BUTANO CREEK FLOODPLAIN RESTORATION GEOMORPHIC RESPONSE

A Thesis submitted to the faculty of
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Master of Science

In

Geographic Information Science

by

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San Francisco, California

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CERTIFICATION OF APPROVAL

I certify that I have read *Butano Creek Floodplain Restoration Geomorphic Response* by Jarrad Fisher, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Science in Geographic Information Science at San Francisco State University.

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San Francisco, California
2018

Floodplains are an important part of a healthy function stream system. Restoring floodplain within impaired stream systems can increase biotic diversity, minimize flood hazards, provide sediment storage and improved water quality, reduce channel incision, and improve instream habitat for aquatic and riparian species. Assessing restoration projects gives valuable insight into the successes and limitations of human constructed remediation efforts and is key to understanding how these degraded systems react to human induced change. Terrestrial LiDAR surveys, longitudinal profiles and cross sections, and habitat mapping were conducted before and after the installation of the Butano Creek Floodplain Restoration Project to assess the geomorphic responses that have occurred in Butano Creek San Mateo County, California. A net sediment storage gain of 760.8 m^3 was recorded within the surveyed areas of Butano Creek channel, 125.5 m^3 of sediment was recorded as stored within the floodplain, and total pool volume increased 2,421 percent. The methods for assessing stream restoration projects presented in this study can be useful tools for resource managers, conservationists, watershed stewards, and other professionals who want to further our understanding of these complex systems and the impacts of human restoration efforts.

I certify that the Abstract is a correct representation of the content of this thesis.

_____ _____
Chair, Thesis Committee Date

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1.1.1 Introduction

Promoting healthy, self-sustaining, watersheds is critical for maximizing ecological diversity and ensuring that these vital resources, upon which all life depends, can thrive in the human altered landscapes (Palmer et al. 2005; Postel & Richter 2003). Watersheds can contain diversity across many landscape properties, such as vegetation and soil, and are a complex mixture of spatiotemporal and local, regional, and global climactic inputs (McDonnell et al. 2007; Rosgen 1997). These inputs impact watershed function and affect the geomorphic thresholds of the landscape, which is the point where the stability or equilibrium of a landscape is exceeded by a given input into the system (Chin et al. 2014; Schumm 1979).

Anthropogenic activities such as farming, urban development, timber harvesting, and mining have put extrinsic pressure on watersheds causing stream systems to unravel and become incised, simplified, straightened, and disconnected from their former floodplain (Florsheim et al. 2013). This connection between human-induced landscape transformation and direct impact on stream function is well documented throughout stream restoration literature (Chin et al. 2014; Cluer & Thorne 2013; Goudie 2013; Leopold et al. 2005; Rosgen, 1997). Understanding how anthropogenic activities influence the stage of a stream, or the current morphological procesesses that a given

stream is undergoing, is critcal to informing restoration projects and moving towards a healthy watershed ecosystem (Cluer & Thorne 2013; Rosgen 1997; Schumm & Lichty 1965)

Stream restoration projects, that focus on human impacted watersheds, often use pre-human, pristine conditions, as a baseline for restoration success (Rosgen 1997). However, it may be more beneficial for these projects to instead focus on restoring the natural function, equilibrium, and biological conditions suitable to ensure that stream function is optimized given anthropogenic restraints (Cluer & Thorne 2013; Florsheim et al. 2013; Rosgen 1997). Focusing on stream restoration through the lens of re-establishing functionality, within the constraints of the ecosystem, and providing benefits that can be measured, assessed, and repeated will act as a building block for future studies and indicate which projects are effective in restoring stream function (Rohde et al. 2006). Assessing stream restoration projects gives valuable insight into the successes and limitations of human constructed remediation efforts and is key to understanding how these degraded systems react to human induced change.

In this paper the effectiveness of the Butano Creek Floodplain Restoration Project is measured. The objective of this assessment is to add to the ever-evolving conversation centered on stream restoration and monitoring techniques, and quantify the ecological benefits of the project in relation to a set of pre-determined success

criteria. By quantifying the successes and limitations of this project this study hopes to inform future restoration efforts.

1.1.2 Pescadero-Butano Watershed

Located in San Mateo County, Pescadero-Butano Watershed is part of the Santa Cruz Mountains within the greater Central California Coastal Range (Bay & Jackson 2004). The watershed is characterized by steep forested slopes in the upper reaches, with rolling hills, grass lands, and low gradient valleys in the mid-lower reaches and drains approximately 210 km^2 (81 mi^2) (Bozkurt-Frucht 2013). The watershed has two main stream systems, Pecadero and Butano Creeks (Figure 1). Pescadero-Butano Watershed is the largest coastal watershed between the Golden Gate Bridge and the San Lorenzo River, and is one of the most significant coastal wetlands on the Central California Coast (California Department of Fish and Wildlife 2004).

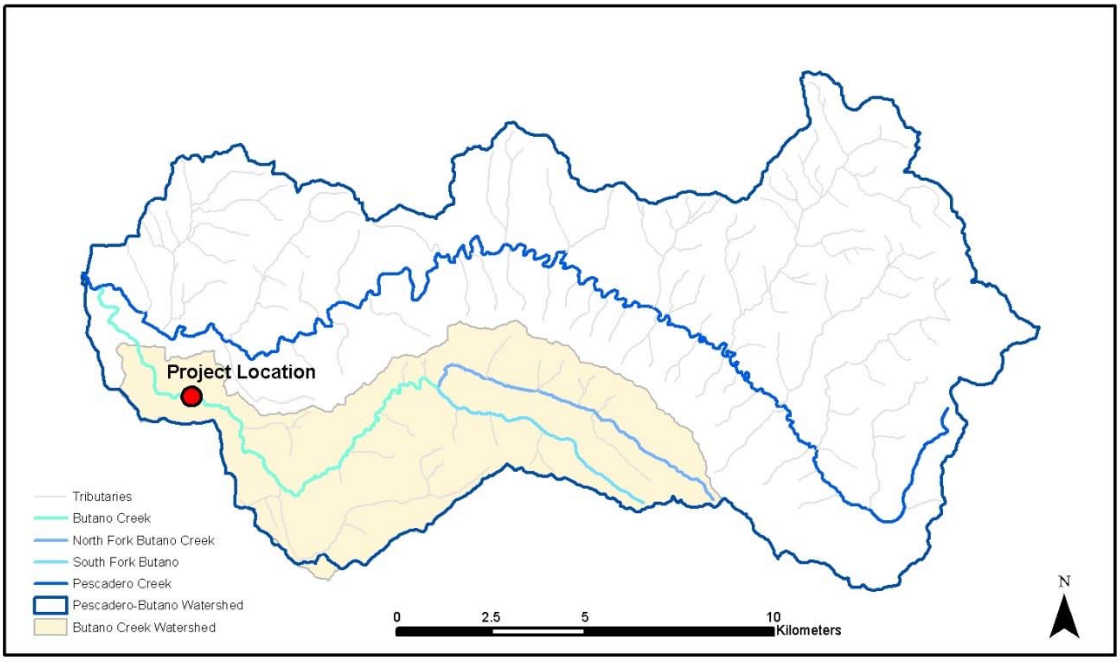

Figure 1. Pescadero-Butano Watershed. The project site is located within the historic floodplain of the Butano watershed.

The underlying geology of the Pescadero-Butano Watershed is predominantly composed of sedimentary rock. The middle portion of the watershed is underlain by folded coarse-grained marine sandstones (Upper Cretaceous) with shales and mudstones of moderate erodibility in the west-central and southwest areas of the watershed (Bay & Jackson 2004). This area is adjacent to the San Gregorio Fault, which cuts through the watershed from southeast to northwest. West of the fault, Quaternary marine terrace and alluvial deposits are common, along with upper Tertiary (Purisima) siltstones and fine-grained sandstones (Bay & Jackson 2004). The eastern portions of the watershed are adjacent to the San Andreas Fault Zone and have experienced a higher

level of deformation. This area is characterized by extensive folding and highly fractured rocks that are made up of volcanics, sandstones, shales and mudstones (Bay & Jackson 2004). Regular seismic activity, highly weathered bedrock, and steep hillslopes lend themselves to excessive deformation and naturally occurring erosion.

From the mid-1850s through the late 1950s, large scale extraction of Pescadero-Butano watershed's natural resources took place, including timber, ore minerals, fish, water, wildlife, oil, and gas (Bay & Jackson 2004). The most damaging extractive industry in the upper portions of the watershed was timber harvesting. Early timber harvesting activities were intensive and involved manual clear-cutting of and skidding of old growth Redwood Trees (*Sequoia sempervirens*) and Douglas Firs (*Pseudotsuga menziesii*) (Figure 2). On-channel shingle mill dams were used throughout the watershed to take advantage of the watercourses as transport corridors for logs, maximizing the amount of timber that could be harvested. On-channel dams, and the formation of new rail lines to haul timber, led to initial stream incision in this portion of the watershed and fragmentation of habitat for aquatic species (Bozkurt-Frucht 2013). Furthermore, this large scale timber harvesting effort greatly increased sediment loading into the streams, destabilized hillslopes, and created poorly drained road and railway networks that were the catalyst for future mass wasting events (Trso 2015).

Figure 2. Historic photo of logging operations in the Pescadero-Butano Watershed.

Historically, the main land use type in the mid-lower portions of the Pescadero-Butano Watershed has been agriculture. Agricultural practices included dry farming, row crop production, dairy farming, hunting, fishing, and grazing (Bay & Jackson 2004). As in many coastal watersheds on the California coast, early agricultural practices included ditching and channelizing streams in low lying floodplain areas that could be used for prime farm lands. Trso (2015) indicates that 99% of the natural floodplains in the Pescadero-Butano Watershed were abandoned by the 1940s. The loss of floodplain at such a large scale greatly reduced the capability of the landscape to capture and store sediment in the alluvial valleys. This, coupled with the rise of more intensive mechanized agriculture in the early 1940s, led to channel incision, severe fragmentation

of natural channel alignment, and change in channel substrate that resulted in finer-grained materials moving through the system (Bozkurt-Frucht 2013).

The creeks in the mid-lower portions of the Pescadero-Butano Watershed are channelized and characterized by incised creek beds with steep banks and high stream velocities during storm events. The magnitude and frequency of flooding in the lower reaches of Butano Creek has increased dramatically over the past few decades as a direct result of the decreased channel capacity of Butano Creek and Pescadero Marsh (Bozkurt-Frucht 2013). Channel capacity in this instance is not just the stream's ability to move water but also its ability to carry and disperse stream load into its floodplain. Stream load is a measure of the sedimentary materials moved by water in the form of suspended load, bed load, and dissolved load (Schumm 1979). A stream's ability to move these particles is a product of not only stream power but also the frequency and duration of storm events.

In Pescadero-Butano watershed, the occurrence of storms that can cause flooding and can reach bankfull level are fairly frequent. Bankfull is a measure of stream stage, or the quantity of water within the stream, where the channel is filled to the top of the stream banks before water spills out into the floodplain (Florsheim et al. 2013; Leopold & Miller 1956). A two-year event, which has a 50% chance of occurring in any given storm year, can reach bankfull levels and move thousands of tons of sediment

through the system (Table 1) (Bay & Jackson 2004; Hammersmark et al. 2016). Due to past incision and channelization of Butano Creek, including within the Butano Floodplain project reach, high water velocities and sediment loads carried during bankfull events are mostly contained within the stream channel, causing further streambank erosion. Given the high probability of an event of this magnitude occurring within any given year, the importance of connected floodplain areas within the stream network is necessary to slow water down and allow the sediment contained in the water column to be dispersed.

Recurrence Interval	Frequency	Estimated Peak Flow Magnitude (cfs)		
		Butano Creek Gage[1]	*Scaled* Pescadero Creek Gage[2]	Regression Equations[3]
1.25-yr	0.8	**423**	335	N/A[4]
1.5-yr	0.667	**611**	545	N/A[4]
2-yr	0.5	**870**	**870**	837
5-yr	0.2	1,571	**1,930**	1,674
10-yr	0.1	2,039	**2,760**	2,283
25-yr	0.04	2,602	**3,878**	3,093
50-yr	0.02	2,993	**4,728**	3,714
100-yr	0.01	3,356	**5,568**	4,361

Notes:

1) Developed using maximum annual instantaneous discharge data from 1963-1974 water years for the Butano Creek gage.

2) Developed using maximum annual instantaneous discharge data from 1952-2013 water years for the Pescadero Creek gage. Computed Pescadero Creek peak values were then scaled by 0.4, the ratio of the watershed areas.

3) Developed for the USGS Butano Creek gage location, using the recently updated north coast region regression equations (Gotvald et al., 2012) with a watershed area of 18.3 mi^2 and an average annual precipitation of 35.3 in.

4) Regional regression equations are not available for these low recurrence intervals.

Table 1. Taken from Hammersmark et al. 2016. Flood peak magnitude estimates for Butano Creek.

Sedimentation in the Pescadero-Butano Watershed is a focal point of local and regional conservation efforts. An estimated 19 million metric tons (21.2 million tons) of sediment were naturally produced on hillslopes across Pescadero-Butano Watershed from 1820-2010 (Trso 2015). An additional 23 million metric tons (25.2 million tons) were produced, within the same time period, as a result of geomorphic changes to the landscape caused by anthropogenic land use (Trso 2015). This additional 23 million metric tons, that made its way into the stream systems, came from surface erosion, landslides, debris flows, channel incision, and gullying directly linked to intensive land use practices like agriculture, timber harvesting, and the development of rural infrastructure (Trso 2015). Increased sediment input from anthropogenic activities, along with changes in sediment transport, storage, and stream hydrology modification, has resulted in numerous problems. Many of the historic floodplains in Pescadero-Butano Watershed no longer provide valuable habitat and sediment storage capacity. The channel itself has incised, resulting in a loss of habitat and sediment storage capacity along with additional sediment supply increase from bank erosion and creek incision.

1.1.3 Floodplain Restoration

Like many of California's watersheds, the Pescadero-Butano Watershed has been highly altered by anthropogenic forces. Due to the highly altered state of the watershed, it is likely anthropogenic impacts are irreversible without implementing watershed wide restoration (Trso 2015). Principle among these restoration efforts is the revival and reestablishment of historic floodplain.

The ability of a given stream to support a varied and sustainable ecosystem increases with the morphological diversity within the system (Cluer & Thorne 2013; Rohde et al. 2006). Restoring floodplain within impaired stream systems, such as Butano Creek, can increase biotic diversity, minimize flood hazards, provide sediment storage and improved water quality, reduce channel incision, and improve instream habitat for aquatic and riparian species (Bayley 1990; Cluer & Thorne 2013; Koh et al. 2008; Naiman et al. 1998; Rohde et al. 2006; Rosgen 1997; Weber & Fripp 2012). Reestablishing floodplains can increase morphological diversity and mirror natural balanced channels that retain and discharge floodwater, increase inundation time, slow the time period to concentrated flow, reduce downstream flood peaks, and supply aquafers that enhance base flows (Cluer & Thorne 2013).

Channel Evolution Models (CEMs) can help outline the processes a stream undergoes once incision has begun and the stream has become disconnected from its former floodplain (Cluer & Thorne 2013; Schumm, et al. 1984; Simon & Hupp 1984). Cluer and Thorne (2013) built upon previous CEMs to develop a Stream Evolution Model (SEM) that not only takes into account the evolution of the channel, but also takes into account the morphological adjustments that impact the diversity and richness of stream ecosystems. In this SEM, eight stages of stream evolution are identified in which streams are either aggrading, degrading, narrowing or widening (Figure 3). Stream stage and morphology is directly tied to flow and sediment loading/dispersion that impacts stream health (Cluer & Thorne 2013). Ideally, streams are connected to their floodplain (stage 0 and 8) where flood attenuation and base flow allow for maximized habitat diversity and sediment dispersion. With channelized systems (stage 1-7) flows are generally contained within the stream prism and are not able to spill out onto the floodplain.

Not all stream systems in their natural state are stage 0 anastomoseded~~ing~~ streams, and in project reach the gradient of ~~. Within the lower portions of~~ Butano Creek is between 1 and 2 ~~the gradient is below 2~~ percent, steeper than typical anastomosed systems. Ho~~ allowing the formation of stage 0 streams.~~wever ~~The~~ the lower portions of Butano Creek~~, including within the project site,~~ have been noted as a historically anastomoseded~~ing~~ system (Cluer & Gavette 2017; Klochak et al. 2016)

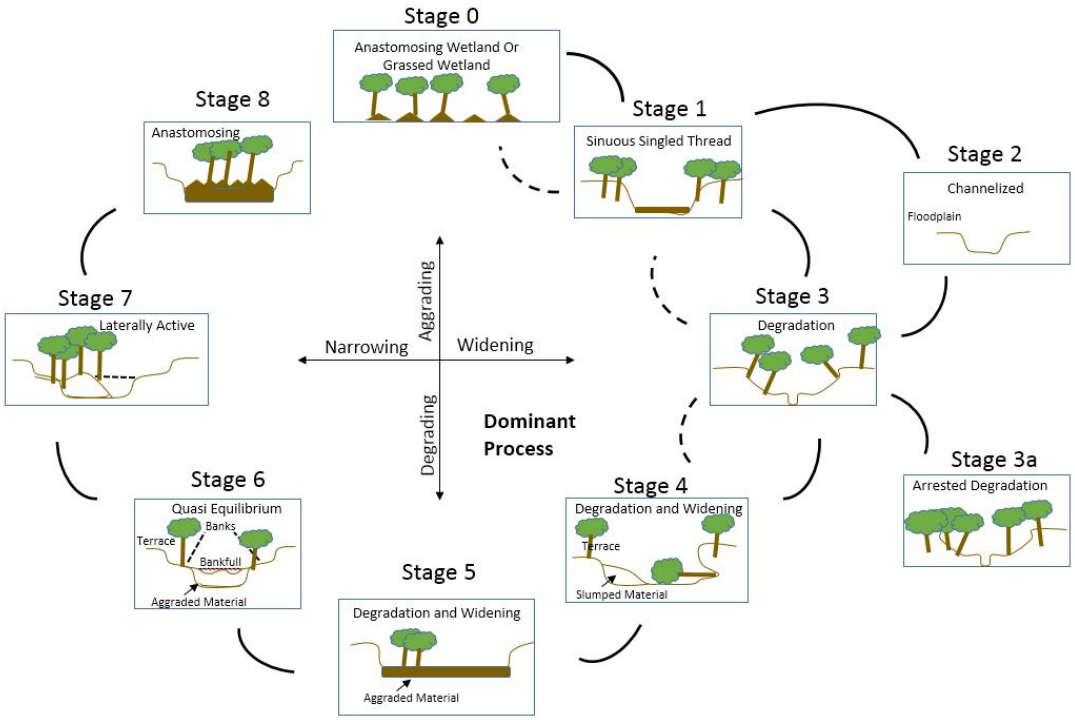

Figure 3. Modified after Cluer & Thorne 2013 SEM. Represents a cyclical process where streams move towards equilibrium but can become stuck in dead end processes where channel incision cannot be reversed.

Within the Cluer and Thorne (2013) stream evolution model, the pre-project condition at the Butano Creek project reach is stage three. The stream has become channelized (stage two) degraded and incised (stage three) causing it to become disconnected from the former floodplain, which is now a terrace. In stage three streams the channel either continues to degrade and widen (stage four) or gets stuck in a cyclical process between stage one, two, and three where the stream cannot achieve widening to eventually reach equilibrium in stage eight. The Butano Creek Floodplain Project

attempts to jump start the process of aggradation and stage evolution by adding roughness and allowing the stream to reconnect to the historic floodplain. In the Pescadero-Butano Watershed, floodplain reestablishment has been identified as a priority action by state and federal agencies to promote habitat rehabilitation for endangered species such as steelhead trout and Coho salmon, reduce flooding hazards to the town of Pescadero, and alleviate the impacts of sediment accumulation that are blocking fish passage from Pecadero-Butano Marsh into Butano Creek (California Department of Fish and Wildlife 2004; NMFS 2016).

The Butano Creek Floodplain Restoration Project implemented restoration actions on approximately 1.61 km (1 mile) of Butano Creek at five sites where the channel has been disconnected from the floodplain due to channel simplification and incision. These restoration actions include construction of two engineered log jams (ELJs), a 73.5 m rock ramp, floodplain connector channels, and recruitment of living bank side alder trees (Figure 4). The San Mateo Resource Conservation District (RCD) and project engineering firm CBEC indicate that the installation of these features is meant to 1) reduce further incision of the creek bed and erosion of banks, 2) raise the elevation of the stream bed to reconnect Butano creek with 40 + ha (100+ acres) of its former floodplain, 3) restore the floodplain's ability to store sediment, 4) reduce

downstream sediment loads, and 5) improve habitat conditions for wildlife. (Hammersmark et al. 2016).

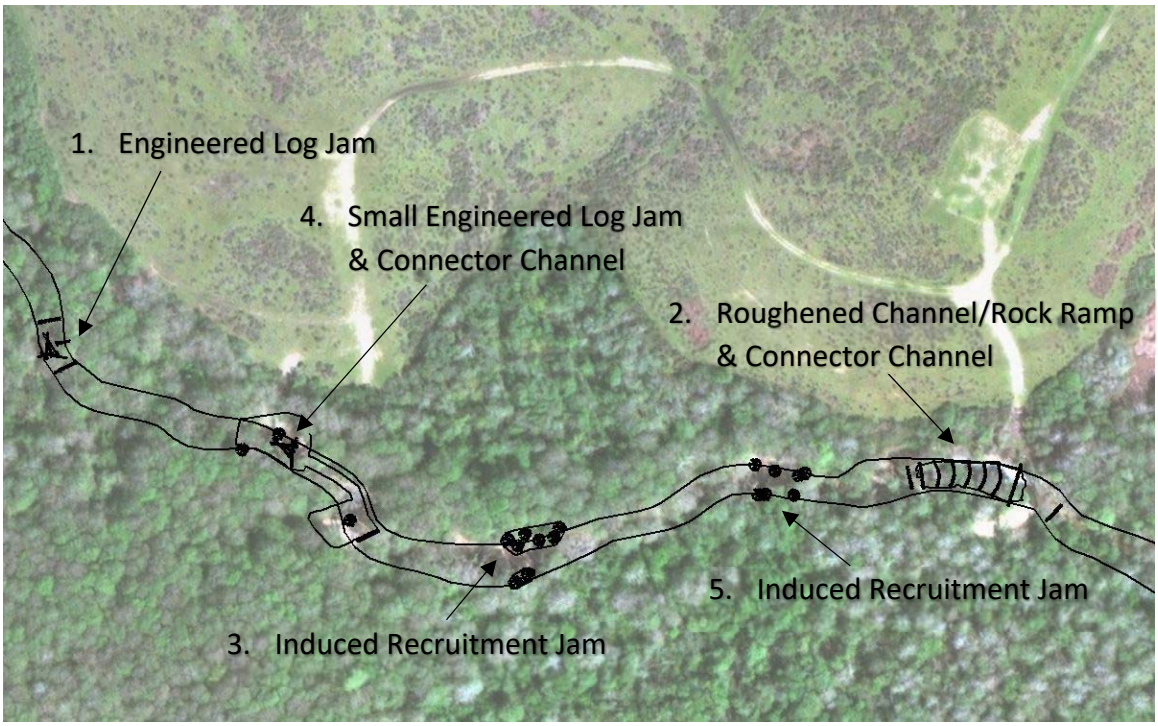

Figure 4. Butano Floodplain Restoration Project implemented sites.

1.1.4 Project Site and Design Criteria

The 59 km^2 Butano Creek Watershed originates in the Santa Cruz Mountains. Butano Creek is a perennial stream and the largest tributary to Pescadero Creek in the

Pescadero-Butano Watershed. Human modification of Butano Creek has doubled the amount of sediment that moves through the system and makes its way into the stream channels (Trso 2015). Butano Creek is highly incised in the middle and lower portions of the watershed, where the project occurred, and is overly connected to a small portion of floodplain in the lower section of the watershed near the town of Pescadero. Areas that once flooded frequently e.g. every two years or more frequently, now are only inundated during large magnitude, infrequent events e.g., greater than 10-yr return interval runoff events. Butano Creek was also channelized for farming in the 1940s pushing the creek out of its historic alignment (Bay & Jackson 2004). Butano Creek was moved to the eastern side of the valley which perched the creek at the uphill side of the floodplain. This was done to recharge aquifers that could be used during dry periods for farming.

The project reach encompasses approximately 1.6 km (1 mile) of Butano Creek and is characterized by an incised creek bed and over steepened banks. Riparian vegetation is dense and consists of willows, alders, stinging nettle, and blackberries. Pre-project habitat complexity within the reach was low, with only four minor pools being recorded during habitat surveys. The absence of woody debris appears to have increased velocities, resulting in a straightened creek with simplified morphology and a plane-bed character. The restoration hypothesis for this project is that roughening the

channel in the project reach via engineered log jams, induced recruitment of alder trees, the installation of connector channels, and a 73.5 m rock ramp will 1) reduce further incision of the creek bed and erosion of banks, 2) raise the elevation of the stream bed to reconnect Butano Creek with 40+ ha (100+ acres) of its former floodplain, 3) restore the floodplain's ability to store sediment, 4) reduce downstream sediment loads, and 5) improve habitat conditions for wildlife.

Design criteria for the Butano Floodplain Project, such as the flow rate at which the floodplain is inundated, was selected by the San Mateo Resource Conservation District (RCD) and CBEC Eco Engineering (CBEC) in consultation with the project technical advisory committee (TAC). The TAC was comprised of experts in both physical and biological sciences, including technical staff from the National Oceanic and Atmospheric Administration -National Marine Fisheries Service Restoration Center, United States Fish and Wildlife Service (USFWS), California Department of Fish and Wildlife, and the Regional Water Quality Control Board, among others. Using information provided by CBEC, the TAC and RCD determined the type of structures to be used and best placement within the Butano Creek project reach.

Hammersmark et al. (2016) outline the structures used at the Butano Floodplain Project. Sites one and two used ELJs at strategic locations to limit the capacity of the channel, slowing water to promote deposition of sediment in the channel and enhance

the formation of pools for instream habitat. Sites three and four used live alder recruitment to add channel roughness and promote deposition and the formation of pools increasing channel complexity. At site five, a rock ramp structure was installed to provide grade control allowing for aggradation of the creek bed and limiting the capacity of the creek. This will ensure that floodplain inundation occurs at a lower stream flow rate. Two connector channels were also installed at sites two and five to lower the stream bank evaluation allowing floodplain inundation to occur more often.

2.1.1 Methods

The way in which fluvial topographic data is collected has shifted over time from simple longitudinal and cross-sectional surveys to more sophisticated and precise data collection methods such as light detection and ranging (LiDAR) (Andrew et al. 2014; Bangen et al. 2014; Gallay et al. 2013). This method provides a higher resolution by which to model and assess changes that occur within a landscape over time. LiDAR uses lasers to measure distances from a collection unit, i.e. a terrestrial laser scanner (TLS), to a point on the ground. Based upon these point measurements elevation data can be used to generate an elevation map or digital elevation model (DEM) from the individual X, Y, and Z (northing, easting, and vertical elevation) point data. Producing accurate

terrain models is a critical part of assessing changes in fluvial systems (Bangen et al. 2014; Wheaton et al. 2010). Given the advances in spatial data gathering tools, the ability to create ever increasing accuracy in DEMs allows for better representation of landforms and surface variability (Hohenthal et al. 2011).

A particularly useful application for TLS is in fluvial systems with dense vegetation and complex topography because the high density of returns allows for modeling minute changes in stream function, such as sediment transport and other characteristics of stream morphology (Bangen et al. 2014; Wheaton et al. 2010). Using this information we can map sediment deposition on floodplains and determine hydraulic inundation for flooding mapping (Blasone et al. 2014; Goulden et al. 2016; Hohenthal et al. 2011; Lindsay & Dhun 2015).

In order to investigate topographic deviation within a landscape, geographic information systems (GIS) methods are used to create DEMs which can be compared over time. Difference of DEM (DoD) analysis uses two or more DEMs taken of the same terrestrial features, at different time intervals, to look at the variability in landscape structure (James et al. 2012; Milan et al. 2011; Wheaton et al. 2010). To perform DoD analysis, the difference between to surfaces is subtracted allowing the user to assess measurable differences in elevation and volume (Blasone et al. 2014; Milan et al. 2011;

Wheaton et al. 2010). This operation can allow the user to interpret alterations in landforms and deduce the processes that drive them.

This study collected high-resolution LiDAR for use in GIS based DEM modeling and DoD analysis to measure the geomorphic change that has occurred as a result of the Butano Floodplain Project. The results of the geomorphic change will then be used to determine the level of effectiveness of the project and inform future stream restoration efforts. This will be accomplished by assessing the changes in channel morphology and net adjustment in sediment accumulation/dispersion within the floodplain and stream channel over winter 2016-2017. Three TLS surveys, two longitudinal profiles with cross sections, and observational mapping were taken within the project reach to ascertain changes in sediment distribution and channel morphology. Habitat surveys were conducted to monitor channel complexity and identify net gain/loss of habitat value within the project reach.

2.1.2 Data acquisition and processing

The Butano Creek Floodplain Restoration Project can be broken down into three main elements. The first element is the Project Reach in which structure sites 1-5 were installed and the TLS LiDAR surveys were conducted, second is the Upstream Reach

where the cross sections and longitudinal profiles were taken, and third is the connector channels and floodplain where LiDAR surveys and manual floodplain mapping were collected (Figure 5).

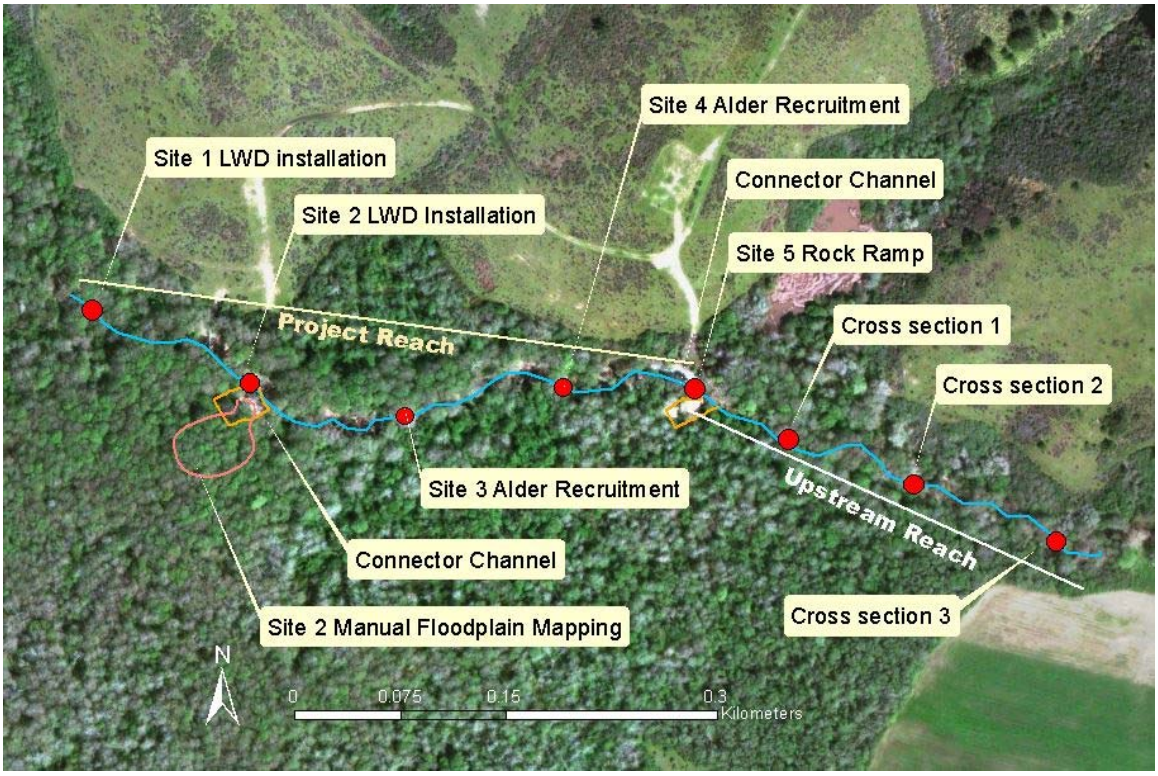

Figure 5. Plan Map of the Butano Creek Floodplain Restoration Project.

Assessment methods were selected by Jarrad Fisher of the RCD and John Klochak of the USFWS with input from CBEC engineer Chris Hammersmark. The RCD and USFWS decided that LiDAR surveys within the Project Reach would give the most insight into channel adjustment as a result of the Butano Floodplain Project and provide the greatest level of insight into project success. LiDAR surveys were not conducted on the

Upstream Reach due to funding limitations however, CBEC had previously conducted surveys using a longitudinal profile and cross section. It was decided that the CBEC data would be used as a baseline to conduct a repeat survey informing deposition volumes in the Upstream Reach. Three cross sections were chosen as repeat survey locations at the upstream, downstream, and middle of the Upstream Reach. These were chosen as the best representative cross sections by the RCD and USFWS.

Data acquisition was performed in conjunction with Moss Landing Marine Labs (MLML), CBEC, USFWS, Peninsula Open Space Trust (POST) and the RCD. LiDAR surveys were conducted by the RCD, MLML, and USFWS. Long profiles and cross-sections were conducted by the RCD, MLML, and CBEC. Habitat surveys were conducted by the RCD and POST. All data was stored at the RCD.

The Project Reach and adjacent floodplain were surveyed using a Trimble VX Spatial Station terrestrial LiDAR scanner. The Trimble VX can be used as a conventional total station and LiDAR unit. Both functions were used during surveys to maximize precision in densely vegetated areas within the floodplain. Surveys were taken pre-construction (summer 2016), immediately post-construction (fall 2016), and post 2016-17 winter (summer 2017). Close attention was paid to make sure survey techniques used during the data acquisition were duplicated through all three surveys.

Benchmarks established by CBEC were used to tie-in, correct, and establish vertical and horizontal accuracy for each of the three surveys. In addition, control points were established by the RCD and CBEC, using T-posts, throughout the project reach to create additional tie in points further increasing vertical and horizontal accuracy (Figure 6). Stream-bank surveys conducted by CBEC were used as extents for channel DEM interpolation.

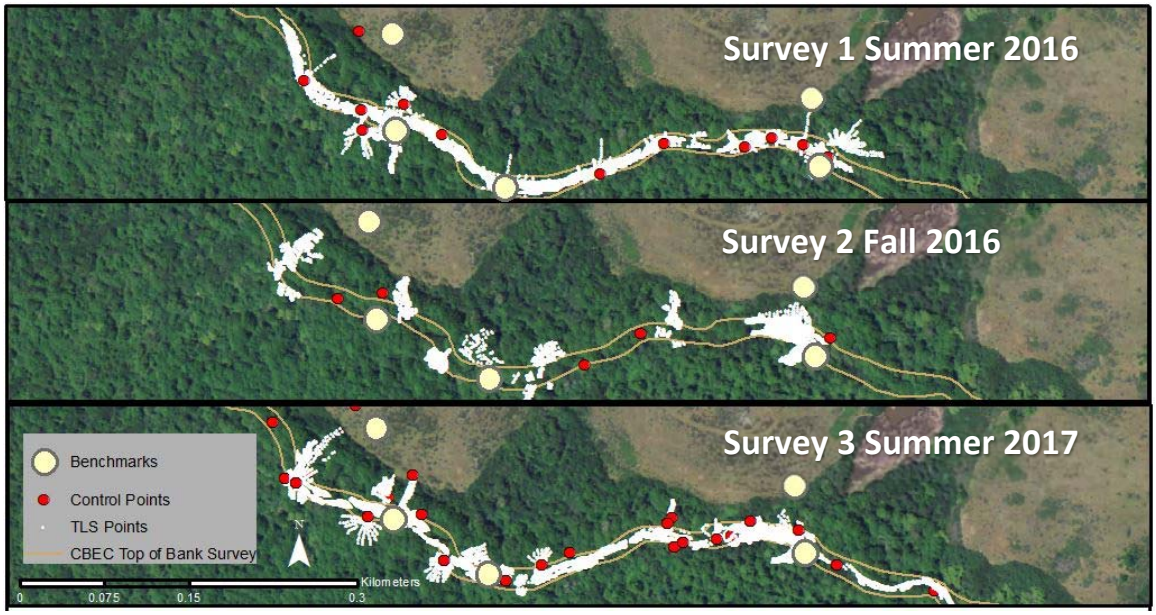

Figure 6. LiDAR point could surveys conducted by the RCD, MLML, and USFWS.

The RCD and MLML collected over 64,000 points within the Butano Creek channel and floodplain during summer 2016, just prior to construction of the Butano Creek Floodplain Restoration Project. The points were post-processed and cleaned using Trimble RealWork v.10.1, and subsequently transformed using ArcGIS for Desktop

Advanced v. 10.3 to match the original floodplain benchmarks established by CBEC in 2015. The resulting point cloud was then used to create DEMs that were interpolated using the Spline with Barriers tool in ArcGIS (Figure 7). The "barrier" used for this process was the "top of bank" polyline that was established by CBEC in 2015. Both 1 meter and 30 cm resolution DEMs and hillshades were produced. The RCD and MLML returned to Butano Creek following construction in fall 2016 and collected an additional 30,900 points that were post-processed and used to create interpolated DEMs. Again in summer 2017, following an extremely wet winter, 29,364 survey points were collected and processed to create the post winter 2016-17 DEM.

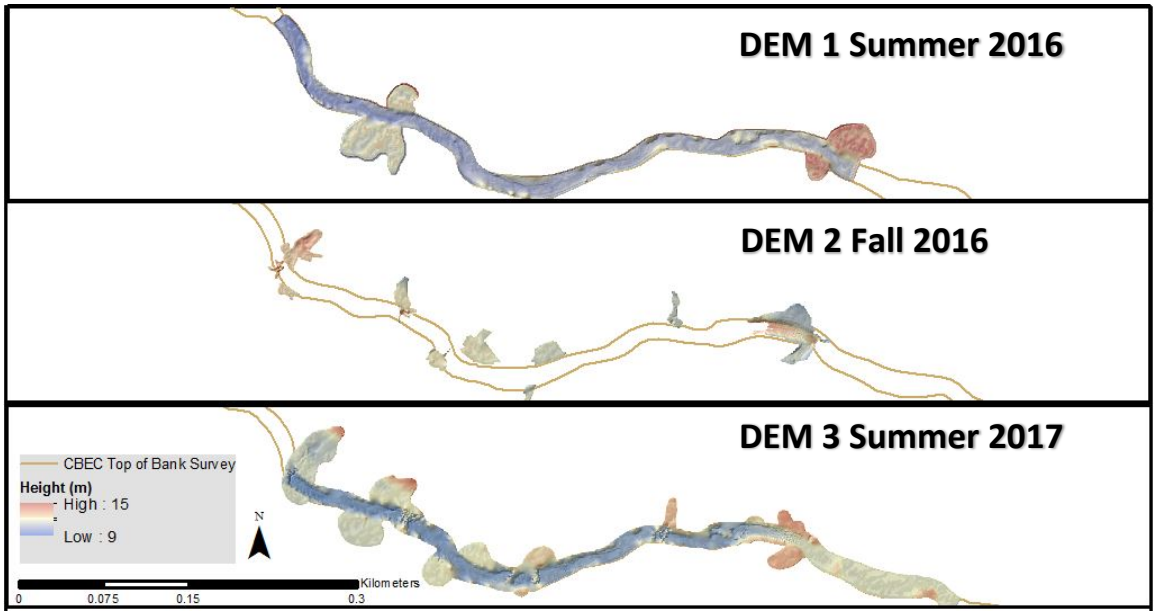

Figure 7. Stream survey DEMs

Traditional cross sections and a long profile were used to assess topographic change within the 324 m of immediate upstream channel from the project reach. Cross sections and long profiles of the Upstream Reach were taken pre-construction (summer 2016) and post construction (summer 2017) by the RCD and CBEC. Cross sections and longitudinal profile were taken using a traditional total station. Long profiles recorded thalweg elevations and cross sections recorded top of bank, toe of slope, bar, wetted edge, and thalweg.

A hand-held Garmin GPSmap 64s unit was used to map the extent of floodplain inundation and sand splay with an accuracy of .5 m. Sixty-six Random sample points were collected within the deposition area, based upon the visually defined area of sand splay, to measure deposition depths at the site two connector channel and adjacent floodplain (Figure 8). This method was used only in areas of the floodplain where vegetation and leaf litter made TLS surveying infeasible. Deposition depths were taken manually using a shovel to dig test pits which identified the breaking point between new sand and buried relic leaf litter (Figure 9).

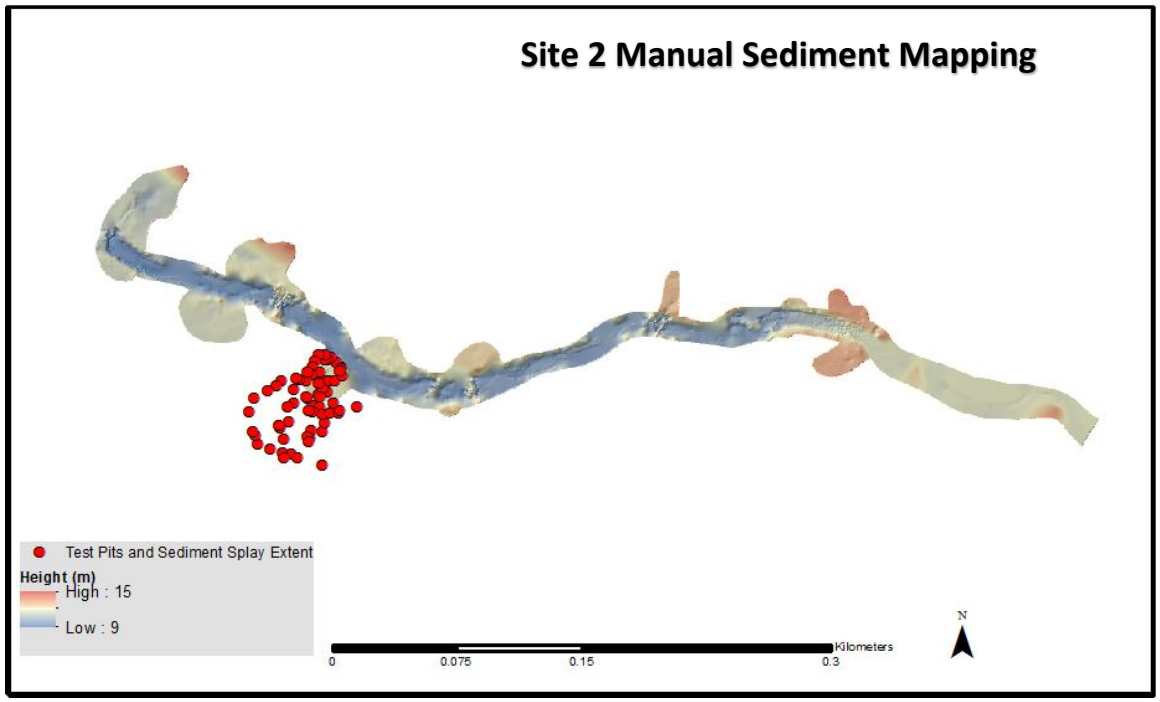

Figure 8. Manually mapped sediment distribution in site 2 floodplain.

Figure 9. Sediment deposition test pit.

Fifty sediment tiles were placed pre-winter 2016-17 to measure initial deposition within the connector channels and floodplain at sites two and five. The tiles used for this project were square ceramic kitchen tiles that are 30.5 cm (12 in) x 30.5 cm x 3 mm. Tiles were placed flush to the ground and marked individually with stakes to discern their position once covered by sediment. Sediment tiles were also used as a means to roughly measure accuracy of topographic sediment accumulation. Inundation of the floodplain and stream stage was tracked using time-lapse cameras during storm events

to visually observe flooding events. Time-lapse cameras were placed at sites two and five adjacent to the connector channels.

Data processing tor TLS surveys was done using Esri Arc Map 10.3. DoD analysis was used to extrapolate topographic variation between TLS surveys, compare channel form, and estimate sediment storage/loss. A traditional longitudinal profile and cross sections were used in Microsoft Excel from the initial Upstream Reach CBEC pre-construction survey and post project RCD MLML survey. This information calculated sediment storage volumes for the 323 m of stream directly above the Project Reach.

Habitat surveys for instream habitat variables such as pools, riffles, and residual pool depth were conducted using methods outlined in “Stream Channel Reference Sites an illustrated Guide to Field Technique” (Harrelson, et al. 1994). These methods of assessment are included in the manual for the USDA Forest Service. Habitat assessments were conducted pre-construction (July 2016) and post 2016-17 winter (August 2017).

3.1.1 Results

The DoD analysis of pre-construction vs. post winter 2016-17 TLS surveys indicates that net degradation occurred within the Project Reach portion of Butano

Creek (Table 2). Degradation in this reach was estimated at 2134.9 m^3. Post construction vs. summer 2017 surveys also indicate that another 225.1 m^3 of sediment (in addition to the 2134.9 m^3) was lost in in the Project Reach. In pre-construction vs. post winter 2016-17, the rock ramp had a net gain of 904.1 m^3 of material, however this was due to the installation of the ramp which had an average vertical change of .75 m and was not a result of sediment storage within the channel. At the rock ramp site an additional 38.2 m^3 of sediment was lost between post-construction vs. post winter 2016-17 surveys with an average vertical change of -.06 m. This results in a net loss of material within the Project Reach of 2398.2 m^3.

	Type	Overlap Area (m^2)	Average Vertical Change (m)	Total Volume Change (m^3)
Pre-construction (summer 2016) to Summer 2017 (post winter 2016-17) Change	Channel	6748.83	-0.32	-2134.9
	Floodplain	1607.13	-0.05	-78.5
	Rock ramp	1200.06	0.75	904.1
Post-construction (fall 2016) to Summer (post winter 2016-17) 2017 Change	Channel	421.83	-0.53	-225.1
	Floodplain	2567.16	0	-8.5
	Rock ramp	672.03	-0.06	-38.2

Table 2. Volumetric calculations of sediment deposition in the project reach. Overlap area indicates the area of surface that corresponded to the pre-construction survey. Average vertical change is a measure of degradation or aggradation that occurred from pre to post construction surveys. Total Volume change is the overall amount of material stored or lost from pre to post construction surveys.

In the 324 m of Upstream Reach above the rock ramp at site five, an estimated 3159 m^3 of sediment was stored based upon the longitudinal profile and cross sections

taken pre-construction and post winter 2016-17 (Figure 10). These calculations were based off an average channel width off 9.75 m (based on cross sections 1-3), an average depositional depth of 1.00 m (based on longitudinal profile), and a length of 324 m. When taking into account the aggradation in the Upstream Reach, the data shows a net storage gain of 760.8 m^3 within the surveyed areas of Butano Creek channel.

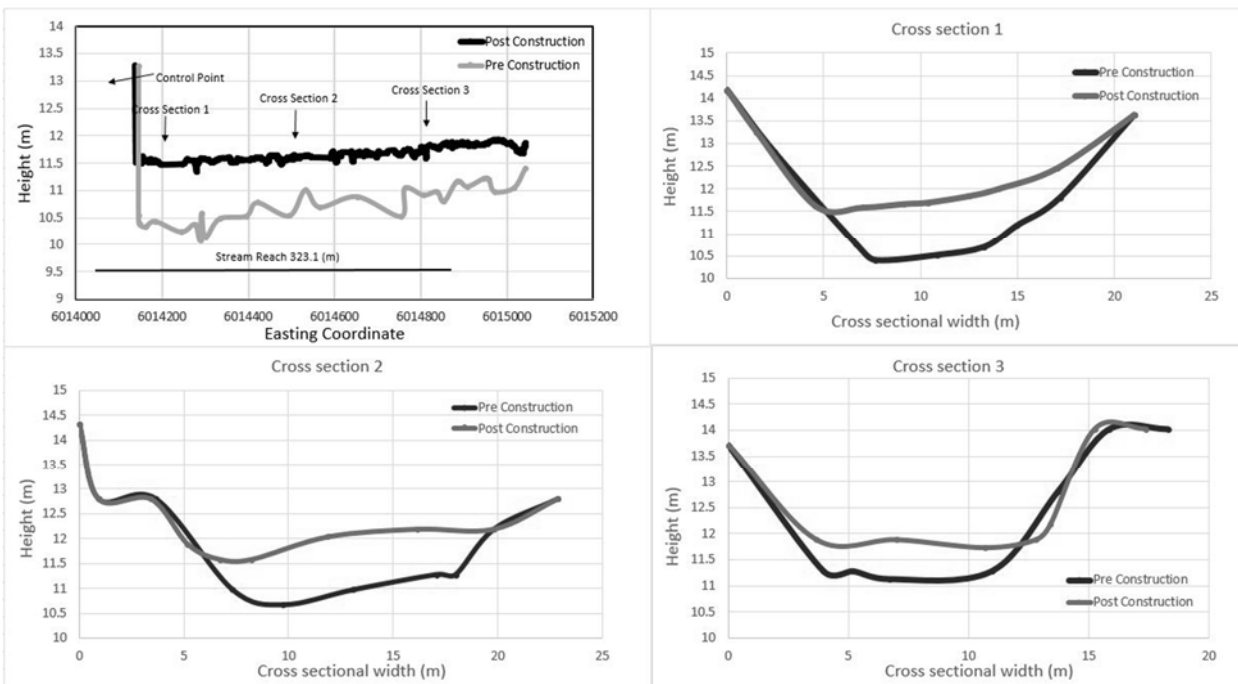

Figure 10. Volumes for the Upstream Reach were calculated using multiple cross sections and longitudinal profile.

As is evident from the volumetric calculations taken within the channel, most of the sediment stored in the channel was above the top of the Project Reach. This

deposition was a direct result of the project since the aggradation occurred because of the installation of the rock ramp at site five. Although there were areas of deposition within the Project Reach, an average vertical loss of 0.32 m was recorded from pre-construction to post winter 2016-17 TLS surveys (Figure 11).

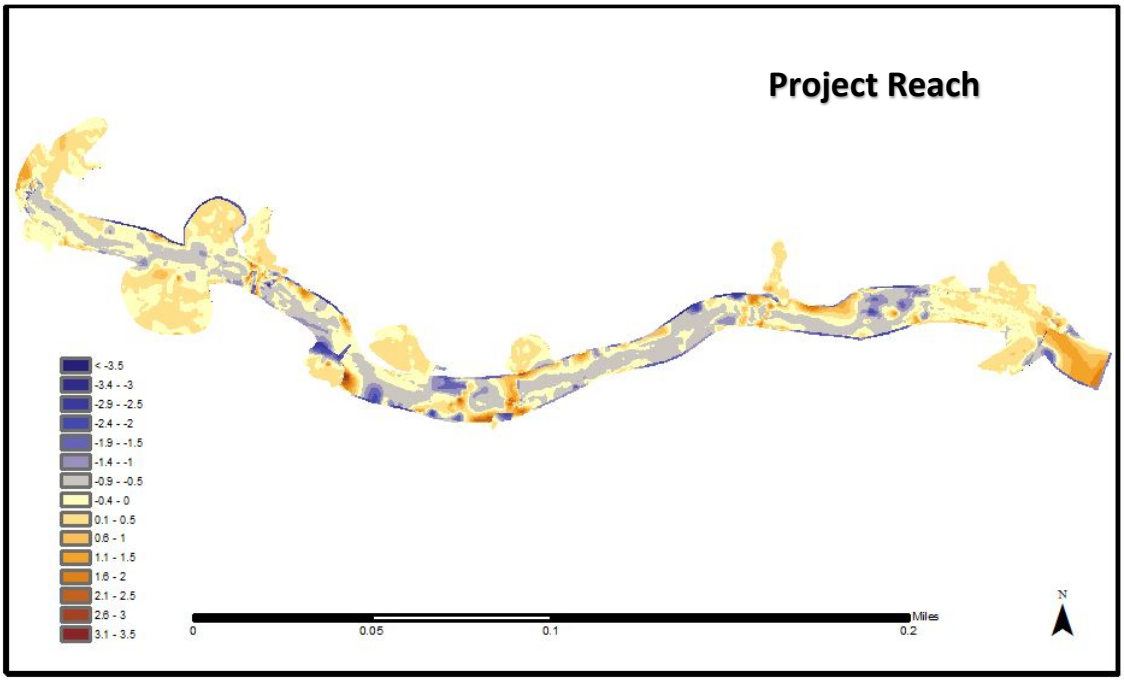

Figure 11. Topographic DoD analysis of the Project Reach. Graphic depicts change in elevation in meters.

DoD analysis of the floodplain estimated net sediment storage and extent of inundation into the floodplain. The TLS surveys conducted covered approximately 0.6 ha (1.5 acres) of floodplain with another 0.2 ha (0.5 acres) being manually surveyed at site two via GPS points and manual deposition observation. The extent of sediment deposition in the floodplain was also mapped using TLS in all areas except for 0.2 ha of

site 2 where vegetation was too dense to survey. Visual observation and a hand-held GPS at an accuracy of 0.5 m was used to estimate the extent of inundation at site two.

DoD analysis showed a net loss of 78.5 m^3 from pre-construction vs. post winter 2016-17 and a net loss 8.5 m^3 from post-construction vs. post winter 2016-17 in the floodplain areas that were surveyed using TLS. The additional floodplain area at site 2 that was manually surveyed had an average deposition of 0.1 m with an area of 2097 m^2. The total net gain of sediment in the manual survey area was 213 m^3. Although the manually surveyed area is not at as fine a scale as the TLS surveys, this area of floodplain was the largest area of inundation within the Project Reach. It is vital to take this area into account to get a realistic picture of overall floodplain volumetric change. When including the 213 m^3 of additional deposition taken with GPS and manual observation the net gain in the floodplain was 125.5 m^3.

Considering potential error estimates associated with TLS surveys and DEM interpolations is important. The TLS surveys used the upland CBEC control points as the main registration points for matching successive surveys. Only 4 other control points that were installed in 2016 were found and re-measured in 2017, with a Root Mean Squared Error (RMSE) of 0.018 m. RMSE values were also calculated from 100 random survey points, when compared against the interpolated DEM, the RMSE error was 0.039.

Increased frequency of floodplain inundation during 2 year or larger storm events as a result of this project was confirmed over winter 2016-17. Observations of floodplain inundation during 2+ year storm events were recorded via time lapse cameras. Time lapse cameras were able to capture 3 separate storm events that activated the floodplain. An additional 2 events were large enough to activate the floodplain but were not captured since they occurred during the night.

Visual observations of sand splay in the floodplain confirm that stream load material was deposited on the floodplain up to approximately 35 m from the channel. Time-lapse photography taken during the winter floods show that the floodplain was activated at both connector channels and that stream stage rose approximately 2.4m (8 feet) during a 5 year event. These events inundated the connector channels and portions of the adjacent floodplain in up to 1 m of water.

The installation of LWD and alder recruitment sites did have a positive impact on habitat within the project reach. Surveys conducted pre-construction (fall 2016) and post-construction (fall 2017) reveal that pool frequency increased from 4 pools (pre-project) to 15 pools (post-project) (Table 3). Total pool volume increased 2,421% and average residual pool depth increased 8.6 cm (3.38 in). Additionally, the installation of LWD and alder recruitment also increased the amount of cover provided for pools making instream habitat refugia more viable.

Survey 1 07/23/2016	Max Pool Depth (cm)	Pool Length (cm)	Max Pool Width (cm)	Critical Riffle (cm)	Residual Pool depth (cm)	Pool Volume (m^3)
Pool 1	56	25	17	10	45.72	234
Pool 2	48	28	10	15	33.02	137
Pool 3	46	36	10	13	33.02	165
Pool 4	51	41	20	13	38.1	420
Survey 2 08/13/2017						
Pool 1	53	15	15	15	38.1	120
Pool 2	56	69	18	23	33.02	681
Pool 3	51	51	25	15	35.56	655
Pool 4	48	52	13	13	35.56	319
Pool 5	36	30	20	18	17.78	212
Pool 6	43	43	15	15	27.94	284
Pool 7	43	41	16	18	25.4	285
Pool 8	61	69	38	18	43.18	1593
Pool 9	56	58	21	20	35.56	688
Pool 10	76	91	46	20	55.88	3239
Pool 11	76	41	15	20	55.88	472
Pool 12	81	41	19	20	60.96	629
Pool 13	137	152	64	25	111.76	13274
Pool 14	58	58	20	25	33.02	694
Pool 15	104	64	25	23	81.28	1680

Table 3. Results of habitat surveys. Pools in survey 1 are different from survey 2. The original pools that existed pre-construction were infilled during winter 2106-17 and new pool formation occurred.

4.1.1 Discussion

The goal of reconnecting floodplain to a stream channel is to minimize bank erosion, alleviating stream incision, increase biodiversity, enhance morphology and allow for greater storage of sediment (Bayley, 1990; Rohde et al., 2006; Rosgen, 1997) . Floodplain restoration is the first step in the long process of restoring a watershed (Bayley, 1990). This is because floodplains are generally located in low-gradient areas, which can be easily accessed, and allow for the processes of incision and channel degradation to be reversed through aggradation of the channel and minimizing stream power. The Butano Creek Floodplain Project was the first step in a long process of restoring watershed function.

Floodplain reestablishment efforts have had varying success due to the complex nature of hydraulic response to engineered river restoration efforts and limitations given initial project restraints (Peters 2012; Rohde et al. 2006). Because of this, extensive monitoring is required to establish success or failure. However, reaching an agreement on what constitutes success for river restoration projects has been a point of contention in the restoration community (Palmer et al. 2005). For the purposes of this project a set of restoration hypotheses were developed to set clear guidelines by which to judge success criteria. This project sought to restore natural function to Butano

Creek by: 1) reducing further incision of the creek bed and erosion of its banks; 2) raising the elevation of the stream bed to reconnect the creek with 40 + ha (100+ acres) of its former floodplain; 3) restoring the floodplain's ability to store sediment; 4) reducing downstream sediment loads; and 5) improving habitat conditions for wildlife.

4.1.2 Restoration Hypotheses

Hypothesis One: Channel Incision and Bank Erosion

Approximately 760.8 m^3 of sediment was stored within Butano Creek channel, within first year after construction, as a direct result of the Butano Floodplain Project. Most of this aggradation occurred in the Upstream Reach (see Figure 5). This was likely due to the constructed rock ramp, at the upstream end of the project, which acted as an impermeable structure that was particularly effective at trapping sediment and aggraded the channel rapidly during storm events.

Upstream sediment deposition likely contributed initially to downstream "hungry water" and ensuing bank scour and channel degradation within the Project Reach. An explanation for this is that with the large volumes of aggradation happening above the Project Reach, the channel below was sediment starved causing higher

velocities and creating scour. The channel is also likely adjusting to changed sediment loads within the system (i.e. sediment starved area downstream of the rock ramp and deposition on the floodplain) and the changes within the channel with the installation of the LWD, ELJ, and rock ramp. All of these structures affect the velocity and flow path of water and create various velocity profiles within the water column. Until the stream is able to equilibrate, there will continued be bank failure, scour, and channel adjustment.

Bank adjustment within the project occurred at all of the LWD and ELJ sites. Time-lapse observation, TLS surveys, and visual observations taken at the sites post storm events show that water was forced around and backed up behind the structures eroding the banks. Time-lapse video was also able to capture alder recruitment above site two and directly below site three indicating that banks were adjusting to the addition of roughened features in the channel. This bank adjustment was anticipated and will likely slow as channels form around the structures and banks lay back creating the potential for inset floodplain.

Compared to 2013-2015, the 2016-2017 winter was very wet and likely mobilized sediment from local gullies that had been dormant in previous years as well as landslides and bank failures upstream. This mass mobilization in sediment could have contributed to the rapid infill of the Upstream Reach. Also, in 2016-2017 winter, a large pre-existing LWD feature at the bottom of the project site partially blew out, potentially

resulting in significant channel lowering and loss of material within the Project Reach. It is possible that this channel lowering stopped at the rock ramp which may have acted as a grade control structure. This factor could have compounded with the hungry water scenario leading to the degradation that was measured within the Project Reach.

Hypothesis Two: Raising the Elevation of the Stream Bed to Reconnect Floodplain

Based upon findings from post winter observations taken in the field, conclusions can be drawn about channel aggradation and stream reconnection to the floodplain. First and foremost, the project was successful at storing sediment within the channel. The Upstream Reach stored approximately 3159 m^3 of sediment and aggraded an average depth of 1 m. Pre-winter 2016-17 a 2.5-m deep pool stretched from the top of the rock ramp approximately 100 m upstream. This pool completely aggraded after the winter storms and raised the level of the stream bed significantly reconnecting the floodplain in areas directly surrounding site five. In the Project Reach, a net loss of 2398.2 m^3 occurred, which may be due to the loss of the large LWD structure at the bottom of the project site and hungry water. Although this loss occurred in the Project Reach, the floodplain was still inundated at all five sites due to the slowing and backing up of water behind the structures. This effect was seen from sand splay formation around the structures, time-lapse video, and from measurements taken using TLS surveys.

Time-lapse video confirmed that the floodplain was inundated more regularly and was activated on several occasions during 2-year and greater storm events. Time-lapse video, TLS surveys, and visual observation also showed the floodplain was activated at both connector channels and that stream stage rose approximately 2.43m (8 feet) during a 5-year event (Figure 12). Visual observations of sand splay in the floodplain also confirm that stream load material was stored on the floodplain up to approximately 35 m away from the channel at sites two and five.

The re-alignment of the Butano Creek channel from anthropogenic activities may have lasting impacts on creek function and floodplain restoration efforts. The channel is currently perched on the uphill side of the alluvial valley and could see adjustment as the stream moves to align with its historic flow path. Although this was not part of this study it should be noted that alteration of the channel alignment could impact how the stream stores and moves sediment through the system. This also could have lasting effects on stream morphology and the impact floodplain function.

Figure 12. Stakes mark sediment tiles on the connector channel above the 73 m long rock ramp.

Hypothesis Three: Restoring the Floodplain's Ability to Store Sediment

Overall the floodplain had a net gain of 125.5 m^3 of sediment stored which indicates that the floodplain is storing sediment as a result of the project. A factor that led to the negative values within the TLS floodplain calculations is bank adjustment. Since much of the bank adjustment occurred at the edge of the connector channels and floodplain, these values were counted as net loss in the overall floodplain volume. At all

of the LWD and alder recruitment sites bank scour occurred as a result of the stream finding paths around the installed structures creating higher velocities due to constriction. Especially at the connector channel at site two, and directly below site five, bank failure was a large factor that led to negative values for floodplain volumes. This was likely due to high velocities and minimal vegetation re-establishment after construction. Now that the banks have set, vegetation has established, and the channel has widened, bank failure is expected to decrease within the Project Reach and net volume increase within the floodplain are expected to be higher.

Although measurements were not taken downstream of the project, visual observations taken during annual site visits indicate that sediment deposited in the floodplain and channel downstream of the project site. The floodplain area below the project site is lower gradient and was possibly inundated by the connector channels at sites two and five via off-stream channels. If this is the case major amounts of material could have moved downstream in a diffuse path (outside of the main channel) and deposited. During the most recent site visit conducted in spring 2018, fresh sediment deposition was seen across nearly 12 ha (30 acres) of floodplain below the project site and the entire area was noted as a stage 0 anastomosed system. Although this cannot be tied directly to the project it is likely that the installed structures and reconnected floodplain did have a direct impact on the formation of this stage 0 system.

*Hypothesis Four: R*educing *Downstream Sediment Loads*

Data collection during this project did not capture the necessary information to inform this restoration hypothesis. Future efforts are underway by the RCD and project partners to measure sediment loading within Butano Creek and calculate the impact of sediment reduction downstream of the project.

Hypothesis Five: Improving Habitat Conditions for Wildlife.

Based upon habitat surveys, new pool habitat, bars, and side channels have formed indicating an improvement in habitat conditions for wildlife. Pool volume increased 2,421% and average residual pool depth increased 8.6 cm (3.38in). At the bottom of the rock ramp, natural alder recruitment led to the formation of a side channel and large pool that was previously a small inset floodplain area covered with large woody debris. Likewise, at the bioengineered log structures at sites two and one, side channels formed creating large pools and prompting the formation of large sediment bars upstream. At the ELJ structures pools have formed as a result of the roughness increase to the channel and alder recruitment from winter 2016-17 has added to stream shading and enhanced instream refuge for salmonids.

5.1.1 Conclusion

This study demonstrated methods and criteria for evaluating the success of stream restoration projects. The project was assessed using Terrestrial LiDAR surveys, longitudinal profiles and cross sections, manual GPS mapping and sediment test pits, habitat surveys, time-lapse photography, and visual observation. The methods for assessing stream restoration projects presented in this study can be useful tools for resource managers, conservationists, watershed stewards, and other professionals who want to further our understanding of these complex systems and the impacts of human restoration efforts.

The restoration goals of the Butano Creek Floodplain Restoration Project were to 1) reduce further incision of the creek bed and erosion of banks, 2) raise the elevation of the stream bed to reconnect Butano creek with 40 + ha (100+ acres) of its former floodplain, 3) restore the floodplain's ability to store sediment, 4) reduce downstream sediment loads, and 5) improve habitat conditions for wildlife. This study found that the project was successful in goals 1, 2, 3 and 5; we did not assess goal 4.

Further research can improve our understanding of Butano Creek and how stream systems in general react to restoration projects. Monitoring efforts can be improved via more extensive and successive TLS and habitat surveys. A fourth TLS

survey is planned to take place after the next major winter and will add to the body of knowledge informing the Butano Creek Floodplain Restoration Project.

Watersheds and their stream systems play an important ecological role in our landscapes. Understanding how these systems function, and in what ways restoration projects can enhance these features, is critical for future research efforts and restoration professionals. Monitoring is a tool that can illuminate the successes and failures of these projects and lead to holistic watershed restoration which can revitalize our watersheds and help protect nature's most important resource, water.

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