SEDIMENT YIELD IN SALMON CREEK AFTER DECOMMISSIONING LOGGING ROADS, NORTHERN HUMBOLDT COUNTY, CALIFORNIA

By

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ABSTRACT

SEDIMENT YIELD IN SALMON CREEK AFTER DECOMMISSIONING LOGGING ROADS, NORTHERN HUMBOLDT COUNTY, CALIFORNIA

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Salmon Creek watershed is located in the Headwaters Forest Reserve in northern California and is known for the ecological value of its old-growth redwood forest, high biodiversity, and sensitive habitat for endangered species. The Bureau of Land Management primarily manages the Reserve. The land-use history of the Upper Salmon Creek watershed includes extensive timber harvest and road development. Watershed restoration in the Upper Salmon Creek watershed started in 2000 with the primary goal for the Reserve to protect and recover ecologic diversity and threatened native species. Since then, of the 23 miles, 13.5 miles of logging roads and 101 stream crossings have been decommissioned and treated, with 2 miles maintained, 2.4 miles passively restored, and 5.1 miles still requiring assessment. The restoration work is focused on long term reduction in sediment delivery from erosional sites that have historically degraded water quality in the Salmon Creek watershed.

A stream monitoring station is located in the Upper Salmon Creek watershed that uses a turbidity threshold sampling protocol based on turbidity, stage, and temperature. The objective is to evaluate the data collected from Water Year (WY) 2012 to 2019 to assess the sediment yield in the watershed. The field and laboratory data collected at the stream monitoring station were used to further understand the relationships between hydrology, sediment transport, and land-use, and to estimate sediment load from WY 2012 to 2019.

Additionally, two precipitation-monitoring stations were installed in the Upper Salmon Creek watershed during WY 2019, to provide a more spatially representative rainfall data set.

Discharge rating curves and turbidity-sediment rating curves were developed to estimate continuous discharge and suspended sediment concentration (SSC) at the stream monitoring station, which were then used to estimate annual sediment yield. The annual sediment yield from WY 2012 to 2019 ranged from 9 tons/mi^2 to 178 tons/mi^2 (49 tons to 944 tons). The discharge rating curves need to be established every year due to periodic geomorphic changes in the channel cross-section at the monitoring station. However, the relationship between turbidity and SSC does not appear to change from year to year, and the existing data that was collected is adequate to quantify the relationship between turbidity and SSC. The exception is at high values of turbidity, where it is recommended to reprogram the automated sampler to draw water samples only at the very highest turbidity thresholds to refine the relationship with SSC.

On average, storms were responsible for 77% of the total annual sediment yield over the period of record. Annual sediment yield varied from year to year, and seemed to be strongly influenced by the characteristics of individual storms within a WY such as rainfall intensity in the watershed. Additionally, episodic events such as bank failures and landslides may have elevated turbidity and discharge. Estimating sediment load by individual storm events is the first step in exploring the meteorological, hydrological, and other temporal changes that contribute to variability in sediment transport and sediment load. Future studies should focus on normalizing the data to effectively remove the interannual variability in sediment yield that is related to rainfall variability and episodic events so that trends in sediment yield that may be due to land use changes and restoration actions can be identified.

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cfs: cubic feet per second

FNU: Formazin Nephelometric Unit

ft: feet

lbs: pounds

mg/L: milligram per liter

NTU: Nephelometric Turbidity Unit

Reserve: Headwaters Forest Reserve

SSC: Suspended sediment concentration

SL: Sediment load

SY: Sediment yield

TTS: Turbidity Threshold Sampling

TSRC: Turbidity Sediment Rating Curve

WY: Water Year

INTRODUCTION

Nestled within the Northwestern Coastal Ranges of California is the Headwaters Forest Reserve (Reserve), an intact old-growth redwood forest ecosystem (BLM 2017). The Reserve is located between the cities of Eureka and Fortuna (Figure 1). The Reserve is known for its ecological value of old-growth Redwood forest, high biodiversity, biologically important stream networks, and sensitive habitat for endangered species (Jones and Stokes 2003; PWA 2005; BLM 2017). The Reserve consists of 7,472 acres of protected land acquired by the Secretary of Interior and the State of California in 1999 (BLM 2017). The Reserve contains 3,088 acres of old-growth redwood forest surrounded by 4,384 acres of previously harvested forest and bushlands. The vegetation in the Reserve is mostly dominated by coniferous forest of redwoods (*Sequoia semperivirens*), Douglas-fir (*Pseudotsuga menziesii*), and tan oak (*Lithocarpus densiflorus*). The Reserve is co-managed by the Bureau of Land Management (BLM) and California Department of Fish and Wildlife (CDFW). The goal of the Reserve is to conserve, and study the land, fish, wildlife, forest, and provide public recreation opportunities (BLM 2017).

The Upper Salmon Creek watershed encompasses the entire south end of the Reserve and drains to southern Humboldt Bay (Figure 1). The Reserve contains the headwaters of Salmon Creek. The study site boundary is located in the Salmon Creek watershed within the Reserve, with a drainage area of 3,400 acres. The Salmon Creek watershed contains 1,569 acres of old-growth forest and unharvested terrain, and 1,831 acres of harvested terrain. There were approximately 23 miles of logging roads that were

constructed, creating approximately 100 stream crossings, and 22 road-induced landslides have been documented since 2003 (Jones and Stokes 2003). The historical anthropogenic disturbances introduced high loads of sediment into the waterways of Salmon Creek, and excessive sedimentation has resulted in negative impacts to the stream quality, aquatic habitat, and downstream residents (BLM 2017).

Sedimentation is one of the leading causes of impaired streams and rivers in the US, and the increase in turbidity and sediment in waterways has been recognized as a significant impact of logging activities (Klein et al. 2011; US EPA 2017). Measuring suspended sediment and turbidity in streams and rivers is essential for monitoring the health of the stream ecosystems, estimating coastal sediment budgets, and estimating sediment yield in watersheds. Excessive in-stream sediment can impact fish habitat by clogging fish gills, reducing growth rates, and altering egg and larval development. Sediment input can also decrease the size and depth of pools, which degrades spawning and rearing habitat. Additionally, an increase in turbidity and sediment concentration can increase the temperature in a stream and reduce light penetration leading to reduced dissolved oxygen levels (US EPA 2006).

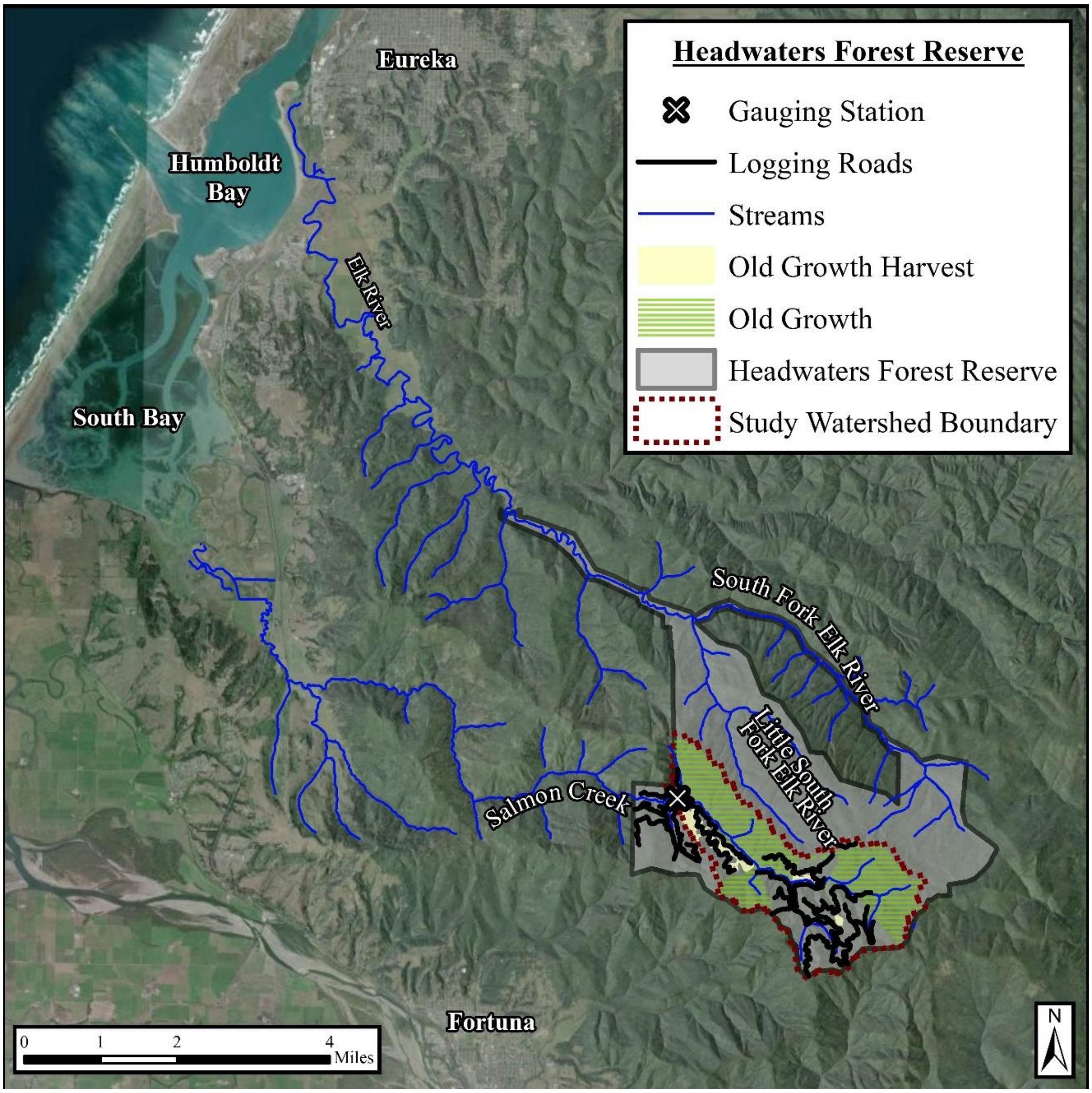


Figure 1: Map of the Headwaters Forest Reserve and the Upper Salmon Creek watershed. The study site (outlined in red) is located in the Upper Salmon Creek watershed, which contains old-growth forest and logging roads (Data Source: Jones et al., unpublished data, 2018).

A natural barrier outside the Reserve has resulted in the absence of anadromous salmonids in the Upper Salmon Creek (BLM 2017). However, Upper Salmon Creek supports rainbow trout, sculpin, and three-spine sticklebacks as well as non-migratory cutthroat trout (BLM 2017). Threatened anadromous salmonid runs are present downstream of the Salmon Creek barrier outside the Reserve boundary, including Coho salmon (*Oncorhynchus kisutch*), Chinook salmon (*Oncorhynchus tshawytscha*), Steelhead (*Oncorhynchus mykiss*), and Coastal Cutthroat trout (*Oncorhynchus clarkii*) (BLM 2017). The historical and continued sediment delivery from existing logging roads and stream crossings within the Upper Salmon Creek watershed still pose a threat to stream water quality, which may contribute to the reduction in the ecological habitat for these species downstream.

A primary goal for the Reserve is to protect and recover ecologic diversity and threatened native species within and downstream of the Reserve. These goals are dependent on long-term reduction in sediment delivery from current and future erosion that has historically degraded water quality in the Salmon Creek watershed (PWA 2005). In the late 1990s, assessment and implementation of Best Management Practices for reducing ongoing and potential sediment delivery from logging roads were implemented in the Salmon Creek watershed. Beginning in 1999, high priority logging roads (vulnerable to failure) were removed in the Salmon Creek watershed (PWA 2005). Decommissioning of old logging roads in the Upper Salmon Creek watershed has continued, and 13.5 miles have been removed since 2017. There are currently 9.5 miles of abandoned logging roads still present in the Upper Salmon Creek watershed (Jones et

al., unpublished data, 2018). These remaining roads will continue to be accessed and treated (BLM 2017).

A stream gauging station located in the Upper Salmon Creek was designed and constructed by BLM in cooperation with the Humboldt State University (HSU) Environmental Resources Engineering (ERE) department for measuring long-term sediment related water quality impacts. The gauging station uses a turbidity threshold sampling protocol developed by the United States Department of Agriculture Redwood Sciences Laboratory, and measures turbidity, stage, and temperature (Lewis and Eads 2009).

The objective of this project is to evaluate the impacts of watershed restoration activities on sediment yield by continuing to collect data for water years (WY) 2018 and 2019, which contributes to long term stream monitoring. The field and laboratory data collected were used to further understand the relationships between hydrology, sediment transport, and land-use, and to estimate sediment load from WY 2012 to 2019. Additionally, two precipitation-monitoring stations were installed in the Upper Salmon Creek watershed during WY 2019, to provide a more spatially representative rainfall data set. The closest permanent precipitation monitoring station is in Eureka, California (approximately 20 miles from the gauging station) and rainfall may be different between there and the sampling location at Salmon Creek.

Site Description

The Reserve spans over two coastal watersheds, the South Fork Elk River and the Salmon Creek. The South Fork Elk River joins the North Fork Elk River outside the Reserve boundaries and drains into Humboldt Bay, south of Eureka, California (Figure 1). The Elk River drainage basin is approximately 33,800 acres (PALCO 2005). The Salmon Creek watershed is adjacent to the southern ridge of the Elk River watershed and drains into southern Humboldt Bay near Fortuna, California (Figure 1). The Salmon Creek drainage basin is approximately 13,000 acres (PALCO 2005). Salmon Creek is the largest stream that enters into southern Humboldt Bay.

The study site has a stream gauging station located in the Upper Salmon Creek watershed, near the boundary of the Reserve to capture the entire upper watershed area (Figure 2). The Upper Salmon Creek watershed drainage basin is approximately 3,400 acres, which contains 1,026 acres of old-growth redwood forest, 543 acres of natural stand with no harvest, and 1,831 acres of shrub-, early-, mid-, late, and old-harvest (Figure 2) (Jones et al., unpublished data, 2018). Approximately two miles of the headwaters of Salmon Creek flows through the old-growth redwood forest.

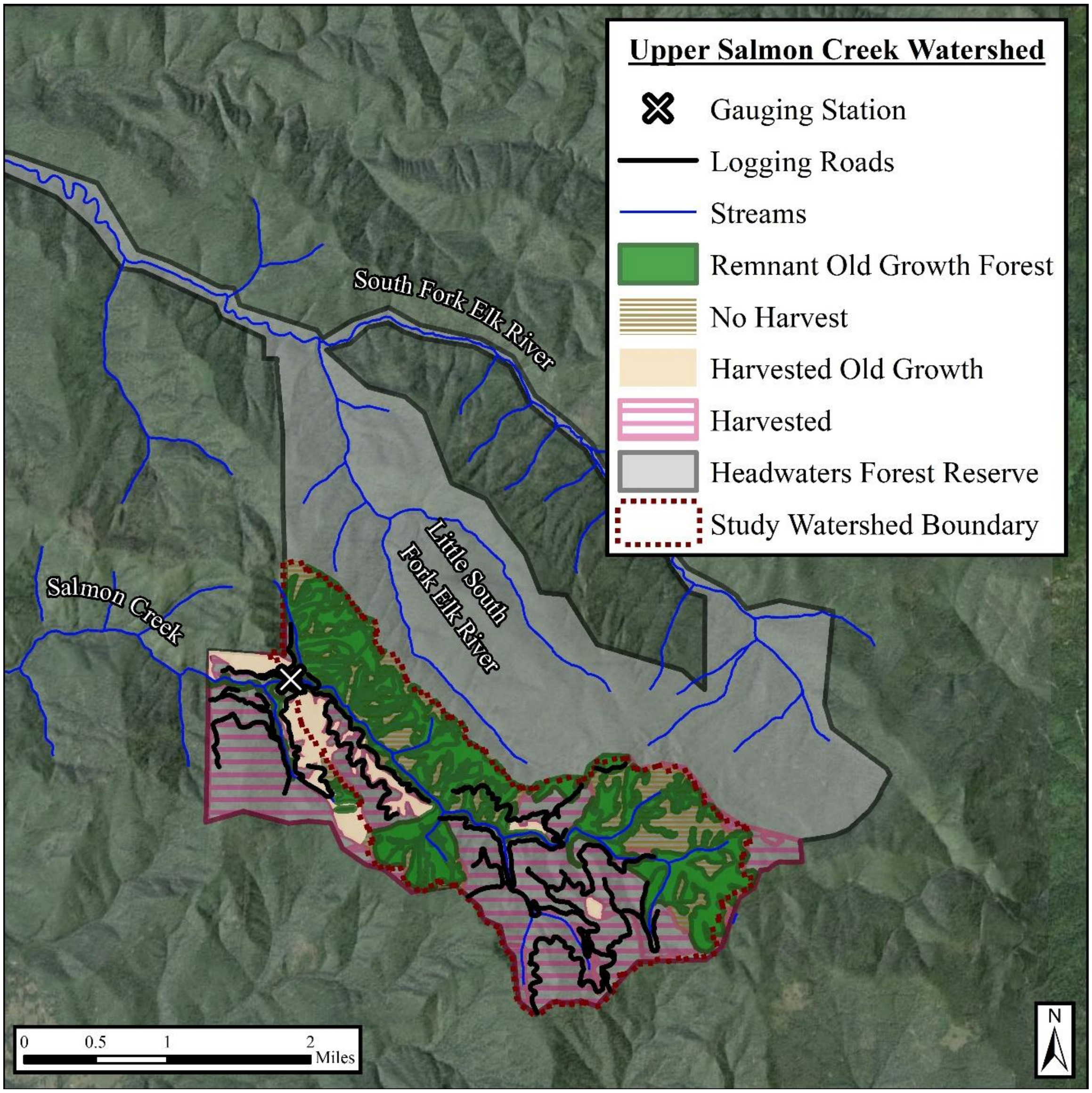


Figure 2: Stream gauging station located in the Upper Salmon Creek watershed in the Headwaters Forest Reserve (Data Source: Jones et al., unpublished data, 2018).

The Upper Salmon Creek is well shaded, with cold-water temperatures, averaging 50^{o}F. Salmon Creek has numerous deep pools with large woody debris jams that make it ideal for aquatic habitat (Figure 3). However, natural and anthropogenic disturbances have contributed to sediment delivery into Salmon Creek, where fine (silty) sediment

covers the channel-bottom (Jones and Stokes 2003). The excessive sediment delivery into Salmon Creek not only affects the aquatic habitat in the Reserve, but the downstream anadromous fish habitat, and other habitat in the southern Humboldt Bay, estuaries (Humboldt Bay National Wildlife Refuge), and the floodplain. The lower portion of the Salmon Creek watershed is a depositional zone as indicated by the channel gradient becoming less steep and the valley floor widening. Legacy and continued pulses of sediment and turbidity in the lower watershed pose a threat to agriculture water supply during winter; to salmonid spawning, rearing, and feeding; to flooding residential or access roads; and to dense vegetation growth in the mainstem channel (MacDonald et al. 2016).

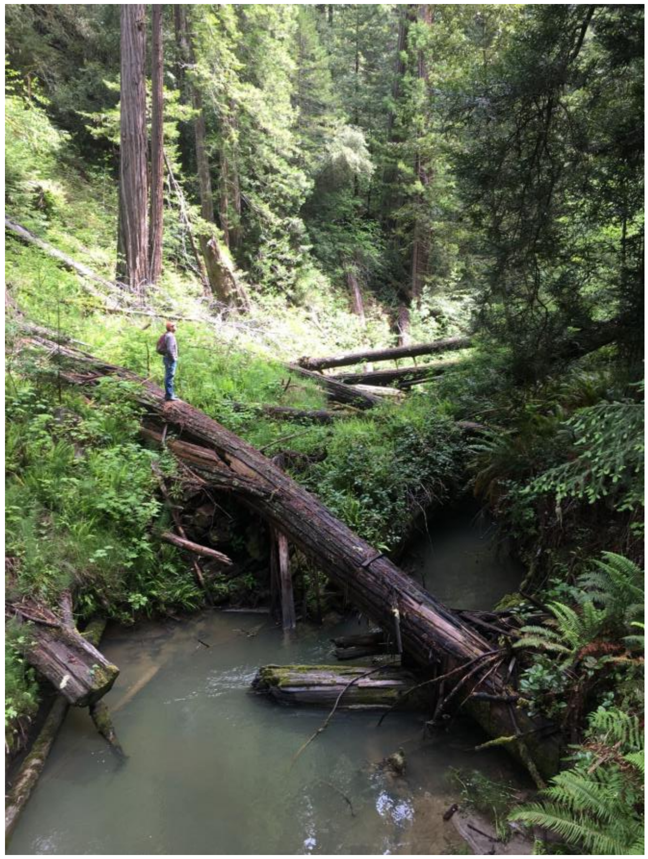


Figure 3: Large woody debris and pools located upstream from the gauging station. Picture was taken on May 31st, 2019 looking upstream.

Upper Salmon Creek Logging History and Forest Management

Logging activities in the Reserve started in the mid-1800s. The first logging mill was developed along Salmon Creek in 1856, and by 1875, additional logging mills were constructed (CDFG 2003). Logging activities grew through the 1900s and the second round of timber harvesting began in the 1940s. During this period, with the growth of timber harvesting came extensive road development (CDFG 2003).

In the mid- to late 1970s, over 500 acres in the Upper Salmon Creek watershed were developed with logging roads and harvested along the roadways (Jones and Stokes 2003). By 1987, additional new road construction was developed and 40 acres of clear-cutting occurred. Between 1987 and 1994, timber harvesting and road development continued with nearly half or more of the Upper Salmon Creek watershed harvested (Jones and Stokes 2003). By 1999, the Upper Salmon Creek watershed, owned and managed by Pacific Lumber Company was acquired by the Secretary of the Interior and the State of California as part of the Headwaters Forest Reserve (BLM 2017).

Since 1999, the Bureau of Land Management, partner organizations and agencies (e.g. California Department of Fish and Wildlife and North Coast Regional Water Quality Control Board) worked on a number of restoration projects in the Upper Salmon Creek watershed. These projects focused on sediment source inventory, sediment reduction efforts by decommissioning and treating 13.5 miles of logging roads, replanting of old logging roads and landings, removal of invasive plants, and landslide stabilization to reduce sediment loads into Salmon Creek (Table 1) (BLM 2005; BLM 2017; PWA

2005). BLM continues to conduct road decommissioning and revegetation efforts. There are currently 9.5 miles of roads remaining in the watershed, with 2 miles maintained, 2.4 miles that have been passively restored, and 5.1 miles that need assessment (Figure 4). The 4.4 miles that still need assessment are all located in the headwaters of Salmon Creek, which poses a threat of sediment delivery into the creek.

Table 1: Preliminary data for work carried out from 2000 to 2017 for the BLM Salmon Creek Road Decommissioning Project (Data Source: BLM, unpublished data, 2019)

Water Year	Total # of Miles Treated/ Decommissioned	Total # of Stream Crossings Treated	Total # of Slope Stabilizations Treated
2000	0.2	2	2
2001	3.9	27	19
2002	2.1	13	9
2003	0.6	2	9
2004	0.6	3	13
2005	0.5	11	5
2006	1.3	10	8
2007	1.1	6	3
2008	0.7	7	0
2009	0.3	2	0
2010	0.0	0	0
2011	0.2	0	2
2012	1.3	7	11
2013	0.0	0	0
2014	0.0	0	0
2015	0.0	0	0
2016	0.4	6	8
2017	0.3	5	4
Total	**13.5**	**101**	**93**

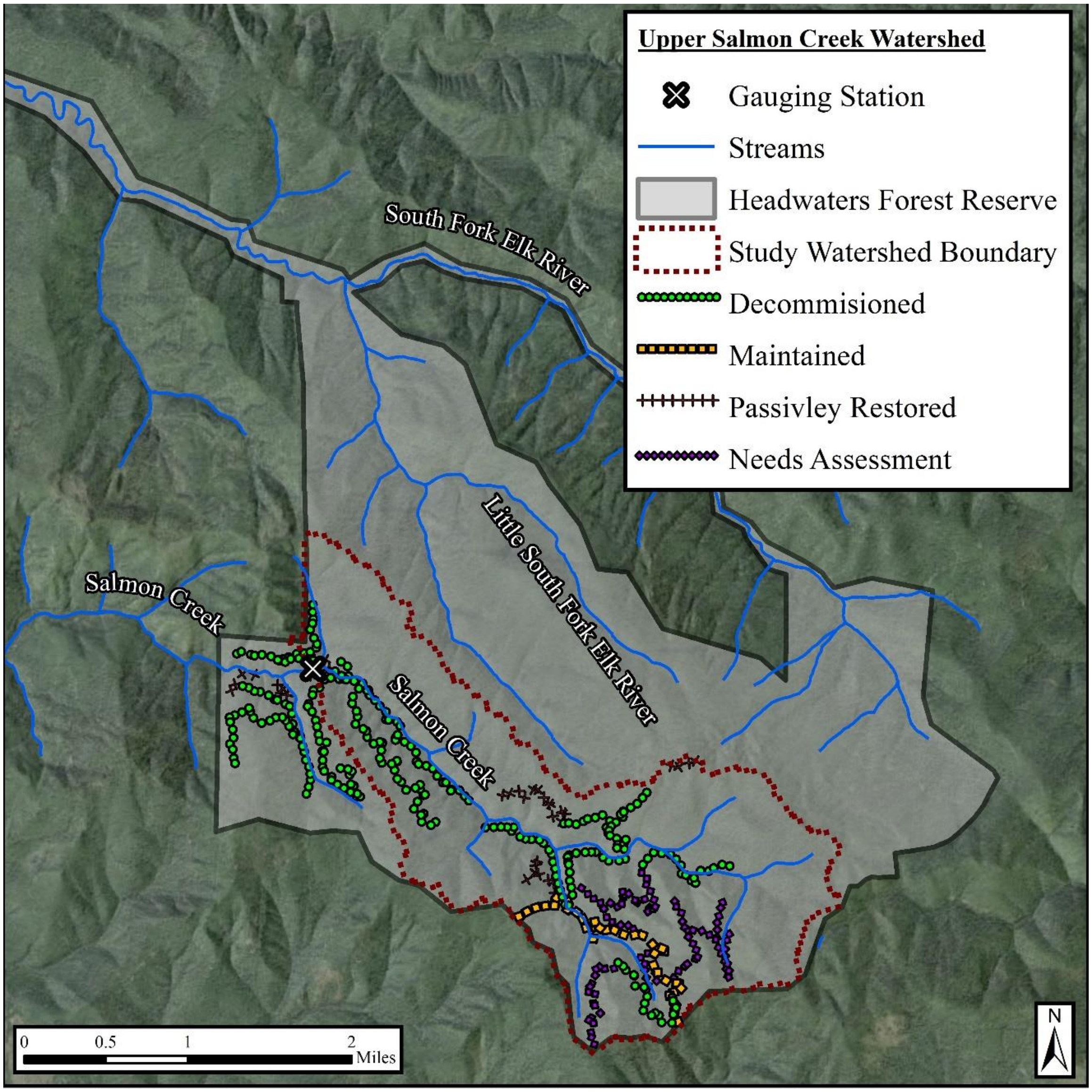


Figure 4: There is 13.5 miles (green circles) of decommissioned logging roads in the Upper Salmon Creek watershed. The remaining 9.5 miles of abandoned logging roads in the Upper Salmon Creek watershed consists of: 2 miles of maintained roads (orange squares), 2.4 miles of passively restored roads (black crosses), and 5.1 miles of roads that need assessment (diamond).

Climate and Hydrology

The climate in the Salmon Creek watershed is characterized by wet, cool, humid, and maritime atmospheric conditions (Jones and Stokes 2003). The wet season occurs from October to April, accounting for over 90% of the annual rainfall. The dry season lasts from May to September, with cool to warm temperature and low clouds and/or fog. Temperatures are moderate in Salmon Creek watershed due to its proximity to the Pacific Ocean. Eureka, California is the nearest weather station to Salmon Creek. The average monthly high and low temperatures in Eureka range from 54.8 ^{o}F to 61.5 ^{o}F and 42.1 ^{o}F to 52.0 ^{o}F, respectively (NOAA 2019).

Precipitation tends to be dominated by seasonal variation from global atmospheric and oceanic conditions. Annual precipitation in Eureka, CA has ranged from 18 to 74 inches (Jones and Stokes 2003). The Salmon Creek watershed receives most of its precipitation in the form of rainfall due to its low elevation (CDFG 2003). According to PRISM (parameter-elevation Regression on Independent Slopes Model), on average, the annual rainfall for the lower watershed is approximately 40 to 45 inches and the upper watershed receives approximately 50 to 65 inches of annual rainfall (CDFG 2003).

Topography

The Salmon Creek basin drains northwest through alluvial floodplain valleys in the coastal plain and into southern Humboldt Bay. In the headwaters of Salmon Creek

watershed, the channels are pinched by narrow valleys with moderate to steep slopes on either side (PALCO 2005). Approximately three miles before exiting into southern Humboldt Bay, the mainstem joins with Little Salmon Creek, where the channel meanders through a low-gradient and broad valley (Figure 5). The elevation within the watershed ranges from sea level at southern Humboldt Bay to approximately 2,100 feet (USGS 2018).

Figure 5: Salmon Creek Estuary: Humboldt Bay National Wildlife Refuge (Michael Love & Associates (2014)).

Geology

There are two main geological formations in the Reserve: the Yager Formation and the Wildcat Group (Jones and Stokes 2003). The Yager Formation is older, strongly

cemented, and resilient to erosion while the Wildcat Group is soft, weakly cemented, and more susceptible to erosion. Yager rocks are overlaid by the Wildcat Group in most places in the Upper Salmon Creek watershed. Wildcat Group underlies most of the forested areas and upper slopes in the Salmon Creek watershed and Yager Formations are only exposed near streams and gorges of main tributaries (Figure 6).

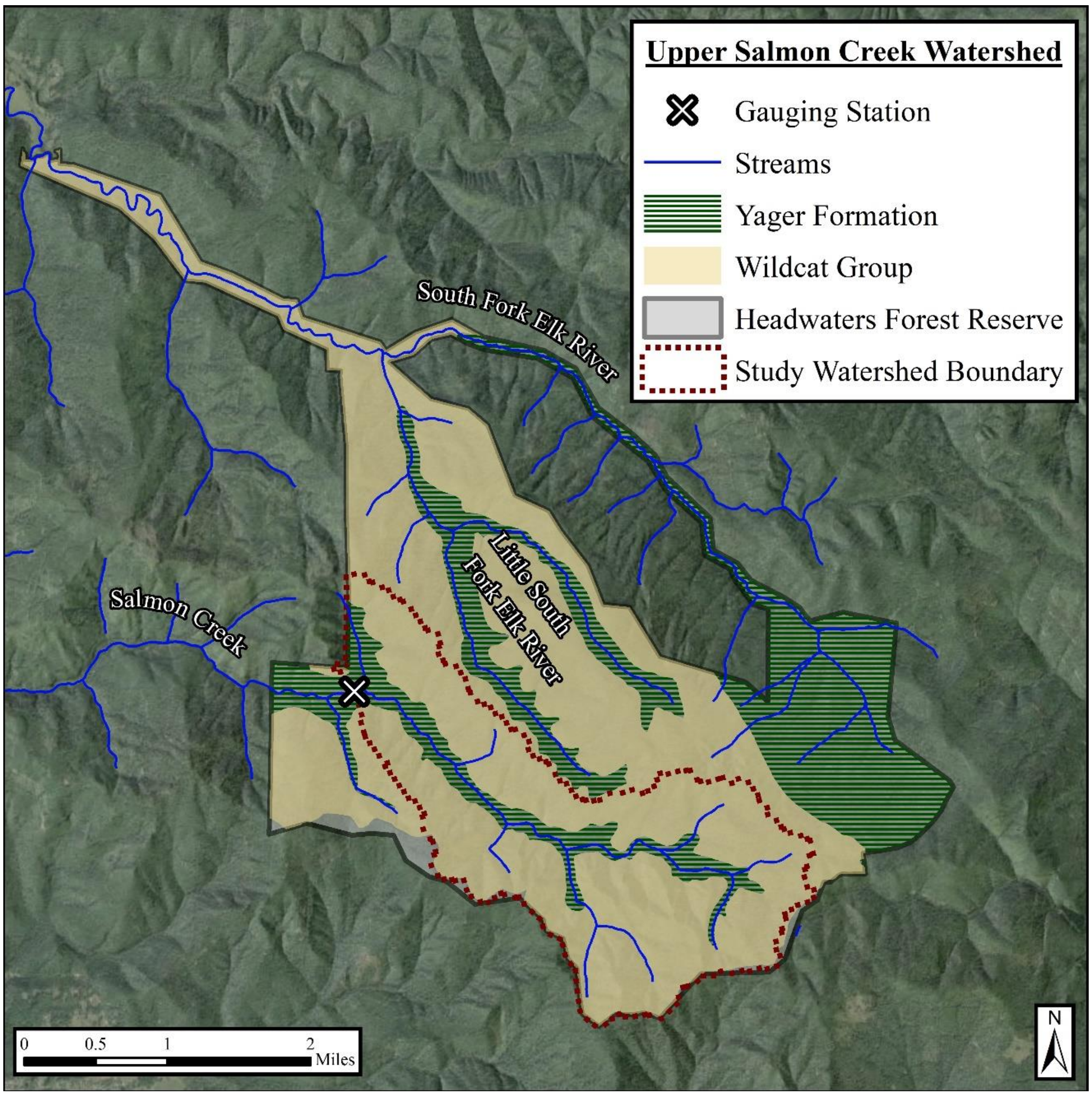


Figure 6: The Headwaters Forest Reserve mainly consist of the Yager Formation and the Wildcat Group (Data Source: Jones et al., unpublished data, 2018).

Materials deposited into Salmon Creek from the Yager Formation are composed of sandstone and conglomerate pebbles, cobbles, boulders, and some smaller amounts of sand and silt (Jones and Stokes 2003). Soils formed from Yager formation are easily drained due to the soil composition and fragments developed, and are moderately erosive (Jones and Stokes 2003).

The Wildcat Group is highly erosive and is composed of marine sandstones, siltstones, and claystones. These soft rocks are weakly cemented and are broken down into finer components – sand, silt, and clay, and contribute to streamside landslides in the Salmon Creek watershed (Jones and Stokes 2003). Wildcat rocks are prone to surface or sheet erosion in areas of no vegetation cover, particularly logging roads, landings, and skid trail networks. These areas are at high risk of transporting fine sediment during large storm events that eventually get deposited in the stream (Jones and Stokes 2003).

From geological and sediment source inventory assessments, areas of high risk for erosion and sediment delivery into Salmon Creek are areas of the Wildcat Group. The majority of the logging roads and stream crossings were developed on the Wildcat Group in the Reserve. Roads and landings upslope of Salmon Creek are at the highest risk of erosion and sediment delivery (Jones and Stokes 2003). Other serious threats are abandoned roads, crossings, and landings in the watershed. These locations have a high potential for sediment delivery into the waterway and result in impacts to the aquatic habitat.

Upper Salmon Creek Watershed Landslide History

Since 2003, there have been 49 road-induced landslides that have been documented in the Reserve (Jones and Stokes 2003). Of the 49 road-induced landslides, 22 of them were located in the Salmon Creek watershed. On March 30, 2012, during a high-intensity storm event, a large landslide occurred along a re-contoured logging road just upstream of the stream monitoring station (Figure 7). The landslide introduced a significant amount of large woody debris, rocks, and soil into Salmon Creek (Figure 8). The debris flow stopped before reaching the gauging station and stage and turbidity were recorded during this event. The landslide resulted in a change in the channel bed morphology such that the equipment had to be adjusted to the new conditions.

Figure 7: The photo on the left illustrates the view spanning the top of the landslide and on the right views the bottom of the landslide (Bailey 2013).

Figure 8: Landslide debris that was introduced into the waterway of Salmon Creek, upstream of gauging station (Bailey 2013).

Since the 2012 landslide, vegetation has grown along the eroded hillside. During a site visit, a scarp on the hillside was observed, indicating the potential to slide again (Figure 9). Most of the large woody debris is still present in Salmon Creek, and vegetation has grown heavily on the woody debris and on the banks (Figure 10). The landslide created a large natural barrier for aquatic habitat, but it also created ecological habitat in the stream (Figure 10).

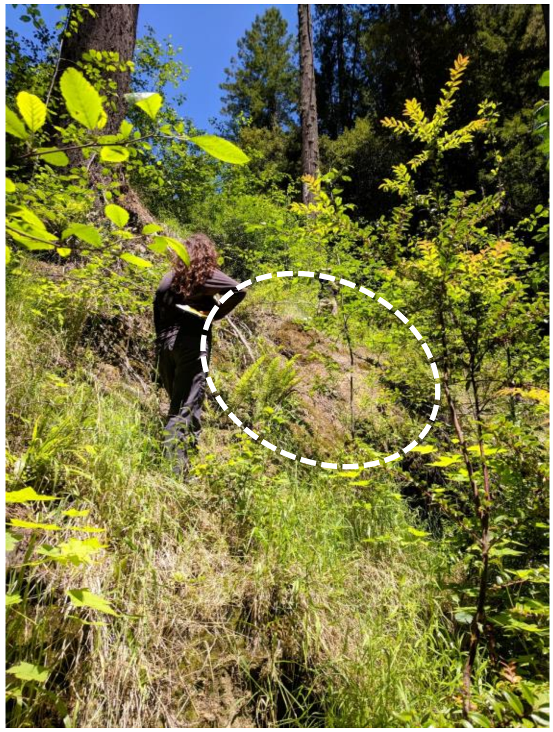


Figure 9: Standing near the top of the landslide. A scarp was observed while hiking around the hillside (circled in white dashed line). Photo taken June 1st, 2018.

Figure 10: Top photo is looking downstream and illustrates the debris present in Salmon Creek after the landslide in 2012. The bottom photo is looking downstream and demonstrates the vegetation grown on the eroded hillside. Photos were taken in June of 2018.

A large landslide along the forest road, approximately 0.75 miles away from the Salmon Creek parking lot occurred after a series of large rainfall events on March 1st,

2019 (Figure 11). The initial landslide took out the road fill and after a few weeks the initial slide took out the forest road up to the weathered bedrock (March 15th, 2019). This landslide was not adjacent to the creek but demonstrates the vulnerability of logging roads placed on steep terrain with poor drainage.

Figure 11: Top photo illustrates the initial landslide (March 1st, 2019) and the bottom photo is a few weeks after the initial slide, which took out the forest road and up to the weather bedrock (March 15th, 2019).

Humboldt Redwood Company (HRC) developed a new logging road near the landslide to allow access for HRC staff, BLM staff, and others. The development of a new road will allow the continuation of data collection at the stream monitoring station.

LITERATURE REVIEW

Introduction

Sedimentation is one of the leading causes of impaired streams and rivers and the degradation of water quality from turbidity and suspended sediment in waterways has long been recognized as one of the risks from timber harvest and road development (Klein et al. 2011). Increased sediment concentration and turbidity have been observed in numerous watersheds based on poorly designed and unmaintained logging roads, and the style of timber harvesting in the 20th century (Lewis et al. 2011; Klein and Ozaki 2016; Reiter et al. 2009). Lieberman and Hoover (1948) determined that there was a 22-fold and 42-fold increase in mean and maximum turbidity, respectively, because of the style of early 20th century logging practices. A study in the Deschutes River, Washington with over 30 years of data found decreasing trends in turbidity that appeared to be directly related to improvements in road construction and maintenance (Reiter et al. 2009). Nolan and Janda (1995) estimated sediment discharge in logged watersheds of Redwood Creek yielded 10 times more suspended sediment than watersheds in the unharvested terrain.

Measuring suspended sediment and turbidity in streams and rivers is essential for monitoring the health of the stream ecosystems, evaluating the effects of land use, and estimating sediment yield in watersheds. A review of previous research on suspended sediment concentration measurements, the turbidity threshold sampling method, turbidity sediment rating curves, and suspended sediment load estimates will inform the analysis

of sediment characteristics in the Salmon Creek watershed. This review compiles the available information on estimating sediment load in a stream or river and examples summarizing results from similar research studies.

Measuring Suspended Sediment Concentration

Suspended sediments originate from erodible soils and weathered bedrock, and are transported downstream as part of the cycle of erosion (Ellison et al. 2010). Although erosion is a natural process, and some watersheds have greater erosion rates and sediment load due to the geology, climate, soil, vegetation, and topography, the erosion process can be accelerated by anthropogenic land uses (Steffy et al. 2018; Ellison et al. 2010; Lewis et al. 2011; Klein and Ozaki 2016). Excessive sedimentation is one of the causes of biological impairment to freshwaters, and the concentration of suspended solids may have negative effects on the aquatic ecosystems (Packman et al. 2009). Negative effects include clogging fish gills, reducing growth rates and spawning habitats, altering egg and larval development, and difficulty finding food (Packman 1999; US EPA 2012; Newcombe and McDonald 1991). Thus, measuring suspended sediment concentration (SSC) is essential for monitoring the health of the stream, estimating suspended solid loads (SSL), and evaluating land-use practices.

Suspended sediment concentration in streams and rivers are difficult to measure because it is a nonpoint pollutant whose value varies over time and space, and with storm events, seasons, anthropogenic disturbances, land-use changes, and natural hydrologic

occurrences (e.g. landslides, debris jams, change in channel morphology) (Lewis 1996). Suspended sediment concentration can be measured from collected water samples that are processed in a laboratory by filtration and drying (APHA 1998). Suspended sediment concentration is commonly reported in units of milligrams per liter (mg/L) and recorded as SSC or total suspended sediment concentration (TSS).

Traditionally, estimations of SSL were based on infrequent sampling that was unable to properly characterize the temporal variability in SSC. It was common to miss the greatest value of SSC in a stream because daily grab sampling poorly represents the variation in SSC throughout a day (Lewis and Eads 2009). Stream turbidity and discharge can be monitored in real-time and provide information on variability in SSC. Discharge was the primary estimate for SSC before technological advancement in turbidity monitoring. The relationship between discharge and SSC is called a discharge sediment rating curve, which was used for estimating SSC and SSL (Lewis and Eads 2009). This relationship typically results in poor estimations of SSL because (Walling and Webb 1981, Lewis and Eads 2009):

- SSC is often varying independently of discharge, which may lead to systematic biases in the estimation of SSL;
- discharge rating curves change with time;
- and rating curves cannot represent episodic events that cause suspended sediment concentration to increase (e.g. bank erosion and landslides).

Discharge sediment rating curves account for the power provided from stream discharge, but do not consider the processes and sources that cause variability in SSC (Lewis and Eads 2009). Since the development and advancement of submersible light-scattering turbidity sensors, in-stream turbidity measurements became the preferred surrogate for estimating SSC than using discharge rating curves (Lewis and Eads 2009; Uhrich et al. 2014; Susfalk et al. 2008). Turbidity measures the concentration of light-scattering particles suspended in water and is related to particle concentration. Turbidity is also a property of the type of instrument used because turbidity readings vary between sensors. Turbidity sensors differ in their optical geometry, the wavelength of light emitted, range of turbidity values, and internal signal filtering (Lewis and Eads 2009). Turbidity-based sampling relates the concurrent instantaneous in-stream turbidity and sampled SSC measurements to develop a turbidity-sediment rating curve, which is described in more detail in the section "Turbidity Sediment Rating Curve".

Walling (1977) assessed the accuracy of SSL estimates using a rating curve. The rating curve describes the relationship between suspended sediment concentration and discharge. Continuous discharge and sediment concentration was measured in river Creedy in the United Kingdom and a rating curve was developed to estimate SSL. Walling found that using a rating curve to estimate annual SSL can involve errors up to +280% (Walling 1977). Walling also measured turbidity in river Creedy by using a photoelectric turbidity meter and found that turbidity readings were strongly correlated with SSC. Walling determined that recording turbidity in small to medium watersheds of predominantly fine materials can be employed to provide a continuous SSC data set

which can be used to estimate annual SSL. Dana et al. (2004) performed a study in the Middle Truckee River, California, finding that discharge-based SSL was two to six times lower in magnitude during hydrological events than using a turbidity-based estimate. Sufalk et al. (2008) also determined that discharge-based estimates under-predicted SSL at four sites in the Carson River, Nevada when compared to turbidity-based estimates, and concluded it was due to the inability of discharge to account for the variability of total suspended sediment during hydrologic events. Estimating SSC by monitoring stream turbidity has become the common method due to the advancement of turbidity meters, and the improvement and efficiency of measuring SSC in a laboratory (Walling and Webb 1981).

Turbidity Threshold Sampling

The Turbidity Threshold Sampling (TTS) method was developed by the U.S. Department of Agriculture Forest Service Redwood Sciences Laboratory in Arcata, California. The TTS method utilizes real-time continuous stream turbidity and stage measurements to trigger water samples from an automatic pump sampler. Water samples are stored in an ISCO sampler (commonly 24 samples) (Lewis and Eads 2009). A programmable data logger collects and stores continuous recordings of turbidity and stage at a constant time interval (commonly 10 or 15 minutes). Turbidity threshold values are programmed in the data logger, and if these thresholds are exceeded and the stage in

the stream is adequate for the pump sampler to activate then water samples are taken (Lewis and Eads 2009).

Turbidity threshold values are inputted into the data logger and are programmed to capture the rising and falling turbidity conditions in a stream while aiming to measure all significant peaks and events. Once the criteria have been met, a sample from the stream is physically pumped by the automatic pump sampler and stored in a bottle. Samples are processed in the laboratory to quantify suspended sediment concentration of that sample at the measured turbidity value. The TTS method provides a set of turbidity and SSC pairs to construct a turbidity-sediment rating curve, which can be used for estimating suspended sediment loads over a given time period.

Turbidity Threshold Sampling method location

The first step to implement the TTS method is to determine the monitoring station location within the watershed that is applicable for field equipment. Field equipment that is essential for the TTS method includes (Lewis and Eads 2009):

- current meter or flow measurement device (weir or flume);
- stage sensor;
- turbidity sensor;
- data logger;
- pump sampler;
- power source;
- and shed or shelter to house equipment.

The equipment must be located in the watershed of interest and meet study objectives. The selection criteria for location often include accessibility to the site, watershed area, topography, geology, proximity to tributaries, channel controls, soil type, and location of movable debris. An additional consideration is to find a location with sufficient stream depth that allows placing the turbidity meter and the pump intake at a level that does not touch the channel bed or pick up bed load material.

The site must be accessible for field crews to maintain/service the equipment and to collect data. Accessibility is important during storm events when discharge measurements need to be taken, and when the pump sampler needs to be emptied to capture more samples. Lewis and Eads (2009) recommend the access time to be less than one hour and no longer than three hours. Sites that are difficult to access should be avoided because it can reduce the amount of data collected during peak events and the quality of data in response to storm events (Lewis and Eads 2009). Maintaining and servicing the equipment may be difficult to predict because of unexpected local conditions. In general, site visits are conducted before a storm event, during and after storms, and periodically throughout inter-storm periods.

The site location needs to be an adequate distance downstream from a tributary to allow for complete mixing of sediments (Lewis and Eads 2009). Complete mixing of sediments depends on the velocity and turbulence in the stream, particle size, and the contribution of sediment from the tributary and main channel. Complete mixing can be determined by collecting depth-integrated samples along a downstream vertical cross-section and measuring SSC for each sample. The distribution of SSC may vary during

storm events due to local hydrologic conditions, but it is possible to determine the mixing trend (Lewis and Eads 2009). Besides determining if complete mixing is occurring, this sampling method will also determine the best location for a turbidity sensor and pump sampler.

A well-defined and stable thalweg is desirable for a monitoring station. Steep and wide channel beds with a coarse substrate and high velocities should be avoided because bed load is mainly carried during large storm events in steep channels, and wide channels may have inadequate mixing and unstable channel geometry. Locations with high turbulence should also be avoided as it may affect turbidity sensor readings. Depositional channels are undesirable because sufficient depths are difficult to maintain during low discharge periods, stage sensors may be buried, and turbidity sensors are positioned close to the bed (Lewis and Eads 2009). Wagner et al. (2006) suggest that adequate flow depth and mixing of sediments occur during the riffle sequence in a small to medium alternating pool-riffle stream. Pools may be the best location for monitoring equipment in small to medium channels to avoid poor quality data or lack of data collection from inadequate flow depths (Lewis and Eads 2009).

Discharge measurements at the monitoring location are essential for estimating SSL. Stable channel geometry and consistent discharge rating curves can be obtained by hydraulic structures, such as weirs, flumes, metal, or concrete sills (Ackers et al. 1978; Lewis and Eads 2009; and Harrelson et al. 1994). This is important because inaccurate discharge measurements might result in the largest source of error when computing SSL (Lewis and Eads 2009). However, hydraulic structures require large capital investment

and may cause negative impacts on the habitat and stream morphology. The velocity-area method may be used in channels for developing a stage-discharge rating curve. This method utilizes a current meter to measure velocity along an established cross-section. If the bed is unstable and lacks a natural control, then errors may occur when developing a stage-discharge rating curve (Lewis and Eads 2009).

Organic materials, such as logs, root wads, and branches, are to be avoided when choosing a monitoring location. Large woody debris can be mobilized during storm events, which may damage field equipment or alter the local hydraulic conditions (Lewis and Eads 2009). Debris traps should also be avoided when choosing a monitoring location. This includes locations with channel constrictions, spanning logs or root wads, and bends in the channel. Debris can get trapped on the equipment boom or the turbidity sensor leading to flawed readings. Physical samples may be collected during such events and processed in the laboratory to confirm or eliminate this data. However, if samples are not collected during these events, errors in the collected data may not be easily identified.

Turbidity Threshold Sampling method implementation

The Redwood Sciences Laboratory first implemented the TTS method in eight locations along Casper Creek in Mendocino County, California in 1996. Lewis (1996) measured SSC and turbidity in Casper Creek during five storm events on a 10-minute interval using the TTS method. Simulations containing on average 4 to 11 water samples were used from each storm's record to develop a regression between SSC and turbidity. Using a simple linear regression, SSL estimates were calculated with root mean square

errors between 1.9% and 7.7%, whereas using a discharge sediment-rating curve resulted in errors between 8.8 to 23.2% (Lewis 1996). This method has the potential to acquire a stronger correlation between variables and a more accurate estimate of SSL.

The TTS method is most successful in rain-dominated watersheds with fine sediments and channels that allow for complete mixing (Lewis and Eads 2009). There are limitations to the TTS method that make it difficult for monitoring sediment and utilizing the gauging equipment. These limitations include freezing temperatures, snowmelt, fouling, particle size, channel size, and turbidity range. Freezing temperatures in a watershed can cause several problems with ice buildup on equipment leading to invalid measurements and/or equipment failure (Lewis and Eads 2009). Snowmelt can cause inconsistency in the data set. Fouling can occur on the turbidity sensor (algal growth), which can lead to inaccurate recordings of turbidity. It is essential to have an automatic wiper blade or another cleaning mechanism on the sensor to avoid fouling. Streams with predominantly sand and coarse particles are difficult to sample using the pump sampler. Course particles tend to be non-uniformly distributed in the stream cross-section, making it less likely for a point source to capture a representative sample. Additionally, these particles are difficult to capture due to their mass and high momentum (Lewis and Eads 2009). It is difficult to establish a consistent relationship between SSC and turbidity in channels that are wide with low gradients because the materials are not well-mixed. Lastly, the TTS method should be avoided for slightly turbid streams as most sensors have a maximum limit of 2,000 turbidity units.

Turbidity Sediment Rating Curve

Commercially available turbidity sensors became widely used in the 1990s for estimating SSC and SSL in northern California streams to monitor the impacts of hydrology and land management (timber harvesting, logging roads, etc.) (Lewis 1996). Nephelometric turbidimeters measure light-scattering particles suspended in water at an angle (90^{o} or 180^{o}) to the beam. The turbidity sensor response to particle suspension in water is mainly governed by the light source, geometry, and detector (Lewis 1996). If the sensor is calibrated to give a linear response, then the response of varying SSC should be linear if the particle geometry stays constant (Gippel 1995).

A turbidity-sediment rating curve utilizes turbidity as the predictor variable, which is used for estimating the response variable SSC at each time interval. A simple linear regression of turbidity and SSC for each event, season, and/or annual time scale is typically adequate for estimating SSL (Christopher et al. 2010, Susfalk et al. 2008, Lewis and Eads 2008, Lewis 1996). However, a linear relationship between turbidity and SSC can have a negative intercept, resulting in negative SSC values when low turbidity values are recorded (Lewis and Eads 2008). Solutions are to set negative predictions to zero, fit a piece-wise relationship to the low and high turbidity and SSC data, or develop a model that transforms the data so that it never predicts negative SSC, such as log-log regression. Additional options for addressing a low turbidity and SSC data, is to fit a piece-wise turbidity sediment rating curve to the data. Transformations on turbidity and SSC can be used to (Lewis and Eads 2008):

- produce a model that does not predict negative values;
- develop a linear relationship;
- normalize data/residuals;
- and to equalize variance.

Log-log regression transformation is always positive, but predications cannot be computed when the predictor variable is zero. Square root transformations are similar to log-log regression except it does not eliminate predictions at zero. Transformations may improve the accuracy of estimating SSC but applying multiple fits or nonlinear fits to SSC data, particularly in the presence of outliers, may result in large sources of error for SSL estimates (Lewis 1996 and Lewis and Eads 2008). Thus, simplifying the relationship between turbidity and SSC with a single linear regression may reduce error for estimating SSL.

The relationship between turbidity and SSC varies between watersheds due to the geology, topography, soil type, and land uses (Steffy and Shank 2018). Thus, each watershed may have a unique turbidity-sediment rating curve. The turbidity-sediment rating curve can change with time because particle composition can change with time. To investigate the nature of the relationship between turbidity and SSC, a turbidity-sediment rating curve can be developed for each storm event, each season or episodic period, rising and falling turbidities, or one annual average rating curve for each WY (Lewis and Eads 2009; Rasmussen et al. 2009; and Walling 1977).

In northern California, the majority of the annual precipitation occurs from October to April, and the use of one turbidity-sediment rating curve during that period

can be used to estimate SSL. However, if the first flush of sediment is delivered by the first precipitation event for that year, it may be desirable to separate turbidity-sediment rating curves into storm events. If the time elapsed is short between estimate periods (e.g. storm events), then there should be minimal variability in the relationship.

Suspended sediment load estimates

Once a relationship between turbidity and SSC is determined (i.e. annual regression, storm event regression, rising and falling turbidity regression, and/or seasonal regression), and the data has been examined and corrected for errors in stage and turbidity sensor readings, a turbidity-sediment rating curve and discharge rating curve can be applied to the full data set to estimate SSL over a storm, a season or a water year (Equation 1). The SSC and water discharge at each time interval are multiplied and summed to estimate SSL (Equation 1):

$$L = \sum_i k t q_i c_i \qquad \text{(Eq. 1)}$$

where L is sediment load, k is a conversion factor, t is the time between measurements, and q_i and c_i are estimated discharge and SSC for interval i (Lewis and Eads 2009).

Annual turbidity-sediment rating curves may be adequate for estimating SSL within a year. However, variation in erosion, land use, and climatic conditions might alter annual SSL estimations. Uhrich et al. (2015) collected turbidity and SSC measurements from the 2010 to 2013 WY in the North Fork Toutle River Basin, Washington. These data sets were separated by year, season, and high turbidity and discharge events. Annual

data were organized by WY, seasonal data were grouped into three periods (e.g. Oct-Dec, Jan-March, etc.), and event data were organized by selecting major events during the time period. Uhrich et al. (2015) found that an annual time span may not be appropriate for the North Fork Toutle River Basin near Mount St Helens as variable sediment sources and episodic erosional events may need shorter time scale models to accurately predict SSC from turbidity. Seasonal time frames may improve accuracy as precipitation patterns in the Pacific Northwest occur at certain times of the year, and may capture the episodic erosional events. Although seasonal models may improve accuracy over annual models, the time scale can miss episodic events that occur within a season (Uhrich et al. 2015). Thus, Uhrich et al. (2015) suggest that smaller data sets might capture more variation in turbidity and SSC relationships than larger data sets, which is associated with the improvement in SSL estimates.

Turbidity and Land-Use History Relation

The TTS method has been widely used in the Pacific Northwest to monitor water quality by characterizing relationships between turbidity and SSC and estimating SSL in various watersheds. Monitoring and determining relationships between turbidity and SSC allows for an understanding of natural erosion processes with respect to hydrology, geology, and soil types, and to estimate impacts from historical commercial timber harvesting and road development.

Klein et al. (2011) utilized data being collected by the TTS method to identify watershed characteristics and land-use history linkages that are the cause of elevating turbidity regimes. Continuous turbidity data from 2004-2005 winter runoff seasons (October to May) were assessed in 28 coastal watersheds in northern California to link chronic turbidity and land-use history. Chronic turbidity is represented by the 10% exceedance probability, or in other words, turbidity levels exceeded 10% of the time. Klein et al. (2011) describes that chronic turbidity values capture stormflow turbidities during peak events, providing a single value to index chronic exposure to salmonids. The coastal watersheds varied in disturbance, and to link land-use history with chronic turbidity, the 28 northern California watersheds were categorized by harvest rate. Klein et al. (2011) expressed harvest rate as ‘clearcut equivalent area’ (CCE), which consists of 15 years of harvest, yarding, and road development data (1990 to 2004). The 15-year CCE period was broken up into 5-year subperiods. CCE is expressed on a mean annual percentage of the watershed area for the individual periods (Klein et al. 2011). The pristine redwood forest is considered no timber harvest activity, legacy is no harvest since 1990, the low harvest is less than 1.4% CCE area from 1990 to 1994, and high harvest is greater than 1.5% CCE area from 1990 to 1994 (Lewis et al. 2011).

Klein et al. (2011) found that pristine watersheds had a mean turbidity of 8 FNU (formazin nephelometric units) at the 10% exceedance level for the 2005 WY, and for legacy, low, and high timber harvest the mean turbidities were 16, 32, and 61 FNU, respectively. The pristine watersheds at the 10% exceedance level were an order of magnitude lower than the legacy, low and high harvest streams, which emphasizes the

near pristine conditions of the contributing watershed. Additionally, the high timber harvest mean chronic turbidity was double the low harvest rate, which may indicate that the rate of timber harvesting in a watershed over a short period can trigger serious cumulative effects to a stream (Klein et al. 2011).

Conclusion

Measuring suspended sediment and turbidity in streams and rivers is essential for monitoring the health of the stream ecosystem, evaluating the effects of land use, and estimating sediment yield in watersheds. Sediment impaired streams and rivers result in degradation of water quality from turbidity and suspended sediment concentration, which has severe impacts on aquatic ecosystems. This degradation to water quality has been recognized as one of the risks from timber harvest and road development (Steffy et al. 2018, Ellison et al. 2010, Lewis et al. 2011, Klein et al. 2011, Klein and Ozaki 2016).

Traditional SSL estimations were based upon using discharge as the surrogate for estimating SSC in a stream. Studies have shown that discharge-sediment rating curves account for the power provided from stream discharge, but do not consider the processes and sources that cause variability in SSC (Lewis and Eads 2009). With the development and advancement of submersible light-scattering sensors, in-stream turbidity measurements have become the preferred surrogate for estimating SSC rather than discharge rating curves (Lewis and Eads 2009, Uhrich et al. 2014, Susfalk et al. 2008).

The TTS method collects real-time continuous stream turbidity and stage height measurements, which are used to trigger water sample collection by an automatic pump sampler. These water samples are processed in a laboratory to quantify suspended sediment concentration (SSC). This data provides a set of turbidity and SSC measurements that can be used for developing a turbidity-sediment rating curve. Turbidity-sediment rating curves can be developed for each storm event, each season or episodic period, rising and falling turbidities, or one annual average rating curve for each WY (Lewis and Eads 2009; Rasmussen et al. 2009; and Walling 1977). Transformations (log, square root, quadratic, etc.) on turbidity and SSC in conjunction with multiple regressions (storm event, annual, seasonal, rising/falling turbidities) may result in less variability in SSL estimations. However, a single linear regression between turbidity and SSC performs as well or better than other methods (Lewis 1996).

The TTS method has been widely used in the Pacific Northwest and throughout the country and world for monitoring turbidity and suspended sediment concentration. The TTS method provides a finer temporal scale than prior methods and may allow for more accurate turbidity-sediment rating curve relationships and estimates of SSL. Reducing variability in sediment yield estimates may increase the certainty of the estimation and determining trends that may be due to land-use changes.

METHODS AND MATERIALS

This section describes the stream monitoring station and field equipment, the discharge measurement location and method, the TTS procedure and programming, the laboratory procedure, and the development of a discharge rating curve and a turbidity-sediment rating curve.

Stream Monitoring Station

The construction of the stream monitoring station (station) occurred in the summer of 2011, when a monitoring shed was constructed and gauging equipment was set up in the stream (Figure 12). The station is located in the Upper Salmon Creek watershed near the boundary of the Reserve to capture the entire Reserve watershed area (Figure 2). The location for the station was chosen in an area of the stream that had sufficient depth for submerging the turbidity probe and the water sampler intake. The location was also selected near a bedrock wall to facilitate a stable cross-section for discharge measurements. The equipment boom, turbidity probe, and the water sampler intake hose were placed in a shallow pool between riffles (Figure 13). A pressure transducer was placed a few feet downstream from the turbidity probe, behind woody debris for protection from large flows carrying debris (Figure 14). Data started recording on a 15-minute time interval October 7th, 2011 at 20:45 and is still recording. There is

missing data within the period of record due to equipment failure or from equipment being offline. Missing data ranges are described in more detail in the results section.

Figure 12: The left photo is the monitoring shed house that stores the data logger, ISCO sampler, and other field equipment. The right photo illustrates the inside of the shed.

Figure 13: The equipment boom, turbidity probe, and water hose located in a medium pool between riffles. Photo taken looking upstream.

Figure 14: Pressure transducer sensors attached to a T-post, placed in-stream behind woody debris on river right.

Station equipment

Turbidity and temperature were measured at the monitoring station using a Forest Technology System (FTS) DTS-12 Turbidity Sensor (DTS-12) (Figure 15). The DTS-12 uses an optical backscatter and employs a detector at 90 degrees to the incident light beam (FTS 2010). The light is emitted into the water and any reflection from the suspended matter is measured as turbidity of the water. The DTS-12 measurement ranges from 0 to 1500 NTU (FTS 2010). The turbidity sensor reads approximately 60 measurements within a 30-second interval and records the median. This reduces reading errors caused by bubbles or floating debris. The median is recorded rather than the mean because it is less sensitive to outliers (Lewis and Eads 2008). Additionally, the DTS-12 has a built-in wiper that reduces silt build-up and biological fouling of the sensor optics.

Figure 15: A Forest Technology System DTS-12 Turbidity Sensor measures turbidity in the Upper Salmon Creek.

The DTS-12 probe is attached to the articulating boom and is placed in the stream (Figure 16). The boom is positioned perpendicular to the stream and downstream to allow

an increased flow to push the boom downstream and keep the probe at approximately 60% of the water depth to ensure bedload is not captured (Bailey 2013). Additionally, the articulation allows for the boom to move up or down, preventing any large debris moving downstream from damaging the equipment. The setup of the boom and DTS-12 probe is placed in a shaded and calm area to prevent interference from light and turbulence.

Figure 16: The DTS-12 turbidity probe is attached to an articulating boom in Salmon Creek.

The stage is measured in the stream by a Submersible Pressure Transducer SDI. The pressure transducer is attached to the bottom of a T-post and is placed downstream of the monitoring station (Figure 14). The pressure transducer is set up behind large woody debris in the stream, and the logs act as barriers for protecting debris from hitting the

equipment. The range of stage heights that the pressure transducer can record is from zero to five meters.

Water samples are pumped from the stream and stored in an ISCO 6721 Portable Sampler (Figure 17). The intake hose is parallel to the stream and is attached to the articulating boom, approximately four centimeters lower than the DTS-12 sensor (Bailey 2013). The pump hose and DTS-12 sensor are housed in a perforated plastic housing located at the bottom of the boom. Water is pumped and transported in a 1-centimeter diameter vinyl tube with a distance of 50 feet from the pump intake to the sampler. The sampler is located in the monitoring shed, less than ten feet of vertical distance above the pump intake. The sampler holds 24 bottles, and for every sampling period, the water fills a 500-milliliter bottle to 350 milliliters.

Figure 17: Top photo is the intake hose connected to the articulating boom. Bottom photo is the ISCO 6721 Portable Sampler, which stores 24 water samples.

The DTS-12 sensor, pressure transducer, and ISCO sampler are all connected to a Forest Technology System H2 Datalogger which records the date, time, turbidity, stage, and water temperature on a 15-minute interval (Figure 18). The data logger is stored in the monitoring shed and has a waterproof case for protection. The logger has a

touchscreen user interface that is used for downloading data as a CSV file by plugging a flash drive into the USB port. The datalogger and all other equipment are charged via a battery that is connected to a solar panel located at the ridge top above the monitoring station (Figure 19).

Figure 18: Forest Technology System H2 Datalogger that records and stores date, time, turbidity, stage, and water temperature. Datalogger stored in monitoring shed.

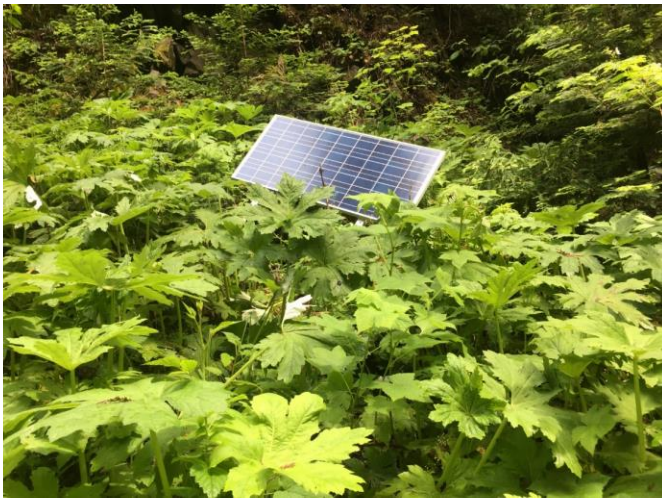


Figure 19: Solar panel located on a ridge above the stream monitoring station.

Precipitation data were collected by two rain gauges located in the Upper Salmon Creek watershed (Figure 20). Rain Gauge One is located upslope from the monitoring station on an abandoned logging road and Rain Gauge Two is located in the upper watershed where an old rain gauge had previously been installed (Figure 20). The gauges were constructed by hammering a T-post into the ground and mounting a wood platform for the rain gauges to be placed on the top (Figure 21). These rain gauges provide a more spatially representative precipitation data set for WY 2019 and beyond. Currently, the closest precipitation gauges to Salmon Creek are Eureka National Weather Service, Woodley Island (20 mi), and Bridgeville, Van Duzen river basin (17 mi) (CDWR 2017).

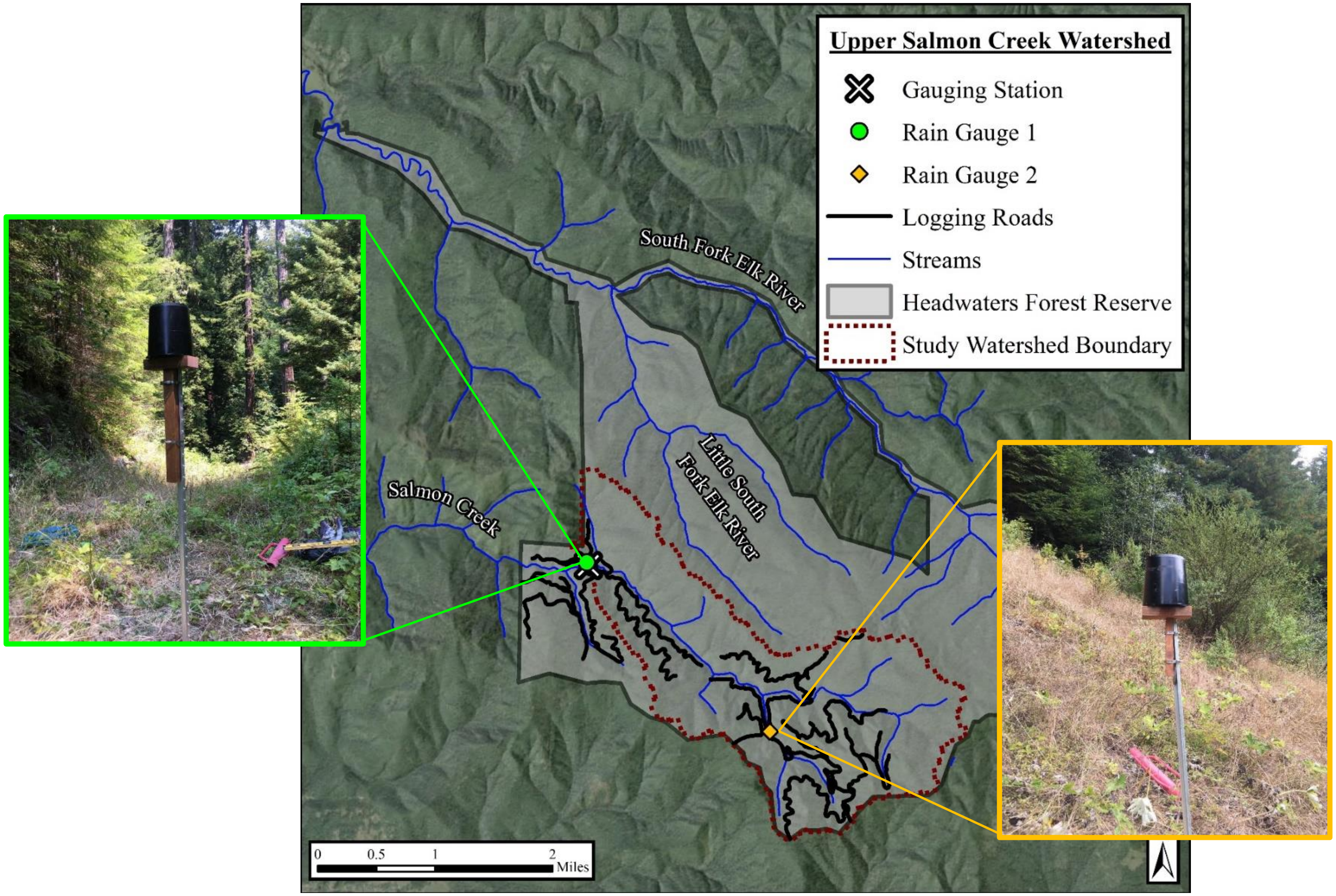


Figure 20: Rain Gauge #1 (left photo) is located on an abounded logging road above the stream monitoring station, and the Rain Gauge #2 (right photo) is located in the upper watershed near an old rain gauge installation.

Figure 21: Installing Rain Gauge #1.

Discharge measurements

An established cross-section downstream of the station stabilized by a bedrock wall was used for collecting flow measurements (Figure 22). Flow measurements were conducted using the mid-section method with a Swoffer Model 3000 current meter for measuring velocity. Flow measurements were collected during 2012, 2016, 2017, 2018, and 2019 WY and were used for developing discharge rating curves.

Figure 22: Established cross-section downstream from monitoring station for recording flow measurements.

Turbidity Threshold Sampling and programming

The stream monitoring station uses a TTS method developed by the U.S. Department of Agriculture Forest Services Redwood Sciences Laboratory (Lewis and Eads 2009). The TTS method utilizes real-time continuous turbidity and stage height measurements to trigger water samples to be pumped from the stream across a range of turbidity thresholds. The water samples taken from the automatic pump sampler (ISCO) are collected in person and are brought back to the water quality laboratory at HSU to measure SSC. This method provides a set of turbidity and SSC pairs to be used for computing a turbidity-sediment rating curve. A rating curve using turbidity as the surrogate variable for estimating SSC is more accurate than using discharge (Lewis and

Eads 2009). Therefore, a turbidity-sediment rating curve was utilized in this analysis for estimating SSC values for calculating sediment yield in Salmon Creek.

Turbidity threshold values are programmed into the datalogger to control sampling events. The turbidity needs to rise 20% above the previous peak value or fall 10% below the previous trough value and must continue for at least two sampling periods in order to trigger a water sample (Bailey 2013). Additionally, the change in the observed turbidity needs to be five NTU different from the previous turbidity reading. If these criteria are met, and the pressure transducer indicates that the depth is sufficient for taking water samples, then a physical water sample will be taken and stored in the ISCO sampler.

The turbidity threshold values were developed by Bailey 2013 and were used during the 2012 to 2018 WY (Table 2). Turbidity threshold values were modified during the 2019 WY to capture water samples with turbidities greater than or equal to 100 NTU
(

Table 3). The rising turbidity threshold values of 30 NTU and 77 NTU were replaced with 100 NTU, and for the falling turbidity conditions, the two threshold values of 40 NTU and 62 NTU were replaced with 105 NTU, based on previous values (Table 3).

Table 2: Rising and falling turbidity threshold values developed from 2013.

Rising Turbidity Thresholds (NTU)	Falling Turbidity Thresholds (NTU)
30	40
77	62
170	105
230	135
300	200
400	350
550	490
670	600
800	750
920	860
1100	1050
1350	1200
1500	1400
1600	1550
-	1600
-	1620
-	1640

Table 3: Rising and falling turbidity threshold values for the 2019 WY.

Rising Turbidity Thresholds (NTU)	Falling Turbidity Thresholds (NTU)
100	105
170	135
230	200
300	350
400	490
550	600
670	750
800	860
920	1050
1100	1200
1350	1400
1500	1550
-	1600
-	1620
-	1640

Site visits

Site visits were periodic and were more frequent during the wet season due to the increase in turbidity, suspended sediment concentration, flow, and precipitation in the Salmon Creek watershed. During site visits, field notes were taken and standard maintenance and sampling tasks were conducted, including:

- Checking the turbidity probe for debris or algal growth and cleaning if necessary
- Checking the pressure transducer probe to ensure it wasn't buried
- Checking the pump intake hose for debris and cleaning if necessary
- Checking the solar panel and battery for maintaining charge to equipment
- Downloading the turbidity, stage, and water temperature data

- Retrieving water samples from the ISCO and refilling ISCO with new sample bottles
- Labeling the water sample bottles and transporting samples to the water quality laboratory at HSU for lab testing
- Measuring flow at an established cross-section
- Collecting the precipitation data from the two rain gauges

Laboratory Procedure

Water samples collected from the ISCO Pump Sampler were retrieved during site visits and were transported back to the HSU water quality laboratory where a suspended solids concentration procedure was performed. Each water sample was measured with a Hach 2100P laboratory turbidity meter to compare the turbidity readings taken from the DTS-12 sensor. The suspended solids concentration procedure follows the American Public Health Association Standard Method 2540D "Total Suspended Solids Dried at 103-105^{o}C" (APHA 1998).

Once the procedure is completed, Equation 2 is used for calculating the suspended solids concentration. This procedure is applied to all water samples taken from Salmon Creek.

$$SSC = \frac{(A - B) * 1000}{V_{sample}} \qquad \text{(Eq. 2)}$$

Where *SSC* is suspended solids concentration (mg/L), *A* is the filter mass plus the tray weight plus solid content (g), *B* is filter mass plus the tray weight (g), and V_{sample} is the volume of water sample (L).

Discharge Rating Curve

A simple stage-discharge relation procedure was followed from Gupta (2008) to develop a relation between stage height and discharge. It is recommended to have at least ten to twelve data points ranging from low to high flows to develop a relationship between stage and discharge (Gupta 2008). Additionally, periodic measurements should be recorded and applied to the rating curve to check the validity of the relation.

The stage-discharge relation developed is a parabolic form, given by (Gupta 2008):

$$Q = A(h \pm a)^n \quad \text{(Eq. 3)}$$

Where *Q* is discharge (cfs), *h* is stage height (ft), a is the stage reading at zero flow for datum correction (ft), *n* is the slope (ft/ft), and *A* is the y-intercept. The stage reading at zero flow, *a*, was determined by using an Arithmetic Procedure (Gupta 2008). The procedure is as follows:

1. Select two well-separated points on the stage-discharge plot and read values for Q_1, Q_2, h_1, and h_2. Compute Q_3 by the using the geometric mean as follows:

$$Q_3 = \sqrt{Q_1 Q_2} \quad \text{(Eq. 4)}$$

2. Determine h_3 on the stage-discharge plot by using the calculated Q_3.

3. The stage reading at zero flow (a) is determined by the straight-line property on the log plot:

$$a = \frac{h_1 h_2 - {h_3}^2}{h_1 + h_2 - 2h_3} \quad \text{(Eq. 5)}$$

If a is positive, then the relation is $Q = A(h - a)^n$.

Once a is determined, then discharge, Q and the "adjusted" stage, $(h - a)$ can be plotted on a log-log plot for each WY. A power function equation best fit line can be fit to the data to find the n and A parameters (Equation 6).

$$Q = A(h - a)^n \quad \text{(Eq. 6)}$$

Once n and A are determined, the equation can be used to approximate discharge given continuous stage recordings in Salmon Creek (Equation 6).

Slope Area Method

The Slope Area Method was used to estimate a peak discharge in Salmon Creek for the 2019 WY. The upstream survey location was approximately 115 feet upstream from the monitoring station and the downstream survey location was approximately five feet upstream from the monitoring station. A stadia rod, level, and measuring tape were used to estimate the longitudinal slope in the stream. Four cross-sections were measured

along the longitudinal distance. An estimate of high-water elevations was made from indicators present on both banks of each cross-section. Indicators included changes in the character of soil and the destruction of terrestrial vegetation (Figure 23).

Figure 23: Performing the Slope Area Method in Salmon Creek to estimate a peak discharge after the largest storm in WY 2019 (surveying on March 15, 2019).

An average cross-section was determined from the four cross-sections surveyed. A trapezoidal cross-section was fitted to the average cross-section and the dimensions of the channel were used in Manning's Equation to estimate a peak discharge (Equation 7). A range of Manning's n values were chosen (0.048 to 0.130) based on published literature values for streams with similar channel reach morphology to Salmon Creek (Table 4, Yochum et al. 2014). The roughness values were applied to Equation 7 to obtain peak discharge estimates for WY 2019.

$$Q = \frac{1.49}{n} AR^{2/3} S^{1/2} \qquad \text{(Eq. 7)}$$

Where Q is discharge (cfs), A is area of the channel (square feet), R is the hydraulic radius (ft), S is the channel slope (ft/ft), and n is the Manning's roughness

coefficient. Each peak estimate was individually added to WY 2019 discharge rating curve and three new rating equations were developed for WY 2019.

Table 4: Roughness coefficients for different channel reach morphologies (Yochum et al. 2014).

Site Location	Channel Reach Morphology	Manning's Roughness Coefficient
East St. Louis Creek, CO	Flat Plain	0.048
Fool Creek, CO	Plane-Bed/Step-Pool	0.095
Fool Creek, CO	Step Pool	0.130

The slope area method is one method for estimate peak flows. Other methods for measuring peak flows are installing a cable system to measure velocities at intervals along an established cross-section or repairing the existing granulated cork inside the PVC pipe at the monitoring station.

Turbidity Sediment Rating Curve and Sediment Load Estimates

Turbidity-sediment rating curves were analyzed for each WY. Various transformations to the turbidity and SSC data were explored (e.g. linear, log-log, polynomial, etc.). The log-log transformation with a log-log regression equation fit the turbidity and SSC data the best. Within each WY, seasons, events, and annual regressions were explored to determine the strongest correlation coefficient. Additionally, the slopes from the regression equation were investigated to determine if different time periods had significantly different slopes.

Once the relationship between turbidity and SSC was established, the turbidity sediment rating equation was applied to the continuous turbidity data set to estimate SSC at the same frequency as the recorded turbidity. The discharge rating curve was applied to the stage data to predict discharge in Salmon Creek. The SSC and water discharge at each time interval are multiplied and summed to estimate SSL in Salmon Creek (Equation 1).

RESULTS AND DISCUSSION

This section presents the field and laboratory data collected in the Upper Salmon Creek watershed from WYs 2012 to 2019. The field and laboratory data were used to develop discharge rating curves and turbidity-sediment rating curves. The rating curves were then used to compute discharge volume and suspended sediment concentration in 15-minute increments by using continuous stage and turbidity data. Discharge volume was multiplied by suspended sediment concentration to estimate a sediment flux for each time period and was summed to estimate a sediment yield for a WY or by storms within a WY.

Annual sediment yield estimates in the Upper Salmon Creek were compared to four northern California coastal watersheds with accessible data that use an automated turbidity sensor and pump sampler. Additionally, an analysis of the raw data collected at these four streams was conducted to determine if these data sets can be used to fill in missing data from Salmon Creek.

Field Data

The monitoring station began collecting data in the Upper Salmon Creek on October 7th, 2011 at 20:45. Stage, turbidity, and temperature were recorded on a 15-minute interval. Discharge was measured periodically during site visits and water samples were collected from the ISCO sampler based on the exceedance of turbidity threshold values in Salmon Creek. Rain gauges were set up on August 8th, 2018, and are still collecting data. The last set of precipitation data collected for this report was on May 31st, 2019. Data recorded or measured from October 7th, 2011 to May 31st, 2019 are described in more detail in the following sections.

Stage and turbidity data

There should be a total of 35,040 turbidity and stage data points every WY. Missing data can occur due to equipment failure from natural occurrences (debris lifts boom out of water, landslide, etc.) and/or electrical failure (ISCO interface cable not communicating with ISCO and data logger, turbidity sensor not recording accurately). Table 5 summarizes the WYs with a complete set of turbidity and stage data, WYs with an incomplete set of turbidity and stage data, and WYs with missing critical data. A complete set of data is defined as a data set that has 95 percent or more of its total observations (35,040). An incomplete set of data is defined as missing more than five percent of its observations. Critical missing data is defined as data that was not recorded during the wet season (October to April) when the majority of the sediment is

transported. Appendix A, Table A-1, contains a detailed table with dates for existing and missing data.

Table 5: Upper Salmon Creek existing and missing turbidity and stage data.

Water Year	Existing or Missing Data
2012	Incomplete set of data (not critical)
2013	Complete set of data
2014	Incomplete set of data (not critical)
2015	NO DATA
2016	Critical Missing Data
2017	Complete set of data
2018	Incomplete set of data (not critical)
2019	Incomplete set of data (not critical)

Complete set of data

Incomplete set of data (not critical)

Critical Missing Data

WYs 2012, 2014, 2016, 2018, and 2019 are missing data within the data set and WY 2013 and 2017 are missing less than five percent of the data. WY 2012 and 2014 are missing data recordings during the dry season, which is between May to September. This data is not critical since most sediment transports during the wet season (October to April). In contrast, WY 2016 is missing over two months of data recordings during the wet season (February 26th to April 30th). WY 2019 is missing approximately three days in October due to switching the turbidity sensor. During this time, there were no storm events and the turbidity was less than 1 NTU. Salmon Creek was not monitored in WY 2015 because of malfunctions with the field equipment.

Next, the total number of turbidity and stage recordings within a given WY was determined (Table 6). Each WY was further examined by tracking the number of stage and turbidity error recordings (values less than zero or had -99999). These missing/error

recordings were removed from the data set and were not used for estimating suspended sediment yield. Table 6 summarizes the number of raw data recordings, the number of stage and turbidity errors, the total number of stage and turbidity data without the error data, and the percent total missing data within a WY (there should be a total of 35,040 data points in one year).

Table 6: Summary of the number of raw data recordings, the number of missing stage and turbidity data, and the percent of missing data within a WY.

Water Year	# of Raw Data Recordings	# of Error Stage Data	# of Error Turbidity Data	Total # of Stage and Turbidity Data	Percent of Missing Data
2012[a]	28,459	478	5	26,972	23%
2013[a]	34,563	475	0	34,563	1%
2014	29,710	0	0	29,710	15%
2015	No Data	No Data	No Data	No Data	100%
2016	26,740	13,977	1	12,762	64%
2017[a]	34,932	816	0	34,114	3%
2018	35,037	11,993	6	23,038	34%
2019	32,255	2,041	9[b]	30,214	14%

a: Removed data with time periods that did not follow a 15-mintue interval (e.g. 2:10, 2:40, 2:43, etc.)

b: Nine turbidity error recordings are included in the 2,041 stage error recordings.

WY 2013 and 2017 have approximately all data available (35,040) with some stage error measurements (Table 6). WY 2012, 2014, and 2019 have the majority of the data, with some stage and turbidity error recordings. WY 2016 has 14,000 stage error recordings and has missing data recordings during the wet season, which results in missing 64% of its total data. The majority of these stage error recordings were during the dry season (May – September), which may have occurred from minimal depth in Salmon Creek. WY 2018 has approximately 12,000 stage error readings (-99999) from October to

December. This missing stage data is critical since it is during the wet season when the majority of sediment is moving down the stream.

The maximum turbidity recording in Salmon Creek was 1,646 NTU, which was during a landslide in 2012. The second largest turbidity recording was in WY 2016 with a turbidity value of 1,350 NTU (Table 7). The turbidity value seems high compared to other years (except for WY 2012), and the field turbidity and stage data were further examined to determine if there were poor data recordings. During December 21st to 27th, 2015 turbidity values illustrated short-duration turbidity pulses, varying from 244 NTU to 1,350 NTU within 15-minutes (Figure 24). According to Lewis and Eads (2009), the most typical strategy for validating questionable turbidity peaks is by examining plots of pumped SSC samples, field turbidity records, and stage. Turbidity and stage were plotted from December 21st to 27th, 2015 (Figure 24). The graph demonstrates short-duration turbidity pulses, which may indicate sediment delivery from local streambanks or hillslopes, or the DTS-12 turbidity sensor had progressive fouling, debris fouling, air bubbles, nonsubmergence, buried by bed load, interference from a channel, and interference from water surface (Figure 24). This data was taken out of the data set before estimating annual sediment yield.

Table 7: Turbidity statistics for each water year in Salmon Creek. Units are in NTU.

Turbidity Statistics	2012	2013	2014	2016	2017	2018	2019
Maximum	1,646	875.9	219.1	1,350	924.7	120.6	657.9
Median	4.2	2.8	0.10	5.8	5.8	1.8	9.4
Average	12	5.8	2.2	40	10	5.4	17
Standard Deviation	41.8	20.6	7.41	118	22.1	9.32	41.4

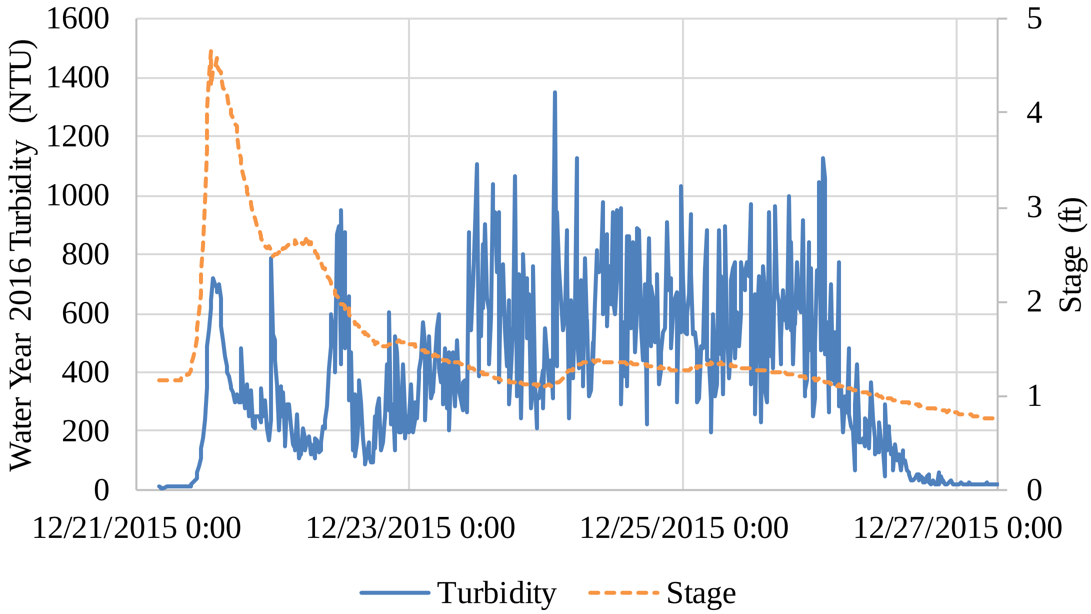


Figure 24: Late December storm in WY 2016 that had poor turbidity readings due to a natural occurrence or equipment malfunctions.

The maximum stage recording from WY 2012 to 2019 was 6-feet (Table 8). This stage value was recorded during a large storm on February 25th, 2019, which had an approximate daily rainfall of 2.7 inches. During this time, the turbidity value was 558 NTU. The second largest stage recording of 5-feet was in WY 2016.

Table 8: Stage statistics for each water year in Salmon Creek. Units are in feet.

Turbidity Statistics	2012	2013	2014	2016	2017	2018	2019
Maximum	3.4	3.7	2.0	4.8	3.7	1.6	5.8
Median	0.29	0.48	0.37	0.29	0.65	0.31	0.63
Average	0.40	0.54	0.42	0.45	0.73	0.43	0.74
Standard Deviation	0.35	0.30	0.19	0.46	0.44	0.31	0.66

Suspended sediment concentration

Water samples were collected in the ISCO sampler and processed at the HSU Water Quality Laboratory to estimate suspended sediment concentration during WY 2012, 2017, 2018, and 2019 (Table 9). No water samples were taken during WY 2013 to 2016. The ISCO interface cable was not communicating between the ISCO sampler and data logger during WY 2016, but continuous turbidity and stage were recorded during that time frame. WY 2015 was offline and no water samples or continuous data were recorded. WY 2013 and 2014 have continuous turbidity and stage recordings but no water samples were collected during this period. HSU was not under contract to collect and process water samples during WY 2013 and 2014.

Table 9: Total number of SSC measurements for each WY.

Water Year	Total # of SSC Measurements
2012	102
2013	No Data
2014	No Data
2015	No Data
2016	No Data
2017	65
2018	24
2019	77

Discharge and precipitation measurements

Discharge measurements were taken periodically at an established cross-section that is located downstream from the monitoring station. Discharge measurements were typically taken after a storm event when it was safe to get into the stream. Ten to 14

discharge measurements were taken each year with the exception of WYs 2013-2015 (Table 10).

Table 10: Total number of discharge measurements recorded in Salmon Creek for each WY.

Water Year	Total # of Discharge Measurements
2012	11
2013	No Data
2014	No Data
2015	No Data
2016	10
2017	14
2018	11
2019	10

Two rain gauges were installed in the Salmon Creek watershed on August 8th, 2018. A landslide in WY 2019 took out the access logging road and made it difficult to retrieve precipitation data at the rain gauge located in the upper watershed. Since 2019, a new access logging road was constructed and the rain gauge can be accessed. Hourly precipitation data were collected at the rain gauge located on a ridge above the monitoring station from August 3rd, 2018 8:00 to May 31st, 2019 10:15.

Summary of field data

Table 11 summarizes the data collected in the Upper Salmon Creek watershed from WY 2012 to 2019. The data for WYs 2012, 2016, 2017, 2018, and 2019 data were further analyzed to develop discharge rating curves and turbidity-sediment rating curves for the Upper Salmon Creek.

Table 11: Summary of data collected in the Upper Salmon Creek.

Water Year	Total # of Turbidity and Stage Data	Total # of SSC Measurements	Total # of Discharge Measurements
2012	26,972	102	11
2013	34,563	No Data	No Data
2014	29,710	No Data	No Data
2015	No Data	No Data	No Data
2016	12,762	No Data	10
2017	34,114	65	14
2018	23,038	24	11
2019	30,214	80	10

Discharge Rating Curve

The discharge rating curve describes the relation between stream stage (measured by a pressure transducer) and discharge (measured with a current meter using the mid-section method). The measured discharge was plotted against the concurrent stream stage to develop a discharge rating curve. The discharge rating curve is then applied to the stream's record of stage and is used to estimate discharge every 15-minutes.

Fifty stage-discharge measurements were plotted to develop a discharge rating curve for the Upper Salmon Creek (note: six outliers were removed due to low flow conditions and/or field notes stating poor discharge measurements) (Figure 25). A logarithm scale was applied to the discharge rating curve to obtain a straight line. The log plot is between discharge and stage plus a datum correction, a. The datum correction was determined by using the Arithmetic Procedure described in the Methodology section. Note, the stage and the datum correction will be addressed as the "adjusted stage" from now on. Furthermore, a power function equation was fit to the adjusted stage-discharge relation (Figure 25).

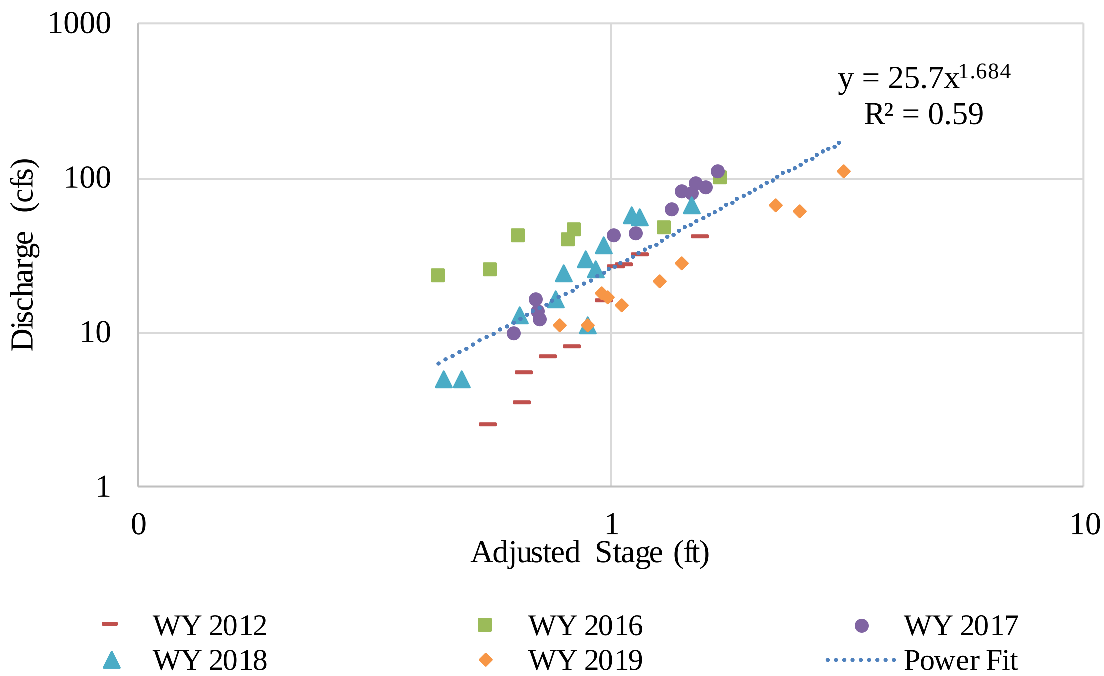


Figure 25: Salmon Creek discharge rating curve. The datum correction using the Arithmetic procedure is *a* = -0.032.

A visual inspection of the discharge rating curve (Figure 25) indicates the rating curve is not constant over the period of record. There is a shift in both the slope and the intercept of the curve, which may be caused by periodic geomorphic changes in the channel cross-section. From 2012 to 2019, Salmon Creek had a few natural occurrences in the watershed/stream that potentially altered the flow regimes and stage. During WY 2012 and the Bailey 2013 study, a landslide upstream from the monitoring station deposited numerous rocks, soil, and woody debris. There were a few field notes describing changes in the stream channel from 2013 to 2018. During WY 2019, large woody debris jammed between the bedrock wall and the riverbank, approximately 5 feet upstream from the discharge measurement cross-section, was flushed out of the system

after a storm in March 2019 (Figure 26). This may have altered the discharge-stage relation. Additionally, in November 2018 redwood trees fell into Salmon Creek approximately 20 feet downstream of the discharge measurement cross-section (Figure 27). There is a potential for the fallen trees to cause backwatering if debris is not flushed out after a large storm event. These natural occurrences emphasize how often the stage-discharge relation changes with time, and thus, the discharge rating curves were explored in smaller time scales.

Figure 26: Top photo illustrates the large woody debris jammed between the river bank. Bottom photo illustrates the large woody debris flushed out of the system

Figure 27: Top photo illustrates the Redwood trees in Salmon Creek, approximately 20 feet downstream of the cross-section where flow measurements were collected. This photo was taken at the cross-section looking downstream. Bottom photo illustrates the debris and trees on river left bank.

Discharge rating curves were developed for each WY to determine if smaller time scales result in better stage-discharge relations (Figure 28 to 32). A logarithm scale was applied to the discharge rating curves to obtain a straight line. A datum correction was determined for each WY. A power function equation was fit to the discharge rating curve

for each WY. Additionally, two power function equations, one for the lower stage values and one for the higher stage values, was fit to the discharge rating curve to account for different controls becoming operative from different stages. Ideally, selection of low and high stage values would relate to channel controls, but since there were no detailed cross-sections conducted from WY 2012 to 2018, the low and high stage values were chosen based on graphical visualization of slope breaks in the discharge rating curve. During WY 2019, a survey of the discharge measurement cross-section and longitudinal profile in the Salmon Creek was conducted, but low and high stage values were not assessed to determine how stage relations change with channel controls becoming operative (Appendix B, Figure B-1 and B-2). Thus, graphical visualization of slope breaks was also used for WY 2019 to determine two power function equations.

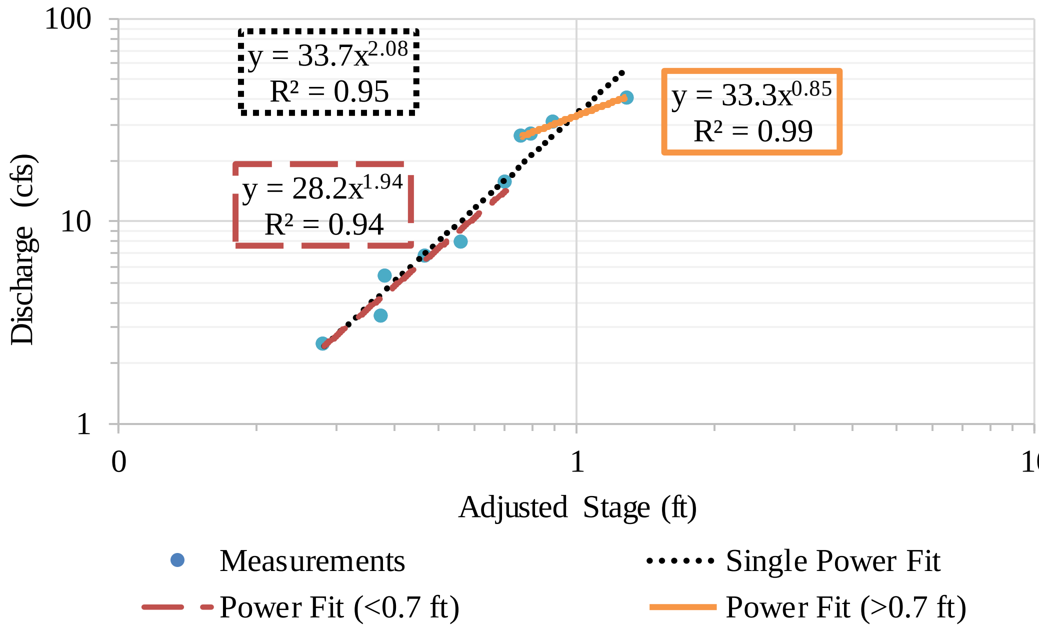


Figure 28: Discharge rating curve for WY 2012. The graph illustrates a single power function equation and two power function equations fit to the data. The datum correction using the Arithmetic procedure is *a* = -0.244.

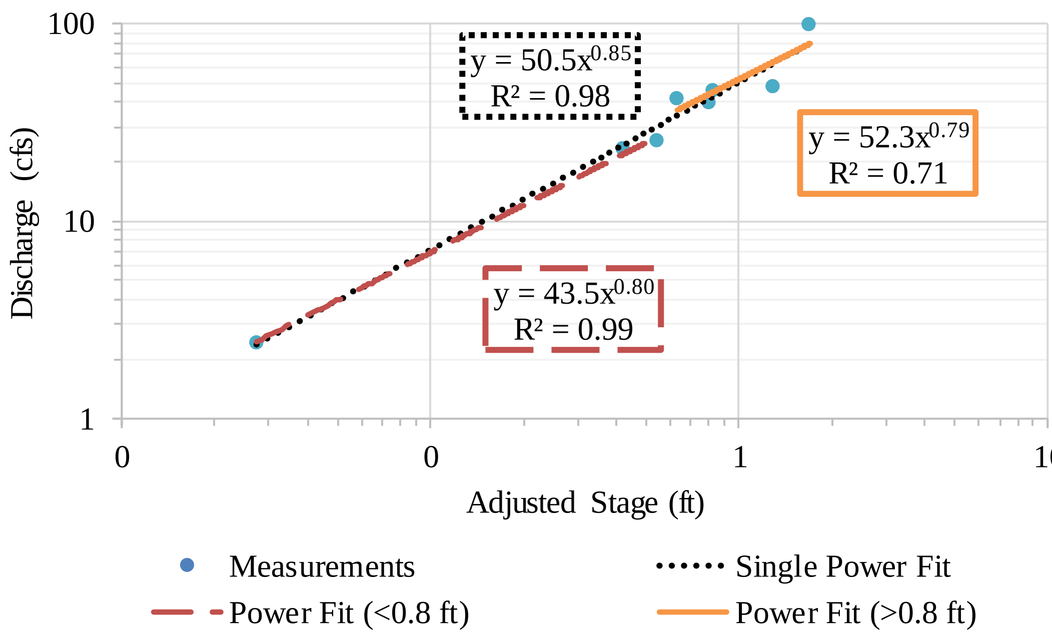


Figure 29: Discharge rating curve for WY 2016. The graph illustrates a single power function equation and two power function equations fit to the data. The datum correction using the Arithmetic procedure is *a* = -0.024

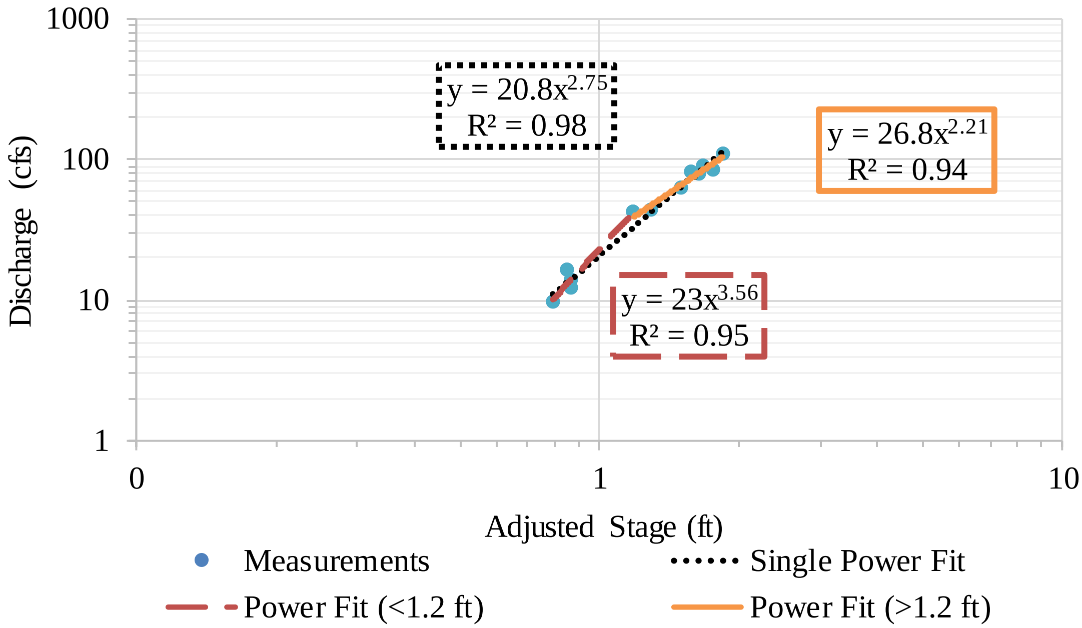


Figure 30: Discharge rating curve for WY 2017. The graph illustrates a single power function equation and two power function equations fit to the data. The datum correction using the Arithmetic procedure is a = 0.20.

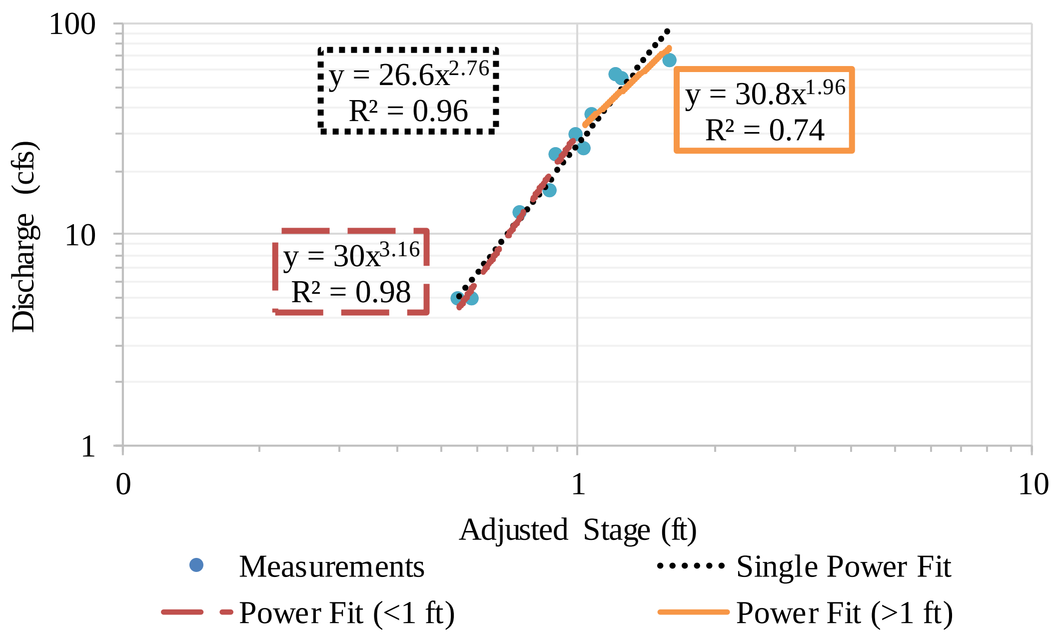


Figure 31: Discharge rating curve for WY 2018. Top graph illustrates a single power function equation two power function equations fit to the data. The datum correction using the Arithmetic procedure is a = 0.136.

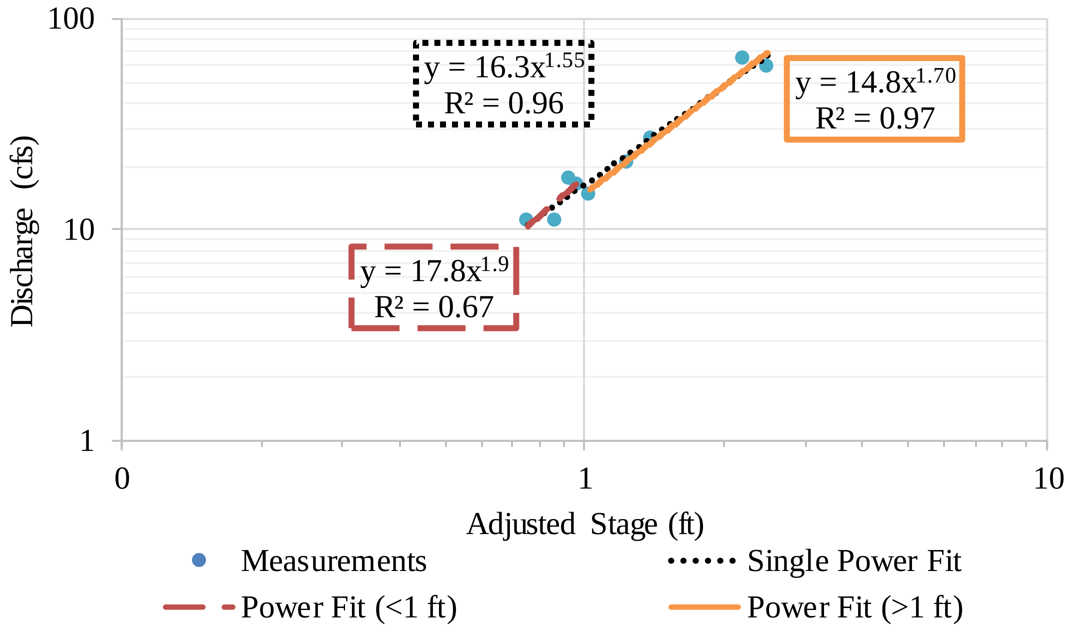


Figure 32: Discharge rating curve for WY 2019. The graph illustrates a single power function equation and two power function equations fit to the data. The datum correction using the Arithmetic procedure is *a* = -0.007.

A longitudinal thalweg profile survey was conducted after a large storm on March 15th, 2019. Four cross-sections were also measured along a 100-foot longitudinal distance (Appendix C, Table C-1 to C-5). An estimate of the high-water elevation was made from indicators present on both banks of each cross-section (changes in the character of soil and destruction of terrestrial vegetation). An average cross-sectional area was determined from the four cross-sections, and the average channel depth was 5.3 feet. The average cross-sectional area and depth were used in Manning's Equation (Equation 7) to estimate a peak discharge. Peak discharge of 436 cfs was estimated at a stage of 5.3 feet. This peak discharge and stage were added to the 2019 discharge rating curve, and a single power regression equation was fit to the data (Figure 33).

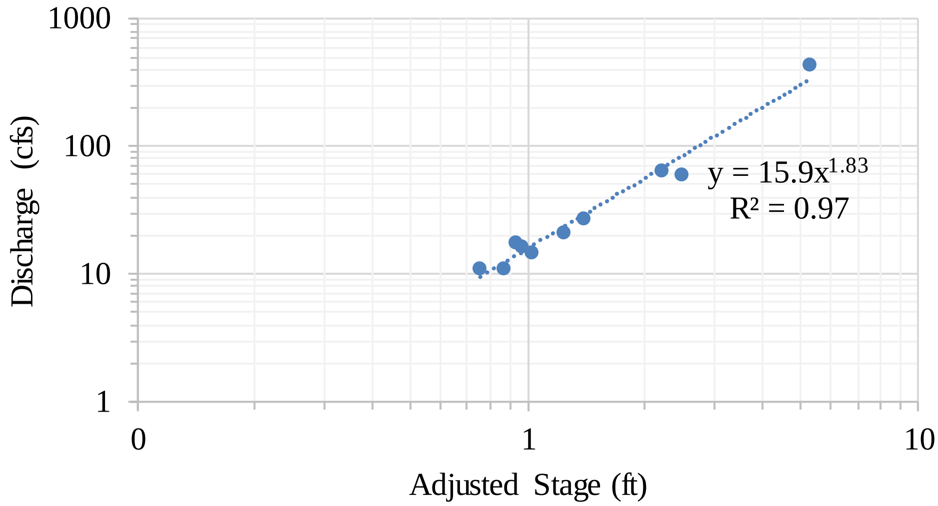


Figure 33: Peak discharge and stage value added to the discharge rating curve for WY 2019. The datum correction using the Arithmetic procedure is *a* = -0.007.

Peak discharge measurements were not measured from WY 2012 to 2018 because of the safety of hiking during a high intensity storm event, the long travel times to the site, and the rapid response to precipitation events in the small watershed. Furthermore, it was necessary to extrapolate the discharge rating curve beyond the range of measurements obtained. Table 12 shows the maximum stage data recorded with a discharge measurement; the maximum stage recorded by the data logger, and the percent exceedance of the measured stage. WY 2012 had a maximum stage of 1.53 feet with a concurrent discharge measurement and the maximum stage recording from the data logger was 3.36 feet. The maximum stage recorded with a discharge measurement was exceeded 5% of the total 2012 data set. WY 2018 maximum stage with a concurrent discharge measurement was 1.46 feet and this value was exceeded 2% of the entire 2018 data set. Though the percent exceedance values are low, the extrapolated portion of the

rating curve can account for a large percentage of the sediment yield estimates in Salmon Creek.

Table 12: Summary of maximum stage recorded with a discharge measurement, maximum stage recorded from the data logger, and percent exceedance of the maximum stage recorded with a discharge measurement.

Water Year	Maximum Stage with Discharge Measurement (ft)	Maximum Stage Recorded (ft)	% Exceedance of Stage Data
2012	1.53	3.36	5%
2016	1.67	4.75	3%
2017	1.65	3.70	3%
2018	1.46	1.58	2%
2019	2.48	5.80	3%

Summary of discharge rating curves

Discharge rating curves were developed for the Upper Salmon Creek. A single power regression equation was fit to all data collected in Salmon Creek from 2012 to 2019. The discharge rating curve demonstrated annual shifts between the stage-discharge relation that are likely caused by the periodic geomorphic changes in the channel cross-section. Thus, a single power function equation and piecewise power function equations were fit to the stage-discharge data for each WY to examine if stage-discharge rating curves developed over smaller time periods produced better relationships. Appendix D, Table D-1, summarizes the discharge rating curve power function equations. Reducing the time scale to WYs increases the correlation value between discharge and stage. These WY specific single and piecewise power regression equations were applied to the continuous stage recordings to estimate discharge in Salmon Creek. These equations are further discussed in the Suspended Sediment Yield section.

Turbidity Sediment Rating Curve

Turbidity-sediment rating curves describe the relationship between stream turbidity data (measured by a DTS-12 Turbidity Sensor) and suspended sediment concertation (quantified by SSC laboratory procedure). The rating curve is used on stream's record of turbidity to estimate suspended sediment concentration (SSC). Measured SSC was plotted against concurrent stream turbidity to develop a turbidity-sediment rating curve.

WY 2012 to 2019 had a total of 268 turbidity-SSC measurements that were collected. Twenty-four outliers were removed from this analysis due to inaccurate field and/or laboratory measurements. The remaining 244 turbidity-SSC measurements were plotted to develop a turbidity-sediment rating curve for Salmon Creek (Figure 34). A logarithmic scale was applied to the rating curve to obtain a straight line, and a log-log regression equation was fit to the curve.

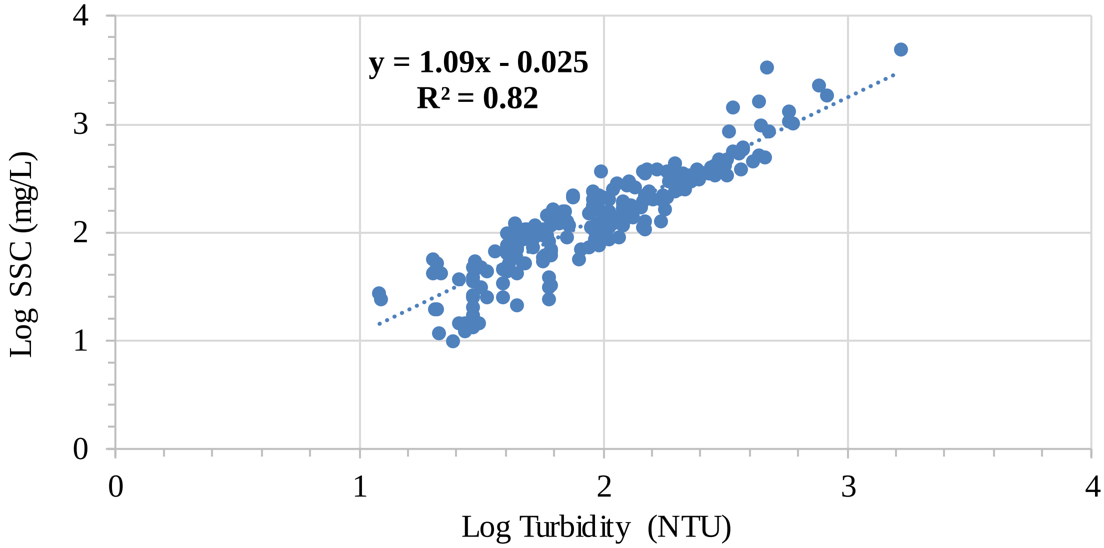


Figure 34: Turbidity-sediment rating curve for Salmon Creek.

The turbidity-sediment rating curve is uniform over the entire range of data with slightly greater scatter at the lower and higher ends of the turbidity-SSC measurements. The majority of the SSC samples captured were at the low to the mid-turbidity range from zero to 150 NTU, which accounts for 75% of the total SSC samples captured (Figure 35). Future studies should consider reprogramming the automated sampler to draw water samples only at the very highest turbidity thresholds. Increasing the turbidity thresholds will provide savings in terms of fewer samples to collect and analyze in the laboratory, and an increased likelihood of sampling at storm peaks before the sampler fills up. Additionally, increasing the turbidity thresholds may help distribute the samples and improve the turbidity-SSC relation.

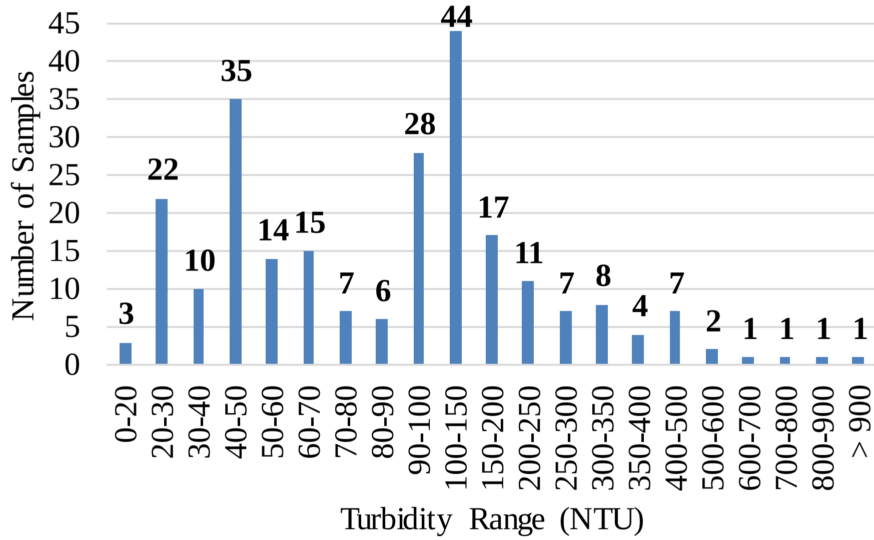


Figure 35: Number of SSC samples taken based on the turbidity range over the period of record (2012 – 2019).

Similar to a discharge rating curve, turbidity-sediment rating curves can change over time because particle composition or availability of easily transported material can change with time. Thus, turbidity-sediment rating curves were explored for each WY (Figure 36 and Table 13) and season within a WY (Table 14) to determine if smaller scales result in less scatter between the turbidity-SSC and strengthen the relationship. Seasons were defined as October to February and March to September. WY 2012 was an unusual year since there was a landslide upstream from the monitoring station, so turbidity-sediment rating curves were broken into three categories: Pre-Landslide, Landslide, and Post-Landslide (Figure 37 and Table 13).

A log-log regression equation was fit to the turbidity-sediment rating curves, with turbidity and SSC logged to obtain a straight line (Figure 36 and 37). The intercept of the regression equations were not forced to cross at the origin because it altered the slope and

did not fit the data properly. Since the regression equation was not forced to cross the origin, some of the equations can have a negative intercept, resulting in negative SSC values when low turbidity values have been recorded. Negative SSC values typically had turbidity values less than 1 NTU. It was assumed that low turbidities had little to no SSC in the stream, and negative SSC values were assumed to be zero. These log-log regression equations are summarized in Table 13 and 14.

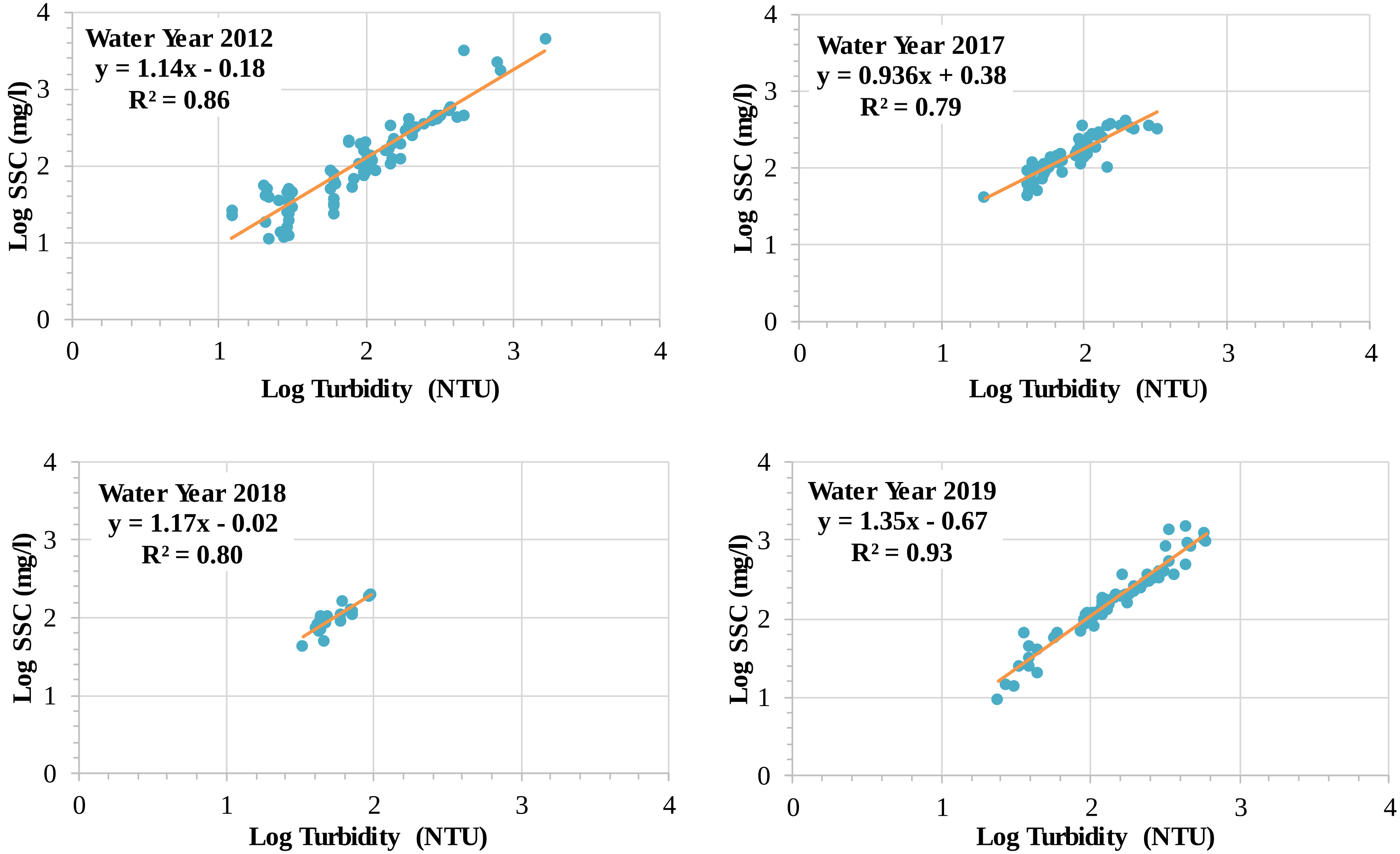


Figure 36: Annual turbidity-sediment rating curve for each individual WY with its associate log-log regression equation.

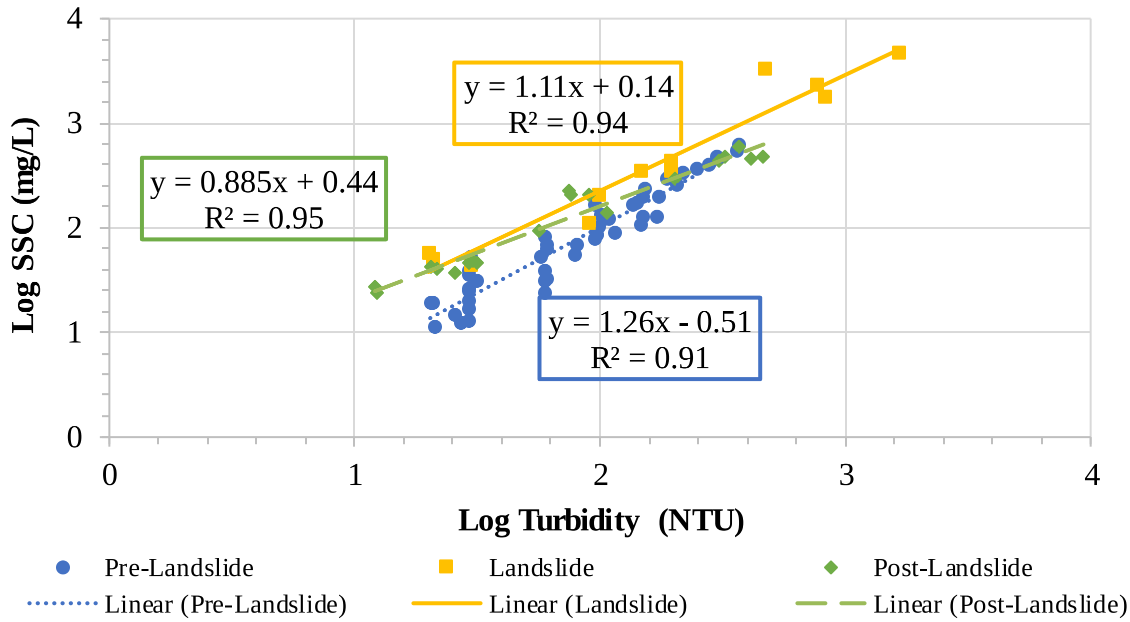


Figure 37: WY 2012 turbidity-sediment rating curve for Pre-Landslide, Landslide, and Post-Landslide period

Table 13: Summary of regression equations for the Single Turbidity Rating Curve and the Annual Turbidity Rating Curve.

Turbidity Sediment Rating Curve	Regression Equation y=Log SSC (mg/L) and x= Log Turbidity (NTU)	R^2
Single – All Data	y = 1.09x-0.025	0.82
2012 Pre-Landslide	y=1.26x-0.51	0.91
2012 Landslide	y=1.11x+0.14	0.94
2012 Post-Landslide	y=0.885x+0.44	0.95
2012 Annual	y = 1.14x-0.18	0.86
2017 Annual	y=0.946x+0.38	0.79
2018 Annual	y=1.17x-0.02	0.8
2019 Annual	y=1.35x-0.66	0.93

Table 14: Summary of Seasonal Turbidity Rating Curve log-log regression equation for each WY.

Regression Period	2012	2017	2018	2019
October-February	y=1.29x-0.57 R^2=0.93	y=0.913x+0.43 R^2=0.77	y=1.17x-0.25 R^2=0.80	y=1.37x-0.70 R^2=0.94
March-September	y=1.03x-0.21 R^2=0.93	y=1.14-0.15 R^2=0.93	y=1.15x+0.01 R^2=0.76	y=1.06x-0.013 R^2=0.88

WY 2012 and 2019 log-log regression equations resulted in higher R^2 values than the Single-All Data log-log regression equation, R^2= 0.86 (Table 13). WY 2017 and 2018 log-log regression equation resulted in lower R^2 values (Table 13). WY 2017 and 2018 have more data points scattered away from the best fit line than WY 2012 and 2019, which resulted in lower R^2 values. The R^2 values for WY 2017 and 2018, R^2 = 0.79 and 0.80, respectively, still indicate a strong correlation between turbidity and SSC. WY 2012 was further analyzed by breaking the turbidity-SSC relation into Pre-landslide, Landslide, and Post-Landslide. This seemed to strengthen the relation, as the R^2 value increased from R^2=0.86 to R^2= 0.91, 0.94, 0.95 (Figure 37). Furthermore, seasonal log-log regression equations resulted in higher R^2 values for WY 2012, 2017 (March-September), and WY 2019 than the Single-All Data log-log regression equation. The turbidity-sediment rating curves are further discussed in the Suspended Sediment Load section.

Precipitation Data

The closest rain gauge to the project site operated by the National Weather Service is at Woodley Island in Eureka, approximately 20 miles due north. The average annual precipitation at this gauge is 48 inches (NOAA 2020). WYs 2012, 2016, and 2017 had rainfall amounts slightly above average, while the remaining years were below average rainfall. Four WYs (2013, 2014, 2015, and 2018) were significantly below average (Figure 38).

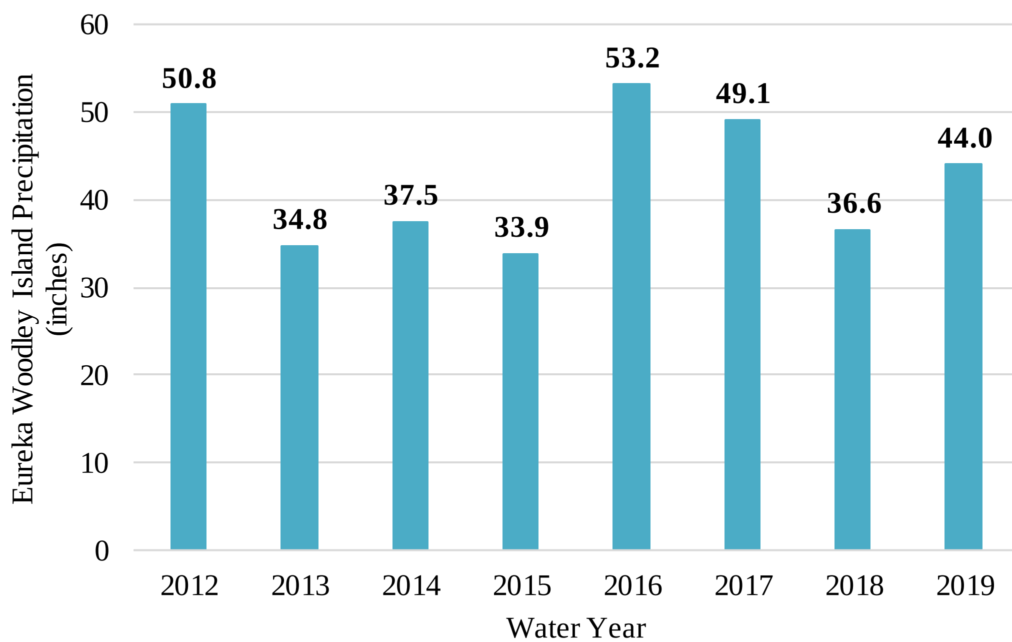


Figure 38: Total annual precipitation in Eureka, CA (NOAA 2020).

Hourly precipitation data within the watershed were collected from August 3rd, 2018 8:00 to May 31st, 2019 10:15 using a HOBO Tipping Bucket rain gauge located on the ridge above the monitoring station (Figure 20). There was a total rainfall of 53 inches

during this period (Figure 39). According to PRISM, on average, the lower watershed receives approximately 40 to 45 inches of annual rainfall, while the upper watershed receives approximately 50 to 65 inches of annual rainfall (CDFG 2003). Furthermore, the Eureka National Weather Service at Woodley Island recorded 42 inches of rain from August 3rd, 2018 to May 31st, 2019 (NOAA 2020). Monthly precipitation events were similar between Salmon Creek and Eureka, with Salmon Creek typically having more rainfall (Figure 40). However, Eureka recorded 4.4 inches from January 17, 2019, to January 20, 2019, while Salmon Creek recorded 0.07 inches (Figure 40). There may have been debris clogging the tipping bucket, which would alter the rainfall data.

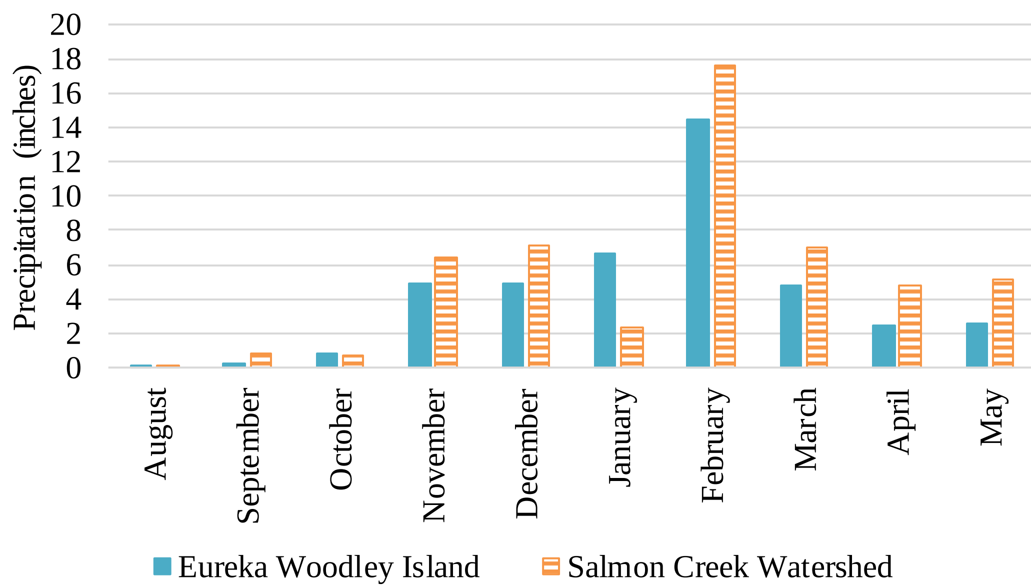


Figure 39: Monthly precipitation in Eureka, CA and the Upper Salmon Creek watershed during WY 2019.

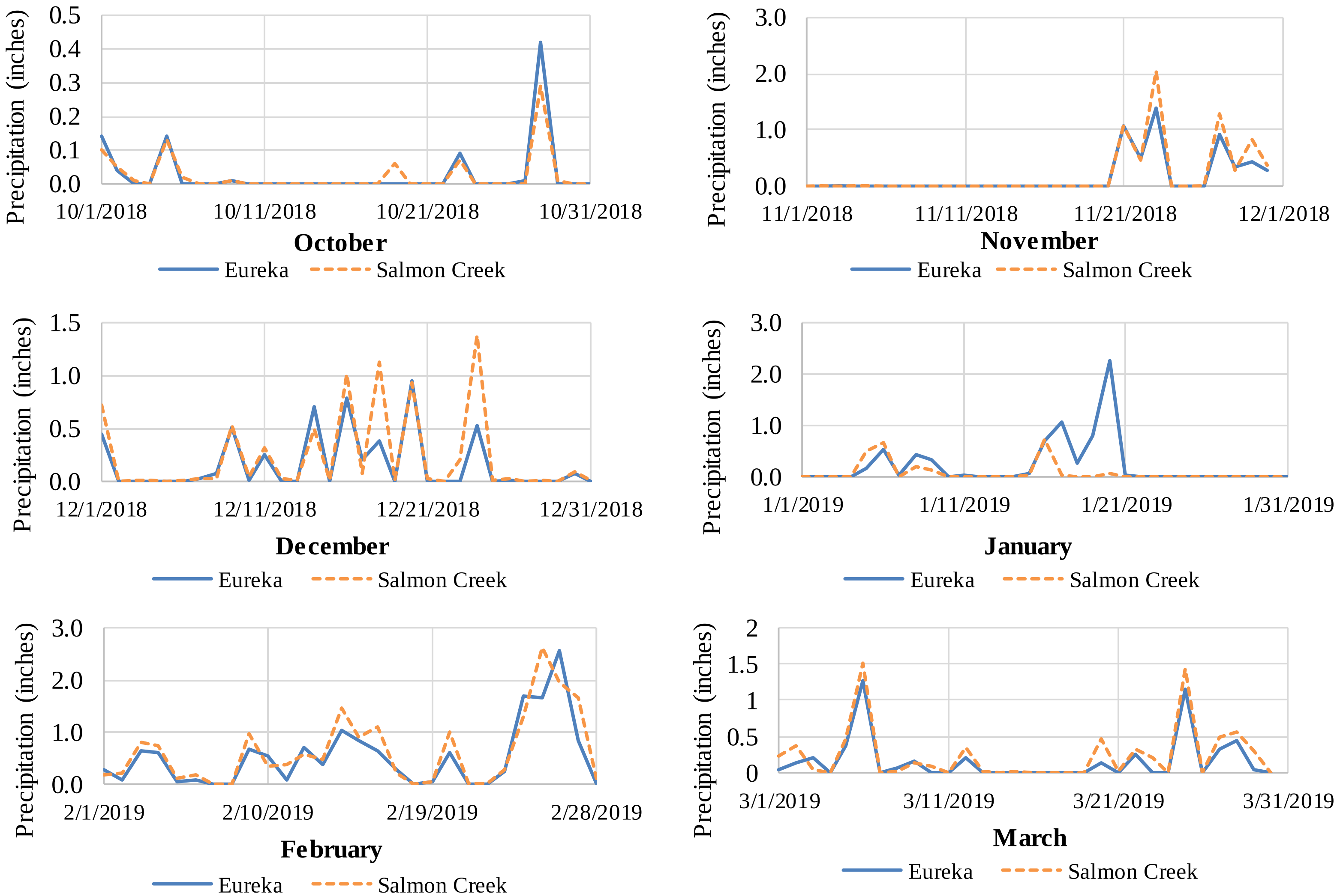
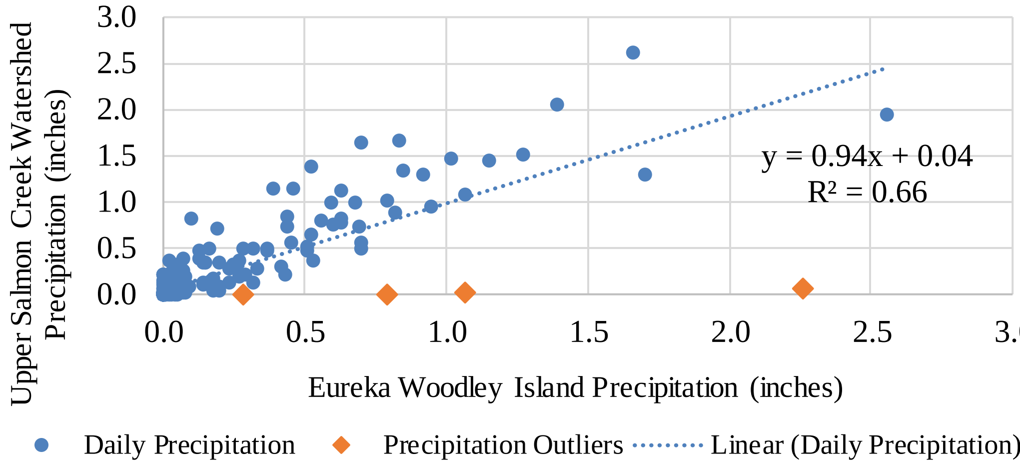


Figure 40: Monthly time series precipitation in Eureka, CA and the Upper Salmon Creek watershed for WY 2019.

A comparison between the precipitation data serves as a way to validate the more comprehensive Eureka precipitation as a suitable measure of storm events occurring in the Upper Salmon Creek watershed. However, since there is some variability between the precipitation data sets, a linear regression equation was fit to the data, which can be used to derive an adjustment factor for the use of the Eureka precipitation data (Figure 41).

Two linear regression equations were fit to the data, with one including all data from August 3rd, 2018 to May 31st, 2019, and the second equation excluding the four data points measured from January 17th to 20th. Removing the four data points increased the slope of the equation and improved the R^2 value, indicating a stronger fit between the Eureka-Salmon Creek precipitation data (Figure 41). The precipitation from January 17th to 20th, 2019 in Salmon Creek was estimated at 5.2 inches when using the second linear regression equation. Furthermore, Eureka recorded 2.3 inches of rain on January 20, 2019, while the Salmon Creek gauge recorded 0.1 inches. The estimated Salmon Creek rainfall for this date was 2.7 inches using the linear regression equation. Figure 42 illustrates a rise in the turbidity and the discharge data during January 20th and 21st and further supports the hypothesis of a gauge malfunction over this time period.



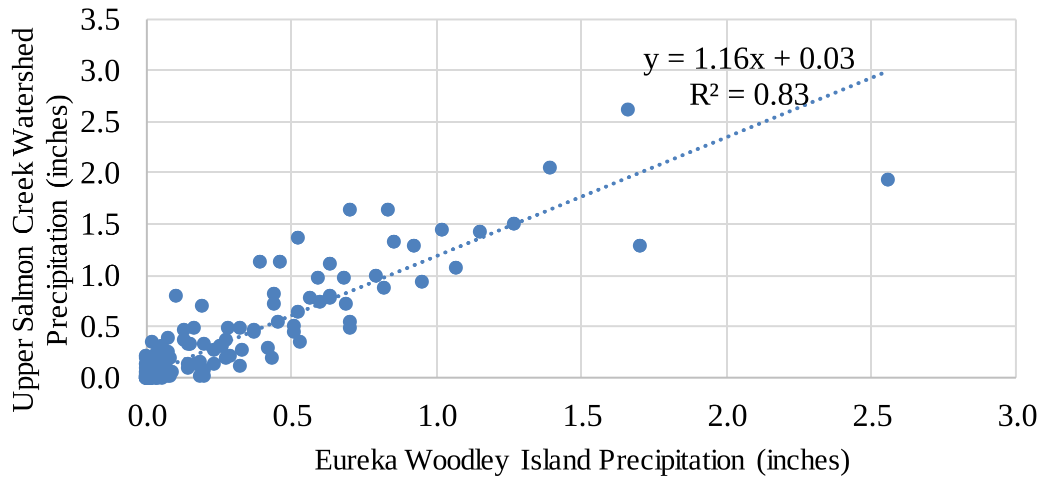


Figure 41: Linear regression between Eureka and Salmon Creek precipitation data. Top graph includes all data from 8/3/2018 to 5/31/2019. Bottom graph excludes data from 1/17/2019 to 1/20/2019, which is illustrated in the top graph as diamonds.

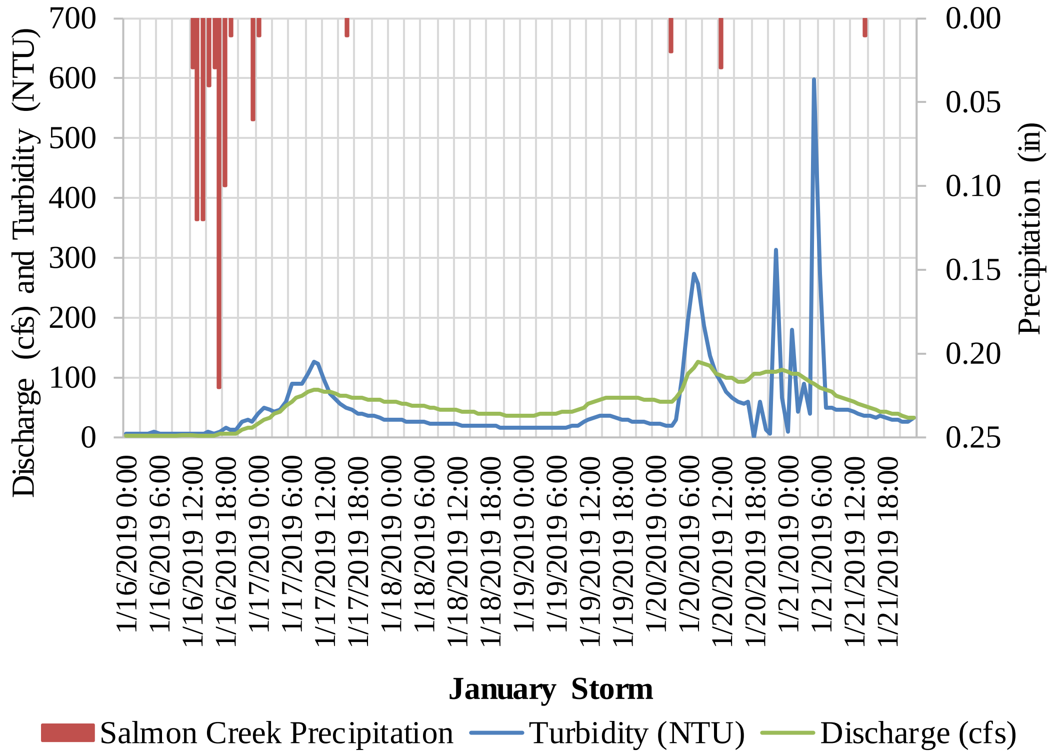


Figure 42: January storms in Salmon Creek from 1/16/2019 to 1/21/2019. The left y-axis is discharge and turbidity, and the right y-axis is precipitation.

Bailey (2013) collected precipitation data with a Rainwise Inc. RainLogger located on the ridge above the monitoring station from December 1, 2011 to June 22, 2012 (Figure 43). Total rainfall recorded for the period was 43 inches in Salmon Creek and 32 inches in Eureka (NOAA 2020). Monthly precipitation events between Salmon Creek and Eureka were similar, with Salmon Creek typically having more rainfall (Figure 43).

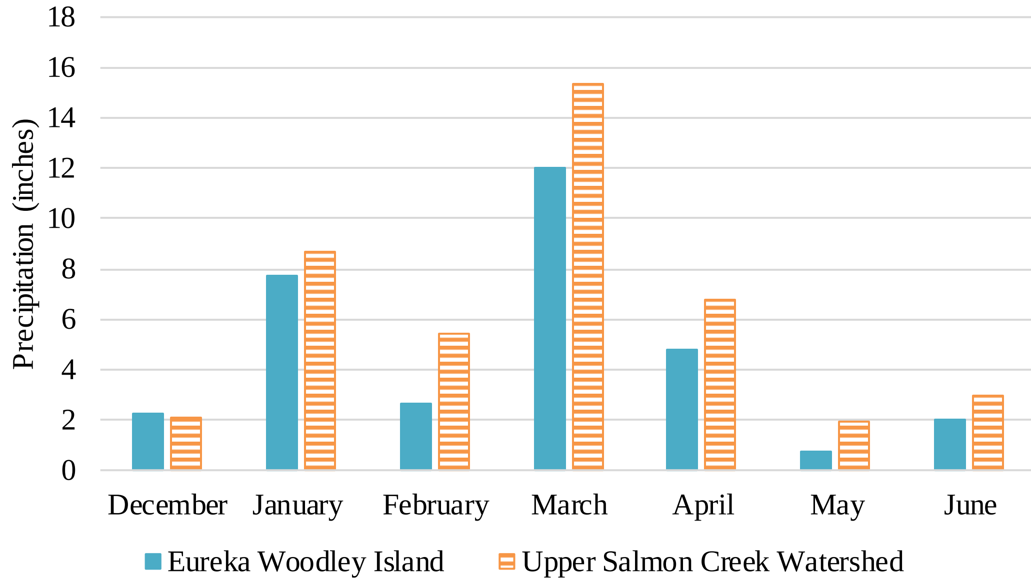


Figure 43: Monthly precipitation in Eureka, CA and the Upper Salmon Creek watershed during WY 2012.

A linear regression equation was fit to WY 2012 precipitation data (Figure 44). There is some scatter between the Salmon Creek-Eureka precipitation relationship (Figure 44). February 13th, 2012, Salmon Creek recorded 1.52 inches of rain while Eureka recorded 0.32 inches. This data point was the biggest outlier. There was a rise in the turbidity, stage, and discharge data during this period, which may be an indicator that there was 1.52 inches of rain, and Eureka might have had less rain. Furthermore, the 2012 precipitation linear regression equation (y= 1.12x + 0.03) has a similar y-intercept and slope to the 2019 linear regression equation (y= 1.16x + 0.03).

The 2012 WY precipitation data was added to the data collected in WY 2019 (Figure 44). The slope and intercept of the regression equation are similar to WY 2012 and 2019 individual regression equations (Figure 41 and 44). There is some scatter

between the precipitation data in the upper range, 1.5 to 3 inches (Figure 44, middle figure).

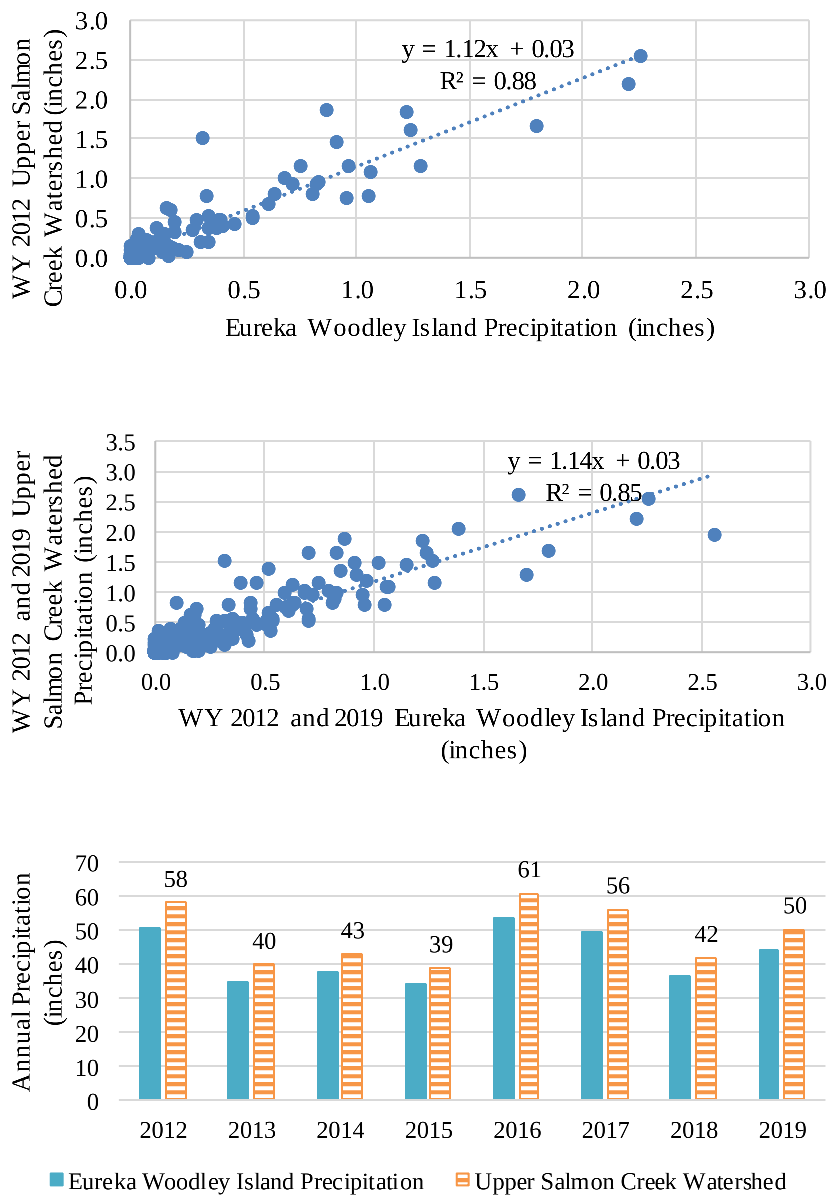


Figure 44: Linear regression between Eureka and Salmon Creek precipitation data. Top graph is WY 2012 precipitation data from 12/1/2011 to 6/30/2012. Middle graph includes precipitation data collected in WY 2012 and 2019. Bottom graph illustrates annual precipitation estimated in the Upper Salmon Creek watershed using the linear regression equation (middle graph).

The correlation between the 2012 and 2019 Salmon Creek and Eureka rainfall data resulted in an R^2 value of 0.85. A comparison between the precipitation data can serve to validate the more comprehensive Eureka precipitation as a suitable measure of storm events occurring in the Upper Salmon Creek watershed. The continuation of rainfall data collection will not only strengthen the relationship between the two data sets but can be used to derive an adjustment factor for the use of the Eureka precipitation data. The regression equation was applied to the Eureka Woodley Island hourly precipitation data from 2012 and 2019 to estimate precipitation in the Upper Salmon Creek watershed (Figure 44, bottom graph).

Suspended Sediment Yield

Annual suspended sediment yield (SY) was estimated for the 2012 to 2019 WY in Upper Salmon Creek with the exception of WY 2015 (no stream data was collected). The SY was computed independently for each WY due to nuances that make the analysis of estimating annual SY slightly different for each year.

Each WY has a unique discharge rating curve and a turbidity-sediment rating curve to approximate discharge and SSC. Two power function equations were fit to each WY discharge rating-curves: a single and a piecewise fit. A log-log regression equation was fit to the turbidity-sediment rating curves for each water year. Three different turbidity-sediment rating curves were developed: "All Data", "Annual", and "Seasonal". The All Data log-log regression equation was fit to all the turbidity-SSC data from 2012 to 2019, Annual log-log regression equation was fit to each WY turbidity-SSC data, and Seasonal log-log regression equation was fit to subdivided turbidity-SSC data by seasons within a WY (e.g. October to February and March to September). The 2017, 2018, and 2019 WY analysis is presented below and discusses the sensitivity of using different rating curves to estimate sediment yield. WY 2012, 2013, 2014, and 2016 sediment yield analysis is presented in Appendix E.

Sediment yield estimates were also calculated for each individual storm during a given WY. For ease of sediment load (SL) estimates, a single power function equation for the stage-discharge relation and the Annual turbidity-sediment rating curves were used to

estimate SSC. This analysis examines the amount of SL moving downstream during storm events in a given WY and is described in more detail below.

Annual sediment yield estimates and sensitivity

Annual SY estimates are summarized in Figure 45 and Table 15 to 17. The x-axis on Figure 45 indicates the different turbidity-sediment rating curves used to estimate SSC, and the y-axis is annual sediment yield in tons. Additionally, each figure shows sediment yield estimates using a single and piecewise power function equation to estimate discharge. Table 15 to 17 summarizes the sediment yield estimates using the All Data, Annual, and Seasonal turbidity-sediment rating curves (TSRC) and the discharge rating curves. The tables also present the percent difference between sediment yield estimates using the single and piecewise power fit equation, and the percent difference between sediment yield using the All Data, Annual, and Seasonal TSRC.

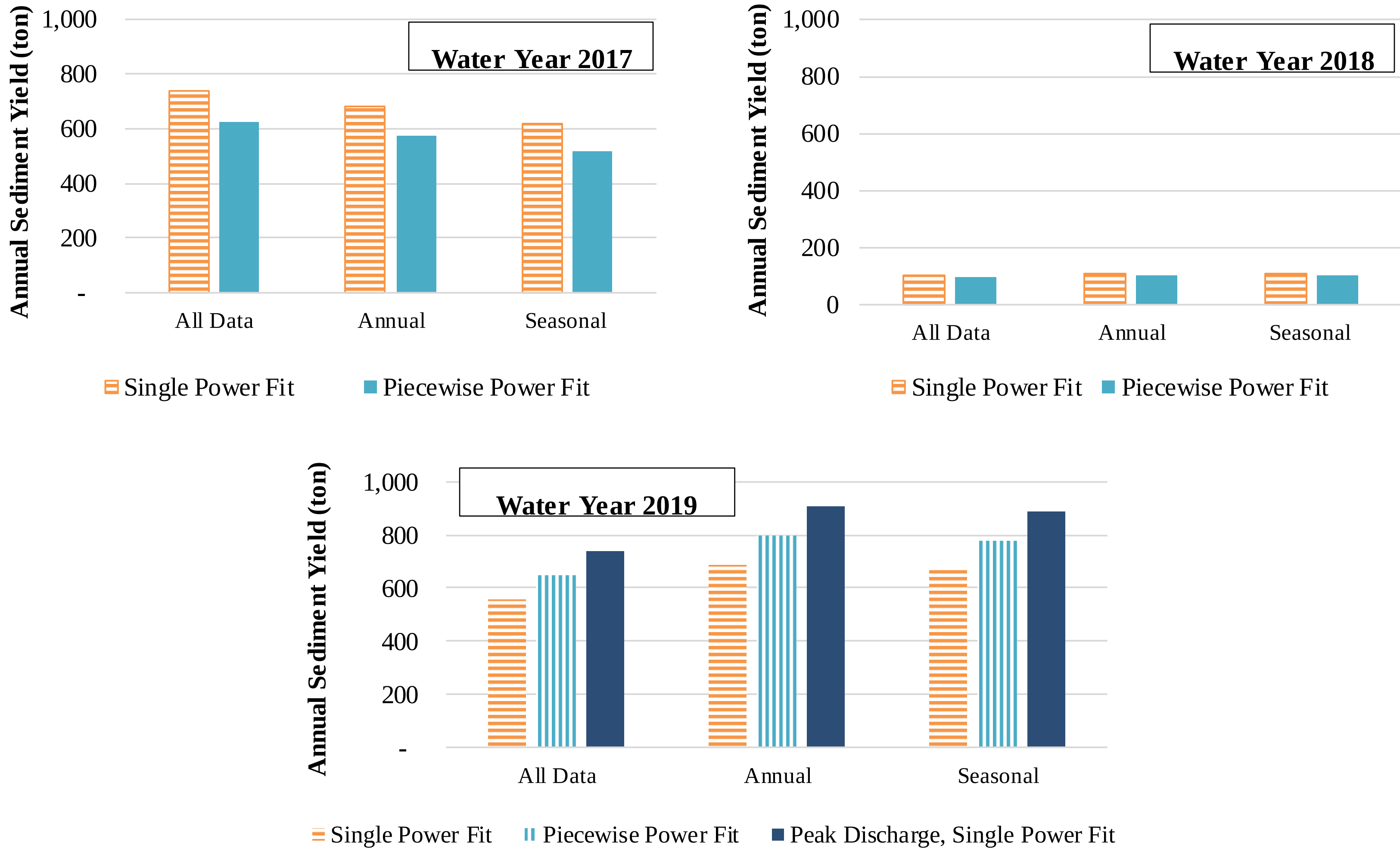


Figure 45: Annual sediment yield estimates for the 2017, 2018, and 2019 WY in the Upper Salmon Creek.

WY 2017 sediment yield estimates ranged from 616 tons to 742 tons (116 tons/mi^2 to 140 tons/mi^2) when using the single power function equation and All Data-, Annual-, and Seasonal-TSRC, and ranged from 520 tons to 623 tons (98 tons/mi^2 to 118 tons/mi^2) when using the piecewise power function equation with the various TSRC (Table 15). On average, there was a 17.2% difference in SY estimates when using the single or piecewise power regression equation for the discharge rating curve. The Seasonal TSRC had the largest percent difference between the Annual sediment yield estimates. The Seasonal TSRC sediment yield estimate is 10% less than the Annual estimate (Table 15).

Table 15: Summary of the 2017 sediment yield estimates using different turbidity-sediment rating curves and discharge rating curves. SY estimates are in units of tons.

Turbidity Sediment Rating Curve	Single Power Fit	Piecewise Power Fit	% Diff of SL Estimate using Single vs. Piecewise Fit	% Diff of SL Estimate using Annual vs. other TSRC
All Data	742	623	17.3%	9%
Annual	681	572	17.4%	-
Seasonal	616	520	16.9%	-10%

WY 2018 sediment yield estimates ranged from 103 tons to 110 tons (116 tons/mi^2 to 140 tons/mi^2) when using the single power function equation and All Data, Annual, and Seasonal TSRC, and ranged from 94 tons to 101 tons (98 tons/mi^2 to 118 tons/mi^2) when using the piecewise power function equation with the various TSRCs (Table 16). WY 2018 had lower SY estimates than all the other years of data except for WY 2014 (Appendix E, Table E-3). This year had lower stream flows (Table 7 and 8) and the annual rainfall was 36.6 inches in Eureka, CA. Furthermore, WY 2018 had

approximately 12,000 stage error readings (-99999) from October to December. Missing this data is critical since the majority of sediment transport is during the wet season, and the 2018 SY estimate should be considered with caution.

The annual 2018 SY estimates were similar between the Seasonal TSRC and the Annual TSRC with only a 1% percent difference, while the All Data TSRC may have over or under estimated the SY value. Furthermore, the average percent difference between the SY estimate when using the single and the piecewise power function equation is 8.7%.

Table 16: Summary of the 2018 sediment yield estimates using different turbidity-sediment rating curves and discharge rating curves. SY estimates are in units of tons.

Turbidity Sediment Rating Curve	Single Power Fit	Piecewise Power Fit	% Diff of SL Estimate using Single vs. Piecewise Fit	% Diff of SL Estimate using Annual vs. other TSRC
All Data	103	94	9.1%	- 7%
Annual	110	101	8.5%	-
Seasonal	109	100	8.6%	- 1%

WY 2019 sediment yield ranged from 560 tons to 686 tons (105 tons/mi^2 to 130 tons/mi^2) when using the single power function equation and All Data, Annual, and Seasonal TSRC, and ranged from 649 tons to 796 tons (122 tons/mi^2 to 150 tons/mi^2) when using the piecewise power function equation with the various TSRC (Table 17). SY estimates ranged from 738 tons to 986 tons (140 tons/mi^2 to 186 tons/mi^2) when using the peak discharge rating curve (Table 17). As suspected, the SY estimate is 28% greater when using the peak discharge rating curve than the single power fit discharge rating curve because the peak discharge rating curve may be overestimating discharge values.

The Annual and Seasonal TSRC were close in SY estimates, with a percent difference of 2.8%, while the All Data TSRC was 20% less than the Annual TSRC sediment yield estimates (Table 17)

Table 17: Summary of the 2019 sediment yield estimates using different turbidity-sediment rating curves and discharge rating curves. SY estimates are in units of tons.

Turbidity Sediment Rating Curve	Single Power Fit	Piecewise Power Fit	Peak Discharge Single Power Fit	Average % Diff of SL Estimate using Annual vs. other TSRC
All Data	560	649	738	- 20%
Annual	686	796	906	-
Seasonal	668	778	886	- 2.8%
Average % Diff of SL Estimate using Single vs. Piecewise Fit	15%			
Average % Diff of SL Estimate using Single vs. Peak Single Fit	28%			
Average % Diff of SL Estimate using. Piecewise vs Peak Single Fit	13%			

The annual sediment yield from WY 2012 to 2019 ranged from 49 tons to 944 tons (9 tons/mi^2 to 178 tons/mi^2). The discharge rating curves were the most sensitive to changing the sediment yield estimate, and further analysis between using a single and piecewise power fit needs to be done to determine if one is over or under estimating SY estimates. Additionally, the discharge rating curves had to be extrapolated, where the extrapolated portion accounted for 33 to 84% of the sediment yield estimate. The relationship between turbidity and SSC does not change from year to year, and thus, the All Data turbidity-sediment rating curve can be used for WYs that did not collect SSC data.

Storm event sediment load estimates

Rainfall data was not collected from 2013 to 2018, and thus, storm events were not based on rainfall data and duration of an event. Instead, a storm event for this analysis was defined as a hydrologic event that causes sediment to move downstream. To determine the number of storm events in a given WY, a visual inspection of the time series plot for turbidity and stage was observed. Anytime there was a peak or rise in turbidity and stage, and if there was a water sample taken, then it was considered a storm. The duration of the storm was based on a visual observation of when the flow returned to base flow.

Sediment load estimates were calculated for each individual storm during a given WY (Table 18). The All Data TSRC was used for estimating SSC for WYs that had no SSC data collected (WY 2013, 2014, and 2016). WY 2017, 2018, and 2019 used the

Annual TSRC to estimate SSC. The single power fit function equation was used for this analysis, and WY 2013 and 2014 discharge was estimated using the 2016 single power function equation. Table 18 summarizes the total number of storms within a WY, the total rainfall during the storm events, peak turbidity and discharge, the total sediment load transported during the storm, the total sediment load within an entire WY, and the percent sediment transported during a storm. Total rainfall was estimated using the precipitation linear regression equation with the daily Eureka Woodley Island precipitation data set (Figure 44). Figure 46 summarizes the sediment load estimate during the storms and the total sediment yield in a given WY.

Table 18: Summary of the number of storm events within a WY, total rainfall during the storms, peak turbidity and discharge, sediment load estimates during the storms, total sediment load in a given year, and the percent sediment transported during storms.

Water Year	# of Storms	Total Rainfall (inches)	Peak Turbidity (NTU)	Peak Discharge (cfs)	Storm Sediment Load (tons)	Total Sediment Load (tons)	% of Annual Sediment Transport
2012	18	32	1646	358	522	557	94%
2013	11	21	876	169	209	319	65%
2014	6	10	219	98	51	88	58%
2016	9	23	1017	214	488	541	90%
2017	15	29	925	878	592	681	87%
2018	11	18	72	112	72	90	82%
2019	13	23	658	250	556	686	81%

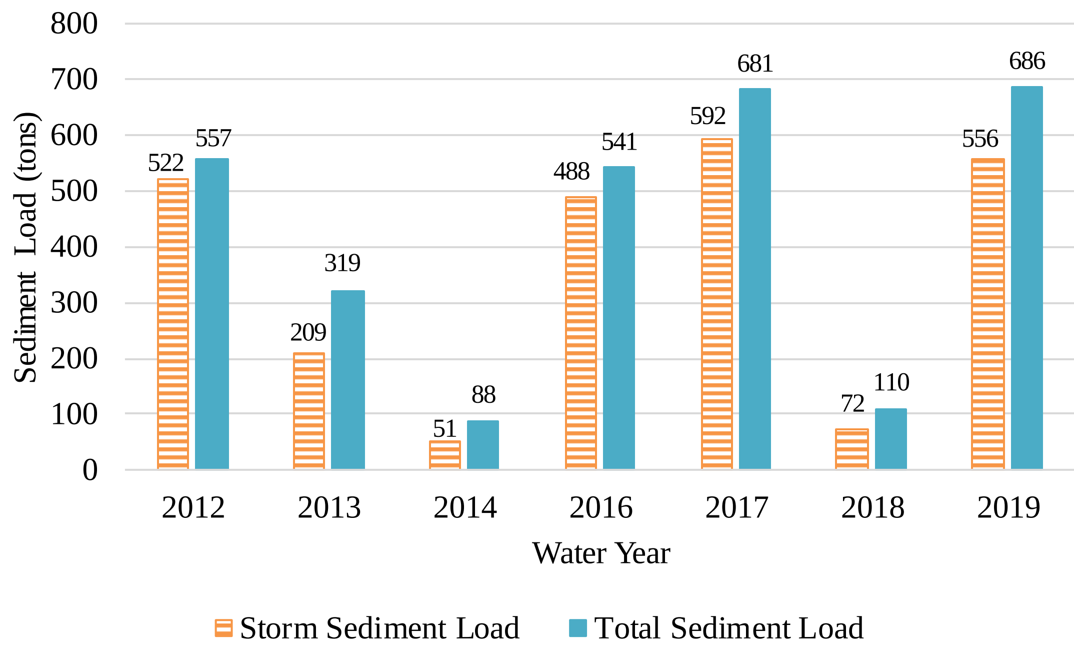


Figure 46: Sediment load estimates during storms within a given water year and the total sediment load transported within a year.

Figures 47 to 53 illustrate the largest storm event that occurred in a WY. Precipitation data collected in the field for the 2012 and the 2019 WY was used, while WY 2013, 2014, and 2016 to 2018 daily precipitation was estimated using the linear regression equation (Figure 44) given the daily Eureka Woodley Island precipitation data. WYs 2012 to 2018 show the left y-axis as 15-minute discharge and turbidity data and the right y-axis as daily precipitation (Eureka Woodley Island precipitation data provides daily and not 15-minute data). Daily precipitation data for WYs 2012 to 2018 were plotted at the beginning of the day on the x-axis (12:00 AM). WY 2019 shows the right and left y-axis as hourly discharge, turbidity, and precipitation data (hourly precipitation data was collected in the rain gauge).

WY 2012 had 18 storms, which generated 522 tons (98 tons/mi^2) of sediment load (Appendix F, Table F-1). The storm events accounted for 94% of the sediment transported. The largest storm was March 27th to March 31st, 2012 (Storm #12), which was during the landslide upstream from the monitoring station (Figure 47). This storm accounted for 46% of the overall sediment transported (Appendix F, Table F-1). During this event, there was 261 tons of sediment transported downstream, 6.6 inches of rainfall, a peak turbidity and discharge of 1,646 NTU and 358 cfs, respectively (Table F-1 and Figure 47). Storm 12 begins with a constant discharge and turbidity, and around March 29th at noon the turbidity and discharge gradually rises until a large pulse of sediment enters the stream on March 30th at 9:45 AM. The turbidity and discharge rise up to 1,640 NTU and 250 cfs, and gradually falls back down until another pulse of sediment enters the stream from the landslide. As seen, turbidity typically rises first and then follows the peak discharge after a few hours. This is known as the “first flush” of sediment delivered by the first large storm event, where the deposited finer material is more readily mobilized as bed load during the rising limb of the discharge curve, and once the peak discharge occurs, most of the deposited fine sediment has been transported downstream.

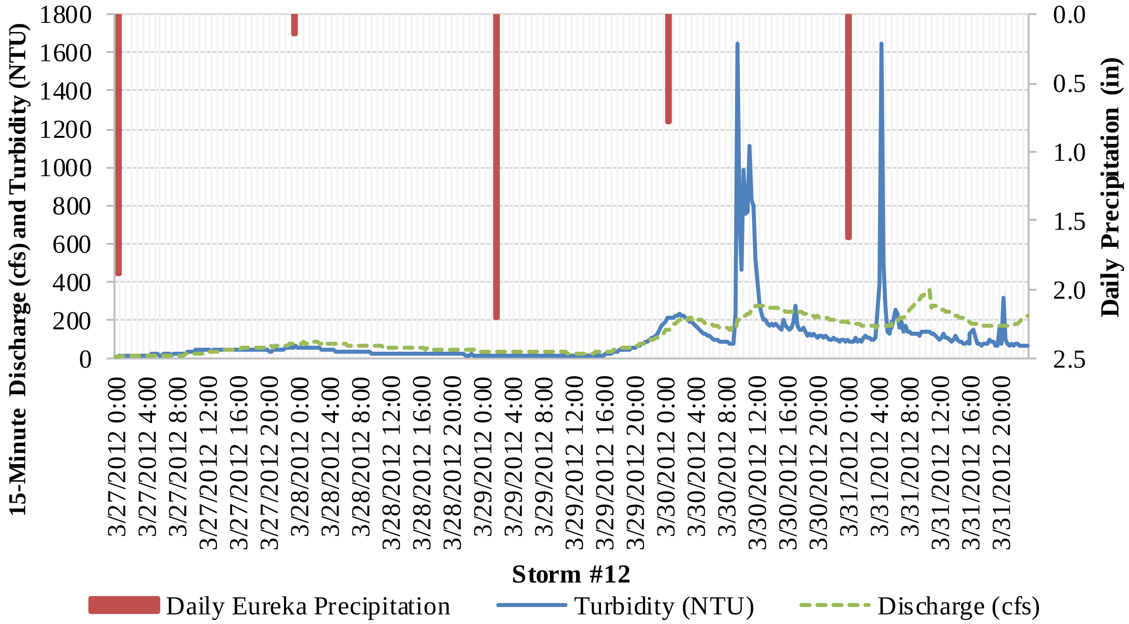


Figure 47: Storm #12, March 27th to March 3rd, was the largest storm during WY 2012. This storm was during the landslide upstream from the monitoring station, which generated 261 tons of sediment, or 46% of the total sediment load. Note, the plotted daily precipitation data was plotted at the beginning of the day on the x-axis.

WY 2013 had 11 storms, which generated 209 tons (40 tons/mi^2) of sediment load (Appendix F, Table F-2). The storm events accounted for 65% of the sediment transported in 2013 WY. There was a total rainfall of 21 inches during these 11 storms, which accounted for 52% of the total rainfall during WY 2013 (total rainfall was 40 inches, Figure 44). This indicates that there was approximately 19 inches of rainfall in the watershed that did not generate large amounts of sediment transport in Salmon Creek. The largest storm was from December 1st to December 2nd, resulting in 77 tons of sediment load (Figure 48). This accounted for 24% of the sediment transported downstream (Appendix F, Table F-2). The total duration of this storm was 48 hours (2 days) with a total estimated rainfall of 3.34 inches, and peak turbidity and discharge of

876 NTU and 169 cfs, respectively (Figure 48 and Table F-2). Storm 5 shows an initial sudden rise in turbidity from the first flush after which turbidity follow more closely with discharge (Figure 48).

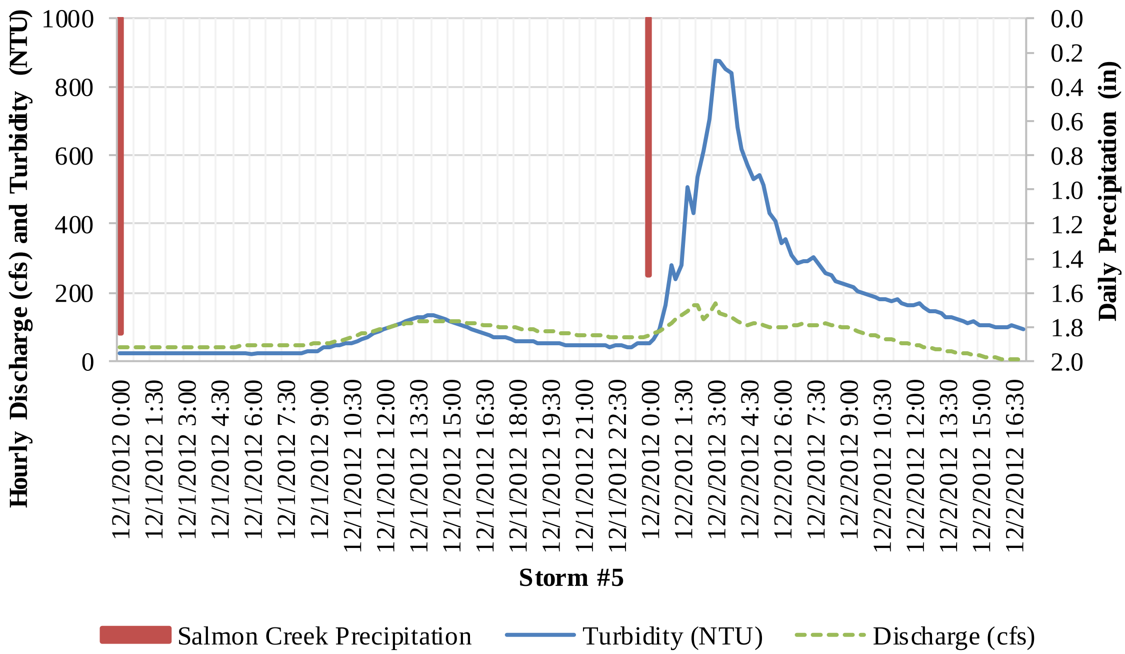


Figure 48: Storm #5, December 1st to December 2nd, was the largest storm during WY 2013. There was a total sediment load of 77 tons, which accounted for 24% of the total sediment load. Note, the plotted daily precipitation data was plotted at the beginning of the day on the x-axis.

There were six storms during WY 2014, which generated 51 tons (10 tons/mi^2) of sediment load (Appendix F, Table F-3). This accounted for 58% of the annual sediment transported. There was a total rainfall of 10 inches in these six storms, which accounted for 23% of the total rainfall during WY 2014 (total rainfall was 43 inches, Figure 44). This year had low turbidity and stage recordings in the stream and drier conditions, which corresponds to lower sediment load (Table 7 and 8). Furthermore, the largest storm was

from March 9th to the 10th, resulting in 25 tons of sediment load. This accounts for 28% of sediment load transported in Salmon Creek that WY (Figure 49). The total duration of this storm was 48 hours with a total estimated rainfall of 3.12 inches, and peak turbidity and discharge of 172 NTU and 98 cfs, respectively (Figure 49 and Table F-3). Figure 49 demonstrates a gradual rise and fall in the turbidity and discharge data, with the discharge peaking a few hours after the peak turbidity.

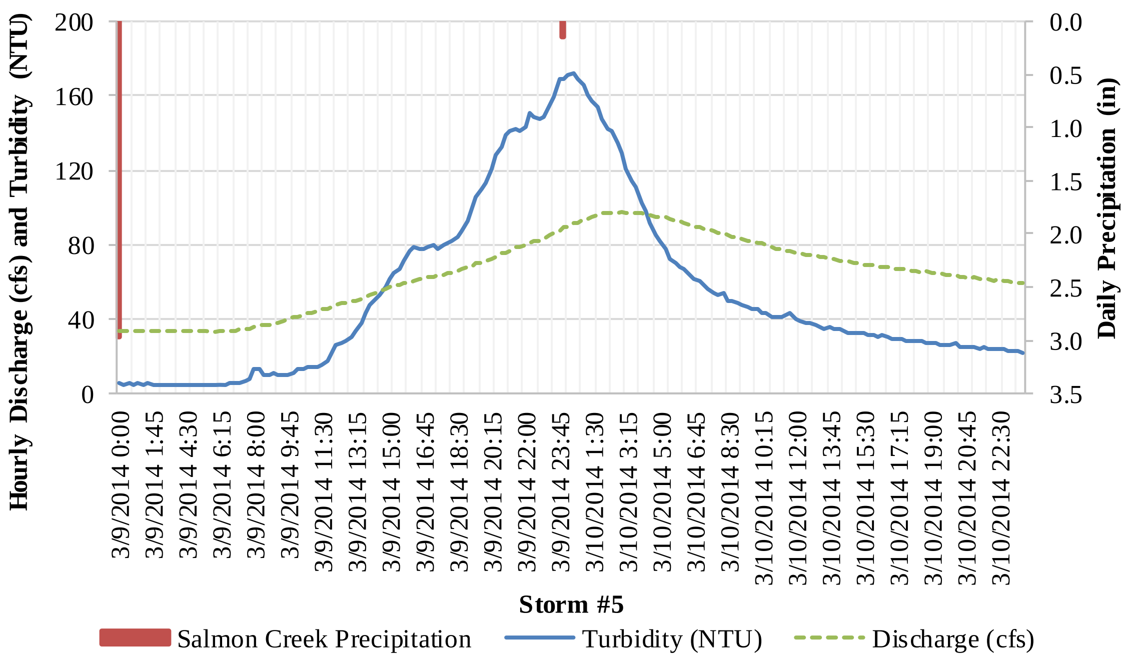


Figure 49: Storm #5, March 9th to the 10th, was the largest storm during WY 2014. There was 25 tons of sediment load during this storm, which accounted for 28% of the total sediment load. Note, the plotted daily precipitation data was plotted at the beginning of the day on the x-axis.

There were nine storms during WY 2016, which generated 488 tons (92 tons/mi^2) of sediment (Appendix F, Table F-4). This accounted for 90% of the total sediment transported downstream in WY 2016. There was a total rainfall of 23 inches, which accounted for 38% of the total rainfall during WY 2016 (total rainfall was 61 inches,

Figure 44). The largest storm was from January 13th to the 18th, resulting in 184 tons of sediment load which accounts for 34% of the total sediment load in WY 2016 (Figure 50). The total duration of this storm was 144 hours (6 days) with a total estimated rainfall of 5.06 inches, and a peak turbidity and discharge of 652 NTU and 214 cfs, respectively (Figure 50).

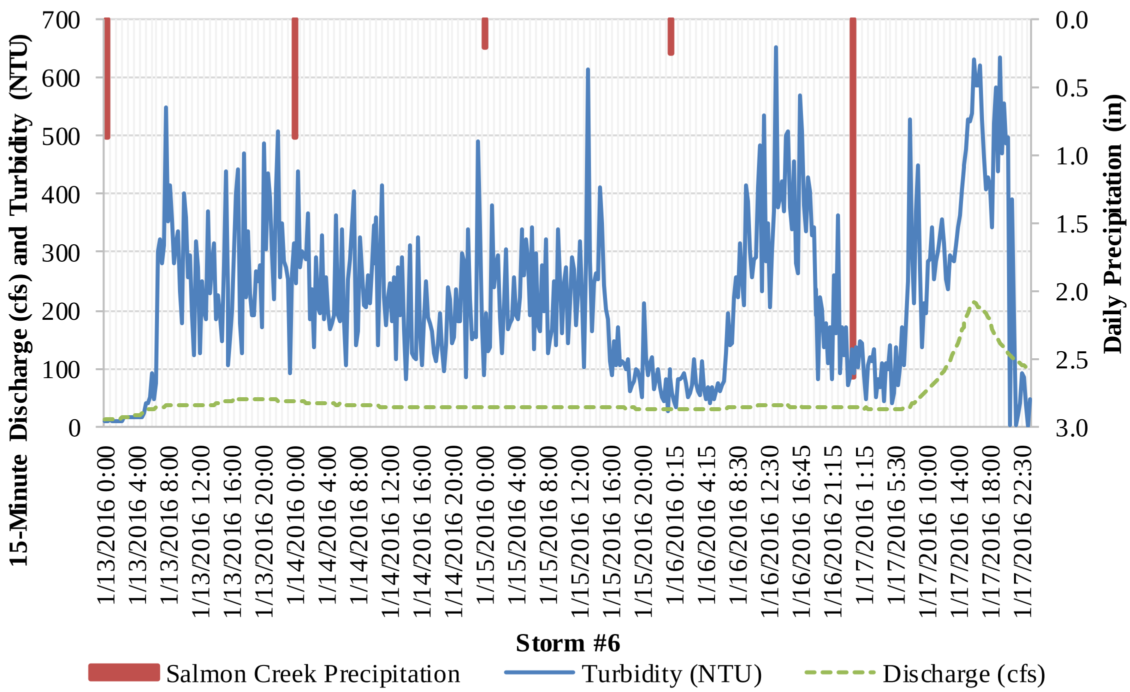


Figure 50: Storm #6, January 13th to the 17th, was the largest storm during WY 2016. There was a total sediment load of 184 tons, which accounted for 34% of the total sediment load. Note, the plotted daily precipitation data was plotted at the beginning of the day on the x-axis.

WY 2016 data is slightly questionable because the raw turbidity data demonstrates short-duration turbidity pulses (Figure 50). As previously discussed, poor turbidity data may be examined by plotting turbidity and stage (Figure 24). Figure 50 illustrates turbidity and discharge, where the discharge stays constant, around 47 cfs,

while the turbidity rises and falls quickly. This may indicate sediment delivery from local streambanks or hillslopes, or equipment issues with the DTS-12 turbidity sensor. The sediment load estimates for WY 2016 should be taken cautiously as there may have been equipment issues or erratic sediment delivery, all of which may provide inaccurate turbidity readings.

There were 15 storms during WY 2017, which generated 592 tons (112 tons/mi^2) of sediment load (Appendix F, Table F-5). This accounted for 87% of total sediment transported downstream in WY 2017. The total rainfall during these storms was 29 inches (52% of total rainfall). The largest storm was from December 15th to the 16th, resulting in 239 tons of sediment load (Figure 51 and Table F-5). This accounts for 35% of the total storm sediment load in that year (Figure 51). The total duration of this storm was 48 hours with a total estimated rainfall of 1.25 inches, and peak turbidity and discharge of 925 NTU and 878 cfs, respectively (Figure 51). The interaction between peak discharge and turbidity is different during this storm than the storms described above, where the turbidity peaks first then discharge. This storm, however, had the peak discharge occurring 11 hours before the peak turbidity of 925 NTU (Figure 51). The peak discharge may have caused bank failure, or an event not tied to hydrology of the stream.

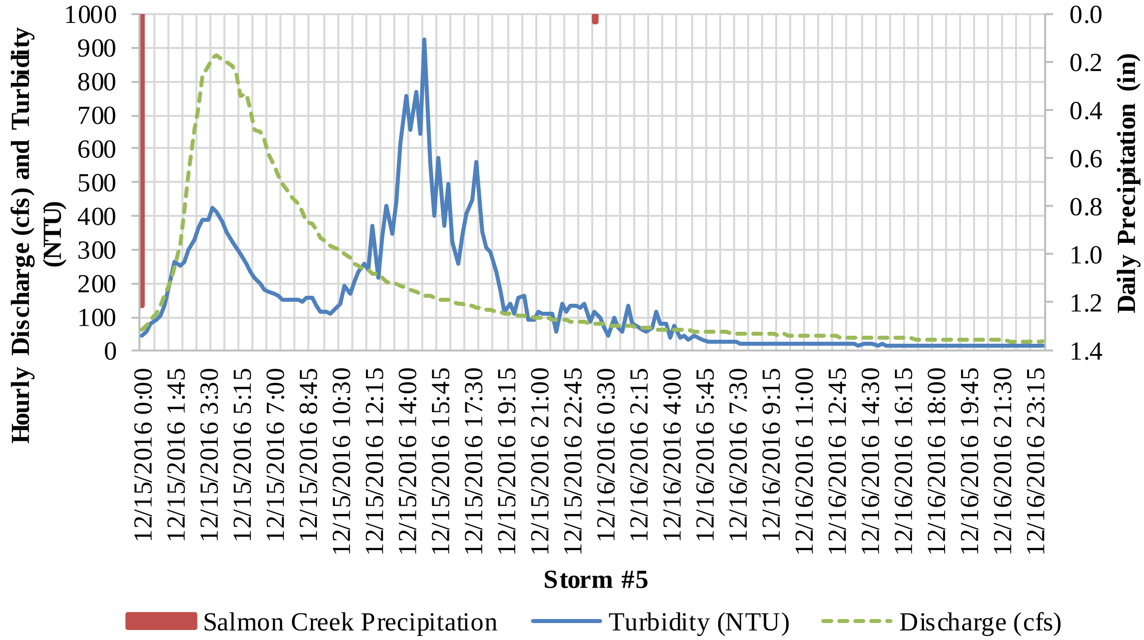


Figure 51: Storm #5, December 15th to December 16th, was the largest storm during WY 2017. There was a total sediment load of 239 tons, which accounted for 35% of the total sediment load. Note, the plotted daily precipitation data was arbitrarily chosen on the 15-minutes x-axis.

There were nine storms during WY 2018, which generated 90 tons (17 tons/mi^2) of sediment (Appendix F, Table F-6). This accounted for 82% of total sediment transported downstream in WY 2018. The largest storm was from March 15th to the 17th, resulting in 20 tons or 18% of the total sediment load (Figure 52 and Table F-6). The total duration of this storm was 72 hours with a total rainfall of 1.6 inches, and peak turbidity and discharge of 72 NTU and 112 cfs, respectively (Figure 52).

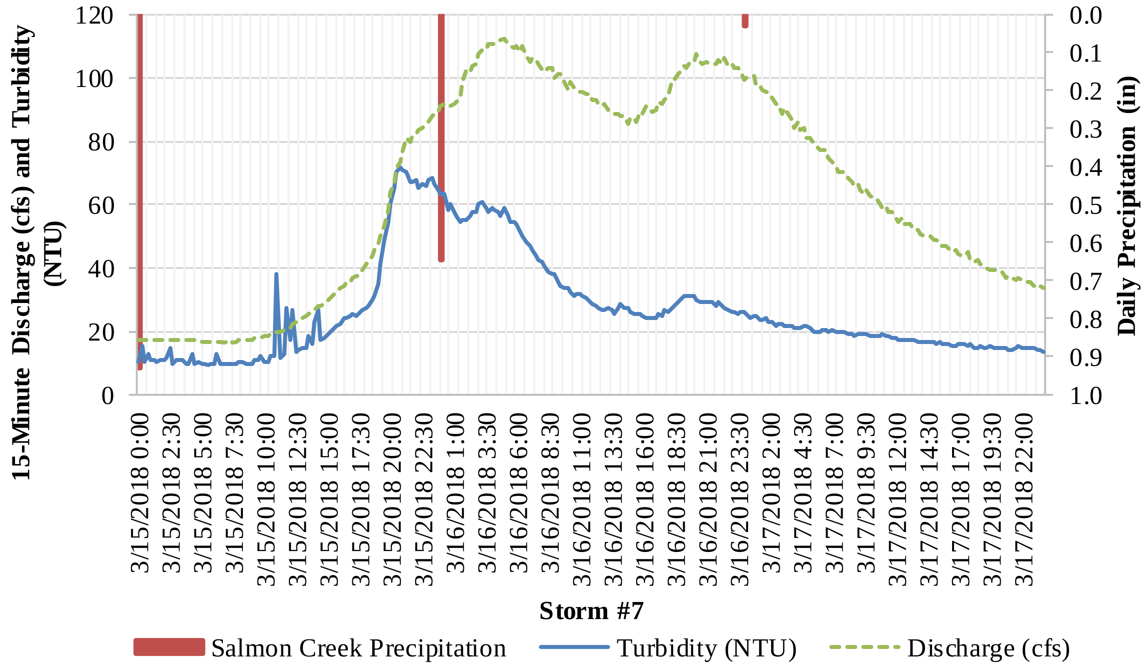


Figure 52: Storm #7, March 15th to the 17th, was the largest storm during WY 2018. There was a total sediment load of 20 tons, which accounted for 18% of the total sediment load. Note, the plotted daily precipitation data was arbitrarily chosen on the 15-minutes x-axis.

There were 13 storms during WY 2019, which generated 556 tons (105 tons/mi^2) of sediment load (Appendix F, Table F-7). This accounted for 81% of the total sediment transported downstream in WY 2019. The largest storm was February 25th to 28th, resulting in 383 tons, which accounts for 56% of total sediment load (Figure 53). The total duration of this storm was 96 hours (4 days) with a total rainfall of 6.3 inches, and peak turbidity and discharge of 658 NTU and 250 cfs, respectively (Figure 53 and Table F-7). The turbidity and discharge in Salmon Creek seemed to react to the amount of precipitation in the watershed (Figure 53). The first storm, February 25th from 12:00 AM to 2:00 PM, had a total rainfall of 2.4 inches with approximately 0.2 inches after 2:00 PM. The peak discharge of 255 cfs occurred two hours after the rainfall, 4:00 PM. The

peak turbidity of 555 NTU followed one hour later at 5:00 PM (Figure 53). The second storm, February 26th from 8:00 AM to February 27th at 8:00 PM had a total rainfall of 3.6 inches. The peak discharge of 187 cfs and peak turbidity of 650 NTU occurred at the same time on February 27th at 2:00 AM, where 2.4 inches of rain had already fallen.

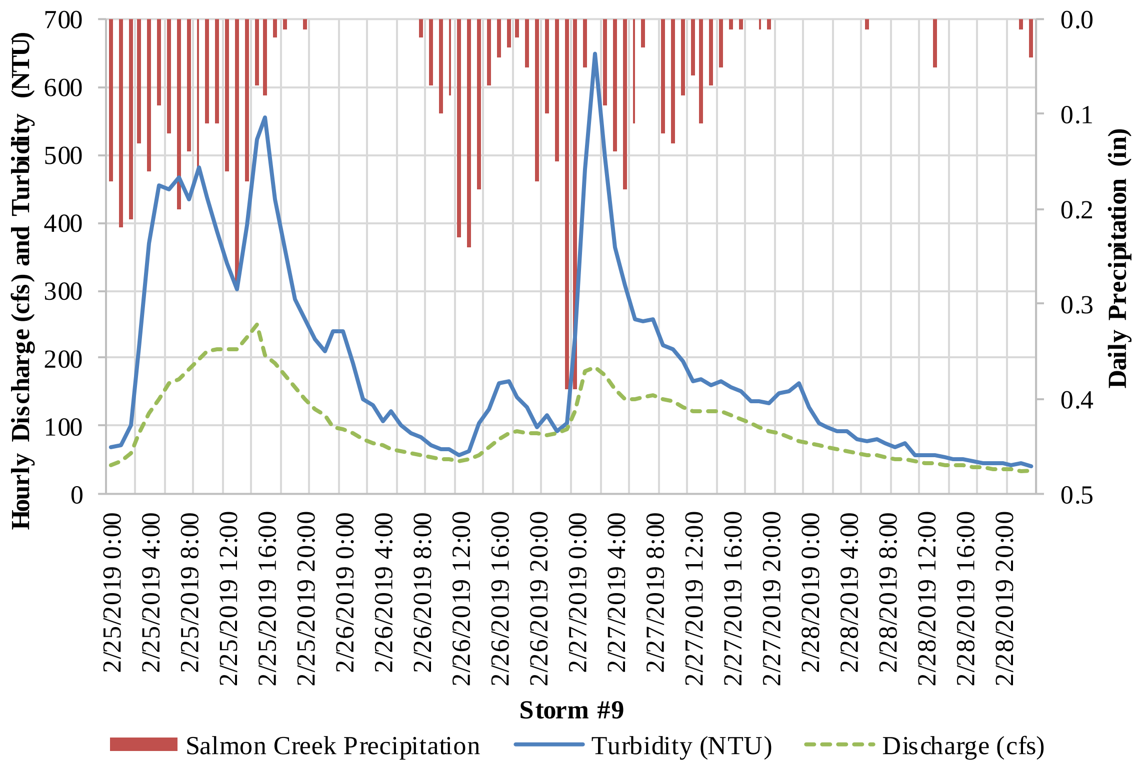


Figure 53: Storm #9, February 25th to the 28th, was the largest storm during WY 2019. There was a total sediment load of 383 tons, which accounted for 56% of the total sediment load. Note, the 2019 WY has hourly precipitation data on the right y-axis and was plotted with hourly discharge and turbidity on the left y-axis.

Summary of sediment yield estimates in Upper Salmon Creek

Sediment yield was estimated for the 2012 to 2019 WYs (excluding WY 2015) in Salmon Creek by using various discharge rating curves and turbidity sediment-ratings curves. Sediment yield estimates appear to be most sensitive to using different discharge

rating curves. Additionally, the discharge rating curves had to be extrapolated beyond the range of measurements obtained and extrapolated portion of the rating curve accounts for 33% to 84% percent of the sediment yield estimates in Salmon Creek (Table 19). For example, in WY 2012 the maximum stage recorded with a concurrent discharge measurement was 1.53 feet, and the maximum stage recorded from the data logger was 3.36 feet. Five percent of the 2012 stage data exceeded 3.36 feet, which accounted for 84% of the total sediment yield (Table 19).

Table 19: Summary of maximum stage recorded with a discharge measurement, maximum stage recorded from the data logger, and % exceedance of the maximum stage recorded with a discharge measurement, % exceedance of the stage value, and the % total sediment yield.

Water Year	Maximum Stage Recorded with a Discharge Measurement (ft)	Maximum Stage Recorded from Data Logger (ft)	% Exceedance of Stage Value	% of Total Sediment yield
2012	1.53	3.36	5%	84%
2016	1.67	4.75	3%	33%
2017	1.65	3.70	3%	76%
2018	1.46	1.58	2%	44%
2019	2.48	5.80	3%	68%

Sediment yield estimates were less sensitive to the different turbidity-sediment rating curves, but overall, the All Data turbidity-sediment rating curve had the biggest difference in sediment yield estimates (average difference of 11.3%) than using the Annual or Seasonal turbidity-sediment rating curves. Furthermore, the relationship between turbidity and SSC does not significantly change from year to year, and the existing data that was collected is adequate to quantify the relationship between turbidity and SSC.

Ideally, one turbidity-sediment rating curve and one discharge rating curve for Salmon Creek could be used to estimate sediment yield. However, periodic geomorphic changes in the channel cross-section can shift the relation between stage and discharge. The relationship between turbidity and SSC should not significantly change with time but particle composition or availability of easily transported material can change with time, which may shift the turbidity-SSC relation.

Sediment load estimates were also calculated for each individual storm during a given WY. Individual storm events provide information on the character and response of the watershed to storm events. Erosion and sedimentation are driven by events, with most occurring for a short duration of high intensity rainfall and discharge. On average, sediment load during storms accounted for 77% of the total sediment load. Sediment delivery to Salmon Creek and sediment transport vary from storm to storm and from year to year. The continuation of collecting rainfall data can be useful by acting as a guide for erosion and sediment activity. The storms that generated the largest sediment load contribution typically had the largest rainfall (Table F-1 to F-7).

Watershed Characteristics and Historical Disturbances

Four northern California coastal watersheds with publicly available data use an automated turbidity sensor and pump sampler to estimate suspended sediment yield. Lost Man Creek (LMC), Little Lost Man Creek (LLM), and Prairie Creek (PAB) have data collected from WY 2012 to 2018, and the Lower Jacoby Creek (JBW) has data collected

from WY 2012 to 2017 (Figure 54). Annual sediment yield estimates for these locations were compared to sediment yield estimates in the Upper Salmon Creek. Additionally, an analysis of the raw data collected at these streams was explored to determine if whether these data sets can fill in missing data from Salmon Creek.

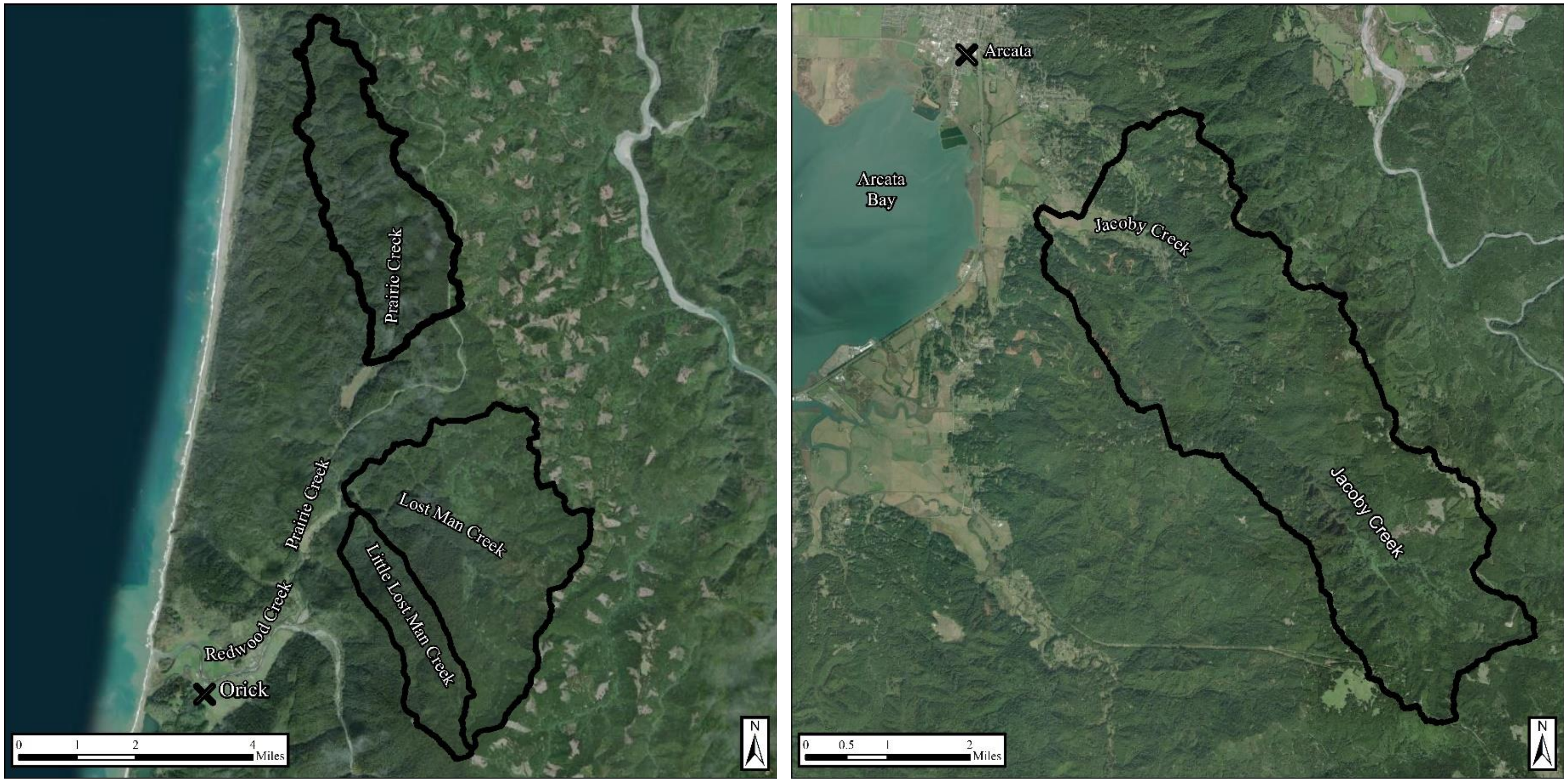


Figure 54: Left map shows Prairie Creek watershed, Lost Man Creek watershed, and Little Lost Man Creek watershed. The right map shows Jacoby Creek watershed.

Overview of the coastal watersheds

Lost Man Creek at the hatchery (LMC), Little Lost Man Creek (LLC), and Prairie Creek above Boyes Creek (PAB) are located in Redwood National Park and Prairie Creek Redwoods State Park (Figure 54). LMC is a major tributary to Prairie Creek, which joins with Redwood Creek 6 miles upstream from the mouth of the Pacific Ocean. LMC was heavily timber harvested and developed with logging roads from the 1950s to the early 1970s (Klein and Ozaki 2016). During this period, logging roads and landings were unregulated, and the forest was heavily clearcut with intensive ground disturbance from construction (Klein and Ozaki 2016). By 1978, the stream was highly disturbed from severe erosion and sediment delivery, and the entire watershed became parkland. Road decommissioning in LMC started in 2000, and by 2011, nearly all unmaintained roads were removed with an objective to sustain and support salmonid species. LLM and PAB are predominantly pristine old-growth redwood forest, with minor influences from older road development.

Lost Man Creek is underlain by the Prairie Creek Formation and the Coherent Unit of Lacks Creek (Franciscan Assemblage, approximately 2/3 of the entire watershed) (Klein and Ozaki 2016). The Prairie Creek Formation is described as weak consolidated shallow marine and alluvial sediments, and is susceptible to surface erosion after disturbances (Cashman et al. 1995). The Franciscan Assemblage is interbedded with sandstone and mudstone and shallow landslides are commonly associated with hillslopes underlain by these rocks (Cashman et al. 1995). PAB is mostly underlain by Prairie Creek Formation and LLM is underlain by Franciscan Assemblage.

The Jacoby Creek watershed (JBW) is located south of Arcata, California, and discharges into the Arcata Bay. The drainage area is 19 square miles with approximately 80% consisting of timbered hillslopes. The lower gradient of the drainage area is pastures, wetlands, and residential lands (Klein 2004). Table 20 summarizes land use, acreage, and percent of the watershed as of 1995 (Klein 2004). Note, land transfers and the continuation of timber harvest will change these values. Furthermore, JBW is predominantly underlain by Franciscan mélange, and sandstone overlain by scattered remnants of Falor Formation. Debris slides were dominant in the sandstone units and earth flows were dominant in the mélange units (Alpert and Durgin 1985).

Table 20: Land-use in Jacoby Creek as of 1995 (Klein 2004).

Land-Use Category Acres	Acres	% of Watershed Area
Timberland	7,289	67
Residential	2,805	26
Agriculture	753	7
Total	**10,847**	**100**

The five coastal watersheds (LMC, LLM, PAB, JBW, and Salmon Creek) are in geographically, climatology, and geologically similar areas, but the size of the watersheds and land-use history vary (Table 21). To link land-use history with turbidity and sediment load, the five coastal watersheds were categorized by harvest rate. Klein et al. (2011) expressed harvest rate as ‘clearcut equivalent area’ (CCE), which consists of 15 years of harvest, yarding, and road development data (1990 to 2004). The 15-year CCE period was broken up into 5-year subperiods. CCE is expressed on a mean annual percentage of the watershed area for the individual periods (Klein et al. 2011). Table 21 summarizes the watersheds harvest category from pristine redwood forest to legacy and low harvest

(Klein et al. 2011). The pristine redwood forest is considered no timber harvest activity, legacy is no harvest since 1990, the low harvest is less than 1.4% CCE area from 1990 to 1994, and high harvest is greater than 1.5% CCE area from 1990 to 1994 (Lewis et al. 2011).

Klein et al. (2011) determined Lost Man Creek (LMC) is a legacy harvest, Lower Jacoby Creek (JBC) is a low harvest, and Prairie Creek (PAB) and Little Lost Man Creek (LLM) are pristine redwood forest (Table 21). LLM and PAB act as controls for this analysis. The Upper Salmon Creek watershed was categorized as a low harvest (<1.4% CCE) from 1990 to 1994. In the early 1990s, there were 1.5 miles of road construction and about 15 acres (0.023 square miles) of harvested old-growth redwood forest (Jones and Stoke 2003). It was assumed the logging road developed was 8 feet wide, which results in a road development area of 0.0023 square miles. The total CCE in the early 1990s was approximately 0.5%, which is less than the low harvest threshold of 1.4% CCE.

Table 21: Watershed characterstics and stream data period.

Stream	Site Code	Harvest Category	Drainage Area (mi^2)	Mean Basin Slope (%)	Basin Relief (ft)	30 Year Normals Precip. (in)[c]	Data Period
Lower Jacoby Creek[a]	JBW	Low	13.6	32	2,100	49	2012-17
Upper Salmon Creek[b]	SMC	Low	5.3	30	1,150	57	2012-19
Lost Man Creek at Hatchery[a]	LMC	Legacy	12.2	43	2,400	60	2012-18
Little Lost Man Creek[a]	LLM	Pristine	3.6	43	2,230	60	2012-18
Prairie Crk above Boyes Crk[a]	PAB	Pristine	7.8	46	1450	60	2012-18

[a]Klein et al. 2011 and Klein and Ozaki 2016
[b]USGS 2019 StreamStats
[c]PRISM 2019

<u>Salmon Creek missing data</u>

No stream data were collected during the 2015 WY in Salmon Creek. LMC, LLM, and PAB measured raw continuous turbidity and stage during the 2015 WY. Correlation between Salmon Creek and LMC, LLM, and PAB 2014 raw turbidity and stage data was explored (Figure 55). The Lower Jacoby Creek 2014 raw data was not used to estimate turbidity or stage in Salmon Creek because turbidity was measured in different units (Formazin Nephelometric Unit - FNU). Linear regression was used to estimate continuous (10-minute intervals) turbidity and stage data for the 2015 WY in Salmon Creek (Figure 56). The annual turbidity-sediment rating curve was used to estimate suspended sediment concentration for WY 2015 in Salmon Creek, and the single 2016 power function equation was used to estimate discharge (no discharge data was measured in the 2014 WY).

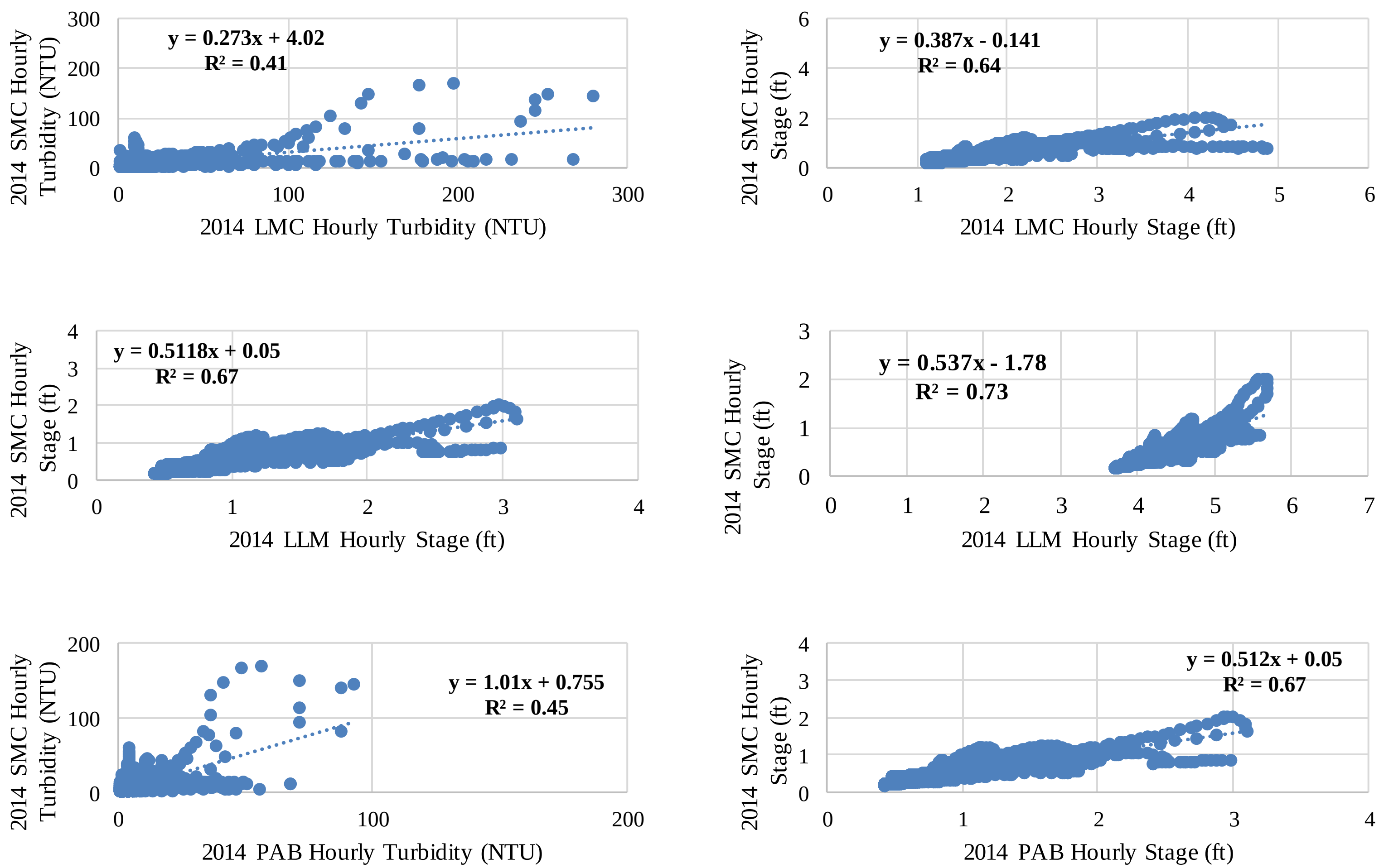


Figure 55: Regression analysis between the 2014 WY Salmon Creek and LMC, PAB, and LLM, turbidity and stage data. Top two graphs are SMC vs. LMC, middle two graphs are SMC vs. LLM, and bottom graphs are SMC vs. PAB.

The correlation between LLM and SMC turbidity and stage data resulted in the highest R^2 values of 0.67 and 0.73, respectively (Figure 55 – middle two graphs). These linear regression equations were applied to LMC, LLM, and PAB 2015 WY turbidity and stage data to estimate stream data in Salmon Creek. The 2015 sediment yield was estimated in Salmon Creek by utilizing the three different 2015 data sets for Salmon Creek, the annual turbidity-sediment rating curve, and the 2016 discharge rating curve. The 2016 discharge rating curve was used since it is the closest discharge data to WY 2015 and no discharge measurements were recorded for WY 2014. Sediment yield estimates using LMC, LLM, and PAB raw data are 187 tons, 87 tons, and 209 tons, respectively (Figure 56).

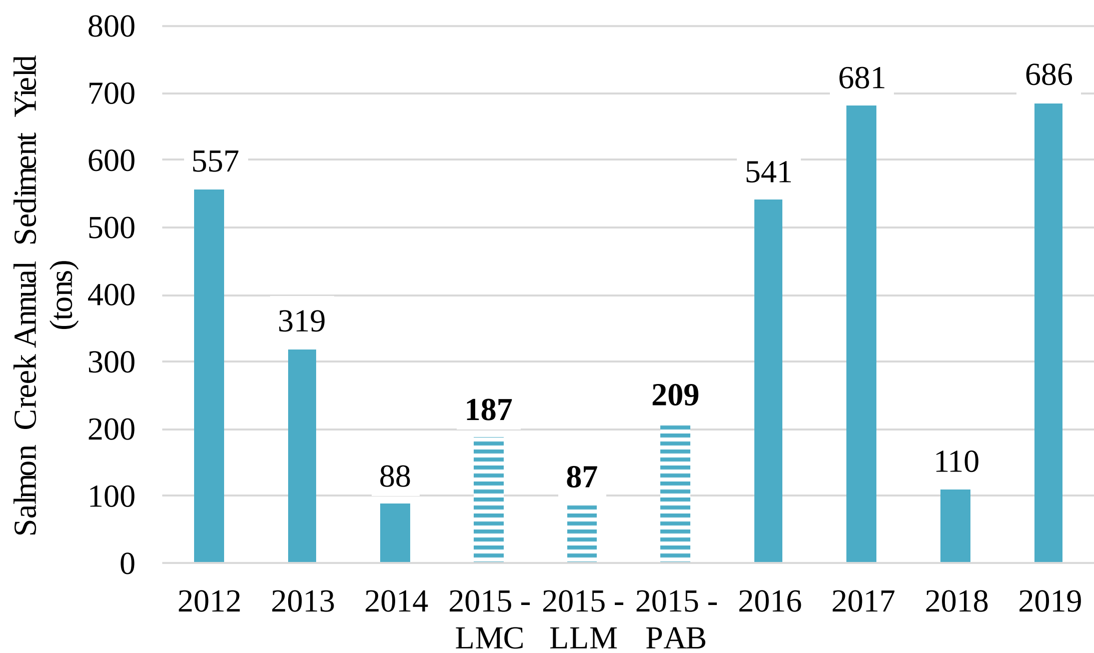


Figure 56: Annual sediment yield estimates in Salmon Creek. The 2015 WY illustrates three sediment yield estimates based on LMC, LLM, and PAB raw data.

WY 2018 in Salmon Creek had approximately 12,000 stage error readings (-99999) from October to December. This missing stage data is critical since it is during the wet season when the majority of sediment is moving down the stream, and a low sediment yield estimate may be caused by the missing data. Lost Man Creek WY 2018 stage data was used to estimate the missing stage error readings. A linear regression equation was fit to the 2018 stage data from Salmon Creek and Lost Man Creek (Figure 57). The correlation between stage data was strong with an R^2 value of 0.89. Sediment load was estimated for the missing data from October 13th to December 14th by using the 2018 turbidity-sediment rating curve, 2018 single power function equation, raw hourly turbidity in Salmon Creek from October 13th to December 14th, and LLM raw hourly stage data. This missing data accounted for eight tons of sediment load, which results in an annual sediment yield estimate of 118 tons. Eight tons of sediment load is a small contributing amount to the annual sediment yield estimate, which may indicate that the creek had minimal depth and coincides with the stage errors readings. Another reasoning for a small contributing amount is that WY 2018 annual precipitation was lower than the average annual rainfall in the area, which may indicate that there was minimal storms during this period.

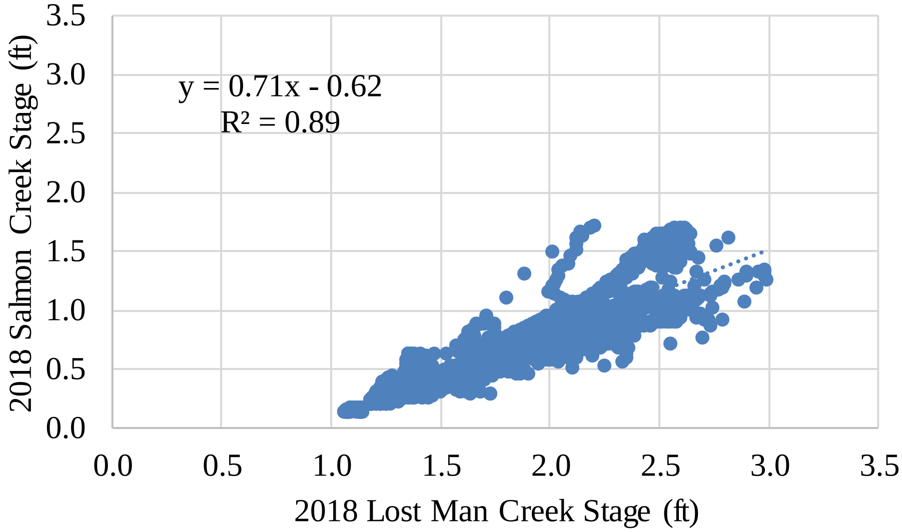


Figure 57: Correlation between WY 2018 Lost Man Creek and Salmon Creek stage data.

Comparison of turbidity and sediment load

Chronic turbidity and land use history linkages from WY 2012 to 2018 was explored between the five coastal watersheds. Chronic turbidity is represented by the 10% exceedance probability, or in other words, turbidity levels exceeded 10% of the time. Klein et al. (2011) describes that chronic turbidity values capture stormflow turbidities during peak events, providing a single value to index chronic exposure for salmonids. Turbidity at the 10% exceedance probability was determined from the continuous data for each WY and watershed to represent chronic turbidity. Table 22 summarizes the turbidity at the 10% exceedance level for each WY and stream.

Table 22: Turbidity at the 10% exceedance for each WY and stream. Units are in NTU except for JBC, which are in FNU.

Stream	Harvest Category	2012	2013	2014	2015	2016	2017	2018	Average
LLM	Pristine	6	5	3	4	7	7	5	5
PAB	Pristine	1	1	2	3	5	5	4	3
LMC	Legacy	10	11	6	10	25	25	15	15
SMC	Low	27	13	7	15	36	16	14	18
JBC	Low	38	29	8	19	51	46		32

The average value for the 10% exceedance turbidity is 4 NTUs for pristine watersheds, 15 NTUs for legacy watersheds, and 18 NTU and 32 FNU for low harvest watersheds. This trend indicates a relationship between chronic turbidity levels and land use. Note, Lower Jacoby Creek measures turbidity with an infrared light source, which gives units in Formazin Nephlometric Unit (FNU), while the other four watersheds measuring turbidity using units of Nephelometric Turbidity Unit (NTU), which uses a white light. A direct comparison between the Lower Jacoby Creek and the other watersheds should not be considered since the units are different.

The control sites (LLM and PAB) turbidities at the 10% exceedance level were significantly lower than the legacy and low harvest streams, almost by an order of magnitude, which emphasizes the near pristine conditions of the contributing watershed. Chronic turbidity at each site varied from year to year, which is expected due to seasonal variation, watershed responses from road restoration, and/or natural erosion triggered by larger storms.

Erosional responses occur within the first few years following road decommissioning and greatly diminish with time (Flanagan et al. 2012; Klein and Ozaki

2016). Majority of road decommissioning in the Salmon Creek watershed occurred from 2000 to 2009 (11.3 miles removed), with 2.2 miles removed from 2011 to 2017. The Upper Salmon Creek watershed is still in the first few years of post-road decommissioning, and may explain why some years generate more suspended sediment than other years.

Erosion and sedimentation are driven by storm events, with most occurring for a short duration of high intensity rainfall and discharge. Figure 58 illustrates Salmon Creek 10% exceedance values, annual sediment yield estimates, and annual Eureka Woodley Island precipitation. The 10% exceedance values and the annual sediment yield estimates follow a similar trend to the variations in annual rainfall with the exceptions to WY 2014 and 2017. WY 2014 had no discharge measurements or a discharge rating curve, which can alter the estimation of sediment yield, and this year had low turbidity and stage recordings in the stream, which corresponds to low sediment yield. WY 2017 generated a high sediment yield estimate but a low 10% exceedance value, which may indicate a few storms in WY 2017 accounted for most of the annual sediment yield, and the remaining year had low turbidity conditions.

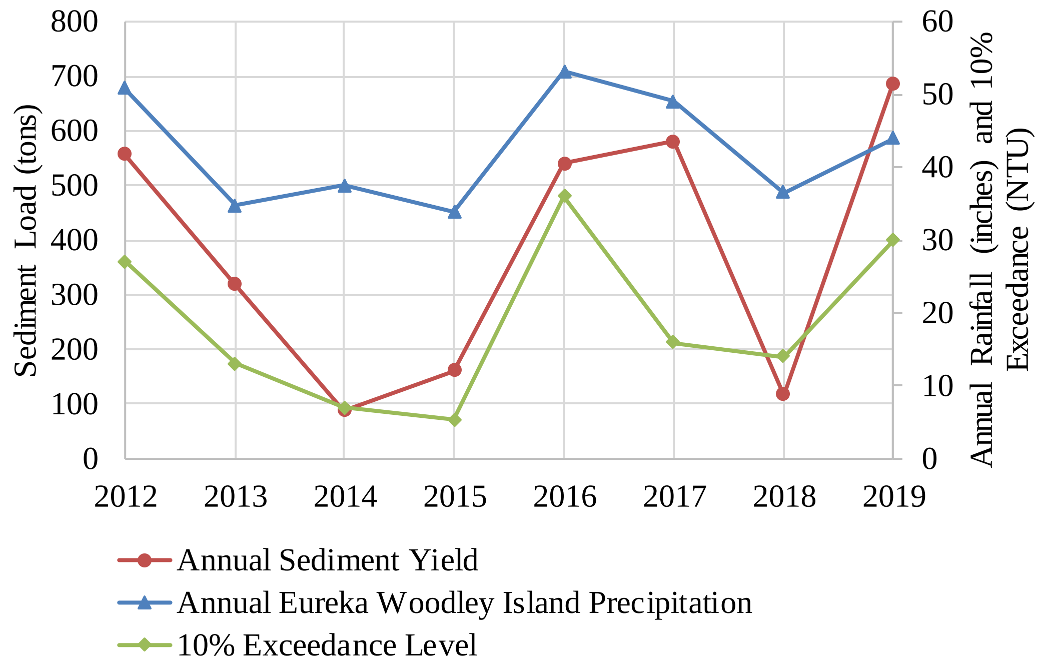


Figure 58: Salmon Creek annual sediment load, rainfall, and 10% exceedance turbidity levels.

Turbidity duration curves for each watershed and WY were plotted to illustrate the differences in turbidity amongst different timber harvest categories (Figure 59 and 60). Differences at the 10% exceedance were large, and increased at the 0.1% exceedance (higher turbidities, less frequent). The pristine streams (LLM and PAB) 10% turbidity exceedance ranged from 1 NTU to 7 NTU and the 0.1% exceedance ranged from 25 NTU to 178 NTU, while the legacy harvest category (LMC) 10% exceedance ranged from 6 NTU to 25 NTU and the 0.1% exceedance from 137 NTU to 613 NTU. The low harvest category (JBW) and SMC 10% exceedance ranged from 8 FNU to 51 FNU and 7 NTU to 36 NTU, respectively, and the 0.1% exceedance ranged from 340 FNU to 1,141 FNU and 117 NTU to 683 NTU, respectively (Figure 59 and 60).

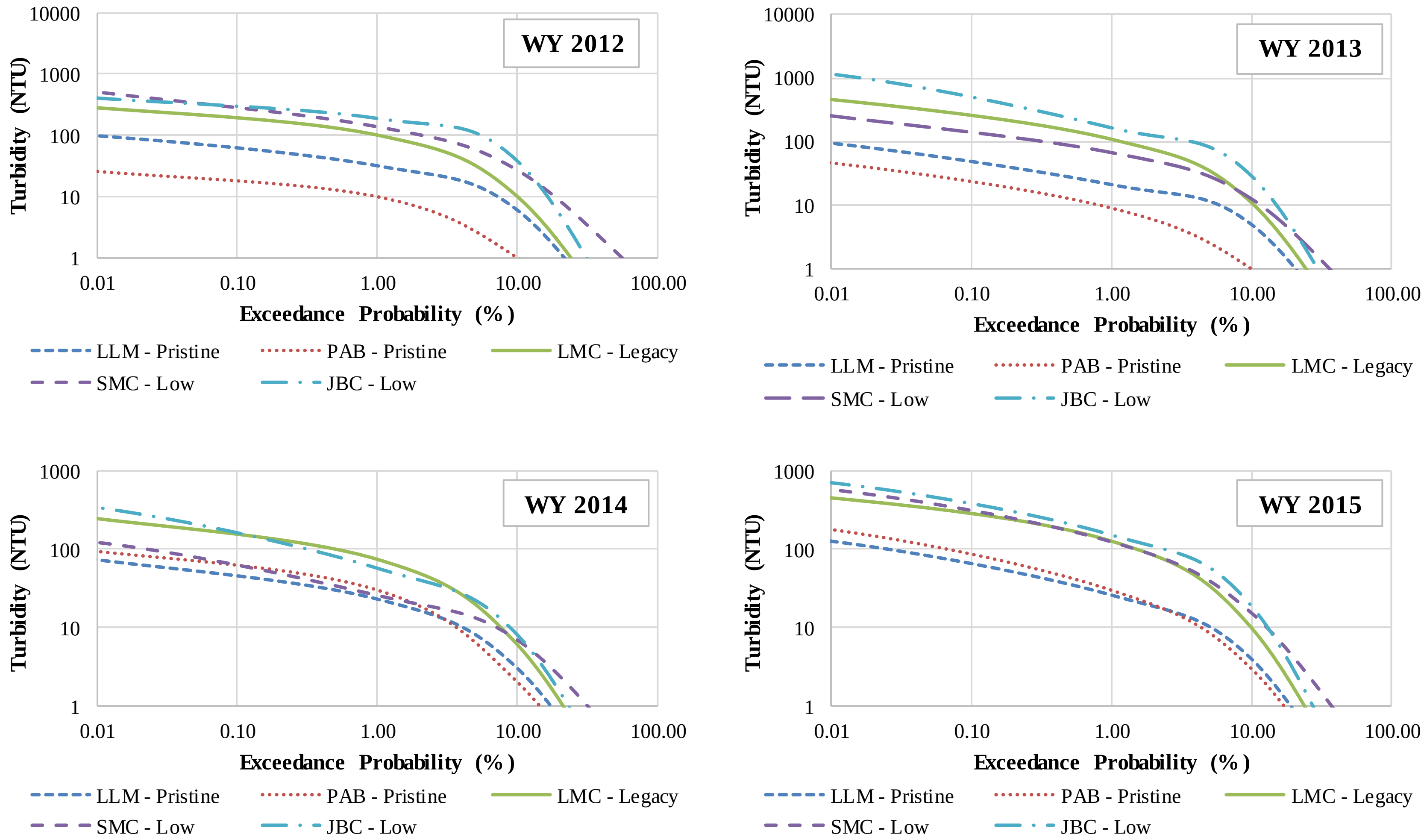


Figure 59: Turbidity duration curves for WY 2012 to 2015 for five northern California coastal watersheds and its associate harvest category.

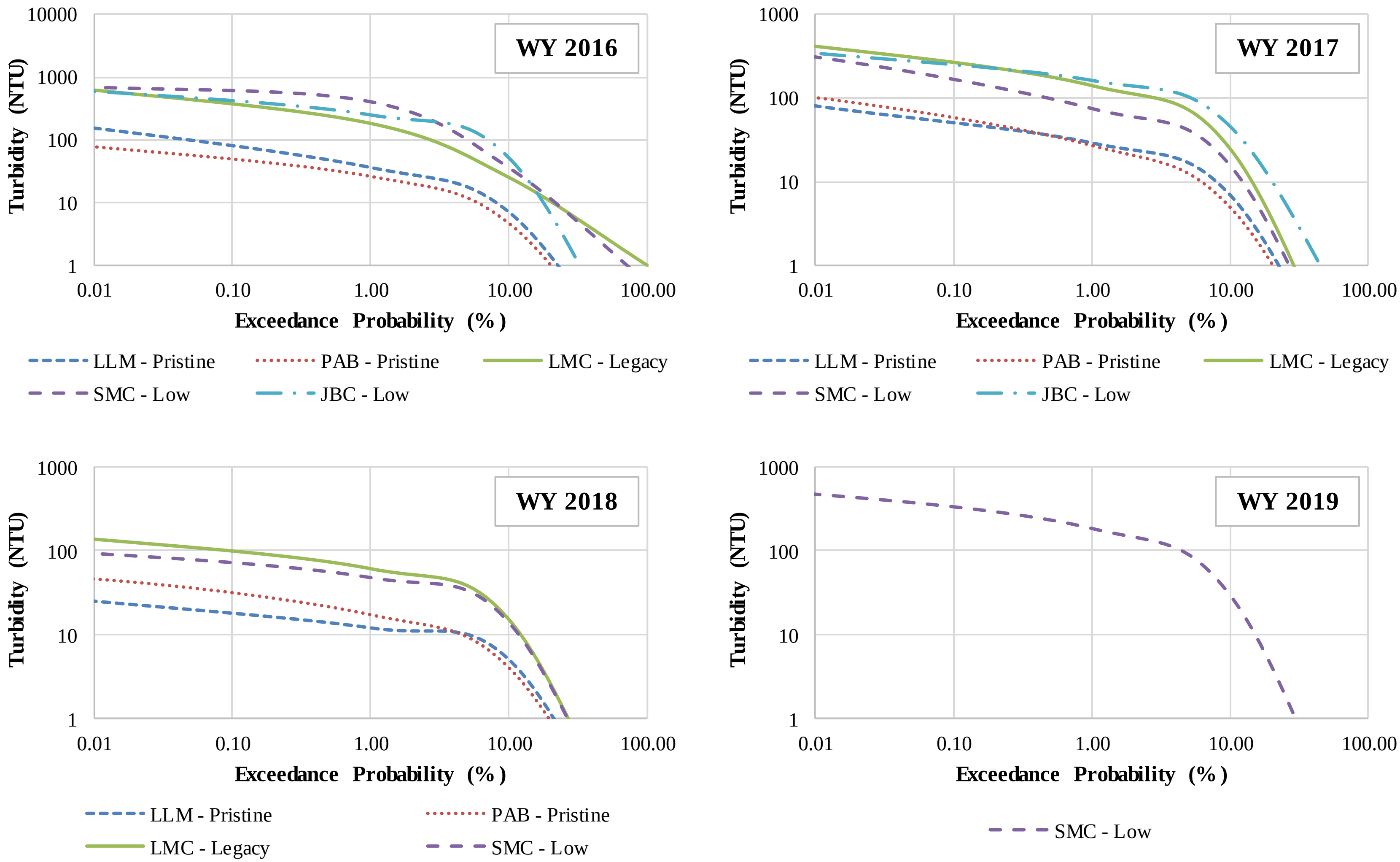


Figure 60: Turbidity duration curves for WY 2016 to 2019 for five northern California coastal watersheds and its associate harvest category.

Annual sediment yield was estimated for each northern California coastal stream (Figure 61). Salmon Creek annual sediment yield was estimated by using the annual turbidity-sediment rating curve and the single power function equation for the discharge rating curve. Missing data for WY 2015 was filled in by using LLM, LMC, and PAB raw data, and an average sediment yield for the 2015 WY is shown in Figure 61 and Table 23. Salmon Creek sediment yield lies between the pristine watersheds and the low and legacy watersheds. Lower Jacoby Creek and Lost Man Creek on average have 195 tons/mi^2 and 140 tons/mi^2, respectively, more sediment yield than Salmon Creek. Little Lost Man Creek and Prairie Creek on average have 40 tons/mi^2 and 45 tons/mi^2, respectively, less sediment yield than Salmon Creek (Figure 61 and Table 23).

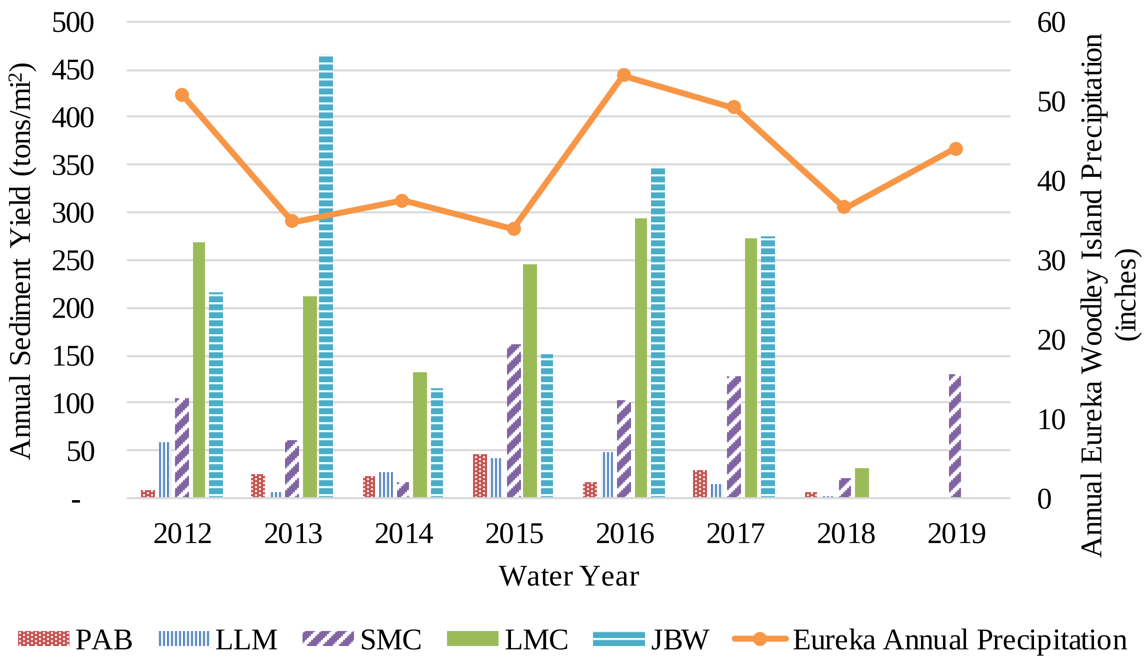


Figure 61: Annual sediment yield estimates for the five northern California coastal watersheds from WY 2012 to 2019.

Table 23: Annual sediment yield estimates for the five coastal watersheds in northern California. Sediment yield units are in tons/mi^2. Note, ND means “no data” for that year.

Stream	Harvest Category	2012	2013	2014	2015	2016	2017	2018	2019	Average 2012-2017
LLM	Pristine	58	6	28	42	48	15	3	ND	33
PAB	Pristine	9	25	23	46	17	30	6	ND	25
LMC	Legacy	269	211	133	246	293	274	33	ND	238
SMC	Low	105	60	17	30	102	128	21	129	74
JBC	Low	216	466	116	150	347	274	ND	ND	262

Logging activity is still present in the Jacoby Creek watershed and may be a source to explaining why the average annual sediment yield is 195 tons/mi^2 more than Salmon Creek. In contrast, there is no logging activity and all unmaintained logging roads were removed in Lost Man Creek, but the average annual sediment yield is 140 tons/mi^2 more than Salmon Creek. Potential factors that may elevate suspended sediment sources in LMC are the rate of road restoration work; the rate of timber harvest activity, which can trigger serious cumulative effects to the watershed; LMC is further north which may get more rain; or LMC may have more highly erodible soils that make the hillsides more susceptible to failure than Salmon Creek. LLM and PAB have lower average annual sediment yield estimates than the other streams, which highlights the near-pristine conditions of a contributing watershed. The sediment delivery in Salmon Creek is lower than low-harvest and legacy-harvest categories but higher than the pristine watersheds, which may be indicative of a watershed that is recovering from legacy logging impacts. However, given the short data record it is difficult to detect a clear trend of decreasing annual sediment yield from the Salmon Creek watershed due to due to

interannual variability in rainfall and flow and the impacts of episodic events such as landslides and bank failures.

SUMMARY, CONCLUSION, RECOMMENDATIONS

This project evaluated the impacts of watershed restoration activities on sediment yield in Salmon Creek by continuing collecting data for WY 2018 and 2019, which contributes to long term stream monitoring. A stream monitoring station is located the Upper Salmon Creek watershed and uses a TTS protocol, and measures turbidity, stage, and temperature. The field and laboratory data collected were used to further understand the relationships between hydrology, sediment transport, and land-use; and to estimate sediment yield from WY 2012 to 2019. Additionally, two precipitation monitoring stations were installed in the Upper Salmon Creek watershed during the 2019 WY, to provide a more spatial representative rainfall data set.

Discharge rating curves and turbidity-sediment rating curves were developed to estimate continuous discharge and suspended sediment concentration (SSC), which were then used to estimate annual sediment yield. Turbidity-sediment rating curves were developed for various time periods (All Data, Annual, Seasonal), and a single and piecewise power function equation was fit to the annual (WY) discharge rating curves. The annual sediment yield from WY 2012 to 2019 ranged from 9 tons/mi^2 to 178 tons/mi^2 (49 tons to 944 tons).

The discharge rating curves need to be established every year due to periodic geomorphic changes in the channel cross-section at the monitoring station. Additionally, there were no peak discharge measurements in the stream, and it was necessary to extrapolate the discharge rating curve. The extrapolated portion accounted for 33 to 84%

of the suspended sediment load estimate, depending on the WY. This can result in the largest source of error when estimating suspended sediment yield. However, the relationship between turbidity and SSC does not change from year to year, and the existing data that was collected is adequate to quantify the relationship between turbidity and SSC. The exception is at the high end of the curve, where turbidity values greater than 100 NTU accounted for 46% of the total sediment yield, and turbidity greater than 200 NTU accounted for 30% of the total sediment yield.

Sediment load estimates were also calculated for each individual storm during a given WY. On average, storms were responsible for 77% of the total annual sediment yield. Annual sediment yield varied from year to year, and seemed to be caused by the number of storms within a WY, the rainfall intensity in the watershed, and landslides that may have elevated turbidity and discharge. Estimating sediment load by individual storm events is the first step in exploring the meteorological, hydrological, and other temporal changes that contribute to variability in sediment transport and sediment yield.

The rain gauge above the stream monitoring station for the 2012 and the 2019 WY was compared with the Eureka National Weather Service Woodley Island precipitation data set. A comparison between the precipitation data can serve to validate the more comprehensive Eureka precipitation as a suitable measure of storm events occurring at Salmon Creek. A linear regression equation was fit to the Eureka Woodley Island precipitation data and the Salmon Creek precipitation data. The correlation of the 2012 and 2019 rainfall data between the two locations resulted in a high R^2 value of 0.85. Continued collection of rainfall data will not only strengthen the relationship between the

two data sets but can be used to derive an adjustment factor for the use of the Eureka precipitation data.

Lastly, four northern California coastal watersheds with accessible data use an automated turbidity sensor and pump sampler to estimate suspended sediment yield. Estimated suspended sediment yield was compared to sediment yield estimates in the Upper Salmon Creek. Additionally, the raw data from the coastal watersheds were used to fill in missing data from Salmon Creek. Correlation analysis between the 2014 Salmon Creek and Lost Man Creek, Little Lost Man Creek, and Prairie Creek raw continuous turbidity and stage data was conducted to develop an equation to approximate the missing data during WY 2015. An average sediment yield estimate for the 2015 WY in Salmon Creek was 161 tons (30 tons/mi^2).

The five coastal watersheds turbidity data were explored to determine chronic turbidity and land-use history linkages from WY 2012 to 2019. Chronic turbidity is described as the 10% turbidity exceedance probability (turbidity levels exceeded 10% of the time), which according to Klein et al. (2011), turbidity at the 10% exceedance value captures stormflow turbidities during peak events, providing a single value to index chronic exposure for salmonids. The control sites (LLM and PAB) turbidities at the 10% exceedance level were significantly lower than the legacy and low harvest streams, almost by an order of magnitude, which emphasizes the near pristine conditions of the contributing watershed. Furthermore, the pristine watersheds resulted in lower sediment yield estimates than the legacy and low harvest watersheds, and Salmon Creek. Salmon Creek average annual sediment yield was 170 tons/mi^2 less than Lower Jacoby Creek and

Lost Man Creek, and 40 tons/mi^2 tons greater than the pristine streams, Little Lost Man Creek and Prairie Creek.

The sediment delivery in Salmon Creek is lower than low-harvest watersheds and legacy-harvest watersheds but higher than the pristine watersheds, which may be indicative of a watershed that is recovering from legacy logging impacts. However, it is difficult to detect a clear trend of decreasing annual sediment yield from the Salmon Creek watershed due to interannual variability in rainfall and flow, and the impacts of episodic events such as landslides and bank failures.

This project revealed several recommendations for future analysis of the watershed:

- The discharge rating curves need to be established every year due to periodic geomorphic changes in the channel cross-section at the monitoring station. It is recommended to have 10 to 12 data points ranging from low to high flows to develop a relationship between stage and discharge. If high flows are collected in the stream and there is a shift in the discharge rating curve, then a piece-wise rating curve should be fitted to the data. Since the majority of stage and discharge data were collected during low flow, it was best to fit a single power function equation to the data.
- Future studies should expand on the discharge rating curve by collecting peak and/or high flows to not only strengthen the discharge rating curve but to also provide more certainty in the sediment yield estimates. Methods for measuring peak flows are: surveying a longitudinal profile and cross-sections within the

channel reach after a large storm event, installing a cable system, or repairing the peal stage recorder.

- Future studies should consider reprogramming the automated sampler to draw water samples only at the very highest turbidity thresholds. Increasing the turbidity thresholds will provide savings in terms of fewer samples to collect and analyze in the laboratory, and an increased likelihood of sampling at storm peaks before the sampler fills up. Additionally, increasing the turbidity thresholds may help distribute the samples and improve the turbidity-SSC relation. Recommended new turbidity threshold values are shown in Table 24, which is a slightly modified threshold values recommended from Bailey (2013).
- Future studies should do weekly site visits during the wet season to check on field equipment.
- Future studies should continue collecting rainfall data in the Upper Salmon Creek watershed as it provides information on the response of the watershed and the relationships between hydrology, metrology, sediment transport, and land-use.
- Future studies should continue developing a correlation between the Upper Salmon Creek watershed precipitation data and the Eureka Woodley Island Precipitation data. Fitting a linear regression equation to the precipitation data can be a useful tool for filling in missing data in the Upper Salmon Creek watershed and also a tool for validating the data collected from the rain gauge (gauge malfunction).

- Future studies should do a more vigorous approach to the storm event analysis by determining a threshold value that clearly defines stage or flow returning to base flow in the stream. Since storm events for this analysis were determined by a visual inspection of when turbidity and stage returned to base flow. Additionally, as more rainfall data is collected in Salmon Creek, then storm events can be determined by precipitation data and duration.
- Future studies focus on normalizing the data to effectively remove the variability due to rainfall variability and determine trends in sediment yield that may be due to land-use changes.

Table 24: Recommended new threshold values that should be programmed in the data logger.

Rising Turbidity Threshold Values (NTU)	Falling Turbidity Threshold Values (NTU)
170	105
230	135
300	200
400	350
550	490
670	600
800	750
920	860
1100	1050
1350	1200
1500	1400
1600	1550
	1600
	1620
	1640

REFERENCES

Alpert. M, and P. Durgin. (1985). Hazard rating of Arcata's Jacoby Creek forest. In Redwood Country: American Geomorphological Field Group, Field Trip Guidebook, 1985 Conference, Northwestern CA. Co-conveners: H.M. Kelsey, T.E .Lisle and M.E. Savina. M.E. Savina, editor. p. 94

American Public Health Association (APHA). (1998). Total suspended solids dried at 103-105 degrees Celsius Method 2540D. In: Standard methods for the examination of water and waste water. 20th ed. Washington, DC: 2-57 to 2-58.

Bailey, K. N. (2013). "Characterization of discharge, turbidity and suspended sediment, Upper Salmon Creek Watershed, Humboldt County, California". Humboldt State University Master Thesis.

Bureau of Land Management Arcata Field Office California Department of Fish and Wildlife (BLM). (2017). Headwaters Forest Restoration Draft Resource Management Plan Amendment and Environmental Assessment/Mitigated Negative Declaration.

California Department of Fish and Game (CDFG). (2003). Lower Salmon Creek Delta Salmonid Habitat Enhancement Opportunities, Humboldt Bay National Wildlife Refuge, Humboldt County, CA. Prepared under California Department of Fish and Game Contract No. P001342.

Cashman, S.M.; Kelsey, H.M.; Harden, D.R. (1995). Geology of the Redwood Creek basin, Humboldt County, California. In: Nolan, K.M.; Kelsey, H.M.; Marron, D., eds. Geomorphic processes and aquatic habitat in the Redwood Creek Basin, northwestern California. Washington, DC: U.S. Geological Survey Professional Paper 1454: B1–B13.

Dana, G.L., A.K. Panorska, R.B. Susfalk, D. McGraw, W.A. McKay, and M. Dornoo. (2004). Suspended Sediment and Turbidity Patterns in the Middle Truckee River, California for the Period 2002-2003. Desert Research Institute Publication No. 41196.

Ellison, C. A., Kiesling, R. L., and Fallon, J. D. (2010). "Correlating Streamflow, Turbidity, and Suspended-Sediment Concentration in Minnesota's Wild Rice River". 2nd Joint Federal Interagency Conference, Las Vegas, NV, June 27 – July 1, 2010.

Gippel, C.J. (1995). Potential of Turbidity Monitoring for Measuring the Transport of Suspended Solids in Streams. Hydrological Processes 9:83-97.

Gupta, R. S. (2008). *Hydrology and Hydraulic Systems*, 3rd ed., Waveland Press, Inc., Long Grove, IL., 320-328.

Jones and Stokes. (2003). Headwaters Forest Reserve Resource Management Plan/EIS/EIR. Administrative Final. Sacramento, CA. Prepared for USDI Bureau of Land Management and California Department of Fish and Game. Arcata, CA.

Klein, R. (2004). Sediment Budget Strategy for Jacoby Creek Watershed, Humboldt County, California. Redwood Community Action Agency, CPESC No. 361.

Klein, R., Lewis, J., and Buffleben, M. S. (2011). "Logging and turbidity in the coastal watershed of northern California." *Geomorphology*, 139-140, 136-144.

Klein, R. and Ozaki, V. (2016). "Effects of Logging Road Removal on Suspended Sediment Loads and Turbidity." *Proceedings of the Coast Redwood Science Symposium*.

Lewis, J. (1996). "Turbidity-controlled suspended sediment sampling for runoff-event load estimation". *Water Resources Research*, 32 (7), 2299–2310.

Lewis, J, and Eads, R. (2009). Implementation guide for turbidity threshold sampling: principles, procedures, and analysis. Gen. Tech. Rep. PSW-GTR-212. Arcata, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Oct 2008.

MacDonald, L. H., Miles, M. W., Beach, S., Harrison, N. M., House, M. R., Belmont, P., and Ferrier, K. L. (2016). "Development and Implications of a Sediment Budget for the Upper Elk River Watershed, Humboldt County. *Proceedings of the Coast Redwood Science Symposium*.

Manka, P. (2005). Suspended Sediment Yields in the Tributaries of the Elk River, Humboldt County, California. Humboldt State University. Arcata, CA.

Mikael Love & Associates. (2014). Salmon Creek Estuary Expansion. Michael Love & Associates. < http://h2odesigns.com/salmon-creek-estuary-expansion/> (Accessed January 21, 2020).

Newcombe, C. P., and MacDonald, D. D. (1991). "Effects of suspended sediments on aquatic ecosystems". *North American Journal of Fisheries Management.* 11, 72-82

Nolan, K.M., Janda, R.J. (1995). Impacts of logging on stream-sediment discharge in the Redwood Creek basin, northwestern California. In: Nolan, K.M., Kelsey, H.M., Marron, D.C. (Eds.), Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin,

Northwestern California. Professional Paper, 1454. U.S. Geological Survey, U.S. Government Printing Office, Washington, DC, pp. L1–L8.

National Oceanic & Atmospheric Administration (NOAA). (2020). Interactive Map Tool – Daily, Monthly, Annual Summaries. <https://gis.ncdc.noaa.gov/maps/ncei#app=cdo&cfg=radar&theme=radar&display=nexrad> (Accessed December 6, 2019).

Pacific Watershed Associates (PWA). (2005). Final Report: 2004-2005 South Humboldt Bay Coastal Resources Protection Project, Salmon Creek and South Fork Elk River Watersheds, Humboldt County, CA. California State Water Resources Control Board Agreement #03-211-551.

Pacific Lumber Company (PALCO). (2005). Elk River/Salmon Creek Watershed Analysis Scotia, California. Cumulative Watershed Effects Assessment, Report 16020-00.

Rasmussen, P. P., Gray, J. R., Glysson, G., and Ziegler, A. C. (2009). Guidelines and procedures for computing time-series suspended sediment concentrations and loads from in-stream turbidity sensor and streamflow data. U.S. Geological Survey Techniques and Methods, Book 3, Chap. C4, 52p.

Reiter, M., Heffner, J. T., Beech, S., Turner, T., and Bilby, R. E. (2009). "Temporal and Spatial Turbidity Patterns Over 30 Years in a Managed Forest of Western Washington". *Journal of the American Water Resources Association*, 45(3), 793-808.

Steffy, L. Y., and Shank, M. K. (2018). "Considerations for using turbidity as a surrogate for suspended sediment in small, ungaged streams: Time-series selection, streamflow estimation, and regional transferability". *River Research and Application,* 34: 1304 – 1314. https://doi.org/10.1002/rra.3373

Susfalk, R. B., Fitzgerald, B., and Knust, A. M. (2008). Characterization of Turbidity and Total Suspended Solids in the Upper Carson River, Nevada. *Desert Research Institute, Nevada System of Higher Education.*

Uhrich, M. A., Kolasinac, J., Booth, P. L., Fountain, R. L., Spicer, K. R., and Mosbruker, A. R. (2014). Correlations of Turbidity to Suspended-Sediment Concentration in the Toutle River Basin, near Mount St. Helens, Washington, 2010-11. U.S. Geological Survey, U.S. Department of Interior, and the U.S. Army Corps of Engineers, Portland District.

Uhrich, M. A., Spicer, K. R., Mosbruker, A. R.M and Christianson, T. S. (2015). Evaluating Turbidity and Suspended-Sediment Concentration Relations from the North Fork Toutle River Basin near Mount St. Helens, Washington: Annual, Seasonal, Event,

and Particle Size Variations – A Preliminary Analysis. U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington.

U. S. Environmental Protection Agency (US EPA). (2006). Voluntary Estuary Monitoring Manual Chapter 15: Turbidity and Total Solids, 2nd Ed., EPA-842-B-06-003 United States Environmental Protection Agency.

U. S. Environmental Protection Agency (US EPA). (2017). National Water Quality Inventory: Report to Congress. EPA-841-R-16-011. United States Environmental Protection Agency. August 2017.

U.S. Geological Survey (USGS). (2018). StreamStats Application Version: 4.3.0. <https://streamstats.usgs.gov/ss/> (Accessed January 10, 2019).

Wagner, R. J., Boulger, R. W. Jr., Oblinger, C. J., Smith, B. A. (2006). Guidelines and standard procedures for continuous water-quality monitors: station operation, record computation, and data reporting. Techniques and methods 1-D3. U.S. Geological Survey.

Walling D. (1977). Assessing the accuracy of suspended sediment rating curves for a small basin: Water Resources Research, 13: 531-538.

Walling, D. E., and Webb, B. W. (1981). The reliability of suspended sediment load data. In: Erosion and sediment transport measurement. Proceedings of the Florence symposium. IAHS Publ. No. 133. International Association of Hydrological Sciences: 177–194.

Yochum, S. E., Comiti F., Wohl, E., David, G. C., and Mao, L. (2014). Photographic Guidance for Selecting Flow Resistance Coefficients in High-Gradient Channels. Gen. Tech. Rep. RMRS-GTR-323. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 91 p.

Appendix A

Table A-1 summarizes the existing and missing raw data ranges for the stage and stream turbidity recordings in Salmon Creek.

Table A-1: Existing and missing raw data ranges for the continuous turbidity and stage recordings from WY 2012 to 2019.

Water Year	Existing Data Range		Missing Data Range[a]	
	Start	Stop	Start	Stop
2012	10/7/2011 20:43 9/14/2012 12:00	6/27/2012 11:00 9/30/2012 23:45	6/27/2012 11:15	9/14/2012 11:45
2013	10/1/2012 0:00	9/30/2013 23:45	No Missing Data	No Missing Data
2014	10/1/2013 0:00	8/6/2014 13:00	8/6/2014 13:15	9/30/2014 23:45
2015	No Data	No Data	No Data	No Data
2016	10/12/2015 12:30	9/30/2016 23:45	10/1/2015 0:00 2/26/2016 16:45	10/12/2015 12:15 5/6/2016 11:00
2017	10/1/2016 0:00	9/30/2017 23:45	No Missing Data	No Missing Data
2018	10/1/2017 0:00	9/30/2018 23:45	No Missing Data	No Missing Data
2019	10/1/2018 0:00	5/31/2019 9:15	10/19/2018 11:45	10/22/2018 10:45

a: The Missing Data Range column may include some existing data in the data range shown.

Appendix B

A survey of the cross-section and longitudinal profile in the Salmon Creek was conducted and this information will be used for estimates of discharge in the future (Figure B-1 and B-2). The cross-section has a channel width of approximately 16 ft and the deepest point in the channel is located on river left near the bedrock wall (Figure B-1). A longitudinal profile along the creek thalweg was surveyed that started approximately 50 feet upstream of the monitoring station and ended approximately 90 ft below the station. The survey was not georeferenced and elevations reported are relative to an arbitrary datum. The fluctuations in elevation are caused by riffle-pools sequences and areas where there are deep pools (Figure B-2). The overall slope of the channel is approximately 1%, which is a relatively steep slope.

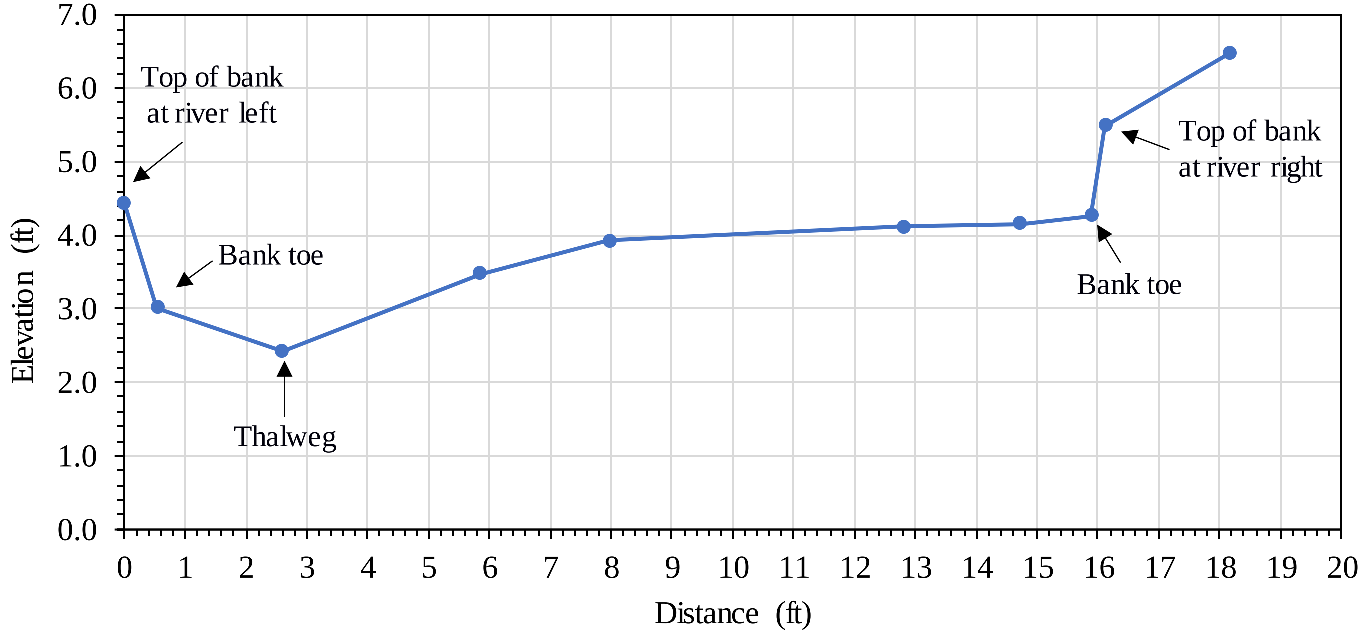


Figure B-1: Survey of the discharge measurement cross-section in Salmon Creek. The elevation is relative to an arbitrary datum.

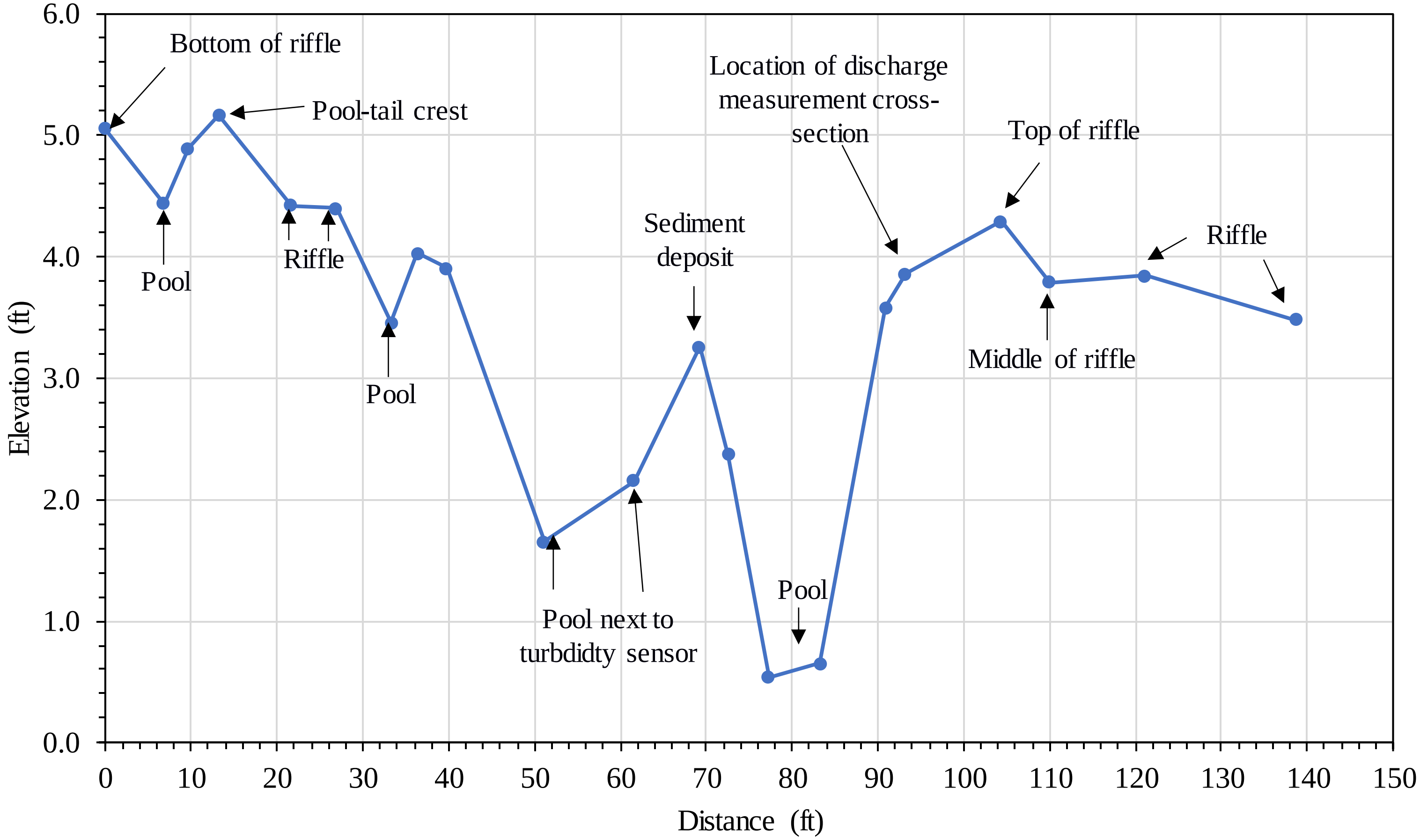


Figure B-2: Longitudinal profile along the creek thalweg of Salmon Creek near the monitoring station. The elevation is relative to the same datum used for the cross-section.

Appendix C

Table C-1 illustrates the raw longitudinal survey data in Salmon Creek from March 15th, 2019. Table C-2 to C-5 show the raw cross-sectional data in Salmon Creek. The four cross-sectional data were plotted to determine the best representative cross-sectional area (Figure C-1). Cross-sections three and four were measured in a pool-riffle channel sequence, and were not representative of the average cross-section. Cross-sections one and two have similar geometry with an average bottom width of 15 ft, top width of 24 ft, and depth of 5.9 ft. A trapezoidal cross-section was fit to the average cross-section (Figure C-2). The trapezoidal channel slopes (side slopes) followed a similar slope to XS-2 because XS-1 side slopes are vertical, and the side slopes within longitudinal profile surveyed were typically gradual slopes rather than vertical. The dimensions determined from fitting a trapezoidal cross-section were used in Manning's Equation to estimate a peak discharge (Equation 7).

A range of Manning's n values were chosen (0.048 to 0.130) based on published literature values for streams with similar channel reach morphology to Salmon Creek (Table 4, Yochum et al. 2014). The channel reach morphology of the surveyed section in Salmon Creek is pool-riffle. These roughness values were applied to Equation 7 to obtain peak discharge estimates that ranged from 412 cfs to 1,115 cfs.

Table C-1: Raw longitudinal data in Salmon Creek.

Total Distance (ft)	Upstream Elevation (ft)	Downstream Elevation (ft)	Slope (ft/ft)
110.1	8.37	5.20	0.029

Table C-2: Raw data for cross-section one. Cross-section one is at 93.5 ft (28.5 m) on longitudinal tape

River Left (ft) = 4.2	River Right (ft) = 26.6	Width (ft) = 22
Elev. (ft)	Distance (ft)	Notes
0.04	4.2	At high water mark.
3.05	4.5	RL bank
4.4	7	In stream
4.1	13	On rock deposit
5.6	18.7	In pool
5.63	22.3	Up against a log in-stream
4.05	23.7	Top of bench
4.72	25.5	At base of bank
-0.02	26.6	At high water mark on RR

Table C-3: Raw data for cross-section two. Cross-section two is at 67.3 ft (20.5 m) on the longitudinal tape.

River Left (ft) = 3.9	River Right (ft) = 30.3	Width (ft) = 26
Elev. (ft)	Distance (ft)	Notes
1.71	3.8	Above high-water mark
1.9	4.2	At high water mark on RL
4.66	6.2	On RL bank
6.91	8.5	In stream
7.31	12.6	
7.33	16.7	At longitudinal measuring tape
5.6	24	At edge of RR bank (still in stream)
4.03	27.3	On RR bank
2.3	30.3	At high water mark on RR

Table C-4: Raw data for cross-section three. Cross-section three is at 53.5 ft (16.3 m) on longitudinal tape

River Left (ft) = 4.3	River Right (ft) = 27.8	Width (ft) = 24
Elev. (ft)	Distance (ft)	Notes
1.4	4.3	At high water mark on RL
3.99	5.3	On RL bank
6.15	7	Edge of channel bed (in stream)
6.95	11.7	
6.1	15.9	
5.18	16.4	On cobble bed
4.9	22.7	At edge of RR bank
3.7	25	On RR bank
2.3	27.8	At high water mark on RR

Table C-5: Raw data for cross-section four. Cross-section four is at 21.0 ft (6.4 m) on the longitudinal tape.

River Left (ft) = 4.3	River Right (ft) = 30.3	Width (ft) = 26
Elev. (ft)	Distance (ft)	Notes
4.1	4.3	At high water mark on RL
5.95	6.4	Base of bank, at edge of bed
2.7	8.4	Deep spot in channel, in pool
5.75	14.6	
5.75	16.8	At intersection of longitudinal tape
5.3	25.2	Right edge of channel bed
4.65	29	RR edge bench
2.95	30.3	At high water mark on RR

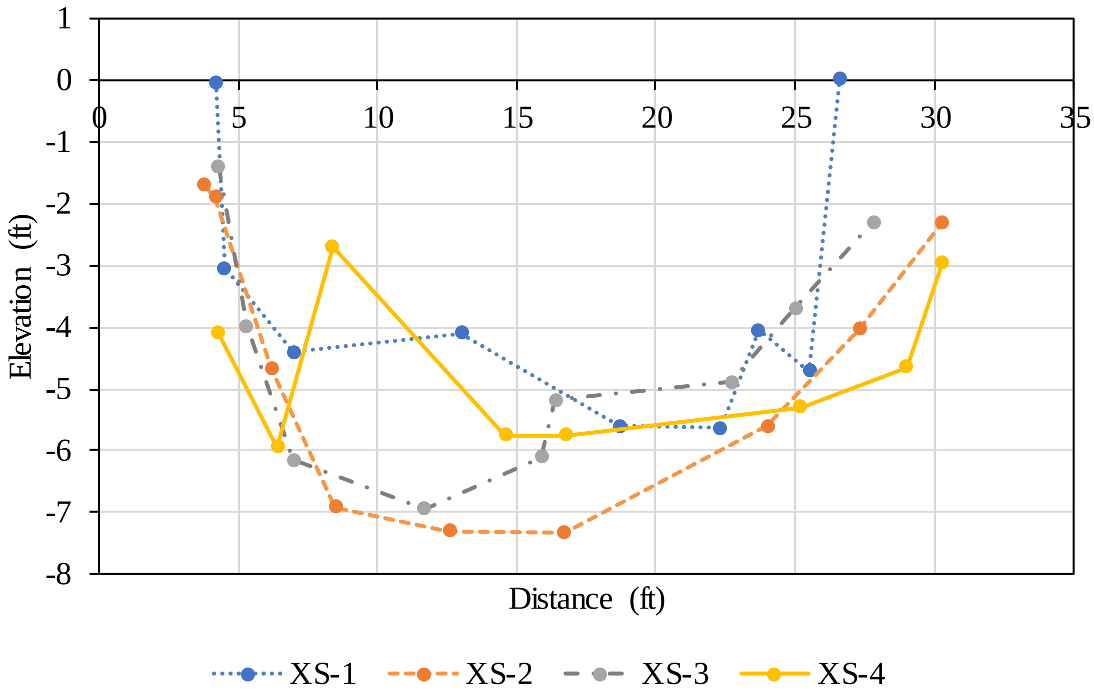


Figure C-1: Four cross-sections measured in Salmon Creek with the x-axis and y-axis illustrating distance and elevation, respectively. Note the channel bottom datum for each cross-section has not been adjust for slope.

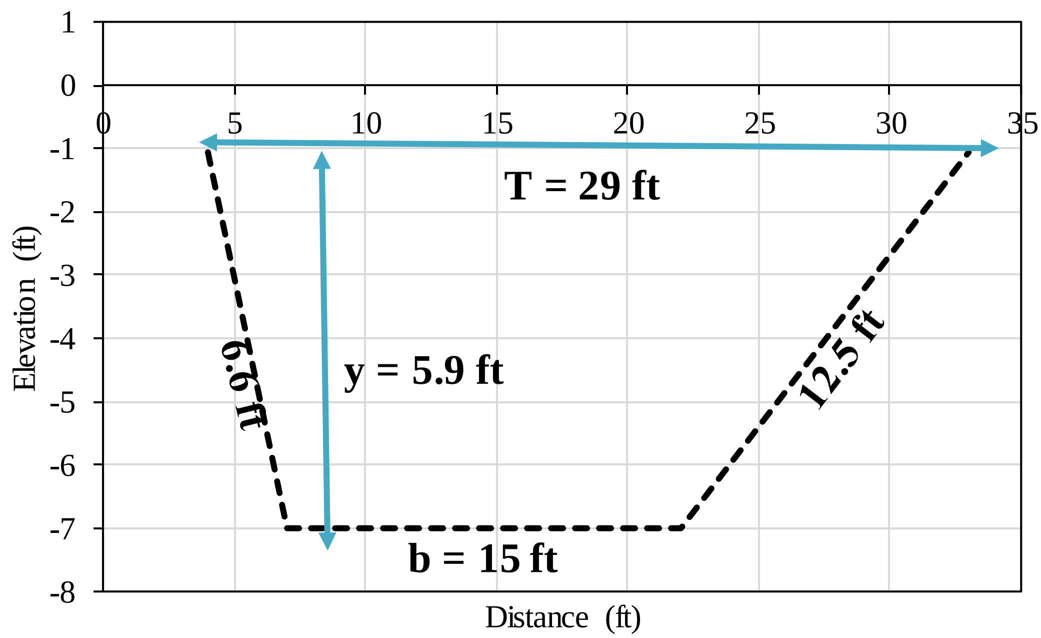


Figure C-2: Trapezoidal cross-section dimensions.

Appendix D

Table D-1 summarizes the discharge rating curve power function equations developed for WY 2012, 2016, 2017, 2018, and 2019.

Table D-1: Summary of discharge rating curves – power function equations for each WY in Upper Salmon Creek.

Discharge Rating Curve	Power Function Single or Piecewise Equation	Power Function Equation	R^2
All Data	Single Fit	$y = 26.7x^{1.60}$	0.72
2012	Single Fit	$y = 33.7x^{2.08}$	0.95
	Piecewise Fit (h>0.7 ft)	$y = 33.3x^{0.85}$	0.99
	Piecewise Fit (h<0.7 ft)	$y = 28.3x^{1.94}$	0.94
2016	Single Fit	y = `50.5x$^{-0.85}$	0.98
	Piecewise Fit (h>0.8 ft)	$y = 52.3x^{-0.79}$	0.71
	Piecewise Fit (h<0.8 ft)	$y = 43.5x^{-0.80}$	0.99
2017	Single Fit	$y = 20.8x^{2.75}$	0.98
	Piecewise Fit (h>1.2 ft)	$y = 26.8x^{2.21}$	0.94
	Piecewise Fit (h<1.2 ft)	$y = 23x^{3.56}$	0.95
2018	Single Fit	$y = 26.6x^{2.76}$	0.96
	Piecewise Fit (h>1 ft)	$y = 30.8x^{1.96}$	0.74
	Piecewise Fit (h<1 ft)	$y = 30x^{3.16}$	0.98
2019	Single Fit	$y = 16.3x^{1.55}$	0.96
	Piecewise Fit (h>1 ft)	$y = 14.8x^{1.70}$	0.97
	Piecewise Fit (h<1 ft)	$y = 17.8x^{1.9}$	0.67
	Peak Discharge, Single Fit	$y = 15.9x^{1.83}$	0.97

Appendix E

Annual SY estimates are summarized in Figure E-1 and Table E-1 to E-2. The x-axis on Figure 44 illustrate the different turbidity-sediment rating curves used to estimate SSC, and the y-axis is annual sediment yield in tons. Additionally, each figure demonstrates sediment yield estimates using a single and piecewise power function equation to estimate discharge. Table 15 to 17 summarizes the sediment yield estimates using the All Data-, Annual, and Seasonal- turbidity-sediment rating curves (TSRC) and the discharge rating curves. The tables also present the percent difference between sediment yield estimates using the single and piecewise power fit equation, and the percent difference between sediment yield using the All Data-, Annual-, and Seasonal-TSRC.

The All Data turbidity-sediment rating curve was used for WYs that had no turbidity-SSC data collected (2013, 2014, and 2016). WY 2013 and 2014 had no discharge-stage data collected, and sediment load estimates were calculated using the 2012 and 2016 discharge rating curve single and piecewise power function equations.

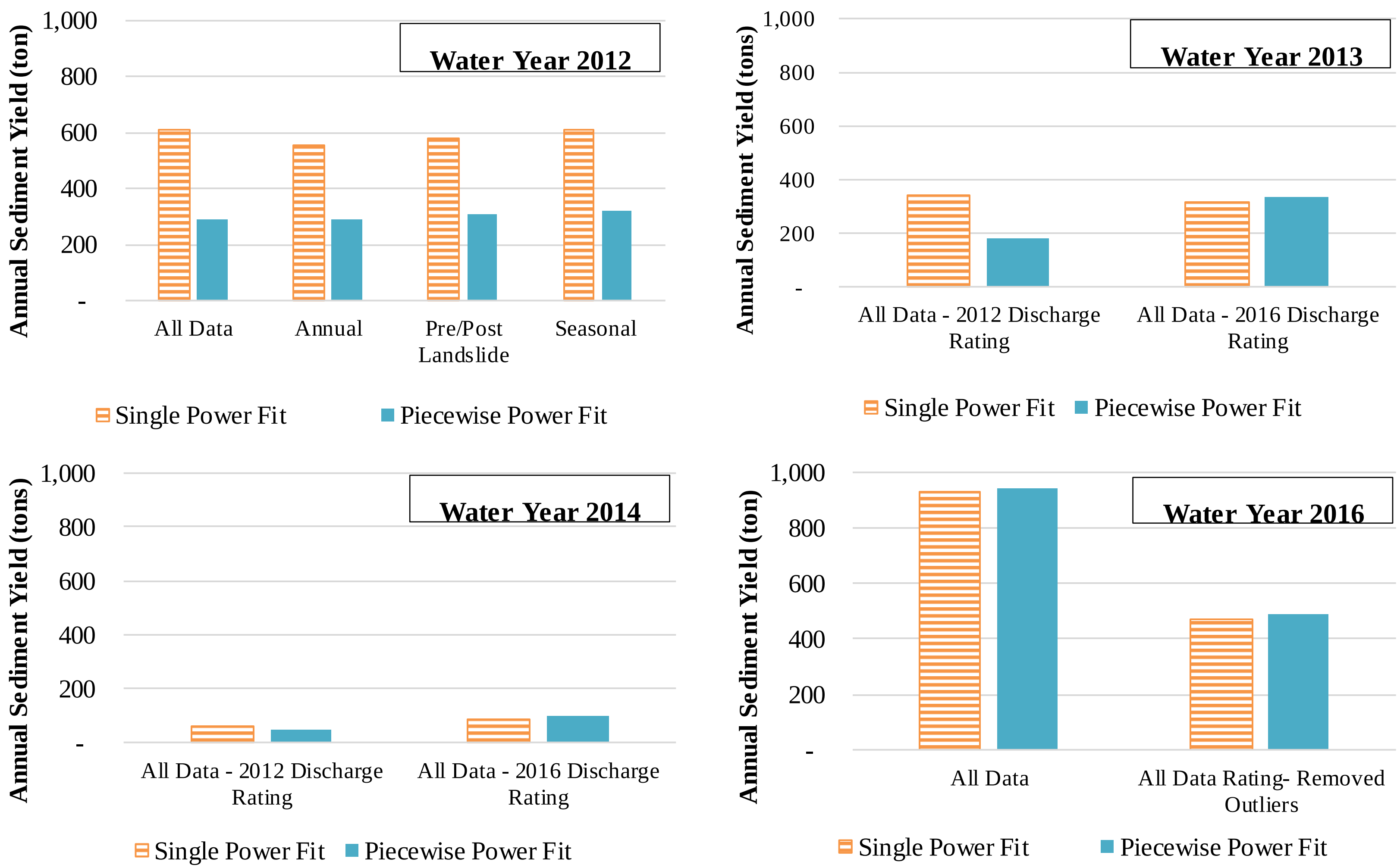


Figure E-1: Sediment load estimates for WY 2012 to 2016 in the Upper Salmon Creek.

Table E-1: Summary of WY 2012 sediment yield estimates using different rating curves. Sediment yield is in units of tons. Note TSRC = Turbidity Sediment Rating Curve. Sediment yield are in units of tons.

Turbidity Sediment Rating Curve	Single Power Fit	Piecewise Power Fit	% Diff of SL Estimate using Single vs. Piecewise Fit	% Diff of SL Estimate using Annual vs. other TSRC
Single (All Data)	612	287	72%	- 9%
Annual	557	292	62%	-
Pre and Post Landslide	582	307	62%	- 4%
Seasonal	608	323	61%	- 9%

Table E-2: Summary of the 2013 sediment yield estimates using different rating curves. Note TSRC = Turbidity Sediment Rating Curve. Sediment yield are in units of tons.

Turbidity Sediment Rating Curve	Single Power Fit	Piecewise Power Fit	% Diff of SL Estimate using Single vs. Piecewise Fit	% Diff of SL Estimate using Single Power Fit
Single (All Data) – 2012 Discharge rating curve	344	178	63%	8%
Single (All Data) – 2016 Discharge rating curve	319	336	5%	

Table E-3: Summary of the 2014 sediment yield estimates using different rating curves. Note TSRC = Turbidity Sediment Rating Curve. Sediment yield are in units of tons.

Turbidity Sediment Rating Curve	Single Power Fit	Piecewise Power Fit	% Diff of SL Estimate using Single vs. Piecewise Fit	% Diff of SL Estimate using Single Power Fit
Single (All Data) – 2012 Discharge rating curve	61	49	23%	36%
Single (All Data) – 2016 Discharge rating curve	88	97	10%	

Table E-4: Summary of the 2016 sediment yield estimates using different rating curves. Note TSRC = Turbidity Sediment Rating Curve. Sediment yield are in units of tons.

Turbidity Sediment Rating Curve	Single Power Fit	Piecewise Power Fit	% Diff of SL Estimate using Single vs. Piecewise Fit	% Diff of SL Estimate using Annual vs. other TSRC
Single (All Data)	928	944	1.7%	65%
Single (All Data) – Removing Error in Data	541	561	3.1%	

Appendix F

Sediment load estimates were calculated for each individual storm during a water year. Table F-1 to F-7 provides a detailed summary of the sediment load, percent sediment transport, total precipitation, duration, peak discharge and turbidity, and volume of total flow to total precipitation.

Table F-1: WY 2012 sediment load estimates by storm events.

Storm Event	Sediment Load (tons)	% Sediment Transport	Total Precipitation (inches)	Total Duration (hrs)	Peak Turbidity (NTU)	Peak Discharge (cfs)	Volume of Total Flow/Total Precipitation
1	0.6	0.1%	1.30	48	53	7	0.07
2	0.5	0.1%	0.05	24	55	9	0.80
3	0.2	0.0%	0.07	23	21	7	0.41
4	6.1	1%	0.15	48	197	30	1.85
5	1.3	0.2%	1.01	48	72	14	0.11
6	70	13%	5.27	120	360	175	1.13
7	14	2.5%	1.57	72	136	98	1.00
8	38	6.9%	1.62	48	372	179	0.76
9	6.9	1.2%	1.93	72	64	55	0.49
10	39	7.1%	3.94	120	151	145	1.56
11	2.4	0.4%	0.20	24	43	38	0.83
12	**261**	**47%**	**6.64**	**120**	**1646**	**358**	**2.24**
13	50	8.9%	1.57	120	666	277	4.35
14	28	5.1%	2.93	96	595	168	0.85
15	1.4	0.3%	0.12	48	464	9	1.59
16	0.9	0.2%	1.02	24	627	9	0.04
17	0.4	0.1%	0.67	48	149	7	0.19
18	1.4	0.2%	1.55	48	218	12	0.08
Total	**522**	**94%**	**32**	**1151**			

Table F-2: WY 2013 sediment load estimates by storm event.

Storm Event	Sediment Load (tons)	% Sediment Transport	Total Precipitation (inches)	Total Duration (hrs)	Peak Turbidity (NTU)	Peak Discharge (cfs)	Volume of Total Flow/Total Precipitation
1	1.1	0.3%	0.52	24	32	28	0.27
2	0.8	0.3%	0.97	24	47	32	0.15
3	4.3	1.3%	1.62	48	54	42	0.45
4	24.6	7.7%	3.35	72	331	91	1.26
5	**77.3**	**24.2%**	**3.34**	**48**	**876**	**169**	**0.85**
5	0.9	0.3%	0.42	24	136	18	0.16
6	50	16%	4.77	96	204	116	1.50
7	15	4.9%	2.05	72	49	91	1.66
8	23	7.3%	2.10	48	157	89	0.55
9	1.3	0.4%	0.98	24	77	41	0.17
10	10	3.1%	1.25	48	109	65	0.88
Total	**209**	**65%**	**21**	**528**	**876**	**169**	

Table F-3: WY 2014 sediment load estimates by storm event.

Storm Event	Sediment Load (tons)	% Sediment Transport	Total Precipitation (inches)	Total Duration (hrs)	Peak Turbidity (NTU)	Peak Discharge (cfs)	Volume of Total Flow/Total Precipitation
1	0.4	0.5%	0.06	48	219	19	6.21
2	0.5	0.6%	0.32	24	56	28	0.44
3	6.8	7.8%	1.73	96	63	50	1.73
4	6.5	7.4%	2.28	72	31	52	0.93
5	**25**	**28%**	**3.12**	**48**	**172**	**98**	**0.43**
6	12	13%	2.33	144	47	63	3.50
Total	**51**	**58%**	**10**	**432**			

Table F-4: WY 2016 sediment load estimates by storm event.

Storm Event	Sediment Load (tons)	% Sediment Transport	Total Precipitation (inches)	Total Duration (hrs)	Peak Turbidity (NTU)	Peak Discharge (cfs)	Volume of Total Flow/Total Precipitation
1	3.9	0.7%	1.76	48	47	46	0.38
2	32	6.0%	5.57	96	261	121	0.93
3	5.9	1.1%	2.28	24	77	82	0.13
4	97	18%	2.35	48	785	199	0.69
5	7.7	1.4%	1.44	72	160	30	0.78
6	**184**	**34%**	**5.06**	**144**	**652**	**214**	**1.42**
7	70	13.0%	2.28	72	561	67	1.08
8	81	14.9%	1.53	48	1017	131	0.90
9	5.6	1.0%	0.94	37	466	44	0.39
Total	**488**	**90%**	**23**	**589**			

Table F-5: WY 2017 sediment load estimates by storm events.

Storm Event	Sediment Load (tons)	% Sediment Transport	Total Precipitation (inches)	Total Duration (hrs)	Peak Turbidity (NTU)	Peak Discharge (cfs)	Volume of Total Flow/Total Precipitation
1	1.3	0.2%	2.28	24	58	24	0.03
2	3.1	0.5%	1.26	48	47	38	0.37
3	29	4.3%	1.49	48	254	179	0.82
4	53	8%	0.71	24	337	282	0.98
5	**239**	**35%**	**1.25**	**48**	**925**	**878**	**2.97**
6	4	1%	1.29	48	44	50	0.44
7	15	2.3%	1.57	48	105	149	0.81
8	32	4.6%	2.93	72	100	229	1.38
9	51	7.6%	3.84	72	284	283	1.26
10	4	0.6%	0.84	48	50	51	0.76
11	56	8.3%	3.03	96	195	302	2.53
12	69	10%	2.16	72	193	481	2.41
13	9	1.4%	1.61	48	47	121	0.84
14	20	3%	3.35	96	211	182	0.78
15	6	0.9%	1.02	48	70	71	0.65
Total	**592**	**87%**	**29**	**840**			

Table F-6: WY 2018 sediment load estimates by storm.

Storm Event	Sediment Load (tons)	% Sediment Transport	Total Precipitation (inches)	Total Duration (hrs)	Peak Turbidity (NTU)	Peak Discharge (cfs)	Volume of Total Flow/Total Precipitation
1	1.2	1%	0.37	24	53	20	0.16
2	1.4	1%	1.06	24	56	28	0.07
3	18	17%	4.83	120	121	104	0.78
4	14	13%	3.66	48	121	104	0.29
5	3.2	3%	0.17	24	73	40	0.86
6	5.7	5%	1.48	48	52	60	0.50
7	**20**	**18%**	**1.61**	**72**	**72**	**112**	**1.92**
8	14	13%	3.07	72	80	117	0.69
9	11	10%	1.75	48	107	118	0.43
Total	**90**	**82%**	**18**	**480**			

Table F-7: WY 2019 sediment load estimates by storm events.

Storm Event	Sediment Load (tons)	% Sediment Transport	Total Precipitation (inches)	Total Duration (hrs)	Peak Turbidity (NTU)	Peak Discharge (cfs)	Volume of Total Flow/Total Precipitation
1	1.5	0.2%	2.05	48	98	13	0.05
2	1.5	0.2%	2.40	72	101	9	0.11
3	1.7	0.3%	0.72	48	44	17	0.35
4	17.0	2%	3.17	120	179	66	0.50
5	9.3	1.4%	1.38	24	122	75	0.13
6	15	2%	0.02	24	136	80	16.33
7	29	4.3%	0.05	18	288	128	5.55
8	11	1.6%	1.46	24	102	83	0.18
9	**384.3**	**56%**	**7.6**	**120**	**658**	**250**	**1.36**
10	15	2.2%	1.51	24	289	60	0.15
11	15.0	2.2%	1.69	48	179	49	0.39
12	5	1%	0.33	24	135	26	0.31
13	52	7.5%	1.77	48	371	92	0.55
Total	**557**	**81%**	**24**	**618**			