial fans. However, our model volumes for Centerville Canyon are within two residual standard errors.

RAINFALL AND SNOWMELT DEBRIS-FLOW VOLUMES

Intense rainfall and rapid snowmelt have triggered the majority of historical debris flows in Davis County. Unlike fire-related debris flows, analytical techniques do not exist to estimate flow volumes and are unlikely to be available in the foreseeable future (Hungr and others, 2005), due to the large variations in debris-flow volume and the complexity of debris-flow processes. For volume estimates in drainage basins, most debris-flow scientists agree the best approach is to collect field data on the potential sediment bulking along channels, and then evaluate estimated volumes with those produced historically or measured on the alluvial fan.

We measured 18 cross-channel profiles across the main channel and an upper-basin tributary channel (appendix) to estimate the volume of sediment stored along specific channel reaches. We used the profiles and field observations to estimate volumes of debris flows initiating in the upper, middle, and lower parts of Centerville Canyon. The main and tributary channels used to estimate these volumes are shown by different colors on figure 4. On each profile, we show the stream topographic cross section and a trapezoidal area underneath extending to our estimated erodible depth (appendix). We also show the elevation, debris-flow levees, estimated volume of stored sediment, and channel photographs on the profiles.

We limit our upper bound sediment-bulking rate based on observed historical bulking rates. Based on their research of historical debris flows, Williams and Lowe (1990) suggested a maximum 36 yd^3/yd (30 m^3/m) bulking rate. For some channel reaches, our stored sediment volumes exceed 36 yd^3/yd (30 m^3/m). For these reaches, including the entire stored sediment volume is likely inappropriate because the stored volume exceeds the observed historical sediment-bulking rate. There-

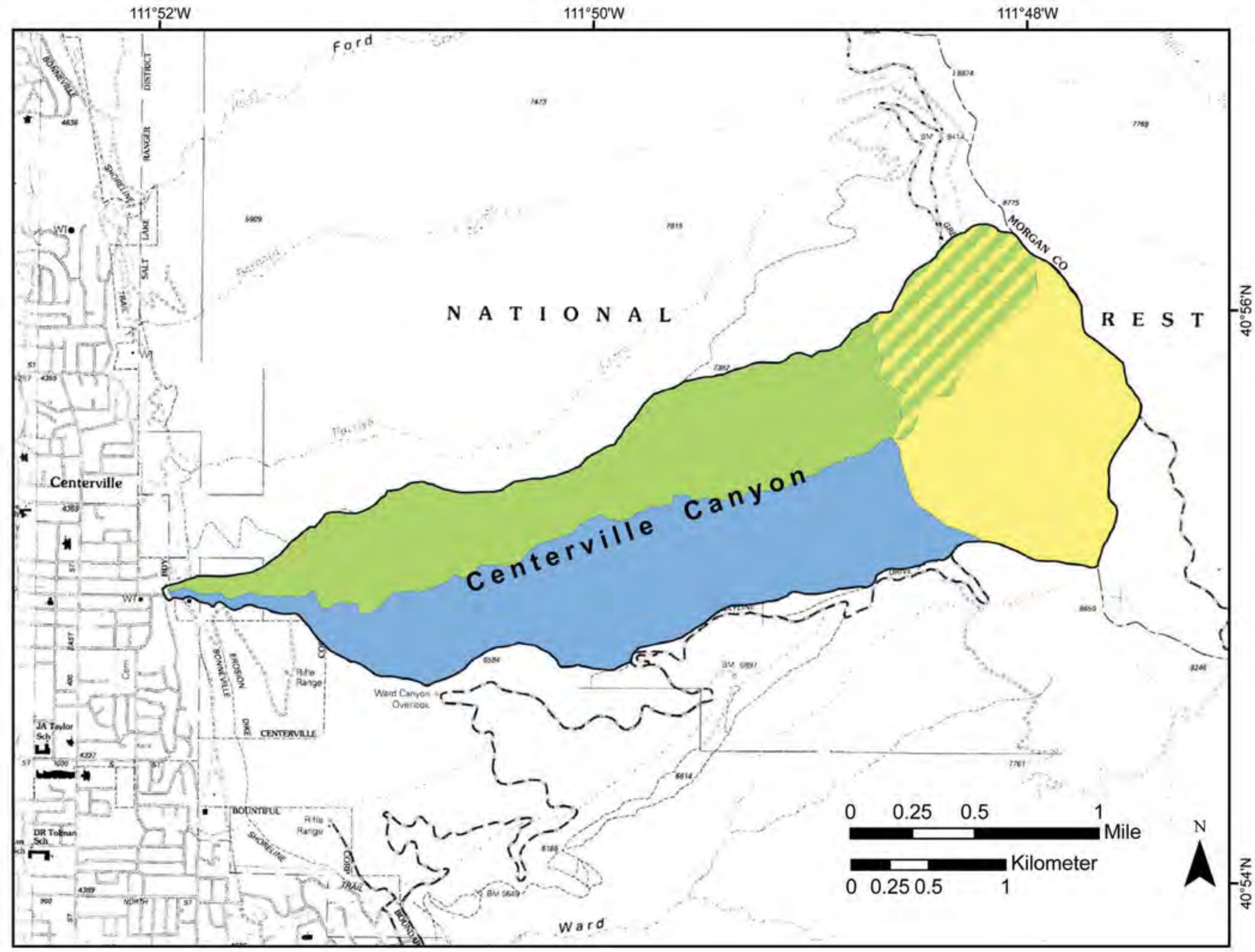


Figure 3. *Burn areas used to estimate fire-related debris flow volumes in Centerville Canyon. The four burn areas include the entire drainage basin, south area (blue), north area (green) and upper (yellow). The yellow and green hachure area is an overlap of north and upper burn areas. Base map from USGS 7.5-minute Farmington and Bountiful Peak quadrangles.*

Table 1*. Estimated fire-related debris-flow volumes using 0.94 inch and 1.14 inch total rainfall. Centerville Canyon burn areas are shown on figure 3.*

Centerville Canyon Burn Area	Total Area (mi^2)	Area Steeper Than 30% Slope (mi^2)	FiveYear 60-min Rainfall Total 0.94 in	1936 Storm Rainfall Total 1.14 in
			Volume (yd^3)	Volume (yd^3)
Total Basin	3.1	2.7	84,000	91,000
Upper Basin	1.0	0.85	19,000	21,000
North Basin	1.3	1.2	27,000	29,000
South Basin	1.1	0.93	22,000	24,000

fore, for channel reaches having stored sediment volumes exceeding 36 yd^3/yd (30 m^3/m), we limited the sediment-bulking rate to 36 yd^3/yd (30 m^3/m). Our erodible depth estimates of stored sediment appear to be conservative because some bulking rates exceed the maximum rate.

We defined relatively homogenous channel reaches based on channel gradient, bedrock along and near stream banks, bedrock near stream banks, channel bed sediment thickness, and channel width. Each individual channel reach is assigned a sediment-bulking rate (table 2; figure 5). Channel sediment consists of weathered schist, gneiss, and quartzite that ranges

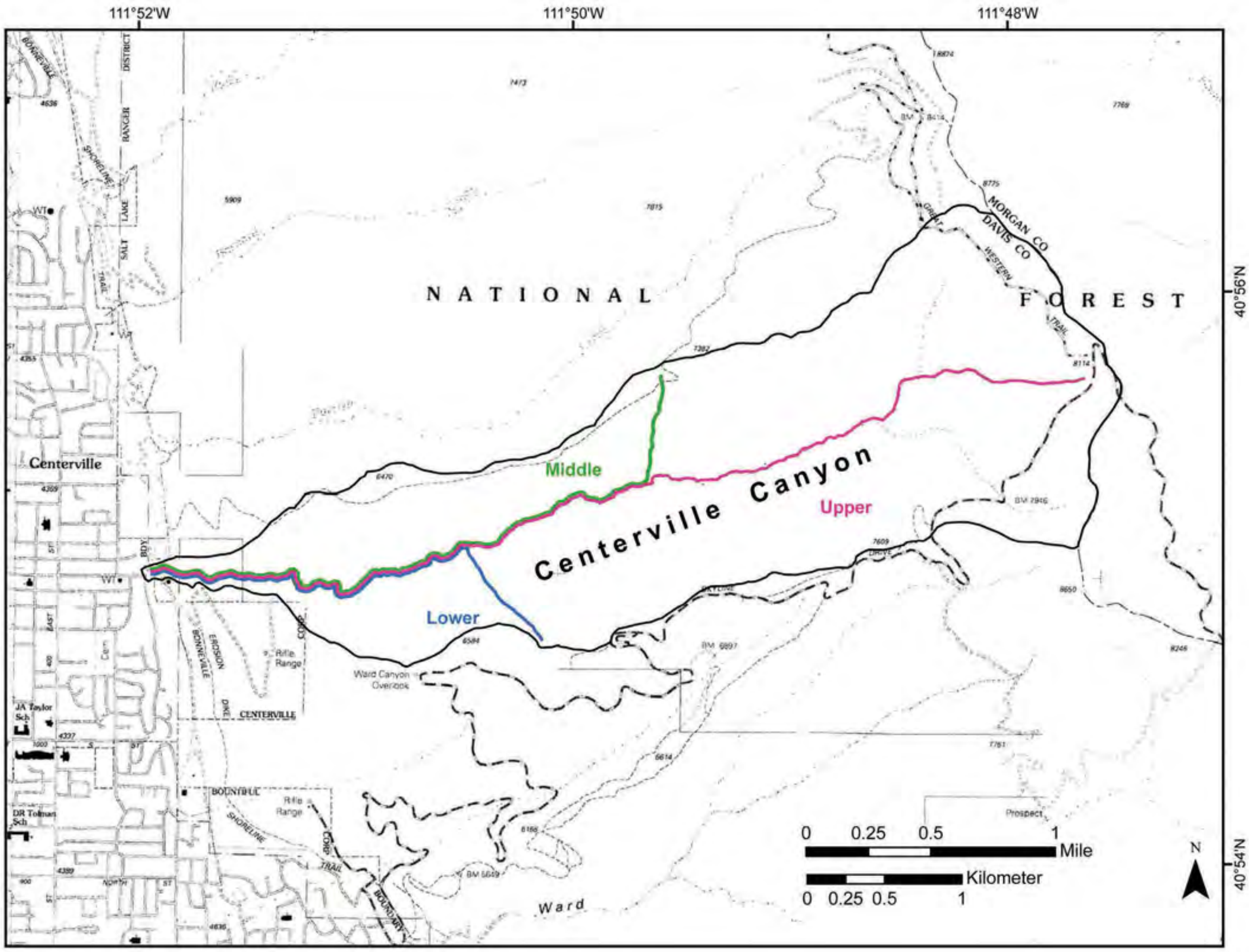


Figure 4. Main and tributary channels for estimating rainfall and snowmelt debris-flow volumes initiating in upper, middle, and lower Centerville Canyon. Base map from USGS 7.5-minute Farmington and Bountiful Peak quadrangles.

in size from sand to cobbles and boulders. The gravel, cobbles, and boulders are angular to subround. The long axis of some boulders ranges up to several feet long, but most are 1 to 4 feet (0.3–1.2 m) long.

Upper Canyon

For the upper canyon debris flow, we divided the main channel and tributary channel into 17 reaches shown on the longitudinal channel profile (figure 5A). We estimate a volume of 196,000 cubic yards (149,900 m^3) for a channel length of 7635 yards (6981 m). The sediment-bulking rates for each reach and the total volume are shown in table 2. Reaches 4, 7, 11, and 13 have estimated stored sediment volumes that range from 38.1 to 53.7 yd^3/yd (31.9 to 44.9 m^3/m), but we limit the bulking rate to the historical maximum of 36 yd^3/yd (30 m^3/m). Bedrock exists along reaches 3 and 9 (table 2; figure 5B). Reach 9 includes a small waterfall. Only 2% of the total main and upper tributary channel length has an exposed bedrock floor, which further indicates the large volume of sediment stored in Centerville Canyon. By comparison, Parrish Creek north of Centerville Canyon has discharged three large volume debris flows (table 3) and has bedrock exposed along an estimated 40 to 50% of the channel (Williams and Lowe, 1990).

The majority of sediment is stored between channel reach 3 and 15 (figure 5B). The cross-channel profiles for these reaches show the creek in a relatively wide, flat-bottom valley with abundant stored sediment. Reaches 1 and 2 have a small bulking rate because the narrow channel has discontinuous bedrock exposed along the stream banks (figure 2C, 2D) and a 3 to 4 foot (1 to 1.2 m) sediment thickness. Similarly, above reach 14 the bulking rates are small due to narrow channels and shallow bedrock.

Middle Canyon

To estimate the volume for a middle canyon debris flow, we used 12 reaches along the main channel and tributary channel

Table 2. *Estimated rainfall and snowmelt volumes for debris flows initiating in upper, middle, and lower Centerville Canyon. The channels for the upper, middle, and lower debris-flow estimates are shown on figure 4.*

Upper Canyon Sediment Bulking				**Middle Canyon Sediment Bulking**				**Lower Canyon Sediment Bulking**			
Channel Reach	Reach Length (yd)	Bulking Rate (yd^3/yd)	Bulked Volume (yd^3)	Channel Reach	Reach Length (yd)	Bulking Rate (yd^3/yd)	Bulked Volume (yd^3)	Channel Reach	Reach Length (yd)	Bulking Rate (yd^3/yd)	Bulked Volume (yd^3)
Main				Main				Main			
1	885	8.7	7700	1	885	8.7	7700	7	885	8.7	7700
2	245	12.9	3161	2	245	12.9	3161	2	245	12.9	3161
3	116	0	0	3	116	0	0	3	116	0	0
4	819	36.0	29,496	4	819	36.0	29,496	4	819	36.0	29,496
5	749	34.5	25,852	5	749	34.5	25,852	5	578	34.5	19,930
6	649	33.3	21,623	6	649	33.3	21,623	Tributary			
7	203	36.0	7308	7	649	36.0	7308	6	658	6.0	3946
8	243	20.7	5023	8	243	20.7	5023	7	280	3.0	841
9	17	0	0	9	17	0	0				
10	187	14.7	2754	10	187	14.7	2754				
11	464	36.0	16,716	Tributary							
12	476	30.0	14,290	11	318	6.0	1908				
13	895	36.0	32,208	12	513	3.0	1539				
Tributary											
14	422	28.5	12,037								
15	446	6.0	2678								
16	452	4.8	2171								
17	215	2.7	581								
Sediment Bulking Volume (yd^3)			185,758				106,363				65,073
Landslide Volume (yd^3)			10,000				10,000				10,000
Total Volume (yd^3)			196,000				116,000				75,000

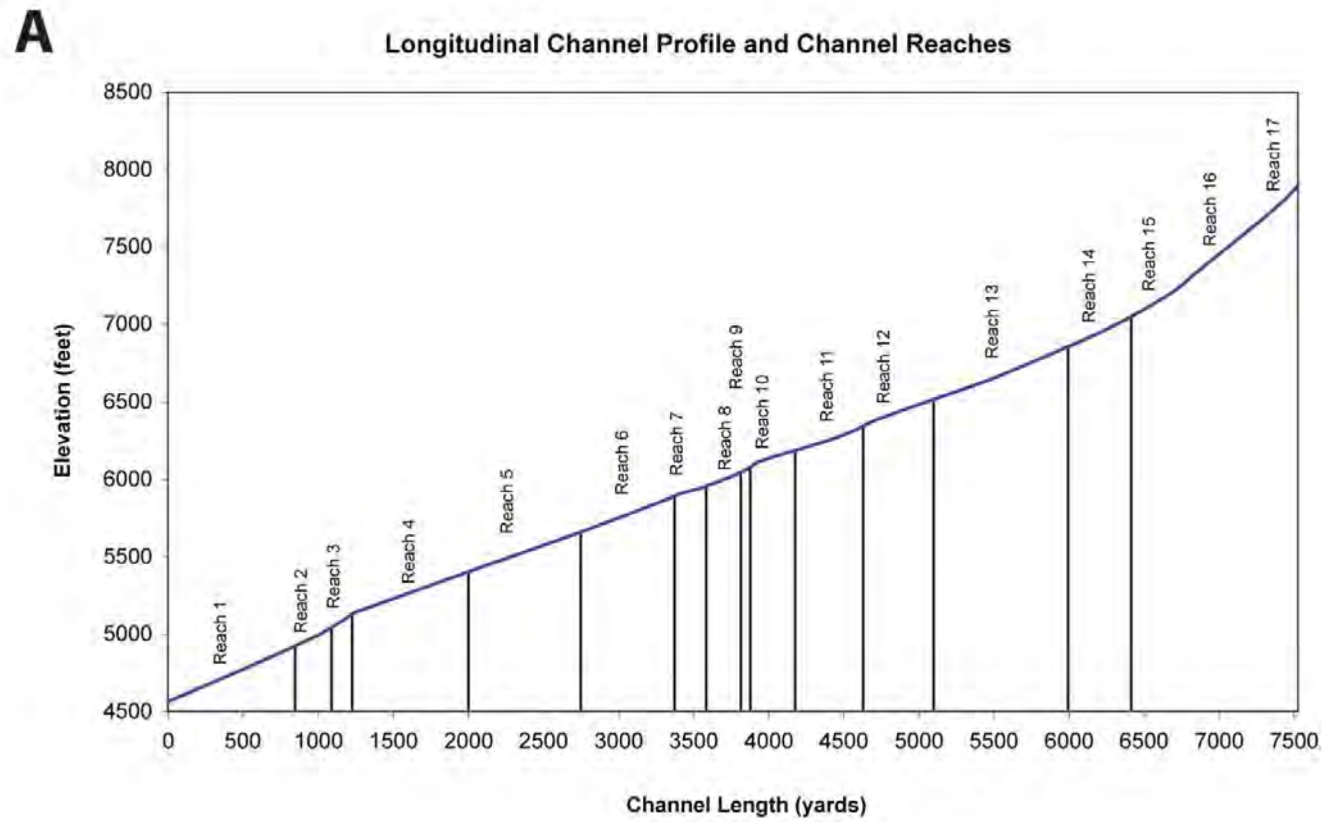
(table 2; figure 4). We estimate a volume of 116,000 cubic yards (88,700 m^3) for a channel length of 4947 yards (4524 m). A small historical debris slide in 1983 or 1984 transformed into a debris flow (DS 872 and DF 873 in Lowe, 1988a), flowed down this tributary, and deposited sediment in the main channel. For the purpose of estimating debris-flow volume, we used this debris-flow initiation location and the corresponding channel length to approximate a scenario debris flow for the middle canyon.

Lower Canyon

For a debris flow in the lower canyon, we used seven reaches along the main channel and tributary channel (table 2; figure 4). We estimate a volume of 75,000 cubic yard (57,300 m^3) for a channel length of 3581 yards (3275 m). The tributary channel does not contain any mapped debris slides or debris flows. For the purpose of estimating debris-flow volume, we used this debris-flow initiation location and the corresponding channel length to approximate a scenario debris flow for the lower canyon.

Rainfall and Snowmelt Debris-Flow Volume Limitations

Our methods for estimating potential rainfall and snowmelt debris-flow volumes use quantitative and objective methodologies that have practical limits. Our volume estimates are approximate and appropriate engineering factors of safety



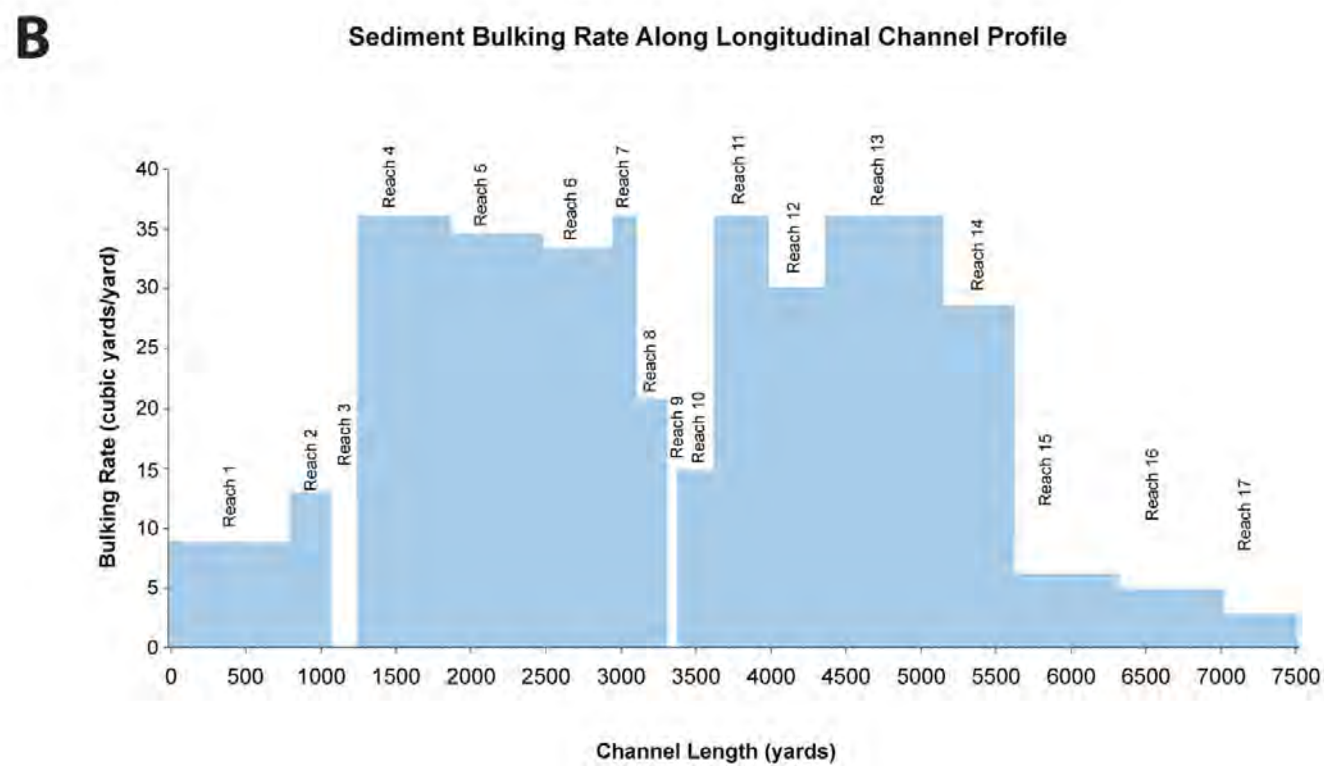


Figure 5. *Longitudinal profile of the main and tributary channels showing channel reaches and sediment bulking rates for a debris flow initiating in the upper part of Centerville Canyon.* ***A.*** *Main and tributary channel longitudinal profile and channel reaches.* ***B.*** *Main and tributary channel reaches and sediment bulking rates. Reach 3 and 9 have a bedrock-floored channel.*

Table 3. *Comparison of historical and estimated debris-flow volumes, Davis County, Utah.*

	Davis County Historical Debris Flows					**Centerville Canyon Estimated Debris Flows**						
	Canyon					**Rainfall and Snowmelt**			**Fire Related**			
	Parrish	Davis	Steed	Rudd	Farmington	Lower	Middle	Upper	North	South	Upper	Total
Drainage Basin Area or Fire-Related Burn Area (mi^2)	2.1	1.6	3.0	0.69	10.5	-	-	-	1.3	1.1	1.0	3.1
Bulked Channel Length (yd)	6567	4267	5853	1807	19,719	3581	4947	7635	-	-	-	-
Volume[a] (yd^3)	220,484[b] 186,446[c] 101,098[d]	146,971	204,243	83,707	690,492	75,000	116,000	196,000	29,000	24,000	21,000	91,000
Debris Basin Capacity[e] (yd^3)	40,000	no basin	no basin	35,200	168,600				no basin			

[a]Largest reported volume from Williams and others (1989)
[b]July 10, 1930
[c]August 11, 1930
[d]August 13, 1930
[e]Debris basin volumes from Keaton and Lowe (1998)

should be incorporated in risk-reduction design. We lack data specific to Centerville Canyon to quantify the amount our estimated volumes under- or over-predict debris-flow volumes to accurately express the uncertainty associated with our volumes. Our methods also rely on historical debris-flow volumes and the measurement uncertainty of these historical volumes, which are unknown. However, we believe our volumes are the best approximation given the techniques and methods currently available.

ESTIMATED AND HISTORICAL DEBRIS-FLOW VOLUME COMPARSION

To provide an independent check of our estimated debris-flow volumes, we compared them with historical debris-flow volumes from other Davis County canyons. Table 3 shows the largest historical volumes (to provide a conservative comparison) compared to our estimated volumes. The drainage basin area and estimates of eroded channel length are also shown. The data in this table were compiled by Williams and others (1989) and are largely based on data in Croft (1967) and Wieczorek and others (1983).

Our fire-related volumes are lower than most historical volumes in nearby canyons. All historical volumes, with the exception of Rudd Canyon, are from denuded watersheds in the 1920s and 1930 due to overgrazing and fires (Cannon, 1931). The historical denuded basin condition should be similar to our total-basin-area burn condition. Our total-basin burn volume of 91,000 cubic yards (69,600 m^3) is less than half the historical volumes (table 3) for the first two debris flows produced in Parrish Creek north of Centerville Canyon (figure 1). Our volume is likely smaller because the Western U.S. model (Gartner and others, 2008) does not incorporate a variable for sediment bulked along perennial channels. Therefore we believe our empirical fire-related debris-flow volume estimates are too low and additional work is needed to refine methods for accurately estimating fire-related debris-flow volumes in canyons with long perennial stream channels. Our fire-related volumes compare more closely to historical fire-related volumes (Giraud and McDonald, 2007) and ephemeral channel volume from Cameron Cove in northern Weber County (Mulvey and Lowe, 1992). Rainfall-triggered debris-flow volumes from denuded canyons are indirectly considered in our rainfall and snowmelt volumes because we applied the unit-volume analysis method and bulking rates that account for historical debris flows produced from denuded canyons.

Our estimated rainfall and snowmelt debris-flow volume initiating in upper Centerville Canyon compares relatively closely with historical volumes based on similar eroded or bulked channel lengths. Our rainfall and snowmelt upper canyon volume of 196,000 cubic yards (149,900 m^3) compares most closely to the first two 1930 Parrish Creek debris flows of 220,484 cubic yards (168,600 m^3) on July 10 and 186,446 cubic yards (142,500 m^3) on August 11 (table 3). Based on the historical volumes of sediment produced from Parrish Creek prior to 1930, Parrish Creek was likely similar to Centerville Canyon and contained an abundant supply of sediment. Because our upper canyon volume compares favorably with other historical volumes, we believe the 196,000 cubic yards (149,900 m^3) is the most appropriate volume to consider for sizing a debris basin at the mouth of Centerville Canyon. Debris flows initiating in the middle and lower canyon would have smaller volumes (table 3).

Our upper canyon 196,000 cubic yards (149,900 m^3) estimate is slightly (10%) lower than Williams and others' (1989) and Williams and Lowe's (1990) 216,000 cubic yards (165,100 m^3) estimate where they applied a single bulking rate for an 18,000-foot (5486 m) channel length. Our volume is likely lower because we more accurately constrained the channel geometry and sediment available for bulking. We measured more channel cross sections, applied specific bulking rates for channel reaches, measured bedrock reaches, considered relatively thin depths of stored sediment above bedrock, and considered sediment stored in both wide and narrow channel areas.

DEBRIS-FLOW RISK REDUCTION

Engineered debris basins are the most common type of control structure used to reduce debris-flow risks in Utah. Debris basins are popular because debris-flow behavior is difficult to predict and flows are difficult to route on alluvial fans. Uncertainty exists with the estimated volumes used to size debris basins and the debris-flow volume may exceed the debris-basin capacity. However, if a debris-flow volume exceeds the basin capacity, a basin continues to provide a level of risk reduction because the basin captures the flow, reduces flow velocity, and conveys the excess volume over the spillway at a relatively low velocity back into a channel downstream. The debris-basin capacities for Parrish, Rudd, and Farmington Canyons are shown with the largest historical debris-flow volumes in table 3. Table 3 shows that the historical flow volumes would exceed the existing debris-basin capacity. Even though basin capacity can be exceeded, these basins can reduce the potential for loss of life if areas below these basins are evacuated before the basin volume is exceeded. Depending on the design, debris basins can also reduce the stream-flow and alluvial-fan flooding hazards.

A debris basin would benefit the developed area of Centerville City on the alluvial fan by reducing the debris-flow hazard. Debris basins are expensive, require periodic maintenance, and sediment removal. For these reasons, debris-flow- and flood-risk-reduction basins are commonly government public works or shared public-private responsibilities. In Davis County, local agencies such as Davis Public Works or individual cities manage both debris-flow and stream-flooding hazards and associated infrastructure.

Formal design guidance for sizing debris-basin volume is not available. Debris flows are complex natural processes, and generally accepted return periods for design of debris-flow risk-reduction measures based on probabilistic models do not exist, unlike for earthquake ground shaking and flooding, which have established design return periods of 2500 years (International Building Code) and 100 years (FEMA's National Flood Insurance Program), respectively. Keaton (1988) and Keaton and others (1991) developed a probabilistic model for debris flows in Davis County based on the record of historical debris flows, but the high degree of irregularity and uncertainty in return periods limited their results and the practical application of their model.

Rather than assigning an absolute probability of debris-flow occurrence to guide risk reduction, many studies assign a relative probability of occurrence (VanDine, 1996) based on frequencies in similar basins and alluvial fans in the geographic areas that have experienced historical debris flows. We believe this is the best approach for Centerville Canyon. Williams and Lowe (1990) did not specifically assign a relative probability to the hazard in Centerville Canyon, but they concluded that the most significant debris-flow threat exists from a thunderstorm-generated event in a fire-damaged canyon. They further state that the real danger is from canyons that have not discharged debris flows and have communities below the canyon mouth without engineered protection from debris flows, which applies to Centerville Canyon. We concur with Williams and Lowe (1990) and believe their study and our investigation both show Centerville Canyon to have a high relative probability of producing a large debris flow.

We completed a reconnaissance in the lowermost canyon for potential debris-basin sites because the alluvial fan is developed and limited space exists on the fan for a large-capacity debris basin. Bedrock outcrops are exposed in the lowermost canyon above road and trail crossings, water diversions, and the USGS stream gauge. The bedrock outcrops would likely provide a suitable foundation for a debris-basin embankment, but a site-specific geotechnical investigation is necessary to fully evaluate the site.

CONCLUSIONS AND RECOMMENDATIONS

We provided volume estimates for fire-related debris flows and intense rainfall and rapid snowmelt debris flows from Centerville Canyon to aid in sizing a debris basin. Our fire-related debris-flow volume estimates are significantly lower than historical volumes from denuded canyons, and we do not recommend using these estimates for fire-related debris flows in the canyon. Additional work is needed to refine methods for accurately estimating fire-related debris-flow volumes in Davis County canyons with long perennial stream channels. Because denuded canyons are similar to fire-related conditions, fire-related debris flows are considered indirectly in our potential rainfall and snowmelt volumes.

We estimated rainfall and snowmelt debris-flow volumes using a unit-volume analysis to determine sediment bulking rates for specific channel reaches. Our rainfall and snowmelt volume of 196,000 cubic yards (149,900 m^3), for a debris flow initiating in the upper canyon, compares favorably with historical volumes based on similar eroded channel lengths. We believe the 196,000 cubic yards (149,900 m^3) volume is the most appropriate volume to consider in sizing a debris basin because the volume is comparable to volumes produced from other nearby canyons from both intense rainfall and rapid snowmelt. For debris flows initiating in the middle and lower canyon we estimate flow volumes of 116,000 cubic yards (88,700 m^3) and 75,000 cubic yards (57,300 m^3), respectively.

Centerville Canyon has a high relative probability of producing a large debris flow. The canyon has not discharged a historical debris flow and contains an abundant supply of sediment for future debris flows. Future large debris flows could result from wildfires followed by intense rainfall, intense rainfall without fire conditions, or from rapid spring snowmelt. Other Davis County canyons have discharged historical debris flows, reducing the volume of sediment available for future debris flows. Parrish and Barnard Creeks above Centerville have debris basins in place to reduce the hazard. An adequately sized debris basin would likely result in a relatively high level of risk reduction for the developed alluvial fan below Centerville Canyon.

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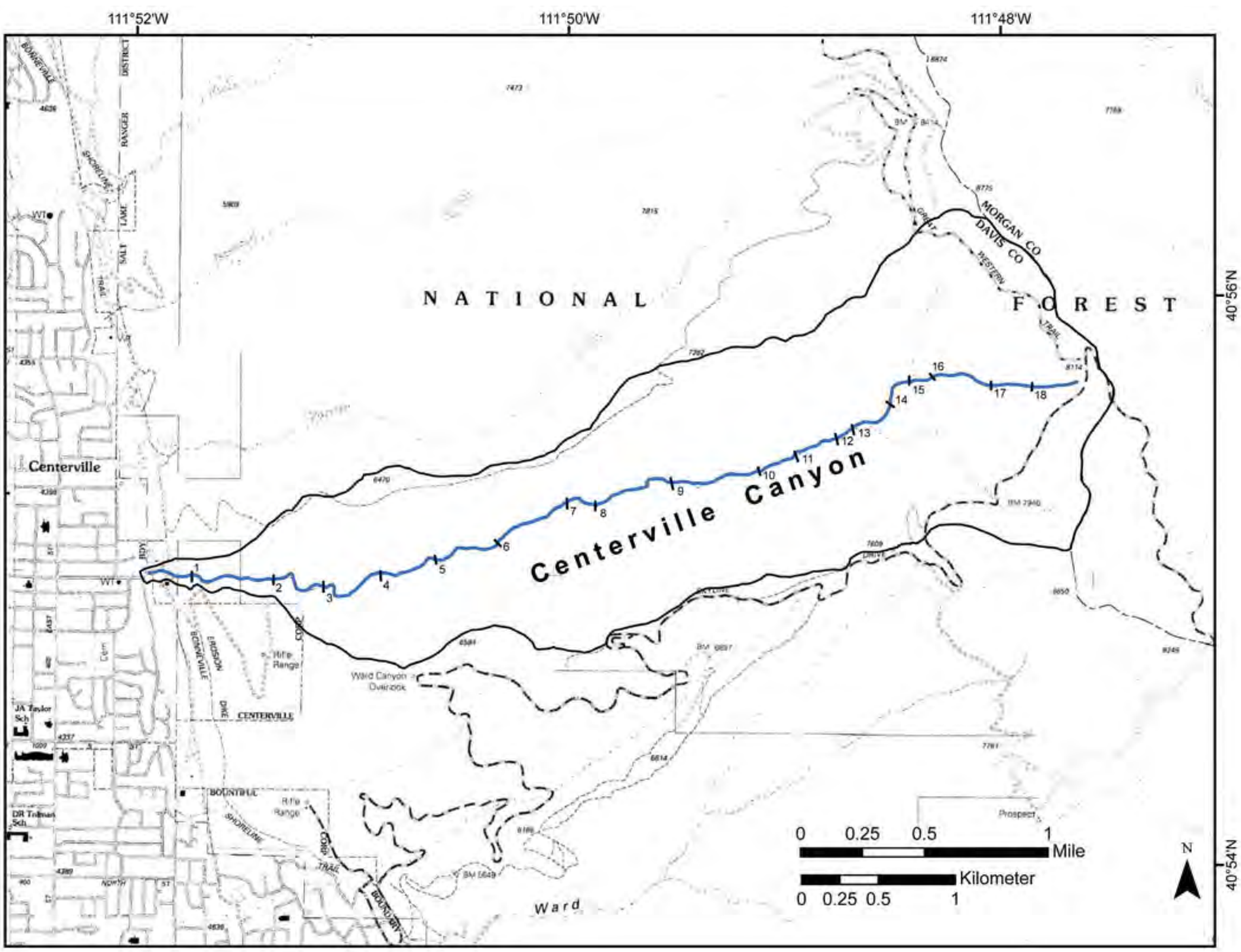
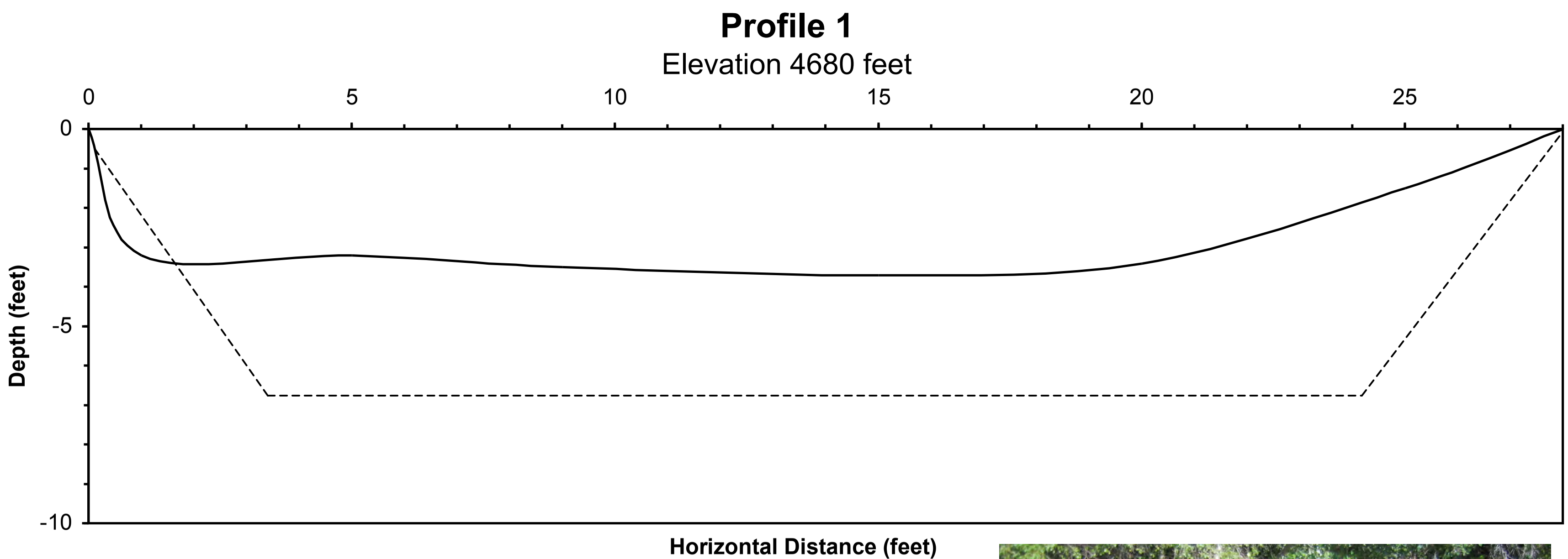
APPENDIX

CROSS-CHANNEL PROFILES, CENTERVILLE CANYON

The cross-channel profiles in this appendix were used to estimate the volume of sediment stored along channel reaches in Centerville Canyon shown in table 2. The cross-channel profile locations are shown on the accompanying figure. On each profile, the solid line shows the measured topographic profile across the channel and the dashed line shows a trapezoidal area representing the estimated depth of erodible channel sediment. All profiles are orientated downchannel. Due to the large variation in channel width the profiles are at different scales. We did not measure a cross-channel profile along reach 10; therefore, we used profiles upchannel and downchannel, field photographs, aerial photos, and widths measured on the detailed topographic map to estimate a sediment bulking rate. Also, the sediment bulking rate for reach 4 is averaged from profiles 3 and 4, and the sediment bulking rate for reach 13 is averaged from profiles 11, 12, and 13.



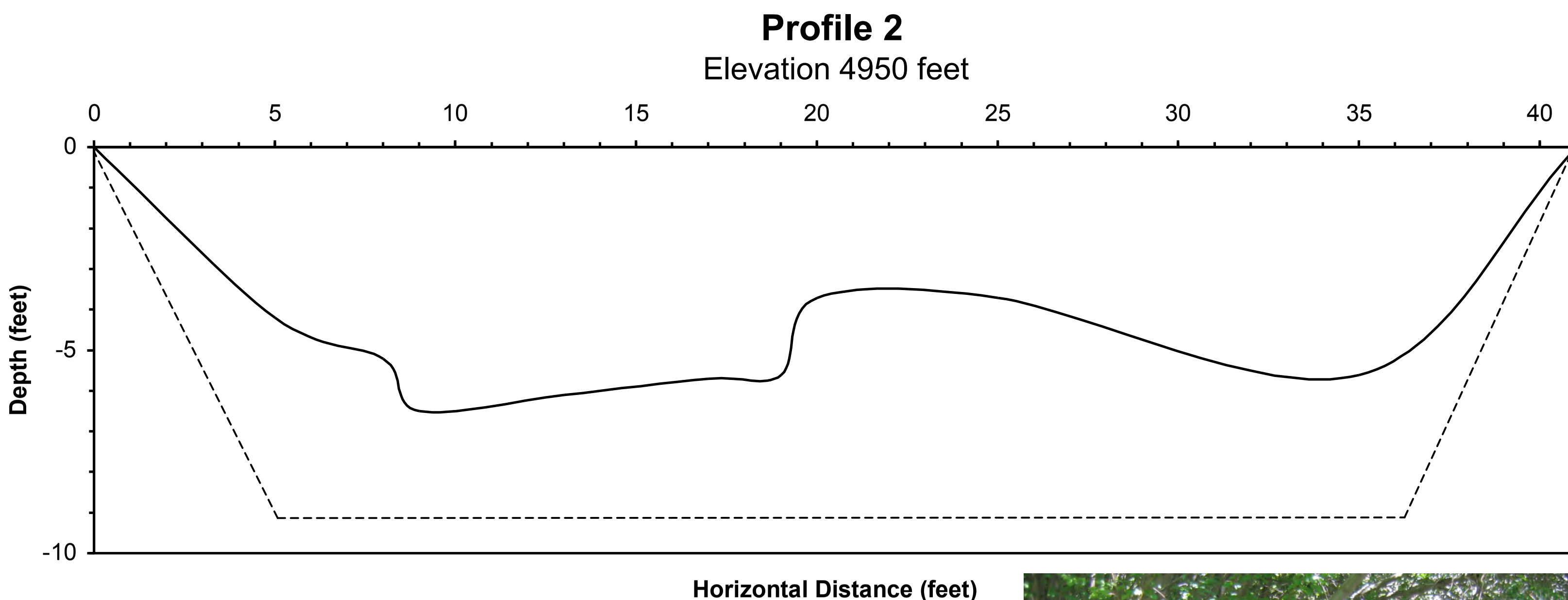
Cross-channel profile locations in Centerville Canyon. *Cross-channel profile locations along the main channel and upper- basin tributary channel are shown with a short line and number. Base map from USGS 7.5-minute Farmington and Bountiful Peak quadrangles.*



Channel Reach 1

Bulked Volume 7700 yd^3

View upchannel



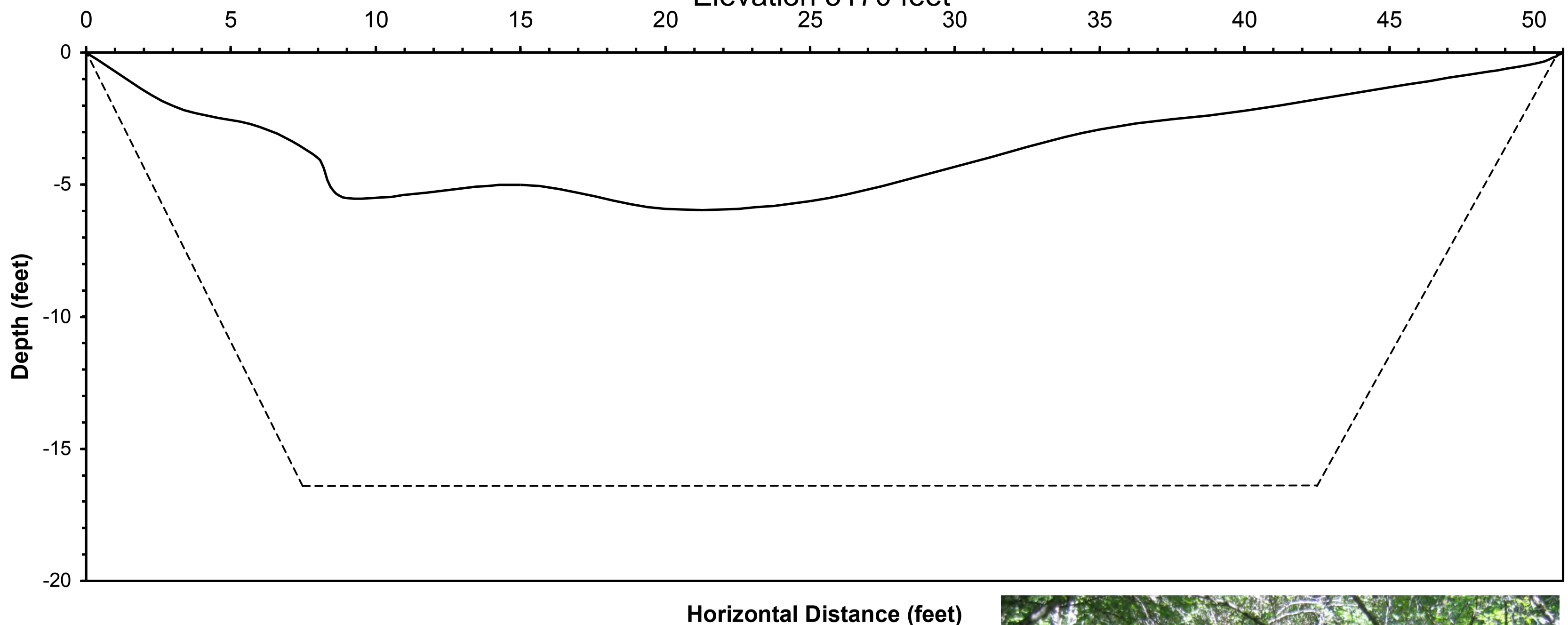
Channel Reach 2

Bulked Volume 3161 yd^3

View upchannel

Profile 3

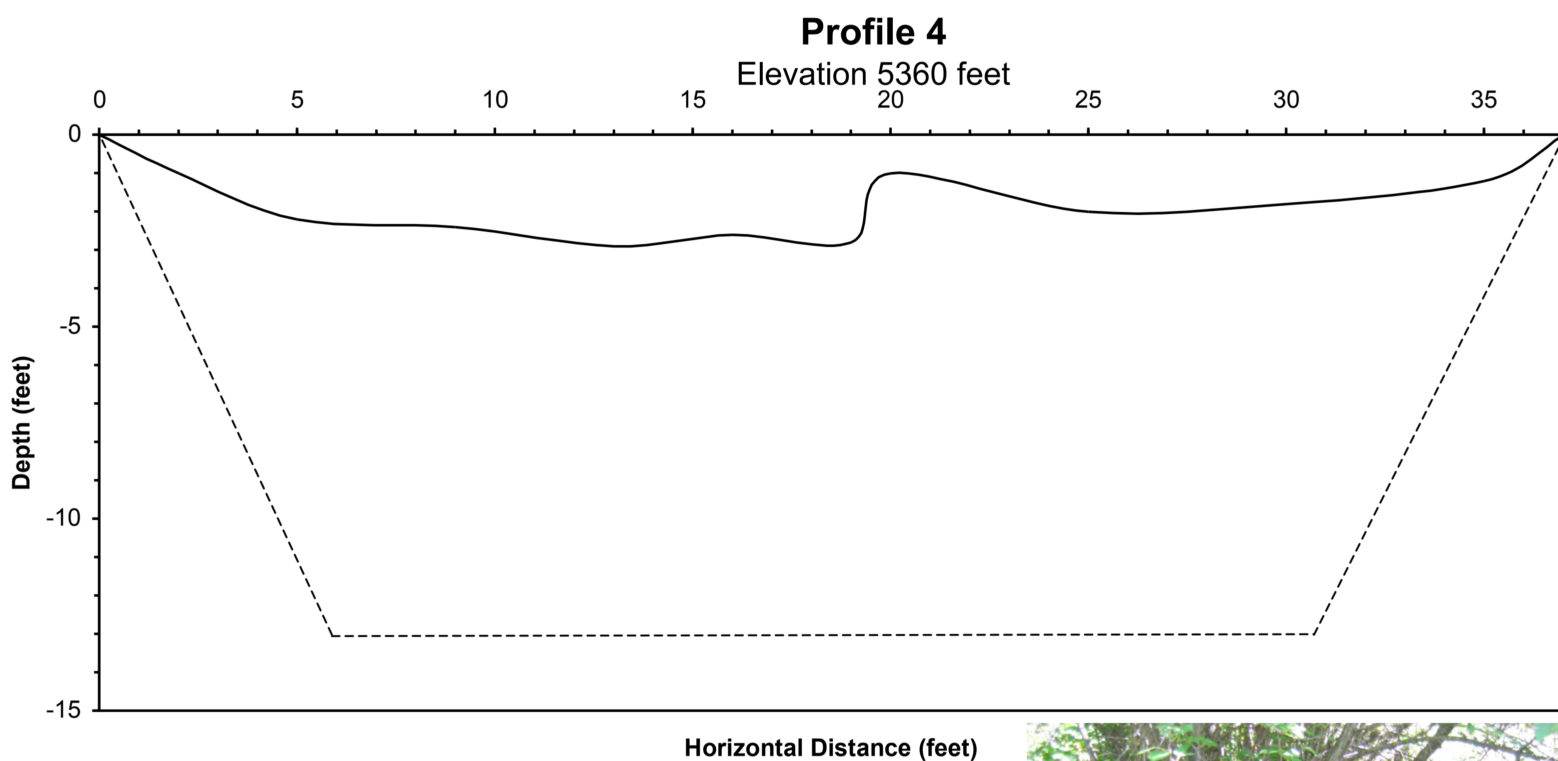
Elevation 5170 feet



Channel Reach 4

Bulked Volume 29,496 yd^3

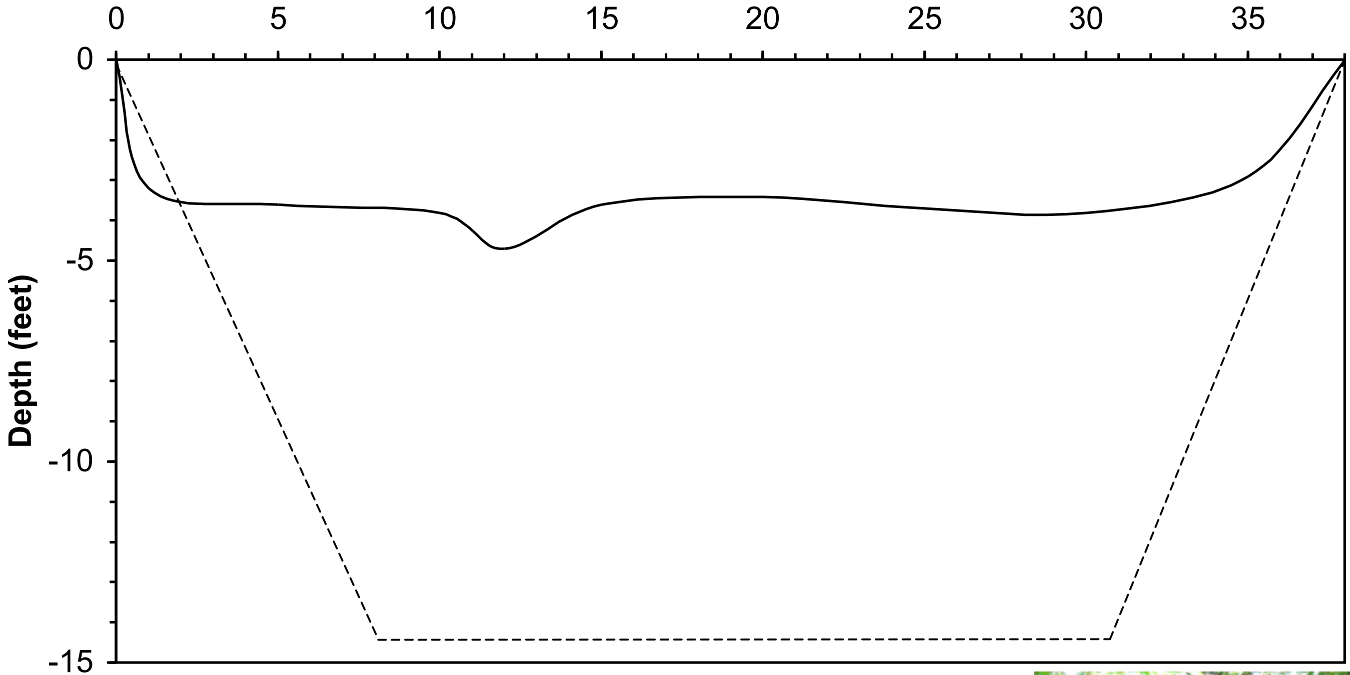
View upchannel



Channel Reach 4

Bulked Volume 29,496 yd^3

View upchannel

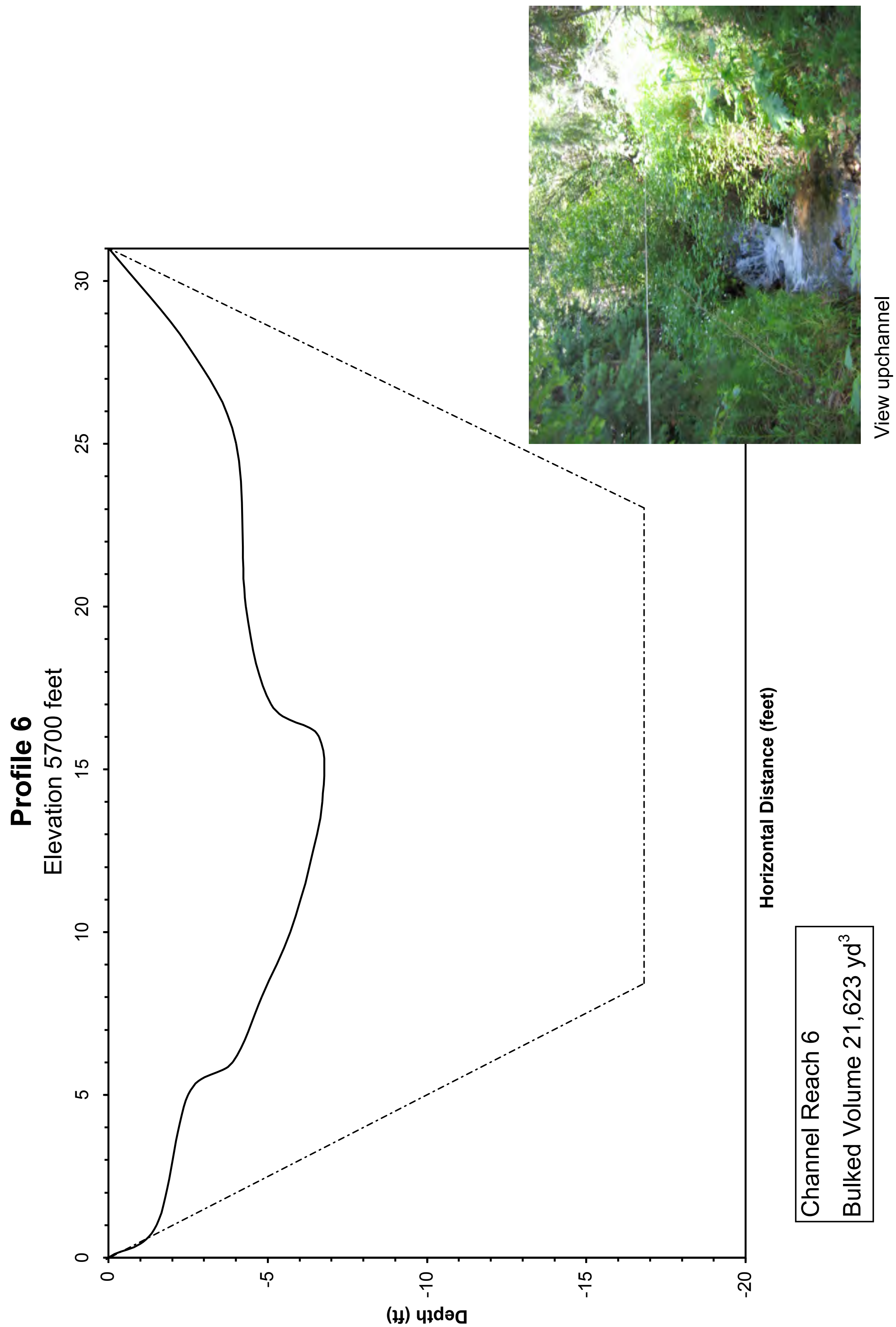


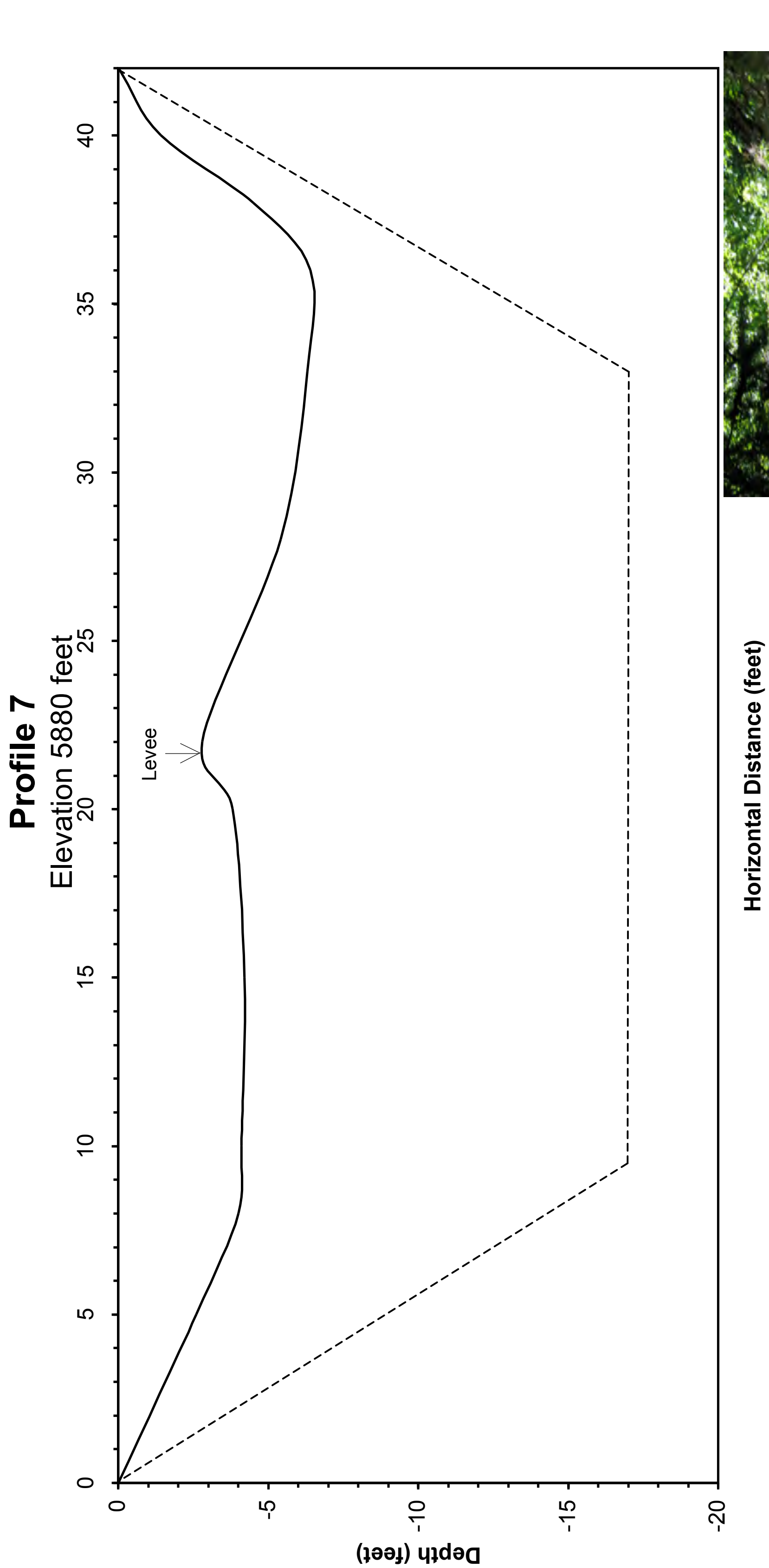
Channel Reach 5

Bulked Volume 25,852 yd^3

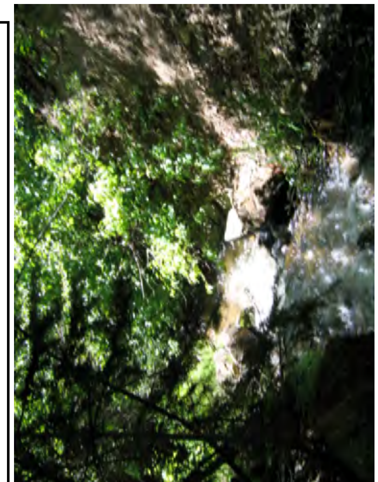
Bedrock at profile 5

View upchannel

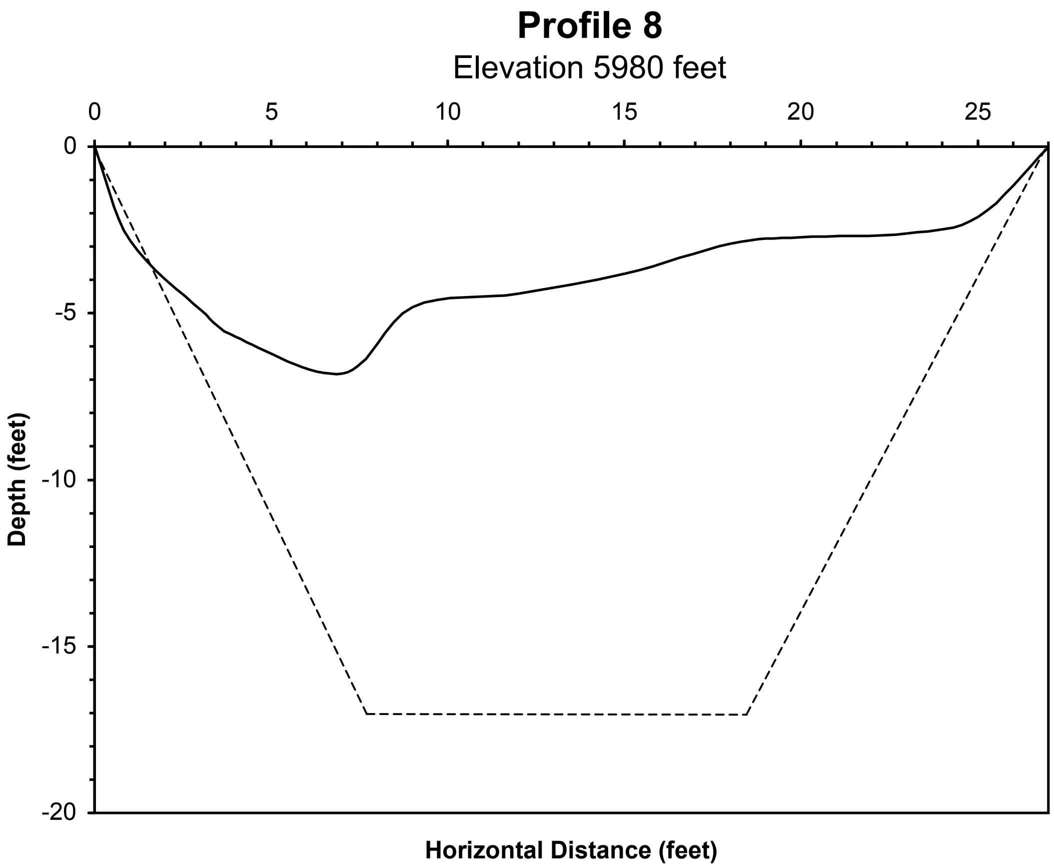

Profile 6
Elevation 5700 feet
Depth (ft)
Horizontal Distance (feet)
0
-5
-10
-15
-20
0
5
10
15
20
25
30
View upchannel
Channel Reach 6
Bulked Volume 21,623 yd3



Channel Reach 7
Bulked Volume 7308 yd^3



View downchannel

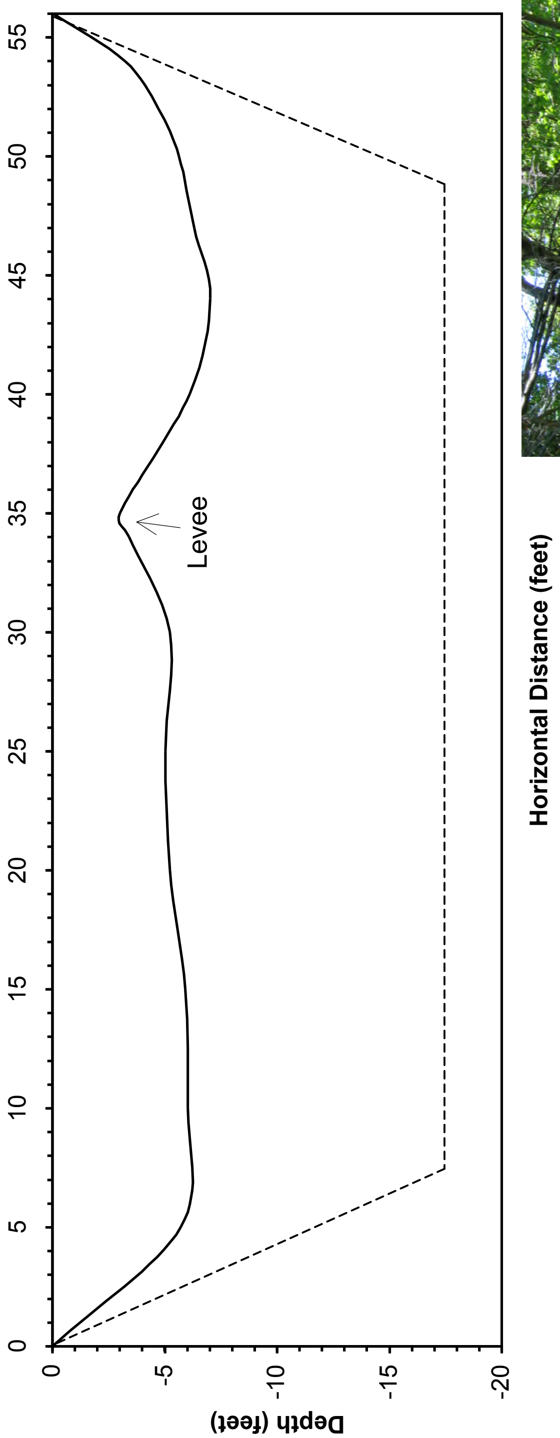


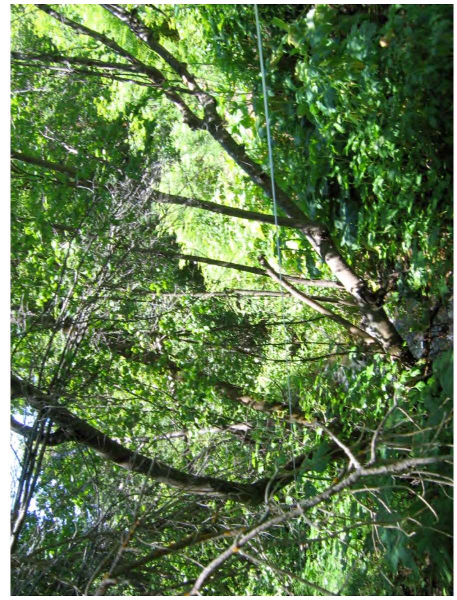
Channel Reach 8

Bulked Volume 5023 yd^3

View upchannel

Profile 9
Elevation 6220 feet

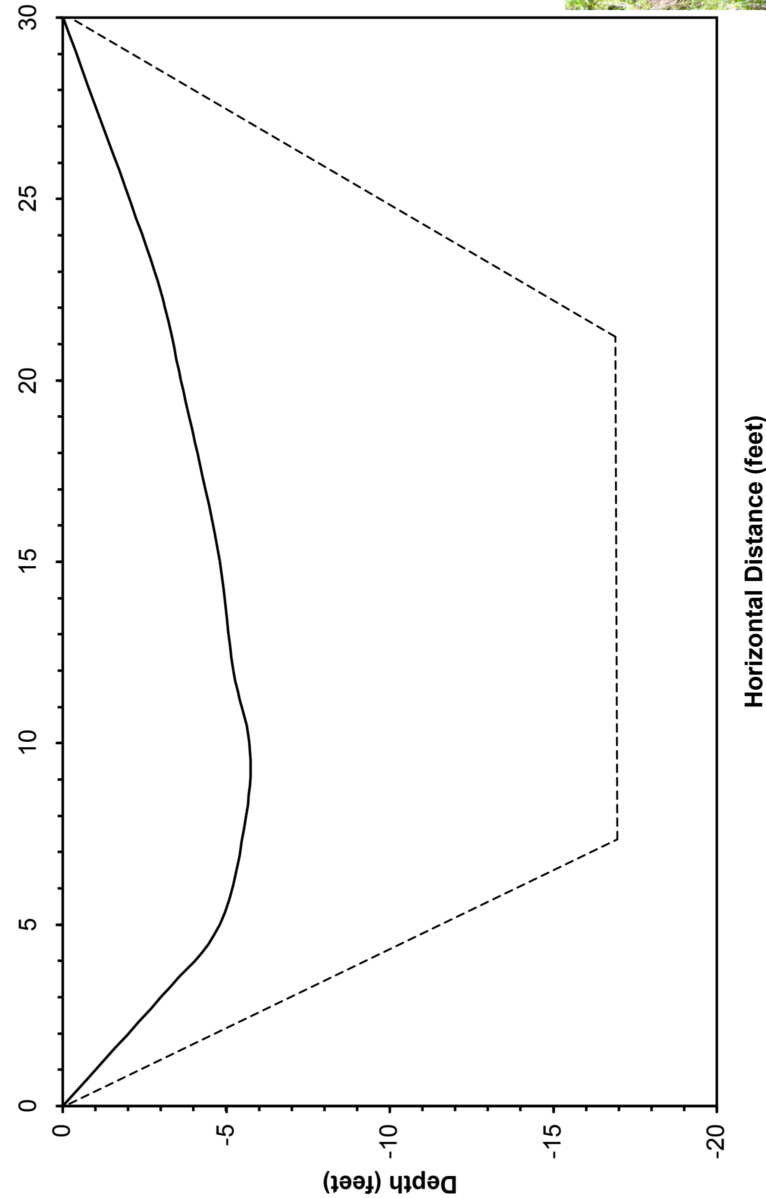




View upchannel

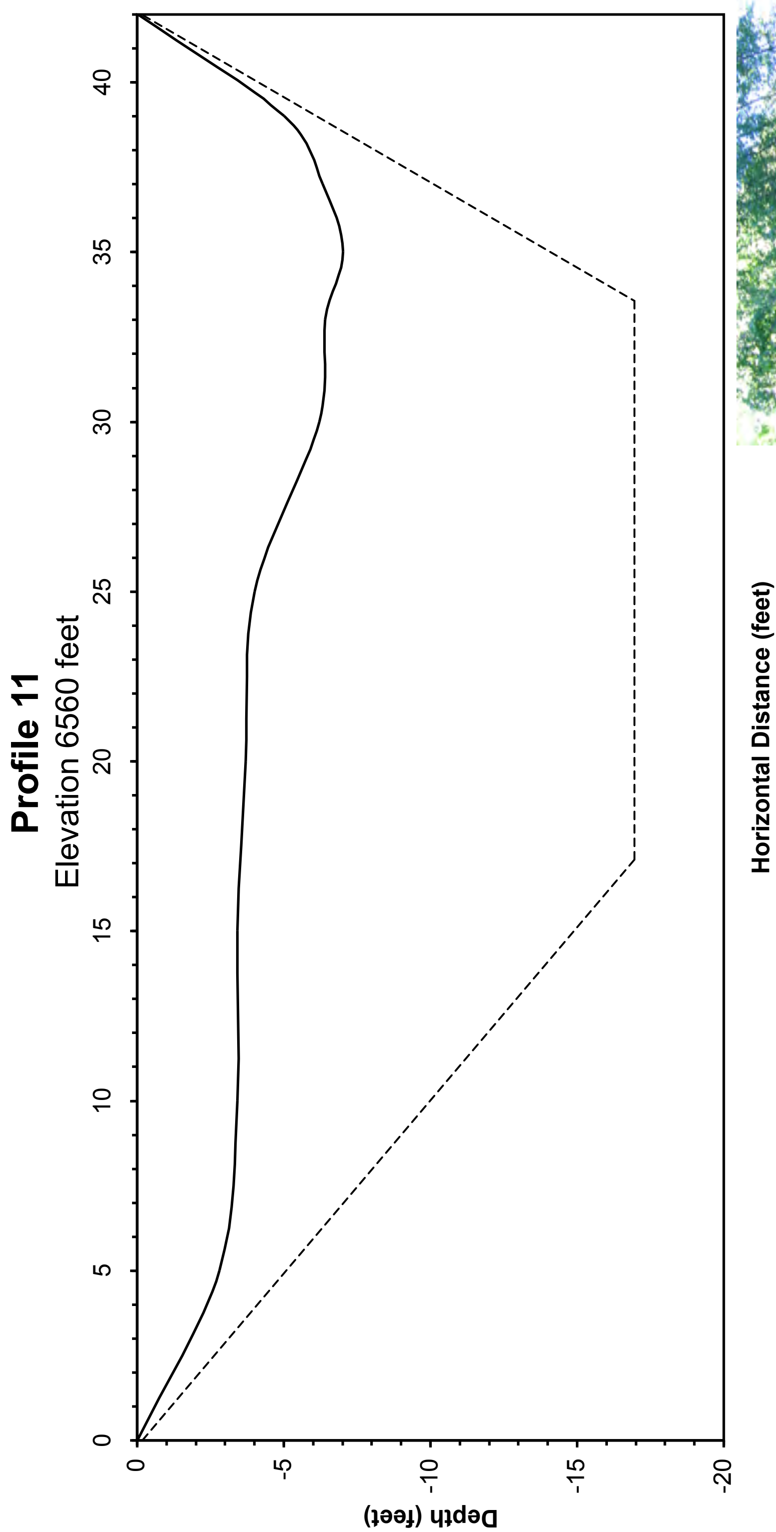
Channel Reach 11
Bulked Volume 16,716 yd^3

Profile 10
Elevation 6460 feet



View upchannel

Channel Reach 12
Bulked Volume 14,290 yd^3

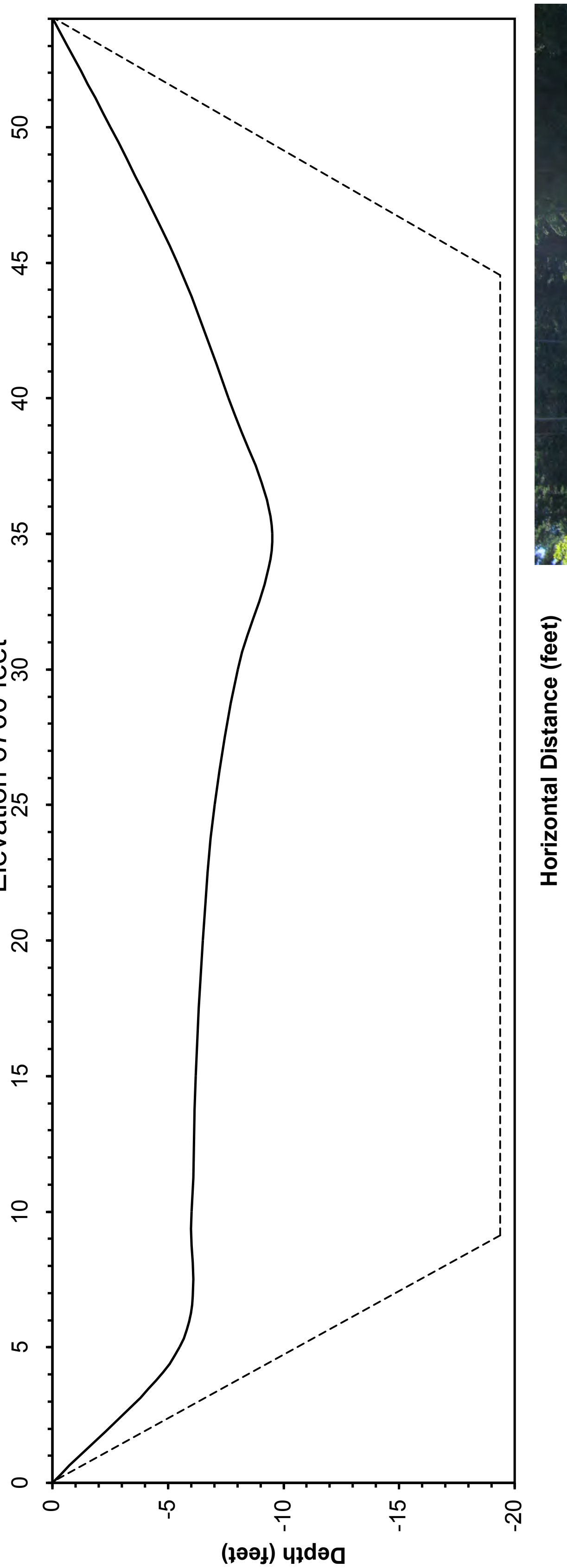


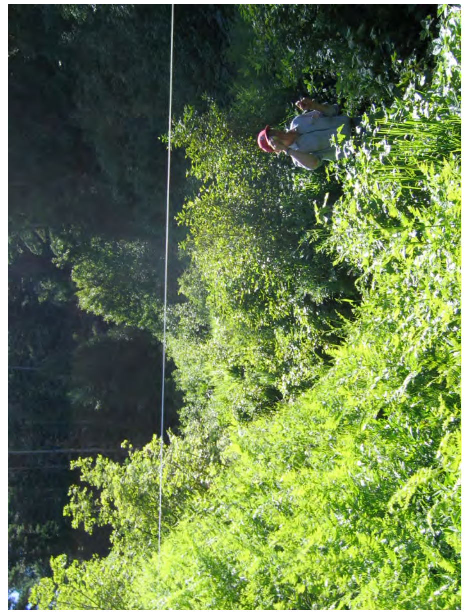
Channel Reach 13

Bulked Volume 32,208 yd^3

View upchannel

Profile 12
Elevation 6700 feet

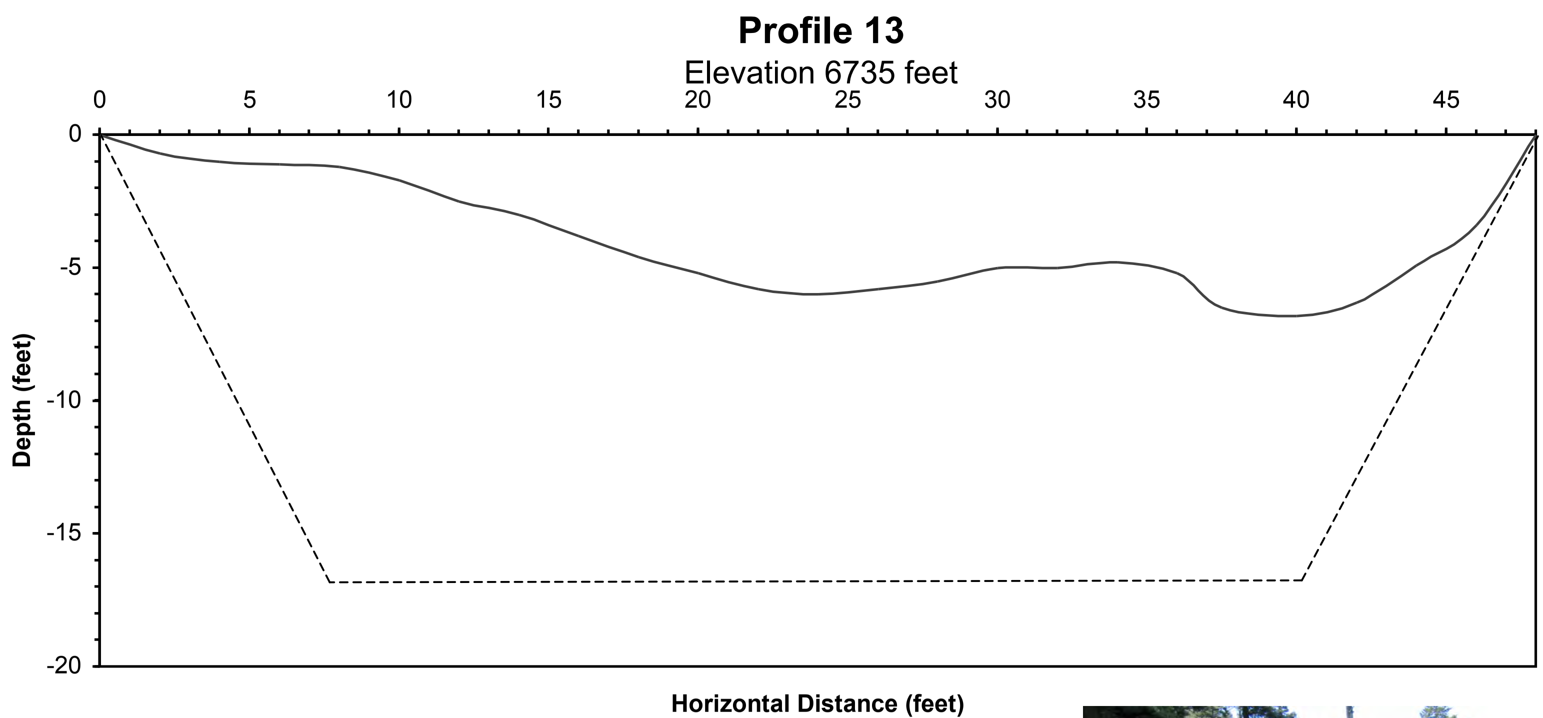




View upchannel

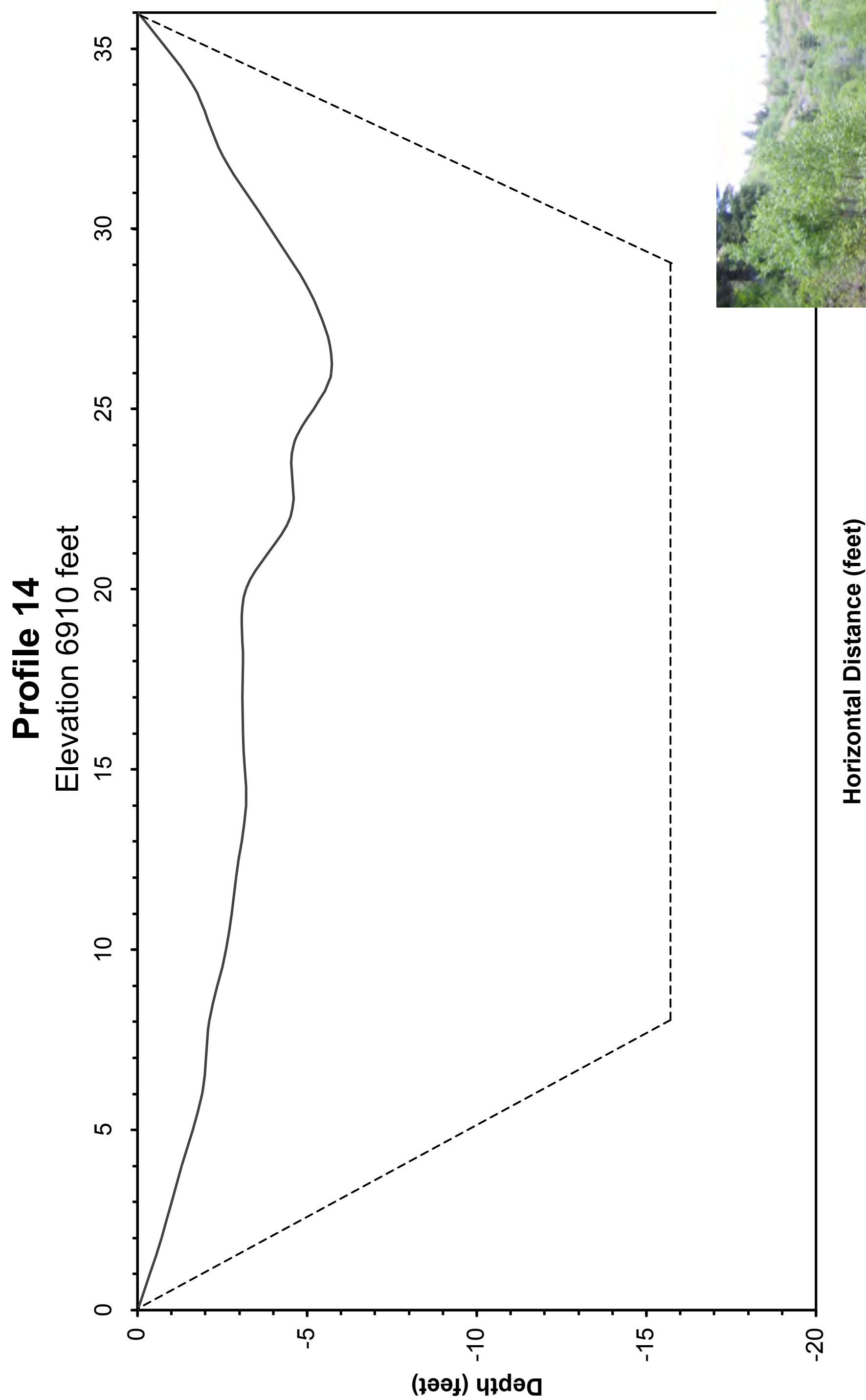
Channel Reach 13

Bulked Volume 32,208 yd^3



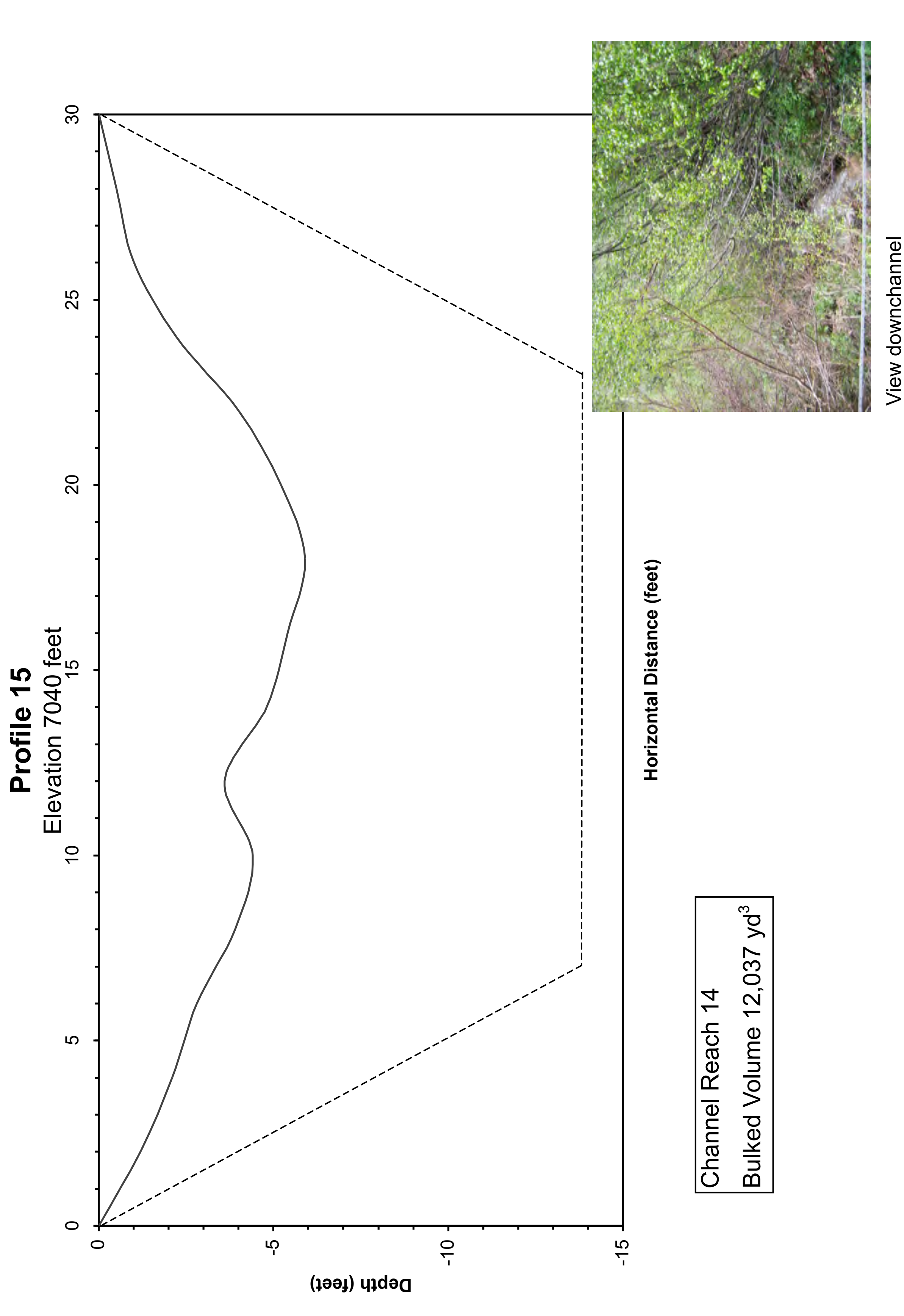
Channel Reach 13
Bulked Volume 32,208 yd^3

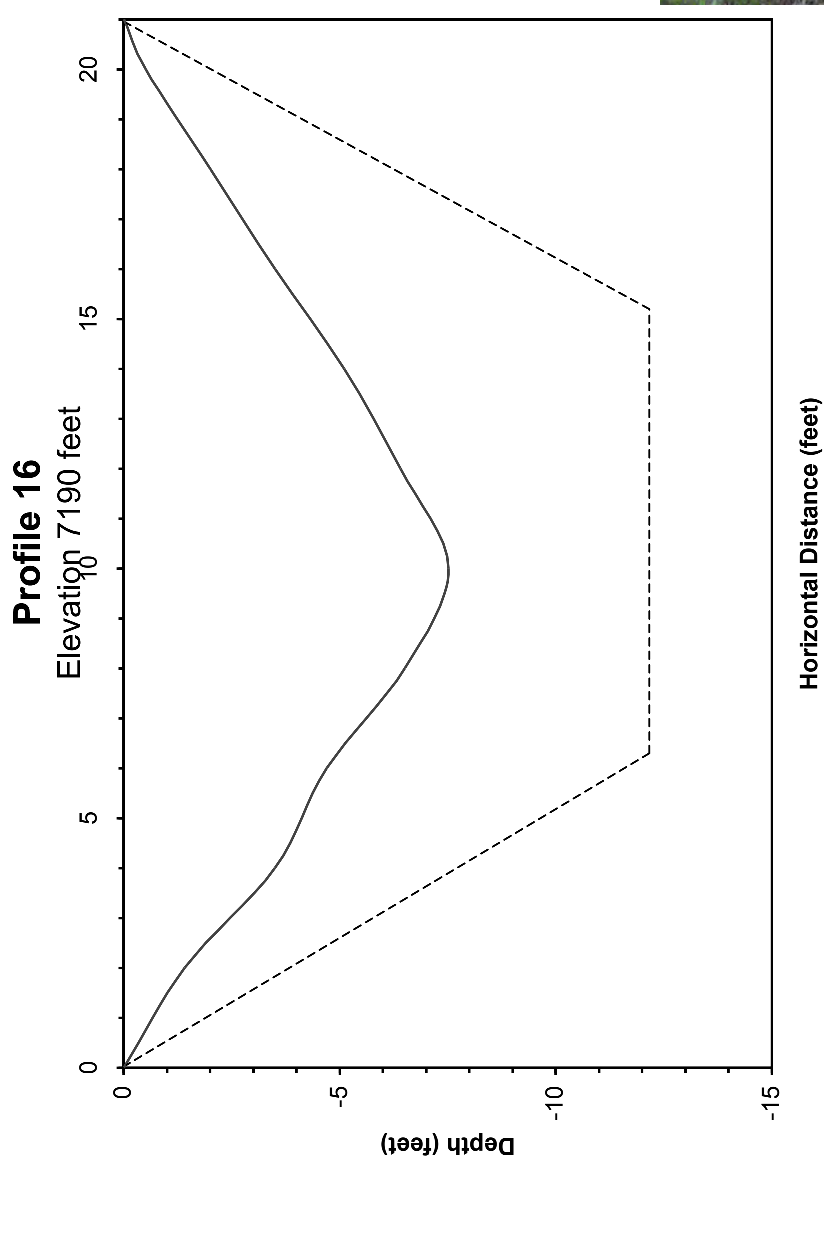
View upchannel



View upchannel

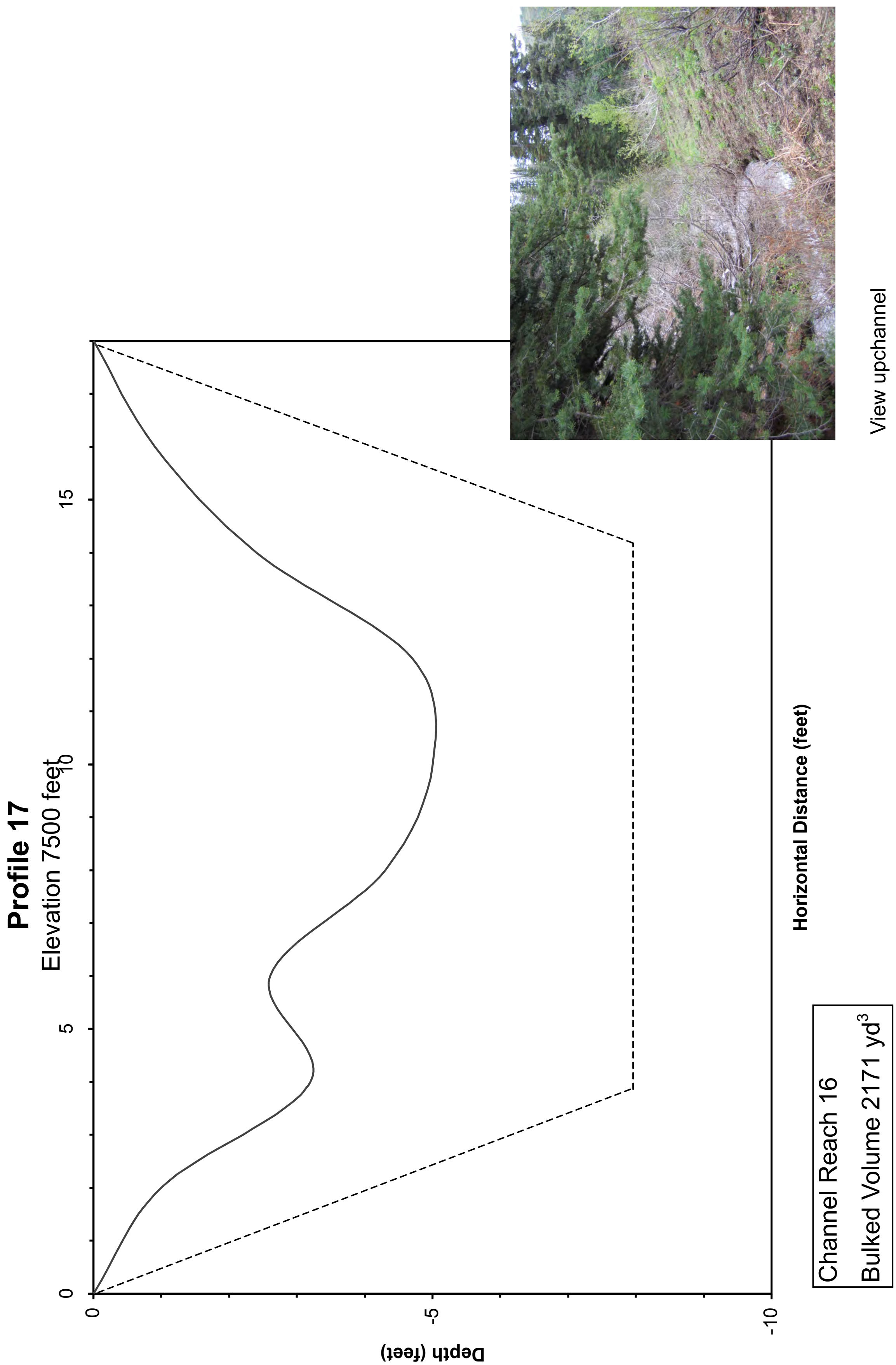
Channel Reach 14
Bulked Volume 12,037 yd^3

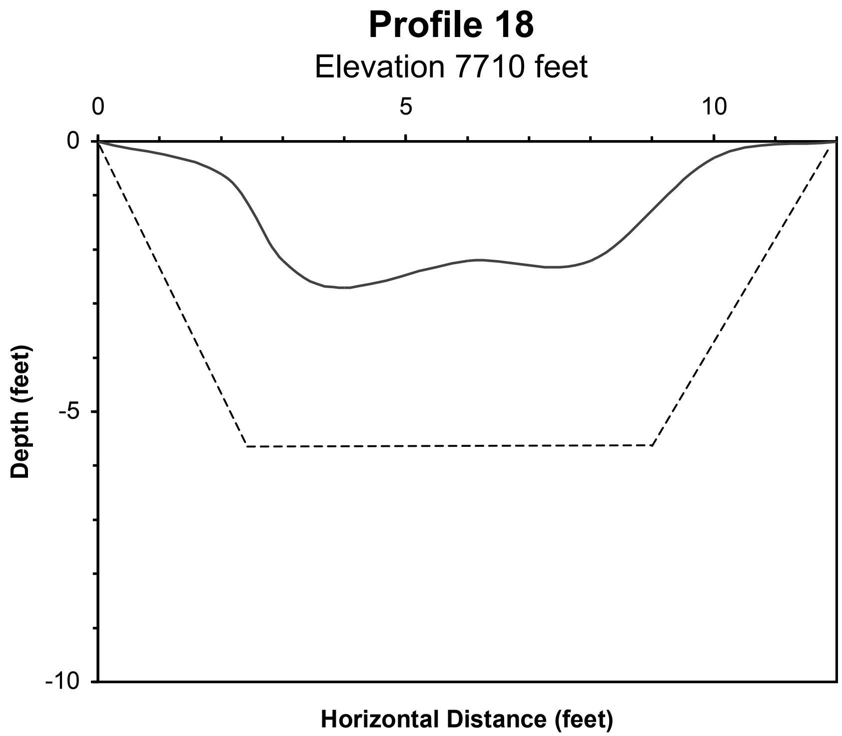

Profile 15
Elevation 7040 feet
Horizontal Distance (feet)
Depth (feet)
0
5
10
15
20
25
30
0
-5
-10
-15
View downchannel
Channel Reach 14
Bulked Volume 12,037 yd³



Channel Reach 15
Bulked Volume 2678 yd^3

View upchannel


Profile 17
Elevation 7500 feet
Depth (feet)
0
-5
-10
0
5
10
15
Horizontal Distance (feet)
Channel Reach 16
Bulked Volume 2171 yd3
View upchannel



View upchannel

Channel Reach 17

Bulked Volume 581 yd^3