A SPATIAL ANALYSIS OF CHANNEL MIGRATION IN RELATION TO CHANNEL-SPANNING LOG JAMS AND RIPARAIN FOREST COVER

by

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DEDICATION

This paper is dedicated to my friends and family, who have been so supportive of me during my time in the Land Resources and Environmental Sciences Program. I would like to thank my partner, Rochelle, especially for doing so much to ensure that I was able to finish my work and schoolwork over the past few years. I cannot express how thankful I am for her help and care. I also dedicate to my father, who passed away during the first year of my time in the LRES Program – I miss you and wish you could be here today.

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ABSTRACT

Log jams play an important role in Pacific Northwest river systems, providing habitat for aquatic species, influencing sediment and organic material dynamics, and shaping channel geomorphology. Riparian forests provide a source of largewood, generally recruited through lateral channel migration that erodes the streambank. The cycle of wood recruitment, log jam formation, and channel migration is a part of a process that drives further changes to channel geomorphology while also creating erosion-resistant hard points in the floodplain that are refugia for riparian forest vegetation that further drive this cycle and river system dynamics. In the Pacific Northwest, development within floodplains since the arrival of European settlers has interfered with the floodplain largewood cycle. My study examines the influence that channel-spanning log jams and riparian forest cover have on channel migration over time to better inform management of floodplain development and facilitate restoration of healthy, dynamic river systems. Satellite imagery, remote sensing data, and GIS software are used to analyze channel migration in the Deschutes River (Thurston County, Washington) in relation to channel-spanning log jam presence and riparian forest cover. Using Google Earth and USGS imagery, I completed tracings of the channel, islands, and channel-spanning log jams for incremental years between 2003 and 2021. I then compared sequential channel year overlays using a QGIS model that calculates the area of channel gain and loss, total area of both merged channels, mean forest cover, and log jam area within a set of 75-m radius study cells. A Normalized Channel Migration Index (NCMI) was then calculated using the area of gain, loss, and total area of both merged channels, and indicated the level of channel migration that occurred within the study cell between the two years of comparison. I found that NCMI values are higher in study cells where log jams are present, and in study cells where log jams are present with varying riparian forest cover. Additionally, NCMI values are highest for study cells with mean forest cover between 0% and 25% that also have a log jam present as compared to all other study groups considering these variables. The higher NCMI values suggest that channel migration is greater in reaches where log jams are present and greater still where there is little to no intact riparian forest. The results of this analysis highlight the need for adequate riparian forest cover and the channel migration capacity of log jams.

CHAPTER 1 – INTRODUCTION

Background

Log jams perform many different functions within river systems by serving as a source of habitat complexity for aquatic animal species, influencing the transport and storage of organic matter and sediments, and by driving fluvial processes that shape the geomorphology of river systems. Riparian forests are the primary source of logjam-forming largewood for river systems, and lateral channel erosion is a common mechanism for the recruitment of largewood into the river system. In Pacific Northwest watersheds, old-growth riparian forests are also crucial to the health of river systems and to sustaining watershed function over time (Latterell and Naiman, 2007).

Once in the river system, pieces of largewood can form log jams that can protect channel features by acting as a hard point that resists erosion, or to drive channel erosion through the redirection of erosive stream flow. The ability of log jams to form refugia within a stream's floodplain provides habitat for many different species of vegetation, including large tree species, such a *Thuja plicata* (Western redcedar) and *Pseudotsuga menziesii* (Douglas fir). These species can grow to a large size over centuries and then, in turn, fall into the stream and establish new log jams within its channel (Montgomery and Abbe, 2017). Where log jams obstruct or deflect streamflow, resulting streambank erosion further recruits largewood into the river system, providing the ingredients to create additional log jams. This self-perpetuating process of old-growth riparian forest establishment, largewood recruitment through bank erosion, and log jam formation that both drives further erosion (and largewood recruitment) and resists erosion (refugia development), is described by Collins et al. (2012) as the floodplain largewood cycle.

Riparian forest vegetation and in-stream largewood provide both physical habitat and a source of nutrients for riparian and aquatic biota. Channel-spanning log jams, specifically, have been found to be more effective than non-channel-spanning log jams at providing at least temporary storage of sediment, organic matter, and water, and creating aquatic habitat complexity in Pacific Northwest streams (Livers & Wohl, 2021). Channel spanning jams can therefore bolster in-stream habitat for species across all trophic levels, and increase water retention capacity of stream reaches (Livers & Wohl, 2021). As such, the loss of riparian forests, particularly old-growth riparian forests, through deforestation and changes to land use breaks the floodplain largewood cycle that provides so many critical ecosystem and watershed functions. Decreases to the amount of largewood input to river systems over time leads to a dramatic simplification of channel and floodplain morphology, a process further exacerbated by the historical removal of largewood from river systems (Montgomery and Abbe, 2017). The loss of in-stream largewood and log jams generally increases the erosive power of streamflow within the channel, resulting in decreases to channel complexity, channel sinuosity, and channel habitat diversity over time while sediment transportation by the stream system increases (Brooks et al., 2003).

Livers and Wohl (2021) found that the increased water, organic material, and sediment storage potential of channel-spanning log jams can also help to drive changes to channel planform and bedform. By obstructing streamflow, channel-spanning log jams can accumulate both sediment and organic materials transported by the stream. Sediment accretion and further accumulation of in-stream wood and other organic materials on the upstream side of the log jam can result in the aggradation of the streambed and the creation of backwater pools (Collins et al., 2012). The temporal persistence of channel-spanning log jams, and the hydrogeomorphic features that they create, are generally influenced by streamflow patterns which are, in turn, determined by precipitation regime, precipitation intensity, watershed hydrology, and upstream channel geomorphology. The combination of these factors makes it very difficult to predict the persistence of channel-spanning log jams over time, and the associated geomorphic changes. Channel avulsion due to streambed aggradation, changes to local hydraulics, and bank erosion are also within the range of possible hydrogeomorphic responses to the presence of a log jam or series of log jams, both channel-spanning and non-channel-spanning.

Within most of the watersheds of the Pacific Northwest, human activities and development since the arrival of European settlers to the region has resulted in the reduction of riparian forest cover and the removal of in-stream largewood and log jams, simplifying many of these river systems (Collins et al., 2012). The continuation and, in some areas, the restoration of the floodplain largewood cycle is a crucial component in the effort to recover threatened and endangered salmonid species populations through habitat restoration (Cederholm et al., 2001). As such, it is critical to consider the impacts that development and land use practices have on river systems and their ability to facilitate the floodplain largewood cycle and provide the complex, cold-water habitats that salmonids require.

Study Objectives

In an effort to better inform the management of development within river floodplains, and to better facilitate restoration dynamic and healthy river system, my study examines the impacts of land cover and channel-spanning log jams on river channel migration in the Deschutes River. I hypothesize that channel migration will be greater in areas near channel-spanning log jams. Further, I hypothesize that channel migration will be greater in deforested reaches where log jams are present than that of forested reaches with log jams present.

CHAPTER 2 - STUDY AREA

The Deschutes River

The Deschutes River watershed (**Figure 1**) is comprised of roughly 442 km^2 of forest land (both natural and managed), agricultural land, rural residential, sub-urban residential, and urban areas, with forest land being the primary land cover (Wagner and Bilhimer, 2015). The headwaters of the Deschutes River lie within the low, forested mountains of northern Lewis County, Washington, and flow in a northwest direction through low-relief forests and grasslands towards the Puget Sound. Most of the Deschutes River watershed lies within Thurston County, Washington, with the mouth of the river discharging to the Puget Sound in Olympia, Washington. This river system, and its adjacent riparian forests and wetlands, provides habitat to many species of invertebrates, birds, aquatic and terrestrial mammals, and fish including salmonid species such as *Oncorhynchus tshawytscha* (Chinook salmon) and *O. mykiss* (steelhead trout).

Past glaciations shaped much of the landscape of the Deschutes watershed, leaving behind glacial outwash plains, glacial terraces, and other remnant landscape features (Wagner and Bilhimer, 2015). Likewise, past glaciations form the basis of the geology of the watershed. Glacial till and outwash materials underly much of the soils in the middle and lower reaches, while shallow and exposed bedrock is common and often dominant in the upper reaches and headwaters (Thorsen and Othberg, 1978). Precipitation, in the form of rain, is the significant contributor to stream flow in the Deschutes River watershed throughout the year (Wagner and Bilhimer, 2015). The rainy season in western Washington often begins in early fall and persists through the winter and into the late spring, during the cooler months of the year. Late spring and summer are typically warm and dry. This climate fosters the perfect conditions for lush forests throughout the region, dominated by *Pseudotsuga menziesii* (Douglas fir), *Thuja plicata* (Western redcedar), *Tsuga heterophylla* (Western hemlock), and *Acer macrophyllum* (bigleaf maple). Additionally, South Puget Sound prairies can be found within the Deschutes River watershed and some of the adjacent basins, which provide habitat for plant species that prefer drier conditions such as *Quercus garryana* (Garry oak).

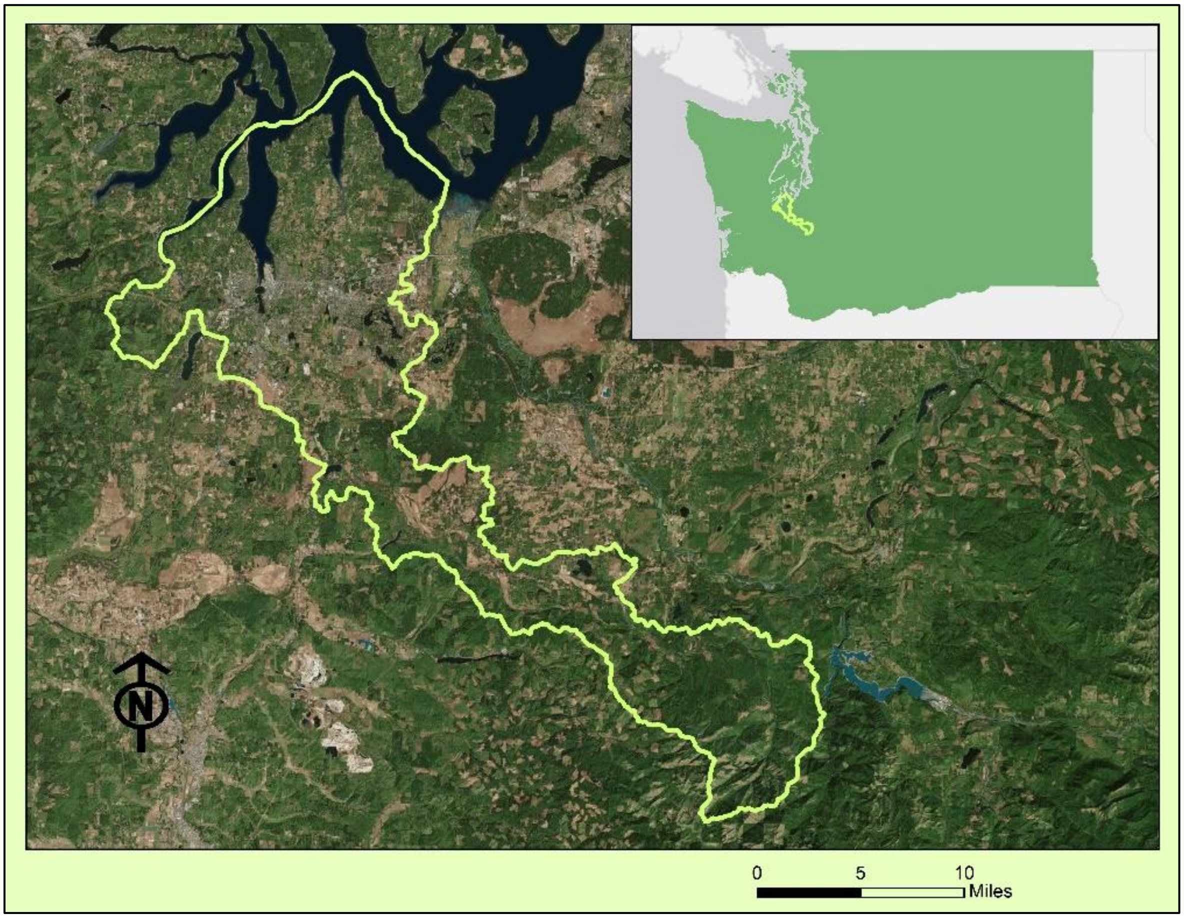


Figure 1 *- Map of the Deschutes River watershed courtesy of the Washington Stormwater Center Deschutes River Watershed Story Map (2022).*

A majority of the Deschutes River watershed is forested, with areas of urban development concentrated towards the mouth and lower reaches of the river in Olympia and

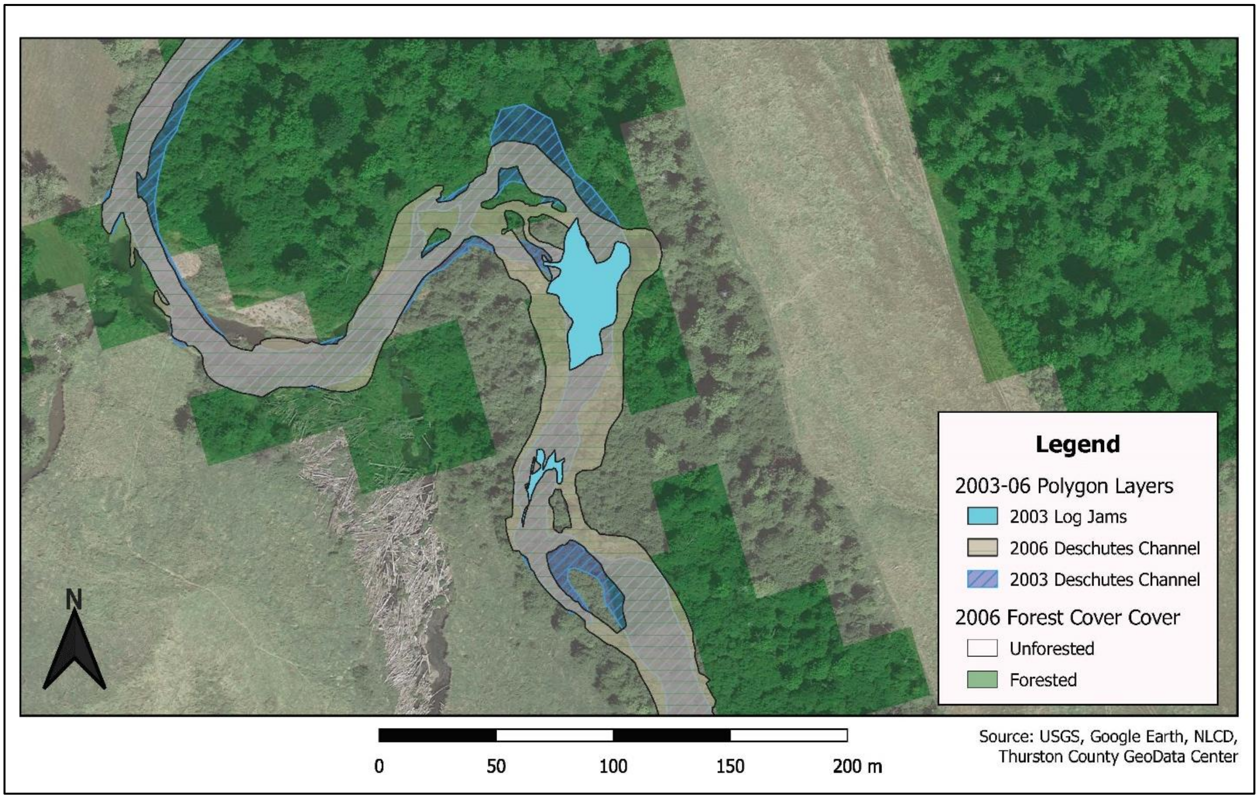
Tumwater, Washington. Riverside development including homes and agricultural areas is common in these lower reaches. Decades of development within the watershed and floodplain have resulted in substantial loss of riparian forest in the middle and lower reaches of the mainstem Deschutes River, particularly over the last decade as development within Thurston County has increased with population growth in western Washington. Reduced habitat quality due to low amounts of in-stream largewood has also been identified as a deficiency in the mainstem of the Deschutes River (Levitt et al., 2015). Several water quality impairments have also been identified in the Deschutes River, including temperature, dissolved oxygen, pH, bacteria, and fine sediment (Wagner and Bilhimer, 2015). This study will focus on an approximately 68-km stretch of the mainstem Deschutes River between Deschutes Falls and Tumwater Falls. Deschutes Falls is located towards the headwaters of the Deschutes River. Tumwater Falls is located approximately 68 km downstream of Deschutes Falls in the city of Tumwater, Washington, one of the three cities making up the greater Olympia area.

CHAPTER 3 - METHODS

Satellite Imagery and GIS

The emergence of freely available high and moderate resolution satellite imagery has provided natural resource planners a valuable resource for studying and observing land cover change. Atha (2013) used Google Earth satellite imagery to identify largewood within the floodplain of the Queets River, Washington, and observe the hydrogeomorphic changes due to largewood. Atha (2013) found that Google Earth satellite imagery, available over several years of their study period, could serve as a powerful tool for observing river systems over a large spatial scale, and that largewood within river floodplains could be successfully identified and measured.

In a similar effort, I used nearly 20 years of satellite imagery from the U.S. Geological Survey (USGS) and Google Earth, and Thurston County GeoData, with forest cover data from the National Land Cover Database (NLCD) to analyze channel-spanning log jams within the Deschutes River, Washington, and their effects on channel erosion and avulsion in forested reaches and deforested reaches of the system. To examine channel migration in the Deschutes River and to capture log jam size and location, I identified and traced the river channel, islands, and channel-spanning log jams within the study area. I defined channel-spanning log jams as a log jam composed of at least three pieces of wood that are large enough to be observed using satellite imagery, which combine to approximately span the width of the stream channel. Log jams that span side channels were also included in the dataset. Google Earth was used to complete five complete tracings and two partial tracings of the Deschutes River channel and logs jams from seven separate years of historical imagery using the polygon drawing tool. Historical aerial imagery from the USGS that is freely available in Google Earth proved to be the imagery for this task due to its high resolution and convenience of use (**Figure 2**). To reduce occlusion, misplaced polygon vectors, and other errors in these tracings, USGS aerial imagery was compared to imagery from Thurston County GeoData, when possible.



Source: USGS, Google Earth, NLCD, Thurston County GeoData Center

***Figure 2** - Example map showing channel polygons, log jam, and forest cover raster layers for the years 2003 and 2006.*

Only the lower half of the study reach was traced for 2013 and the upper half of the study reach was traced for 2012 as that was the extent of the aerial imagery for those respective years. The imagery from the Thurston County GeoData has finer imagery resolution than the USGS aerial imagery but is only available in online reference maps which cannot be used to export polygon vector layers generated within the online map and was therefore only used for comparison and error checking. Overall, 7 channel year tracings and log jam layer tracings were created – 5 full extent tracings and 2 partial extent tracings using USGS and Google Earth imagery (**Table 1**).

Table 1 – Imagery Date, Source, and Number of Log Jams for each Representative Imagery Year

Representative Year	Imagery Date(s)	Imagery Source	Number of Log Jams
2003	5/31/2003	U.S. Geological Survey / Google Earth	36
2006	5/15/2006	U.S. Geological Survey / Google Earth	30
2009	4/30/2009	U.S. Geological Survey / Google Earth	34
2012 (partial extent)	7/5/2012 – 8/14/2012	U.S. Geological Survey / Google Earth	19
2013 (partial extent)	5/5/2013	U.S. Geological Survey / Google Earth	13
2017	6/21/2017 – 7/17/2017	U.S. Geological Survey / Google Earth	27
2021	6/18/2021 – 7/25/2021	U.S. Geological Survey / Google Earth	51

The resulting keyhole markup language (KML) files for each of the seven years within the dataset produced in Google Earth were then exported to QGIS, and then converted to geopackage format (QGIS, 2022). After converting the layers to geopackages, the channel and channel island layers were then combined using QGIS’s Difference Tool into a single channel layer. This approach resulted in two distinct layers – a complete channel layer and a log jam layer – for each year within the dataset. I used NLCD land cover rasters from 2006 to 2019 to provide forest cover data for the analysis period. These rasters were simplified by reclassifying the original 16 land cover classes, for the continental U.S., into just two land cover classes, forested and unforested (Table 2). This spatial data provided the necessary inputs for the analysis performed here.

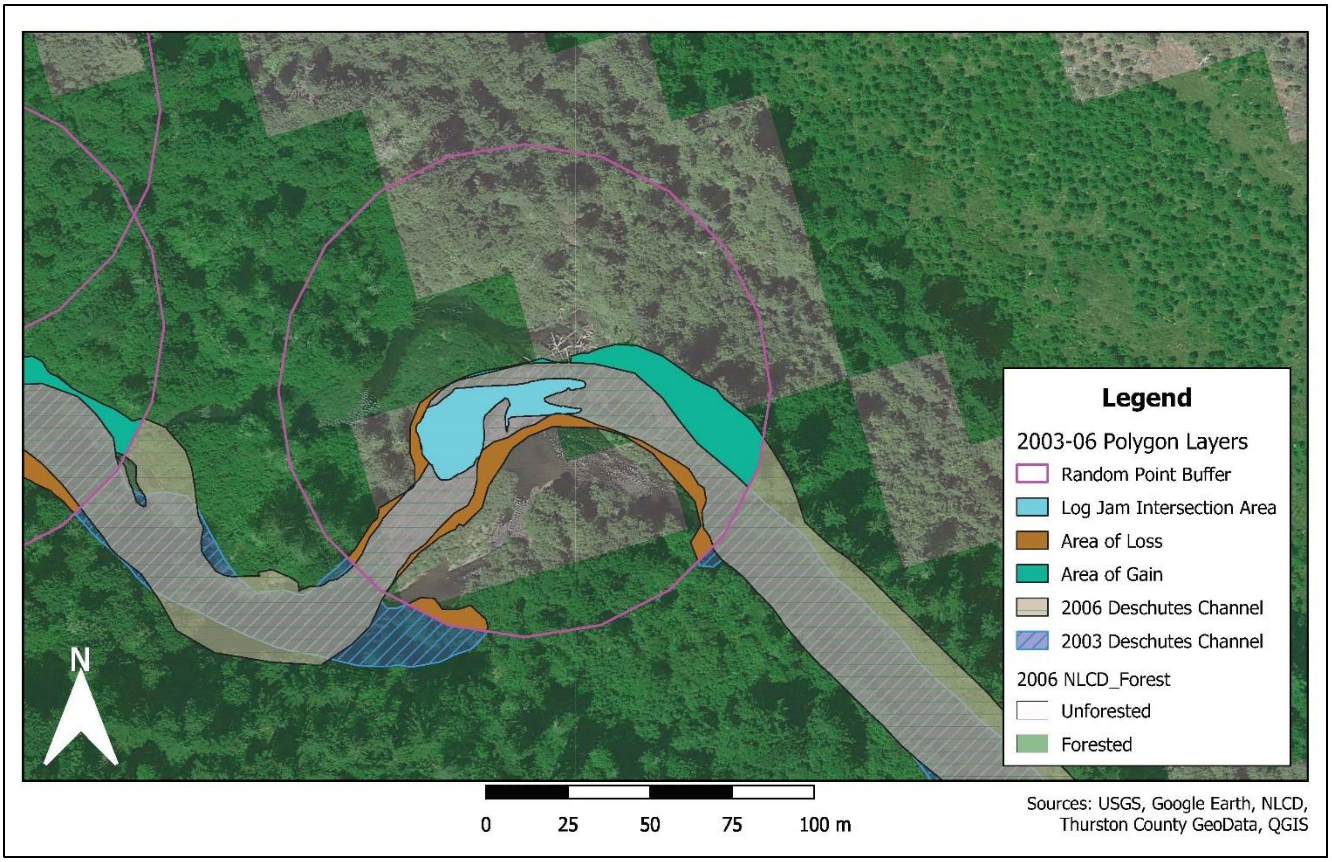
Table 2 – Initial NLCD Land Cover Classes vs. Model Land Cover Class following Reclassification

Initial NLCD Land Cover Class	**Model Land Cover Class**
Deciduous Forest (41), Evergreen Forest (42), Mixed Forest (43), Woody Wetlands (90)	Forested (1)
Open Water (11), Perennial Ice/Snow (12), Developed Open Space (21), Developed Low Intensity (22), Developed Medium Intensity (23), Developed High Intensity (24), Barren Land (Rock/Sand/Clay) (31), Shrub/Scrub (52), Grasslands/Herbaceous (71), Pasture/Hay (81), Cultivated Crops (82), Emergent Herbaceous Wetlands (95)	Unforested (0)

Channel Migration, Log Jam, and Land Cover Model

To simplify the analysis, the following analytical steps were combined into a tool termed the Channel Migration, Log Jam, and Land Cover Model. This model is applied to many small study cells, each of which is defined by a buffer with a 75-m radius surrounding a randomly generated point placed within the channel area. The first step of the model is complete the placement of random points to serve as the buffer centroids. To do this, the two channel tracings being compared are merged together using the Union Tool, and then combined using the Dissolve Tool within QGIS. The GRASS vector tool V.Random is then used to place random points within the two merged channels. Each study cell is then defined by creating a 75-m-radius buffer around each point using the QGIS Buffer Tool. For the comparison of two full-extent channels (both channels were traced to the full extent of the study area), 2,000 random points and buffers are generated to form the basis for the model. For the comparison to the partial-extent channels (2012 and 2013), 1,000 random points and buffers are generated as only half of the study reach is included in each of those study years. To complete the comparison between these partial-extent years and full-extent years, full-extent channels were split at the same location. To compare the 2009 channel tracing to the 2012 and the 2013 channel tracings, the 2009 channel polygon was split into an upper and a lower section – the 2009 upper section was compared to the 2012 channel tracing and the 2009 lower section was compared to the 2013 channel tracing. This same splitting step was applied when comparing 2012 and 2013 to the 2017 channel tracing.

The study cells were then used to calculate mean forest cover from the reclassified forest cover rasters for the year closest to the second year of the comparison. For example, when comparing the 2003 channel to the 2006 channel, the 2006 forest cover raster was used to calculate the mean forest cover within the buffered areas. Using the forest cover raster from the same year as the later year channel or using the closest year that was before the second comparison year if the forest cover raster year did not match accounted for any changes in forest cover between the two years of comparison. Mean forest cover output values were calculated as a decimal value representing the forested portion of the buffer area (e.g., a mean forest cover value of 0.25 means that 25% of that buffer is forested).



Sources: USGS, Google Earth, NLCD, Thurston County GeoData, QGIS

Figure 3 *- Map of an example study cell, which includes study cells, area of gain, area of loss, and log jam intersection area layers.*

Channel migration was then assessed for each study cell by calculating three metrics that were derived from the two channel polygons being compared: area of gain (m^2), area of loss (m^2), and total merged dissolved area (m^2). The Channel Migration, Log Jam, and Land Cover Model calculated the extent associated with each of these metrics using the QGIS Intersection and Difference tools. The Intersection Tool was then used to extract the total extent of the merged channel and the extents of gain and loss that lie within each study cell. The areas of each of these extents were then determined with the Add Geometry Attributes tool (**Figure 3**). Log jam intersection area was calculated from the year one log jam polygon, which is another model input. The log jam polygon was unified using the QGIS Collect Geometries Tool, which produced a single (multipart) feature containing all of the input log jams. The resulting log jam intersection area feature was intersected with the study areas, and the Log Jam Intersection Area for each study area was calculated using the Add Geometry tool (**Figure 4**).

After the calculation of the areas of forest cover, log jams, channel gain, channel loss, and total merged channel, these metrics were joined to the study cell attributes using their feature identification numbers, which included each of these five metrics. The resulting attribute table, with the joined metrics, were then exported as a Comma-Separated Values (CSV) file. Then, Microsoft Excel (Excel) was used to calculate a Normalized Channel Migration Index (NCMI) for each specific buffer. NCMI is an index representative of the degree of channel migration that occurred between the first and second year of comparison and is calculated using the following formula:

$$NCMI = \frac{Area\ of\ Gain_{year\ 1 \rightarrow year\ 2} + Area\ of\ Loss_{year\ 1 \rightarrow year\ 2}}{Merged\ and\ Dissolved\ Channel\ Area_{year\ 1 \rightarrow year\ 2}}$$

The result of this calculation is a value between 0 and 1, where 0 indicates that both channels in the comparison occupy the same area (i.e., there was no observed channel migration) and where 1 indicates no channel overlap between the first comparison year and the second comparison year (i.e., the second-year channel is completely different from the first-year channel). I also used Excel to categorize Mean Forest Cover values into four quartile percentage categories for analysis: 0-25%, 26-50%, 51-75%, and 76-100% forest cover. Similarly, the log jam intersection area metric was used to create a log jam presence indicator, with all buffers with a log jam intersection area greater than 0 m^2 having a “TRUE” indicator and all buffers with a log jam intersection area equal to 0 m^2 having a “FALSE” indicator.

Table 3 - Deschutes River Channel Comparison Group Data

Comparison Years	Year 1	Year 2	Study Reach Extent	Log Jam Year	Forest Cover Raster Year	Study Cells Generated
2003-06	2003	2006	Full Extent	2003	2006	2,000
2006-09	2006	2009	Full Extent	2006	2008	2,000
2009-12	2009	2012	Partial, Upper Reach	2009	2011	1,000
2009-13	2009	2013	Partial, Lower Reach	2009	2013	1,000
2012-17	2012	2017	Partial, Upper Reach	2012	2016	1,000
2013-17	2013	2017	Partial, Lower Reach	2013	2016	1,000
2017-21	2017	2021	Full Extent	2017	2019	2,000

There was a total of 10,000 study cells generated using the analytical model, across all years of comparison in this study, each of which having all the of metrics and attributes described previously (**Table 3**). Together, these metrics characterize channel migration, forest cover, and log jam presence in the Deschutes River through the study period.

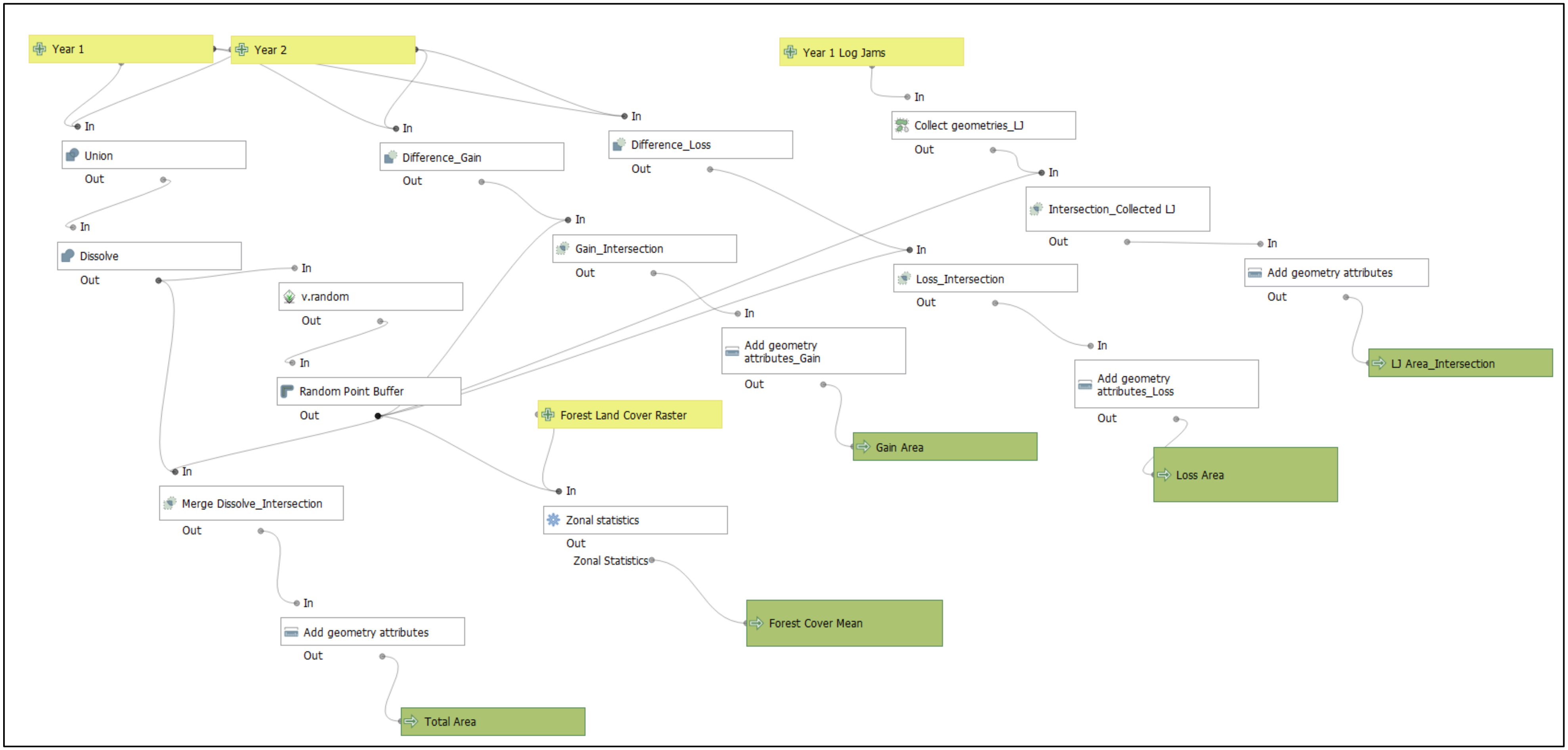


Figure 4 *- Channel Migration, Log Jam, and Forest Cover Model in QGIS Model Designer*

Statistical Analysis

To analyze the data from the seven comparison groups, across all of the metric groups described previously, I used R Statistical Software to complete an Analysis of Variance (ANOVA) and Tukey’s Honestly Significant Difference (HSD) test. Taking this approach allowed for the comparison of multiple groups simultaneously while still maintaining a high level of confidence. However, due to the considerable overlap of study cells and the data collected using these buffers in QGIS model, my data had an irregular distribution and could not be considered independent data points. Parametric hypothesis tests, like ANOVA and Tukey HSD, are not as reliable for these data as they would be for data with a normal distribution. So, to overcome the irregular distribution of the dataset, I used a bootstrap comparison of these groups (resampling across the study cells) to augment the findings of the Tukey HSD test.

My statistical analysis approach focused on the NCMI, Forest Cover Category, and Log Jam Presence groups, all of which were derived from the data collected from QGIS Channel Migration, Log Jam, And Forest Cover Model to examine the effects that Log Jam Presence and Forest Cover have on NCMI values. The first comparison examined the NCMI values for areas with log jams present versus those of areas without log jams to establish that the there was a detectable difference between these two types of reaches. Next, NCMI values were compared across the four levels of classified Forest Cover Categories (0-25%, 26-50%, 51-75%, and 76-100% mean forest cover) to establish that channel migration differed within reaches of differing levels of forest cover. Finally, the effects of log jam presence or absence on NCMI were compared across all four levels of Forest Cover Categories to understand how these two factors influenced geomorphology.

Each of the analyses used three values to determine the meaning and significance in NCMI values between the groups in the comparison – the difference between mean NCMI values of each group, the p-value determined by the Tukey HSD test, and the p-value determined by the bootstrap approach. Additionally, each comparison included a box-and-whisker plot (boxplot) to visualize the distribution of each group. R Statistical Software (R) was used to make the boxplots for the different statistical categories. In R, the whiskers in the boxplots indicate the range of data up to 1.5 times the interquartile range. Data falling outside of the whiskers in these boxplots are plotted as points.

CHAPTER 4 – RESULTS

Log Jam Presence and NCMI

The distribution of NCMI values for study cells in which log jams are present (Log Jam Presence = “True) and for those in which log jams are absent (Log Jam Presence = “False”) were projected in boxplots using R Statistical Software (**Figure 5**). The NCMI values of the study cells where log jams were present are on average 0.2204 greater than the NCMI values for study cells where log jams are absent, indicating that sections of channel near log jams exhibit an additional 22% NCMI compared to other sections of channel. Specifically, channels in study cells where jams are present exhibit an average NCMI of 0.4876, while channels in study cells where jams are absent exhibit an average NCMI of 0.2672. Both the Tukey HSD test and the bootstrap analysis of the difference between the mean NCMI values of study cells where log jams are present and where log jams are absent produce a p-value of <0.0000, indicating NCMI values differ with log jam presence.

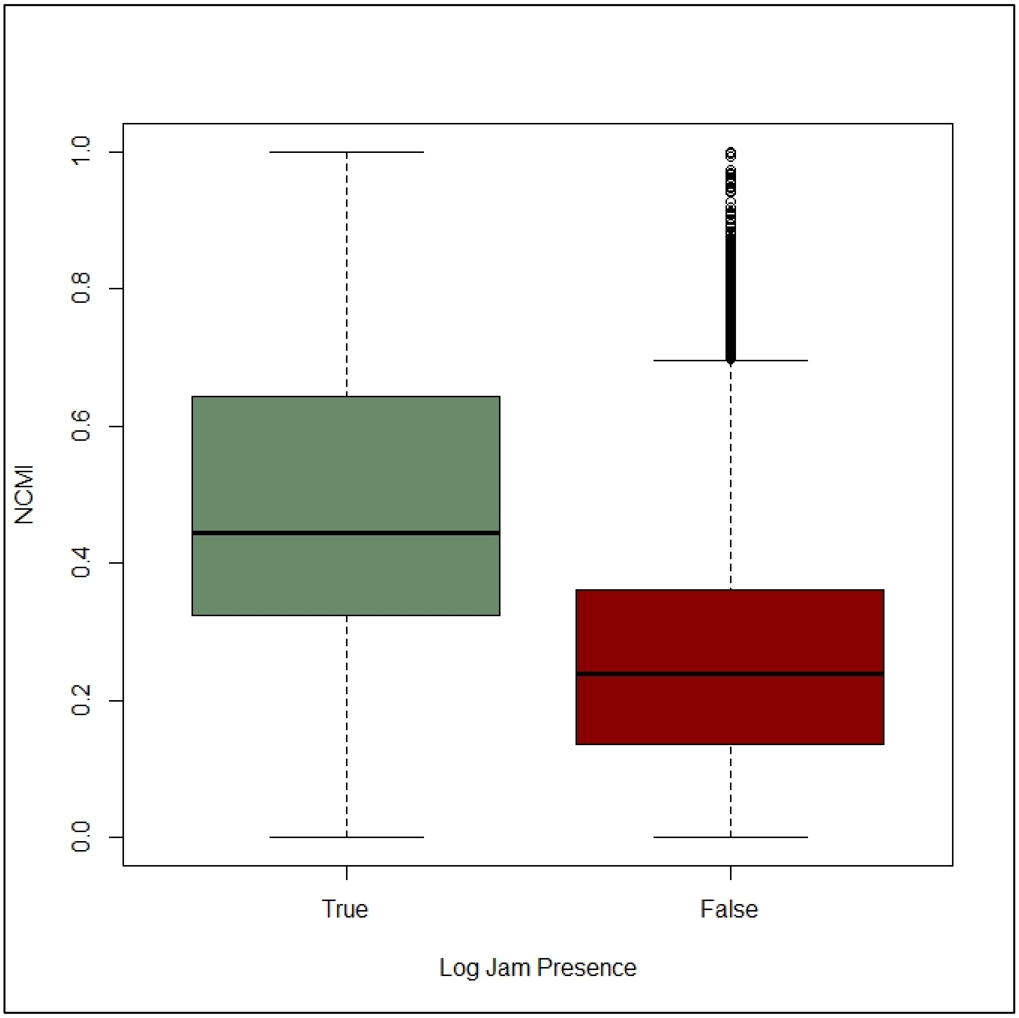


Figure 5 *- Log Jam Presence vs. NCMI Boxplot, showing the distribution of NCMI values for study cells where log jams are present versus where log jams are absent.*

Forest Cover and NCMI

The distribution of NCMI values for study cells that were classified into the four forest cover categories, based on their respective mean forest cover, were analyzed, and projected into boxplots. Based on the difference of mean NCMI values and the resulting p-values from the Tukey HSD test and bootstrap test for this group of six comparisons (**Table 4**), there is a significant difference in NCMI between each group of forest cover category except for the study cells where there is 76-100% forest cover and areas with 51-75% forest cover. The NCMI values of the study cells in the 26-50% forest cover category are on average 0.0586 greater than the NCMI values for study cells in the 0-25% forest cover category. Greater NCMI values in the 26-50% forest cover category than in the 0-25% forest cover category indicates that sections of channel with a mean forest cover between 26% and 50% have an additional 5.9% NCMI than sections of channel with a mean forest cover between 0% and 25%. Both the Tukey HSD test and the bootstrap analysis of the difference between the mean NCMI values of study cells in the 26- 50% forest cover category, and the study cells within the 0-25% forest cover category, produce a p-value of <0.0000, indicating that there is a significant difference in NCMI. Similarly, study cells in the 51-75% forest cover category, and study cells in the 76-100% forest cover category, each have 0.0268 and 0.0193 greater NCMI, respectively, than study cells in the 0-25% forest cover category.

There is also a significant difference in NCMI between study cells in the 76-100% forest cover category and cells in the 26-50% forest cover category. The NCMI values of the study cells in the 26-50% forest cover category are on average 0.0393 greater than the NCMI values for study cells in the 76-100% forest cover category. The Tukey HSD test and the bootstrap analysis of the difference between the mean NCMI values of study cells in the 76-100% forest cover category group and the 26-50% forest cover category group produce a p-value of <0.0000, indicating that there is a significant difference in NCMI. The comparison between the 51-75% forest cover category group and the 26-50% forest cover category group produces a similar result: NCMI values are on average 0.0318 greater in the study cells in the 26-50% forest cover category than in the study cells in the 76-100% forest cover category. The Tukey HSD test and bootstrap analysis of the difference between the mean NCMI values of study cells within 51-75% forest cover category group and study cells in the 26-50% forest cover category group produce a p-value of <0.0000, also indicating a significant difference in NCMI.

Table 4 - Results of the Tukey HSD Test and Bootstrap Test for the six groups of Forest Cover Categories

Groups Compared	**Difference**	**Tukey HSD Test**	**Bootstrap Test**
Forest Cover Categories		**p-value**	**p-value**
26-50% - 0-25%	*0.0586*	*0.0000*	*0.0000*
51-75% - 0-25%	*0.0268*	*0.0009*	*0.0003*
76-100% - 0-25%	*0.0193*	*0.0161*	*0.0019*
51-75% - 26-50%	*-0.0318*	*0.0000*	*0.0000*
76-100% - 26-50%	*-0.0393*	*0.0000*	*0.0000*
76-100% - 51-75%	*-0.0075*	*0.3557*	*0.0633*

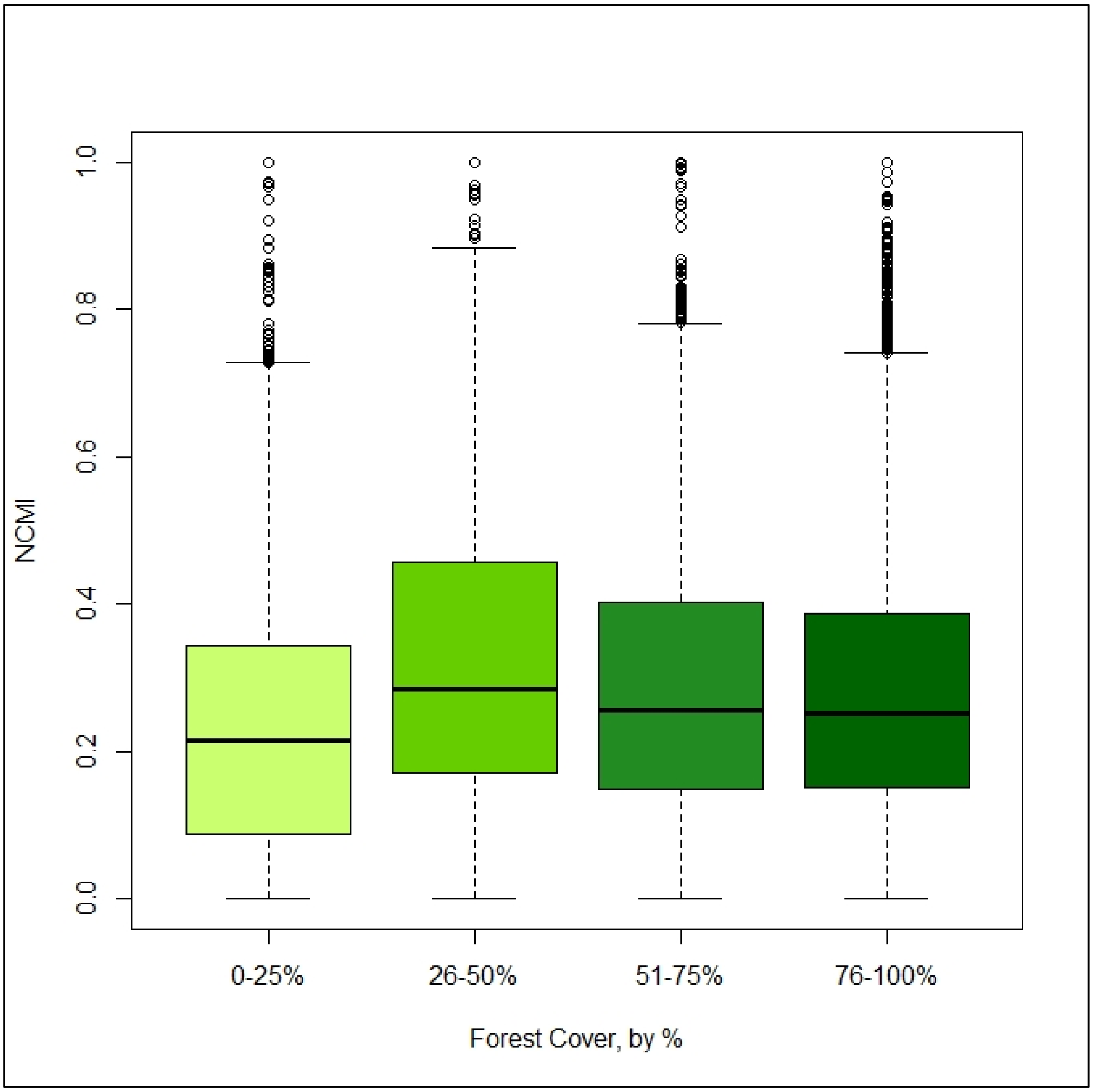


Figure 6 *- Forest Cover Categories vs. NCMI Boxplot, showing the distribution of NCMI values for study cells in each of the forest cover category groups.*

Log Jam Presence, Forest Cover, and NCMI

The distribution of NCMI values for study cells that are both classified into the four forest cover categories based on their respective mean forest cover, and into the two log jam presence categories, resulting in 8 groups for the log jam presence and forest cover category versus NCMI comparison (**Figure 7**). Analysis of the difference of means and the p-values from the Tukey HSD test and the bootstrap test for the log jam presence and forest cover category versus NCMI comparison resulted in a set of 28 comparisons (**Table 5**). Based on the values listed in this table, there is a statistically significant difference in the mean NCMI values for 24 of the 28 total group combination of Log Jam Presence and Forest Cover Category. Notably, the NCMI values for study cells where log jams are present are greater than the NCMI values for study cells where log jams are absent for each of the log jam presence group within the same forest cover category. For study cells with a mean forest cover between 0% and 25%, the NCMI values of the study cells where log jams are present are on average 0.3453 greater than the NCMI values for study cells where log jams are absent. This indicates that sections of channel near log jams, that are within the 0-25% forest cover category, exhibit an additional 35% NCMI than sections of channel within the same forest cover category without log jams. Both the Tukey HSD test and the bootstrap analysis of the difference between the mean NCMI values of study cells within the 0-25% forest cover category group and where log jams are present and where log jams are absent produce a p-value of <0.0000, indicating that there is a significant difference in NCMI. Likewise, NCMI values are found to be greater in study cells where log jams are present versus the study cells without log jams when both of these groups are within the same forest cover category, follow this same pattern.

The four comparison combinations that do not have significant differences in mean NCMI values between groups are for study cells in which log jams are present (Log Jam Presence = True) and where Forest Cover Categories groups are greater than 25% Mean Forest Cover. The Tukey HSD test and the bootstrap analysis for the differences between mean NCMI values for these groups produce p-values greater than 0.05, indicating that there is no difference in NCMI values for these groups.

Table 5 - Results of the Tukey HSD Test and Bootstrap Test of the NCMI values for the 28 Groups of the Combined Forest Cover Categories and Log Jam Presence variables

Groups Compared	**Difference**	**Tukey HSD Test**	**Bootstrap Test**
Log Jam Presence: Forest Cover Categories		**p-value**	**p-value**
TRUE:0-25% - FALSE:0-25%	*0.3453*	*0.0000*	*0.0000*
FALSE:26-50% - FALSE:0-25%	*0.0770*	*0.0000*	*0.0000*
TRUE:26-50% - FALSE:0-25%	*0.2484*	*0.0000*	*0.0000*
FALSE:51-75% - FALSE:0-25%	*0.0391*	*0.0000*	*0.0000*
TRUE:51-75% - FALSE:0-25%	*0.2534*	*0.0000*	*0.0000*
FALSE:76-100% - FALSE:0-25%	*0.0318*	*0.0001*	*0.0001*
TRUE:76-100% - FALSE:0-25%	*0.2444*	*0.0000*	*0.0000*
FALSE:26-50% - TRUE:0-25%	*-0.2683*	*0.0000*	*0.0000*
TRUE:26-50% - TRUE:0-25%	*-0.0969*	*0.0021*	*0.0000*
FALSE:51-75% - TRUE:0-25%	*-0.3062*	*0.0000*	*0.0000*
TRUE:51-75% - TRUE:0-25%	*-0.0919*	*0.0014*	*0.0005*
FALSE:76-100% - TRUE:0-25%	*-0.3135*	*0.0000*	*0.0000*
TRUE:76-100% - TRUE:0-25%	*-0.1010*	*0.0001*	*0.0000*
TRUE:26-50% - FALSE:26-50%	*0.1714*	*0.0000*	*0.0000*
FALSE:51-75% - FALSE:26-50%	*-0.0379*	*0.0000*	*0.0000*
TRUE:51-75% - FALSE:26-50%	*0.1764*	*0.0000*	*0.0000*
FALSE:76-100% - FALSE:26-50%	*-0.0452*	*0.0000*	*0.0000*
TRUE:76-100% - FALSE:26-50%	*0.1673*	*0.0000*	*0.0000*
FALSE:51-75% - TRUE:26-50%	*-0.2092*	*0.0000*	*0.0000*
TRUE:51-75% - TRUE:26-50%	*0.0051*	*1.0000*	*0.4044*
FALSE:76-100% - TRUE:26-50%	*-0.2166*	*0.0000*	*0.0000*
TRUE:76-100% - TRUE:26-50%	*-0.0040*	*1.0000*	*0.3981*
TRUE:51-75% - FALSE:51-75%	*0.2143*	*0.0000*	*0.0000*
FALSE:76-100% - FALSE:51-75%	*-0.0073*	*0.7939*	*0.0761*
TRUE:76-100% - FALSE:51-75%	*0.2052*	*0.0000*	*0.0000*
FALSE:76-100% - TRUE:51-75%	*-0.2216*	*0.0000*	*0.0000*

TRUE:76-100% - TRUE:51-75%	*-0.0091*	*0.9981*	*0.2708*
TRUE:76-100% - FALSE:76-100%	*0.2126*	*0.0000*	*0.0000*

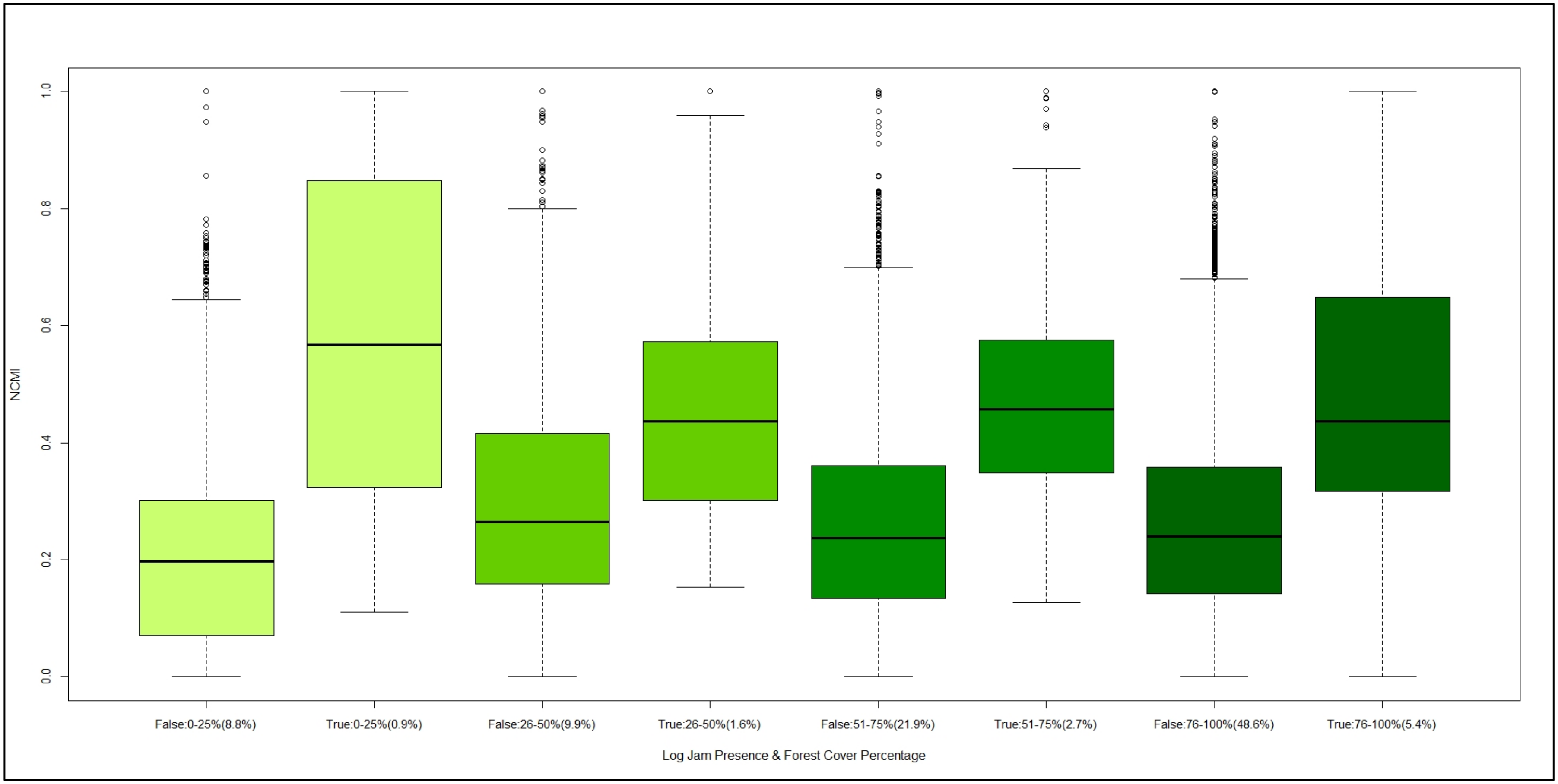


Figure 7 - *Log Jam Presence and Forest Cover Categories vs. NCMI Boxplot, showing the distribution of NCMI values for study cells considering both log jams presence and forest cover category.*

CHAPTER 5 – DISCUSSION

Interpretation of Results

The statistical analysis of these data supports the hypothesis that channel migration, characterized by NCMI values, was greater in study cells that contain channel-spanning log jams. Further, the statistically significant differences in NCMI values across the Forest Cover Categories suggest that channel migration is influenced by riparian forest cover. Specifically, the analysis finds that the 26-50% Forest Cover Category experiences greater amounts of channel migration than any of the other Forest Cover Categories, including those Mean Forest Cover falling between 0% and 25%. However, when channel migration is analyzed in relation to both Log Jam Presence and Forest Cover Categories, NCMI values are often highest in study cells where log jams are present and Mean Forest Cover is within the 0-25% Forest Cover Category as compared to the other variable combination groups. On the other hand, in study cells with a Mean Forest Cover between 0% and 25% and that are also absent of channel-spanning log jams, NCDMI tends to be the lowest out of any of the groups including study cells with 75-100% forest cover and without log jams.

These results are counter-intuitive and do not fully support my initial hypothesis that channel migration will be greater in areas with little to no riparian forest cover than in areas with intact riparian forests. There are several explanations that could possibly be responsible for these differences. First, the channel tracings were captured in intervals of three to five years and, due to the unpredictability of channel-spanning log jam persistence over time, log jams could have formed in some areas, had some level of impact to an area, and then break apart leaving little evidence of their existence in the next tracing period other than channel geomorphological changes. A second possibility is that streambank armoring or artificial channelization in some developed reaches of the river, such as the golf course that exists near the mouth of the Deschutes, reduce the amount of channel migration that may have occurred otherwise, skewing the data in this group. Finally, in-stream largewood and channel-spanning log jams could be removed, breached, or prevented in these developed reaches to protect homes, buildings, or other infrastructure. Historically, the removal of in-stream largewood has been fairly common practice in many parts of the US to reduce channel migration and avulsion, including the Pacific Northwest (Swanson et al., 1976). While there were some log jams observed and captured within developed reaches with little intact riparian forest communities, there is a possibility that the practice of in-stream largewood still occurs within these reaches, whether properly permitted or not. In-stream largewood tends to concentrate in close proximity to areas of streambank avulsion and channel migration that occur within forested or partially forested reaches (Moulin et al., 2011). Therefore, it is not surprising that greater proportions of the log jams within this study are concentrated in areas with greater riparian forest cover than those with little to no forest cover adjacent to the channel. So, while channel-spanning log jams within reaches with little to no riparian forest cover would be very helpful in building a more robust dataset, the actual occurrence of these log jams within these reaches is likely to be consistently limited according to Moulin et al. (2011).

Another interesting result of this analysis is that there is no meaningful difference in NCMI across the Forest Cover Category groups when mean forest cover is 26% or greater and where log jams are present. Similar NCMI values across the forest category groups with mean forest cover greater than 26% suggests that riparian forests are most effective at streambank stabilization when approximately 26% or more of the riparian area within a 75-m buffer is forested, particularly in stream reaches that experience high occurrence of channel-spanning log jams. By contrast, when log jam presence is not considered, the 26-50% forest cover category experiences the greatest amounts of channel migration, as characterized by the NCMI values, of the forest cover category group. A possible explanation for the conflicting NCMI values between the 26-50% forest cover category groups from the NCMI versus forest cover category comparison and from the NCMI versus log jam presence and forest cover category comparison is that unvegetated areas within the channel band, where the channel had previously reworked the river system's floodplain and vegetation has not yet reestablished, are being categorized as unforested area. Deposited alluvial material is likely to be eroded easily, due to a lack of cohesiveness and a lack of vegetation, possibly skewing this dataset to suggest greater amounts of channel migration.

Method Limitations

Tracing river channels and log jams is a time-consuming process that depends on high resolution imagery with accurate and complete spatial coverage of the project area. These requirements can drastically reduce the amount of freely available imagery that can be used to complete these tracings, particularly if the goal is to observe changes within the subject river system over time as is the purpose of this study. Additionally, errors within the imagery, such as object occlusion, image stretching, misalignment, cloud cover, and poor-quality imagery, can all contribute to error within the tracing datasets and result in inaccurate conclusions. High-quality aerial imagery from Thurston County GeoData Center is, fortunately, available for this project area, making navigation of these challenges easier for this study. However, use of these materials, and the correction of tracing errors, increased the time to complete these already time-consuming channel tracings. Similarly, higher resolution land cover rasters could provide higher levels of forest cover accuracy for this type of analysis

Variation in the imagery period is another challenge when using satellite or aerial imagery for these purposes, particularly when observing surface waterbodies within consistently fluctuating discharge levels throughout the year, depending on weather conditions. Simple differences in discharge level between the channel years in comparison could result in a false-positive conclusion that there were changes to channel between years when, really, there may have been little to no change in that period. Using NCMI values that are calculated using channel data collected within specific study cells helps to reduce errors stemming from differences in stream discharge level because it is based on both the area of gain and area of loss within the study cells. Use of high-resolution imagery captured by commercial satellites, with specified data ranges, may reduce some of the previously described errors. However, the cost and the storage space required to analyze this imagery are additional considerations that prohibited their use in this study.

Additionally, the overlap of study cells within the QGIS model for this study produce data points that are not independent from one another and produces data that are irregularly distributed. To improve confidence in the statistical analysis of the multiple data groups, I use two statistical tests to calculate, and then compare p-values so that I can determine statistical significance. While the use of two statistical tests to calculate the p-values for the comparison groups, and the sheer number of the data points within the dataset, improves my confidence in the analysis results, this limitation must be acknowledged. Further, additional channel-spanning log jams in reaches with a Mean Forest Cover between 0% and 25% will provide greater insight into the influence of these log jams within reaches with little to no riparian forest cover. This group is the least represented of the log jam data groups and, thus, the results of the statistical analysis are not quite as robust as the other Log Jam Presence: Forest Cover Categories data groups.

Finally, the effects of log jam area on the eroded area are not addressed by this study. To properly analyze these two variables, independent datapoints for both of these variables will be necessary, which is not a benefit of this dataset, unfortunately. I cannot speak to any sort of a relationship between channel migration and the total area of the log jams that were identified and traced in the GIS layers as a result. The channel polygons created as a part of this study will be helpful, should this analysis take place within the Deschutes River watershed. However, an alternative GIS model – a model without as much study cell overlap – would be necessary.

Further Implications

The role of channel-spanning log jams, and riparian forests, in shaping channel geomorphology has been documented and analyzed in many studies over the past several decades (Brooks et al., 2003; Brummer et al., 2006; Burton et al., 2016; Collins et al., 2012; Dixon, 2015; Harwood and Brown, 1993; Latterell and Naiman, 2007; Livers and Wohl, 2021; Montgomery and Abbe, 2017; Swanson et al., 1976). The findings of this study further support conclusions made in these studies, many of which have been cited in this analysis, using freely available imagery and software resources without extensive field data collection. Multi-year studies, with in-field data collection, require consistent application of data collection methods and management of the study over the years within the study period. The benefits of a “desk-top” analysis, such as this study, is that years of data can be compared within a short period of time, though this type of analysis has its own challenges, as previously described. Additionally, these methods can be applied to study river systems in different areas that are further away from those conducting the study, adding an additional layer of convenience. My hope is that the methods developed in this study can be further used and refined over the course of additional studies so that they can provide additional insight into channel geomorphology dynamics over time. Inclusion of additional metrics and analysis subcomponents, such as the location and spatial distribution of streambank armoring, non-channel-spanning log jams data groups, and additional years of analysis, could contribute to improvements to Deschutes River watershed and habitat management. Further refinement of the GIS Channel Migration, Log Jam, and Forest Cover Model could also reduce the overlap in study cells, providing additional information regarding geomorphology dynamics in relation to log jam presence and characteristics.

CHAPTER 6 – CONCLUSION

Channel-spanning log jams provide a multitude of stream geomorphology, aquatic habitat, and water quality functions within river systems of the Pacific Northwest. However, river management, land use practices, and forestry management practices have, over time, resulted in changes to the spatial distribution and density of in-stream largewood and log jams. The purpose of this study is to analyze the interactions between riparian forest cover, channel-spanning log jams, and channel migration within the Deschutes River watershed over a 19 year period. The results of this analysis found that channel migration is often greater in reaches where log jams are present and where there is 25% Mean Forest Cover or less within 75 m of the river channel. These findings add further support to our understanding of the relationship between log jams and channel geomorphology dynamics.

This study also suggests that channel migration in reaches with 26% to 50% mean forest cover within the riparian area is higher than areas with 0% to 25% and 51% to 100% mean forest cover when log jam presence is not considered. I speculate that the low NCMI values in study cells within the 0-25% forest cover category, when log jam presence is not considered, may be a result of streambank armoring along channel reaches within developed areas, where there is little to no riparian forest cover, which may skew the results of this analysis. However, a longer study time frame and additional data are needed to substantiate this speculation and to further understand the relationship between channel migration, log jam presence, and riparian forest cover.

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