AGGRADATION IN THE CARBON RIVER: A CASE STUDY AT MOUNT RAINIER, WASHINGTON

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Abstract

The Carbon River is a glacially fed river system located within the boundary of Mount Rainier National Park in Washington State. The river is actively experiencing a high rate of aggradation, which is inevitably leading to flooding and damage to trails and park infrastructure. Seven cross sectional measurements in two specific areas of the river were calculated in the summer of 2014; two near the Park Entrance and five near Ipsut Campground. These results show that the integrated area of cross sectional data between the two reaches are very similar. The park entrance showed an average 325.55m² while the area near Ipsut Campground produced a comparable value of 331.82m² revealing a comparable amount of area in the riverbed. LiDAR ground returns from 2008 and 2012 were used to create subtraction maps in order to display areas of aggradation and erosion, and determine if those values are similar. The results were split into three sections of the river: The upper section yielded a gain of 0.009m² per year. The middle section yielded a gain of 0.002m², while the lower section yielded a loss of -0.01m² per year. These results show that the Carbon River is aggrading in areas and eroding in others. The Carbon River should be classified as a laterally-active gravel-dominated anabranching river system to encompass all the various influences in the watershed. The role of climate change should be addressed in future studies due to the possible influx of glacial melting and subsequent increase in sediment.

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CHAPTER 1

INTRODUCTION

Mount Rainier (Figure 1.1) is an active stratovolcano located in The Cascade Mountain Range of Washington State. Mount Rainier is the tallest member of the Cascade Range, and lies within 96 km of the major metropolitan areas of Tacoma and Seattle. The volcano is a celebrated landmark in the Pacific Northwest, and can be seen on the horizon from hundreds of miles away.

Figure 1.1
Mount Rainier looking North from Paradise Visitors Center

Mount Rainier National Park (Figure 1.2) is located in the southwestern region of Washington State. The park was established in 1899, and encompasses 956.6 square km around the mountain. More than two million visitors come to the park each year, allowing the public to visualize the magnitude of the volcano, as well as the geologic processes that actively work to create and shape the mountain. There are five entrances to Mount Rainier National Park, three of which reside on the Eastern side of the Mountain. The Nisqually entrance serves as the gateway into the park from the Southwest and is the most traveled entrance to the park, while the Carbon River entrance serves as the only entrance from the Northwest and is closest to the major metropolitan areas of Washington State (Driedger and Scott, 2002).

The peak of Mount Rainier resides at an elevation of 14,410 ft (4,392 m) and is actively fueled by the subduction of the Juan de Fuca plate that lies off the Western coast of North America. The last eruption of lava from Mount Rainier occurred 2,200 years ago; however, pyroclastic emissions were reported less than 1,100 years ago (Driedger and Kennard, 1986). Mount Rainier is thought to have been active for the last 500,000 years, making the 2,200 year interval since the last known eruption account for a very small percentage of the lifespan of the volcano (Driedger, 1993).

The volcano has 25 major glaciers (Figure 1.3) and has more ice than the entirety of the Cascade Range combined. These glaciers serve as a source for five major rivers. The Carbon Glacier has the greatest thickness (213 m), volume (0.83 km^3), and the lowest terminus elevation out of all the glaciers in the contiguous United States (Driedger and Kennard, 1986).

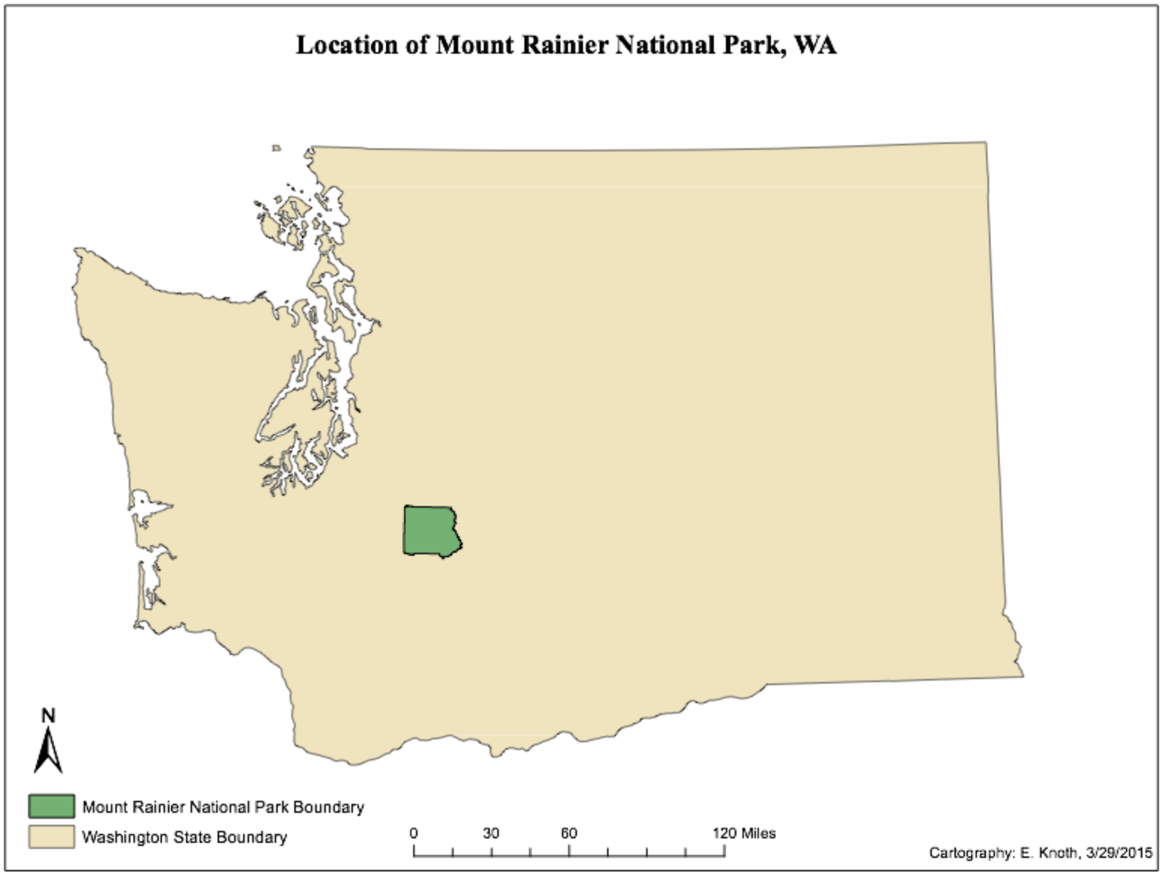

Figure 1.2
Location of Mount Rainier National Park within Washington State

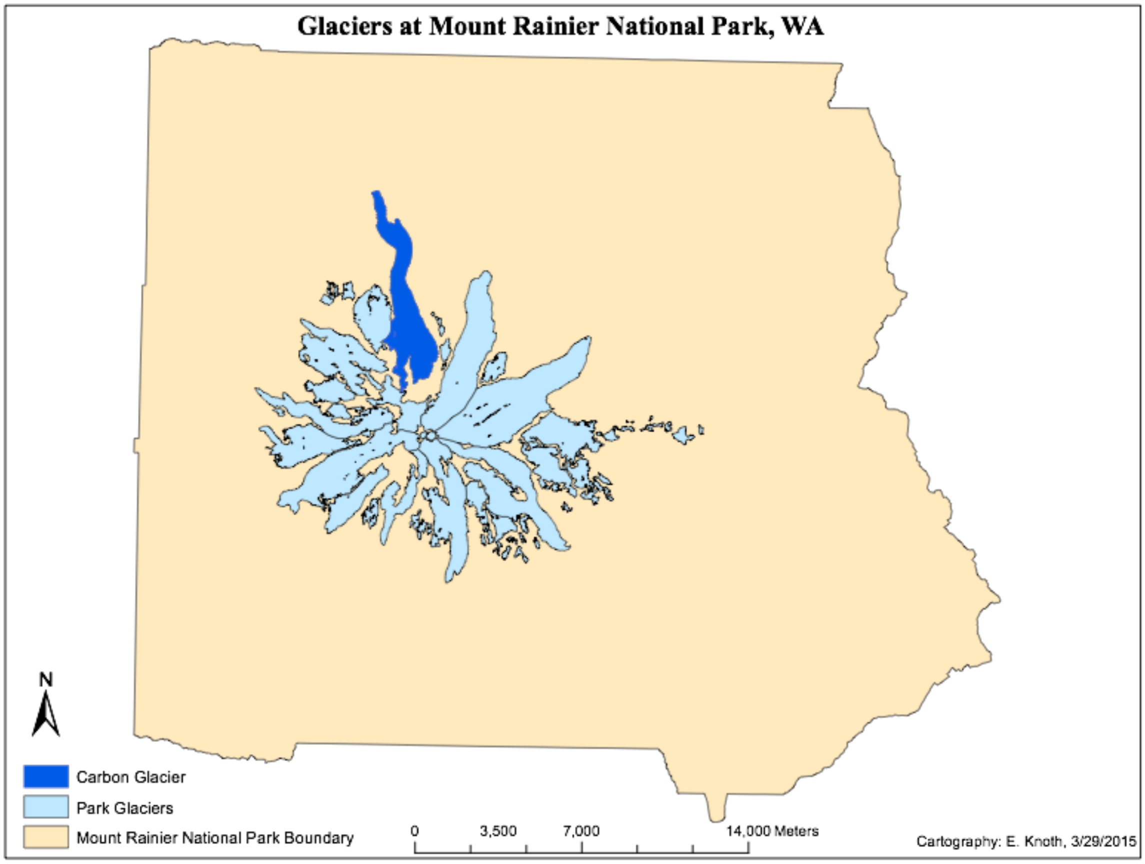

Figure 1.3
Map of the the Glaciers at Mount Rainier National Park. The Carbon Glacier can be seen in dark blue.

Study Area

The Carbon River is complex river system located in western Washington (Figure 1.4). The river flows 48 km from its source at the Carbon Glacier until it joins the Puyallup River in the city of Orting, Washington, eventually draining into the Pacific Ocean. The Carbon River valley, like others in the park, is characterized by tall valley walls which promote lateral floodplain expansion throughout the confined valley. The river course is partially constrained by old growth forests, many of which are still observed within the boundaries of Mount Rainier National Park.

Figure 1.4
Aerial View of the Carbon River Floodplain

Photo used with permission by
Dean Koepfler, Tacoma News Tribune

The Carbon River channel bed, along with many other glacial riverbeds within the park, is aggrading at an elevated rate (Beason et al., 2011). The general aggradation estimate for Mount Rainier's river systems is 3 cm per year, however in the Carbon River the rate of aggradation is much higher and is thought to be currently averaging 18 cm a year (Beason et al., 2011).

Stream aggradation can occur when the sediment load exceeds the capacity of the stream, increasing deposition with very little erosion (Driedger and Kennard, 1986). In order to accommodate the increased bed-load, these streams develop an extensive network of braided stream courses to distribute the sediment. In proglacial areas, stream aggradation is commonly due to the large amount of debris created by upstream glacial dynamics, which then serves as a sediment source for downstream channel reaches. This debris is transported downstream and temporally stored through flooding, diurnal stream patterns and sudden decreases in downstream gradient (Driedger and Kennard, 1986). These methods of aggradation are of concern because increased bed-load can adversely affect the surrounding watershed ecosystem, which leads to a reduction in bank stabilization. This addition of material has proven troublesome for park infrastructure, especially the Carbon River Road.

The Carbon River Road parallels the Carbon River, and terminates at Ipsut Campground. The road was originally constructed starting in 1921, and has been a continual battle against flooding from that point onward. For most of its history, the Carbon River Road has been repaired using stone, gravel and heavy gauge wire, and overlays varying floodplain deposits. In recent years, the role of wood has taken a beneficial place against flooding. Engineered log jams (Figure 1.5) have been installed in several areas of the Carbon River Floodplain. These areas have shown continuous strength in periods of flooding. The old growth forest is diminishing in some parts of the watershed, directly adjacent to the river. The possibility of a connection between this mortality and increasing aggradation, avulsion and erosional events are explored in this study.

Figure 1.5
Standing in front of an Engineered Log Jam located near the Park Entrance

In 2006, the Carbon River flooded due to a high intensity, short-duration storm event in which over 430mm of rainfall fell in less than 36 hours. This influx of water caused major flooding throughout valley bottom. The Carbon River Road was notably affected with large sections of the road completely destroyed, making this area of the park temporarily inaccessible to visitors. Visitor access has now been restored in the area with no vehicular traffic permitted. The Carbon River stream bed has experienced exceedingly high rate of aggradation rates that it is now rests at a higher elevation than the Carbon River Road in several areas (Beason, et al. 2011).

Old growth forests play an important role in bank stabilization throughout the Park; yet, they are diminishing throughout the drainage basin. The old growth is being buried rapidly due to increased aggradation, which reduces their ability to provide any sort of bank stabilization. Commonly the forests that are being killed by increased aggradation and flooding events are referred to as “Ghost Forests”. These forests are noticeably different from the healthy forests because of their lack of coloring (Figure 1.6).

Figure 1.6
“Ghost Forest” (Right) and healthy forest (Left) in the Carbon River Floodplain

Purpose of Study

The general purpose of this study is to analyze the rate at which the Carbon River is aggrading, or increasing in height over time. The Carbon River is a fluid system and changes very often due to the elevated amount of rainfall that occurs in this portion of the park. It is for this reason that the Carbon River should be studied further. The specific goals of this study are threefold:

1. The first goal is to estimate the area for two specific reaches or areas of the Carbon River. The first reach resides near the entrance to Mount Rainier National Park, and the second reach resides in the area parallel to Ipsut Campground. By using cross-sectional data an integrated estimation of area is calculated for each reach. The data are analyzed to determine any similarities or differences within the river system.

2. The second goal of this study is to analyze LiDAR ground returns to determine which areas are aggrading and which areas are eroding throughout the Carbon River valley. By using multiple LiDAR datasets from different years, numerical values correlating with areas of loss and gain are extracted. This data is compared in order to determine if the amount of eroded material is equal, or similar to the amount of aggraded material within the valley, and will be split into three sections: Upper, Middle and Lower. This will help to identify which particular areas of the river are experiencing net gain or net loss.

3. The final goal is to determine if the Carbon River should be reclassified. The classification of the Carbon River as a braided river is simply not sufficient to describe all the various influences found in this system. By incorporating the various vegetative and geomorphic processes taking place in this river system, there may be a term that better describes the river as a whole. The Carbon River valley contains a large amount of old growth forests, and their influence to bank stability will be explored when classifying the river.

CHAPTER 2

PRIOR RESEARCH

Most of the research that has been performed in relation to stream aggradation focuses on the movement of glaciers, due to the increased sediment load that glacial movement produces. In 1979, a simplified model was created to illustrate the possibility of net aggradation and degradation during a period of glacial advance or retreat, using the balance between meltwater capacity and sediment load as the defining factors (Figure 2.1). Several factors that play a significant role in stream aggradation have been defined. These include volume and variability of sediment supply, rate of ice movement and melting, degree of glacial erosion, lithology and slope. All of these factors are applicable to the study area, however not all factors are incorporated into the model (Maizels, 1979).

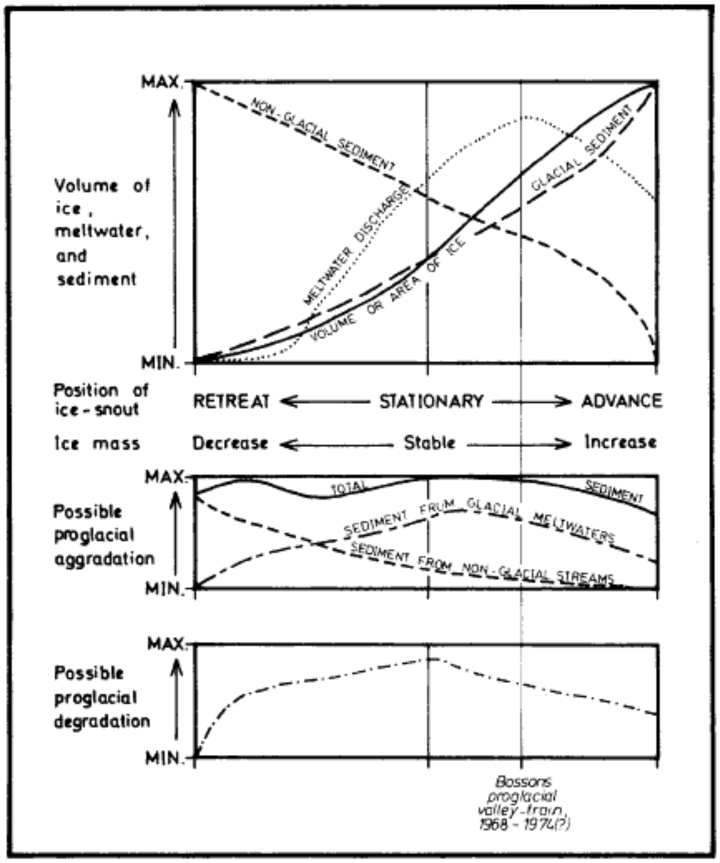

Figure 2.1
Maizel's Model (1979)

In some systems channel morphology with increased bed-load input causes aggradation locally, which in turn increases braiding intensity and also increases the number of stable unit bars. The unit bars tend to gradually migrate downstream and are a major source for transfer of bed-load. A general model was proposed that for a set particle size distribution, intensity of braiding increases with elevated discharge and total stream power (Ashmore, 1991). In the study area these moving bars are not visible via satellite imagery due to dense vegetative cover, however these conveyor belts of bed-load may be able to be observed in the field and would help explain a specific method of transport.

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Perhaps the most relevant research for this topic was performed after the Carbon River flooded in 2006. It was determined that in some areas of Mount Rainier National Park the rivers were rapidly changing, and the main cause can be contributed to glacial thinning and retreat from regional and global climate warming. Due to the increase in aggradation in the park, stream channels and floodplains are enlarging at an alarming rate, and major channel shifts or avulsions are changing the location of river channels. This movement is a major concern since much of the infrastructure in the park is located within the vicinity of these rivers (Beason, et al. 2011).

In 2012 an article was published by the United States Geological Survey that directly addressed the geomorphology of the rivers draining Mount Rainier. This study addressed the sediment-delivery system of several rivers to determine current sediment loads, determine if there were trends in streamflow and sedimentation rates, and to assess how the sedimentation could be effected by climate change. The authors, issuing a conceptual model, found that rockfalls, glaciers, debris flows and main stem flooding act sequentially to export sediment from Mount Rainier to the Puget Lowlands over decades (Czuba, J.A., et al., 2012). Between the four major rivers addressed in this study, the Carbon River was found to have the smallest bed material load, and was determined to have a predicted time of 300 years for a medium size sediment pulse to arrive downstream, a significantly larger transport time than for the other rivers in the park.

The two studies that pertain specifically to the Carbon River were completed in 1994 and 2001. Jon L. Riedel, former NPS Geologist for Mount Rainier published an study for the purpose of a 20 year general management plan. In this report, Riedel assessed 23 visitor and administrative sites in the park, along with numerous trails and waterways. In the Carbon River region, Riedel conducted a detailed floodplain study, collecting 9 cross sections in the Carbon River Valley, from Ipsut Campground to the park entrance (Riedel, 1997).

A second study on the Carbon River floodplain was completed in 2008 by international environmental consulting firm, ENTRIX. This study was conducted to hydrologically model the Carbon River and draw conclusions about the design and stability of the Carbon River Road, in order to reduce flood damage. ENTRIX established 18 cross sections along the Carbon River, and also resurveyed several of Riedel's cross sections from 1994. This study yielded several recommendations for the Carbon River road, including installing road features to divert water in flooding episodes. Some of the recommendations made were put in place and have played a beneficial role in mitigating flood damage (ENTRIX, 2008).

Braided, Anabranching, and Anastomosing Rivers

There are several different ways to describe a river that weaves in and out of vegetated surfaces. Braided is a common term, while anastomosing and anabranching are used less often. These winding rivers contain hidden substrate influences, and maintain various rates of stability. The Carbon River has been classified in past literature as a braided river system, but by looking at the various roles of vegetation and bedrock influence that accompany anastomosing and anabranching rivers, the classification as a braided river may not be the best fit for the Carbon. The purpose of this section is to analyze the various characteristics of anabranching and anastomosing rivers, and to determine the effects of bedrock and vegetation acting on those systems.

Generally anabranching and anastomosing rivers are more similar than they are different. The literature suggests that the reason these two types of rivers turn into multi thread systems, is due to the variation in lithology, bedrock exposure, sediment accumulation and vegetation. These systems typically have a single macro-channel, with several secondary or cross channels that form the various branches or threads. The separation of anabranching and anastomosing rivers is subtle, but it appears that anastomosing rivers should be thought of as a type of anabranching river with varying influences, or perhaps both anastomosing rivers and anabranching rivers should be classified as types of multi thread rivers (Knighton and Nanson, 1996).

Anabranching rivers consist of several channels that are separated by vegetated, semi-permanent alluvial islands that have been excised from the existing floodplain, or formed within channel the channel or by deltaic accretion (Knighton and Nanson, 1996). There are several anabranching styles that describe how these styles are able to maintain stability. These styles include: cohesive sediment, sand dominated:island forming and ridge forming, mixed load: laterally active, gravel dominated: laterally active and stable. (Table 2.1)

Anastomosing rivers are characterized by multiple channels separated by islands excised from the floodplain (Knighton and Nanson, 1993). These islands are usually excised from the continuous floodplain due to widening of the channel, and are relatively large compared to the channels. Anastomosing reaches can grade gradually into entirely braided sections, but are distinguished from them by greater bankline stability and finer grained sediments. These rivers are defined in terms of three variables: flow strength, bank erodibility and relative sediment supply. Anastomosing rivers are typically associated with deltas, which generally constrains these rivers to low gradient environments. This lower flow rate consequentially means a lower ability to erode and transport materials. Generally these rivers have stable banks, which is related to the cohesiveness of fine bank material and some stabilization from root matting. Sediment supply for rivers are variable based on the lithology they flow through, and anastomosing rivers are characterized by moderate to high values.

Flow strength, bank erodibility and relative sediment supply are factors in the continuum concept, where the continuous interactions among the three factors determines the type of river. For example, Flow strength can be subdivided into three speeds. Low flow strength (L) will produce a straight river, medium flow strength (M) will produce a meandering river, and high flow strength will produce a braided river. The exact same constraints apply to both bank erodibility and relative sediment supply. The ever changing characteristics come from the various combinations of these factors. A straight river commonly has a L-L-L ranking, which signifies low values for each of the three factors. A Meandering river may have a M-L-M ranking, which signifies medium values for flow and relative sediment supply, but a low value for bank erodibility (Knighton and Nanson, 1993).

Allogenic processes specifically refer to an externally imposed environmental influence such as scour or inundation (Francis, 2006). Autogenic processes are related to the interactions between the vegetation and external environmental processes, which would not occur without the presence of vegetation and which influence vegetation dynamics. Allogenic influences are directly influenced by sediment calibre and elevation above the water table, which both relate to the amount of water available. Stability is an important regulator of the dominance of allogenic and autogenic processes within succession. Succession is driven primarily by patterns of sediment deposition and hydrological disturbance (Francis, 2006).

Sediment Characteristics			**Channel Characteristics**			
Sediment Load	**Bed Material**	**Bank Material**	**Sinuosity**	**Gradient (mm^-1) w/ d**	**Vertical Activity**	**Lateral Activity**
Mixed; 25% as bedload	Course Sand, granules	Fine sandss, silts	Low		Riding base level downstream	Narrow point bars but very slow lateral accretion
	Medium Sand	Silts, fine sands	Medium	>10	Riding base level downstream	Subtle Banks; avulsion
	Gravel, course sands	Mostly Silts	Variable	13 (mean)	Riding base level downstream	Stable banks, crevassing common
Coarse	Gravel, sand	Mostly Silts	Variable	15 (mean)	Riding base level downstream	Stable banks, crevassing common
Solution and Suspension transport dominant	Silts and Sands	Silty Clay	Moderate	30-140	Isostatic rebound at ~0.7m/ 100yrs	Stable; periodic avulsion
10% as bedload	Medium Sand	Mud, fine sand	__________	__________	Basin Subsidence	Crevassing and avulsion common
Mixed (Mud moved as sand-sized aggregates)	Muds, Sands	Silts	Variable	~ 10 (mean)	Mud drape over sand sheet	Little lateral migration or crevassing
30% as bedload	Medium Sand	Medium and Fine Sands	Low	~ 10 (mean)	Prominent	Stable; little or no migration or crevassing

Table 2.1
Specific terminology for anabranching rivers (Knighton and Nanson, 1993)

The interaction of riparian vegetation and multi thread rivers are complex. Three common trends represent the effects on vegetation in multi thread rivers. The first is a decrease in channel lateral mobility, which creates a decrease in lateral migration rates and increases the stability of the channel due to root matting. The second trend is a decrease in the braiding intensity and the total wetted width. This decreases the number of active channels and narrows and deepens existing channels. The third trend is a nonlinear change in the channel parameters with increasing vegetation intensity. The effects of the vegetation are initially strong, but then weaken as easily occupied channels are eliminated or have diminishing flow (Tal et al. 2004).

Figure 2.2
Surveying an avulsion channel in the Carbon River
Photo used with permission by Dean Koepfler, Tacoma News Tribune

CHAPTER 3

MATERIALS AND METHODS

For the field portion of this study several tools were used. These include Global Positioning Systems (GPS) and a TOPCON Total Station. LiDAR datasets were obtained from the staff at Mount Rainier National Park, and were used in laboratory analysis.

Total Station

A TOPCON GTS-230 series electronic total station (Figure 3.1) was used in order to create cross-sections of the Carbon River. A total station is a tool used to record distances electronically, and uses an external data collector to store measurements. The process works using a laser beam, which is emitted from the total station and “shot” or pointed directly towards a prism. The beam is then reflected back towards the total station where the reflected light is detected. The station uses the time taken to detect the reflected light’s wavelength to calculate the distance. These measurements also calculate the height of the prism, which allows the user to produce elevation measurements throughout the cross section. These x, y, and z coordinates are recorded for each point and stored in a spreadsheet for each individual cross section. The data in these tables are used to create longitudinal profiles and area measurements.

Seven cross sections were recorded in the Carbon River floodplain, in two main areas in order to estimate the cross sectional area of these sections of river. These sites were established based on areas previously surveyed, and also by their proximity to the Carbon

River road. Due to restricted time at the park, the study area was restricted from Ipsut Campground to the Park boundary. (Figure 3.2) Five cross sections were collected near Ipsut Campground, while the remaining two were collected near the Park entrance. (Figure 3.3) By collecting measurements in two locations, the integrated area calculations can be compared and contrasted between the two respective areas.

Figure 3.1
Surveying in the Carbon River using the TOPCON Total Station

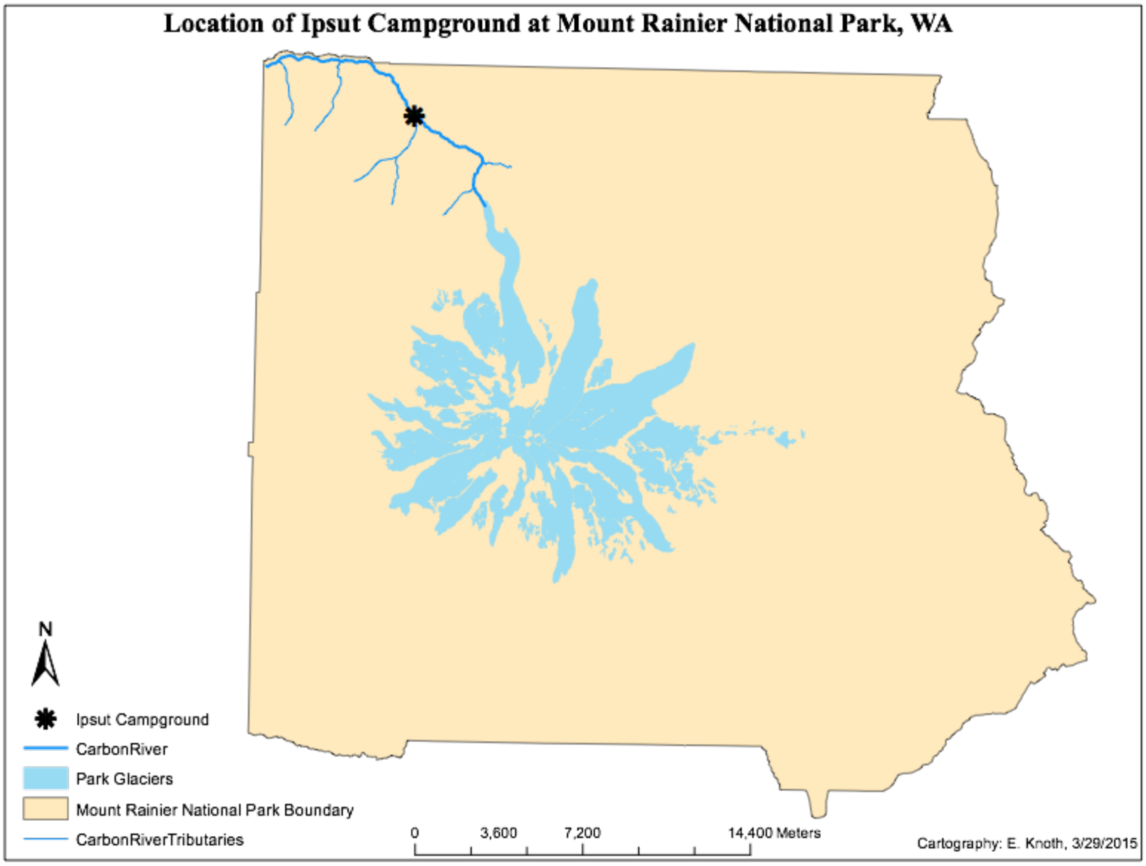


Figure 3.2
Location of Ipsut Campground at Mount Rainier National

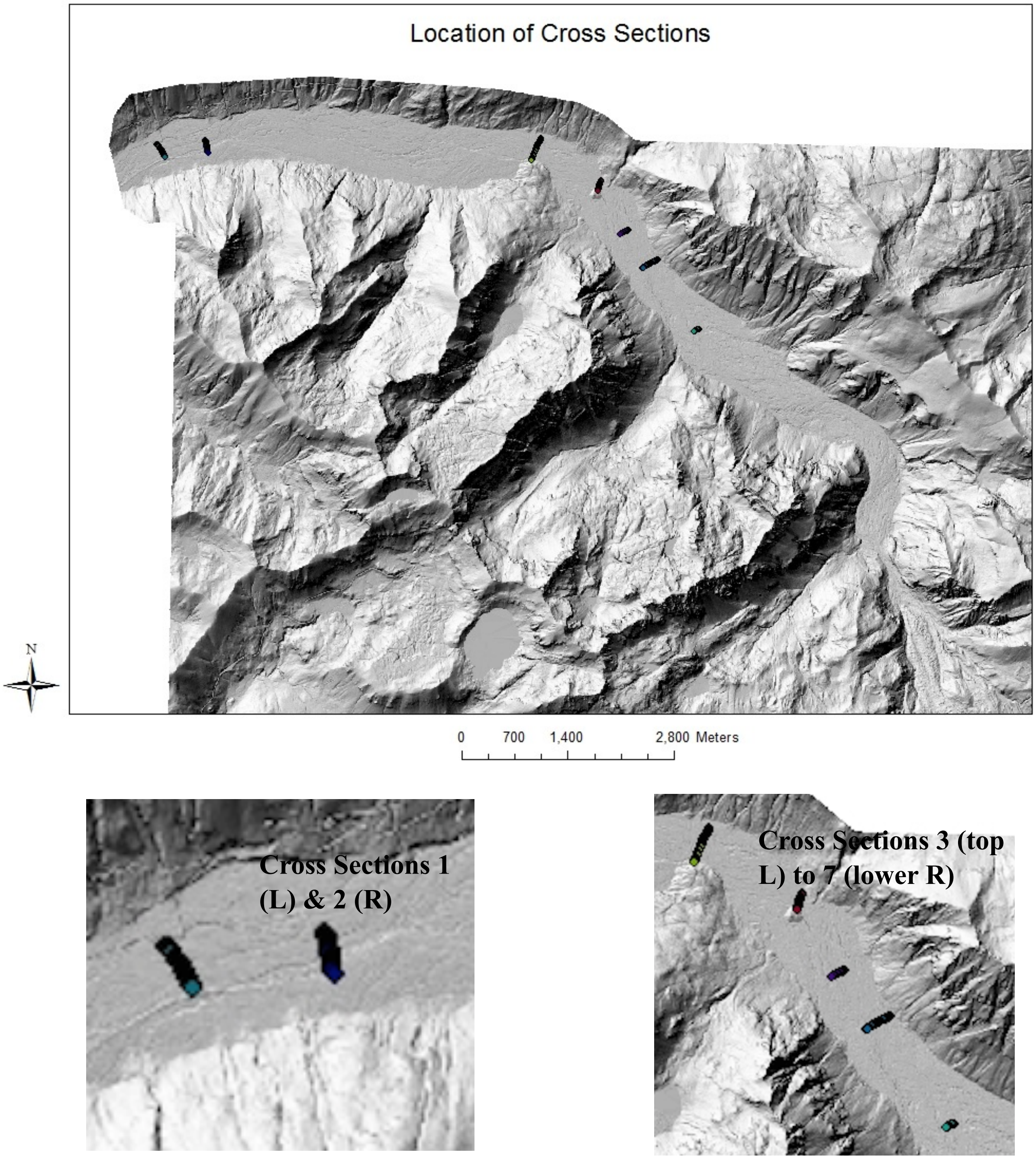


Figure 3.3
Location of Cross Sections. Each cross section was number 1-7 with Cross Section 1 beginning at the Park Entrance (Left of Page) and increasing with Proximity to the Carbon Glacier.

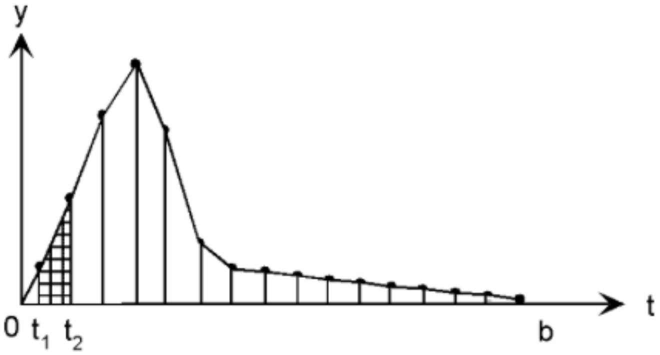
Handheld GPS

A Trimble GPS Unit was used in order to record points for the location of the total station and back sight for each cross section. This step is important because it connects the cross sectional data to the specific location where it was collected. The GPS unit acquires several satellites in order to triangulate measurements are accurate within 10 centimeters. All the points collected in this study were accurate within 20 centimeters (Trimble, 2004). Originally, the exact location of Riedel and ENTRIX cross-sections were to be surveyed, but due to time constraints, these areas were not found using the Trimble.

Surveying Method

After locating the areas where the cross sections were to be obtained, the first step is to set up the total station. Setting up this tool can be a complex task, because the device must be totally level otherwise the measurements recorded will be incorrect. After leveling the machine, it must be referenced to a direction by using a back sight. The back sight allows a reference direction, and also allows for the instrument to be set to the horizontal angle of 0 degrees, minutes and seconds. By setting the instrument to zero, all the shots taken will be referenced back to this point. After the instrument is level and the back sight is established and zero set, the instrument is ready to take shots or points (TOPCON, 2003). The field assistant assigned to the prism would then carefully trek across the river to start the cross section. Due to the lack of radio contact across the large sections of the Carbon River, hand signals were used to signal when a point was recorded. The field assistant in the river would then move forward to the location where the next point was to be taken, an average of 1.5 meters. This measurement was chosen based on the width of the river and previously conducted studies.

The raw data from surveying is then analyzed using Microsoft Excel. A longitudinal cross section was created for each of the seven cross sections. Cross sections 1 and 2 were taken near the Park Entrance while cross sections 3-7 were taken near Ipsut Campground. The integrated cross sectional area was calculated using the trapezoidal rule (Formula 3.1). The total integrated area was calculated for the Ipsut area and the Carbon entrance respectively, and also combined to gather a total integrated area. The integrated area is a way to calculate the area beneath each longitudinal profile. In the respective reaches the values would be expected to contain similar characteristics. The overall integrated area of the two reaches combined is a way to estimate the amount of material for all 7 cross sections combined, however this compiled value may not be as relative as the compiled values for each of the two reaches. Because of this reason, the average of each reach, as well as the overall average of integrated area is calculated.



The area of the shaded trapezoid above is

$$Area = (t_2 - t_1)\left[\frac{f(t_1) + f(t_2)}{2}\right]$$

Formula 3.1

Trapezoidal Rule for Integration in Microsoft Excel (Haggerty, 1999)

LiDAR

Two LiDAR datasets were obtained from the staff at Mount Rainier National Park. They were obtained in 2008 and 2012 respectively. These LiDAR datasets were used to create difference or subtraction maps. This process uses two years of LiDAR coverage for the same area. By extracting the ground returns only, which renders a surface model for the area, the two datasets are subtracted from each other showing the changes in terrain from 2008 to 2012. By subtracting the two LiDAR datasets, a table of values is produced which measure net gain and net loss. In the case of the Carbon River floodplain, the positive values represent added materials while the negative values represent areas of erosion. These values were used to visualize the distribution of the data, and a graph was created to visualize loss compared to gain. Additional shape files and GIS data provided by the National Park Service were also used in the creation of these maps.

CHAPTER 4

RESULTS

Cross Sectional Results

A longitudinal profile was constructed for each cross section and can be seen in Figures 4.1-4.7. The integrated area results can be seen in Table 4.1. Two cross sections taken near the park entrance were within 600 meters of each other and yielded results that were within $40m^2$. Cross section 1 yielded an integrated area of $346m^2$, and Cross section 2 yielded an area of $305m^2$. The five cross sections taken upstream near Ipsut Campground yielded a wider range of results.

Cross Section 3 had the most individual x, y, and z points collected, and it turn produced the highest result of integrated area of all other cross sections in this study at $608m^2$ of material. Cross section 4 yielded an integrated area of $215m^2$ and covered 380 feet of distance. This location was in a predominant erosional feature in the Carbon River Road. The road here is constructed within the Carbon River floodplain, and is consistently eroding this section of the road. Cross section 5 was taken in a similar location as cross section 4, in an erosional area of the Carbon River Road. This area yielded an integrated area of $258m^2$. Cross section 6 was collected in an area with multiple channels close to an area known as Chenuis Falls. This area produced a total of $431m^2$. Cross section 7 was collected directly adjacent to Ipsut Campground. In this area the main channel of the river prevented accessibility for a full survey. The integrated area measurement of $147m^2$ was calculated.

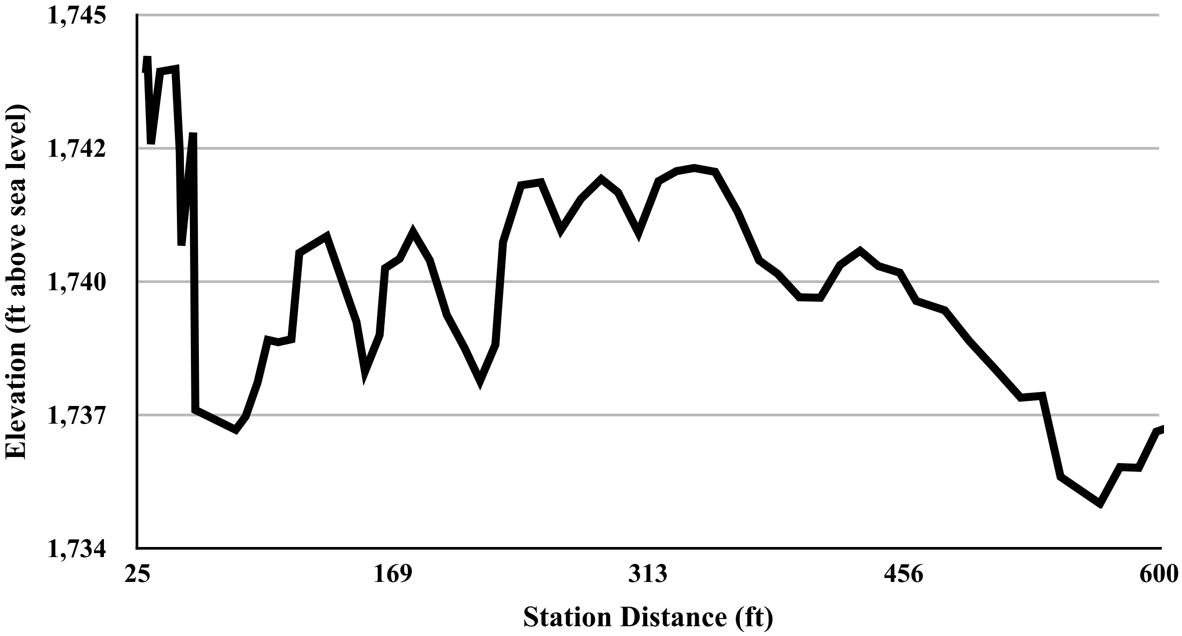
By averaging the integrated area results, the two separate reaches of the river can be compared. The reach near the Park Boundary produced a result of 326m², while the reach near Ipsut Campground produced a result of 332m².

LiDAR Difference Mapping

A detailed subtraction map was created of the Carbon River Floodplain. (Figure 4.8) The location of each cross section is overlaid on bare earth LiDAR 2012 returns near Ipsut Campground and the Park Boundary (Figure 3.3). By subtracting the two LiDAR datasets, a table of values is produced which correlate with net gain and net loss. In the case of the Carbon River floodplain, the positive values represent added materials (shown in blue) while the negative values represent areas of erosion (shown in red). The resolution of both LiDAR datasets are both one meter, which provides mass results in meters, and when subtracted, square meters. A second map was created showing the aggrading versus eroding areas near Ipsut Campground. (Figure 4.9)

The results of the LiDAR subtraction were grouped into three different equal sections of the river. Since these results were created by subtracting a 4 year period of time, the rate of net gain or net loss can be calculated by the simple equation change divided by time. The first section or Upper Reach starts at the terminus of the Carbon River Glacier and yielded a result of 0.036 m². When divided by the four year period, the area produced a rate of 0.009 m² per year. The Middle section covers the area adjacent to Ipsut Campground and continues downstream. This area yielded a net gain of 0.008 m² at a rate of 0.002m² per year. The Lower section covers the remaining area of the river to the park boundary. This area produced the only net loss measurement of -0.046m², resulting in a rate of -0.01m² per year.

Figure 4.1
Longitudinal profile of cross section 1



Left Bank
Looking
Downstream

Right Bank
Looking
Downstream

Figure 4.2
Longitudinal profile of cross section

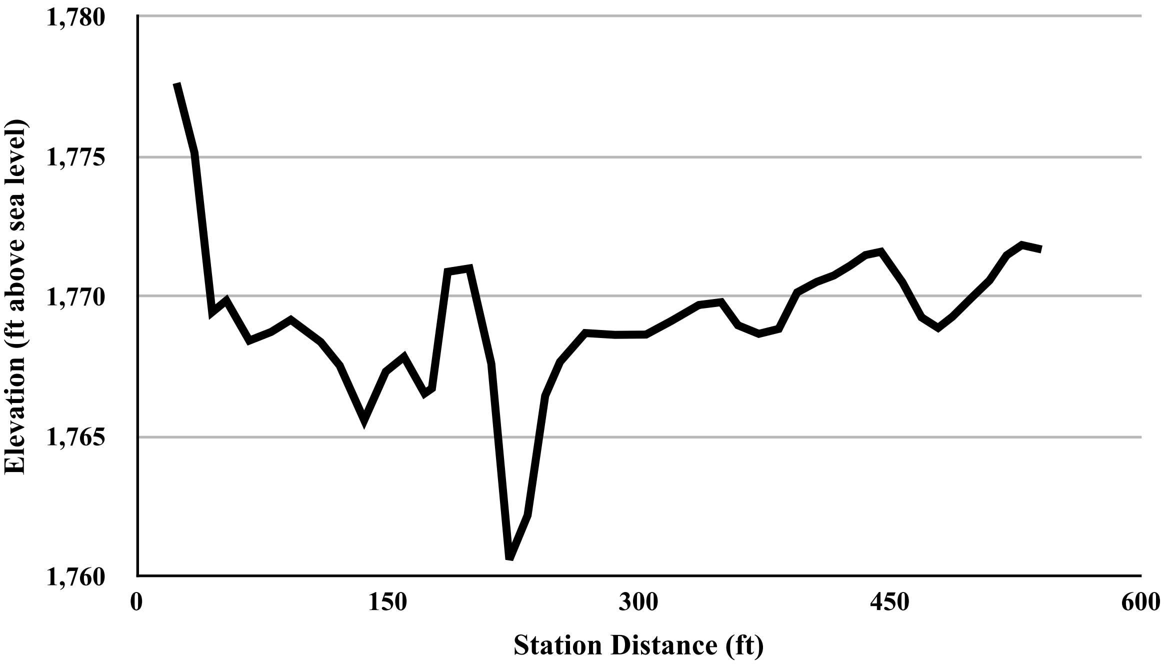
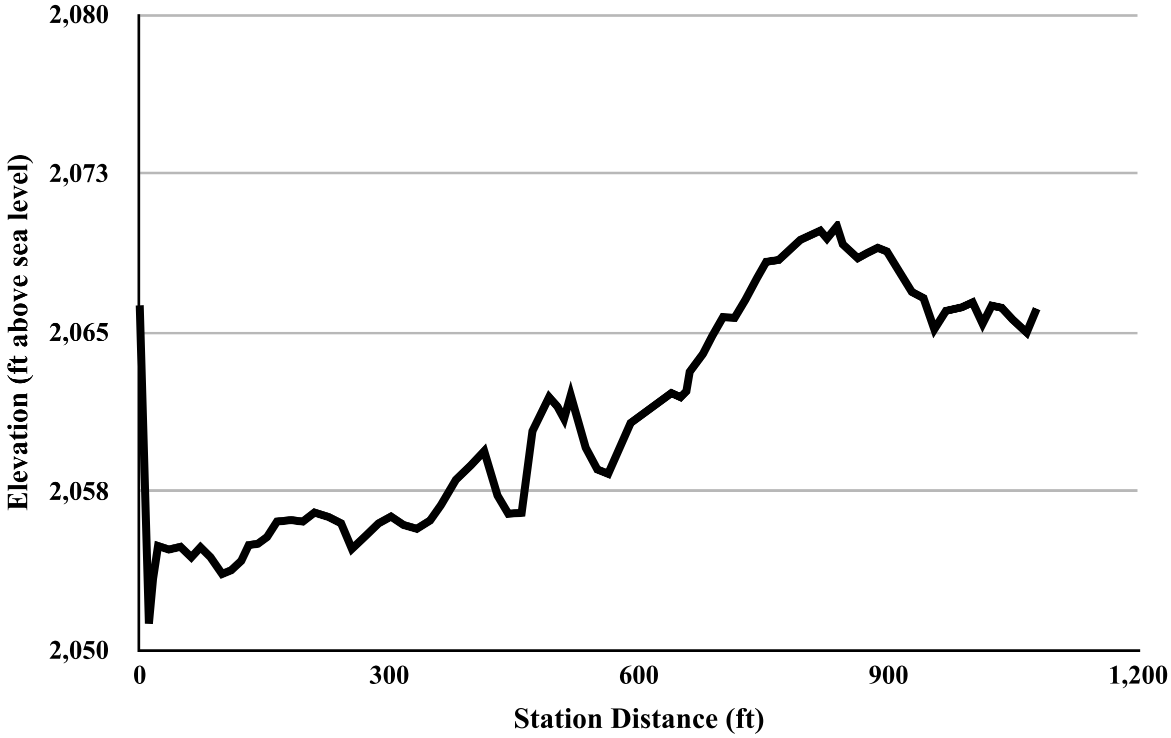


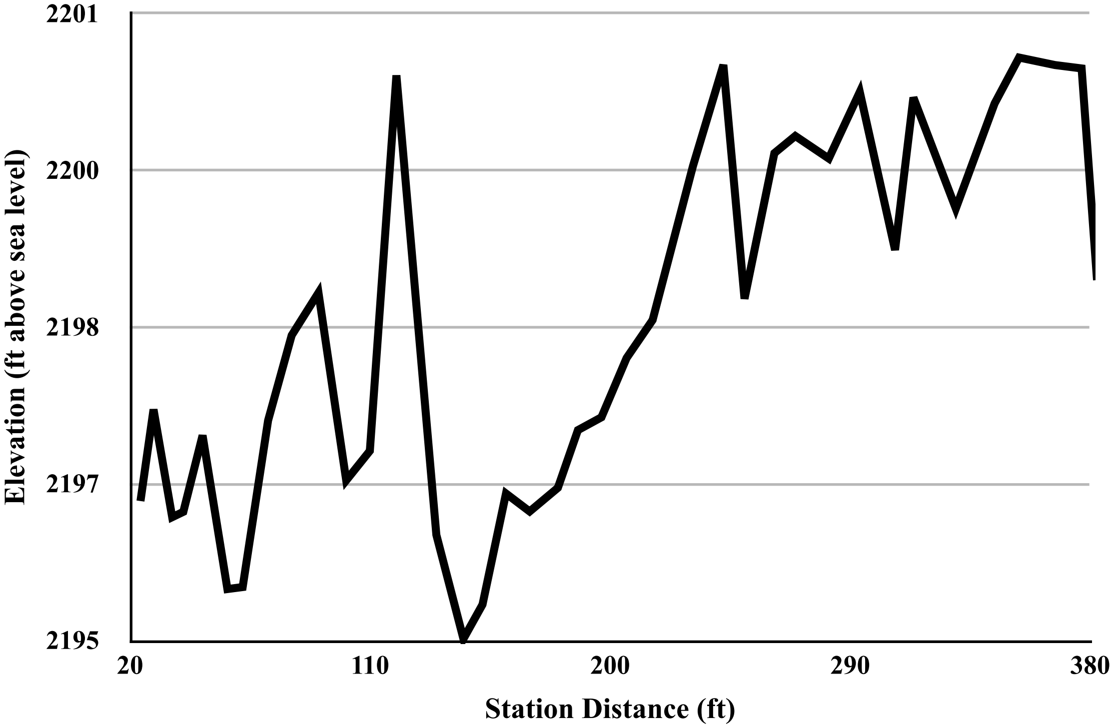
Figure 4.3
Longitudinal profile of cross section 3



Left Bank
Looking
Downstream

Right Bank
Looking
Downstream

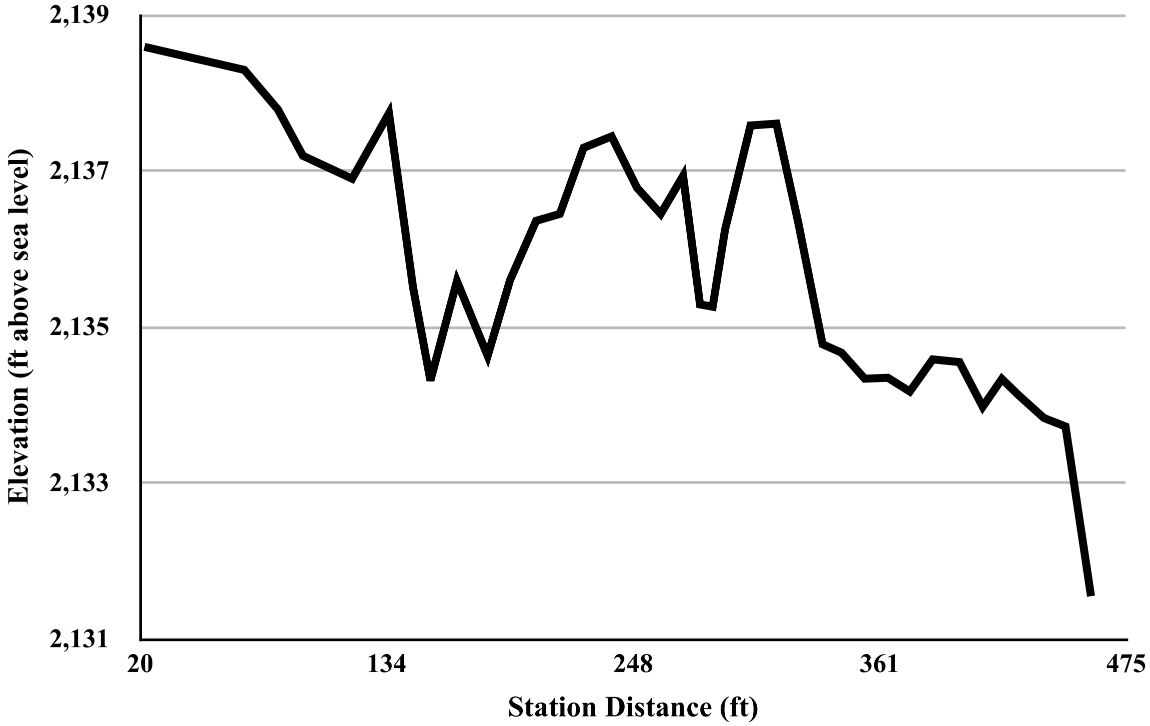
Figure 4.4
Longitudinal profile of cross section 4



Left Bank
Looking
Downstream

Right Bank
Looking
Downstream

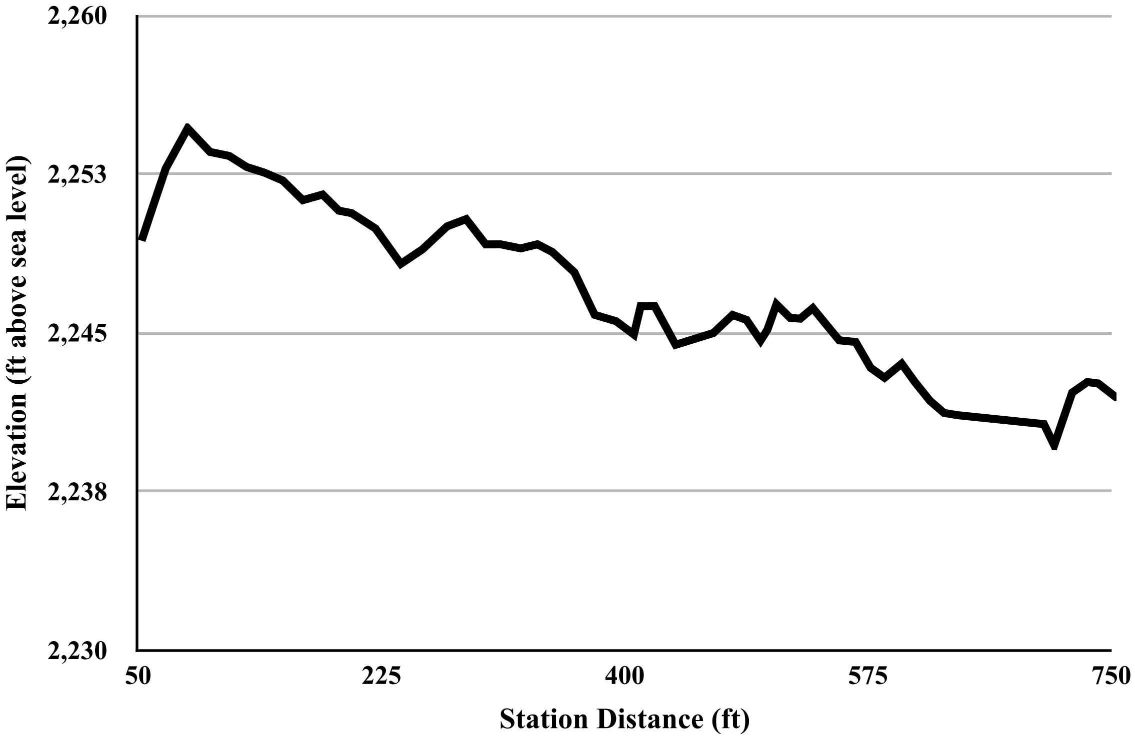
Figure 4.5
Longitudinal profile of cross section 5



Left Bank
Looking
Downstream

Right Bank
Looking
Downstream

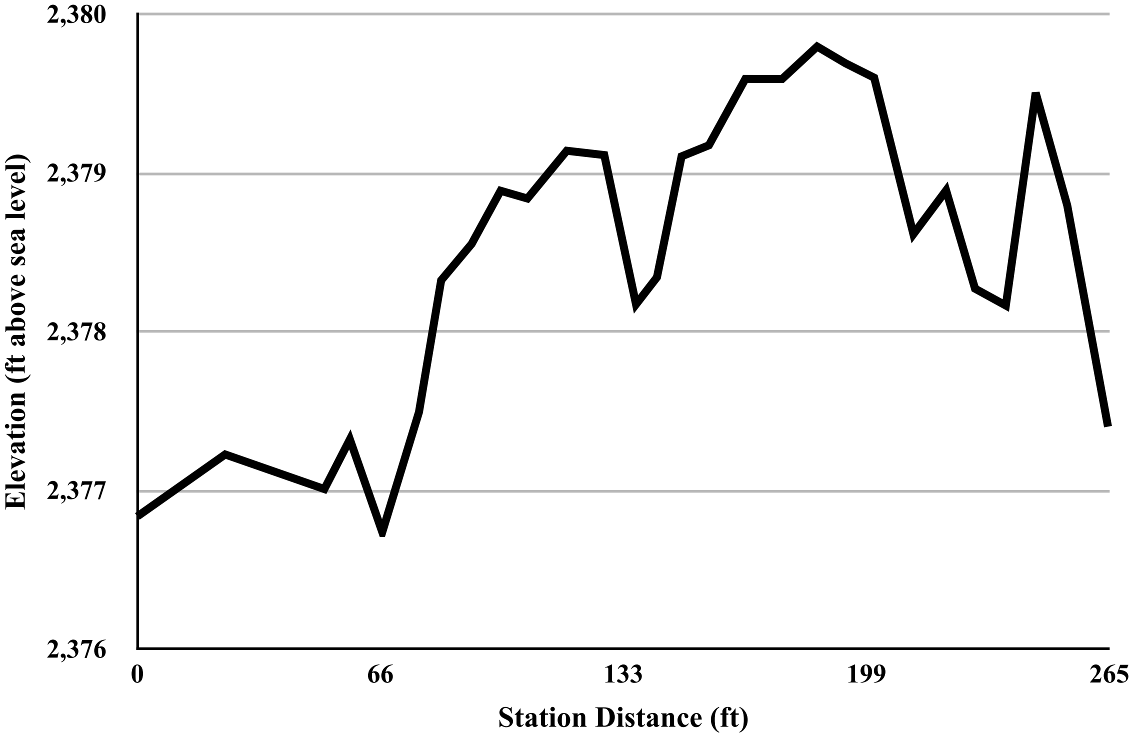
Figure 4.6
Longitudinal profile of cross section 6



Left Bank
Looking
Downstream

Right Bank
Looking
Downstream

Figure 4.7
Longitudinal profile of cross section 7



Left Bank
Looking
Downstream

Right Bank
Looking
Downstream

Table 4.1
Integrated area cross sectional results

	Integrated Area (m²)			
Cross Section 1	346			
Cross Section 2	305			
Cross Section 3	608			
Cross Section 4	215			
Cross Section 5	258			
Cross Section 6	431			
Cross Section 7	147			**Average Integrated Area (m²)**
		Entrance Reach Total (m²)	651	326
		Ipsut Reach Total (m²)	1659	332
		Entire Study Area (m²)	2310	330

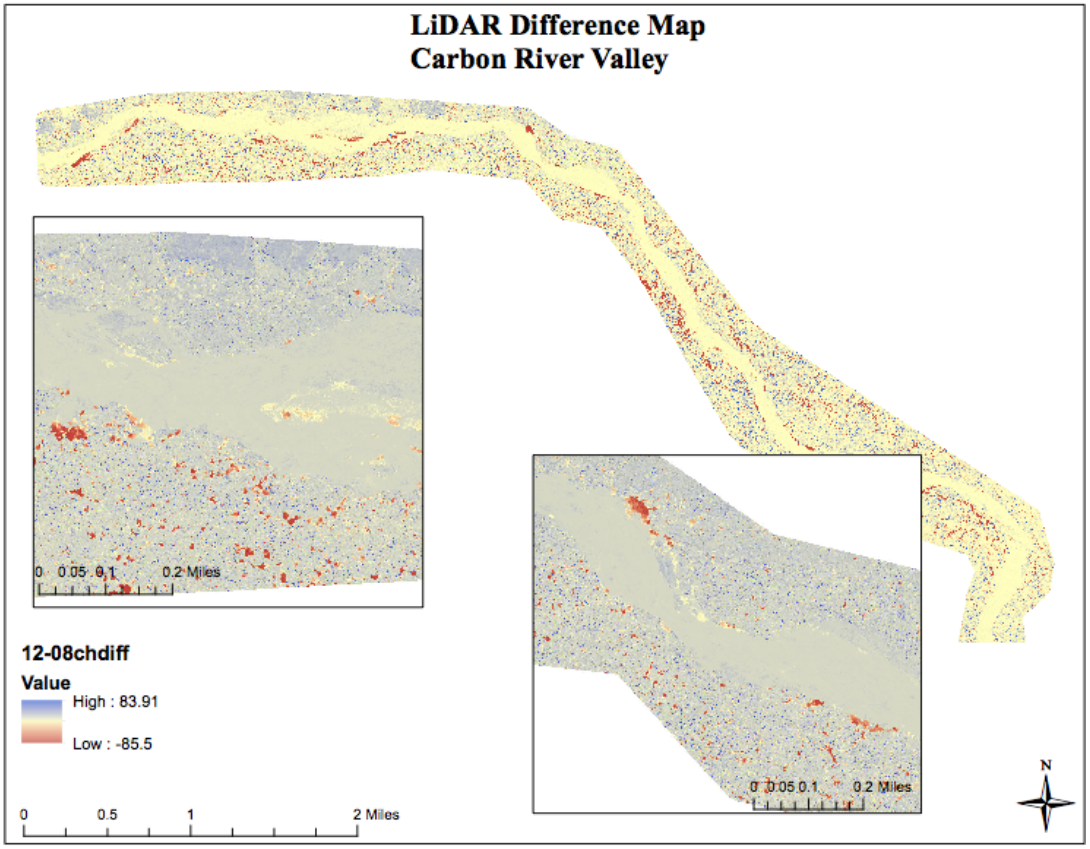


Figure 4.8
Difference Map of the Carbon River Floodplain

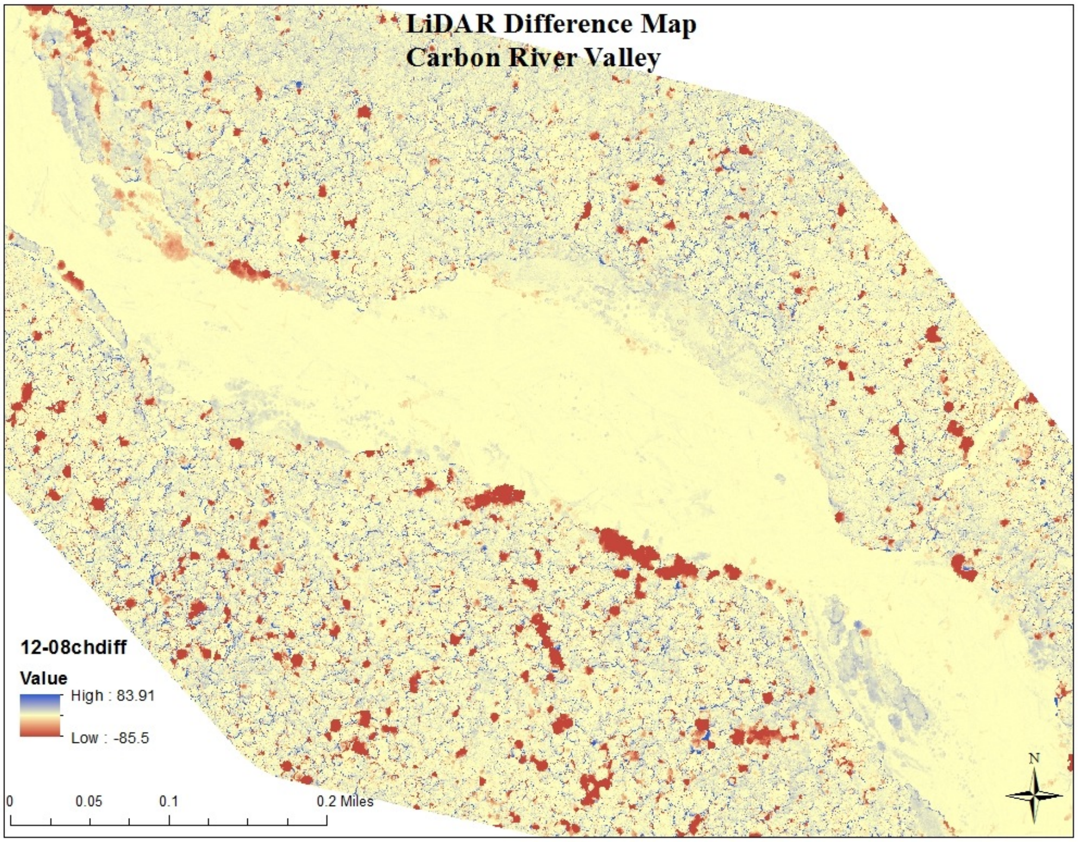


Figure 4.9
Difference Map near Ipsut Campground

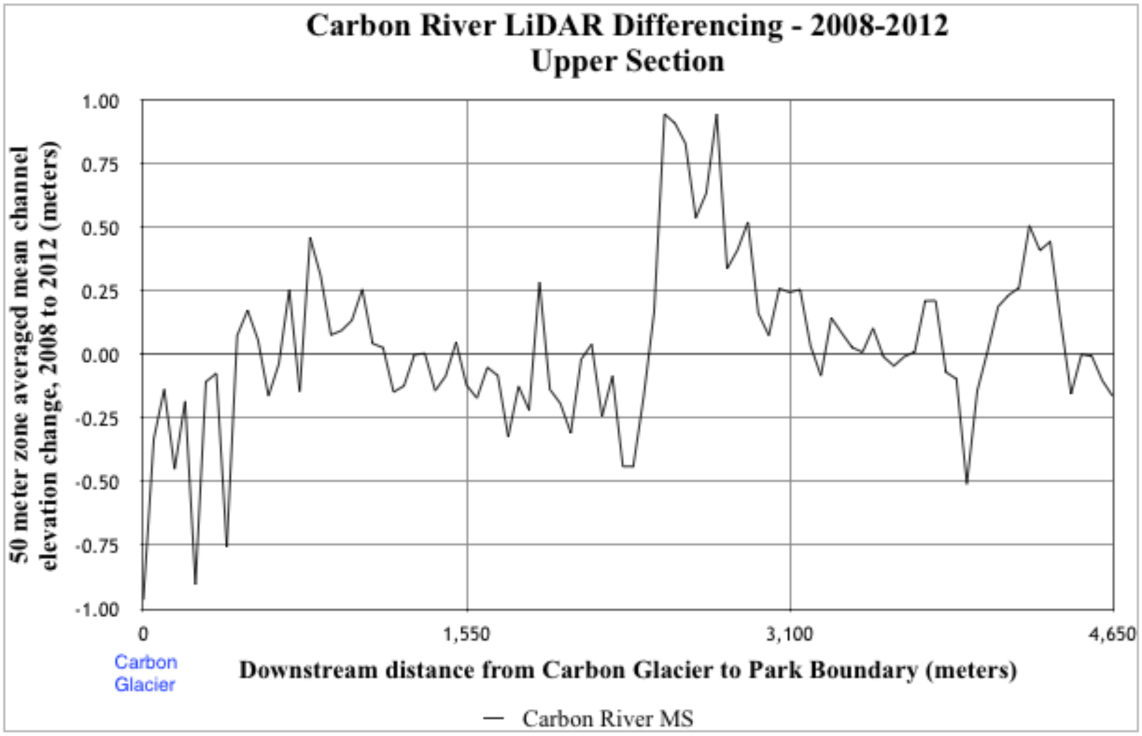


Figure 4.91
Graphical Representation of the Upper Section LiDAR Difference Results in the Carbon River Watershed. This section of the river covers the terminus of the Carbon Glacier downstream.

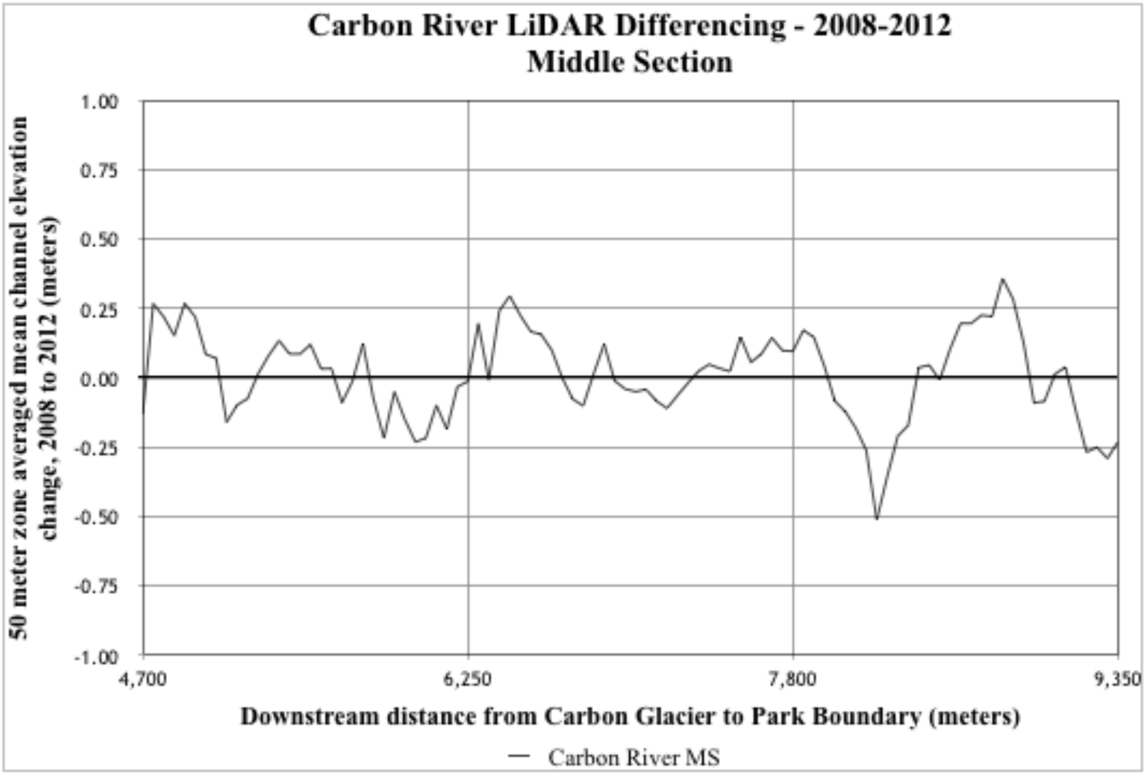


Figure 4.92
Graphical Representation of the Middle Section LiDAR Difference Results in the Carbon River Watershed. This section of the river covers the area of Ipsut Campground.

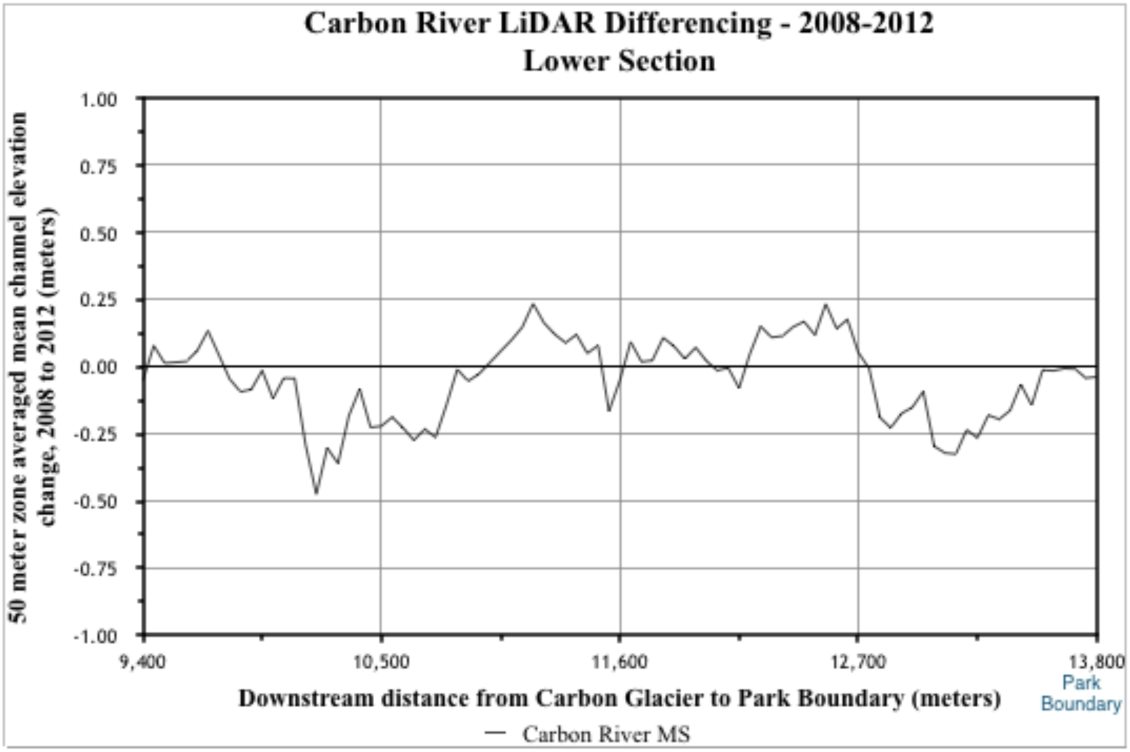


Figure 4.93
Graphical Representation of Lower Section LiDAR Difference Results in the Carbon River Watershed. This section covers the remainder of the river down to the park boundary.

CHAPTER 5

DISCUSSION

Cross Sections

The two cross sections (1 and 2) that were taken near the Park entrance both produced integrated area results that are very similar to each other. Both of these areas are less influenced by surrounding forests, and are also laterally expanding. However, in this area lateral expansion will further put park infrastructure at risk. Camping areas near and outside the Carbon River entrance are also expected to be taken over by the river, and commonly inundate the area with heavy rainfall and minor flooding events. Cross Section 2 was taken near an Engineered Log Jam that was put in place by the National Park Service. This particular area would most likely maintain more bank stability in the event of flooding and lateral expansion.

The five cross sections (3-7) taken near Ipsut Campground produced a wide range of results compared to the measurements gathered near the Park boundary. There are several possible reasons for this increase. Five cross sections were taken in this area compared to the 2 taken near the entrance, so the overall rate of integrated area would be expected to be higher in this area due to the availability of more data points. Individually, the accuracy of the integrated area results are dependent upon the amount of points that were taken for each cross section.

This upper reach of the river also visually appears to be experiencing higher rates of channel movement than the areas near the park boundary, which can be visualized in the LiDAR subtraction maps (Figure 4.8). Since Ipsut campground is in much closer proximity to the Carbon glacier, the flow strength as well as the bank capacity is larger in this area. These factors, along with the reduction of forests in this area, is allowing constant lateral expansion of the floodplain which will ultimately consume the Carbon River Road and the campground itself.

LiDAR Difference Mapping

The values analyzed from the subtraction maps produced interesting results. Channel changes were assigned to the "loss" category had all negative values, while changes assigned to the "gain" category had positive values. The analysis showed that the two categories were not uniformly distributed. This means that one of the two categories had a slightly higher value count. By splitting the river into three sections, the areas of erosion and the areas of aggradation can be identified.

The Upper section of the Carbon River showed the highest rate of aggradation at $0.009m^2$ per year. This makes sense, especially considering the amount of material created by glacial movement and lateral thinning. The Middle section of the river also showed a rate of aggradation at $0.002m^2$ per year. Here, material is still being added to the river system, but a wider valley and less available material make the numerical values lower than in the upper section. The Lower section of the river showed a negative value of $-0.01m^2$ per year, the only section that exhibits erosion. This area is less confined by valley walls and typically contains multiple heavily flowing channels, helping erosional processes more so than upstream near the Carbon glacier.

The graphical results of the LiDAR returns visibly show that the values are comparable. By plotting the elevation change along the course of the river the data shows that the areas of net gain are comparable to the areas of net loss. While the Carbon River is visibly aggrading in areas, it also must be incising or eroding in other areas. This is very interesting, especially because the river doesn't appear to be visibly incising in the field, although is very obvious in the LiDAR maps. This seems to be a good indicator that the Carbon River is trying to reach equilibrium, or an overall balance in sediment export.

River Classification

As previously stated, the Carbon River is a dynamic river system. While the river is commonly referred to as a braided river system, there are influences that should change the Carbon's classification. However, these influences are not uniform throughout the watershed. Near the Carbon glacier, steep valley walls constrain the river with a major vegetative influence while near Ipsut Campground the river has a much broader floodplain due to the river being laterally active. Near the park boundary the vegetative influence is much less, and in some areas Engineered Log Jams have been built in order to act as a natural levee to maintaining the course of the river and reduce flooding and expansion laterally. The Carbon River is exporting such a vast amount of sediment, and aggrading at such a high rate, that the vegetation in its path is either demolished completely, or excised into the floodplain and eventually killed. Avulsion channels are very common in the

Carbon River Valley, and it some instances the entire main stem of the river will migrate into these areas.

Overall the Carbon falls into the anabranching category laterally active-gravel dominated channel as defined by Knighton and Nanson (1993), but could be challenged based on the particular reach of the river, and proximity to the terminus of the Carbon glacier. Gravel dominated laterally active anabranching systems commonly have one dominant channel with several anabranches, but may differ between multi and single channel reaches further downstream. The anabranching of these rivers is driven by the need to maintain the transport of bed material in conditions where the load might otherwise accumulate. Avulsion channels commonly incise into the floodplain, but sometimes these channels grow vertically due to stabilization by vegetation within the channel. Gravel dominated stable anabranching rivers contain steep gradients, high stream power, and bouldery alluvium or finer gravels held together by tree roots, which ensure channel stability. Anabranches found in these stable systems are caused by log jams and/or sediment accumulation (Knighton and Nanson, 1996). All of these characteristic most closely match that of the Carbon River.

This lends a clue to the role of old growth to bank stability. As the transport of the bed material reaches areas of lower elevation, the aggraded material is allowed to build up. This accumulation could begin due to the stability from the root systems of the old growth forests in the region, which are eventually suffocated or killed during a flooding event. The autogenic and allogenic influences defined by Francis (2006) are variable based on the proximity to the terminus of the Carbon Glacier, and proved to be unhelpful when examining the Carbon River watershed.

CHAPTER 6

CONCLUSION AND FUTURE RESEARCH

The first goal of this project was to determine an integrated area for two specific areas of the Carbon River. These results show that the two areas are very comparable, and contain a very similar amount of mass. Although the second area near Ipsut Campground contained a higher number of cross sectional surveys, by averaging the values we conclude that the two areas are more similar than they are different. This lends to the theory that although the areas of the river may look drastically different, they contain a nearly same amount of area.

The second goal of this project was to analyze LiDAR returns from 2008 and 2012 to determine which areas are experiencing aggradation and erosion between the two years in which the datasets were collected. Over the four year period, net gain is more prevalent in the area near the Carbon Glacier down to Ipsut Campground. Net loss is not shown until further downstream, closer to the park boundary. The data doesn't lend any clue as to how the added or eroded materials are moving within the channel banks, however, by incorporating more datasets from various years, the results have the potential to become much more accurate. The resulting maps show defined areas as to where the major location of these areas are based solely on the measurements specific to the time in which the LiDAR was flown.

The third and final goal of this project was to determine whether the Carbon River should be reclassified. Again, this system shouldn't be simply referred to as a "braided river" when the influences on this system are countless. The Carbon River should be reclassified as a Laterally-Active Gravel-Dominated Anabranching system. This term encompasses many more of the influences found in the watershed. Future research should strive to determine whether this classification is uniform throughout the river, and if the proximity to the Carbon Glacier would effect this classification.

The Carbon River is clearly a force to be reckoned with, and future research is needed in order to understand the morphology of this river. The ideal study would encompass the entirety of the Carbon River watershed from the Carbon glacier to the boundary. By re-inhabiting exact locations where previous cross sections were taken and comparing numerical data, a more precise rate of change could be detected. Furthermore this data could be compared to LiDAR datasets from additional years, and even cross referenced to geo-referenced aerial imagery of the area before 2008. Predictive modeling using mapping software could also produce results that show the likely future of the river.

Major structural planning should be re-evaluated in the Carbon River Watershed. The location of the Carbon River Road is not maintainable, and in most areas the road will eventually be consumed by the river. In order to plan for the future of the road, and for the future of visitor access, a long term plan should be put in place. Federal regulations were put in place to protect America's parks, but now make it so it would take an act of congress to move the Carbon River Road. With the progression of climate change and glacial ice reduction, planners need to move on this quickly before the entirety of the current infrastructure is consumed by the river.

In conclusion, aggradation is a problem that will not go away. Mount Rainier is an active volcano, but it is also actively weathering. This weathering coupled with climate change, could produce even larger more devastating rates of aggradation. Other rivers in the park that are considered more stable still experience elevated rates of aggradation and bed height. These problems that are associated with this dynamic geologic process must be combatted against presently, otherwise not only visitor access, but also visitor safety could be effected.

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