

FLUVIAL BIOGEOMORPHIC EVOLUTION OF THE UPPER SOUTH FORK TOUTLE
RIVER, WA AFTER THE 1980 ERUPTION OF MOUNT ST. HELENS

by

SARAH K. PROCTOR

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THESIS APPROVAL PAGE

Student: Sarah K. Proctor

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This thesis has been accepted and approved in partial fulfillment of the requirements for the Master of Science degree in the Department of Geography by:

Mark Fonstad	Chairperson
Patricia McDowell	Member

and

Scott L. Pratt	Dean of the Graduate School
----------------	-----------------------------

Original approval signatures are on file with the University of Oregon Graduate School

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THESIS ABSTRACT

Sarah K. Proctor

Master of Science

Department of Geography

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Title: Fluvial biogeomorphic evolution of the upper South Fork Toutle River, WA after the 1980 eruption of Mount St. Helens.

The eruption of Mount St. Helens in 1980 severely impacted the woody vegetation within the geomorphic floodplain as well as the morphology of the Upper South Fork Toutle River. Historic aerial imagery and LiDAR data were used in combination to create snapshots of the channel and vegetation in 1980, 1983, 1996, 2003, and 2014. This data was mapped and analyzed using GIS, with the primary focus on 2D channel change, vegetation change, and channel-vegetation interactions from 1980 to 2014. No vegetation was discernable in 1980-83 but the vegetation present in 1996 increased in area and in density from 1996 to 2014. The number of channels locations were dependent on vegetation density and presence while vegetation growth occurred predominately in areas previously occupied by the channel.

CURRICULUM VITAE

NAME OF AUTHOR: Sarah K. Proctor

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene, OR
Lane Community College, Eugene, OR
Oregon State University, Corvallis, OR
Cottey College, Nevada, MO
Seattle Pacific University, Seattle, WA

DEGREES AWARDED:

Master of Science, 2016, University of Oregon
Bachelor of Science, 2012, University of Oregon

AREAS OF SPECIAL INTEREST:

Geography
Geographic Information Systems
Remote Sensing
Cartography
Fluvial Geomorphology

PROFESSIONAL EXPERIENCE:

APRS Library Technician 3, University of Oregon, Present
Graduate Teaching Fellow, CASIT, University of Oregon, 2013-2015
Field Work Researcher, University of Oregon, Department of Geography, 2013
Graduate Teaching Fellow, Department of Geography, University of Oregon, 2012-2013
Research Assistant, University of Oregon, 2012
InfoGraphics Lab Student Assistant, University of Oregon, 2010-2012

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CHAPTER I

INTRODUCTION

Vegetation has long been proposed as a key factor in the formation of braided channels (Bertoldi et al., 2009; Coulthard, 2005; Francis and Gurnell, 2006; Kollman et al., 1999; Millar, 2000; Murray and Paola, 2003; Tal and Paola, 2007; Zanoni et al., 2008; and others). Plant growth can increase bank strength due to root enforcement; vegetative cover increases drag and reduces local velocity and can anchor or cover sediment on islands or floodplains, reducing the probability of channel formation in that area (Abernethy and Rutherford, 2001; Eaton and Giles, 2009; Gran et al., 2015; and others).

In general, an increase in vegetation tends to result in the evolution of a braided channel into a single, meandering channel (Gurnell, 2014). Braided channels are dynamic, characterized by multiple channels that, relative to single threaded channels, have high lateral migration rates (Gran and Paola, 2001), and contain vegetated islands (Edwards et al., 1999; Gran et al., 2015). Bank strengthening and stabilization provided by vegetation growth opposes channel migration tendency (Gran and Paola, 2001) but island formation depends on biotic-abiotic feedbacks (Francis et al., 2009).

The main mode of instability for unconstrained flow over non-cohesive sediment is braiding (Gran et al., 2015). Vegetation expansion into areas of the floodplain with inactive braids is relatively easy and can lead to the emergence of one or two dominant channels (Gran et al., 2015). As river systems become less active, such as a few years after a major volcanic eruption, vegetation begins to play a larger role in overall channel formation (Gran et al., 2015).

Vegetation density changes may be caused by water discharge, climate changes, or sediment discharge (Gran and Paola, 2001). The ‘fluvial biogeomorphic succession model’

(Corenblit et al., 2007) suggests that there is a bi-directional relationship between vegetation community development and landform (Schnauder & Moggeridge, 2009). Additionally, fluvial islands that form in the presence of vegetation are relatively unstable over time (Osterkamp, 1998). Instances of high degrees of island turnover and movement have been documented on the Tagliamento River, Italy (Arscott et al., 2002). Habitat configuration and composition of the Tagliamento River stayed relatively stable in direct contrast to the considerable changes in location of aquatic habitat in the floodplain (Arscott et al., 2002). It has been noted that channel migration can be a major determinant of landscape and biotic diversity; periodic disturbances, like flooding, allow for changes in channel location and potential increases in plant colonization and growth (Shankman, 1993).

Relatively few rivers have experienced the sort of large-scale natural disturbances over a short period of time that are characteristic of volcanic eruptions. The Upper South Fork Toutle River (USFTR) in Washington, USA is one of the river reaches most affected by the major eruption of Mount St. Helens in 1980. Due to its remote location and lack of human disturbance, the USFTR has become an important reference for natural channel recovery and vegetation growth after a major volcanic eruption. This paper presents preliminary results from research performed on the USFTR, focusing on vegetation growth and recovery as well as channel formation and evolution over the past 35 years. In particular, the following research questions were the framework for this research:

1. How has the spatial distribution of vegetation changed from 1996 to 2014?
2. In what 2-dimensional ways has the Upper South Fork Toutle River channel changed since 1980?

3. In what ways has vegetation growth have affected channel morphology and floodplain turnover rate between 1980 and 2014?
4. How has channel evolution have affected the spatial distribution of riparian vegetation between 1980 and 2014?

Change analysis based on aerial imagery has been performed on many rivers for time periods of varying scale (O'Connor et al., 2003; Zanoni et al., 2008; Caruso et al., 2013 and others). Long-term change analysis (50 to 100 years) can capture many processes that occur on a variety of time scales (O'Connor et al., 2003). For this research, data is available for the past 35 years. This small period of time experienced a large amount of change and the natural disturbance of 1980 allows for a unique opportunity to study large-scale changes over a small time scale in a reset landscape (Dale et al, 2005).

An important aspect of this research is the quantification and measurement of channel morphology. The influx of sediment on the Upper South Fork Toutle River allowed for the examination of how spatial patterns of river bed morphology evolve over time (Lane et al., 2010). The Upper South Fork Toutle River Valley experienced an abrupt increase in sediment supply as a result of the eruption (Major, 2004). This sediment has steadily moved downstream over the past 35 years (Meyer & Martinson, 1989; Major et al., 2000; Major et al., 2015). Lateral migration of the most active tract of the channel was most likely the primary mechanism of sediment transport and floodplain erosion (Reinfelds & Nanson, 1993). The channel itself seemed to transition over time from braided to anastomosing, based on typical definitions of alluvial channel patterns (Schumm, 1985).

The eruption of Mount St. Helens in 1980 provided the basis for decades of research regarding landscape evolution recently after a natural disaster. Lahars, or volcanic debris flows (Smith, 2014) swept through the North and South Fork Toutle River valleys, “veneering” existing topography (Pierson & Major, 2014); whole forests burned or were swept away, and several people lost their lives. The pyroclastic surge (and resulting debris flows) was a very short-lived event (Major et al., 2005). A single, sharp-crested mud flow peak was created as a result of the collection of water-saturated ejecta in the South Fork Toutle River valley (Janda et al., 1981). The average velocity of the lahar flows on the South Fork Toutle River was around 31 m/s (Janda et al., 1981). The South Fork experienced smoothing, widening, and straightening as well as its gravel-bedded pool-riffle system changed to a sand-bedded corridor stripped of riparian vegetation (Major et al., 2010; Meyer & Martinson, 1989).

Following the 1980 eruption, the Upper South Fork Toutle River was a very active system (Major et al., 2000). From 1982 to 1999, the South Fork Toutle River had an average annual suspended sediment yield of 15×10^6 Mt resulting from stormflow (Major et al., 2000, Figure 1). The large influx of fine sediment into both river valleys created opportunities to study how river channels reform after a volcanic eruption. Many studies have been performed on the North Fork Toutle River but little to no research has been done on the South Fork Toutle River. Thus, it has been increasingly necessary to begin to understand how the smaller of the two river valleys has changed since 1980.

Analysis of this change was performed through examination of historic aerial photos gleaned from the archives of the USGS Volcano Observatory in Vancouver, WA. These air photos provide a glimpse into the past at how the eruption influenced the channel pattern and

vegetation formation of the area over the last 35 years. Digitization of the geomorphic floodplain, vegetation, and channel has allowed for a comprehensive, simplified visualization of change over time.

Numerous studies have illustrated the importance and effectiveness of historic aerial photograph analysis for change detection (Lane et al., 2010; Manone, 2004; Zanoni et al., 2008; Kollmann et al., 1999; O'Connor et al., 2003 and others). While many studies utilized imagery for 3D elevation model derivation, this study used aerial imagery to provide a baseline of data for basic channel characteristics from 1980 to 2014.

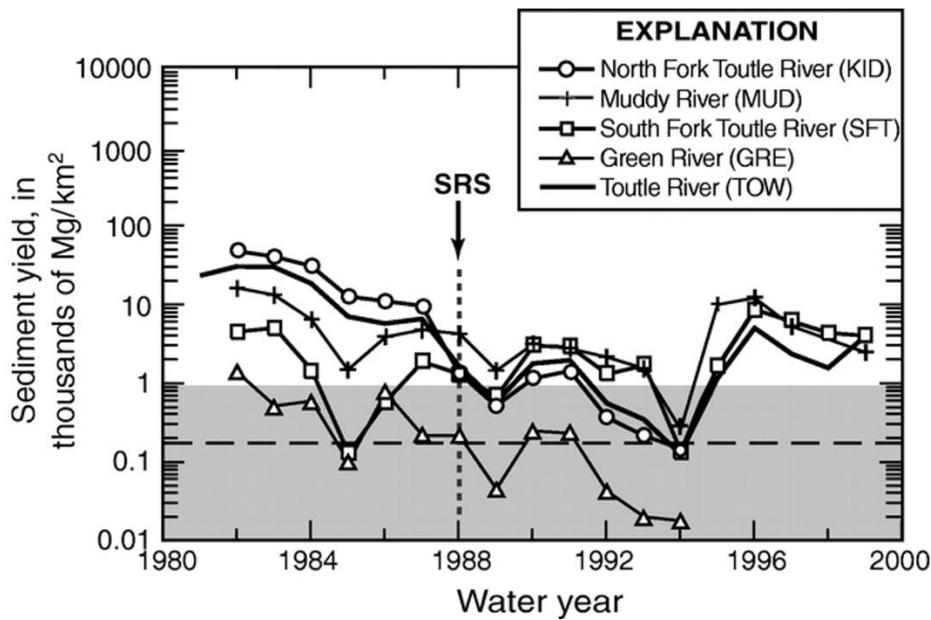


Figure 1. Annual Suspended Sediment Yields at Mount St. Helens. The dotted line shows the year the Sediment Retention Structure was placed on the North Fork Toutle River. From Major et al. 2000.

CHAPTER II

STUDY AREA

The Toutle River system is situated in the Cascade Range of southwestern Washington (Figure 2), with Mount St. Helens currently the most active and relatively young in relation to those in the range (Major et al., 2010). A patchwork of forested and clear-cut land in varying stages of reforestation surrounded the mountain before the eruption in 1980; the undisturbed slopes of the South Fork Toutle River did not show significantly-impacted forest vegetation (Dale, 1988). The river's headwaters are located on the north and west flanks of Mount St. Helens. The total mountainous area drained by this river system is 1,330 km² (Simon, 1999).

Pleistocene-glaciated Tertiary volcanic and metavolcanic rocks eroded to become the valleys (as cited in Simon, 1999). Narrow bedrock gorges separated broad alluvial reaches on the South Fork Toutle River pre-eruption (Simon, 1999). Average upland-hillslope gradients range from 20% to 30% and local relief ranges from 400m to 700m (Simon, 1999).

Climate and hydrology

Around 75% of the annual precipitation occurs between October and March; approximately 95% of the recorded annual flood peaks result primarily from rain-on-snow events between November and February (as cited in Zheng et al., 2014; Simon, 1999). Seasonal snow pack during most winters develops at around 1,000 meters and above (Simon, 1999).

The study area within the Upper South Fork Toutle River (46°14'7"N, 122°29'24"W to 46°12'46"N, 122°14'8"W), is located on the western flank of Mount St. Helens (Figure 2). This is the upper portion of the river, river kilometer 0-18.0 (Figure 3). This is a difference of 13.4 kilometers compared to the delineation made by Simon, 1999, who classified the Upper South Fork Toutle River as river kilometer 0-31.4 (no reasoning was given). Topographic constriction

was the main reason for this difference. Channel and geomorphic floodplain constriction was great enough downstream from river kilometer 18.0 that channel morphology transitioned from braided to a single channel. The larger area of geomorphic floodplain between river kilometer 0 and 18.0, presence of riparian vegetation, and close proximity to Mount St. Helens allowed for greater visualization of channel and riparian vegetation changes from 1980 to 2014. Total drainage area for the Upper South Fork Toutle River is 166.5 km², while the total drainage area of the South Fork Toutle River is 336.6 km².

The valley of the Upper South Fork Toutle River is characterized by flat bottoms with an average width of approximately 800 meters (Simon, 1999). This section contains steep channel gradients ranging from .014 to .24 m/m (Simon, 1999). The channel was hydraulically “smoothed” by the passage of the two main lahars (Simon, 1999). These changes can be seen in the cross section data gathered pre- and post-eruption (Figure 5). All of the cross sections show areas of deposition in 1980 and cross section B-1 shows how some locations experienced some scour as a result of the fast-moving lahars.

The river is home to a variety of fish species, including *Oncorhynchus mykiss* (Steelhead), *Oncorhynchus kisutch* (Coho Salmon), and *Oncorhynchus tshawytscha* (Chinook salmon). It is one of two major rivers to be significantly affected by the eruption of Mount Saint Helens in May of 1980, the other being the North Fork Toutle River. This section of the river contains braided reaches and merges into a single channel when the river valley becomes restricted resulting from steeper valley wall topography (Simon, 1999). This morphology existed pre- and post-eruption.

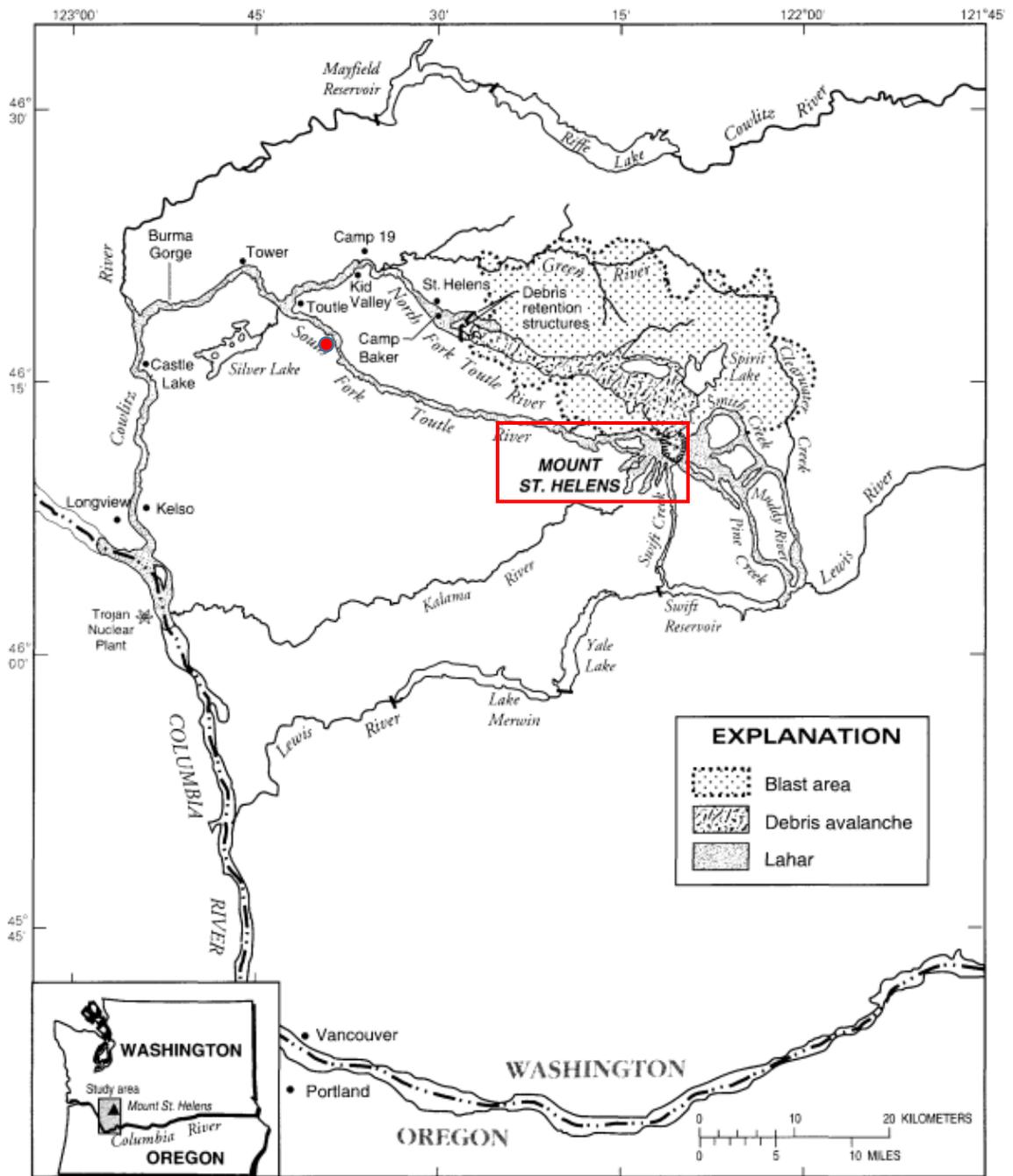


Figure 2. Map showing the location of the study site (red box) and gaging station 14241500 (red circle) within the Cascade Range in Washington State, USA (map from Simon, 1999).

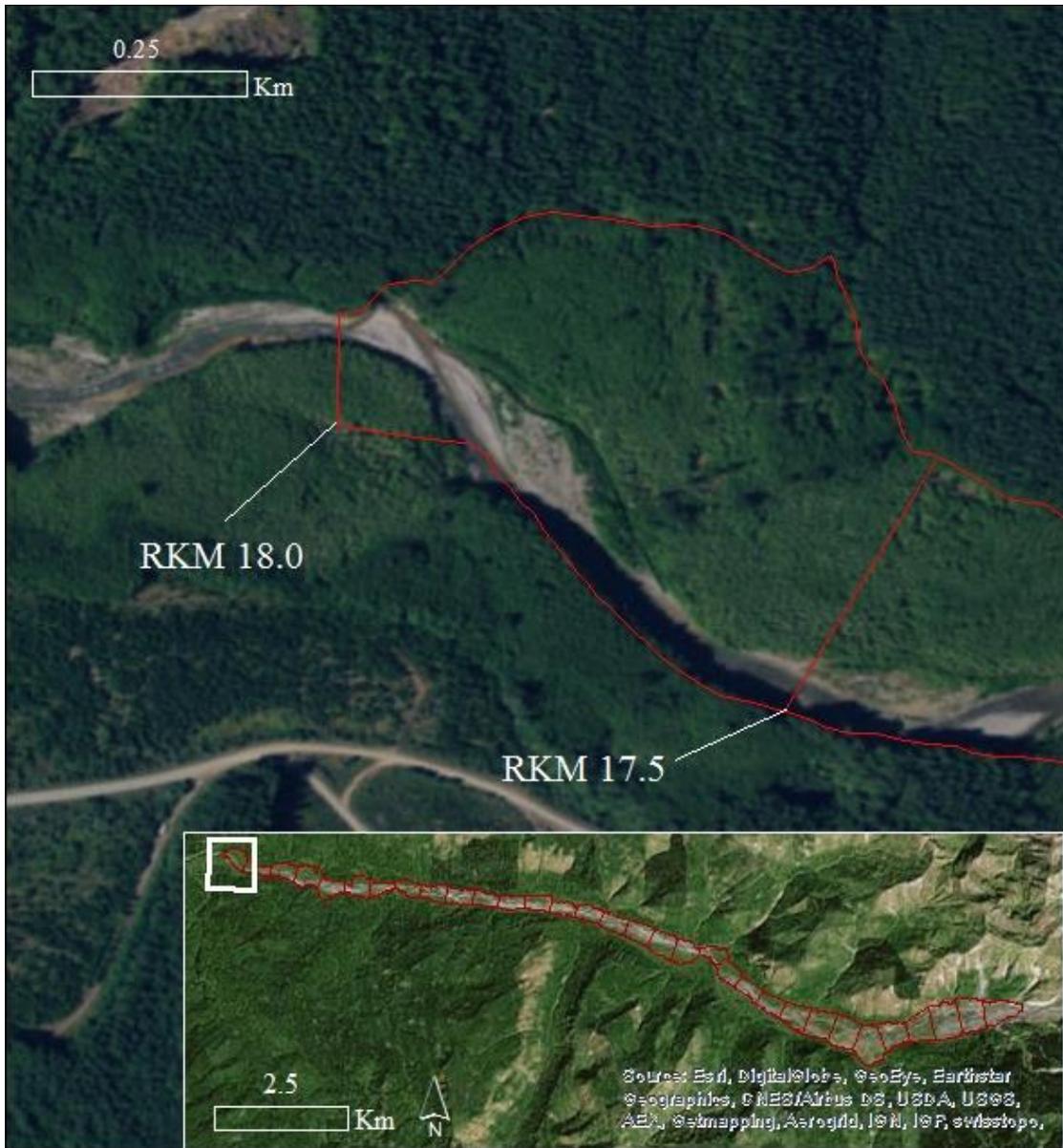


Figure 3. Map showing the confined topography at River Kilometer 18.0.

Herbaceous vegetation and woody shrubs form a short ground layer which was least disturbed by the eruption of Mount Saint Helens (Del Moral, 1983), with growth of *Blechnum spicant* (Deer Fern), *Spirea douglasii* (Douglas Spirea), *Mahonia aquifolium* (Oregon Grape), *Equisetum palustre* (Marsh Horsetail), and *Cytisus scoparius* (Scotch Broom), both before and after the eruption. Dominant tree species include *Populus trichocarpa* (Black Cottonwood), *Betula pendula* (European White Birch), and several species of fir (including *Abies procera* (Noble Fir) that were planted by the lumber company Weyerheuser shortly after the eruption). Dense coniferous forests characterized the Toutle River Basin, dominated by Douglas Fir and Western Hemlock, pre-eruption and before the logging that occurred between 1930 and 1980 (Simon, 1999).

Vegetation returned to the area shortly after the eruption, some areas including up to 2 plants/m² by 1983 (Dale, 1989). Areas that experienced primarily coarse tephra falls tended to recover quickly (Del Moral, 1983). Like the North Fork, a new river channel formed shortly after the eruption, which can be fully seen in 1983 imagery. The pre-eruption channel was nestled into a smaller incised valley while the post-eruption channel, between 1980 and 1983, tended to form within a wider valley resulting from the deposits left from the two lahars that swept the valley (Simon, 1999). While the drainage network does not look to have been fully buried, there was enough deposition in at least the upper 2 km that the channel had to form elsewhere to accommodate (Figure 4). The increased sediment present forced the channel to either relocate or shift slightly along the floodplain to areas with less resistance. This can also be seen in the cross-section data in Figure 5.

Channel geometry, amount of available sediment, and rainfall-runoff relations were altered by the deposits from the various volcanic events (Meyer & Martinson, 1989). These events included 2 large lahar flows as the Upper South Fork Toutle River was outside of the blast zone and did not experience the large debris avalanche that the North Fork Toutle River experienced (Simon, 1999).

Main river channel development in the area was found to follow four main stages: channel initiation, channel incision with relatively constant width-to-depth ratio, channel widening accompanied by aggradation, and channel widening accompanied by scour-and-fill with little change in average channel elevation (Meyer & Martinson, 1989).

Condition of Study Area Immediately Following the May 18th Eruption

The South Fork Toutle River streamflow is monitored by a gage at station 14241500 (South Fork Toutle River at Toutle, WA) (Figure 2). Average annual streamflow between 1940 and 1957 (pre-eruption) was 17.9 m³/s while average annual streamflow between 1996 and 2012 (post-eruption) was 17.8 m³/s.

The eruption of Mount St. Helens affected a majority of the upper reach of the South Fork Toutle River (Figure 6). Areas with hillslopes facing away from the mountain did not experience as much devastation (such as blowdown) as hillslopes facing towards the mountain (Del Moral, 1983). Large amounts of sediment deposition the floodplain, from the lahars, occurred in all areas of the study site, as seen in the imagery for 1980 (Figure 7) and seen in the cross sections visualized in Figure 5. The first lahar was the largest and deposited around 1.0 to 1.5 m of a granular matrix between river kilometers 40 and 45 (Simon, 1999). The second lahar left a veneer of about .05- to .25-m on the previous lahar deposits (Simon, 1999). The lahar flows

were concluded to be highly turbulent and seemed to have sloshed cross-valley, with density decreasing downstream, experiencing an average velocity of around 31 m/s (Janda et al., 1981). By 1981, the majority of ash deposited by the eruption had been supposedly removed (Zheng et al., 2014).

Recovery of the area was steady. By the early 1990's, vegetation had already returned to the area and showed large regrowth by 1996. Fishing of the river continued in the late 1980's, suggesting that the fish habitat was not so severely devastated so as to prevent the return of fishable species. However, migrations of fish were probably interrupted and diverted elsewhere within the Columbia River basin (Leider, 1989). Fishing continues to be popular on the South Fork, indicating that this interruption and diversion did not seem to permanently negatively affect the fish populations.

Flooding can have a large impact on disturbed river systems, with high sediment yields resulting from an individual flooding event (Major et al., 2000). While sediment yield was not a variable examined in this research for the Upper South Fork Toutle River, it is important to note that flood events may impact river formation, vegetation growth and spatial distribution, and overall channel evolution after a major natural disaster. Discharge graphs show lower peak discharges on the South Fork Toutle River from 1951 to 1956 than the peak discharges from 1996 (February flood) to 2006 (Figure 9).

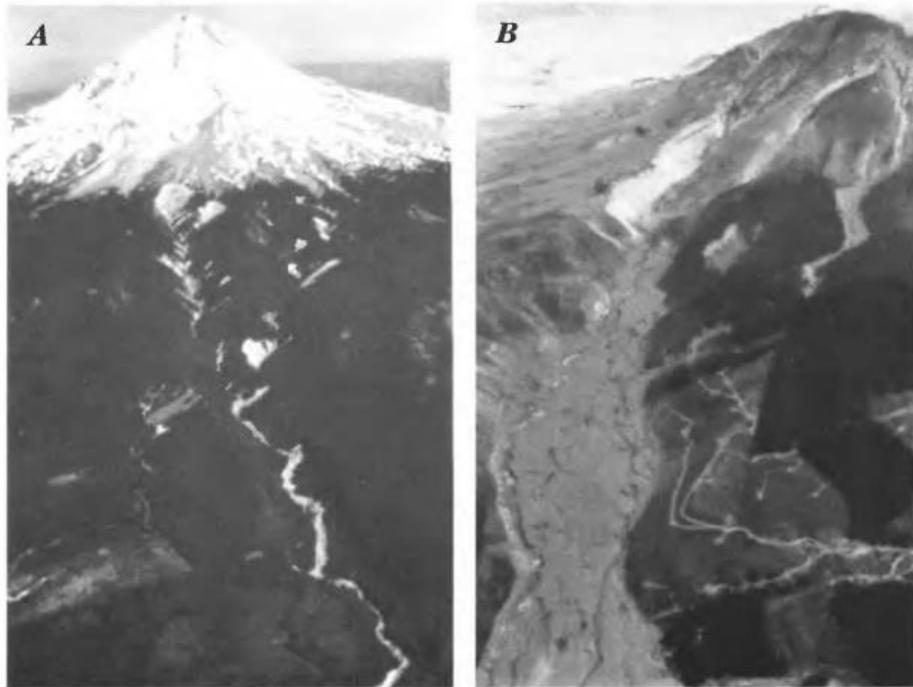


Figure 4. Oblique aerial photographs of bounding boxes 1-5, at a slightly different angle, of the Upper South Fork Toutle River valley (A) prior to and (B) after the passage of the May 18, 1980, lahars (Figure from Simon, 1999).

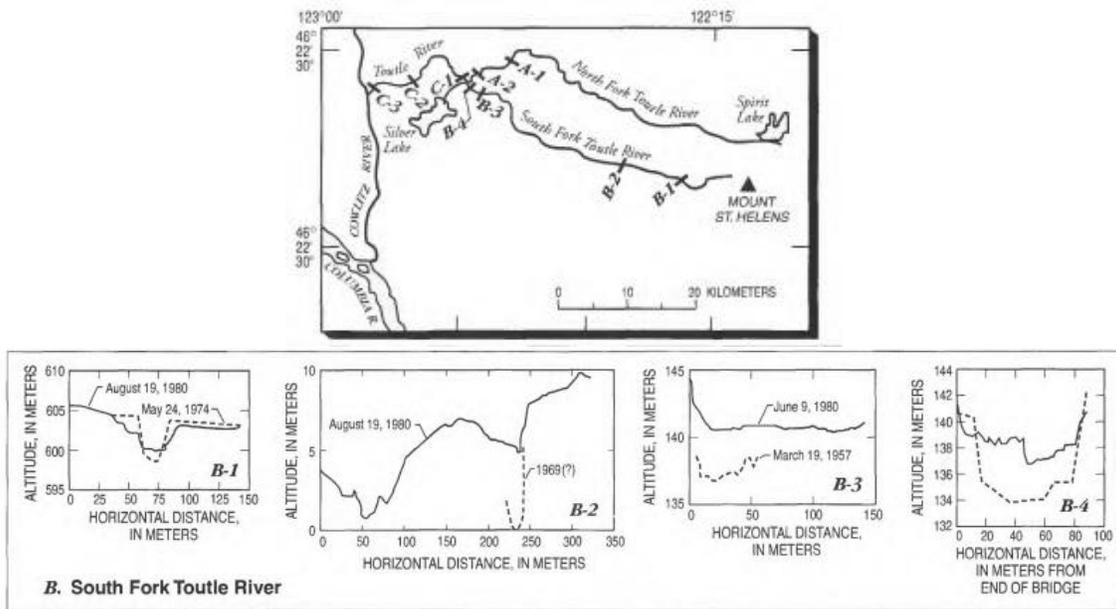


Figure 5. Charts showing pre- and post-eruption cross sections (looking downstream) of the South Fork Toutle River (from Simon, 1999)

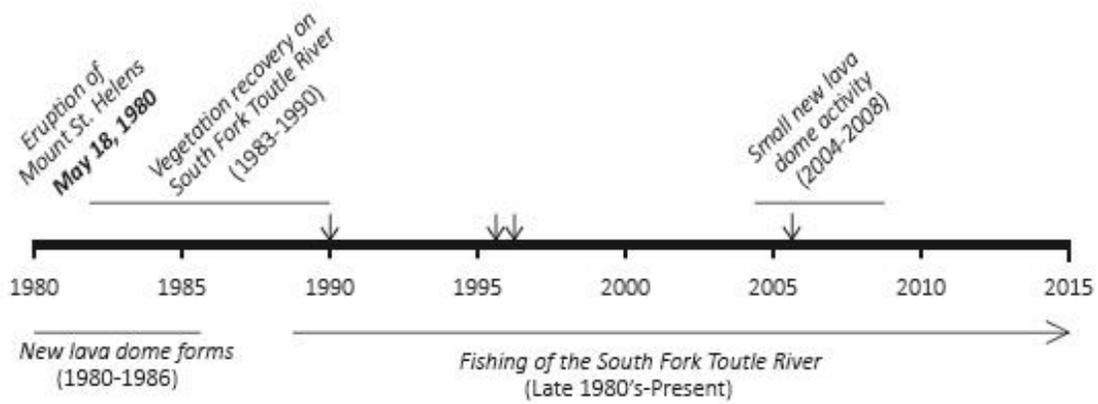
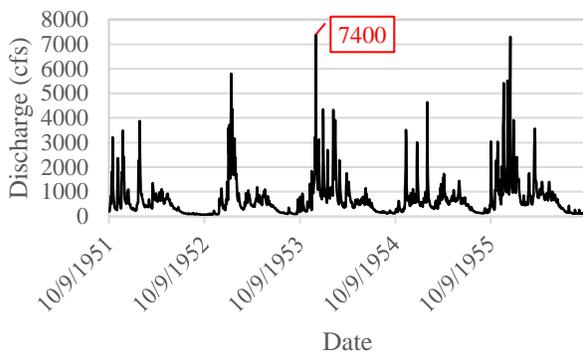


Figure 8. Recent history of the study area. Arrows represent years that contained floods with a discharge larger than 8,500 cf/s. The largest flood occurred in 1996 with a discharge larger than 10,000 cf/s.

a)



b)

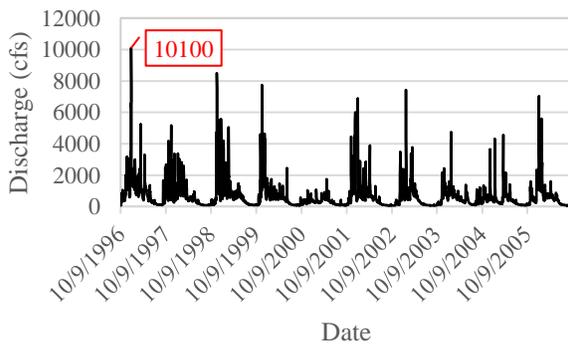


Figure 9. Graphs showing discharge for gaging station 14241500 a) years 1951-1956 and b) years 1996-2006. Red numbers show highest peak discharge during period of record.

CHAPTER III

METHODS

Historic Aerial Imagery Digitization and Processing

Historic aerial imagery for 1980, 1983, 1996, and 2014 was provided by the USGS Volcano Observatory in Vancouver, WA. Google Earth Pro digital imagery was used for a single year (2003) due to the need for a more complete picture of the site between 1996 and 2014. Paper photos (Table 1) were kept in archival-quality casings and all scanned data was created using an Epson 10000XL flatbed scanner and Adobe Photoshop™ (Creative Cloud). Photos were scanned at 1400 dpi and saved in the tagged image file format (TIFF, 8-bit greyscale). All years of aerial historical imagery were flown at a scale of 1:9,600. The dpi was chosen as the highest resolution needed to capture the information available in the prints (Table 2). Imagery for years 1980, 1983, 1996, and 2014 were given project codes by the agency that took the photos (the USGS). These codes were used to distinguish various flights performed during the same year or of the same area throughout time. There were no project codes for 2003 due to the nature of how the images were obtained (through Google Earth).

Table 1. Table showing imagery information for 1980, 1983, 1996, 2003, and 2014.

Year	Paper/Digital	Size	Scale	Project #	B&W/Color
1980	Paper	9x9	1:9,600	24322	B&W
1983	Paper	9x9	1:9,600	1983	B&W
1996	Paper	9x9	1:9,600	USGS-MSH	B&W
2003	Digital	9x9 clips	1:8,400	N/A	Color
2014	Paper	9x9	1:12,000	Toutle	B&W

Table 2. Table showing effective ground resolution pixel size based on photo scale and scan resolution.

Scan Resolution		Ground Resolution (m)
DPI	Micrometers	1:9,600
1200	21	.2
1400	18	.17
1800	14	.13

Digital scans were stored on a portable Seagate hard drive. All imagery was securely (using AES256 encryption) backed up to the cloud multiple times a week using CrashPlan.

Personal Imagery Reconnaissance

Personal aerial imagery was also taken of the study site using a Nikon D3100. The first part of field work was to attempt to capture imagery comparable to the 2014 imagery provided by the USGS. In total, around 3,000 vertical images were taken on (August 6, 2014) with the personal camera from a helicopter provided by the USGS. While these photos were initially intended as a reference for the smaller scale imagery from the USGS, they were eventually used as detailed snapshots to compare with previous decades of imagery. Some details in the 2014 imagery needed magnification, thus the larger scale photos were used (road intersections, individual trees, details of smaller bars, etc.).

These photos were important in determining accuracy of some features that were georeferenced from digitized images. Due to the time required to scan and georectify 3000 photos, these images were eventually excluded from analysis and were only used as reference points.

Field Work

While high resolution aerial imagery provides a quality bird's eye view, on-the-ground work is also necessary to complete the overall study site context. This type of field work was

performed for this study twice to determine actual spatial distribution of riparian vegetation. This data was used to frame the current setting for this research. Types of field work performed were on-the-ground reconnaissance of areas of vegetation that were placed in to categories of sparse, moderate, dense, and seasonal but needed verification due to lack of color imagery. Sparse vegetation was especially difficult to classify, thus images were taken of areas that showed the smallest patches of sparse vegetation to compare with the vertical images for 2014 of the same area (Figure 10).



Figure 10. Example of a sparsely-vegetated area photographed during fieldwork.

GIS and Georeferencing

Once scanned, the historic imagery for 1980, 1983, 1996, and 2014 was imported into a GIS, more specifically, ArcMap 10.2.1, provided by ESRI (ESRI, 2011). No imagery was acquired in digital form that was already georectified. Imagery was then split up into flight lines (as outlined on each photo) and georeferenced to ESRI's non-labeled imagery base map. This

basemap imagery was accessed summer, 2015. Following the methodology recommendations set forth by Hughes et al. (2006), each image was georeferenced with an average of 8 ground control points (GCPs) to maintain spatial accuracy. Most of the GCPs were placed in areas on or close to the floodplain and as close to the wetted channel as possible. Typical features used to place GCPs were road intersections close to the floodplain, areas that showed little change between years (such as small tree stands, small logging roads, and large boulders slightly outside of the floodplain). While the topography in this area is not a relatively flat one, the lack of roads and structures does not allow for many more than 8 GCPs for each photo. No noticeable improvement in spatial accuracy was achieved when 10 or more GCPs were used. To maintain image integrity, only an order of 1 polynomial was used when adjusting to the points used for georeferencing.

Vector Data Creation and Classification

The first step in analysis was to map the active channel and different types of riparian vegetation on the floodplain. To facilitate measurement of areas of change, a channel centerline and a floodplain center were mapped. These were created in order to show change in channel location within the floodplain, relative to the center of the floodplain. The minimum mapping unit for this research was as follows:

Table 3. Table showing classifications for minimum mapping unit.

Channel and Islands	Vegetation	Geomorphic Floodplain
Fluvial islands equal to or larger than the width of the surrounding 50 meters of channel on both sides	Stands of trees of approximately 3 trees	Area discerned as topographically flat in relation to surrounding topography using the 2003 LiDAR

Boxes to measure areas of change were created by spacing transects at 500 meter intervals which were then joined to construct 32 polygons for analysis of down-reach changes across the dates of imagery digitized. These polygons, referred to as “bounding boxes,” were numbered 1-32.

Digital shapefiles of the floodplain, active channel, channel centerline, floodplain centerline, and riparian vegetation were created by manually digitizing from the georectified imagery. The active channel was determined through visual examination of each georeferenced photo for each decade. In general, the active channel was darker than the surrounding floodplain, thus tracing the outline of the channel was a matter of defining the boundary between the darker water of the channel and the lighter surrounding sediment. In situations where the channel edges blended in and was not easily visible, lines were drawn using surrounding shadows; areas with vegetation (and thus slightly darker than the floodplain) were excluded as possible channel edges.

Additionally, the geomorphic floodplain was determined through visual examination of the 3 meter resolution 2003 LiDAR hillshade provided by the USGS. Floodplain lines were determined as areas where the topography was flat relative to the surrounding topography and persisted horizontally towards the opposite side of the valley for more than 6 meters. This floodplain was split up into 4 zones equal-length zones (Zone 1, Zone 2, Zone 3, and Zone 4). The reason for zone-creation was for easy comparison and visualization over time. Each zone contains 8 of the 32 bounding boxes the geomorphic floodplain was initially split into.

Areas and spatial extents of the active channel for each year were compared to each other to determine areas of change. ArcMap 10.2.1 was used for this comparison. Similarly, vegetated areas were also compared for each of the years to determine areas of change and overall landscape evolution from 1980 to 2014.

Vegetated areas were classified into 4 classes: Sparse vegetation, moderate vegetation, dense vegetation, and seasonal vegetation. These classifications are similar to those used by Gran, 2015, who classified vegetation into sparse, clustered, and dense categories. These categories were determined using the percentage of canopy cover in a particular vegetated area (Table 3), also similar to Peixoto et al., 2009, who divided vegetation classes into pioneer and later successional forest based on canopy cover. The classification for the present research used the canopy of woody vegetation due to the difficulty of discerning herbaceous vegetation canopy in the imagery for 1996 and 2003. Figure 13 shows an example of each of the vegetation classes. The darkest green is the dense vegetation. This is vegetation in which 61% to 100% of the ground was covered. The next lighter shade of green represents 16%-60% vegetation cover, or moderate vegetation cover. The lightest shade of green represents sparse vegetation or 15% or less vegetation in the section digitized. Light gray represents the seasonal vegetation located in each section during the time of the photos used. This vegetation class existed most often close to the active channel and was noted to change or disappear in large amounts between years examined. Typically, this vegetation class existed in areas of sparse or moderate vegetation and was found to be densely clustered around smaller tributaries of the active channel. Thus, to include this vegetation in the analyses, it was necessary to include as a separate class from the others. While the seasonal vegetation was considered dense, it should be noted that this type of dense vegetation is different from the dense class shown as a dark green color. Areas shown as dark gray represent bare. This class was visually determined to be areas that were difficult or impossible to differentiate between sparse and no vegetation present. Areas with dark sediment,

small patches of herbaceous or graminoid vegetation (which blended in with the sediment), and dark shadows were placed in the bare category.

Areas that were difficult to classify were placed into classes that matched those visually similar to them. Vegetation polygons were manually mapped and classified through visual examination of each photo. Only vegetation that existed in the active floodplain for a given year was digitized and compared. The comparisons were performed on a class by class basis in order to provide a more complete description of the change in spatial extent, location, and vegetation cover (area).

Due to an 18-year gap in imagery (1996-2014), imagery in Google Earth Pro, was used to map floodplain, vegetation, and channel polygons in 2003. The .xml file was then used to create a layer file which was then exported to a shapefile and added into ArcGIS 10.2.1 to be compared with the other data years.

A centerline was created for the active channel polygon for each year. The centerline was digitized in order to create polygons used for quantifying planform change, such as channel migration rate, similar to the methodology in O'Connor et al, 2003. The ArcGIS extension ArcScan was used for centerline digitization and manipulation. Each vector polygon of the digitized channel for each year of analysis was changed to raster using the polygon-to-raster tool. (ArcScan utilizes rasters to create centerlines of features). The output cell size was set to 0.20 pixels to maintain as much accuracy as possible. In addition to ensuring accuracy, the cell size of 0.20 pixels was the smallest cell size possible that did not make the program crash with each dataset.

Each raster was then reclassified in order to provide two cell values for the resulting analysis. (Smaller cell size resulted in errors when trying to reclassify the rasters, probably due to the large size of the dataset created.) Areas that contained no data were reclassified with a value of 0. Using the vectorization option in ArcScan, a centerline for each raster was then computed. A median intersection solution and noise level of 0 was used in order to obtain accurate centerlines at intersections. This methodology is similar to that used by O'Connor et al., 2003. This automated way of creating centerlines made them ragged. To decrease this, the advanced editing toolbar was used to smooth and generalize the floodplain centerline. The maximum allowable offset for this process was set at 50 meters. This setting was due to the sharp angle in the centerline seen in Zone 1 (Figure 11).

Transect data was also gathered for each of the years 1980, 1983, 1996, 2003, and 2014. The geomorphic floodplain was split up into areas equal distances apart (500m, 32 polygons total). The floodplain was subdivided into boxes for data extraction and analysis in the following way. Lines perpendicular to the centerline of the floodplain, spaced every 500m and extending to the floodplain boundaries, were used as bounding lines for the floodplain boxes. Only one set of boxes was created and was used for analysis for each year of imagery. Floodplain boundaries did not change significantly from year to year in the imagery. For this research, the resulting boxes are called a polygon mosaic. Python code was then used to clip each channel and vegetation year by each of the bounding boxes. Areas of polygons and widths of lines were then recalculated for the clipped sections. This methodology follows a similar method performed by Zanoni et al., 2008.

Channel sinuosity was calculated using the length of the main channel centerline and the straight line distance of each bounding box centerline. Additionally, to gain as much detail of the complexity of the channel or channels for 1980, 1983, 1996, 2003, and 2014, the lengths of all channels present were used to calculate the average channel sinuosity within each bounding box. This was done by finding all of the lengths of all possible combinations of the channels present in each bounding box, calculating the sinuosity based off of these lengths, and then calculating the average of the sinuosity values. Some channels included small islands that looked to be ephemeral. Islands that had a length that was not equal to or larger than the width of the surrounding 50 meters of channel on both sides of the island were eliminated from the dataset for this purpose.

Raster Creation and Processing

In order for a more accurate change detection for each year, the vector polygons had to be converted to rasters and then lined up. These methods were similar to those used by Niculiță & Niculiță, 2008. Since the rasters did not automatically line up due to size differences, the “snap to raster” option was used. This allowed for each output to be lined up with a specified raster in the tool’s environment settings. For this research, the earliest year containing vegetation (1996) was used to snap all outputs. This “snapping” was used so that all raster layers were concurrent (showed the same cell extent), an important attribute when performing change analyses.

Visual examination was also performed for this research in order to obtain a more comprehensive idea of how river morphology and vegetation development may have been related. The vector graphics produced in the previous methods did not include topography. Visual examination of the imagery allowed for steep areas to be identified as well as areas that

experienced relatively little disturbance from the eruption. These areas were important to define for comparison with the vector data created for the floodplain, vegetation, and channel.

The geomorphic floodplain was divided into bounding boxes, following similar methods performed by O'Connor et al., 2003. Each bounding box boundary is located at 500 meter spacing along the geomorphic centerline. Box 1 is 0 to 500 meters, box 2 is 501 to 1000 meters, and each successive box is located every 500 meters, going downstream. Box 32 is located at the farthest downstream end of the study site (Figure 11). The bounding boxes were grouped and then divided into 4 sections of 8 bounding boxes, to facilitate cartographic display. These groups were labeled zones 1 through 4. Zone 1 was located farthest upstream at the headwaters of the channel while zone 4 was located farthest downstream where the area of interest terminated. Vegetation type area and floodplain area was then compared for all years for each zone.

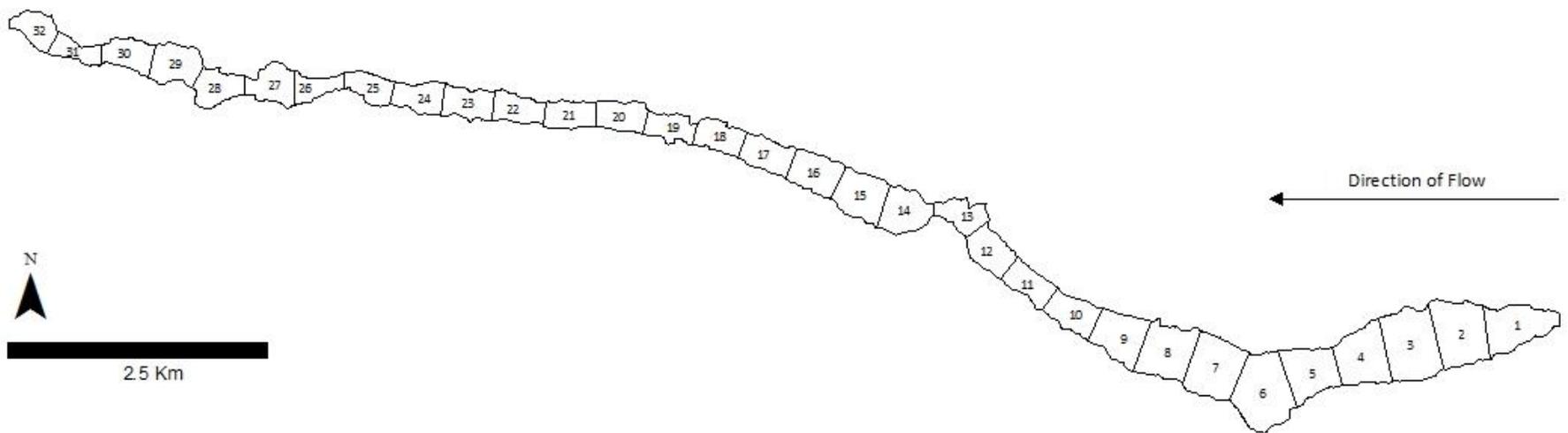


Figure 11: Map showing the Upper South Fork Toutle River active geomorphic floodplain. Numbers represent the individual bounding boxes.

Table 4. Explanation of the tree and shrub cover classes.

	Sparse	Moderate	Dense	Seasonal
Percentage vegetation cover	0%-15%	16%-60%	61%-100%	61%-100%

CHAPTER IV

RESULTS

Vegetation Change

Vegetation from 1980 to 1996

The imagery for 1980 (taken several months after the eruption) and 1983 showed no riparian vegetation at the resolution performed for this study. Herbaceous and graminoid vegetation may have been present at this time, but they either blended in with the surrounding sediment or did not appear in patches large enough to see in this research. Thus these small patches of vegetation were placed into the bare class. Because imagery was only found for 1980, 1983, and 1996, there is no information on vegetation change between 1980 and 1996. The presence of vegetation was observed in the 1996 imagery, meaning that vegetation had begun regrowth and recolonization before 1996.

Overall vegetation (the total of seasonal, sparse, moderate and dense vegetation classes) increased from 1996 to 2014 across all zones (Figure 12). Vegetation in zone 1 increased by 61% from 1996 to 2003. Zone 1 vegetation from 2003 to 2014 decreased by 22% while total vegetation from 1996 to 2014 increased by 25% (Table 5).

Table 5. Summary of dates of imagery used in research, vegetation presence, and vegetation amount in both km² and percentage of floodplain area for each zone.

Year of Imagery	Vegetation?	Vegetation, Zone 1 (km ² / % of floodplain)	Vegetation, Zone 2 (km ² / % of floodplain)	Vegetation, Zone 3 (km ² / % of floodplain)	Vegetation, Zone 4 (km ² / % of floodplain)
1980	No	0	0	0	0
1983	No	0	0	0	0
1996	Yes	969.1 / 44%	168.8 / 13%	29.9 / 3%	3.1 / .3%
2003	Yes	1561.2 / 71%	173.8 / 13%	344 / 33%	416.2 / 42%
2014	Yes	1210.1 / 55%	735.8 / 56%	439.7 / 42%	614.9 / 62%

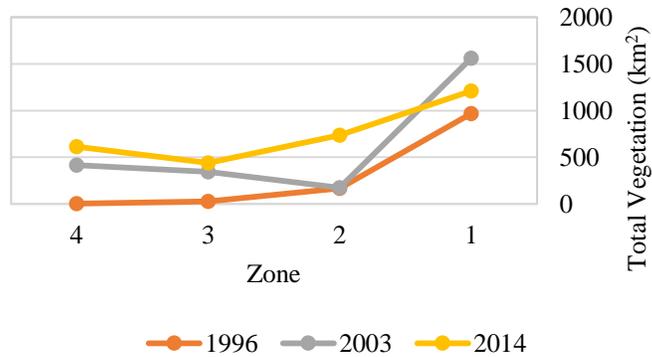


Figure 12. Chart showing overall vegetation amount from 1996 to 2014. Direction of water flow is from right to left.

Vegetation Change 1996-2014, Zone 1

According to Gurnell et al., 2001, "...the nature of colonizing vegetation determines: whether islands develop, their potential size, and their ability to resist erosion." The spatial distribution of vegetation classes (dense, moderate, sparse, and seasonal) is seen in the maps below. Vegetation patterns varied going downstream. Overall vegetation increased from 1996 to 2014, with a slight decrease in vegetation for zone 2 in 2003.

Additionally, spatial distribution of vegetation changed between 1996 and 2003, as well as from 2003 to 2014 (Figure 13). Each bounding box experienced spatial changes to varying degrees (Figure 13). Most notable is the extreme decline of sparse vegetation from 2003 to 2014. This sparse vegetation tended to transition to moderate vegetation in nearly every bounding box. There was also a large increase in seasonal vegetation (grey polygons), possibly due to a wetter time of year in the 2003 imagery. Visual examination of the imagery showed areas of vegetation that primarily existed at the edges of small streams within the floodplain that were present during a wetter season (February-May). These vegetated areas also seems to change a lot from one year of imagery to another, many areas disappearing altogether. Due to the instability of the presence of these vegetated areas, they were classified as "seasonal."

Dense vegetation tended to expand upstream from 1996 to 2014. The majority of dense vegetation occurred in boxes 6, 7, and 8 in 1996 and 2003. 2014 boasted dense vegetation in zones 1 and 2, suggesting that these zones may have not experienced floodplain turnover rates significant enough to eliminate the seasonal, sparse, and moderate vegetation that ultimately either disappeared altogether or became denser.

Bounding boxes 1-8 experienced a shift from a bare floodplain-dominated landscape to one with more sparse and moderate vegetation cover from 1996 to 2003, particularly in Boxes 1, 2, and 3 (Figure 13). Bounding boxes 4, 5, 6, and 7 also experienced a decrease in bare floodplain from 1996 to 2003 and then an increase in bare floodplain from 2003 to 2014. Small vegetation patches tended to grow together into larger patches, some changing classes from sparser to denser.

Dense vegetation that was present in bounding boxes 5 and 6 disappeared altogether from 2003 to 2014 (Figure 14). These dense patches of vegetation were on the north side of the main channel in 2003 and the channel moved south from 2003 to 2014. Sparse vegetation south of the main channel in 2003 changed to moderate vegetation in 2014. Bounding box 7 also experienced a decrease in dense vegetation, while also experiencing a channel movement to the south of the channel location from 2003.

With the exception of bounding boxes 7 and 8, dense vegetation tended to grow along the valley walls. For years 2003 and 2014, this was especially true. This could have been due to a potentially more stable surface than the center of the floodplain (the channel tended to stay in the relative center of the defined floodplain).

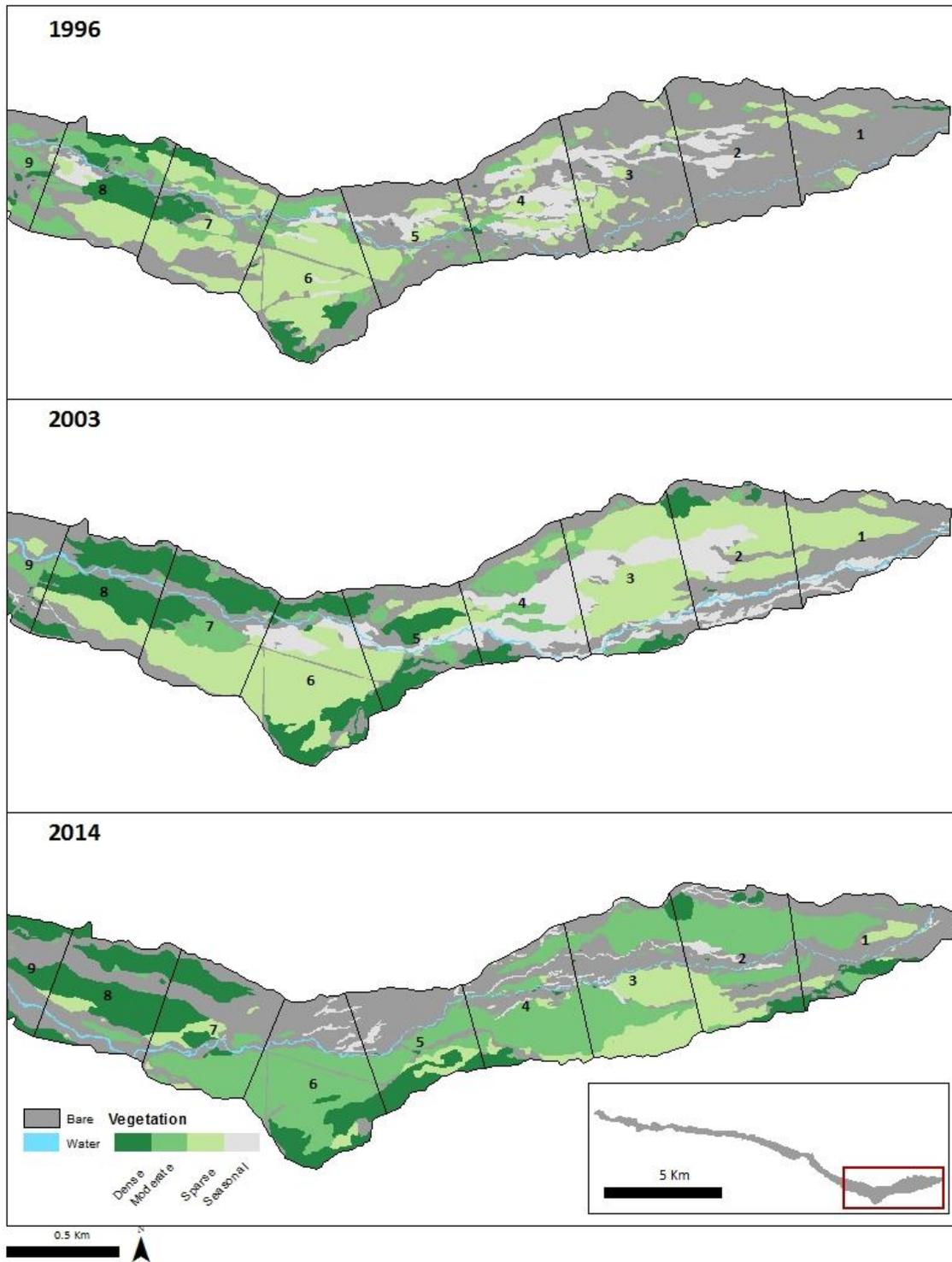
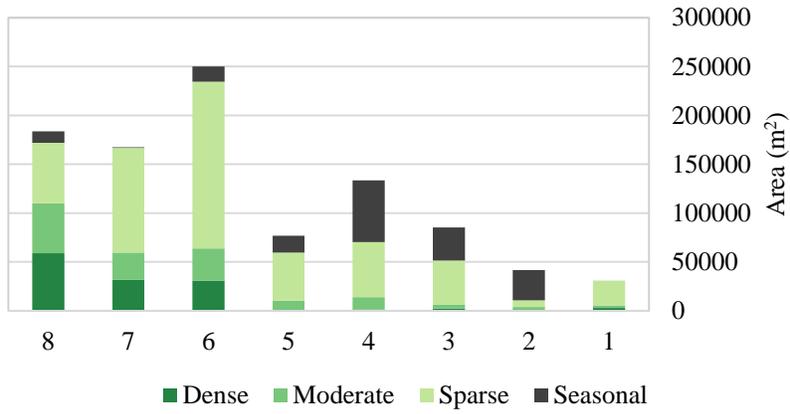
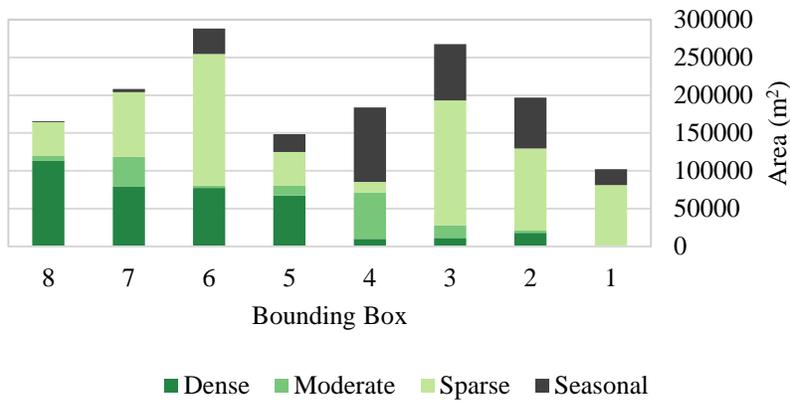


Figure 13. Maps showing the total change in spatial distribution of vegetation from 1996 to 2014 in Zone 1 (bounding boxes 1 through 8).

a)



b)



c)

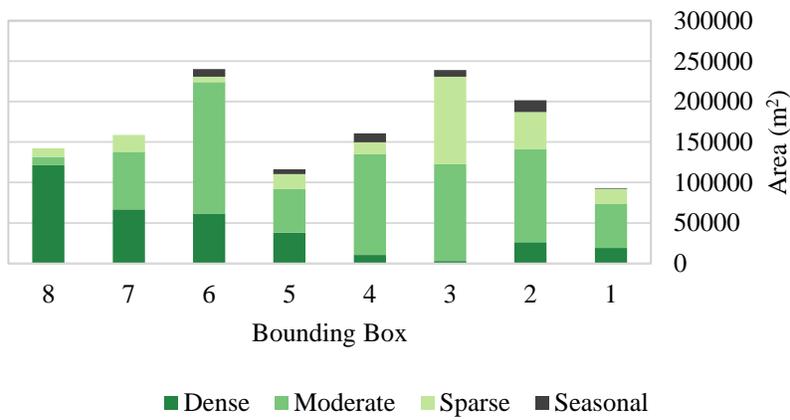


Figure 14. Vegetation by class in zone 1 for a) 1996, b) 2003, and c) 2014.

Vegetation Change 1996 to 2014, Zone 2

Similar to zone 1, zone 2 also experienced an overall increase of 3% in vegetation cover from 1996 to 2003 and an overall 323% increase in vegetation cover from 2003 to 2014. There was also a 336% increase from 1996 to 2014. This zone did not experience any decrease in vegetation cover over time.

The spatial distribution of each class of vegetation also changed from 1996 to 2014 in this zone (Figure 15). Boxes 9, 10, 11, and 12 showed early signs of sparse vegetation in 1996 which then transitioned to either moderate or dense vegetation in 2003 (Figure 16). Some of the sparse vegetation in these boxes also disappeared and did not turn into denser coverage. 2014 saw the greatest increase in dense vegetation. This vegetation tended to be located in large swaths north and south of the active channel, mostly in curved areas of the geomorphic floodplain and channel. This zone had very little total seasonal vegetation.

Bounding boxes 13-16 experienced an extreme increase in dense vegetation from 1996 to 2014 (Figure 16, Table 4). This dense vegetation tended to occur primarily closer to the outside boundaries of the floodplain (i.e. more stable surface for vegetation growth). These dense vegetation areas occurred on opposite sides of the bounding boxes (if dense vegetation growth occurred in the north side of the active channel in several consecutive bounding boxes, the next several consecutive bounding boxes experienced dense vegetation growth on the south side of the active channel (Figure 15).

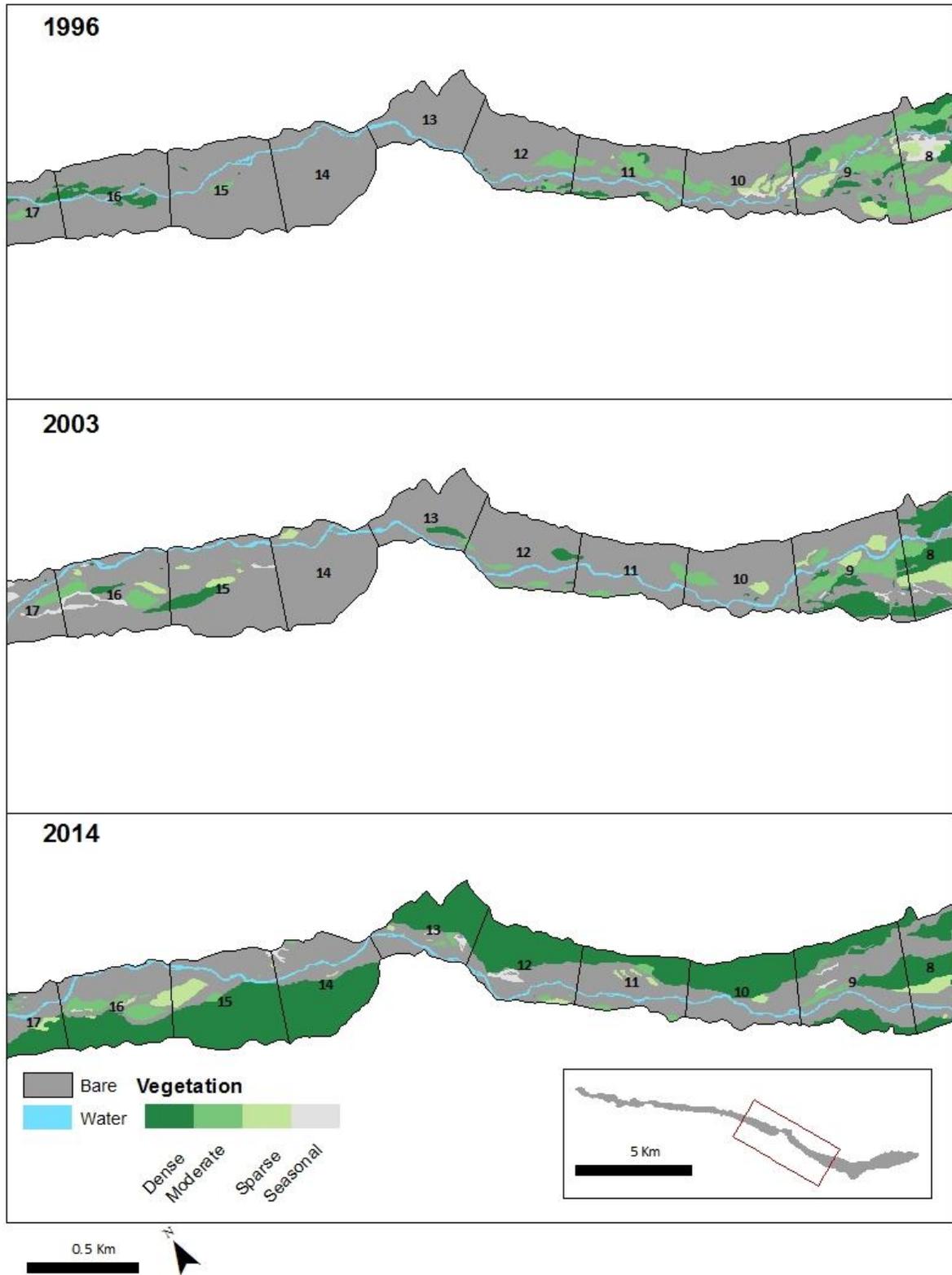
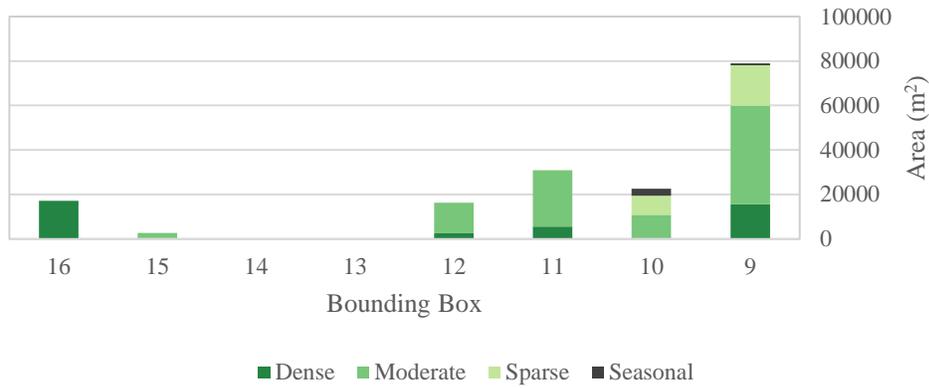
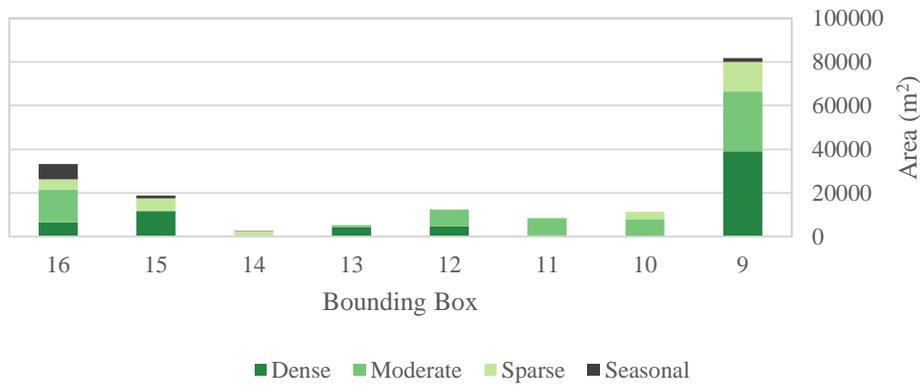


Figure 15. Maps showing Zone 2 vegetated areas for 1996, 2003, and 2014

a)



b)



c)

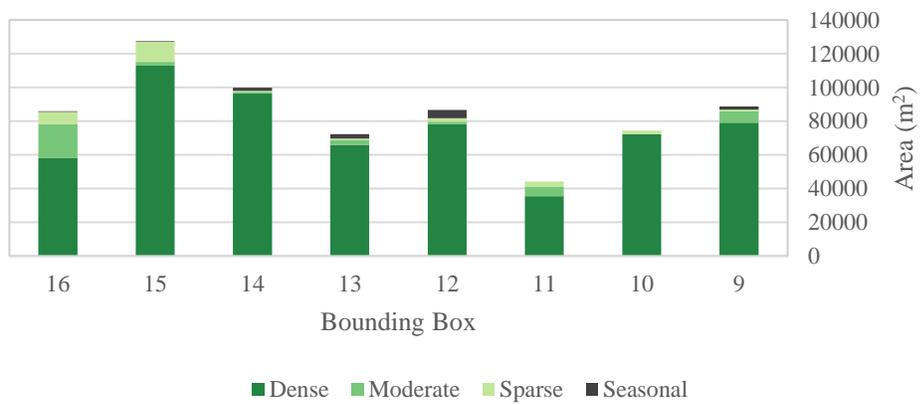


Figure 16. Charts showing total vegetation for zone 2 for years a) 1996, b) 2003, and c) 2014.

Vegetation Change 1996 to 2014, zone 3

Vegetation for 1996 in zone 3 measured 29.9 km² while vegetation for 2003 measured 344 km². Vegetation in 2014 was 439.7 km² (Figure 17). There was an increase in vegetation from 1996 of 1050%. There was also an increase in vegetation from 2003 to 2014 of 28%. Overall percent change from 1996 to 2014 was around 1371%. This zone, like zone 2, did not experience any decreases in vegetation from 1996 to 2014.

The spatial distribution of each vegetation class also underwent change. In 1996, boxes 17 through 20 initially contained some dense vegetation, scattered around in patches. By 2003, new patches began to appear in boxes 18 through 24 and the patches tended to increase in size. Overall, the total vegetation in 1996 for this zone was very little (Figure 18). Vegetation in 2003 showed increases in seasonal, sparse, and dense vegetation. Bounding boxes 20 and 21 contained the majority of the zone's moderate vegetation, which later became dense vegetation in 2014. Similarly, the majority of the sparse vegetation in boxes 21 through 24 then became moderate vegetation in 2014. This falls in line with the temporal patterns of vegetation elsewhere. This moderate vegetation should ultimately become dense vegetation in years to come, barring any large floods or other disturbances.

Vegetation for 2014 showed increases in dense and moderate vegetation cover. While there were patches of seasonal vegetation, there was not an overall increase from 1996 to 2014 of this class. Bounding boxes 17 and 24 saw the highest instances of seasonal vegetation in 2003 but these did not continue in to 2014. Additionally, this zone saw increases in vegetation growth on both sides of the active channel from 1996 to 2014. Vegetation growth did not tend to occur in areas that were occupied by active channel in previous years of imagery, unlike in zone 1.

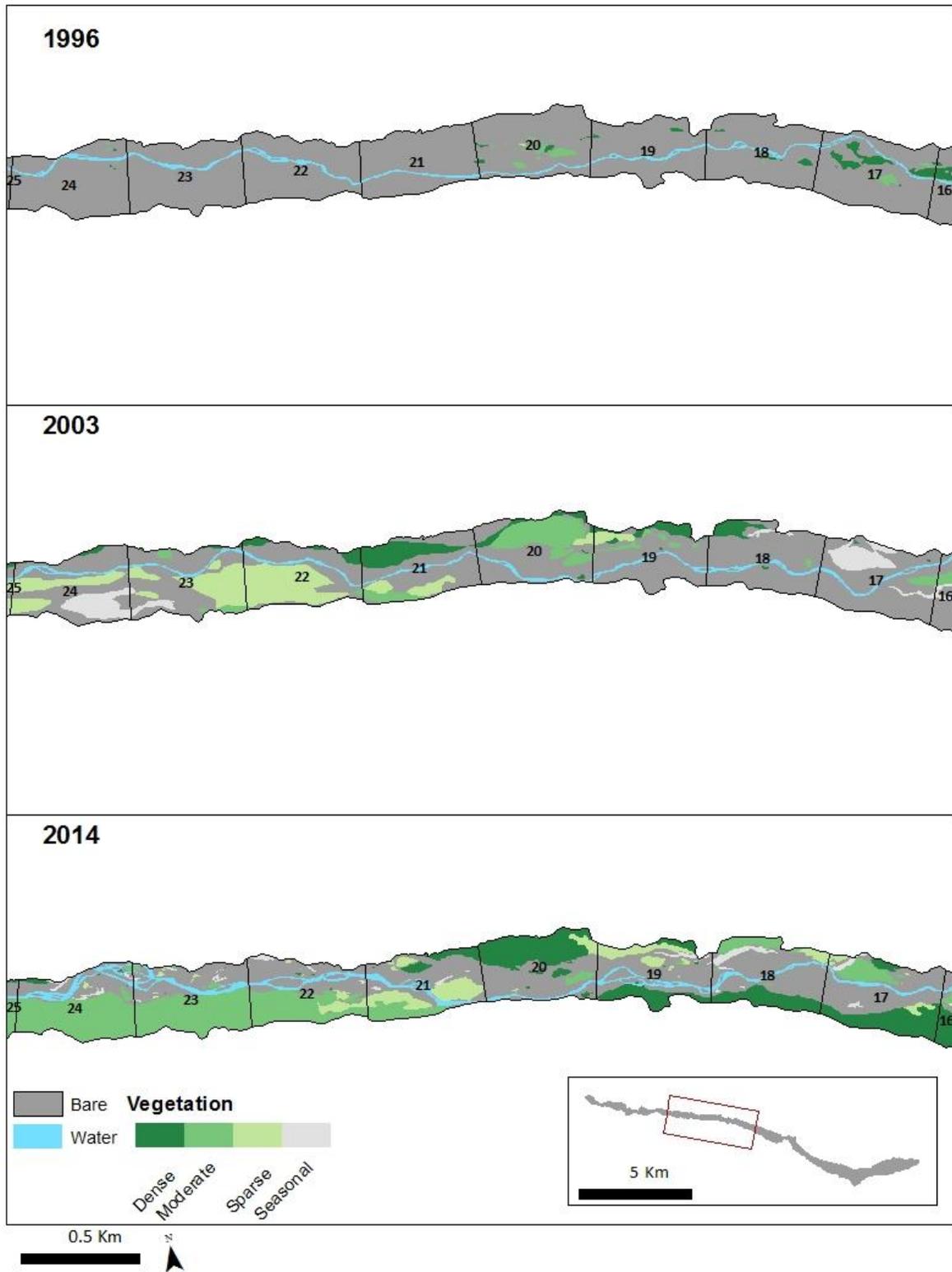
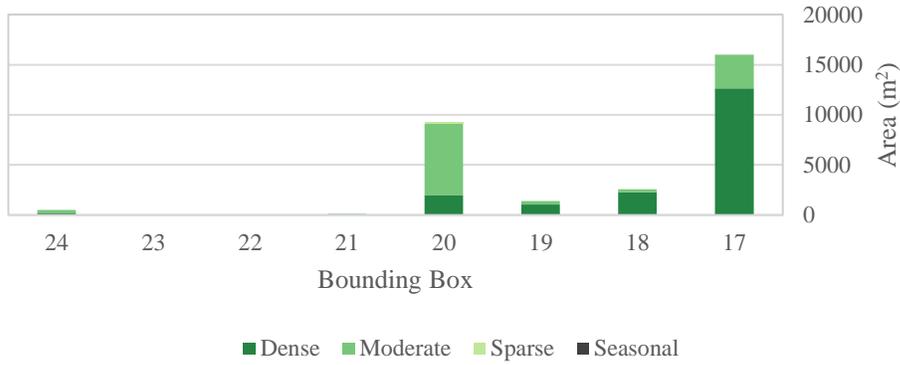
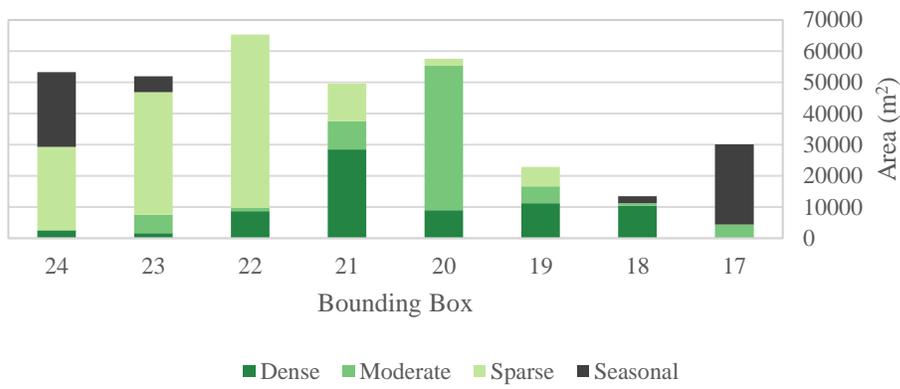


Figure 17. Maps showing Zone 3 vegetated areas for 1996, 2003, and 2014

a)



b)



c)

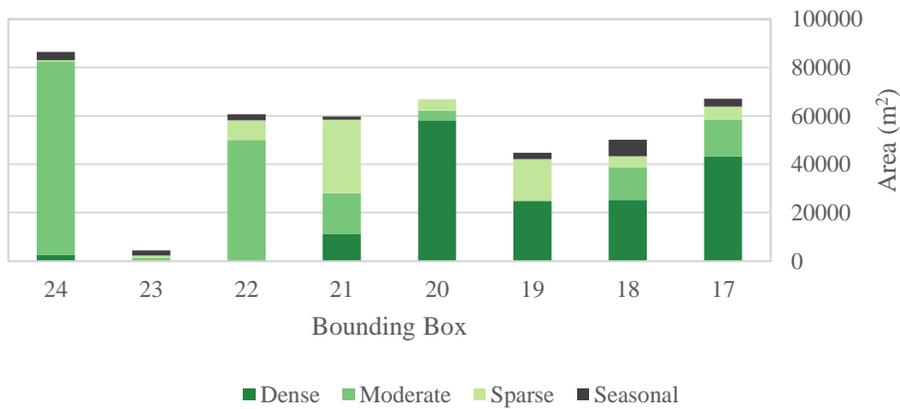


Figure 18. Charts showing vegetation for 1996, 2003, and 2014 for bounding boxes 17 -24.

Vegetation Change 1996 to 2014, zone 4

Vegetation in 1996 for zone 4 was almost nonexistent (Figure 19). There was a 13319% percent increase in vegetation from 1996 to 2003, a 48% increase from 2003 to 2014, and an overall increase from 1996 to 2014 of 19725%. There were no decreases in overall vegetation from 1996 to 2014. 2014 showed the greatest increase in dense vegetation, relative to the other years (Figure 20).

The spatial distribution of vegetation from 1996 to 2014 followed similar patterns to those in the other 3 zones. Little vegetation existed in 1996, with only a few scattered tree stands here and there. 2003 saw an increase in vegetation for all classes. The dense vegetation in 2003 indicates that rapid growth of vegetation could have occurred in this area within a relatively short period of time (<10 years). There was also an increased vegetation growth on both sides of the channel from 1996 to 2003. Vegetation growth from 2003 to 2014 greatly increased. Even some of the vegetation that looked like seasonal vegetation in 2003 tended to grow in to dense vegetation by 2014. The only vegetation class that decreased in overall area was the sparse vegetation, which tended to either evolve into dense vegetation (like in boxes 27, 29, and 30) or blended into moderate vegetation (like in the southern part of box 25).

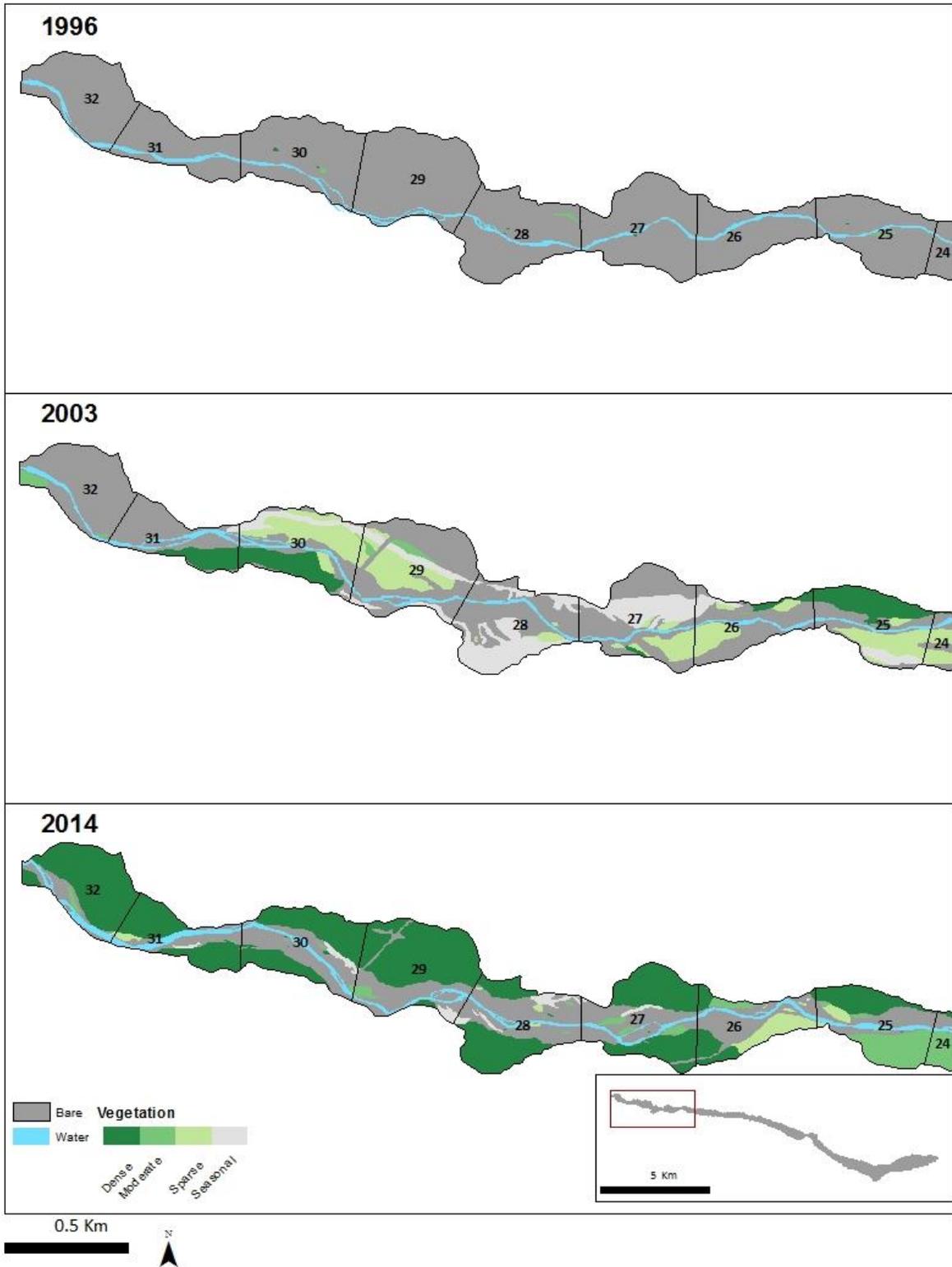
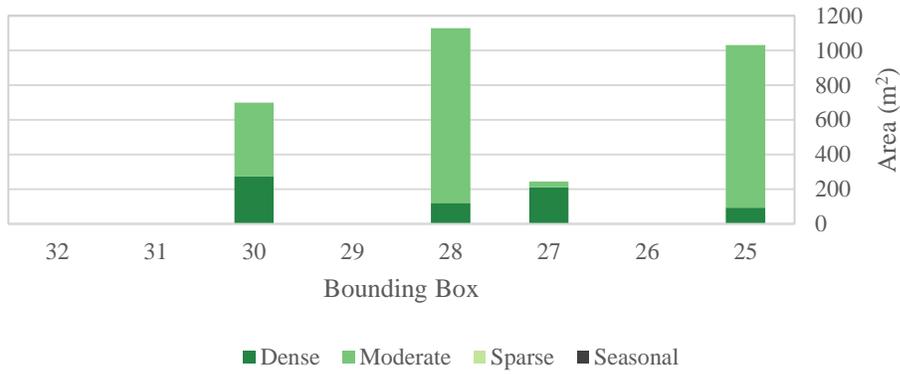
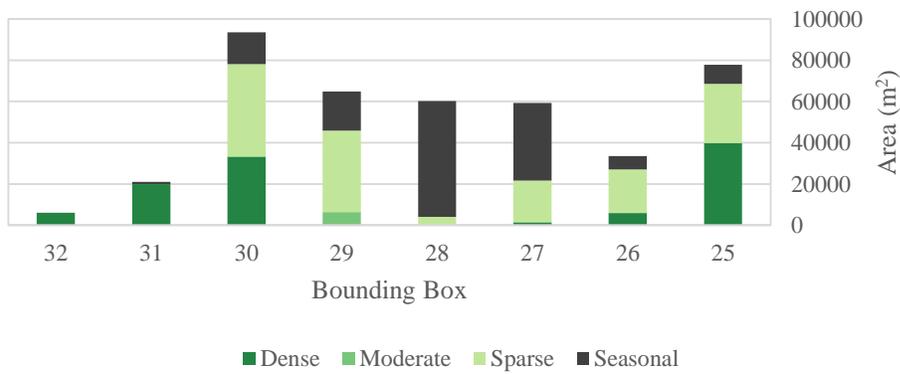


Figure 19: Maps showing Zone 4 vegetated area for 1996, 2003, and 2014

a)



b)



c)

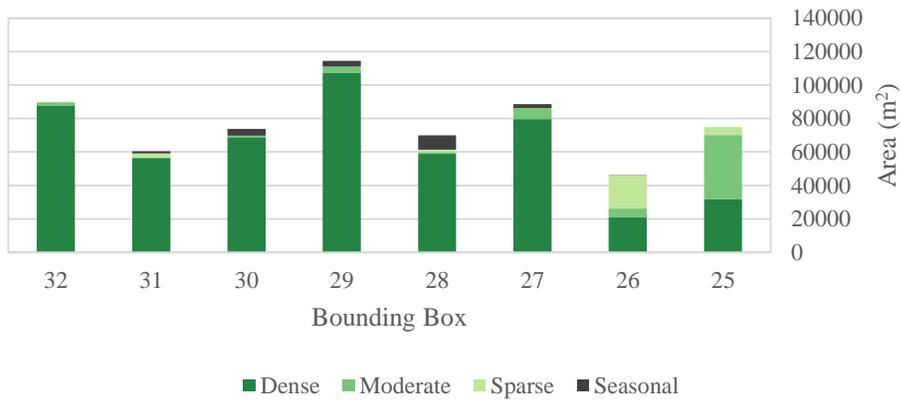


Figure 20. Charts showing total vegetation for 1996, 2003, and 2014 for zone 4.

Overall vegetation trends, 1996 to 2014, all zones

Overall, vegetation increased from 1996 to 2014 (Figure 21). This follows the predicted conceptual response put forth by Crisafulli et al., 2005. Initial vegetation response was greater from 1996 to 2003 and then leveled off slightly between 2003 and 2014. Again, this follows the overall biological evolution viewed within the framework of survivor legacy influence (Crisafulli et al., 2005). This framework supposes that sites with substantial survivor legacies responded rapidly and developed “survivor hotspots” (Major et al., 2009). These hotspots would then, over time, coalesce into larger patches, as seen in all of the 4 zones from 1996 to 2014 (Figures 13, 15, 17, and 19).

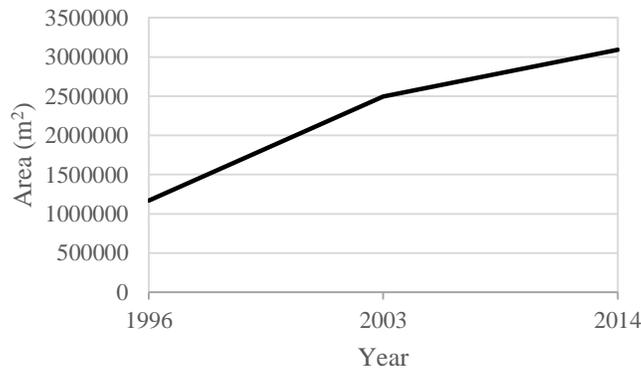


Figure 21: Graph showing change in total vegetation from 1996 to 2014. Vegetation was absent for years 1980 and 1983 and are not shown on this graph.

Channel evolution going downstream from 1980 to 2014

Average channel width generally increased going downstream in 1980, from 2.6m in box 1 to 10.8 m in box 16, to 14.5 m in box 32 (Figure 23). Similarly, average channel width for both 1983 and 1996 increased going downstream (Figure 23). In 2003, channel width was nearly even through the length of the study area. Figure 23 shows that this change is mainly due to channel widening in the upstream section, boxes 1-10. Closer examination of Figure 19d shows that box 31 showed the predicted increase in average channel width going downstream. This instance will be discussed in depth in the discussion section of this research.

Average channel width for 2014 returned to the trend of widening downstream (Figure 22). This change from 2003 was due mainly to narrowing at the upstream end (boxes 1 to 5) and widening at the downstream end (boxes 20-32). Average channel width for 2014 was the largest overall average width of the 5 years used in this study and had the highest variance of all years used for this research (Figure 24).

Average channel width in 1980 ranged from 2.6 to 15.7 meters (Table 6).

Table 6. Table showing minimum and maximum average channel widths for 1980, 1983, 1996, 2003, and 2014.

	1980	1983	1996	2003	2014
Min	2.6	1.7	2.6	4.6	3.7
Max	15.7	18.3	15.8	19	29.4

Lower average channel width occurred between bounding boxes 1 through 7. Channel width then tended to increase going downstream, with a slight decrease in average width in bounding boxes 14 and 15. Average channel width in 1983 followed trends similar to those found in channel width in 1980. Increased widths occurred downstream.

Overall channel width 1980-2014

Channel width did not progressively increase over time (Figure 24). 1980 to 1983 experienced an average increase in channel width. 1983 to 1996 experienced a decrease while 1996 to 2003, average channel width increased, though not to the degree of the increase from 1983 to 1996. Average channel width increased drastically from 2003 to 2014. Overall, average channel width increased from 1980 to 2014 (Figure 24).

One major contributing factor to the increase in channel width is the development of fluvial islands (Figure 25). These island formations tended to increase in number from 1996 to 2014. Some areas where the channel forks were wider than areas with no fork, thus increasing

the average channel width for certain boxes, depending on the number of channels present (Figure 26). This is similar to the lower Horse Creek and Green River reaches studied in Leopold & Wolman, 1957.

1980 and 2014 channels showed more instances of multiple channels (Figure 26). Higher numbers of channels were present starting around bounding box 11 and occurred from that point to further downstream. This could be due to the spatial distribution of the fine sediments that were deposited during the eruption of Mount St. Helens. The high amounts of sediment present closer to the mountain may have created surfaces that were so unstable that channel formation was merely able to occur as a single channel. The erosion of the sediment may have created faster flows which would not promote forks in the active channel. Branching that occurs around the middle and downstream portions of the study site could be a result of the transported sediment depositing as bars, thus becoming more stable (Parker, 1976).

Areas downstream from bounding box 11 showed high variation in number of channels and lower variation in floodplain width compared to bounding boxes upstream from bounding box 11 (Figure 26). Bounding boxes 1-10 contained a single channel, even with the high floodplain width values compared to downstream.

Average channel width over time in this research did not tend to follow typical channel width patterns seen in other research (Gran et al., 2009; Murray & Paola, 2003; and others) where increased vegetation led to narrowed channels, not widened channels, over time.

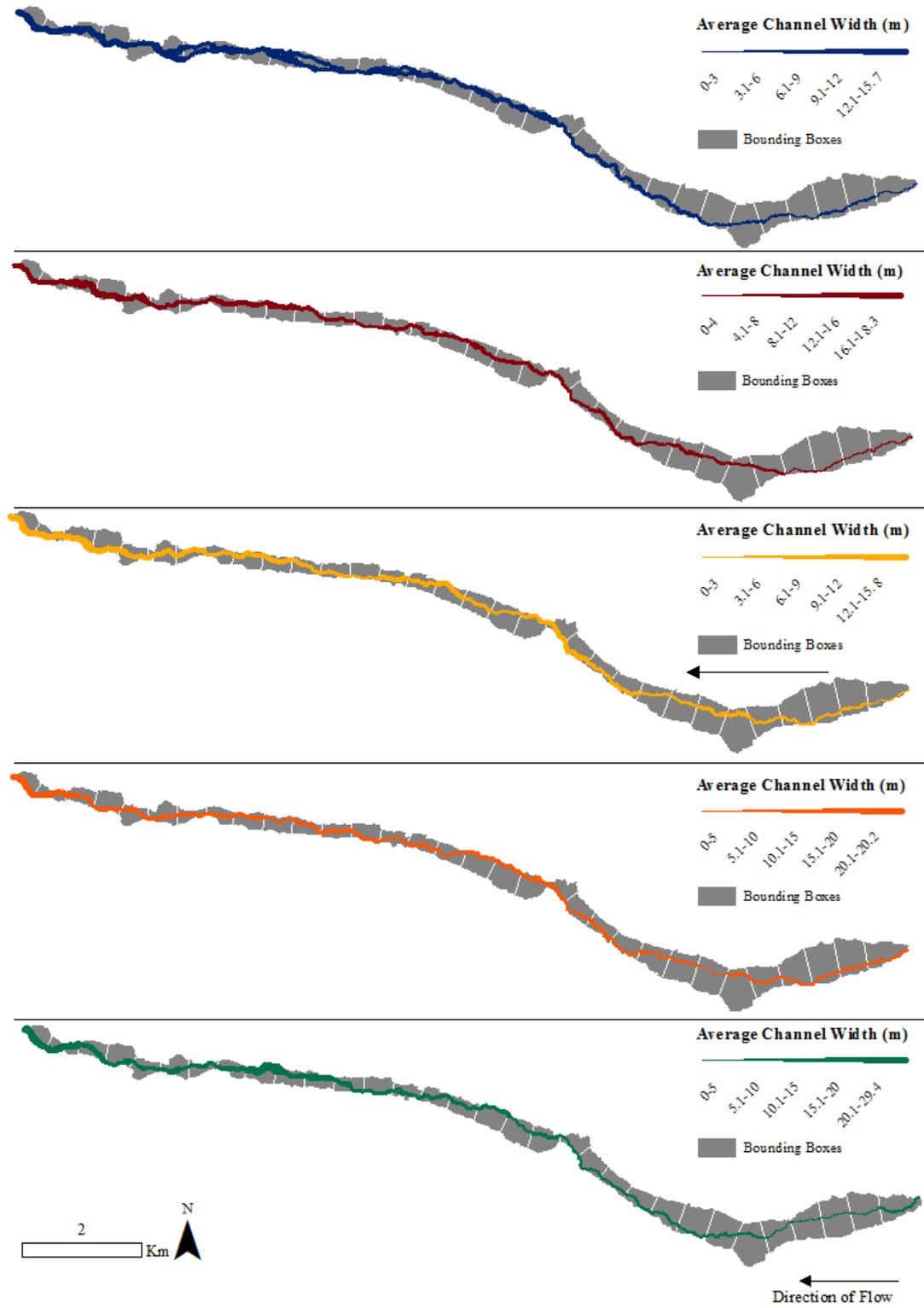
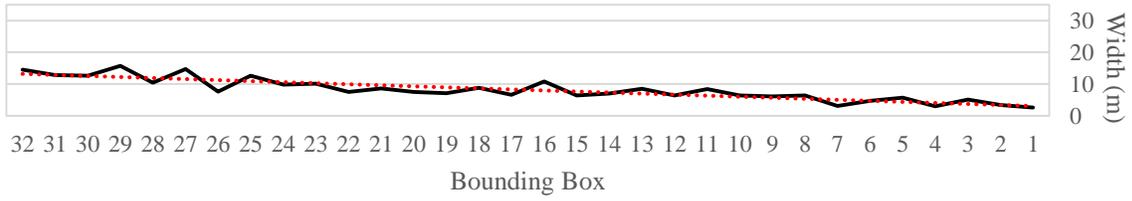
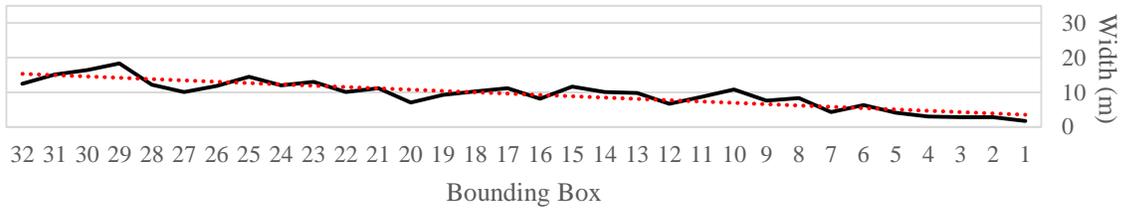


Figure 22. Maps showing average channel width going downstream for 1980, 1983, 1996, 2003, and 2014.

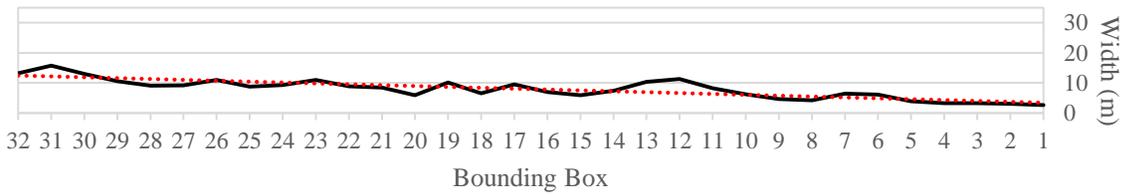
a) 1980



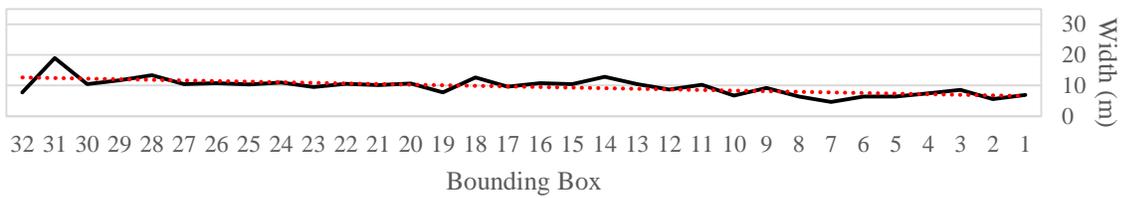
a) 1983



b) 1996



c) 2003



d) 2014

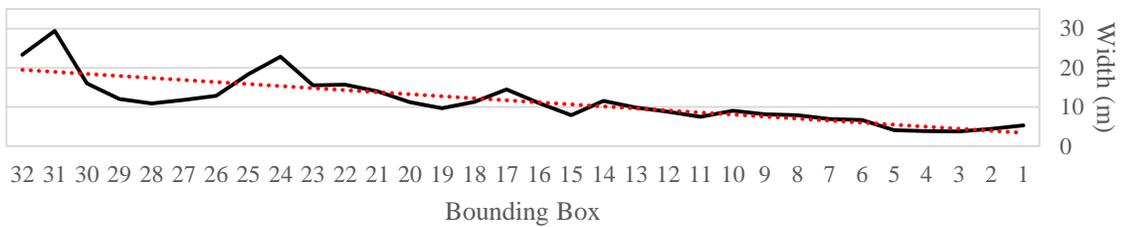


Figure 23. Graphs showing average channel width by bounding box going downstream for 1980, 1983, 1996, 2003, and 2014. Graphs also contain the linear slope for each year.

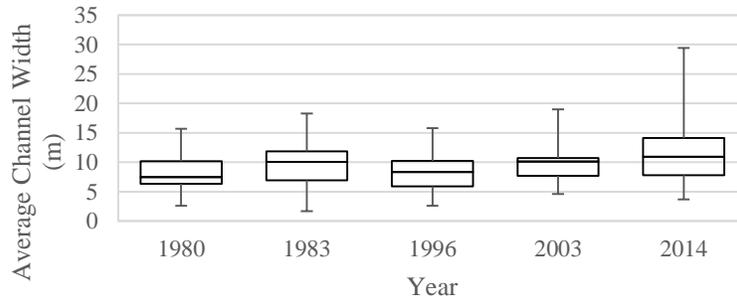


Figure 24. Chart showing average channel widths in meters for each year used in this study. Measurements were taken every .5km. Box plots show maximum, 3rd quartile, median, 1st quartile, and minimum.

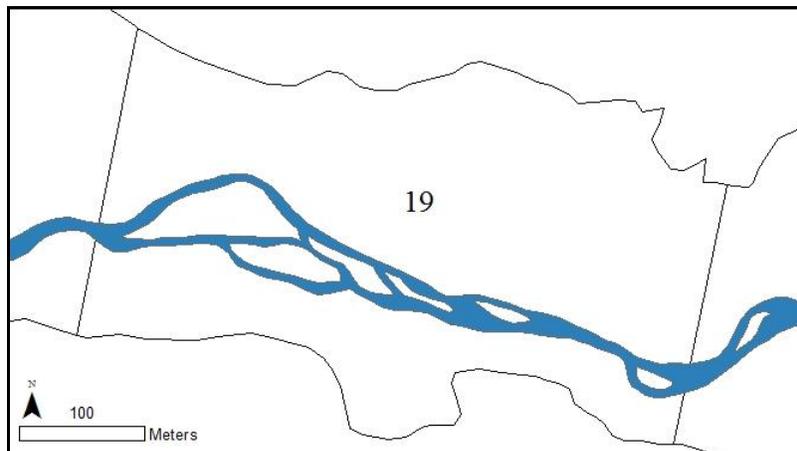


Figure 25. Map showing an example of fluvial islands in 2014 for bounding box 19.

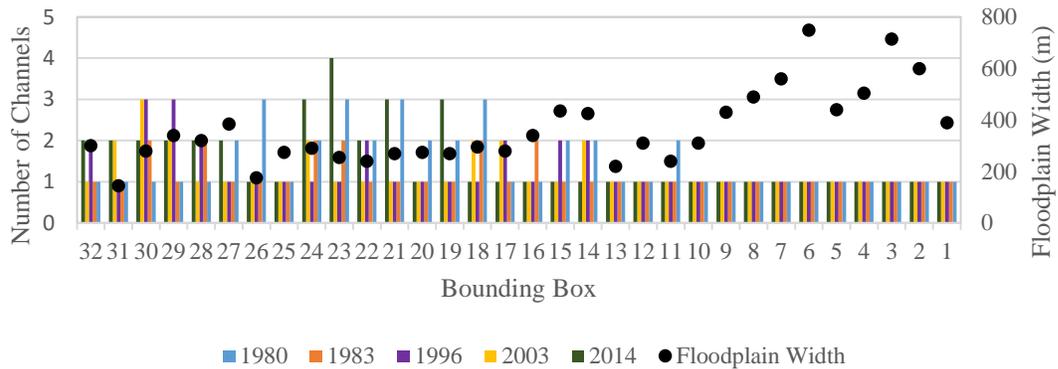


Figure 26. Graph showing the number of channels present (1-4) for each bounding box for 1980, 1983, 1996, 2003, and 2014 as well as the width of each bounding box in meters (0-800).

Channel sinuosity 1980 – 2014

Channel sinuosity in 1980 showed several interesting trends (Figure 27). First, channel sinuosity was greatest in bounding box 6, zone 1, with a value of 1.62. This was the highest sinuosity value for all bounding boxes in all years used for this research. Second, bounding box 11 showed values that differed by .1. This difference was the highest difference in the two sinuosity values calculated for each bounding box for all years. Finally, bounding boxes 27 and 29 were two “spikes” in sinuosity values for zone 4. This trend for both of these bounding boxes was unique to the other years in this research.

Channel sinuosity for 1983 showed smaller and different trends than 1980 (Figure 27). Sinuosity values for this year were generally lower than those in 1980. The highest sinuosity value occurred in bounding box 5, zone 1, with a value of 1.278. This box and bounding box 1, zone 1, were the only boxes for this year to contain a sinuosity value of 1.2 or higher. Bounding box 28 showed a slight difference between the two sinuosity values calculated in this box, with the all-possible-channels sinuosity being slightly higher, at 1.179, than the 1.134 sinuosity value calculated from only the main channel. The sinuosity values for the bounding boxes for 1983 ranged from 1.014 to 1.179.

Similar to 1983, the channel sinuosity for 1996 showed only a few instances of 1.2 or higher (zones 1 and 4) (Figure 27). Sinuosity values ranged from 1.022 (bounding box 21, zone 3) to 1.3 (bounding box 5, zone 1). Overall, the channel sinuosity values for this year in all zones showed instances of increasing and decreasing every few bounding boxes, going downstream.

Channel sinuosity for 2003 showed the familiar high value (1.258) in bounding box 5, zone 1, and a second high value in bounding box 10, zone 2 (1.236) (Figure 27). Like 1996, channel sinuosity for this year increased and decreased every couple of bounding boxes, particularly in

zones 2 and 3. Values for 2003 ranged from 1.021 to 1.258. Bounding boxes 22 through 26 showed decreasing sinuosity values while bounding boxes 27 through 29 showed increases in channel sinuosity. This trend was unique to this year.

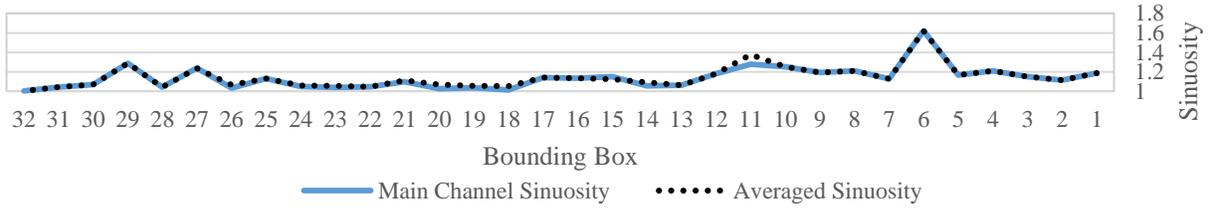
Channel sinuosity for 2014 deviated slightly from the patterns seen in 1983, 1996, and 2003 but looked to be more similar to 1980 channel sinuosity patterns (Figure 27). There was an increase in sinuosity value in bounding box 6 of 1.428. Additionally, bounding box 29, zone 4 showed an increase in channel sinuosity from that in bounding box 28. This was also seen in years 1980, 1996, and 2003. Channel sinuosity values ranged from 1.007 to 1.428.

Channel location 1980 to 2014

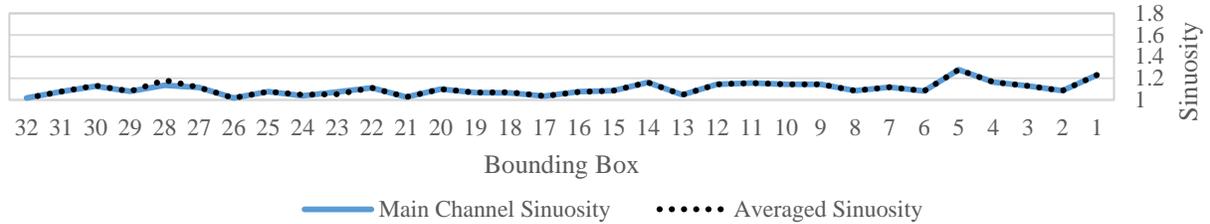
Figure 28 shows channel location within the floodplain from 1980 to 2014. The active channel was located south of the floodplain centerline for years 1980 to 2003 in zone 1. The channel then relocated north of the floodplain centerline from 2003 to 2014. Channel location in zone 2 tended to be approximately half in the southern portion of the floodplain and half in the northern half, with the exception of 1980 and 2014. Channel location for 1980 and 2014 was primarily in the southern half of the floodplain, up to the constricted portion of the zone, when the channel then was located in the northern half of the floodplain. Zone 1 showed the most change in channel location over time while channel location in zones 3 and 4 were more similar to each other over time. There did not seem to be any large changes in channel location from 1980 to 2014 in the downstream half of the study site.

The majority of change in channel location occurred in the southern half of the geomorphic floodplain in zone 1. Also, all zones showed at least one instance where the channel location for 1980 differed from the channel location from any of the other years (Figure 28).

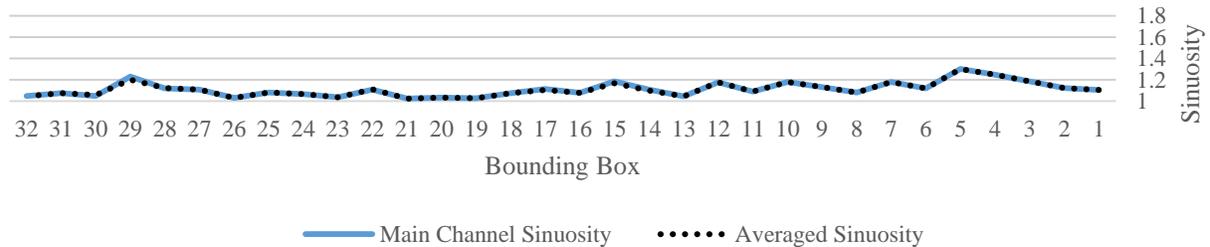
a) 1980



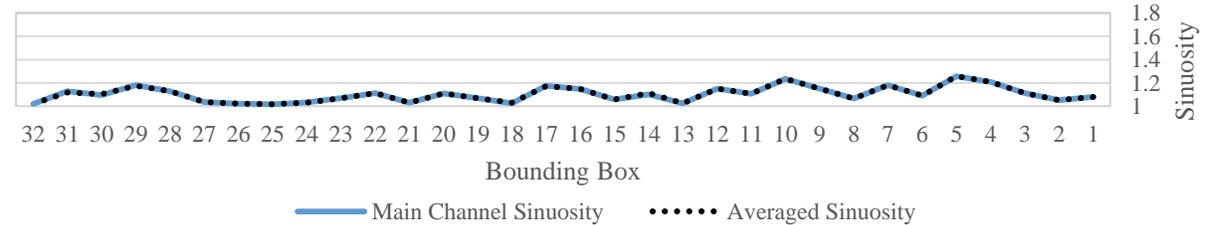
b) 1983



c) 1996



d) 2003



e) 2014

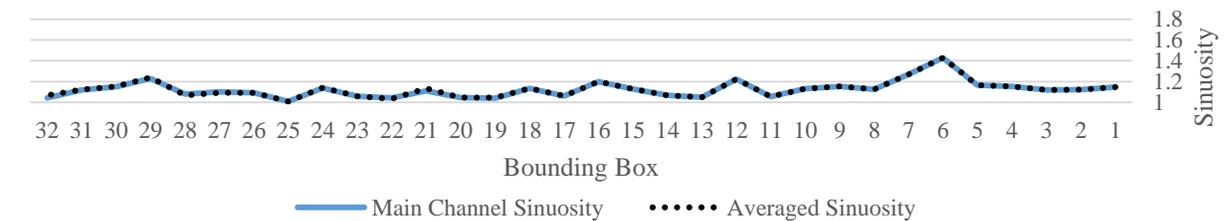


Figure 27. Graphs showing channel sinuosity for each bounding box for 1980-2014. The solid line represents the sinuosity for the main channel within each bounding box while the dotted line represents the sinuosity when all channels are included in each bounding box. Direction of flow is from right to left

South Fork Toutle River Channel Evolution from 1980 to 2014

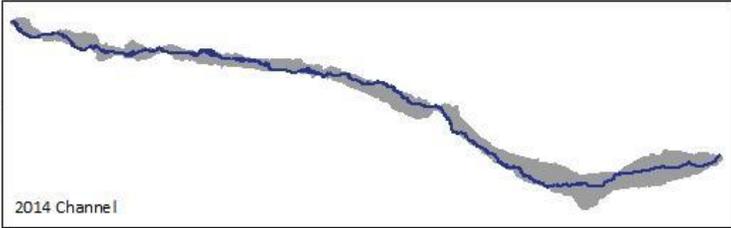
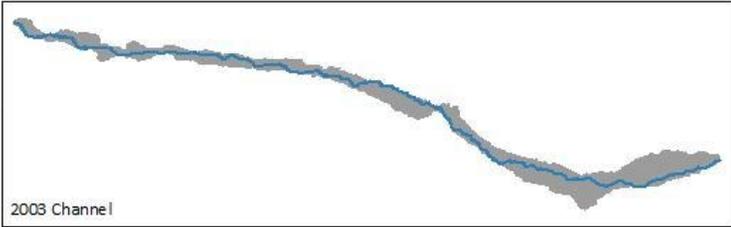
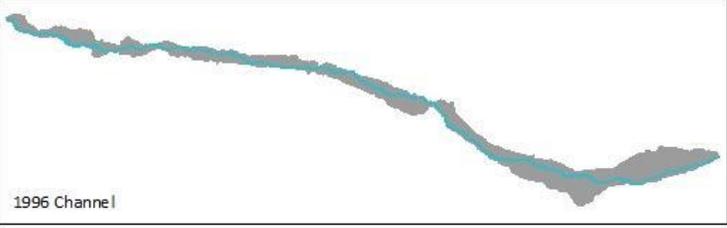
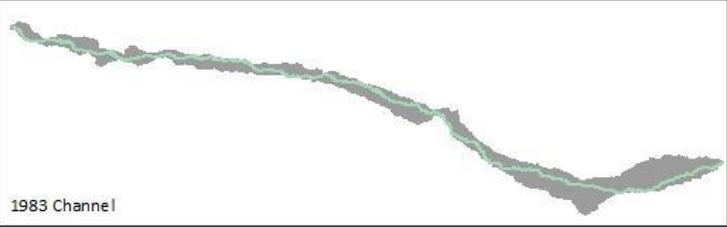
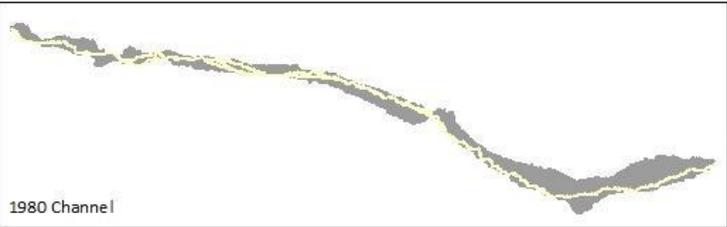
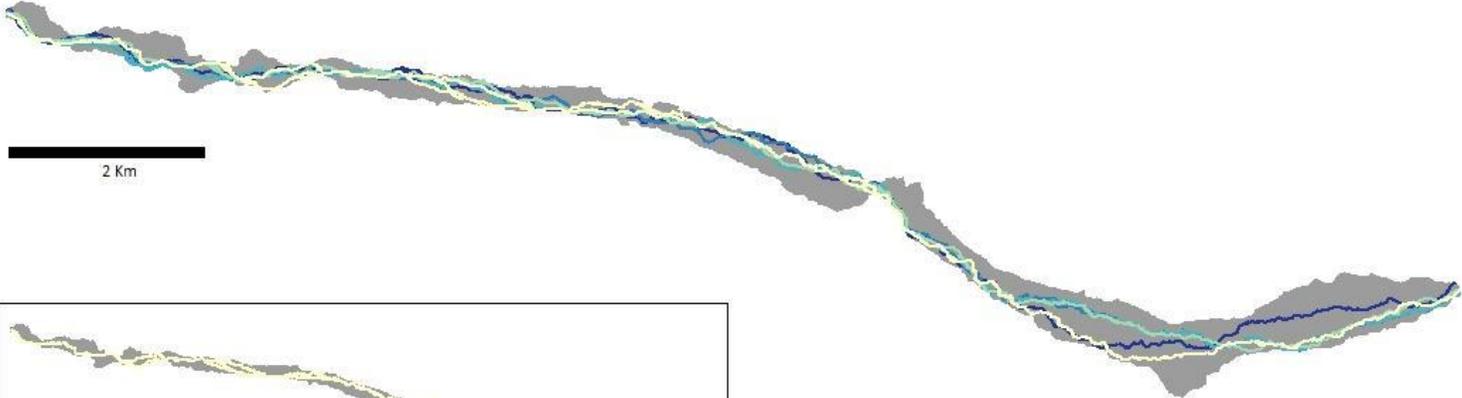


Figure 28. Maps showing channel location and migration within the floodplain from 1980 to 2014. Flow is from right to left.

Vegetation-channel interactions, zones 1-4, 1980 to 2014

Channel location in 1983 and 1996 was in the southern half of the geomorphic floodplain (Figure 28). There was also substantial vegetation present in 1996, of all classes (Figure 13). This vegetation increased in area as well as showed a general increasing trend in density from 1996 to 2014. Channel location did not switch to the northern half of the geomorphic floodplain until 2014, when the primary vegetation in that area changed from sparse and seasonal to moderate and dense. The channel location from 2003 to 2014 migrated across the floodplain in to this more stable vegetation.

Zone 2 also saw changes in channel location from 1980 to 2014, though the changes seemed more spread out spatially along the floodplain (Figure 28). Initial vegetation growth from 1996 to 2003 was minimal compared to the growth seen from 2003 to 2014 (Figure 15). The small patches of vegetation then grew to form large, dense patches, not seeming to influence channel location in 2014. The channel in this zone stayed relatively spatially constant from 1980 to 2014, even with increased area and changes in vegetation density.

Zone 3 showed a similar trend to that seen in zone 2 in channel location changes and vegetation growth from 1980 to 2014 (Figure 17 and Figure 28). Small patches of vegetation were present in 1996 which grew slowly into larger patches of vegetation of all classes. Areas with sparse and moderate vegetation patches showed these patches grow into moderate and dense patches, respectively. In this zone, it looks like vegetation growth appeared in areas where the channel was not present in previous years.

Channel location in zone 4 showed a slightly different trend than in zones 2 and 3 but similar to that seen in zone 1. Channel location was established in the absence of the sizes of vegetation patches seen in the other 3 zones (Figure 19). While this differs from the vegetation

seen in zone 1, the channel behavior was similar once the vegetation in this zone became more established and grew in to dense patches. The channel is clearly located between dense patches of vegetation that are present along both the north and south halves of the floodplain (Figure 19 and Figure 28).

CHAPTER V

DISCUSSION

Presence and Spatial Distribution of Vegetation

Crisafulli et al (2005) found that the recolonization of vegetation, or “rapid ecological response” in the Upper South Fork Toutle River, WA occurred relatively quickly after the eruption of Mount St. Helens in 1980. This was similar to the vegetation recovery rates in the Muddy River Valley (Major et al., 2009; Frenzen et al., 2005). The patterns and rates of succession were governed, in part, by the biotic and abiotic legacies that existed in the disturbed landscape (Crisafulli et al., 2005; Major et al., 2009). These legacies included chemical, soil, and others. The type, amount, and distribution of those legacies have been considered to be possibly the most important characteristic influencing that succession (Crisafulli et al., 2005).

Survivor “hotspots” or areas that experienced less of the devastating effects of the lahars and hot ash due to snowpack or other processes resulted from areas with high survivor legacies, assisted by the presence of dead biotic structures, such as dead trees (Crisafulli et al., 2005; Major et al., 2009). Larger patches were able to grow from these “hotspots” (Major et al., 2009), a trend arguably seen in the vegetation growth patterns of the Upper South Fork Toutle River valley. While vegetation in 1996 did not initially exist within the floodplain in large quantities, the development of vegetation into denser classes may have been assisted by vegetation present outside of the floodplain (Figure 19).

Based on imagery used in this research, vegetation was not observed (or possibly, observable) in 1980 and 1983. The 1996 imagery showed signs of vegetation in all of the 4 zones compared from 1996 to 2014 (Figure 29). Zone 1 contained the most vegetation within the geomorphic floodplain while zone 4 contained the least amount of vegetation for this year. The

geomorphic floodplain was the widest within zone 1, suggesting that, while this zone may be closer to the mountain and thus received the highest amount of sediment from the lahars, it was also the zone in which vegetation would have the greatest opportunity for succession and regrowth. This was due to the high sediment mobility early on. Channel placement in the southern half of the floodplain from 1980 to 2003 created a situation in which sediment transport was possible and thus fine sediment was moved out of this area over the course of several decades. Initially, this fine sediment had low moisture retention capability, little nutrient content, and areas with no tree cover and limited shade hindered vegetation growth (Crisafulli et al., 2005).

As this sediment moved downstream, conditions suitable for vegetation growth and expansion were created, such as windblown nutrients, and vegetation density increased in many areas in the southern portion of the floodplain. By 2014, the channel had migrated to the northern portion of the floodplain, allowing for vegetation maturity and increased density in the southern portion of the floodplain (Figure 28, Figure 13).

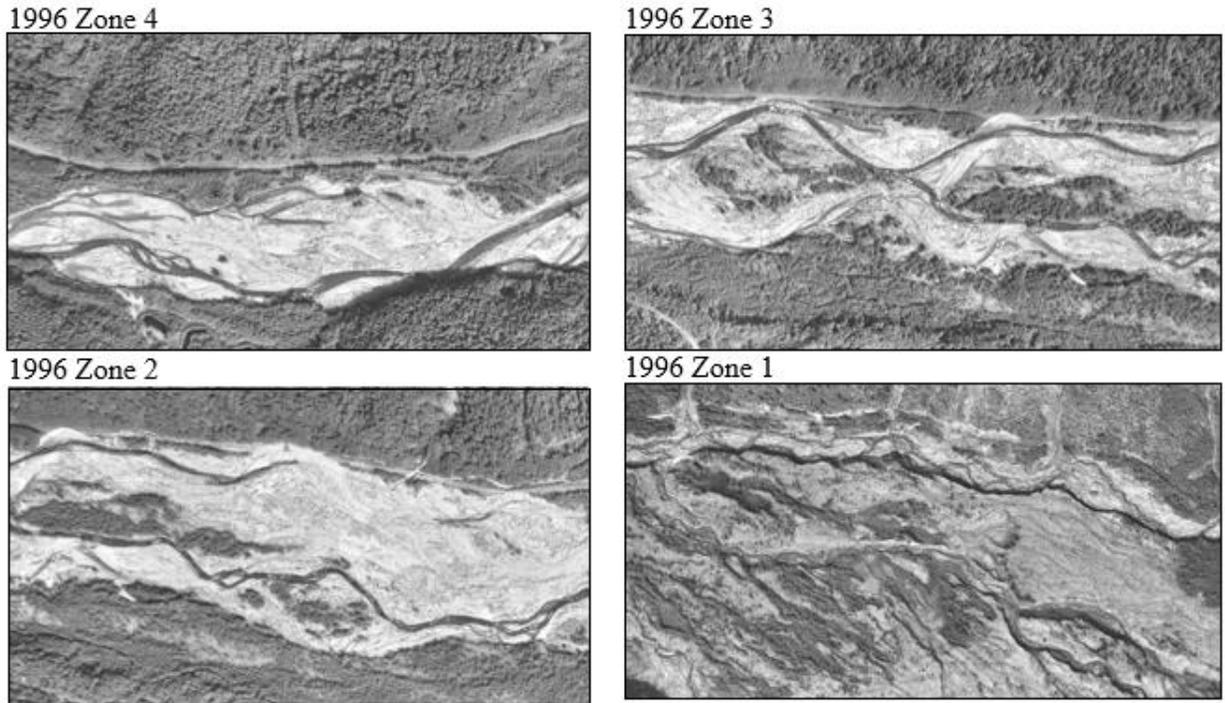


Figure 29. Images showing vegetation present in sample locations in each of the 4 zones. Zone 4 is the farthest downstream. Direction of flow in all images is from left to right.

Areas at the edges of the floodplain, close to the valley walls, that initially showed growth in 1996, were prime candidates for areas of future expansion and maturity. This 16-year gap was similar to findings in which recovery of at least 150 species of vascular plants were observed 13 years after the eruption (as cited in Crisafulli et al. 2005). Some areas increased in density while other areas that possessed no vegetation in 1996 developed moderate and sparse vegetation from 1996 to 2014). This pattern was seen throughout the study area (Figures 13, 15, 17, and 19). Areas in which vegetation was present within area occupied by the active channel were most likely not a resulting growth from survivors or legacies.

It is important to note that individual species were not considered in this research. Species type has been acknowledged to influence initial spatial, succession, and growth patterns of vegetated areas (Crisafulli et al., 2005; Del Moral, 1983; Dale, 1989; Gurnell et al., 2001; and

others). Species data has been collected for other rivers and reaches surrounding Mount St. Helens (Crisafulli et al., 2005; Dale, 1989; Del Moral, 1983; Major et al., 2009; and others), denoting the importance of species data when understanding the overall context of vegetation responses after the eruption in 1980.

Future research would benefit from examining potential ‘ecosystem engineers’ present in this river valley. These species have been found to play an important role in the successional events in other study areas, the River Tagliamento being a prime example (Edwards, 1999).



Figure 30. 2014 image showing the same area in zone 3 as in Figure 29.

There are several constraints to comparing the vegetation growth and expansion to historical data (i.e. data of the area pre-eruption as well as data gathered by other researchers post-eruption), both in this area and elsewhere. First, similar data at this scale is non-existent in the literature. While many studies have explored a variety of environmental responses in the aftermath of the eruption of Mount St. Helens, very few, if any, have focused specifically on the South Fork Toutle River at a finer scale. Research in this area has mentioned the South Fork as part of an overall examination of responses but little has seemed to focus on creating a comprehensive set of evolutionary patterns or characteristics present in this area. Second, changes in vegetative cover have been examined at varying scales with varying methods (Peixoto et al., 2009; Gurnell et al., 2001; Zanoni et al., 2008; and others) and thus make it

difficult when comparing across research. This difficulty is mentioned specifically by Piexoto et al., 2009, suggesting a strong need for methodological consistency.

Interactions of Vegetation Growth Relative to Channel Evolution

Vegetation present in 2003 showed increases in the majority of the 32 bounding boxes in this study, resulting in an overall increase in vegetation from 1996 to 2003 (Figure 21). A similar pattern was seen from 2003 to 2014. Succession, seen as one of two main kinds of vegetation dynamics, is a gradual process that follows a disturbance and progresses towards relatively stable conditions (Edwards, 1999). In the context of this research, allogenic processes such as hydrologic events can be viewed as important factors in initiating succession (Edwards, 1999).

For the purposes of this research (Research Question 4), data on channel location and migration across the geomorphic floodplain were examined in order to provide a framework for vegetation-channel interaction analyses. Understanding how vegetation growth may have influenced channel movement and formation as well as how channel location may have influenced vegetation growth over time is a necessary piece of the post-eruption puzzle that will assist in future research about these interactions (Research Question 3).

Channel morphology was more complex downstream than upstream (Figure 26). This can be inferred from the higher number of channels present for all years in zones 2, 3, and 4 as well as some of the instances of higher sinuosity values in zone 4 (Figure 27). Zones 3 and 4 also experienced moderate rates of channel location change, particularly from 1980 to 1983 and 2003 to 2014 (Figure 28). Channel sinuosity tended to decrease over time from 1980 to 2003. Sinuosity values then showed a slight increasing trend in 2014, suggesting that the river might still be recovering from 2014 to the present.

Additionally, the channel in zone 1 existed in the southern half of the floodplain in 2003 but in the northern half in 2014. The southern half then showed an increase in vegetation growth, most notably of sparse and moderate classes (Figure 13). The northern half of the floodplain in 2003 contained sparse and seasonal vegetation, no moderate or dense, which may have influenced the location of the channel formation. Overall, channel relocation occurs around areas containing dense vegetation, but the channel never bisects an area of dense vegetation (Figures 13 and 15, bounding boxes 7, 8, and 9).

Another pattern seen in vegetation-channel interactions occurred in zones 2 and 4 in 2014. These zones contained channels with vegetation growth occurring at a distance from the channel, and not right alongside it (Figures 19 and 15). This was only present in 2014, suggesting that vegetation growth over time was necessary for this to take place. Vegetation was also mostly dense vegetation, with little or no presence of moderate, sparse, or seasonal. This suggests a control of the channel location on vegetation presence and growth.

Future research should focus on obtaining ground data for the Upper South Fork Toutle River. Vegetation verification is necessary for a more complete and exact understanding of how vegetation may have interacted with the rate of lateral reworking of the geomorphic floodplain. Additional information is needed concerning why all zones in 2014 did not experience similar vegetation growth and distribution.

Channel Formation

The reformation of the South Fork Toutle River occurred relatively quickly after the May 18th eruption of Mount St. Helens, WA (Meyer & Martinson, 1989). Evidence of a flowing channel is clear in the 1980 imagery used for this research, just months after the eruption (Figure 7). The floodplain was completely covered by the large lahars that swept through the river valley

(Figure 4). Fine sediment was deposited on the valley floor, some of which is still present today. As a result, many small islands formed as the channel evolved. These islands became evident in the 1996 imagery used in this research. Overall, vegetation increased from 1996 to 2014. This could be due, in part, to the increased presence of larger sediment islands.

The increase in the number of channels going downstream (Figure 26) suggests that the river underwent a series of changes as new and existing vegetation evolved. Multiple small channels tended to form in areas with vegetated islands (especially seen in Figure 17). Areas with a wider floodplain showed the development of more than one channel in few areas. Sometimes, multiple smaller channels within a split channel formed, usually when vegetated islands were present. This could suggest that vegetation had an effect on the number of channels formed or the location of where multiple channels would form over time. Indeed, areas with vegetation present on the northern half of the floodplain experienced channel formation and branching within the southern half of the floodplain.

Many areas showing dense vegetation did not also show narrower channels over time but instead showed channel widening going downstream, suggesting that the channel has continued to be influenced by the presence of the fine sediments deposited by the lahars that swept through the valley in 1980. It has been noted that bank stability is influenced by sediment composition and that stable banks made by resistant sediment will support different vegetation types than unstable banks (as cited in Huang and Nanson, 1997).

It is important to understand the many factors influencing tree species ability to establish successfully (Gurnell et al., 2001). Only the factor of channel migration was considered in this research. This variable is important in that riparian vegetation may not successfully establish if there are high rates of floodplain turnover. Looking at vegetation location and channel formation

from 1996 to 2014, one can see that areas with high lateral migration, or channel movement across the floodplain, also experienced more vegetation change (Figures 13, 15, 17, and 19).

Channel Evolution

Channel migration occurred between 1980 and 2014. The highest area of channel migration occurred where the floodplain was wider and where more sediment was present. Additionally, several peak flow events occurred during the period of study, specifically in 1990, 1996, and 2006 (Figures 1 and 8). The largest peak flow event occurred in 1996, causing an increase in suspended sediment (Figure 1). After this peak flow event, the channel reworked itself in multiple locations within the floodplain, as seen in 2003 (Figure 22). The channel in zone 1 and zone 2 changed location from occupying the southern half of the floodplain in 1996 to occupying the northern half of the floodplain in 2003 (Figure 28). This channel migration was most visible in zone 1. This would suggest that the peak flow event may have caused an increase in channel migration across the floodplain over time.

Channel width generally increased going downstream. This indicates that either a single channel increased in width or the single channel split into multiple channels, thus increasing overall channel width at the branching points. 1980, 1996, 2003, and 2014 tended to show channel splits at least once at some point downstream from bounding box 11 (with the exception of bounding boxes 12, 13, and 25). Bounding box 23 contained the highest number of channels, 4, specifically for 2014 (Figure 26). Areas with wider floodplain did not tend to contain more channels or have higher channel width (Figure 26 and Figure 22).

The number of active channels present showed two major trends. First, the number of active channels tended to decrease from 1980 to 2014, except for 2003 to 2014. Second, the number of active channels present in a given year tended to increase going downstream up until

the downstream end (after box 32) of the study area where a narrower floodplain probably limited the formation of multiple channels. These results could suggest that, though the Upper South Fork Toutle River may be steadily reaching a more stable state, it has not yet reached pre-eruption conditions. One would expect to see a decrease in complexity as the channel reached a more stable state (however, complexity increased from 2003 to 2014). Due to the high amounts of fine, easily-suspended sediment present in the upper reaches of the valley, the channel in that area may take more time and have increased difficulty in reaching a stable state. Indeed, only a single channel is present in boxes 1-10 in all years (Figure 26). Once more sediment moves out of this area, it may be possible for the active channel in this area to form a more consistent pattern.

Sources of Error and Future Research

Several areas of error were present in the foundation of this research. Due to the nature of the digitization of the data from 1980, comparison of the 1980 dataset to the data from years 1983, 1996, 2003, and 2014 is somewhat inexact. The aerial imagery was taken only a few months after the eruption of Mt. St. Helens and thus contained many areas blanketed by ash and lahar deposits. This made georeferencing the photos extremely difficult and fewer GCPs were used (around 4 to 6 per photo) than for the later photo sets (at least 8). This does not necessarily mean that spatial error was greater for 1980, only that GCPs were fewer and placed only in areas close to the floodplain, not within it. In fact, the lighter grey within the floodplain made creating the outline of the geomorphic floodplain relatively easier than the imagery that contained more complex lines around the floodplain. This difficulty was also encountered by Janda et al., 1981. Additionally, the 2003 imagery was at a lower resolution, thus georeferencing was difficult for

this year as well. The types of error present for this dataset were different than for the 1980 imagery in that the pixel size was the limiting factor, not the landscape homogeneity.

The 1980 imagery provided a baseline for comparison of channel change and floodplain evolution but no riparian or floodplain vegetation was found or compared. Future research in this area should strive to utilize color imagery for this year if possible in order to obtain more accurate visual classification of channel, floodplain, and riparian vegetation.

Shadows in all years of photos used made digitization in some areas difficult and less accurate. Steep terrain sometimes contained tall trees that jutted out over the floodplain and channel which showed up as black in the images. The only sets of imagery in which this occurred less often were the 2003 and 2014 sets. These photo sets were taken in color and shadows were less opaque. Error contained within the georectified imagery provided by Google Earth and ESRI for years 2003 and 2014 could also have contributed to error throughout the digitization process and subsequent analysis.

Imagery for 2003 was provided by Google Earth Pro. This dataset is unlike the other datasets and thus may contain different types and amounts of error. One of the issues with this data is that the resolution is lower than the other datasets used.

Other research of this area should keep in mind the seasonal aspects of the imagery chosen. The researcher should primarily or exclusively use either a dry or wet season for more accurate comparison. Additionally, future research should attempt to understand in more detail how and when specific vegetation classifications changed over time and space. The classes of sparse, moderate, dense, and seasonal allow for in-depth analyses that future research can utilize. This research focused on overall trends but specific trends will be necessary to understand vegetation and channel interactions in depth.

Future research should also examine the potential effects of the 1996 flood on the vegetation and channel morphology within the study area. Floods have been determined to play an important part in sediment transport and floodplain turnover rates (Gurnell et al., 2001; and others). Major (2004) also noted that suspended sediment loads increased in the late 1990's in the Toutle River, the South Fork Toutle River, and the Green River. This could be suggestive of flood-induced increases in sediment transport.

CHAPTER VI

CONCLUSION

Several research questions were posed in the introductory section of this research:

1. *How has the spatial distribution of vegetation changed from 1996 to 2014?*
2. *In what 2-dimensional ways has the Upper South Fork Toutle River channel changed since 1980?*
3. *In what ways might vegetation growth have affected channel morphology and floodplain turnover rate between 1980 and 2014?*
4. *How might channel evolution have affected the spatial distribution of riparian vegetation between 1980 and 2014?*

The spatial distribution of the 4 classes of vegetation has changed drastically from 1996 to 2014. In addition to the overall increase in vegetation, dense vegetation has increased and become more widespread in all 4 zones in this study. Moderate vegetation did not experience such drastic change but areas with moderate vegetation either tended to increase in size or develop into dense vegetation. Sparse vegetation, most likely smaller shrubs and young trees, tended to evolve into moderate vegetation and then dense vegetation, over time. In this way, spatial distribution of vegetation within the study site has been dependent on the presence of pioneer plants that have spread across the floodplain in patches.

The active channel of the Upper South Fork Toutle River has undergone several changes between 1980 and 2014. Average channel width has increased in almost all portions of the study site. Channel location has varied from occupying the northern half of the floodplain to occupying the southern half of the floodplain. The channel has also developed multiple channels with small in-channel islands, as well as ultimately merging into a single channel at the western end of the

study site. It is hypothesized that the decreasing presence of fine sediment from the eruption has allowed the channel to incise into more stable material, resulting in more permanent channel location and size. However, with the increasing sinuosity values seen in 2014, this may not entirely be the case.

The data and evidence gathered concerning potential vegetation influences on channel morphology and floodplain turnover rate between 1980 and 2014 does not provide any conclusive evidence. It was found that areas that had been previously occupied by the channel were likely to be areas where vegetation grew shortly after. It was also shown that areas with dense vegetation did not experience as much lateral migration of the channel and lower floodplain turnover. Additionally, the presence of seasonal vegetation seemed to allow for an increased chance in channel formation in that area.

Channel evolution of the Upper South Fork Toutle River may have played an important role in the spatial distribution and evolution of vegetation in the area. Channel presence allowed for the removal of fine sediment, increasing the chance for vegetation colonization on stable surfaces. However, additional work is needed for an informed understanding of vegetation-channel-sediment dynamics. The insights gained in this research only provide a piece of the puzzle.

The findings in this study provide key data necessary for future analyses along this section of the river. The spatial distribution of vegetation classes may be used to inform researchers of key locations to focus on for potential pioneer species. Understanding the type and structure of some of the first species to recover after such a major disaster will be important for further research in this area as well as other areas that have experienced similar situations.

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