Aggregation and Avulsions: A Case Study of a Carbon River Floodplain, Mount Rainier National Park, Washington

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Senior Integrative Exercise
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ABSTRACT

The Carbon River flows from the Carbon glacier, a major source of unconsolidated sediment and debris on the northwest face of Mount Rainier. Increased river flow from storms and glacial retreat mobilizes and transports large volumes of sediment into the Carbon River, which fundamentally changes the geomorphic functioning of the fluvial system. The resulting channel aggradation and braiding make the river susceptible to channel shifts and active channel migrations. Throughout the last several decades, the Carbon River's responses to changing inputs of water and sediment have damaged surrounding ecosystems and park infrastructure. Few studies have examined the fundamental drivers of avulsions on the Carbon River. Analyses of historic aerial photographs, LIDAR and DEM imagery, hydrograph data, and field measurements suggest that the most substantial geomorphic change since 1950 has occurred in conjunction with high mean daily discharges. My study area, the Crescent floodplain, in the upper alluvial reaches activated a new channel and changed most substantially between 2006 and 2009, when three of the largest mean daily discharges in history were recorded. Aggradation of alluvial sediment in the main stem of the Carbon River led to the avulsion into the Crescent floodplain during peak flow events. Its location at the outside of a bend and the nearby slope-side tributaries made the Crescent floodplain especially susceptible to an avulsion. Although the active channel of the Carbon River's main stem currently flows along the opposite bank, the defined channel and minimal riparian buffer in the Carbon floodplain make it extremely vulnerable to a future reactivation if peak flows increase in frequency and magnitude as a result of climate change.

Keywords
Mount Rainier, fluvial geomorphology, aggradation, avulsion, climate change, sediment loads, mean daily discharge

INTRODUCTION

Mount Rainier in western Washington has the greatest volume of glacial ice of any mountain in the contiguous United States (Beason et al., 2011). The five major rivers that flow from the glaciers respond sensitively to changing inputs of water and sediment. As glaciers slide atop bedrock, they entrain and transport sediment to moraines, where large volumes accumulate and are easily mobilized into fluvial systems (Czuba et al., 2010). The cascading impact on downstream geomorphology is especially substantial on volcanic glaciers, which carry relatively high loads of sediment (Czuba et al., 2010) (Figure 1).

The flux of sediment and debris entering the fluvial system is influenced by many glacial and paraglacial dynamics, like retreat velocity and debris flows (Church et al., 1972). Retreating glaciers expose large volumes of unconsolidated sediment and alpine glacier thinning results in steep valley walls that are prone to frequent rockfalls with high sediment loads. Furthermore, since high precipitation increases streamflow, more frequent and intense storms have the potential to transport greater volumes of sediment and debris (Lancaster et al., 2012). Thus, as climate change melts glaciers and increases storm frequency, more sediment will likely be exposed and transported into rivers on Mount Rainier.

Downstream geomorphic disturbances have been especially substantial on the Carbon Glacier's fluvial network, which is located on the northwest face of Mount Rainier (Beason et al., 2011). Although the Carbon Glacier has not significantly retreated since 1950, the Carbon River is sediment-retentive and aggrading at an unprecedented rate of 1.7 meters per decade on average (Beason, 2007). In fact, aggradation rates of the past ten years are nearly ten times their historic rate on Mount Rainier (Beason et al., 2011). Sediment aggradation creates disequilibrium in the floodplain and perches the active river channel above the surrounding landscape. The lateral gradient perpendicular to river flow often exceeds the downstream gradient and makes the river susceptible to river channel shifts, or avulsions, as well as active channel migrations. These are especially prevalent on the Carbon River where the river is braided and unconfined, rather than flowing through a fixed channel in the valley.

Aggradation also decreases river conveyance capacity, which increases flood potential. In November 2006 a storm delivered 46 cm of rain in less than 36 hours (Beason et al., 2011). The unprecedented peak in discharge that resulted from the precipitation transported volumes of sediment and raised Carbon River channels one meter, an increase that would typically take 20 years (Abbe et al., 2011). The extensive damage closed the park for six months and cost 36 million dollars (Beason et al., 2011). The 2006 storm was just one of the six largest storms on record at Mount Rainier, all of which occurred in the last 25 years (Parzybok et al., 2009).

Recent findings suggest changing precipitation patterns on Mount Rainier and an increase in the magnitude of floods (Beason et al., 2007). Major storm events contributed 2.5 cm more precipitation, on average, in 2006 compared to 1976. Also, the magnitude of the 100-year flood increased from 387 m^3/s to 626 m^3/s between 1972 and 2009 on the Nisqually River on Mount Rainier (Beason et al., 2011). Some models predict that runoff will increase more than 18% in the next 50 years (Elsner et al., 2010). Floods increase streamflow and discharge, which are correlated with bedload transport (Magirl et al.,

2013) (R^2=.7517). These statistics suggest that channel sediment inputs will continue to increase, which will have major implications for river conveyance capacity, aggradation, and future geomorphic responses.

Previous Studies

Previous studies have researched river responses to changing sediment loads. Rivers with increasing sediment loads tend to actively widen their channels, aggrade, and avulse, regardless of whether they are glacially fed or braided (Czuba et al., 2010, Lyons and Beschta, 1983; Madej and Ozaki, 1996; Miller and Benda, 2000; Lisle, 2008; Pierson et al., 2011). In fact, active channel width is often used as a proxy for the volume of sediment inputs due to the consistency of this correlation. Czuba et al. (2010) found an additional correlation between active channel width and the area of supraglacial sediment mantling the glacier (R^2=.78).

Lyons et al. (1983) found that a single flood event in 1964 resulted in a 25-250% increase in channel widths along Upper Middle Fork Willamette River (MFW) in Oregon. The MFW is not glacially fed so they sourced the increased sediment supply from upstream channel bed material and precipitation-induced landslides. Channel widening and new channel activation were most considerable where slope-side tributaries joined the MFW River's main stem. Thus, they suggest that channels are most susceptible to adjustment during peak flows and at junctions of tributaries and the main stem. Widths decreased again in the years following the flood, which they attribute to regrowth and encroachment of riparian vegetation. Their analysis also supports the correlation between aggradation and channel widening. Two-thirds of the aggraded segments along the MFW River had significantly wider channels than reaches with no aggradation, as proven by field measurements. Thus, they conclude that the avulsions and wider channels following the 1964 storm are a result of increased sediment input.

Pierson et al. (2011) also found major river aggradation, braiding, and channel widening in response to sediment loading after an eruption on Mount Hood. The sediment wave migrated downstream in the years following the eruption event, but maximum aggradation was consistently measured in the upper alluvial reach. They also found that streamflow transported most of the sediment (Pierson et al., 2011).

Madej et al. (1996) found that large floods in three different years led to aggradation, bank erosion, and damage to riparian trees on Redwood Creek, a northern California river that is not glacially fed. Aerial photograph analysis showed a 150-300% increase in channel width in the upper alluvial reach after one storm event in 1964. This widening was in conjunction with a 90% increase in channel-stored sediment in the same reach. The sediment wave has been propagating downstream since this event, suggesting that lower flows can transport sediment, albeit more gradually. However, the amount of aggradation decreases exponentially with increasing distance from the river's head. Thus, this study supports Pierson et al.'s conclusion that channel geomorphic change is largest in the upper alluvial reaches of a river. It also reaffirms that aggradation is driven by changing sediment loads, independent of their glacial or non-glacial source.

Mount Rainier Rivers

The floodplain dynamics of two other rivers on Mount Rainier have previously been characterized: Tahoma Creek and the White River. Frequent debris flows on

Tahoma Creek have transported nearly 10^7 cubic meters of sediment since 1976, and led to floodplain disequilibrium and avulsion susceptibility (Walder, J.S. and Driedger, C.L. 1994). Some areas of Tahoma Creek have widened over 150 meters since 1967 and more than 100 acres of old-growth forest were wiped out by avulsions just in the past ten years. Throughout this decade of avulsion events, the river has flowed through three separate channels in the main stem (Walder, J.S. and Driedger, C.L. 1994).

The White River's riverbed is 4.9 meters higher than surrounding forest in some areas, largely due to a sequence of rockfalls and debris avalanches that transported sediment into the fluvial network in 1963 (Czuba et al., 2010). However, the White River's riparian forests have more successfully contained channel migration and prevented avulsions. When the trees uproot and fall into the active channel, they form logjams and deflect flow away from the banks (Abbe et al., 2011).

The Carbon River valley seems to be responding similarly to the MFW River and Redwood Creek and in an "intermediate stage" between Tahoma Creek and White River, though its dynamics have not been closely studied. The Carbon River is bigger than Tahoma Creek and has the potential to cause more major and widespread geomorphic disturbance, especially if the intensity of storms and peak flow continue to increase. Furthermore, the Carbon River's upper alluvial reach has a comparatively high residence time for sediment. Czuba et al. (2010) found that, on average, sediment remained stable in the Carbon's riverbed for 38 years, compared to .5 years in the White River. Additionally, unlike Mount Rainier's other major rivers, few major debris flows have been recorded on the Carbon River throughout the Holocene (Czuba et al., 2010).

The Carbon River's proximity to sensitive ecosystems and park infrastructure raises further concern. Acres of riparian old-growth forests have been compromised and many endangered species, like northern spotted owls and marbled murrelets, depend on these forests for nesting. Thus, an assessment of the Carbon River's susceptibility to avulsions, erosion, debris flows, and flooding will provide crucial information for the park to aid development and implementation of plans to protect ecosystems and infrastructure.

Purpose and Scope

My case study focused on a floodplain in the Carbon River, located about two kilometers downstream of the Carbon Glacier (Figure 2). Thus, it is an example of floodplain response in the upper alluvial reaches of a glacially fed river. My study used aerial imagery, mean daily discharge data from USGS hydrographs, light detection and ranging (LIDAR) data, digital elevation model (DEM) images and field measurements to piece together the geomorphic story of this area. In this paper, I describe and analyze changes in the floodplain between 1950 and today, and associated adjustments of the active river channel. I explore the role that old-growths and natural logjams may have played and I identify the controls to aggradation and incision at different parts of the floodplain. Understanding these various elements allow me to characterize what factors made this floodplain susceptible to an avulsion and the formation of a new channel. My conclusions on this area are likely representative of Carbon River dynamics elsewhere and can then help the park identify other areas at risk and make predictions, especially as the climate continues to change.

STUDY AREA

Mount Rainier

Mount Rainier, located in the Cascade Range of western Washington, is a recurrently active, andesitic stratovolcano rising 4,392 meters above sea level (Czuba et al., 2010). Its volcanism is produced by the subduction of the Juan de Fuca plate under the North American plate and it has erupted at least 10 times in the past 2,600 years. Its most recent magmatic eruption was about 1,000 years ago (Sisson and Vallance, 2009). The mountain's close proximity to the Seattle-Tacoma metropolitan area makes it one of the most potentially deadly volcanoes in the United States. The 25 glaciers on the mountain cover about 36 square miles of the mountain's surface and make up the largest volume of glacial ice in the contiguous United States (Beason et al. 2011; Driedger and Kennard, 1986). Five major rivers drain from the glaciers (Lancaster et al., 2012).

The Carbon River

The Carbon River Valley, located on the northwest side of Mount Rainier, was formed during the repeated advancement and retreat of glaciers throughout the Pleistocene (Czuba et al., 2010). The characteristic pro-glacial valley is U-shaped with steep sides. It has a convex cross-section, due to the high sediment inputs and aggradation tendencies. The Carbon glacier terminates at the lowest elevation of any glacier in the contiguous United States, and sources the pro-glacial, braided Carbon River (Czuba et al., 2010). It carries the largest area of supraglacial sediment of any glacier in the park from the peak of Mount Rainier to the Puget Sound in Tacoma, Washington (Magirl et al., 2013). It is one of three major rivers that make up the Puyallup River watershed (Czuba et al., 2010).

Unaware of the Carbon River's avulsion susceptibility, the park constructed a scenic riverside road in the early 1900s. Completed in 1924, it paralleled the Carbon River all the way to the Carbon Glacier (Burtchard et al., 2011). However, the road was damaged in multiple floods and the main river channel rerouted down the final three-mile stretch to the glacier in the 1950s. The river is currently flowing in areas that used to be road (Burtchard et al., 2011).

The location and topography of the Carbon River valley provide habitat for old-growth rainforests. Thousand-year-old Douglas fir, western red cedar, and western hemlock all inhabit the riparian landscape (Burtchard et al., 2011). Historically, these forests have controlled and confined river channel movement. However, the forests cannot withstand mediums sized avulsions and new channels are actively forming in the forests. Old-growths that historically lined the banks are now found in the middle of the river in many places (Figure 3). Also, large pulses of water and sediment deprive the trees of nutrients and oxygen, and eventually undermine the root systems, causing the trees to uproot and fall. Sturdy trees often create natural logjams as downed wood and alluvium build up behind them. These further alter the path of the river. Ghost forests, where avulsions wiped out old-growths, are found throughout the Carbon River floodplain.

Crescent Floodplain

The Crescent floodplain is located about two kilometers downstream of the Carbon glacier (46° 57' 33.520" N, 121° 47' 33.951" W). It is located at the outer bend of the Carbon River's largest bend (Figure 2). The river veers to the left by nearly 180 degrees directly after flowing past Crescent. The floodplain is about 300 meters long with an average longitudinal gradient of 5.5 degrees. The longitudinal gradient is shallowest at the entrance and exit of the floodplain, about 3.3 and 2.5 degrees respectively. Along the floodplain's length, the gradient varies from 4.2 to 10.4 degrees.

HYDROGRAPH DATA

I compiled all of the daily discharge graphs for each year from 1930 to 2013 measured at the USGS 12094000 Carbon River gage near Fairfax, Washington. The daily discharge is measured in cubic feet per second (CFS). Data were not available prior to 1930 and were missing from 1980-1989. Additionally, this gauge is located about 26 km downstream of the Crescent floodplain and may not be exactly representative of mean daily discharge there.

In this paper, a mean daily discharge that exceeds 6,000 CFS is considered a flood. While there don't appear to be any significant trends in mean daily discharge between 1930 and 2013, the frequency and magnitude of peak events seems to have increased since 1990. Mean daily discharges between 1990 and 2013 surpassed any previous values for mean daily discharge at least five times (Figure 4). Prior to 1990, mean daily discharge reached 7,000 CFS only once, in 1933. However, mean daily discharge surpasses 7,000 CFS five times after 1990: in 1995 (over 7,000 CFS), 1996 (nearly reaches 10,000 CFS), 2006 (reaches 10,000 CFS), 2008 (reaches 7,000 CFS), and

2009 (reaches 9,000 CFS). However, since the large event in January 2009 (9,000 CFS), daily discharge has remained below 4,000 CFS. Aerial photographs support these statistics as the Crescent floodplain is relatively stable between 1930 and 2006 and after 2009. The greatest change in the Crescent floodplain occurs between 2006 and 2009, when the USGS measured three of the largest floods in history on the Carbon River.

Year	**CFS (Cubic feet per second)**
December 1933	7,000
December 1955	7,800
December 1977	6,000
November 1995	7,500
February 1996	9,900
February 2003	6,000
February 2005	6,000
November 2006	10,000
November 2008	7,000
January 2009	9,000

Table 1. All mean daily discharges since 1933 that surpass 6,000 CFS. Seven of the ten peak floods were recorded in the two decades. Data recorded at the USGS 12094000 Carbon River gage at Fairfax.

HISTORIC AERIAL IMAGERY

I compared historic aerial photographs to see the temporal and spatial dynamics of the channel in the Crescent floodplain through time. I specifically looked for the formation and abandonment of channels, changes in vegetation density and floodplain boundaries, tributary dynamics, and head-cut migration. Aerial imagery prior to 1994 has poor quality, although there appear to be no major changes in or near the Crescent floodplain between 1957 and 1994. Thus, my analysis focuses on aerial imagery from 1994, 2003, 2006, 2009, and 2013. The 2006 and 2009 photographs were downloaded from USGS Earth Explorer and geo-referenced in GIS. The 1994 and 2003 photographs were taken from Google Earth and geo-referenced. The 2013 photograph was retrieved from an aerial basemap on GIS.

NOTE: The main stem of the Carbon River refers to the braided main channel that is unvegetated in all aerial photographs. The active channel of the main stem is the particular braid through which the largest volume of water is flowing (Figure 14).

1955 (July)- 2003 (June)

The active channel of the Carbon River appears to remain river right in three aerial photographs (1957, 1969, and 1970) between 1957 and 1970 (Figure 5). By 1994, the active channel has migrated river left and occupies the center of the un-vegetated channel (Figure 6). However, in 2003, the active channel has returned river right and borders the riparian floodplain margin of Crescent (Figure 7).

The Crescent floodplain was thickly vegetated in all aerial photographs prior to 2009. Several small bare areas are visible throughout the study area in these years. Abbe et al. (2011) suggests that avulsion channels less than 8 meters wide are not visible in aerial photography and thus, these may indicate small-scale avulsion channels that are not clearly visible in the air photos. Alternatively, they simply may be a result of a tributary that flows through the Crescent extent.

Compared to 1994, the floodplain in 2003 is more densely vegetated and the riparian forest near Crescent extends farther into the riverbed, resulting in a more vegetated and narrower main channel (Figure 8). The vegetation encroachment between 1994 and 2003 suggests more stability during these years. Although USGS data show flood events in 1995 and 1996 (peaks of 7,000-10,000 CFS), discharge remains below 4,000 CFS from 1997 to 2003, which likely allowed alders and other vegetation to repopulate.

2006 (July)

Between June 2003 and July 2006, nearly all of the younger vegetation visible in the 2003 aerial photograph disappeared (Figure 9). This period includes an event in January 2005 that produced a relatively large daily discharge of 6,000 CFS. Assuming the active channel still flowed along the right riparian margin in 2005 as it did in 2003, high flows would have easily flowed over the margin, undermining and obliterating these trees.

The main stem of the active channel migrated river left by July 2006. There are a few smaller, active braids flowing toward Crescent and there are small openings in the floodplain forest canopy where they enter. The vegetation appears to be shorter overall at the floodplain margin.

A non-vegetated area not visible in the 2003 aerial is present at the lower boundary of Crescent in 2006, at the confluence of a slope-side tributary (Tributary 2) and the unvegetated active channel. Another slope-sourced tributary (Tributary 1) meets the main channel almost exactly at the upper boundary of Crescent, and then appears to flow along its longitudinal extent. The largest unvegetated opening in the forest canopy in 2006 is where the two tributaries and the main channel all meet (Figure 9).

2009 (June)

The Carbon River changed greatly between July 2006 and June 2009 (Figure 10). In some places, the main channel is more than twice as wide as it was in 2003. The Crescent floodplain study area is completely unvegetated and a channel has formed along its extent. The channel's main path seems to follow tributary 1 and it does not appear to be active. Large downed old-growths and a large logjam are present near where tributary 1 meets the new channel. The active channel of the main stem has migrated to river left. Also, many of the slope-side tributaries are more visible on the 2009 aerial, suggesting higher flows have incised these and damaged vegetation since 2006. Since these tributaries are slope-sourced and not fed from the Carbon Glacier, precipitation must have been a main factor.

2013 (August)

In August 2013, the Crescent floodplain appears to have similar dimensions to 2009 and there don't appear to be any drastic changes (Figure 11). The flood record supports this as mean daily discharges are relatively low in these years, ranging from 2,000 to 4,500 CFS.

LIDAR AND DIGITAL ELEVATION IMAGES

I analyzed a LIDAR differencing image, which is based off two DEM images, to understand the channel's dynamics between 2008 and 2012 (Figure 12 and Figure 13). In the LIDAR, red areas are erosion and green areas are aggradation. Visible changes denoted by the LIDAR images suggest that the channel has been changing between 2008 and 2012, even though it has not been active in several years.

The LIDAR differencing map shows a clear path of aggradation in the channel, with erosional bank retreat at the floodplain margins. This was visible in the field, where I saw actively eroding hill-slope in many places (Figure 15). Also, channel aggradation downstream of the eroding hill-slopes was largely made up of angular clasts, suggesting these sediments were sourced from the hill-slopes and were not alluvial.

One major area of erosion was river right of the large downed old-growth. When the channel was active, the old-growth likely deflected the river to the right, causing the flow to strongly incise the hill-slope here. There is also major erosion on the hill-slopes near the outlet, which is especially visible in the 2012 DEM. There is a long stretch of undermined terrace, which has contributed a few large boulders and trees (Figure 15).

FIELD METHODS

I did reconnaissance of the floodplain, during which I defined the upper and lower limits of the study area. I divided my floodplain into four relatively homogenous sections and measured:

1. Channel horizontal width (bank to bank, meters)

2. Channel depth (meters)

3. Channel and valley longitudinal/downstream gradient (degrees)

4. Valley lateral gradient (degrees)

5. Wood survey (down and standing, live and dead wood counts)

6. River bed particle size

I used these field measurements to define the most recent flow path through the channel and also to determine what factors influenced the avulsion's path. Finally, I took GPS points of notable features like head-cuts, natural log jams, tributaries (draining valley walls), and large downed old-growth trees (>1 m diameter) (Figure 14).

FIELD RESULTS

Field results are displayed in Figure 15. The channel is narrowest at the inlet and outlet (Figure 14: GPS points 4 and 13), measuring 10 and 20 meters respectively and widest (70 m) about halfway down the length of the channel, in section C (Figure 14 and Figure 15). The banks are highest near the outlet where an eroding terrace had a height of about 3 m. The longitudinal gradient is shallowest at the inlet and outlet (2 to 3 degrees in sections A and D) and steepest about halfway down the length of the channel (10.4 degrees in Section C).

The main stem has a longitudinal gradient of 5 degrees and a lateral gradient of 3.5 degrees (GPS 2 to 1 and GPS 2 to 4, respectively). Although the lateral gradient does not exceed the longitudinal gradient here, the negative gradient between GPS 2 and GPS

4 indicates the main stem is perched above the Crescent channel. The main stem was dominated by imbricated, rounded cobbles, suggesting an upstream source.

I found a major log jam of downed old growth trees in section C, which contains more than 20 downed trees with a diameter breast height (DBH) less than 1/2 meter and about 50 downed trees with a DBH greater than 1/2 meter. The high concentration of large downed old growth trees provides evidence for high volumes of fast-moving water. Also, the logjam likely deflected water and dictated the path of water following their fall.

The height and DBH of the standing alders populating the small, vegetated island in section B provide evidence for the last major, destructive flow as they likely repopulated following such an event. Also, cobbles on this island were moss-covered, implying that the sediment here had been sedentary for some time.

There are concentrations of pebbles, cobbles, and boulders deposited throughout the channel; clast observations were most useful in determining whether sediment was alluvial or colluvial. Small sediment waves and elevated gravel bars provided additional evidence for the most recent flow path.

Finally, I found several small channels entering Crescent through the forested margin from the unvegetated main channel. There is also a filled in head-cut hidden in the vegetation near the inlet (GPS 5).

DISCUSSION

If climate changes on Mount Rainier in the future, storm events producing rainfall at high elevations may increase in frequency and magnitude and accelerate melting, likely resulting in higher peak river flows carrying larger volumes of debris (Beason et al., 2011). Analysis of the Crescent floodplain provides an emblematic case study of geomorphic change in the Carbon River. As I have discussed, the Carbon River's perched, braided river channel and its trend of aggradation have changed the fundamental functioning of the system. Aerial photograph analysis, LIDAR and DEM data, flood data, and field measurements and observations have helped me characterize and explain geomorphic change in the Crescent floodplain since the mid-twentieth century. These analyses suggest that many variables, like main stem aggradation, river discharge rates, location, nearby tributaries, and storm events have dictated the geomorphic responses and associated landscape adjustments in the Crescent study area.

Geomorphic Change between 1957 and 2009

Aerial photographs from 1957-2003 show active channel migration across the main stem of the Carbon River, but channel width and riparian vegetation density appear unchanged. The active channel that migrates across the main stem is natural in a braided river with little vegetation and non-cohesive banks and beds. The river did not create new channels outside of the main stem, in the riparian floodplain, during this time. Additional data show that the main stem only widened 6 meters, on average, between 1965 and 1994, reflecting the Carbon River's relative stability during these decades (Czuba et al., 2012). The small variances in the locations of vegetation margins are likely due to the migrating active channel.

The openings in the forest canopy and the loss of vegetation around Crescent in 2006 indicate a minor avulsion occurred since 2003. The hydrograph data recorded an event in January 2005 that produced a flood of 6,000 CFS and likely activated this channel at the lower end of Crescent (Figure 9). Also, the new channel formed exactly where the active river channel bordered the Crescent riparian margin in 2003, which likely made this area especially susceptible to an avulsion.

The Crescent floodplain was completely unvegetated in 2009 and the main stem in the upper alluvial reach had widened an average of 45 meters since 1994, equating to a 30 percent increase in only 15 years (Czuba et al. 2008). These data suggest that the channel through the Crescent floodplain was activated between 2006 and 2009. While I cannot conclude that the the record-breaking 2006 flood alone led to the avulsion, it was likely a main factor. Two more extreme events closely followed the 2006 flood: in November 2008, mean daily discharge reached 7,000 CFS and in January 2009, mean daily discharge reached 9,000 CFS. Without aerial photographs in these years, it is difficult to determine whether the Crescent channel was active during all of these events. However, the active channel migrated completely across the main stem of the Carbon River to river left by 2009, suggesting that Crescent was deactivated in an earlier year between 2006 and 2009 (Figure 10).

Avulsion in the Crescent Floodplain: The Crescent Channel

Daily discharge measurements fluctuate depending on precipitation variations and inputs of glacial meltwater. I lack evidence to delineate whether increased flood magnitude is due to high precipitation, increased glacial melting and run-off, or a combination of these. However, previous studies found that regardless of the source, major storms transport large volumes of sediment into rivers (Lyons et al., 1983 and Madej et al., 1996). Thus, I speculate that the floods during storms in 2006, 2008, and 2009 increased the sediment supply to the Carbon River and led to the avulsion into the Crescent floodplain.

This conclusion is supported by field observations. The lateral gradient from the center of the main stem to the Crescent was negative, confirming that the main stem is perched above the Crescent floodplain (Figure 17). This reaffirms previous studies that found most substantial aggradation in the upper alluvial reaches of rivers (Pierson et al., 2011 and Madej et al., 1996). The increased sediment loads transported by the floods likely aggraded in the main-stem channel near Crescent, increased river bed elevation, decreased flow-conveyance capacity, and caused an avulsion into the Crescent floodplain.

Additionally, the Crescent floodplain's location on the outside of a major bend on the Carbon River likely made it especially susceptible to an avulsion during high flows, as fast-moving and highly energetic water would have impinged against the floodplain banks and riparian margin here. The slope-side tributaries that meet the Carbon River near this area likely further encouraged an avulsion, as supported by the findings of Lyons et al. 1983. Tributary 1, in particular, flows almost exactly along the path of the avulsion channel through Crescent (Figure 16). A pre-existing tributary channel would provide an easy, unvegetated path for an avulsing river.

Finally, sediment in the main stem was imbricated and round, suggesting the aggrading loads were sourced from the glacier or paraglacial area upstream, and not from side-slope debris flows.

Recent Geomorphic Change and Future Predictions

The relative stability in the floodplain since 2009 is supported by a lack of floods in these years and the absence of water in the channel in the 2009 aerial photograph. However, the LIDAR and DEM images show that there is still active erosion and deposition occurring, despite the channel's inactivity. As the hill-slopes continue to erode along Crescent, they add more old-growth trees, boulders, and sediment into the Crescent channel. These will be transported into the main stem of the Carbon River if Crescent is reactivated, contributing an additional source of sediment inputs to a system already in a sediment-surplus state.

Additionally, the active erosion weakens the vegetation and sediment on the banks, making them very susceptible to undercutting in a reactivation event. The area of vegetation separating the Crescent channel from the main channel is narrow, furthering the likelihood of it being undermined completely. Thus, the Crescent floodplain's location at the outside of a bend and its defined channel with a undeveloped riparian buffer make it extremely vulnerable to a future reactivation.

Major channel widening and avulsions near the Crescent floodplain occurred during large flood events. My analyses suggest that geomorphic change in the Crescent floodplain was largely influenced by mean daily discharge, and the accompanying and cascading effects of floods (Figure 1). Floods transport large volumes of sediment into the fluvial system, which likely fundamentally drive avulsions on the Carbon River as they aggrade in river channels. Because the Carbon Glacier has not been significantly retreating since 1950, mean daily discharge, and thus, sediment loads and aggradation, are largely influenced by precipitation and storm events. Since aggradation is the primary driver of avulsions and active channel migration, understanding the changing dynamics of sediment loads, precipitation, glacial retreat, and flood peaks that result from climate change on Mount Rainier will be crucial in the future.

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