Effects of Beaver Dam-Break Floods on Downstream Channels in King County, Washington

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Executive Summary

Beaver dam failures were responsible for 13 deaths between 1984 and 2003 and can cause damage to infrastructure and property (Butler and Malanson, 2005). In the Puget Lowland of western Washington State, the unique geologic setting with beaver ponds on steep-sided uplands, surrounding flat alluvial plains of rivers like the Snohomish or Tolt Rivers, creates an environment where beaver dams that fail perched high atop these uplands can erode huge volumes of materials from the channels and valley sidewalls (up to 119,000 cubic yards). While public officials in western Washington have taken an interest in the failures after damage to property and infrastructure has occurred, little to no information exists quantifying the geomorphic response in the channels in this region. With recent failures backing up culverts and wiping out roads and trails, interest has been building in predicting the downstream effects of these failures in King County. Using LiDAR data from before and after the most recent failure events on the Snoqualmie Valley Trail, Deer Creek, Tate Creek, Evans Creek, Preston dam, and Tolt River dam stream channels in King County, the depth of degradation and aggradation in the channel and the volume of sediment evacuated from within 100-feet of the channel are estimated. Kennar et al. (2017) was used to calculate beaver pond volume for use in the peak discharge equations from dam breach peak discharge equations cited by the Washington State Department of Ecology (2007). Peak discharge calculations were compared to the expected 100-year flood events for each of the channels to compare the magnitude of the floods in the failures and their role in forming the channel.

Using correlations between different channel and dam failure parameters (peak discharge, erosional volume, pond volume, and channel length), equations were developed that can be useful for public officials to predict the expected response downstream of these beaver dam failures. Further, understanding the magnitude of the flood that might be expected to enter these channels and intersect culverts or other infrastructure crossings can help officials plan for beaver dam failures. While this study did not focus on the role of the geology of the downstream channels, the strongest predictor of erosional volume in the channel and valley sidewalls is the average peak discharge and the channel length. Since a longer channel should produce more erosional volume, a multiple regression analysis using pond volume and average peak discharge concluded a significant correlation to the volume of material eroded from the channel with a correlation coefficient of $6.85*10^{-3}$ as well as the maximum elevation lost in the channel with a correlation coefficient of $4.28*10^{-2}$. The flows from these failure events were calculated to be anywhere from 2.5 to 40 times the magnitude of the 100-year events. These calculations and measurements show these beaver dam failures could be important in sizing channels and could also play a significant role in incising the valleys of these streams in the Puget Lowlands. A better understanding of the frequency of these dam failure events will help to more precisely be able to predict the associated hazards.

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Acknowledgements

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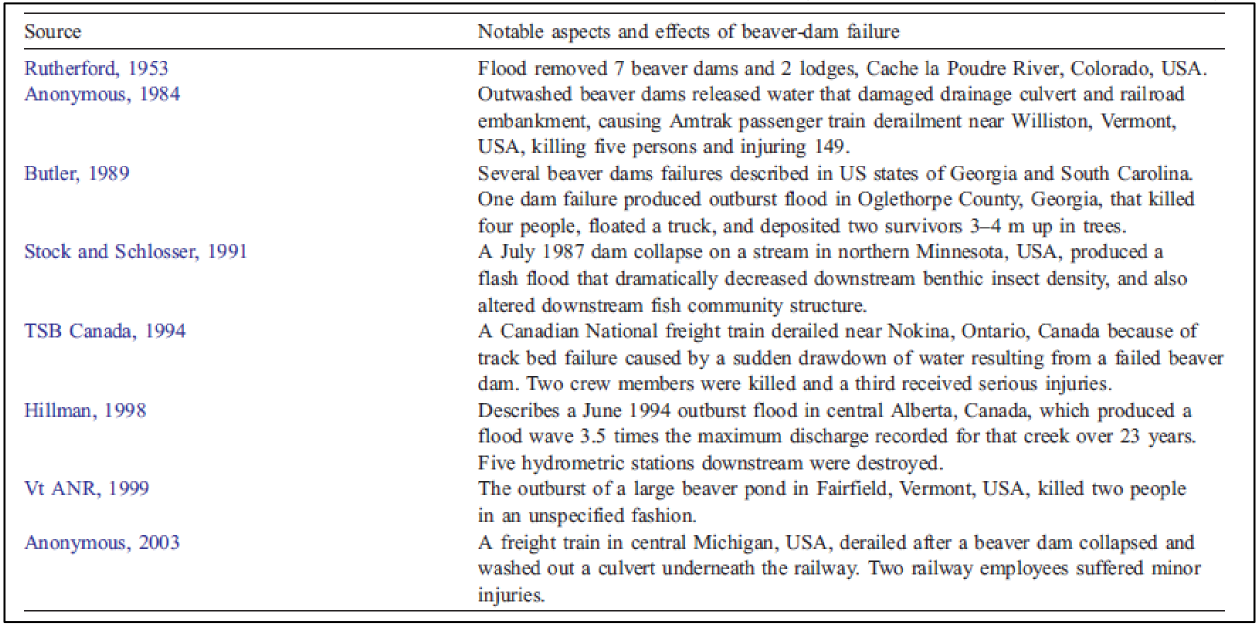
Introduction

Since the end of the last Ice Age, North American beavers (*Castor canadensis* Kuhl) have occupied most of the continent where trees or shrubs grow alongside streams except for the Arctic tundra, the tip of Florida, and the dry Great Basin area of Nevada and southern California (Pollock et al., 2015). Due to massive increases in trapping through the late 19th century for fur, oil, or more productive river valley land, only small, isolated pockets survived out of the estimated 60 to 400 million that once inhabited the continent (Naiman et al., 1988). A recent recognition of the importance of beavers as agents of geomorphic, ecologic, and hydrologic diversity has led to increased protection for the beaver and their population is now estimated to be between 6 and 12 million (Naiman et al., 1988).

As noted by Butler and Malanson (2005), beaver dam failures occur across the Northern Hemisphere but how common these failures are may not be widely known. Previous studies have identified the amount and spatial patterns of sediment trapped by beaver ponds (Butler and Malanson, 2005; Bigler et al., 2001) but little to no research exists identifying the geomorphic effects of beaver dam failures on streams and their interactions with infrastructure, particularly in the Pacific Northwest. The purpose of this study is to identify previous failures within King County (Figure 1) and use available methods and data to determine the geomorphic influence of the failures including the depth of channel degradation and aggradation, volume of erosion within the channel, and document subsequent interaction with infrastructure. Using quantified empirical relationships developed from this study, I identify a predictive tool to predict scour depth and volume from beaver dam failures within stream channels in the Puget Lowland that can be used by public officials to plan and mitigate for the expected downstream response to these failures.

Beavers create habitat for a multitude of different animals and plants. From deer and elk that frequent beaver ponds to forage on shrubby plants where trees have been cut down, to migratory water birds using beaver ponds as nesting areas, to anadromous fish using off-channel habitat in wetlands formed by beaver dams, *C. canadensis* plays a significant role in healthy ecosystems (Pollock et al., 2003, Naiman et al., 1988). As beavers are encouraged to continue to re-occupy prime habitat as their presence in benefitting ecosystems is realized, the ever-encroaching urban development in the Puget Lowland of Washington State will be at risk for the hazards associated with beaver-dam failures. Historically, beaver have been one of the most commonly trapped furbearers. In Washington from 1991 to 2000, an annual average of 5,289 beaver were trapped (WDFW, 2004). However, the average for the past three years has dropped to just over 1,000 due to RCW 77.15.194 which makes it unlawful to use any steel-jawed leghold trap, neck snare, or other body-gripping trap to capture any mammal for recreation or commerce in fur (RCW 77.15.194, 2000). Beaver dam failures are a widespread phenomenon occurring across North America where beaver populations are sustained (Table 1). Descriptions of the damage that can be inflicted by these failures has been noted historically in the Pacific Northwest in news accounts that describe 300-foot-wide by 30-foot-deep mudslides where boulders as big as a box car were swept downstream (Dugmore, 1914). In recent decades, these failures in western Washington have led to catastrophic debris flows and floods causing damage to property and infrastructure (Sullivan, 2012; Kiro 7 News Staff, 2017; J. Bethel, Personal Communication, 2017).

Table 1. Recorded beaver-dam failures and associated effects (from Butler and Malanson, 2005).



Source	Notable aspects and effects of beaver-dam failure
Rutherford, 1953	Flood removed 7 beaver dams and 2 lodges, Cache la Poudre River, Colorado, USA.
Anonymous, 1984	Outwashed beaver dams released water that damaged drainage culvert and railroad embankment, causing Amtrak passenger train derailment near Williston, Vermont, USA, killing five persons and injuring 149.
Butler, 1989	Several beaver dams failures described in US states of Georgia and South Carolina. One dam failure produced outburst flood in Oglethorpe County, Georgia, that killed four people, floated a truck, and deposited two survivors 3–4 m up in trees.
Stock and Schlosser, 1991	A July 1987 dam collapse on a stream in northern Minnesota, USA, produced a flash flood that dramatically decreased downstream benthic insect density, and also altered downstream fish community structure.
TSB Canada, 1994	A Canadian National freight train derailed near Nokina, Ontario, Canada because of track bed failure caused by a sudden drawdown of water resulting from a failed beaver dam. Two crew members were killed and a third received serious injuries.
Hillman, 1998	Describes a June 1994 outburst flood in central Alberta, Canada, which produced a flood wave 3.5 times the maximum discharge recorded for that creek over 23 years. Five hydrometric stations downstream were destroyed.
Vt ANR, 1999	The outburst of a large beaver pond in Fairfield, Vermont, USA, killed two people in an unspecified fashion.
Anonymous, 2003	A freight train in central Michigan, USA, derailed after a beaver dam collapsed and washed out a culvert underneath the railway. Two railway employees suffered minor injuries.

Butler and Malanson (2005) identified beaver-dam failures as having been responsible for 13 deaths and numerous injuries between 1984 and 2005 in North America. King County in Washington State has had to respond to several suspected beaver dam failures in the past few decades that have caused damage to property and infrastructure and even led to lawsuits and evacuations. The rapid release of large volumes of water from upstream can lead to deep channel incision within small, confined channels downstream of the failures (Figure 3a) and deposits of large debris fans spread out across both private and public property and infrastructure (Figure 3b). The large floods also create problems downstream as culverts can become overwhelmed by debris leading to blowouts that damage trails, roads, and property (Figure 4a, b).

Beaver prefer to build dams on small- to medium-sized, low gradient streams (<6% slope) that flow through unconfined valleys, they generally populate the lowest gradient (slope <1-2%) sites first. Beaver build dams on lakes, wetlands, estuaries, and just about any water body where additional water can be retained and thus habitat improved (from a beaver’s perspective) by building a dam (Pollock et al, 2015). Beaver build dams to raise water levels as higher-water levels provide safety from predators, increase forage area and travel routes, and allow for logs and branches to float within their pond. Dam construction is initiated by pushing sediment, rocks, or sticks so that they form a ridge perpendicular to the flow of moving water, or by locating sites to take advantage of existing substrate (Lancia and Hodgdon, 1983) or existing structures, such as abandoned breached dams or large woody debris (MacCracken et al., 2005). Structure is added by anchoring leafy branches, peeled branches, or other material to the substrate, which can be the stream bottom, stream banks, large rocks, or coarse woody debris. Branches in the bulk of the dam are intertwined perpendicular or parallel to the stream (Pollock et al., 2015). Over time dams eventually breach, possibly because of abandonment, high-flow events, human alteration, or all the above. Breached dams often remain in place and may be used as a starting point for new dams when beaver attempt to reoccupy formerly used territory (Pollock et al., 2015).

Measuring the volume of water contained within the beaver ponds is crucial for calculating peak discharge from the dam breaks. Karran et al. (2017) established a method to approximate surface-water storage among the range of environmental settings in which beaver ponds are found using the simplified volume-area-depth (V-A-h) approach. After studying 40 beaver ponds in North and South America, they concluded that with only two measurements of pond depth and corresponding surface area their method estimated surface-water storage in beaver ponds within 5% accuracy on average.

Several methods exist to calculate the peak discharge from both natural and man-made dams. Butler (1989) examined several cases of known dam failure and subsequent rapid drainage of beaver ponds in the Piedmont region and reconstructed the discharge from these ponds using standard hydrologic relationships of stream dimensions or pond volume to discharge. However, Butler noted that most of the channels that drained the ponds were either perched on granite bedrock or had minimal soil mantle covering the bedrock and therefore had little to no incision in the channels. Costa (1988) analyzed multiple types of natural dam failures and derived equations to be used to calculate the maximum discharge expected from different failures. Butler (1989) used the equation for landslide dam failure from Costa (1988) to calculate peak discharge in some observed failures in their study. More recently, King County (2013 a, b) used the 2007 Dam Safety Guidelines, Technical Note 1: Dam Break Inundation Analysis and Downstream Hazard Classification, Publication Number 92-55E from the Washington State Department of Ecology (hereby referred to as Tech. Note 1) to calculate the peak discharge for two different failures observed in this study using equations derived by Froelich (1995) and Fread (1987).

Geologic Setting

The Puget Lowland region of western Washington State displays abundant effects of ice-sheet occupation, a result of multiple advances of the Puget lobe of the Cordilleran ice sheet during several episodes of Pleistocene glaciation (Easterbrook, 1986). At least seven glacial/interglacial cycles have been documented in the subsurface and along upland valley walls in the Puget Lowland (Troost and Booth, 2008). The last major glaciation of the area was the Fraser glaciation (Armstrong et al., 1965), which is subdivided into four stades. The Vashon stade represents the maximum advance of the Cordilleran ice sheet. In the central Puget Lowland, the Vashon drift consists of the Lawton Clay member deposited in proglacial lakes, overlain by the Esperance Sand member (Mullineaux et al., 1965) deposited by meltwater streams from the advancing ice sheet, overlain by the Vashon till member

(Mullineaux et al., 1965), and lastly recessional outwash sand, gravel, and ice-contact deposits. These clean sand and gravel layers are more erodible because they lack silt or clay to bind them and make them more cohesive. Places where debris flows encounter these loose recessional deposits on the hillsides are particularly susceptible to erosion.

Observations from King County show that rapid channel incision from beaver dam failures tends to be concentrated in areas where the channels appear to cut through glacial outwash sands (J. Bethel, Personal Communication, 2017). However, till and hard, fine-grained deposits are also eroded. The erosion of these deposits within the stream channel, as well as sediment coming from the dam and pond itself, can lead to deposition of large alluvial fans composed of fine sand to boulder size material. Removal of substantial amounts of material within the channel also leads to over-steepened channel walls that have the potential to fail and cause further damage by either creating a new landslide dam or by aggrading behind culverts leading to inadequate passage of flow during high water periods.

Study Areas

The watersheds in this study are generally located in the Snoqualmie River valley or in tributaries that feed the Snoqualmie River (Figure 1). The beaver ponds are perched atop the thick Quaternary deposits that compose the hillsides surrounding the river valley and the channels drain down steep slopes towards the relatively flat expanse of the river valley below. All the failures noted in Figure 1 from King County are characteristic of these steep channels. Table 2a below summarizes the characteristics of each of the failure sites.

The Snoqualmie Valley Trail (SVT) washout is located 1 mile (mi.) north of Fall City, WA. The event occurred in late April 2005 following 5.9 inches (in.) of rain in March and 6.0 in. of rain in April of that year (King County HIC, 2018). The failure wiped out the culvert under the SVT crossing and deposited a large alluvial fan at the base of the slope. The channel drains to the southwest towards the Rutherford Slough in the Snoqualmie River valley (Figure 1). I also measured erosional volumes of streams near the SVT site for the same timeframe (between 2003 and 2014) to identify values of erosional volume at other streams with no known beaver activity (Figure 2). This allows for a comparison of the magnitudes of materials that are being eroded from the channels with known beaver dam failures and those without. Table 2b below summarizes the characteristics of the reference reaches near the SVT site.

The Tate Creek washout is located 3 mi. north of North Bend, WA. The last failure occurred in June 2010. McLeod Lake is the headwaters of the stream that drains west before joining Tate Creek and flowing southwest towards the North Fork Snoqualmie River (referred to as Lower Channel in this study) before crossing under SE 73rd Street (Figure 1). Tate Creek consistently deposits substantial amounts of sediment at its mouth on the Mountain Creek Christmas Tree Farm and further downstream at the culvert under SE 73rd Street.

The Deer Creek Washout is located 2 mi. south of Duvall, Washington (Figure 1). On November 5, 2012 a beaver dam failure at the outlet of an unnamed lake caused flooding over the roadway at 269th Way Northeast and Northeast 124th Street (King County Deer Creek Project website, 2016). Two properties downstream of the dam were also impacted by flooding and heavy sediment deposition (King County, 2013a).

The Preston dam is located 1 mi. NW of the town of Preston, Washington along SE High Point Way parallel with Interstate-90. The channel drains south into a flat area where a local business park is located along the I-90 corridor (Figure 1). The last known failure events recorded by King County occurred in late 2015 and in December 2016. LiDAR was collected in this area during March of 2016 and so this study reflects the channel response to the 2015 failure.

The Tolt River dam is located 2.5 mi. east of the town of Carnation, Washington south of the main fork of the Tolt River. The channel drains northwest into an active low-flow channel on the left bank of the Tolt River (Figure 1). The last known failure event recorded by King County occurred in November 2010. The county made no recorded estimates of breach peak flow or volume however the complaint report (Drainage Complaint file 2010-0560 and 2011-0123) includes investigation and citizen observations.

The Evans Creek dam is located on a hill just south of the intersection of Redmond-Fall City Road and 264th Avenue NE, 2 mi. east of the town of Sammamish, Washington (Figure 1). The pond complex consisted of a series of 3 – 4 dams and at least two of them broke at various times in 2000, 2001, and 2005 (Brian Sleight, pers. comm.). The channel drains north towards 264th Avenue NE before meeting up with Evans Creek along NE Redmond-Fall City Road. The pond complex is on the northwestern edge of the Soaring Eagle Regional Park.

Table 2a. Study area site characteristics.

Site	SVT	Tate Crk.	Deer Crk.	Preston	Tolt	Evans Crk.
Latest Failure	2005	2010	2012	2016	2010	2005
Channel Length (ft.)	5,500	3,200 (Upper) 9,400 (Lower)	4,500	3,500	4,500	3,100
Channel Slope	9.6%	5.9% (Upper) 4.9% (Lower)	4.4%	11%	8.3%	5.6%
Pond Elevation (ft. AMSL)	590	1,010*	246	860	530	280
Base Elevation (ft. AMSL)	115	460	54	520	160	120
Average Ravine Width (ft.)	400	75 (Upper) 480 (Lower)	285	285	500	470
Maximum Ravine Depth (ft.)	145	23 (Upper) 170 (Lower)	82	60	160	88
Ravine Side Slope	73%	61% (Upper) 30% (Lower)	58%	42%	64%	37%
Drainage Area (mi.^{2})	0.16	1.9**	0.49	0.35	1.3	0.08

*Upper Channel confluence with Tate Creek is 840 ft. AMSL
**Drainage area for the Lower Channel which includes the Upper Channel area

Table 2b. SVT reference reach site characteristics.

Reference Channel	1	2	3	4	5
Channel Length (ft.)	4,000	4,100	3,700	3,300	3,600
Channel Slope	9.6%	14%	12%	11%	17%
Headwater Elevation (ft. AMSL)	705	692	686	954	737
Base Elevation (ft. AMSL)	320	137	230	590	116
Average Ravine Width (ft.)	745	1,415	431	512	515
Maximum Ravine Depth (ft.)	184	224	147	125	112
Ravine Side Slope	71%	39%	65%	50%	47%
Drainage Area (mi.^{2})	1.0	0.17	0.34	0.22	0.15

Methods

Communication with the King County Department of Natural Resources and Parks (DNRP), Water and Land Resources Division (WLRD), and Stormwater Services (SWS) groups identified the locations of failures within the past two decades (Figure 1). Retired geomorphologist John Bethel and engineers Brian Sleight and Don Althauser also provided anecdotal and photographic evidence of the six identified failures.

Once the ponds were identified, I mapped the extent of the ponds using both aerial imagery and light detecting and ranging (LiDAR) topographic data. The LiDAR data from 2003, 2005, 2014, and 2016 was gathered from the Washington Department of Natural Resources (DNR) LiDAR Portal. Google Earth historical aerial imagery was used to map the extents of the ponds. Analysis of aerial imagery from Google Earth shows the surface area of the ponds at the different sites varies over time. The historical imagery available via Google Earth was important to have to reference the pond area prior to the failures for the peak discharge calculations. The aerial imagery that was closest to the time of the dam failure was used to calculate the surface area. The volume of the ponds was estimated using the equation

$$V_{max} = \frac{A_{max} * h_{max}}{1+\frac{2}{p}} \qquad (1)$$

from Karran et al. (2017) where V_{max} is the maximum volume of the pond; A_{max} is the maximum surface area of the pond; h_{max} is the maximum depth of the pond (estimated here as the dam height); and p is a dimensionless morphometry coefficient that represents the shape of the bathymetric curve (i.e. the area-depth relationship of the pond). Karran et al. (2017) recommend a median coefficient value of 0.91 when the dam height is available. Because the depth of the pond was not measured in the field for all the sites in this study, using the dam height for pond depth likely underestimates the pond volume because it does not consider the bathymetry of the pond. Nonetheless, Karran et al. (2017) note that this method still produces an average pond volume error of only $\pm$ 5%.

Calculations of the pond volume allow for an estimation of the dam breach peak discharge. I computed the peak discharge from dam breaks using two different methods from Tech. Note 1. The first method uses Froehlich (1995) to compute dam break peak discharge using

$$Q_p = 40.1 V_w^{0.295} H_w^{1.24} \qquad (2)$$

where Q_p is the dam break peak discharge (cfs, cubic feet per second); V_w is the volume of water above the breach invert elevation at the time of the breach (acre-feet); and H_w is the height of water over the base elevation of the breach (feet). This method results in the lowest predicted error when compared with observed dam break floods but there is considerable scatter of the observed data about the regression line. The second method from Tech. Note 1 developed by Fread (1988) has the advantage over Froehlich (1995) in that the breach development time and width are used. The equation from Fread (1988) computes peak discharge by

$$Q_p = 3.1 W H_w^{1.5} \left[\frac{A}{A+\tau\sqrt{H_w}}\right]^3 \qquad (3)$$

where Q_p is the dam break peak discharge (cfs); W is the average breach width (see Equation 6 below); H_w is the height of water over the base elevation of the breach (feet); τ is the elapsed time for breach development (hours) (see Appendix A for equation); A is $23.4 S_a/W$ where S_a is the surface area of the pond (acres) at the pond level corresponding to H_w. The Fread (1988) equation has two variations. One variation assumes cohesionless embankment materials in the elapsed time for breach development (τ)

$$V_m = 3.75\ BFF^{.77} \qquad (4)$$

where V_m is the volume of material in the breach (yds^3) which is eroded from the dam face, and BFF is the breach formation factor where $BFF = V_w H_w$. The second variation in the elapsed time for breach development (τ) assumes erosion resistant embankment materials where

$$V_m = 2.50\ BFF^{.77} \qquad (5).$$

For the Fread (1988) equations, I assumed the breach to be rectangular. Because the cohesiveness of any given beaver dam varies by materials being used and because the definition of cohesionless versus cohesive materials is not specified in Tech. Note 1, this study utilizes both equations for V_m to identify two peak discharge values from the Fread (1988) equation. It should be noted that the Fread (1988) equation relies on measurements from the site. For the Preston dam, Tolt dam, and Evans Creek dam sites where dam break dimensions were not measured, H_w was assumed to be the same as the height of the dam. Dam heights were estimated using LiDAR for these sites. Further, Tech. Note 1 allows for calculation of the base width of the breach as a function of the eroded volume of material as

$$W_b = \frac{27V_m}{H_b(C+\frac{H_b Z_3}{2})} \qquad (6)$$

where V_m is the volume of material in the breach (yds^3) which is eroded from the dam face, H_b is the depth of the breach from dam crest to base elevation of breach (feet) (assumed to be the height of the dam), C is the crest width of the dam (feet) calculated by $C = 2 + 2\sqrt{H_b}$, and Z_3 is $Z_1 + Z_2$ where Z_1 is the slope (Z_1:1) of upstream face of dam and Z_2 is the slope (Z_2:1) of downstream face of dam. Where the dam dimensions were not measured in the field (Preston dam, Tolt dam, and Evans Creek dam), Z_1 was assumed to be 5 and Z_2 was assumed to be 1 since those are the dam parameters at the three dams that were measured by King County. Because of the high variability in the dam breach parameters and materials that compose beaver dams, I used the average of the three peak discharge calculations for my study.

The channel long profile was interpolated downstream of the ponds using LiDAR and 3D analyst tools in ArcMap v.10.5. The channel centerline was digitized using the "Hillshade" tool to create a topographic representation of the ground surface. The LiDAR data was used to verify that the digitized channel long profile polylines were indeed within the channel. The profiles were observed downstream of the pond both before and after the failure events to compare and identify areas of downcutting and aggradation. Instances and locations of downcutting were verified by the photographs provided by King County taken immediately after the failures at Snoqualmie Valley Trail, Deer Creek and Tate Creek or by field visits to the channels at Tate Creek and Snoqualmie Valley Trail in the fall of 2017. I further verified the depths of downcutting and aggradation using 'Minus' in the Raster Math tool of the 3D Analyst tool box in ArcMap. This procedure subtracts the raster cell values of one raster (the older 2003 or 2005 LiDAR dataset) from the raster cell values of another raster (the newer 2014 or 2016 LiDAR dataset) to produce a new raster showing the changes in elevation between the two datasets. While this procedure is useful for visualizing the changes to the channel and valley side slopes over time, overall erosion/deposition volumes within the channel and valley side slopes was identified using a cut and fill analysis in the 3D Analyst tools in ArcMap. The "Cut Fill" tool enables you to create a map based on two input surfaces—before and after—displaying the areas and volumes of surface materials that have been modified by the removal or addition of surface material. This tool creates a table of values that can be summed to calculate the total volume change between the two raster surfaces. A 100-foot buffer was created around the channel centerline to clip the LiDAR for the channel area from before and after the event for analysis of erosion/deposition within the channel as well as along the valley side slopes. The 100-foot buffer was chosen to be certain to capture the changes in the valley side wall and not just the channel. Here it should be noted that the older LiDAR obtained from King County is inferior in quality to the newer LiDAR. The older LiDAR may contain remnants or artifacts of post-processing that could skew results of the GIS analysis. For example, areas with heavy vegetative cover could either be identified as false ground surfaces or they could have been removed completely and instead interpolated to create a false ground surface that varies from what is truly present.

To identify vulnerabilities for culvert design on the streams where these failures occur, I wanted to calculate the 100-year discharge for the six streams in this study. Giving officials the opportunity to plan for these large flows could be helpful for avoiding infrastructure damages like those seen at Deer Creek or SVT where culverts became overwhelmed and eventually washed out. I chose the 100-year discharge because (a) new culverts in King County are required to at minimum convey the 25-year discharge and must also convey as much of the 100-year discharge as is necessary to preclude creating or aggravating a severe flooding problem or severe erosion problem (King County SWDM, 2016), and (b) because I want to show how much larger these dam failure events are than the 100-year flow. I used the USGS StreamStats Version 4 online tool to determine the drainage area (square miles), annual precipitation (inches), and percent canopy cover for the streams. A spreadsheet associated with a USGS scientific investigations report (Mastin et al., 2016) then calculates flood discharge in Washington State at ungaged sites based on regional regression equations. For the SVT, Deer Creek, Lower Tate Creek and Evans Creek sites, the 100-year discharge was calculated at known road crossings where culverts are present. At the Tolt and Preston sites, the 100-year discharge was calculated at the mouth of the stream. At the Upper Tate Creek site, the 100-year discharge was calculated at the confluence of the upper channel with Tate Creek.

To determine the factors that most influence the volume of material eroded from the channel downstream of beaver dam failures, the calculated volume of eroded material within

100 feet of the channel centerline was plotted versus channel length, channel slope, pond volume, average peak discharge, and average peak discharge versus 100-year flood event ratio for each of the six observed channels.

Results

Pond Characteristics

Estimates for the pond volumes using the Karran et al. (2017) method vary between 8,020 at the Preston dam site to 59,600 cubic yards (yds^3) at the Tate Creek site (Table 3). One King County report on the Deer Creek failure also provided a calculated pond volume for that failure. The 2013 report notes that the surface area of the lake is between 10 – 12 acres (48,400 – 58,100 yds^2) and the depth of the pond to be between 4 – 5 feet (King County, 2013a). The 2013 report calculated volume of water released was 40 – 60 acre-feet (64,500 – 97,000 yds^3). The Karran et al. (2017) method calculates the volume of water in the pond as 59,600 yds^3 indicating that the pond volume estimations for other sites may be slightly low or that the King County estimate might not be accurate. King County (2013a) simply estimated the volume by using the 4 – 5 foot depth and the pond surface area of 10 – 12 acres to arrive at their volume calculations. Karran et al. (2017) considers the pond bathymetry in their equation which accounts for the variation from the broad estimate from King County (2013a). This discrepancy in pond volume could skew the results of the peak discharge calculations using Equation 2 since that equation relies on the volume of water behind the dam at the time of the breach.

Table 3. Summary of findings for each site.

Site	SVT	Tate Crk.	Deer Crk.	Preston	Tolt	Evans Crk.
Pond Surface Area (yds²)	46,347	85,633*	58,080*	23,440	32,890	33,966
Pond Volume (yds³)	26,600	45,400	59,600	8,020	11,300	10,570
Dam Height (ft.)	5.5*	4.0 – 5.0*	8 – 10*	3.0	3.0	3.0
Dam Crest Width (ft.)	3.0*	3.0*	3.0*	n/a	n/a	n/a
Channel Length (ft.)	5,500	3,200 (Upper) 9,400 (Lower)	4,593	3,281	4,500	3,100
Channel Slope	9.6%	5.9% (Upper) 4.9% (Lower)	4.4%	11%	8.3%	5.6 %
Max. Discharge (cfs)	555 - 761	667 - 806	490 – 856	189 – 284	245 – 368	229 – 353
Channel Bed Elevation Lost (ft.)	38	44	22	17	24	12
Channel Bed Elevation Gained (ft.)	24	16	22	12	33	12
Erosion within 100 feet of channel (yds³)	118,650	130,160	28,973	20,800	23,590	10,100

** measured/calculated by King County in the field or from images provided by King County*

Failure Characteristics

Average peak discharge calculations for the six sites vary between 241 at Preston dam to 718 cfs at Tate Creek (Table 4). Using the maximum volume from the King County report of 96,799 yds^3 for Deer Creek, Equation 2 from Froehlich (1995) yields a peak breach discharge of 987 cfs compared to the peak breach discharge of 856 cfs as calculated using pond volume from Karran et al. (2017). Furthermore, the variation in peak discharges calculated using Fread (1988) for both cohesionless and cohesive materials is apparent at each site (Table 4). This variation underscores the importance of the dam materials in calculating the peak discharge. For further comparison, King County calculated peak discharge between 549 – 888 cfs in their 2013 analysis of the Deer Creek failure (King County, 2013a). My study calculated peak discharges between 490 – 856 cfs for the same failure. With the unknown nature of the strength of the dam material in beaver dams, the lack of field-measured dam heights and break dimensions, and with calculated values from the two methods landing within the range of values calculated by King County, both methods are equally valid.

Table 4. Calculated peak discharges (cfs) from each of the six dam sites.

Site	Peak Discharge Froehlich (1995) (cfs)	Peak Discharge Fread (1988) – cohesionless (cfs)	Peak Discharge Fread (1988) – cohesive (cfs)	Average Peak Discharge (cfs)
SVT	761	571	555	629
Deer Creek	856	490	747	607
Tate Creek	806	682	667	718
Preston dam	251	284	189	241
Tolt dam	278	368	245	297
Evans Creek	272	353	229	285

100-Year Flood Events

Comparison of the 100-year flood event for each stream (Appendix B) to the calculated peak discharges for each dam failure event shows flows anywhere between 2.5 to 40 times the expected 100-year flood events (Table 5). Tate Creek, Tolt dam, and Evans Creek are all large watersheds and therefore larger flows are more likely. These streams would likely not be as affected by the failure of dams as the smaller streams like SVT, Deer Creek, and Preston dam sites might be. Figure 12 is a plot of the drainage area and calculated 100-year flow showing that the range in flow values is correlated to the size of the drainage area for each channel. The 100-year flood event on Tate Creek (labeled lower channel) is only 2.5 times smaller than the calculated peak discharge from the beaver dam failure while the 100-year flood event on the upper channel is 7.5 times smaller than the peak discharge coming from the dam failure.

Table 5. Ratio of calculated average peak discharge compared to 100-year flood event for each stream.

Site	Average Peak Discharge (cfs)	100-Year Flood Event (cfs)	Peak Discharge /100 Year Ratio
SVT	629	17.3	36
Deer Creek	607	40.3	15
Tate Creek – Upper	718	95.9	7.5
Tate Creek – Lower	718	285	2.5
Preston dam	241	44.2	5.5
Tolt dam	297	110	2.7
Evans Creek	285	7.1	40
Average	**463**	**84.0**	**17**

Channel Incision

Analysis of images provided by King County from the field following failures at SVT, Deer Creek, and Tate Creek show maximum channel incision depths of between 10 to 30 feet. Comparison of the channel long profiles from LiDAR data before and after these events also show similar incision depths (Figures 5a, 6a, 7a, 8a). The SVT channel profile shows most incision occurring in two sections: between 800 feet and 2,400 feet downstream of the pond and between 3,800 feet and 4,800 feet downstream (Figure 5a). The Tate Creek Upper Channel profile shows most incision occurs between 500 feet and 2,500 feet downstream of the pond (Figure 6a). The Tate Creek Lower Channel Profile shows most incision occurs between 2,700 feet and 5,000 feet downstream of the confluence (Figure 7a). The Deer Creek channel profile shows most incision occurring between SW Cemetery Road at 1,150 feet downstream of the pond and 2,900 feet downstream of the pond (Figure 8a). The other three profile comparisons, for Preston, Tolt, and Evans Creek, show channel incision depths of 15, 10, and 8 feet respectively (Figures 9a, 10a, 11a).

The most robust geologic analysis comes from King County (2013a) at the Deer Creek site. King County (2013a) split up the channel into 4 reaches: Reach 1 from the outlet to 1,160 feet downstream; Reach 2 from the outlet of the culvert under 269th Way NE to 2,900 feet downstream; Reach 3 downstream 4,750 feet to the culvert at NE 124th Street; and Reach 4 from the culvert downstream 530 feet to where the creek outfalls west of SR203. King County's geotechnical reconnaissance confirms the presence of glacial till deposits underlying most of Reach 1 where scour ranges from 2 – 4 feet in weathered soils. Reach 2 suffered the most substantial channel erosion of the four reaches due to the presence of surficial deposits of recessional sand and gravels where scour ranges from 5 to 30 feet deep, particularly in three knick point areas. The report further describes Reaches 3 and 4 as more of a depositional zone. Photographic evidence of similar geologic units, specifically of the recessional sands and gravels, showing deep scour confirms the control that channel geology appears to be exerting on the local erosional maximums in these channels.

Channel and Valley Sidewall Elevation Change

Cut and fill analysis of the 100-foot buffer around the channel centerline for each site estimates a net loss of between 10,100 yds^3 at Evans Creek to 119,000 yds^3 at SVT (Table 3) with an average amount of 55,400 yds^3. The change in elevation in the channel and valley side walls is visualized in Figures 5b, 6b, 7b, 8b, 9b, 10b, and 11b where the Raster Math tool 'Minus' shows the elevation change between the LiDAR datasets. The maximum elevation loss for all sites is 44 feet at Tate Creek in the Lower Channel (Figure 7b) and the maximum elevation gained is 24 feet at SVT (Figure 5b). These dramatic changes in elevation are not necessarily occurring within the stream channel itself but are direct results of the channel incising and widening causing undercutting of side slopes that leads to larger changes in elevation. The undercutting of the side slopes can also inject logjams and other large debris into the channel where aggradation can occur as the flow is impeded as noted by King County (John Bethel, Personal Communication, 2017).

The amounts of sediment being evacuated from the channels in this study are also of interest for the larger geomorphic landscape evolution of the area. Although the LiDAR datasets are separated by up to 13 years in some cases, the regular stream flow experienced in these channels is so low that little volume should be expected to be evacuated from the channel on an annual basis. This suggests that beaver dam failures are responsible for moving much more sediment than has previously been identified. For example, the cut-fill analysis of 5 streams near the SVT site (Figure 2) during the same time frame yielded an average net volume loss within 100-feet of the channel centerlines of 27,500 yds^3 (Table 6). Therefore, in the same time frame the SVT channel has eroded nearly 4 times more volume than the average surrounding streams and 2.25 times more than the largest stream. In terms of volume loss per drainage area, the SVT channel ratio is 1,160 yds^3/acre while the average is 113 yds^3/acre for the area. While this is only one example area, attempting similar analyses outside of the scope of work for this project could further quantify the amount of work these beaver dam failures can do in stream channels in comparison to non-beaver dam failure streams. This exceptional amount of work done by these beaver dam failures is a phenomenon not previously identified by others.

Table 6. Comparison of erosional volumes and drainage areas from 5 reference channels around the SVT site.

Stream Channel	**Volume Loss (yds^3)**	**Drainage area (acres)**	**Volume Loss/Drainage Area (yds^3/acre)**
Reference 1	52,500	659	79.6
Reference 2	2,880	110	26.4
Reference 3	9,880	217	45.5
Reference 4	58,300	141	415
Reference 5	14,100	141	147
Reference Average	*27,500*	*244*	*113*
SVT	119,000	103	1,160

Predictive Geomorphic Response

Since it is generally expected that the erosion should be greatest in situations where erosive force is large relative to the resisting forces, we should expect to see that factors like peak flow or pond volume should show a pattern of higher erosional volumes or more elevation lost with increases in those factors. We might also expect that channel slope could be a contributing factor to the elevation lost and/or erosional volume as steeper channels would tend to erode more readily. Without considering the role of potential differences in erodibility of different geologic units, Table 7 below shows that the data from this study indicates that average peak discharge and channel length are the key factors in controlling the volume of material eroded from the channel area and in the maximum changes in elevation. The negative R^2 values for the relationships between channel slope and erosional volume as well as maximum elevation lost show that even with the broad range in slope values, overall channel slope is not the predominant factor controlling the geomorphic response. Furthermore, the pond volume R^2 values also indicate that the pond volume behind the dams is not the best predictor for the erosional volume and maximum elevation lost.

These simple linear relationships identify the most useful trends for planners to quickly evaluate the expected geomorphic response of the streams when beaver dam failures occur. However, combining multiple factors in a multiple regression analysis allows for a more robust understanding of the controlling factors and how they relate to one another in determining the volume of eroded material and the maximum elevation lost.

Table 7. Linear equations showing the relationships between different calculated/measured factors and the expected volume of eroded material in the channel area.

Variable 1 (x)	Variable 2 (y)	Linear Equation	R^2 Value
Average Peak Q (cfs)	Erosional Volume (yds^3)	$y = 211x - 42200$	0.68
Channel Length (ft)	Erosional Volume (yds^3)	$y = 12.3x - 13200$	0.65
Pond Volume (yds^3)	Erosional Volume (yds^3)	$y = 1.05x + 27200$	0.17
Channel Slope (%)	Erosional Volume (yds^3)	$y = 669000x$	-0.17
Average Peak Q (cfs)	Max. Elev. Lost (ft)	$y = 0.05x + 3.76$	0.69
Channel Length (ft)	Max. Elev. Lost (ft)	$y = 0.003x + 9.58$	0.73
Pond Volume (yds^3)	Max. Elev. Lost (ft)	$y = 0.0003x + 18.7$	0.23
Channel Slope (%)	Max. Elev. Lost (ft)	$y = 317x$	-0.69

Channel geomorphic response should be expected to be controlled by more than one factor, especially in unique situations where each dam failure, pond volume, and channel dimensions are different. Table 8 below shows the results of a multiple regression analysis using average peak discharge and pond volume as factors influencing both erosional volume and maximum elevation lost. The table also shows the results of a multiple regression analysis using channel length and pond volume as factors influencing both erosional volume and maximum elevation lost. In this case, the relationship between average peak discharge and pond volume is the most statistically significant regression. A less statistically significant, though still useful regression is the relationship between average peak discharge, pond volume, and maximum elevation lost.

Table 8. Regression equations and variables used to show the relationships between multiple controlling factors to determine the erosional volume and maximum elevation lost in the channel area.

Variable 1 (x)	Variable 2 (z)	Variable 3 (y)	Regression Equation	Adjusted R^2 Value	Significance F Value
Average Peak Q	Pond Volume	Erosional Volume	$y = 75000 + 430x - 2.55z$	0.94	$6.85*10^{-3}$
Average Peak Q	Pond Volume	Max. Elev. Lost	$y = -2.50 + 0.09x - 4.70 * 10^{-4}z$	0.80	$4.28*10^{-2}$
Channel Length	Pond Volume	Max. Elev. Lost	$y = 9.32 + 0.003x + 2.88 * 10^{-5}z$	0.55	0.14
Channel Length	Pond Volume	Erosional Volume	$y = -13100 + 12.3x - 0.006z$	0.42	0.20

Discussion

Because we expect total erosion to be higher with longer channel length and because total erosion versus channel length does not consider differences in peak flow or pond volume, the most useful trend from this study is the direct relationship between average peak discharge from the dam and the erosional volume. With a calculation of the expected peak discharge from the dam, planners can use this relationship to identify the volume of material that might be eroded from the channel and valley sidewalls during a failure event. Further, the calculation of peak discharge requires the pond volume. While the pond volume to erosional volume relationship might not be as directly correlated as expected, the pond volume is still a crucial factor in controlling the peak discharge from the dam and therefore the expected volume of material to be eroded downstream.

Previous research focuses on the evacuation of sediment from the ponds themselves (Butler, 1989; Bigler et al., 2001). Many of these studies observe beaver ponds in rather flat, low-lying areas or in sequences of ponds within a wetland complex. The unique geologic setting in the Puget Lowland of erodible sandy deposits in the steep channels downstream of these beaver ponds perched atop bluffs creates an erosional hazard that should not be overlooked. Substantial amounts of sediment deposited in the alluvial fan of some of these failures (the SVT site and at the mouth of the Deer Creek site), are cause for concern for planners where property and infrastructure might be at risk.

While the maximum downcutting downstream that can occur is helpful for planners to prepare for the worst, the maximum downcutting value is not representative of what should be expected along the entire channel length. As seen in the channel cut-and-fill analysis figures, the channel experiences maximum downcutting in certain pockets of the channel rather than along the entire length. I recommend subsequent research examine the controls the geology imparts on the channel responses. Further complicating the effort to predict the expected effects downstream is the presence of large woody debris jams that accumulate in the channels as the debris flows make their way downstream (John Bethel, Personal Communication, 2017). As the channels incise and undercut the banks, the sidewalls can fail from over-steepening and woody debris can enter the system creating secondary dam failures that can cause more damage in the channel as the flows continue until the full volume of pond is drained.

Future Study

While this study did not look in depth into the role that the channel geology plays in the amount of incision or the amount of sediment evacuated from the channel, it is clear from King County's observations that certain geologic units will lead to differing amounts of geomorphic response in different segments of the channel. Further constraining the geologic units in the channels with the amount of incision or erosional volume could help to understand the geomorphic responses of different streams in the region. Using the concepts developed in this study to attempt to predict the geomorphic response to failures can help officials in other areas or counties plan for expected outcomes to hopefully reduce damage and validate the results of this study. Lastly, this study spotlights the amount of geomorphic work that beaver dam failures can do in high peak discharges. A study of the role beaver dam failures plays in the landscape evolution of the Puget Lowland on these small streams might yield surprising results as previous studies of beaver dam failures have concluded that minimal amounts of sediment are evacuated during failures. Lastly, more examples of beaver dam failures in the Puget Lowland can validate the predictions derived from this study. I also recommend that future failures be well documented in a comparable manner to this study and that an inventory of all the beaver dams on uplands be completed.

Conclusions

Recorded beaver dam failure events erode a massive amount of material and this erosion creates havoc along the channel and poses a sedimentation hazard downstream of the dam, particularly in the Puget Lowland where erodible deposits make up the hillsides. This study shows that it might be possible to relate the amount of eroded material from the channel as well as the maximum elevation lost in the channel to some readily-measured attributes, particularly the average peak discharge in congruence with the pond volume using the equation $y = 75000 + 430x - 2.55z$ where y is the predicted volume of eroded material, *x* is the pond volume, and *z* is the average peak discharge or using the equation $y = -2.50 + 0.09x - 4.70 * 10^{-4}z$ where y is the predicted maximum elevation lost in the channel. This is particularly useful for hazard prediction for public officials who should be concerned with the amount of material that could be moved downstream in the event of a beaver dam failure. Furthermore, these failures and the volumes of material they erode are very large relative to normal runoff-generated floods. Peak discharge calculations from the streams are shown to be anywhere from 2.5 to 40 times larger than the 100-year floods. While other large debris flow events can be generated by heavy rainfall downstream of impervious surfaces (i.e. neighborhoods), landslides, or ground-water blowouts, the amounts of material beaver dam failures erode suggests these events could also be a significant geomorphic agent creating these ravines in the Puget Lowland.

References

Armstrong, J.E., Crandell, D.R., Easterbrook, D.J., and Noble. J.B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington, *Geological Society of America Bulletin*, v. 76, pp. 321-330.

Bigler, W., Butler, D.R., and Dixon, R.W., 2001, Beaver-pond sequence morphology and sedimentation in northwestern Montana, *Physical Geography*, v. 22, issue 6, pp. 531-540.

Butler, D.R., 1989, The Failure of Beaver Dams and Resulting Outburst Flooding: A Geomorphic Hazard of the Southeastern Piedmont, *The Geographical Bulletin*, Virginia Beach, VA, v. 31, Issue 1, pp. 29 – 38.

Butler, D.R. and Malanson, G.P., 2005, The geomorphic influences of beaver dams and failures of beaver dams, *Geomorphology*, v. 71, pp. 48 – 60.

Costa, J.E., 1988, The formation and failure of natural dams, *Geological Society of America Bulletin,* v. 100, pp. 1054-1068.

Dugmore, A.R., 1914, The Romance of the Beaver, J. B. Lippincott Co., Philadelphia, 225 pp.

Easterbook, D.J., 1986, Stratigraphy and chronology of Quaternary deposits of the Puget Lowland and Olympic Mountains of Washington and the Cascade Mountains of Washington and Oregon, Quaternary Science Reviews, v. 5, p. 145-149.

Fread, D.L., 1988, DAMBRK: The NWS-Dam Break Flood Forecasting Model, Office of Hydrology, National Weather Service, Silver Spring, MD, June 20, 1988.

Froehlich, D.C., 1995, Peak Outflow from Breach Embankment Dam, ASCE Journal of Water Resources Planning and Management, v. 121, no. 1, pp. 90-97.

Hillman, G.R., 1998, Flood wave attenuation by a wetland following a beaver-dam failure on a second order boreal stream, Wetlands, v. 18, pp. 21-34.

Karran, D.J., Westbrook, C.J., Wheaton, J.M., Johnston, C.A., and Bedard-Haughn, A., 2017, Rapid surface-water volume estimations in beaver ponds, *Hydrology and Earth System Sciences*, v. 21, Issue 2, pp. 1039-1050.

King County, 2013a. Technical Memo: Deer Creek Complaint File (2012-0820 Pickering) – Project 1118768. Subject: Deer Creek Reconnaissance. January 2, 2013.

King County, 2013b. Technical Memo: Tate Creek – Hazard Lakes and Dams File – Project 1117524. Subject: Tate Creek – Hazard Dam Analysis. May 13, 2013.

King County Surface Water Design Manual (SWDM), King County Department of Natural Resources and Parks, April 24, 2016.

King County Natural Resources and Parks Water and Land Resources Division, Stormwater Section, Capital Services Unit, Deer Creek Project website. Online at: https://www.kingcounty.gov/depts/dnrp/wlr/sections-programs/stormwater-services-section/capital-services-unit/deer-creek-flood-project.aspx. Last updated: March 9, 2016. Accessed March 6, 2018.

King County Watersheds and Rivers, Hydrologic Information Center (HIC), Data Download, Annual Summary Data for: Gauge 14u-East Fork Issaquah Rain Gauge. Available at: https://green2.kingcounty.gov/hydrology. Accessed 2/28/2018.

Kiro 7 News Staff, 2017, Beaver dam ruptures, floods roadway in Western Washington, Published: April 28, 2017, Accessed: May 1, 2017. URL: http://www.kiro7.com/news/local/beaver-dam-ruptures-floods-roadway-in-western-washington/517356453.

Lancia, R. A. and H. E. Hodgdon, 1983, Observations on the ontogeny of behavior of hand-reared beavers (Castor canadensis), Acta Zool Fenn. Helsinki : Finnish Zoological Publishing Board 174:117-119.

Mastin, M.C., Konrad, C.P., Veilleux, A.G., and Tecca, A.E., 2016, Magnitude, frequency, and trends of floods at gaged and ungaged sites in Washington, based on data through water year 2014 (ver 1.2, November 2017): U.S. Geological Survey Scientific Investigations Report 2016–5118, 70 p., http://dx.doi.org/10.3133/sir20165118.
MacCracken, J. G., A. D. Lebovitz, and J. Lewis, 2005, Selection of in-stream wood structures by beaver in the Bear River, southwest Washington. Northwestern Naturalist 86:49-58.

Mullineaux, D.R., Waldron, H.H., and Rubin, M., 1965, Stratigraphy and chronology of late interglacial and early Vashon time in the Seattle area, Washington: U.S. Geological Survey Bulletin 1194-O, p. O1-O10.

Naiman, R.J., Johnston, C.A., and Kelley, J.C., 1988, Alteration of North American streams by beaver, *Bioscience*, v. 38, pp. 753-762

Pollock M.M., Heim, M., and Werner, D., 2003, Hydrologic and geomorphic effects of beaver dams and their influence on fishes. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer K, Gurnell A. (eds). American Fisheries Society: Bethesda, MD; 213–233.

Pollock, M.M., Lewallen, G., Woodruff, K., Jordan, C.E., and Castro, J.M. (editors), 2015, The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains, Version 1.02, United States Fish and Wildlife Service, Portland, OR, 189 pp. Online at: http://www.fws.gov/oregonfwo/ToolsForLandowners/RiverScience/Beaver.asp

RCW 77.15.192, Initiative Measure No. 713, Approved November 7, 2000, 2003 c 53 § 374.

Rutherford, W.H., 1953, Effects of a summer flash flood upon a beaver population, Journal of Mammalogy, v. 34, pp. 261-262.

Stock, J.D., and Schlosser, I.J., 1991, Short-term effects of a catastrophic beaver dam collapse on a stream fish community, Environmental Biology of Fishes, v. 31, pp. 123-129.

Sullivan, J., 2012, Broken beaver dam unleashes flood near Duvall, *Seattle Times*, November 5, 2012.

Transportation Safety Board of Canada, 1994, A Special Study of Main Track Derailments-1994, Online at: http://www.bst.ca/en/reports/rail/studies/sr9401/sr9401.asp.

Troost, K.G., and Booth, D.B., 2008, Geology of Seattle and the Seattle Area, in Baum, R., Godt, J., and Highland, L. eds., Landslides and Engineering Geology of the Seattle, Washington Area, *Geological Society of America*, Special Papers XX, pp. 1-37, 2 plates.

Vermont Agency of Natural Resources, 1999, Options for State Flood Control Policies and a Flood Control Program. Online at: www.anr.state.vt.us/flood_control/.

Washington State Department of Ecology (Ecology), 2007. Dam Safety Guidelines, Technical Note 1: Dam Break Inundation Analysis and Downstream Hazard Classification. Publication Number 92-55E.

Washington Department of Fish and Wildlife (WDFW), 2004, Living with Wildlife in the Pacific Northwest, Written by: Russel Link, WDFW Urban Wildlife Biologist, pp. 11. Available online at: https://wdfw.wa.gov/living/beavers.pdf.

Figures

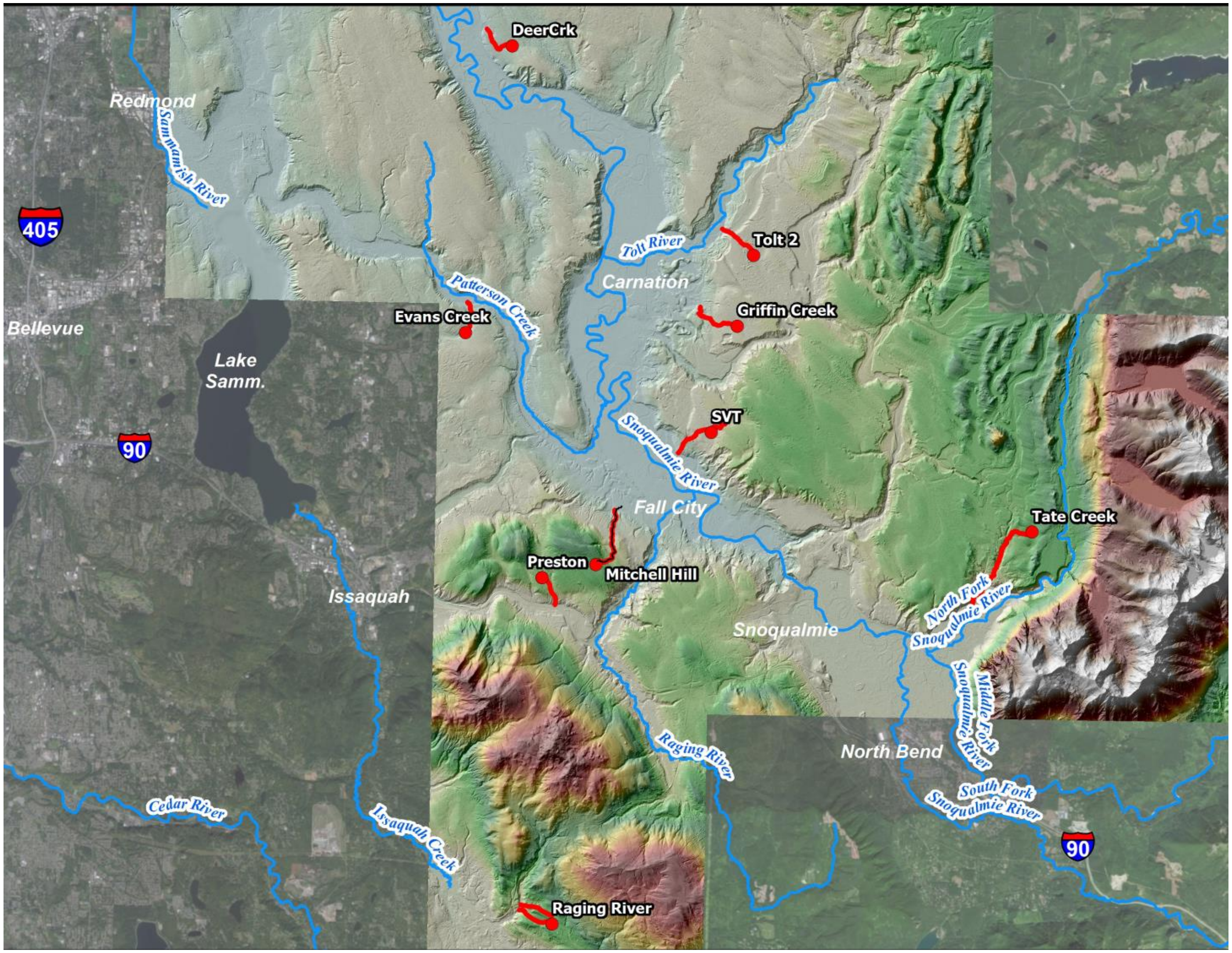


Figure 1. Map showing the locations of previously identified beaver dam failures in King County, Washington (red lines). This project focuses on the sites identified as Tate Creek, SVT, Tolt2, DeerCrk, Preston, and Evans Creek.

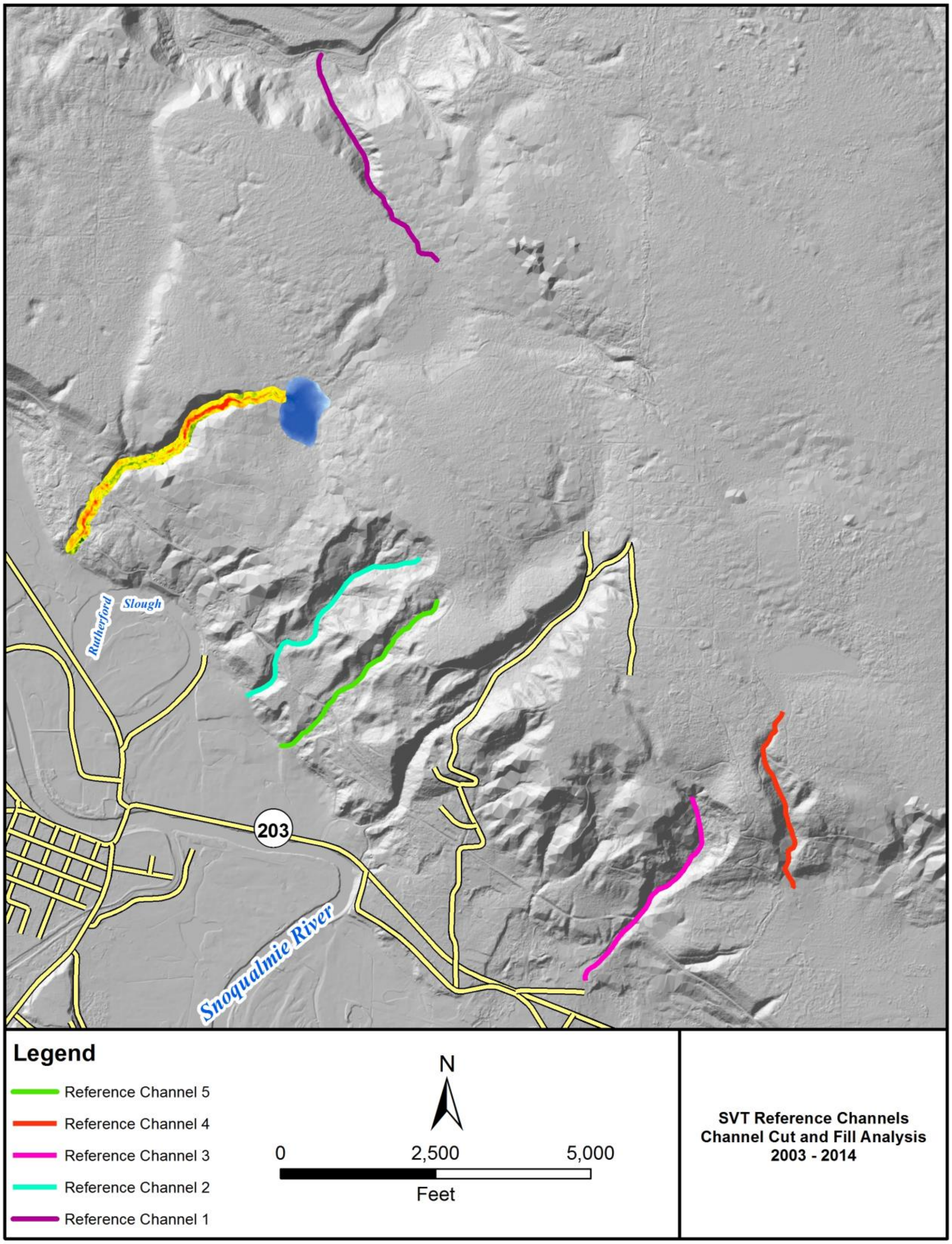


Figure 2. Map showing the locations of the reference reach streams used for comparison of erosional volume to the SVT failure. Base map derived from the 2014 LiDAR.

Figure 3a: Channel incision due to a beaver dam failure in Tate Creek in King County in 2011 (Source: John Bethel. Accessed: 2017).

Figure 3b: Fan deposition at the mouth of a stream below the Snoqualmie Valley Trail where a beaver dam failed in King County in 2005. Notebook is 7 inches tall. (Source: John Bethel. Accessed: 2017).

Figure 4a: Image of a concrete culvert that was blown out and transported downstream by the failure of a beaver dam upstream of the Snoqualmie Valley Trail in King County in 2005. Notebook is 7 inches tall. (Source: John Bethel. Accessed: 2017).

Figure 4b. Image of the damage to the Snoqualmie Valley Trail. Photo is looking across where the trail should connect across the stream in the bottom of the image. A King County employee is in the bottom center of the image wearing high-visibility green jacket. (Source: John Bethel. Accessed: 2017).

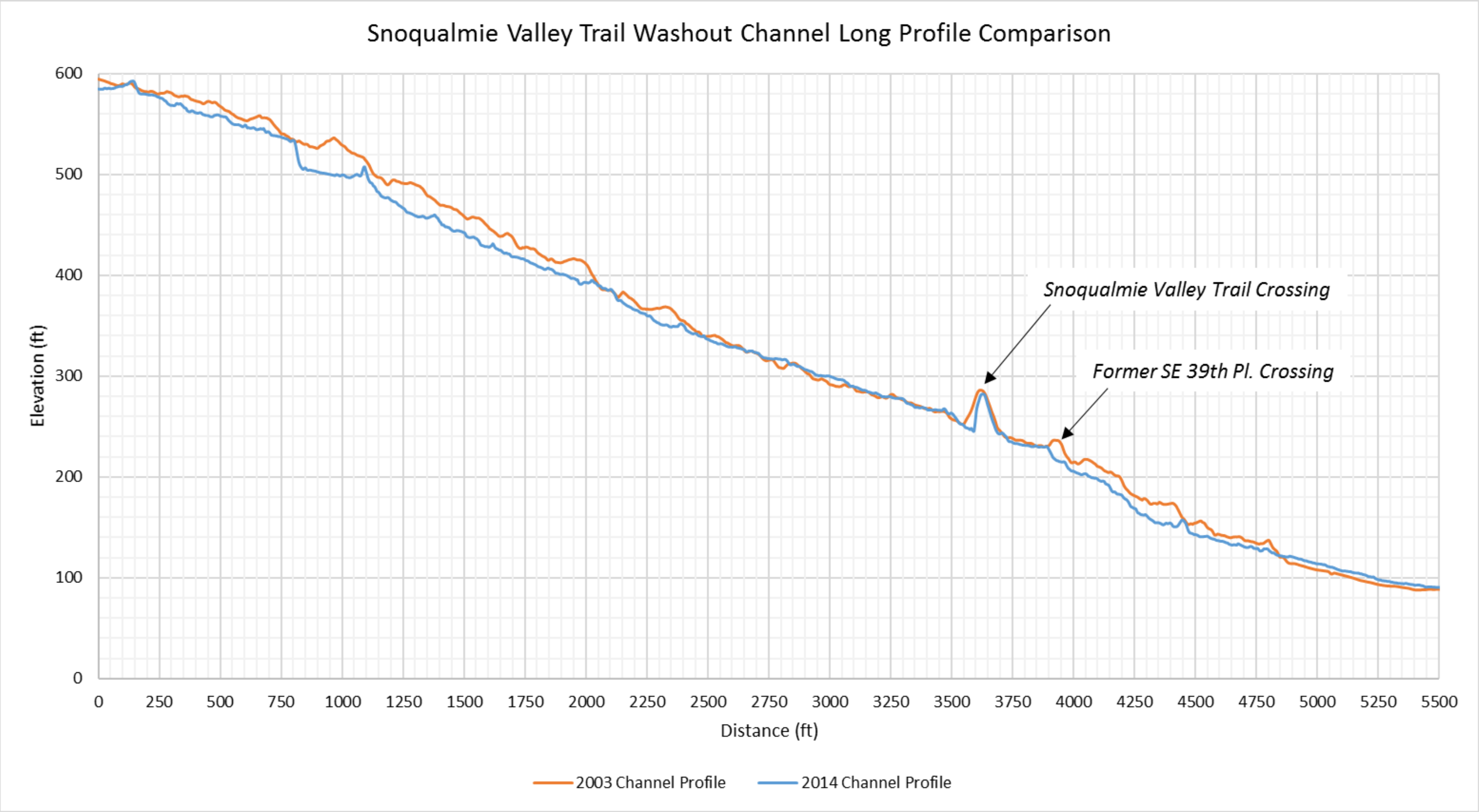


Figure 5a. Long profile channel comparison between 2003 and 2014 for the Snoqualmie Valley Trail Washout.

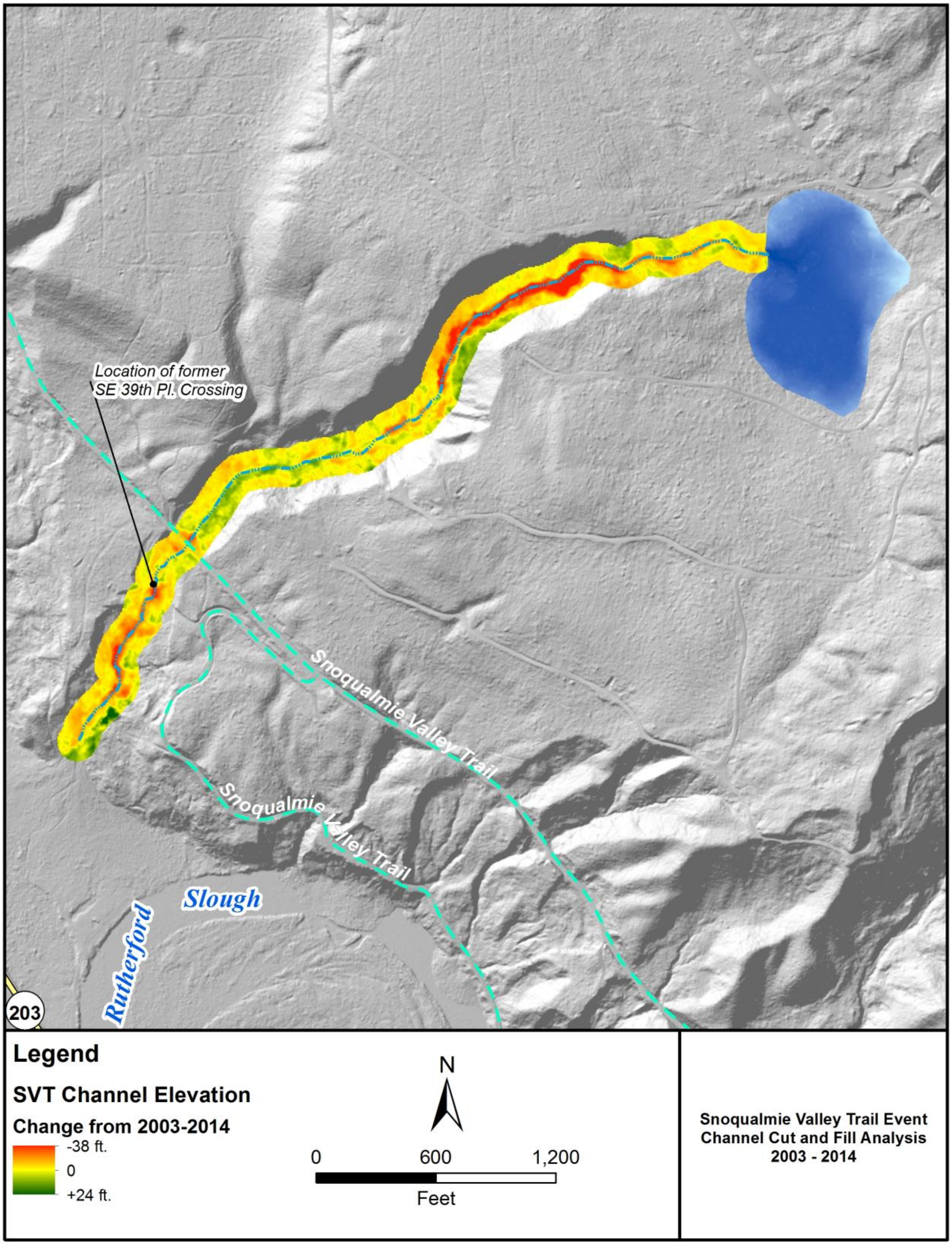


Figure 5b. Cut and fill analysis of the channel that drains the pond (shown in blue) at the site of the Snoqualmie Valley Trail Washout. The channel has degraded in areas of red and aggraded in areas of green between the 2003 LiDAR and 2014 LiDAR. Base map derived from the 2014 LiDAR.

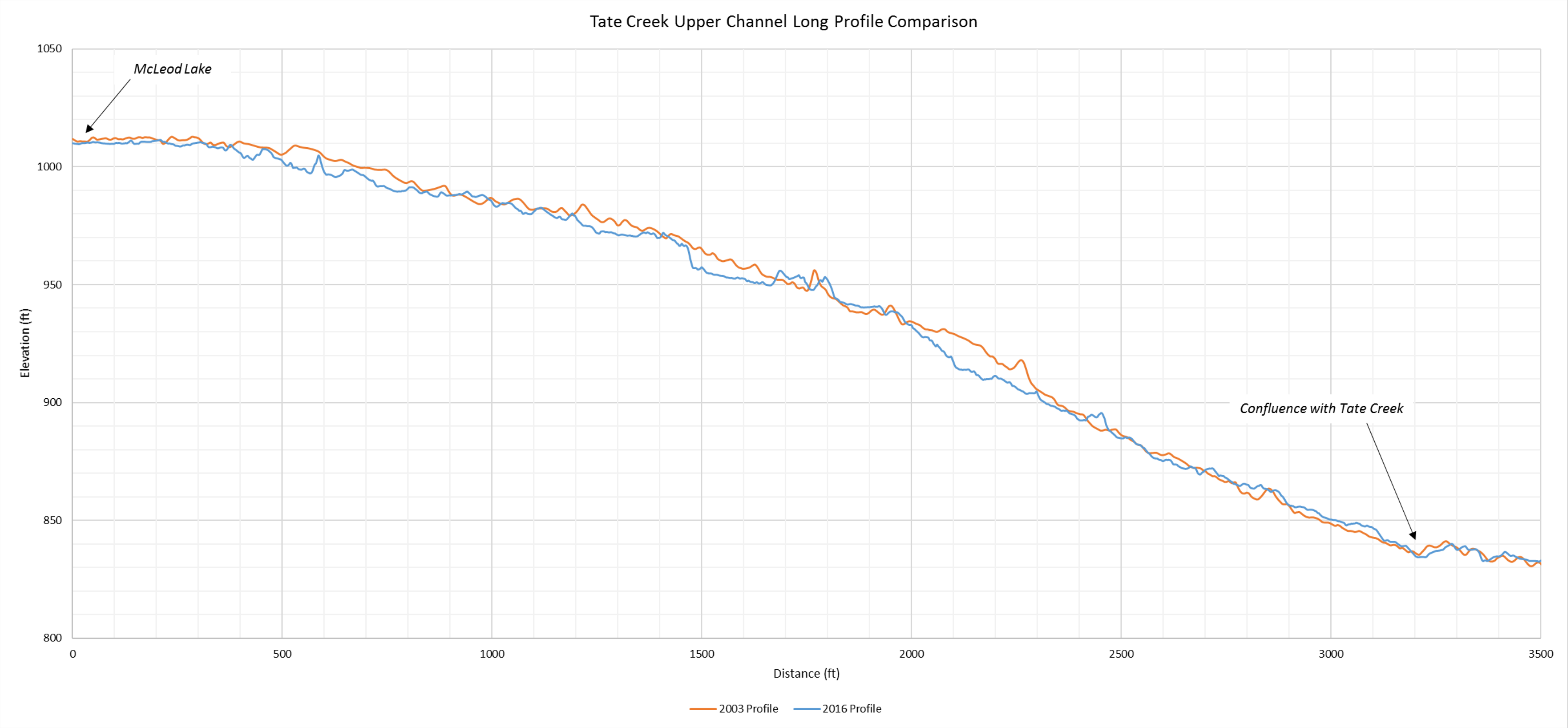


Figure 6a. Long profile channel comparison for the upper 3000 ft. of the Tate Creek failure between 2003 and 2016.

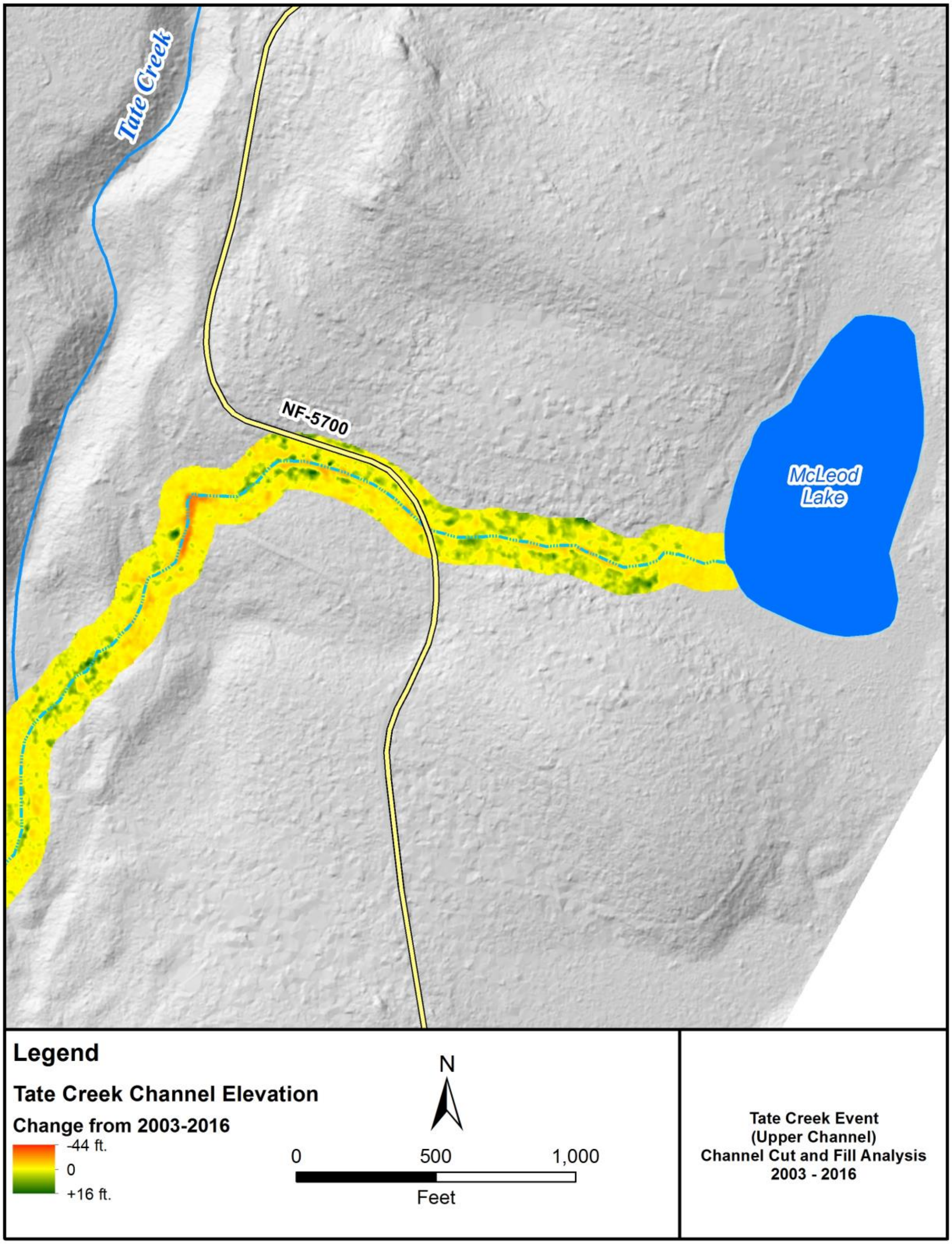


Figure 6b. Cut and fill analysis of the upper channel of the stream that drains McLeod Lake. The channel has degraded in areas of red and aggraded in areas of green between the 2003 LiDAR and 2016 LiDAR. The blue line delineating Tate Creek came from the National Hydrography Database and was not redrawn to match the new LiDAR used in this map. Base map derived from the 2016 LiDAR.

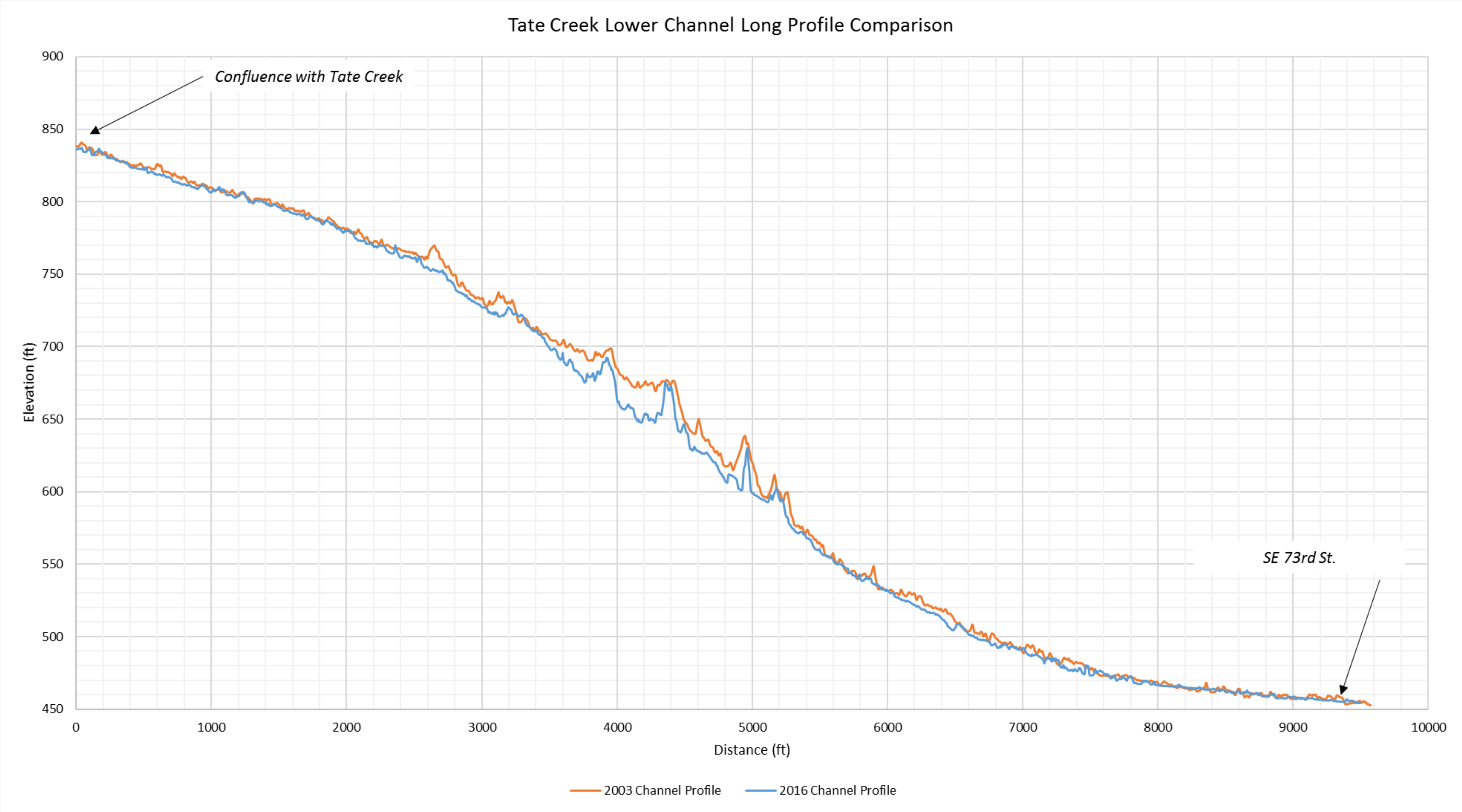


Figure 7a. Long profile channel comparison for the lower channel (downstream of confluence with Tate Creek) for the Tate Creek failure between 2003 and 2016.

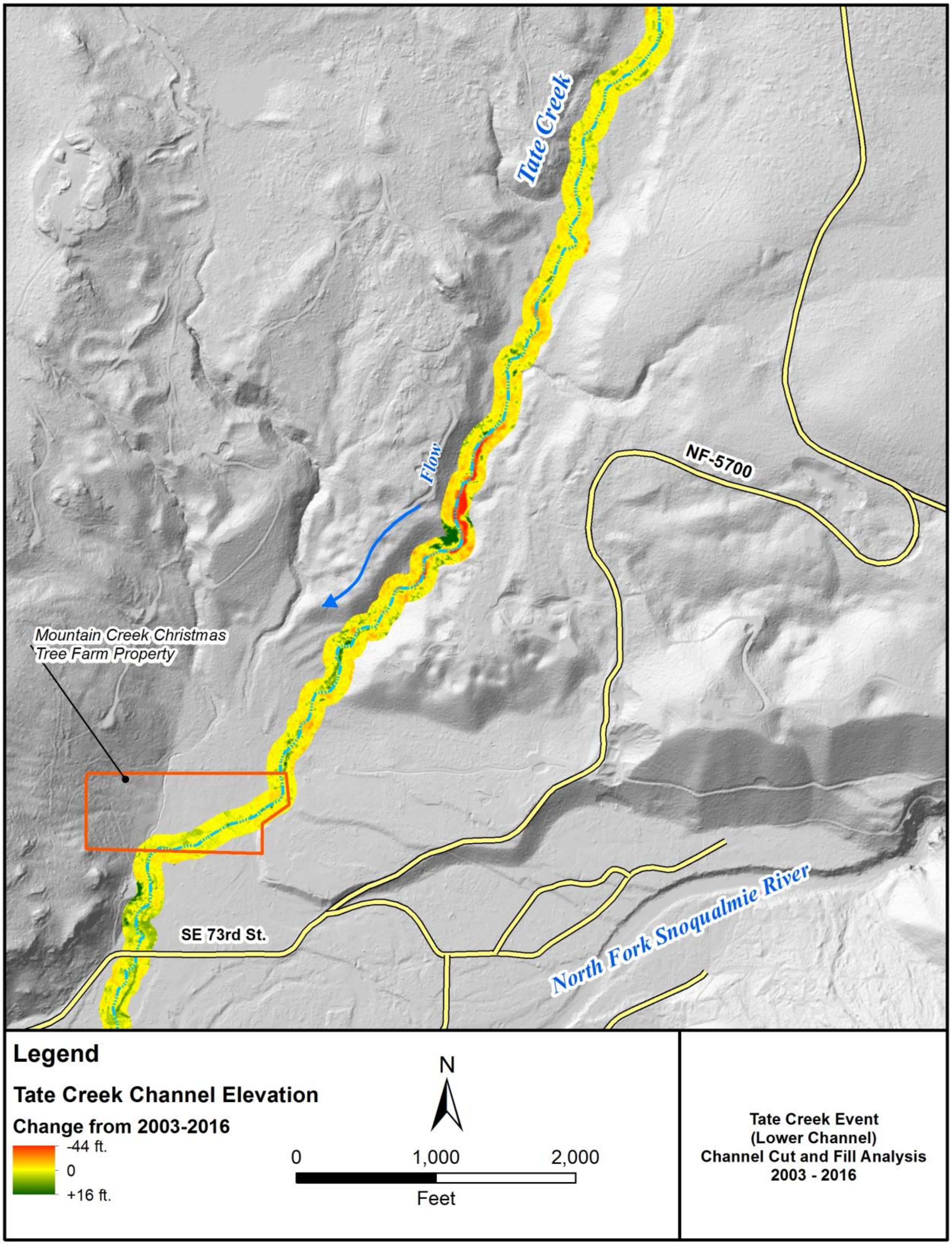


Figure 7b. Cut and fill analysis of the lower channel of the stream that drains McLeod Lake. The channel has degraded in areas of red and aggraded in areas of green between the 2003 LiDAR and 2016 LiDAR. Base map derived from 2016 LiDAR.

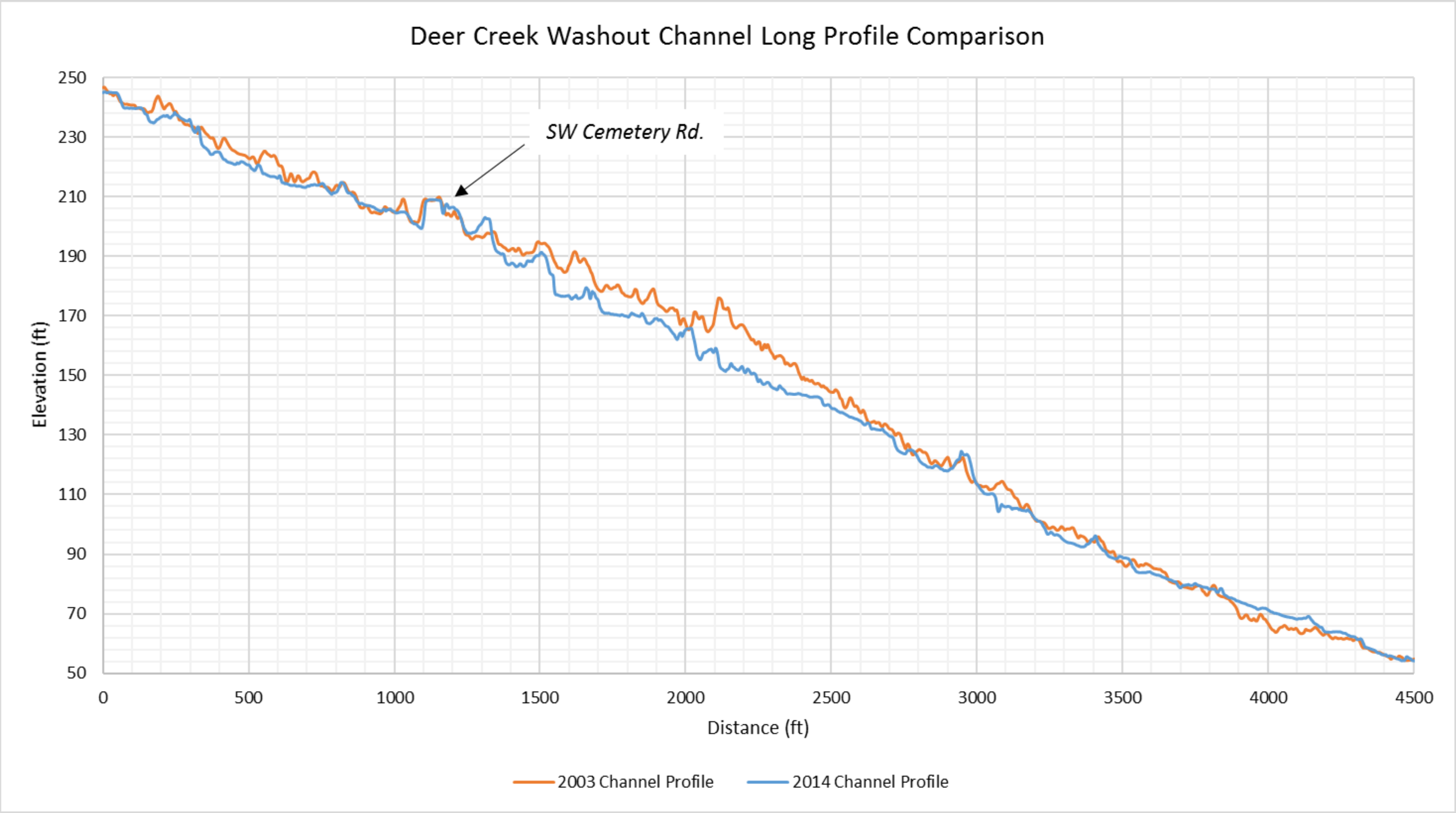


Figure 8a. Long profile channel comparison for the Deer Creek failure between 2003 and 2014.

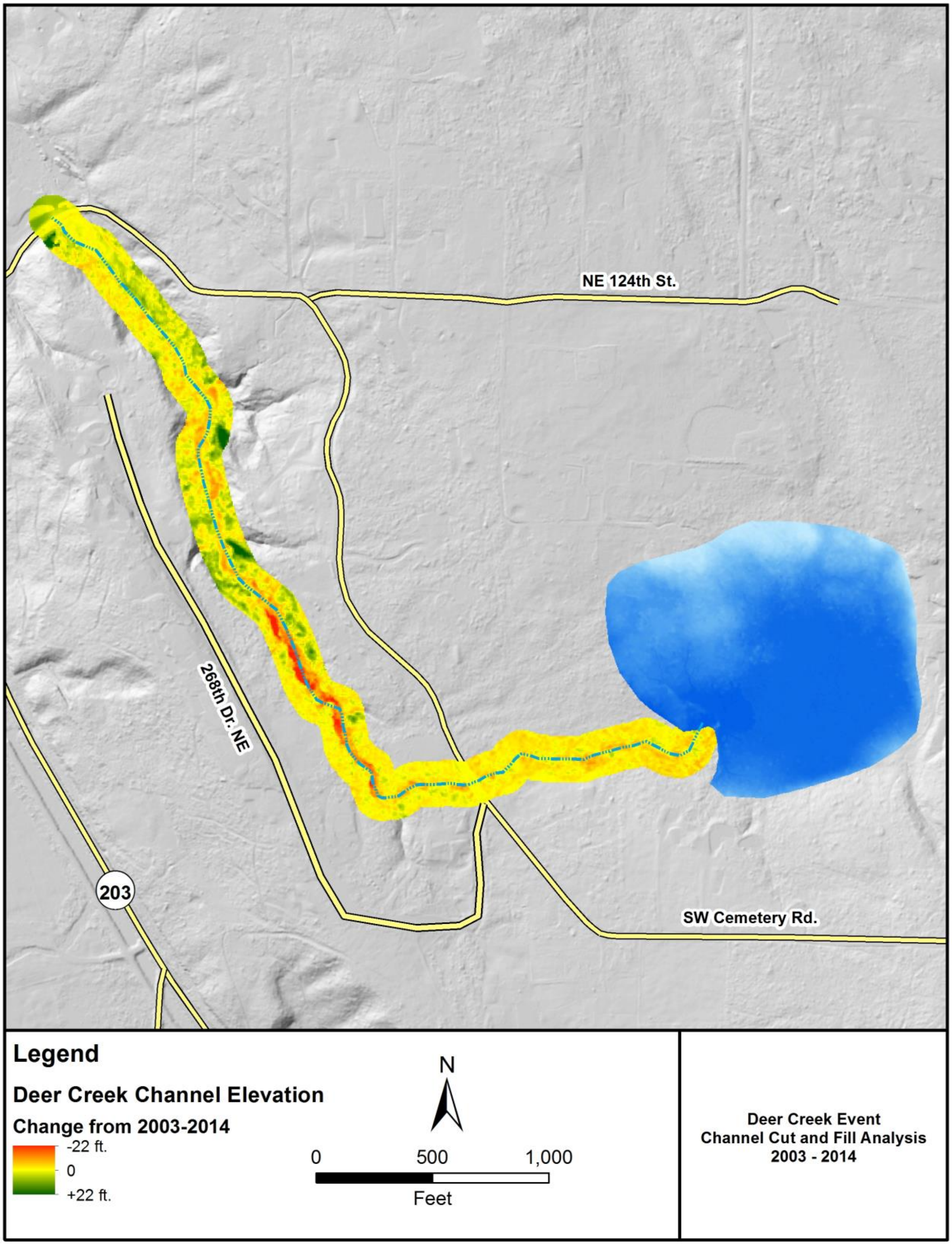


Figure 8b. Cut and fill analysis of Deer Creek which drains an unnamed pond near Novelty, Washington. The channel has degraded in areas of red and aggraded in areas of green between the 2003 LiDAR and 2014 LiDAR. Base map derived from 2014 LiDAR.

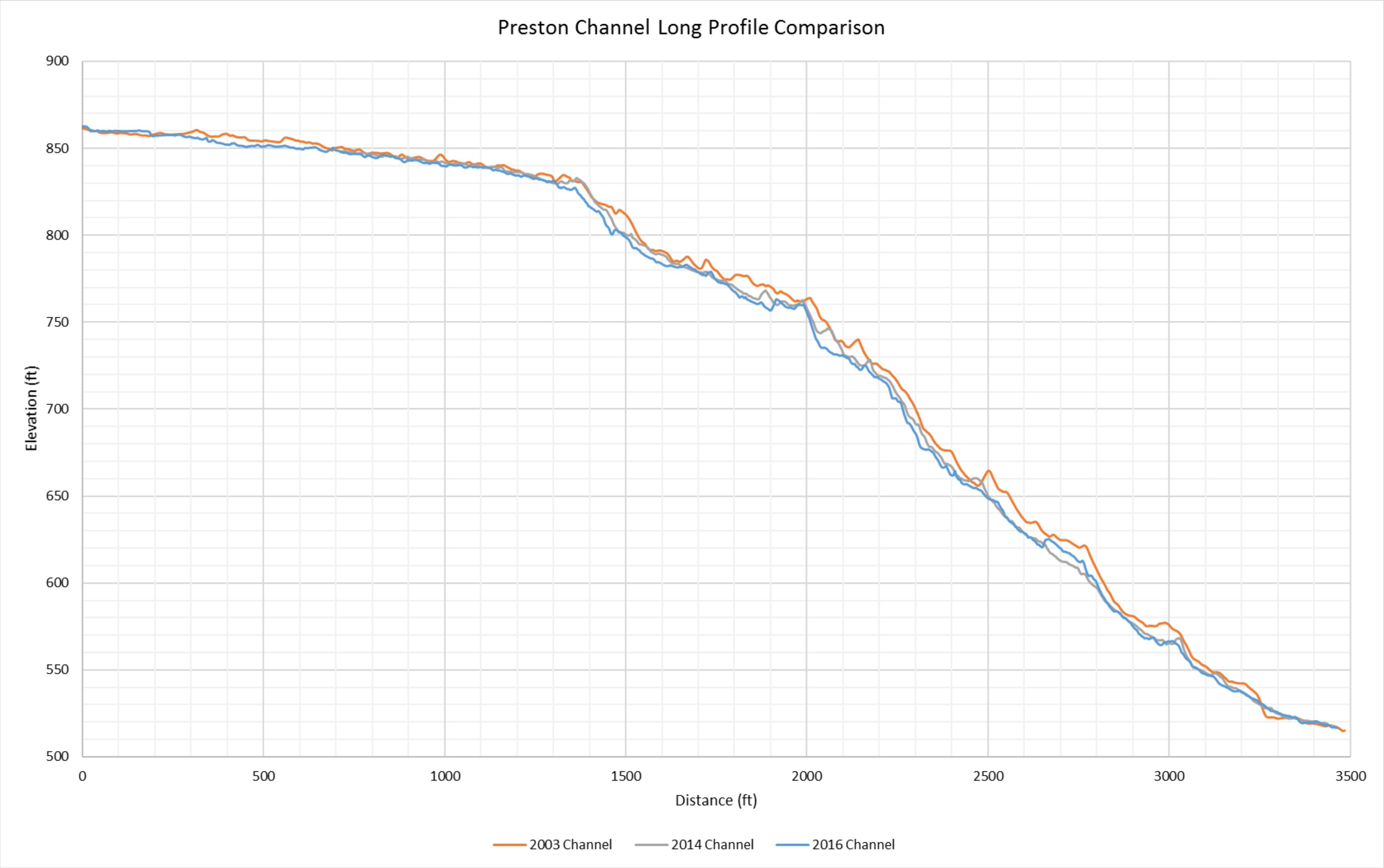


Figure 9a. Long profile channel comparison for the Preston dam channel between 2003, 2014, and 2016. The 2014 LiDAR dataset coverage begins approximately 700 ft downstream of the pond.

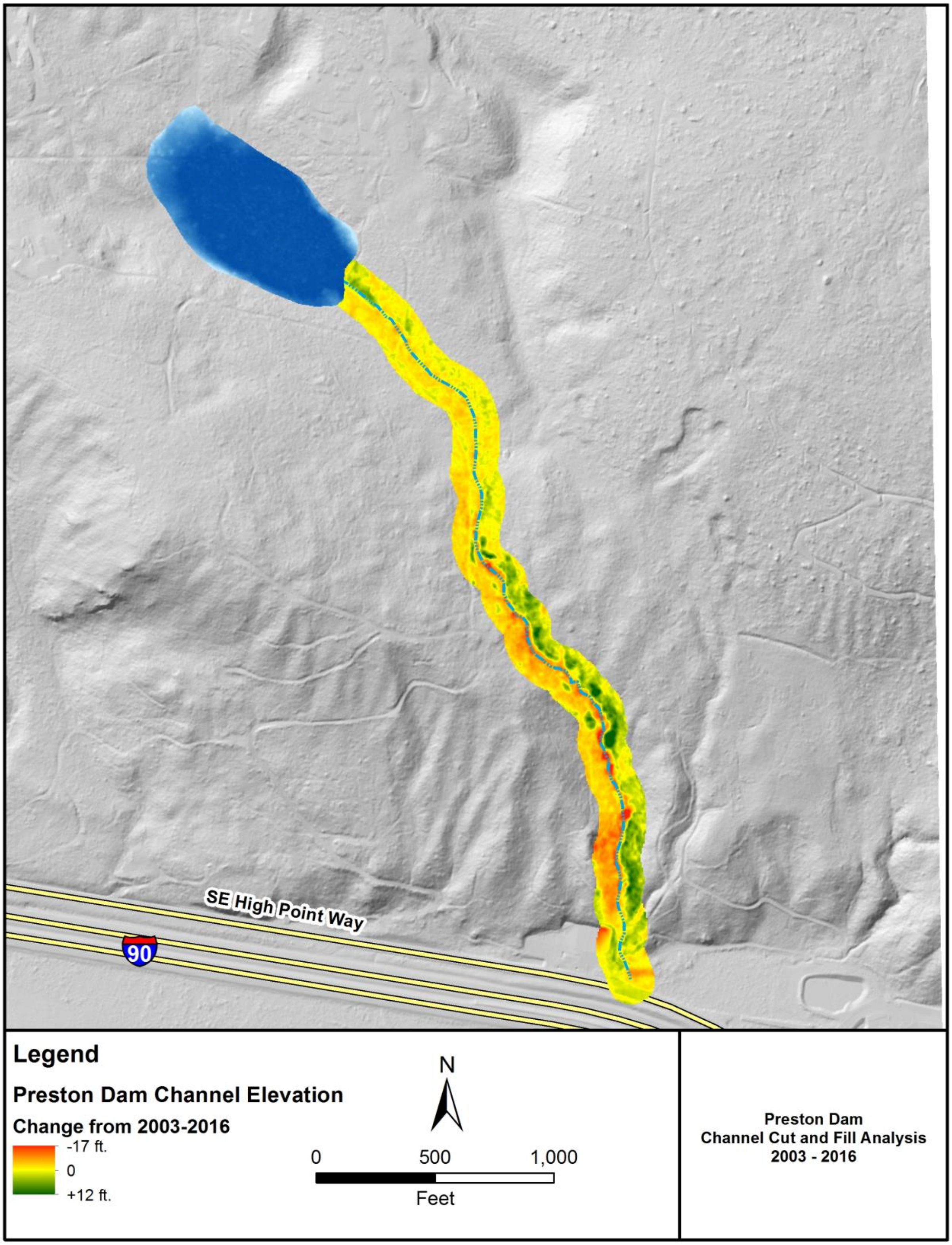


Figure 9b. Cut and fill analysis of the Preston dam which drains an unnamed pond near Preston, Washington. The channel has degraded in areas of red and aggraded in areas of green between the 2003 LiDAR and 2016 LiDAR. Base map derived from 2016 LiDAR.

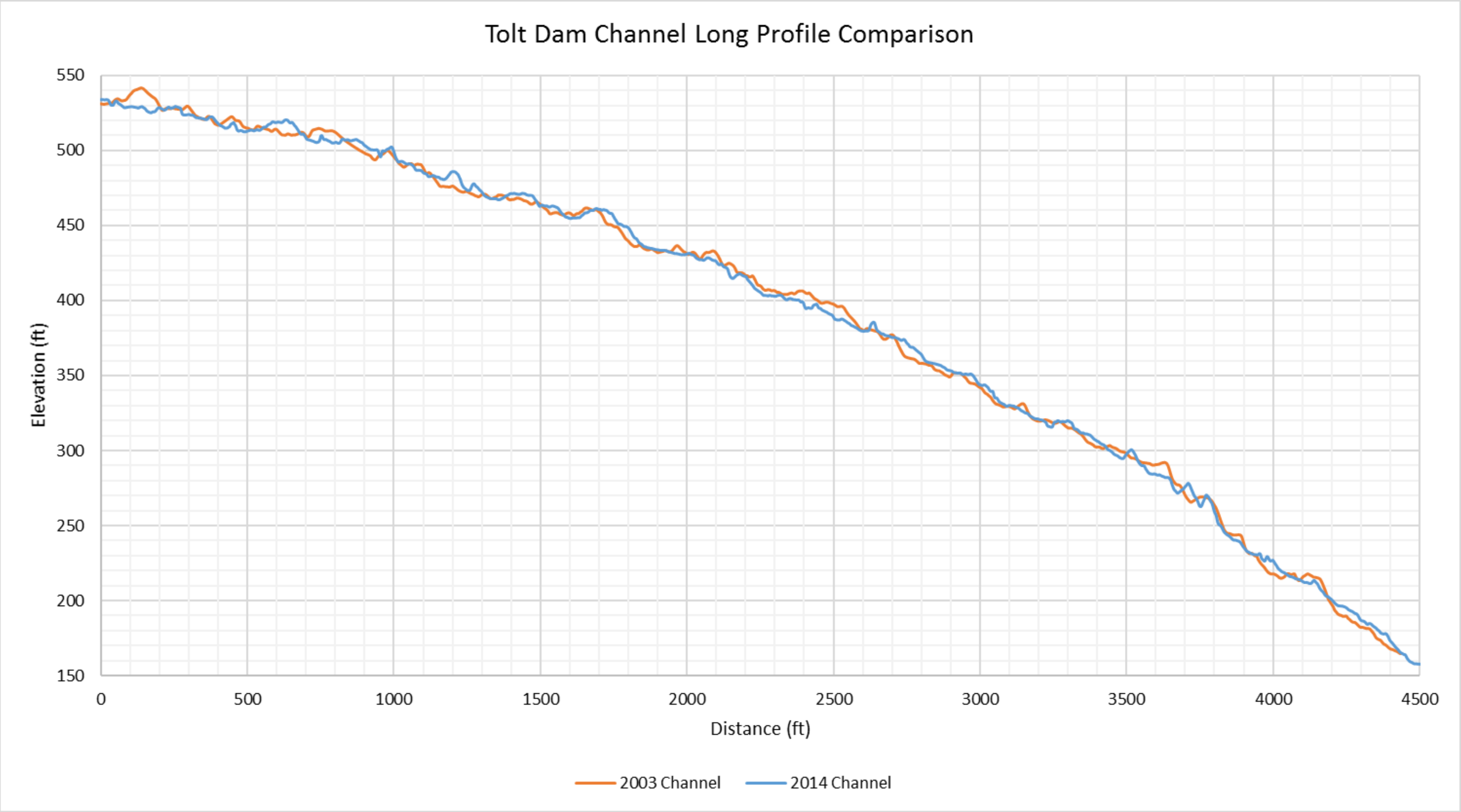


Figure 10a. Long profile channel comparison for the Tolt River dam channel between 2003 LiDAR data and 2014 LiDAR data.

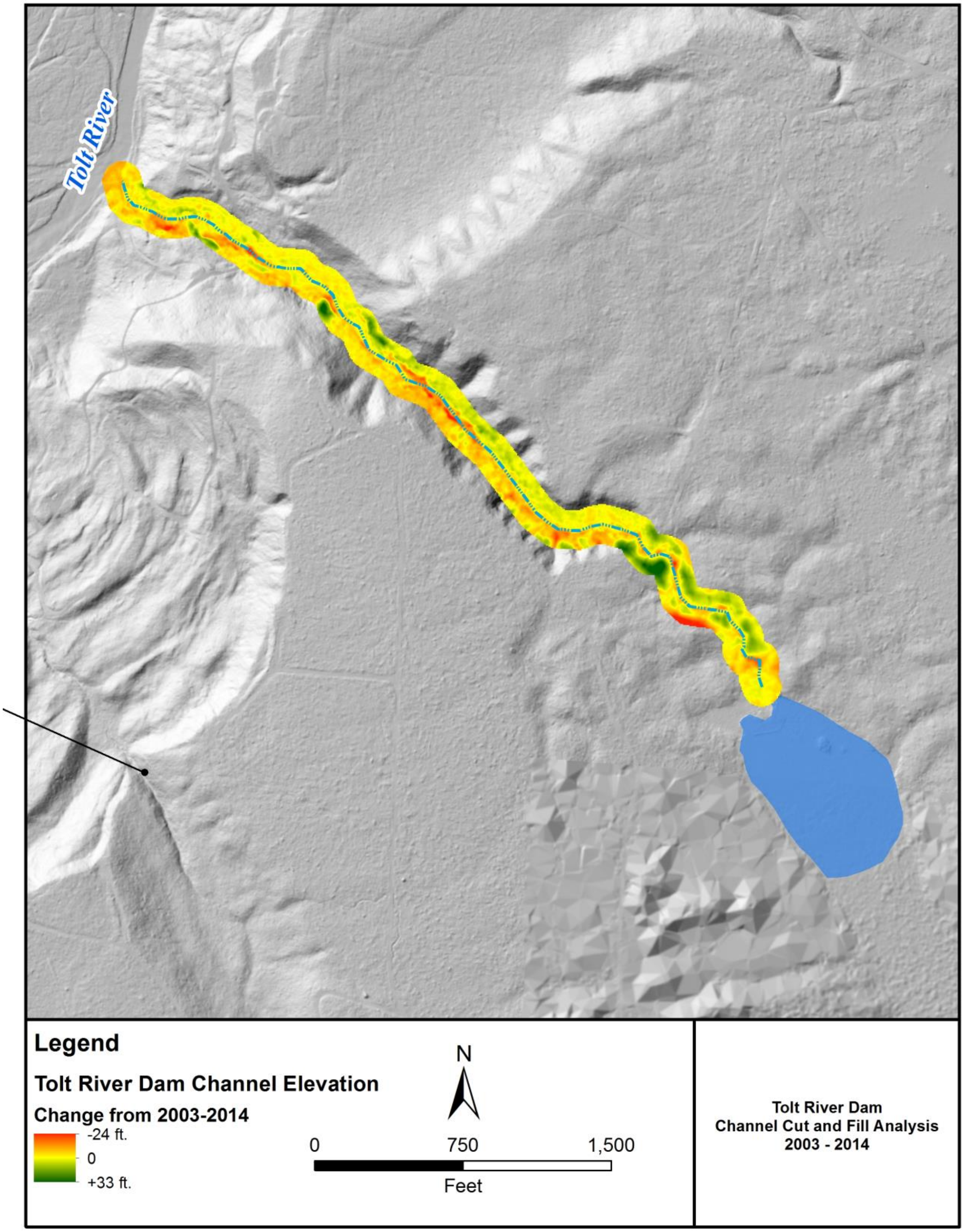


Figure 10b. Cut and fill analysis of the Tolt River dam which drains an unnamed pond east of Carnation, Washington. The channel has degraded in areas of red and aggraded in areas of green between the 2003 LiDAR and 2014 LiDAR. Base map derived from 2014 LiDAR.

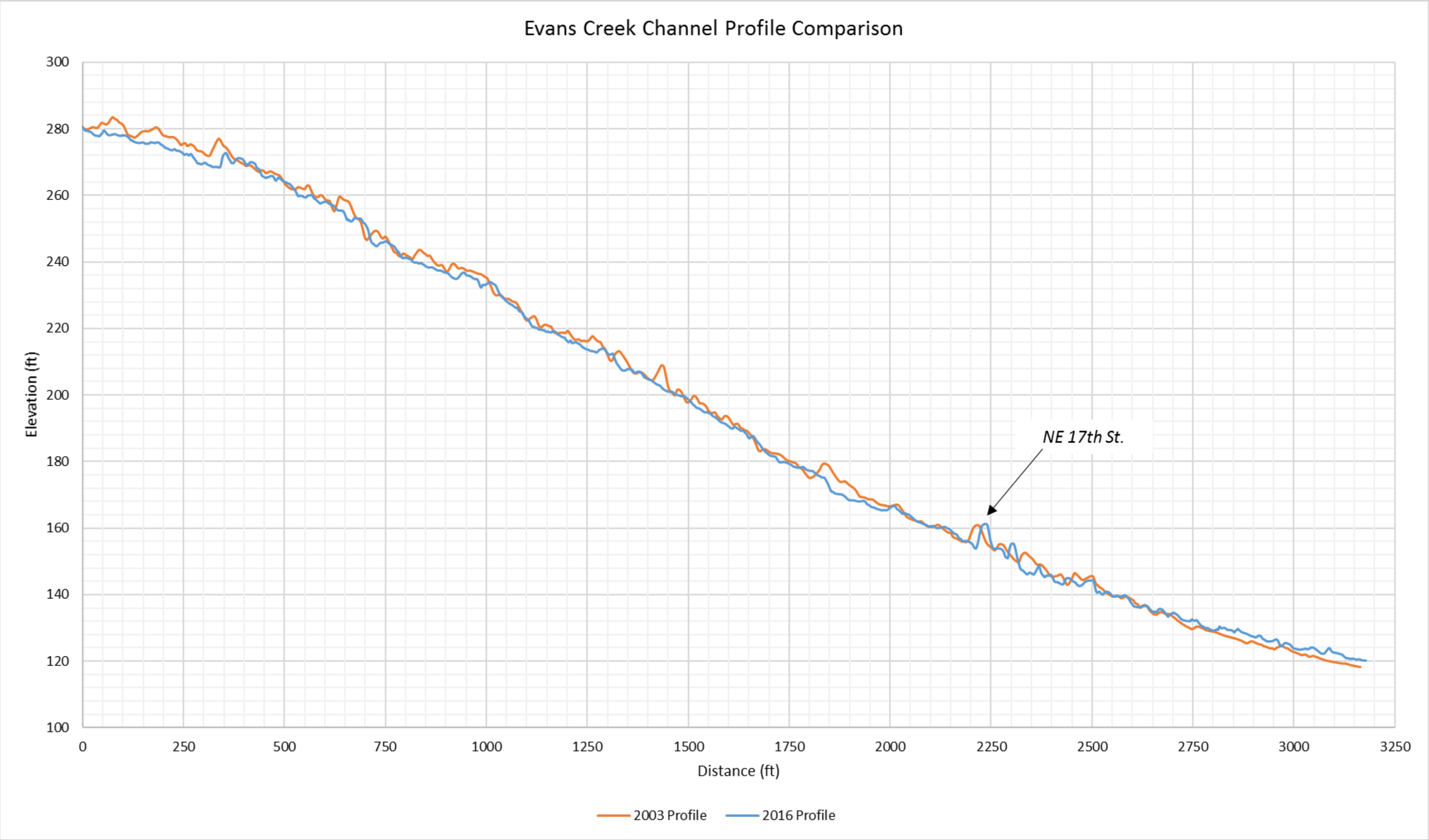


Figure 11a. Long profile channel comparison for the Evans Creek dam channel between 2003 LiDAR data and 2016 LiDAR data.

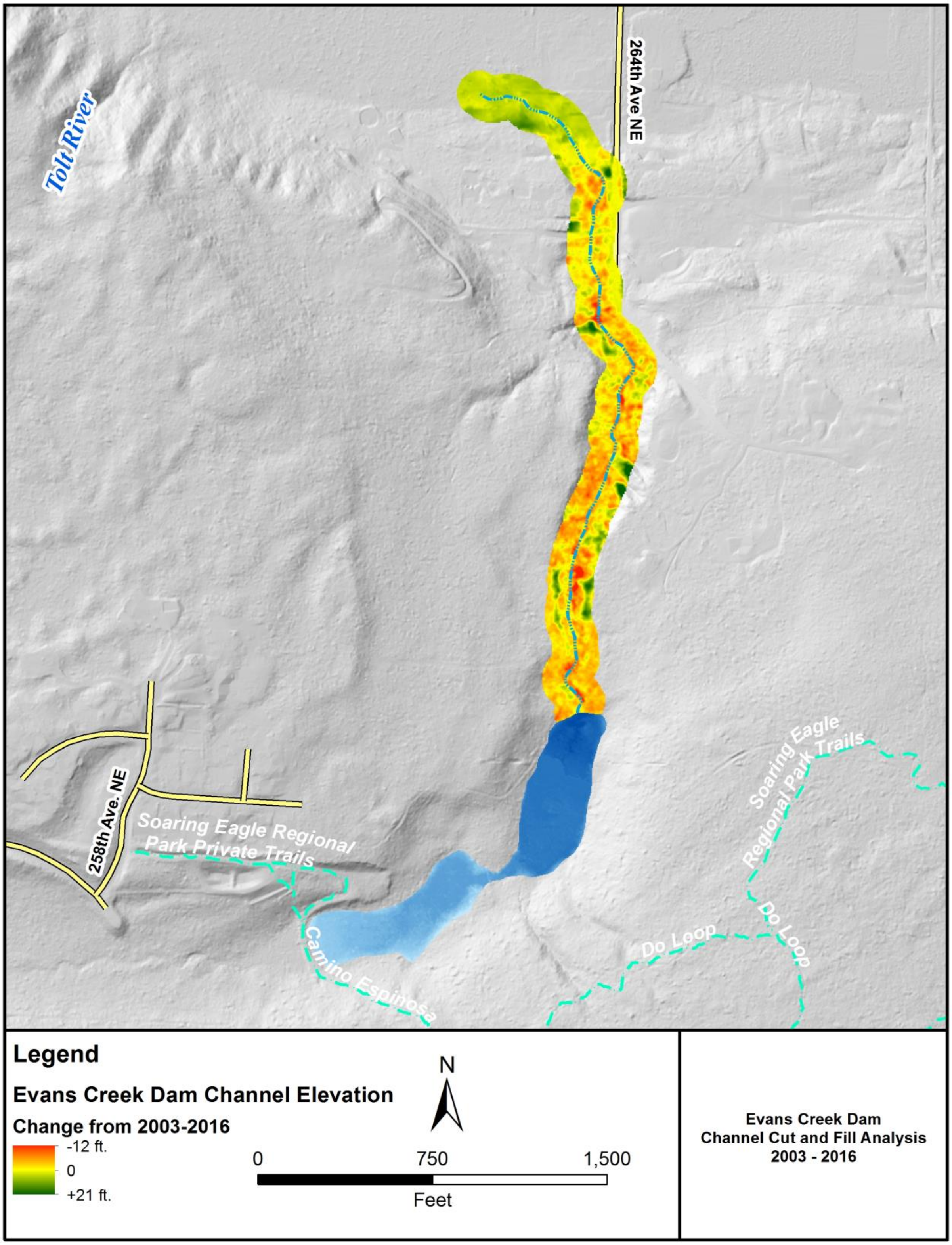


Figure 11b. Cut and fill analysis of the Evans Creek dam which drains an unnamed pond east of Sammamish, Washington. The channel has degraded in areas of red and aggraded in areas of green between the 2003 LiDAR and 2016 LiDAR. Base map derived from 2016 LiDAR.

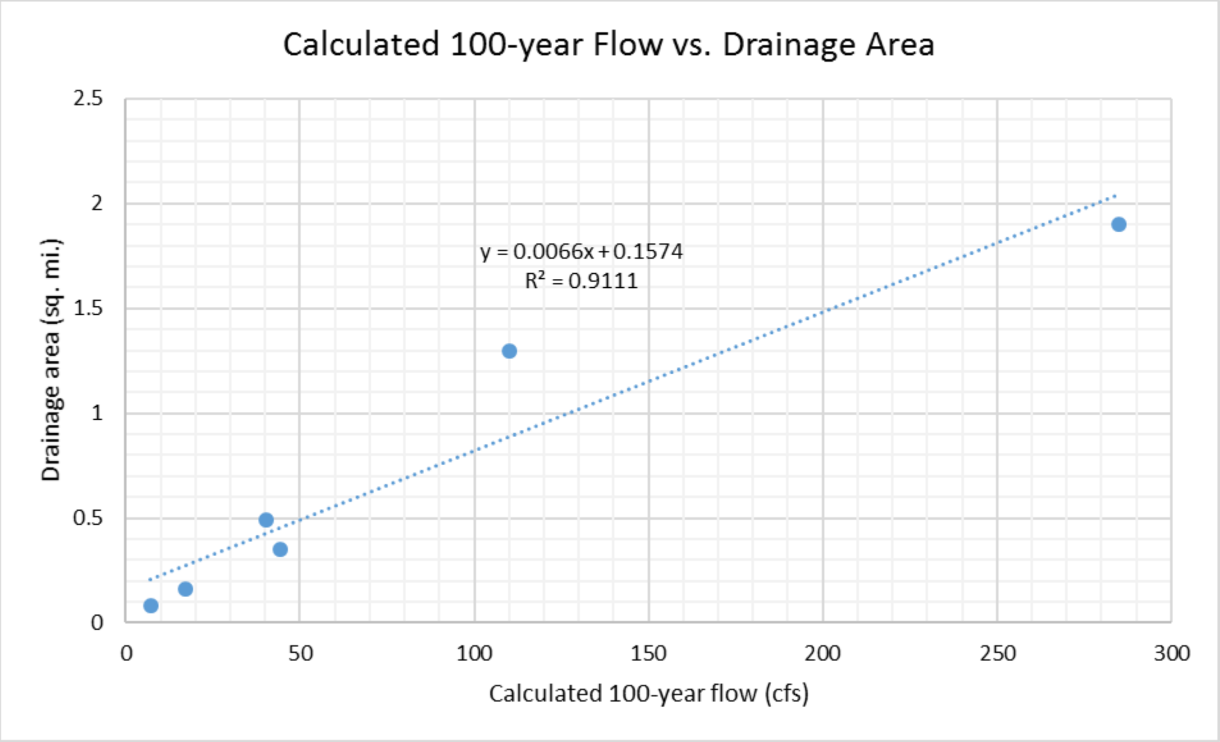


Figure 12. Calculated 100-year flow (cfs) plotted against the drainage area (sq. mi.) for each site. The linear trendline shows that the calculated peak flow is strongly correlated to the drainage area for each channel.

Appendices

Appendix A: Calculations

Breach Formation Time

Dams composed of cohesionless materials: $\tau = 0.020\ V_m^{.36}$
Dams composed of erosion resistant materials: $\tau = 0.036\ V_m^{.36}$

where:
τ = breach formation time (hours)
V_m = volume of material eroded during the breach (yds^3)

Appendix B: Stream Return Flow Interval Data

AEP = Annual Exceedance Probability
Qu = Flood Discharge
PI = Prediction Intervals (L = Lower and U = Upper)
90% confidence level the true discharge value is between the PIL and the PIU

Snoqualmie Valley Trail				Prediction Intervals, 90% confidence level			
AEP	**Years**	***Qu, ft3/s**			**PIL, in ft3/s**		**PIU, in ft3/s**
0.5	2	5.3			2.633652		10.66579784
0.2	5	8.4			4.077138		17.30625955
0.1	10	10.5			5.030935		21.91441404
0.04	25	13.2			6.059108		28.75670983
0.02	50	15.1			6.716551		33.94748286
0.01	100	17.3			7.540804		39.68940072
0.005	200	19.4			8.137363		46.25085744
0.002	500	22.3			8.935425		55.65375805

Deer Creek				Prediction Intervals, 90% confidence level			
AEP	**Years**	***Qu, ft3/s**			**PIL, in ft3/s**		**PIU, in ft3/s**
0.5	2	12.1			6.0423784		24.2305248
0.2	5	19.3			9.4150873		39.5630957
0.1	10	24.2			11.656982		50.2394185
0.04	25	30.5			14.07972		66.0702053
0.02	50	35.2			15.751669		78.6608712
0.01	100	40.3			17.67638		91.8791056
0.005	200	45.3			19.126023		107.293086
0.002	500	52.4			21.143491		129.863136

Tate Creek	Upper Channel						
AEP	**Years**	***Qu, ft3/s**			**PIL, in ft3/s**		PIU, in ft3/s
0.5	2	31.3			15.733286		62.2686182
0.2	5	48.6			23.884719		98.8900038
0.1	10	60			29.139106		123.545315
0.04	25	74.3			34.605876		159.524641
0.02	50	84.6			38.221782		187.253434
0.01	100	95.9			42.492823		216.432077
0.005	200	107			46		250.747862
0.002	500	122			49.798563		298.884129

Tate Creek	Lower Channel			Prediction Intervals, 90% confidence level			
AEP	**Years**	***Qu, ft3/s**			**PIL, in ft3/s**		**PIU, in ft3/s**
0.5	2	92.5			46.77943		182.90625
0.2	5	143			70.724561		289.13577
0.1	10	177			86.544677		361.998
0.04	25	220			103.21724		468.9139
0.02	50	251			114.28929		551.24149
0.01	100	285			127.31828		637.96811
0.005	200	318			136.86717		738.84777
0.002	500	364			149.95262		883.58577

Preston Dam				Prediction Intervals, 90% confidence level			
AEP	**Years**	***Qu, ft3/s**			**PIL, in ft3/s**		**PIU, in ft3/s**
0.5	2	13.8			6.9080809		27.5677144
0.2	5	21.8			10.664728		44.561849
0.1	10	27.1			13.09531		56.08191
0.04	25	33.9			15.703985		73.1795161
0.02	50	38.8			17.428338		86.3788617
0.01	100	44.2			19.465268		100.365428
0.005	200	49.5			20.987968		116.745459
0.002	500	56.8			23.024911		140.119545

Tolt River Dam				Prediction Intervals, 90% confidence level			
AEP	**Years**	***Qu, ft3/s**			**PIL, in ft3/s**		**PIU, in ft3/s**
0.5	2	33.8			16.989445		67.244103
0.2	5	53.3			26.18366		108.49858
0.1	10	66.7			32.372431		137.42836
0.04	25	83.9			39.047708		180.27204
0.02	50	96.6			43.606603		213.9942
0.01	100	110			48.692675		248.49734
0.005	200	124			52.860017		290.88148
0.002	500	143			58.30133		350.74672

Evans Creek				Prediction Intervals, 90% confidence level			
AEP	**Years**	***Qu, ft3/s**			**PIL, in ft3/s**		**PIU, in ft3/s**
0.5	2	2.1			1		4.3
0.2	5	3.4			1.6		7.1
0.1	10	4.3			2		9.1
0.04	25	5.4			2.5		11.9
0.02	50	6.2			2.7		14.1
0.01	100	7.1			3.1		16.5
0.005	200	8			3.3		19.3
0.002	500	9.2			3.6		23.3