MODELING HISTORICAL MEANDER BEND RECONNECTION ON THE LOWER LONG TOM RIVER IN LANE CO. AND BENTON CO., OR

by

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A THESIS

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THESIS ABSTRACT

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Since the damming and channelization of the lower Long Tom River in the 1940s and 1950s, the quality and quantity of habitat for coastal cutthroat trout and spring Chinook salmon in the watershed has dramatically diminished. In order to better understand the potential for stream restoration, this study uses 2D hydraulic modeling to determine the impact of reconnecting historical meander bends to the main stem of the lower Long Tom River on localized flooding, sediment erosion and deposition, and salmonid physical habitat. These models compare the current conditions to two restoration scenarios that allow for fish passage given 1, 2, and 5-year flood events at two study sites. This study reveals important variations in the impact of restoration between the study sites and the reconnection methods. It also suggests that there is the potential for a large increase in the area of accessible habitat with stream restoration.

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CHAPTER I

INTRODUCTION

For more than one hundred and fifty years, Oregon's Euro-American settlers and land managers have made widespread changes to the rivers and watersheds in Oregon. While seeking to manage flooding, increase river navigability, generate hydroelectric power, and provide water for residential and irrigation purposes, Oregonians have transformed thousands of kilometers of river throughout the state. In the Willamette Valley, some of these changes have dramatically reduced migratory fish populations (Schroeder et al. 2015) and decreased river complexity and dynamism. Due to growing environmental concerns in recent decades, river managers have been encouraged by the public and directed by state and federal law to mitigate the impacts of river management practices on aquatic species.

While the term 'river restoration' can describe many different practices, in the U.S. Pacific Northwest, this term often refers to active or passive management strategies that seek to improve ecological conditions and water quality. As Roni et al. (2002) state, the primary goal of river restoration is to "enhance or restore habitat for salmonids and other fish species." Many academics and government employees have observed that Pacific Northwest restoration projects are driven by legal mandates including the Endangered Species Act and the Clean Water Act (Roni et al. 2002, Beechie et al. 2008, Katz et al. 2007). These laws have prioritized the preservation, improvement, and re-creation of physical habitat for aquatic species, particularly of the salmonid species that are listed as endangered in Oregon.

As a part of this river restoration movement, this study will examine the potential for ecological improvements along the Long Tom River located in the southern Willamette Valley of Oregon. Historically, the Long Tom watershed provided aquatic habitat for many species including the coastal cutthroat trout (*Oncorhynchus clarkii clarkii*) and juvenile spring Chinook salmon (*Oncorhynchus tshawytscha*). However, the flood management practices by the United States Army Corps of Engineers (USACE) have reduced the accessible habitat for both species by approximately 70% (Dedrick and Thieman 2005). During the 1940s, the USACE constructed the 13.4 m tall Fern Ridge Dam that bisects the Long Tom River watershed. They channelized the Long Tom downstream of the dam by enlarging and straightening the channel, removing all woody riparian vegetation, and building embankments that act as river training structures (hereafter called levees). They also installed three concrete drop structures (i.e. low head dams) that are between 2.3 m and 3.5 m tall. Each of these structures prohibits juvenile salmonids from moving upstream. By 1951, the highly sinuous channel of the Long Tom had been shortened, straightened, and numerous meander bends were left outside the embankments as side channels (hereafter called historical side channels). These changes further reduced the channel complexity and impaired the quality and quantity of instream habitat. While juvenile spring Chinook salmon have been found in the Long Tom River downstream of the drop structure in Monroe, these modifications have caused the extirpation of Chinook salmon from most of the Long Tom watershed (J. Kaul, personal communication, 2016).

While the USACE continues to maintain the dam and manage the Long Tom River with the goal of minimizing the impact of flooding, regional managers are interested in finding opportunities to increase habitat and improve fish passage within the watershed. One possible restoration strategy would be to connect the current main channel to the historical meander bends that still remain on the floodplain. Side channels have been often shown to be critical sources of salmonid habitat in the Pacific Northwest (Rosenfeld et al. 2008, Morley et al. 2005), and the historical meander bends of the Long Tom are much more sinuous, contain more woody debris, and have more riparian vegetation than the current main stem. Unfortunately, it is not well understood how connecting these historical meander bends or creating any type of secondary channel would change the flood conditions and potential habitat on the Long Tom River. Furthermore, very few academic publications have focused on understanding the historical or current geomorphic and hydrologic conditions of the Long Tom watershed.

The objective of this research is to use 2D hydraulic modeling to address the following question: How will reconnecting a historical meander bend to the main stem of the lower Long Tom River impact localized flooding, sediment erosion and deposition, and salmonid physical habitat? To answer this question, I will model the current 1-year, 2-year, and 5-year flood conditions and compare the area of inundation, velocity, depth, and shear stress characteristics to two different restoration scenarios at two different study sites. In the first restoration scenario, the historical meander bend will be connected to the main channel using a set of culverts, and in the second scenario, it will be connected by breaching the embankments.

This research will provide regional managers with detailed, site-specific insight as to the impact of these restoration scenarios that will enable them to evaluate the suitability and feasibility of each type of historical channel connection. By comparing the differences in impacts at each site, managers will improve the future site selection process by using these models as an example for other future restoration work. In addition, it will help to shed light on the current geomorphic conditions of the Long Tom River and promote the Long Tom River within the scientific literature.

CHAPTER II

BACKGROUND

Location

The Long Tom River, a tributary to the Willamette River, covers 1,066 km^2 of the southwestern Willamette Valley in Oregon. The river flows north, roughly parallel to the Willamette River, through both Lane and Benton Counties (Figure 1). The Long Tom watershed is bordered to the south and west by the Oregon Coast Range and to the east by the city of Eugene. The manmade Fern Ridge Reservoir is in the center of the watershed and is approximately 26 km^2 in area.

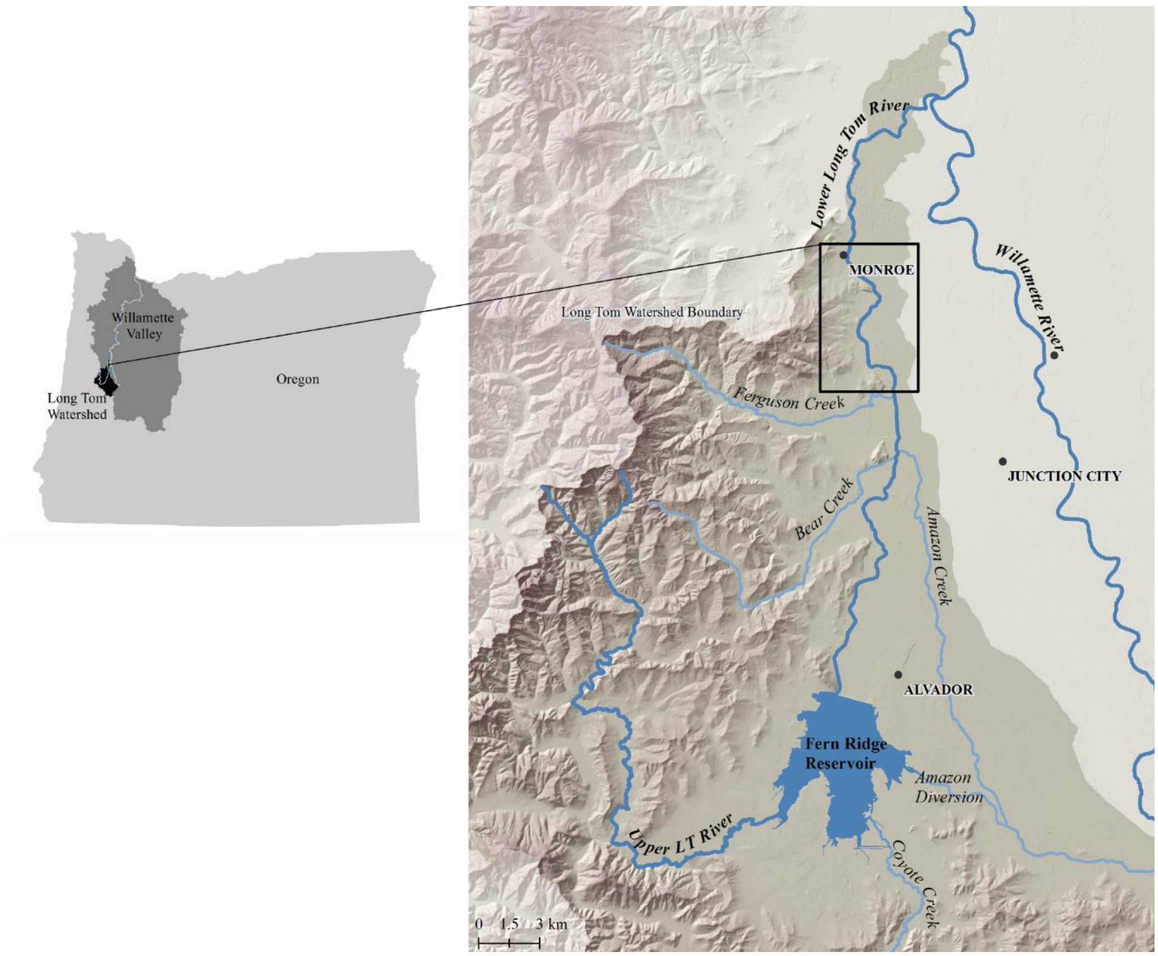


Figure 1: On the left, a context map shows the location of Long Tom watershed within the Willamette Valley, and, to the right, a regional map shows the location of study sites within Long Tom watershed as indicated by a black box.

The lower Long Tom River is separated from the upper Long Tom River by Fern Ridge Dam and Reservoir. The upper channel flows 44.8 km from the headwaters in the Coast Range and, along with Coyote Creek and the Amazon Creek Diversion, it flows directly into Fern Ridge Reservoir. The lower Long Tom River flows 39.4 km from the north end of Fern Ridge Reservoir to the confluence with the Willamette River near Norwood Island. The major tributaries to the lower Long Tom River include Amazon Creek, Bear Creek, Ferguson Creek, and Shafer Creek, all of which originate in the Coast Range mountains.

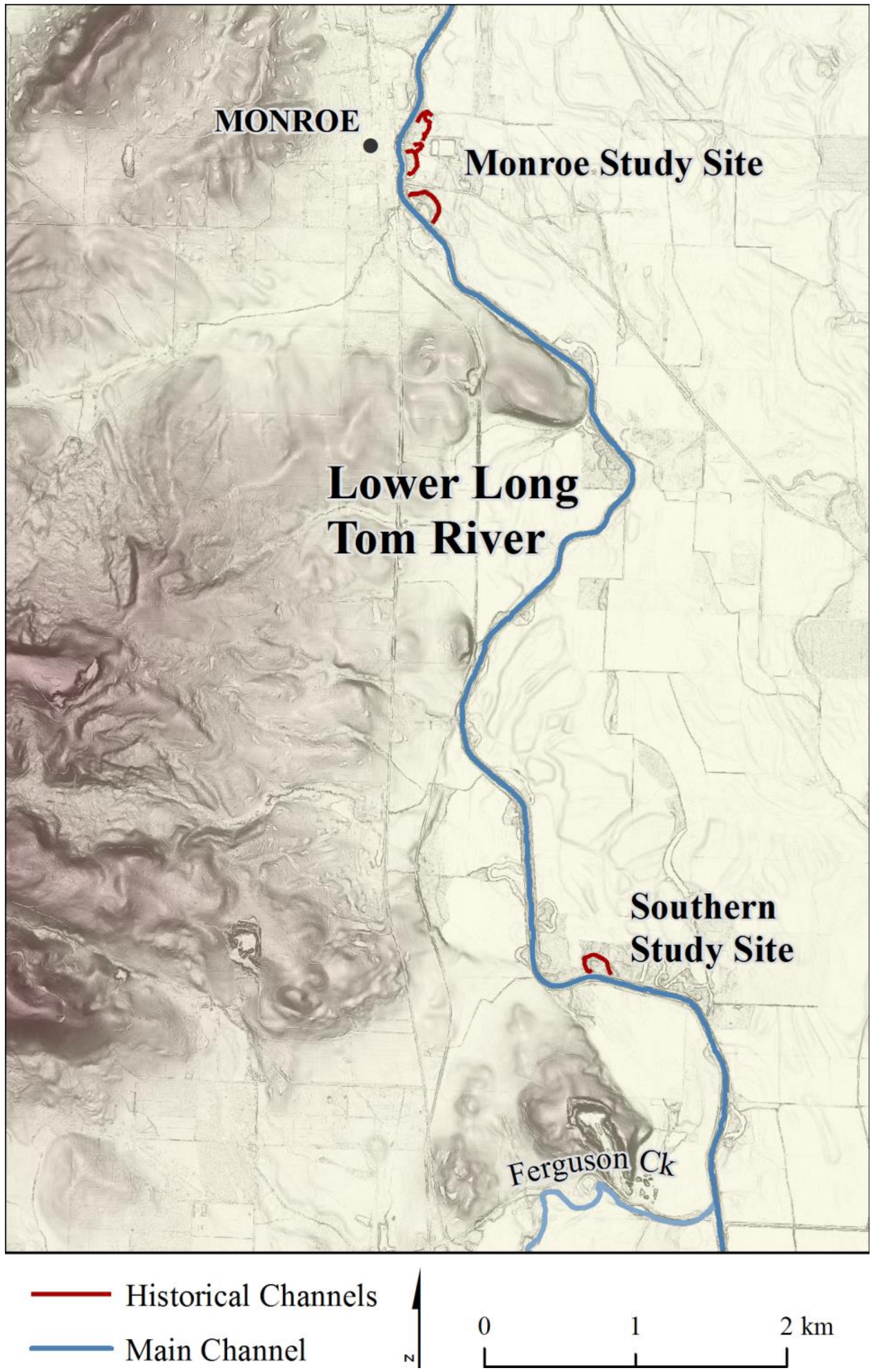


Figure 2: Location of study sites along the lower Long Tom River.

The two study sites examined in this thesis are located in city of Monroe and on a privately owned farm, south of Monroe (Figure 2). Both sites are located along the lower Long Tom River, 11.9 km and 19.4 km upstream of the confluence of the Long Tom and Willamette Rivers respectively. The remainder of the background information will be focused on the lower Long Tom River. The Monroe study site (Figure 3) is located within the city of Monroe, adjacent to the Monroe drop structure, which is a concrete, low head

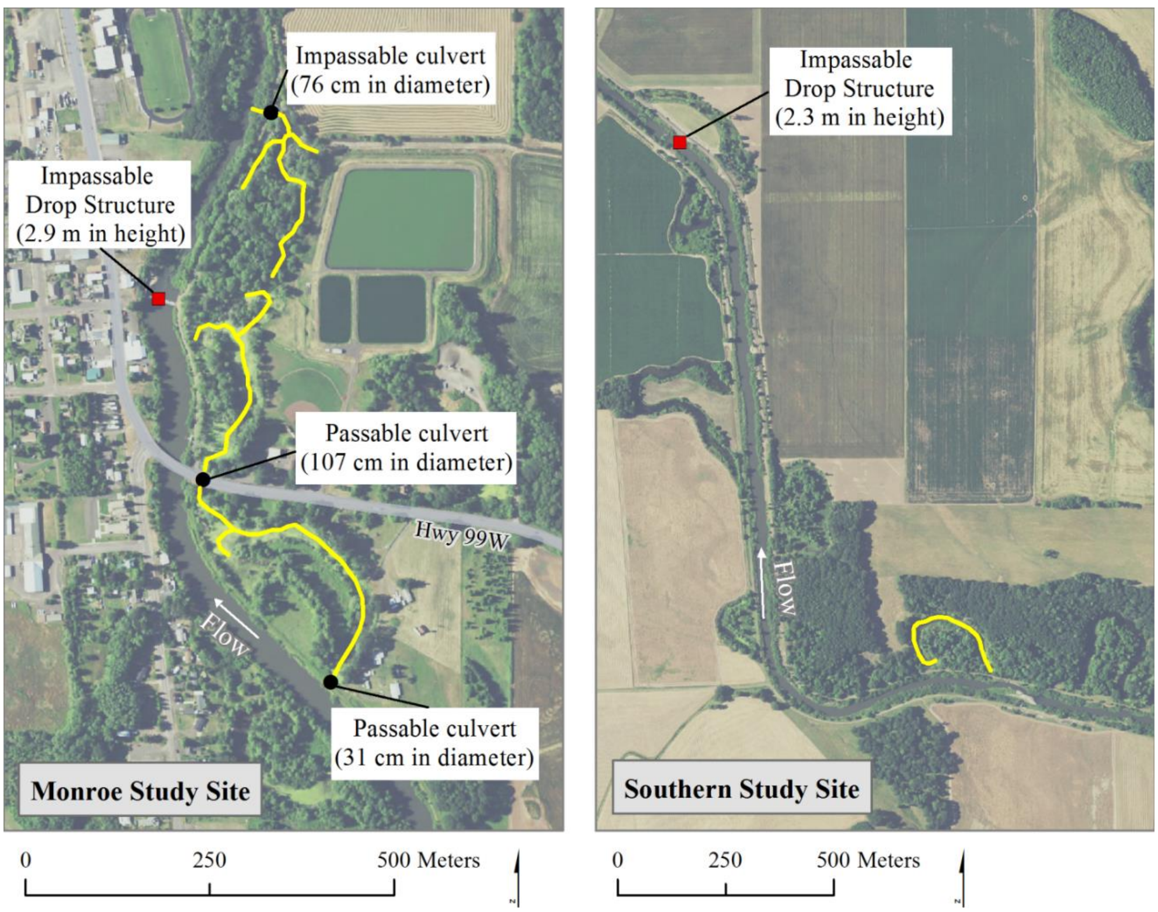


Figure 3: At the Monroe study site (on left), the historical channel is 1440 m in length and runs adjacent to 1260 m of mainstem channel. At the Southern study site (on right), the historical channel is a meander loop 370 m long and adjacent to 150 m of mainstem channel.

dam that was installed between 1946-1948 when the lower Long Tom was re-engineered (USACE 2014) (Figure 4). The Monroe drop structure presents the first fish passage barrier for fish swimming upstream from the Willamette River. The historical channel of interest is 1440 m in length. A series of culverts, shown in Figure 3 connect the historical channel to the modern channel. In addition, the historical channel is composed of two sections that are connected by a culvert under Oregon Route 99W. While these culverts allow fish to move throughout the historical channel upstream from the drop structure but do not allow fish to enter the historical channel from the downstream side.

Figure 4: The 2.9 m tall drop structure in Monroe acts as the furthest downstream fish passage barrier on the Long Tom River. Image taken by author in 2015.

The Southern study site is located 5.5 km south of city of Monroe. Within this study site, there is a second drop structure that also prevents fish passage upstream. The historical meander of bend of interest is 370 m long and has no culverts connecting it to the main channel (Figure 5).

Figure 5: The historical meander bend at the Southern study site. Image taken by author in 2015.

Pre-1960s Human History and River Management

For thousands of years, the Long Tom River basin has been inhabited by Native Americans. When Euro-Americans began to settle the region in the mid-1800s, the Kalapuya tribe was the largest tribe to inhabit the southern Willamette Valley, although throughout the Willamette Valley Native American populations were in rapid decline likely due to the spread of diseases including malaria and smallpox (Whitlock and Knox 2002). Prior to contact with Euro-Americans, it is likely that hunting practices and subsistence lifestyle of the Kalapuya had a limited impact on the landscape. Anecdotes from early Euro-American settlers do indicate that as the Native American population declined and Euro-Americans began to manage the landscape, a decrease in wildfires allowed for an increase in the density of bush and shrubs across the Long Tom floodplain (Thieman 2000). European trappers encountered and recorded numerous species in the region throughout the 1800s including deer, wolves, wildfowl, and bear. According to the Oregon Department of Fish and Wildlife (n.d.), fur trappers nearly drove the once common American Beaver (*Castor canadensis*) nearly to extinction during the 1800s. While these early activities had some impact on the Long Tom River’s ecology and form, the most dramatic changes occurred after Euro-American settlement.

During the 1850s, Euro-American settlers claimed millions of acres of land across the Willamette Valley, built new roads, and introduced new agricultural practices, technologies, and livestock to the region (Theiman 2000). Early Euro-American settlers struggled with flooding along the Long Tom. By the late 1800s, residents began to drain bogs and marshes, brush was removed from creeks, and bridges were constructed to facilitate transportation (Theiman 2000). Several steam ships made attempts to travel from the Willamette River up to the milltown of Monroe at high water, but debris, bars, and poor channel conditions made navigation difficult. In 1899, the Oregon state government attempted to remove debris and gravels, but within years the river again became nearly impossible to pass by steamboat.

The 1940s marked a time of extensive change in the hydrology, geomorphology, and ecology of the Long Tom River. In 1935, the Flood Control Act initiated planning of a flood control project in the Willamette Valley, and in 1940-41 the USACE constructed the Fern Ridge Dam. Behind the Fern Ridge Dam, the Fern Ridge Reservoir is wide but shallow and, when at capacity, covers over 36 km^2.

Although the main purpose of Fern Ridge Dam and Reservoir was flood control, by 1943, it became apparent that flooding had continued to be a problem for residents and by 1951 the USACE had channelized the main stem of the Long Tom River by widening, deepening, and straightening the channel, constructing earthen levees (i.e. river training structures), and installing three large drop structures. Most of the natural meanders of the river were cut off, such as those at the two study sites. For decades following channelization, the USACE routinely removed riparian vegetation from the banks of the Long Tom. These modifications had a direct impact on the hydrology, geomorphology, and ecology of the river and will be discussed in the following sections.

Geology and Geomorphology

Regional Geology

The lower Long Tom River flows through three distinct, locally-derived types of Quaternary geologic deposits (O'Connor et al., 2001). First, from Fern Ridge Reservoir to 1.9 river km south of Monroe, OR, the lower Long Tom River flows through locally-derived Holocene and Pleistocene age fine-grained alluvium (unit Qbf) (see Figure 6). O'Connor et al. (2001) described these deposits as "accumulated clay, silt, sand, and minor gravel from the adjacent hillslopes and small drainages." In the Long Tom basin, these deposits are likely derived from the neighboring Tertiary marine sandstone, siltstone, shale, and claystone of Coastal Range hillslopes and not composed of Missoula Flood deposits, Willamette River alluvium, or Cascade Range-derived sediment. Although O'Connor et al. (2001) did not systematically study the Quaternary basin fill deposits, they suggested that extensive, coarse-grained aggradation along the central axis of the Willamette Valley by the Willamette River created topographic lowlands at margins of the Valley which allowed this region to fill with local alluvium. To the east of the Quaternary basin fill deposits, there are two examples of coarse-grained deposits from the main stem Willamette River: the early Pleistocene, pre-Missoula Flood deposits of sand and gravel from the Willamette River (Qg_2) and the comparatively thin layer of Pleistocene deposits that post-dates the Missoula Floods (Qg_1). Several persisting ponds, including Hulbert Lake, appear in this unit that may have been formed by the Willamette River braidplain.

Second, the lower Long Tom River flows through its own alluvium deposits (unit Qalf) beginning 1.9 river km upstream of Monroe and extending 5.9 km north, downstream of Monroe. The Qalf unit is composed of sand, silt and gravels (O'Connor et al., 2001) and corresponds to the Holocene floodplain and active channel of the Long Tom River. O'Connor et al. (2001) note this alluvium is typically much younger than the Missoula Flood deposits. This narrow section of Long Tom alluvium is flanked to the west by mid-Pleistocene, fine-grained, Missoula Flood deposits (unit Qff_2) and to the east by late-Pleistocene, post-Missoula Flood sand and gravel deposits within the Willamette Valley braidplain (unit Qg_1).

Third, from 5.9 km north of Monroe to the confluence with the Willamette River, the lower Long Tom River flows through Holocene Willamette River floodplain deposits (unit Qalc). These Willamette River deposits are composed of sand, silt and gravel that is distinctly coarser than the smaller tributary deposits (O’Connor 2001). In addition, unlike the Long Tom River alluvium (Qalf), these Willamette River deposits have meander-scroll topography.

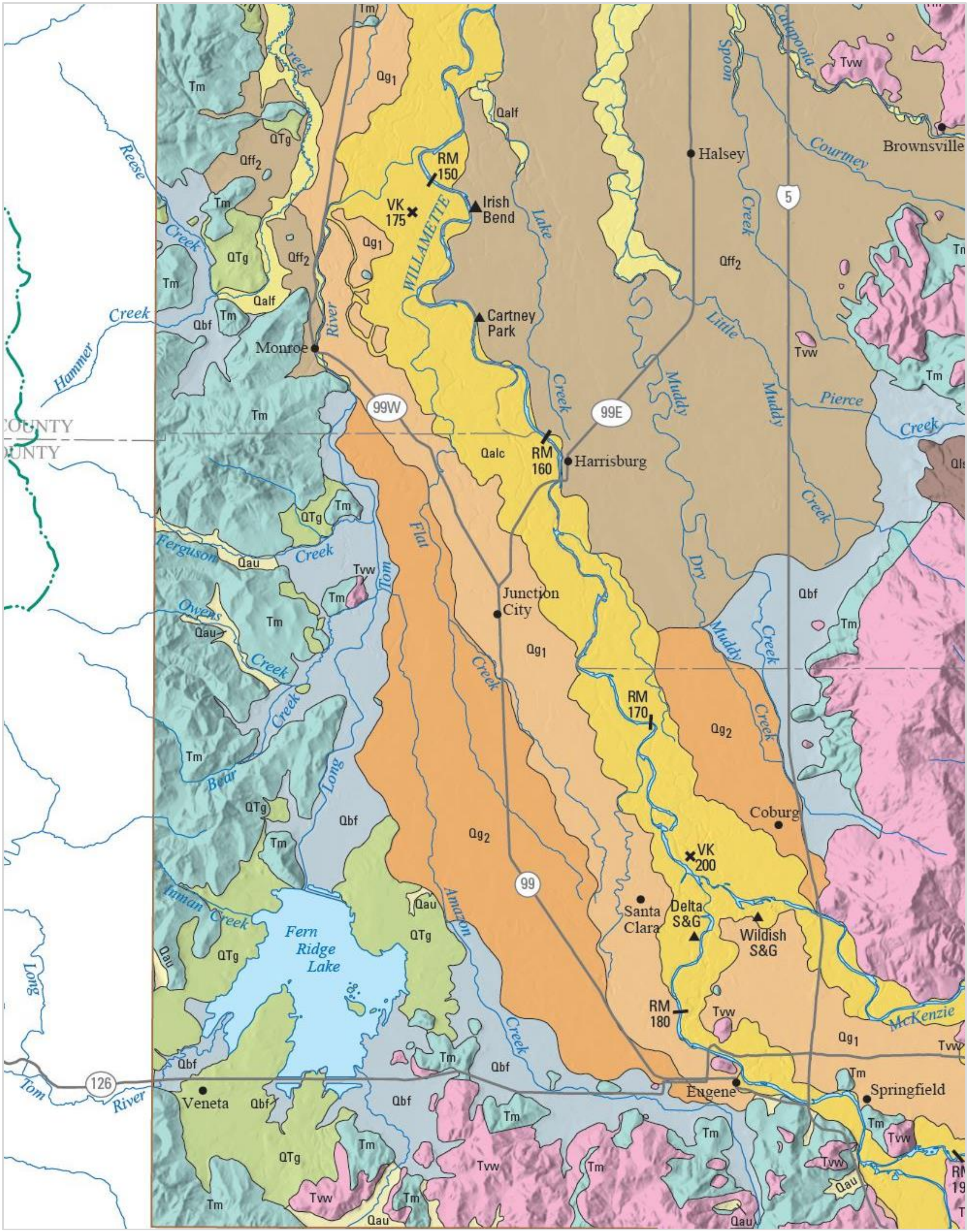


Figure 6: Surficial geology map of the Long Tom Watershed (from O'Connor et al. 2001).

Local Floodplains and Terraces

In order to characterize the location of the pre-1940s floodplains and terraces and their sedimentary composition, I used information from the 1987 Lane County Soil Survey and the 2009 Benton County Soil Survey by the NRCS (Patching 1987, Fillmore 2009). Using the soil descriptions and interpretations by the NRCS authors, I reclassified the soil units into two groups: the pre-USACE reengineered active floodplains and terraces (Figure 7; Tables 1 and 2 in Appendix A). When reclassifying the soils, I relied on the location description in the NRCS survey, the description of the parent material, and the presence or absence of a Bt horizon. Those soils with a Bt horizon were classified as a terrace and those that had not developed a Bt horizon were classified as a floodplain soil.

Based on my classification, the pre-reengineered floodplain deposits are discontinuous, lie adjacent to the historical river channel, and range in width from 200 m to 1,000 m. The soils produced by these floodplain deposits are typically composed of silty clay loam, but also include silt loam, loam, and gravelly sandy loam. While almost all of these units have moderately fine-grained textures, approximately half of the NRCS descriptions include gravels, gravelly sand, or gravelly clay in the substratum or parent material based on pits that were dug up to 1.5 m deep. Most of the units were described by the NRCS as being moderate to poorly draining soils that formed in mixed, recent alluvium and with weak B-horizon. These floodplain soils on the lower Long Tom include the Camas, Chehalis, Cloquato, McAlpin, McBee, Newberg, Waldo, and Wapato series.

The modern, modified channel is often surrounded or directly abutted by terraces. The NRCS described most of the terrace soils as having developed on “stream terraces” or “low terraces” and being formed from older alluvium (Patching 1987, Fillmore 2009). They identified these soils as silty clay loam, silt loam, loam, or gravelly silt loam. Again, approximately half of these soil unit descriptions include a reference to some gravels, gravelly sandy loam as being a possibility within the substratum or parent material.

These descriptions appear to be broadly consistent with O’Connor et al. (2001) characterization of fine-grained alluvium (Qbf) throughout much of this region. Since both the floodplain soils and the low terrace soils are commonly silty clay loam, it is likely that these very fine-grained, cohesive sediments and soils would have restrained fluvial erosion and lateral migration. As a result, the lower Long Tom River likely has a limited gravel supply. A table of the terrace soil units, the soil types, and their map units can be found in Appendix A, Table 2.

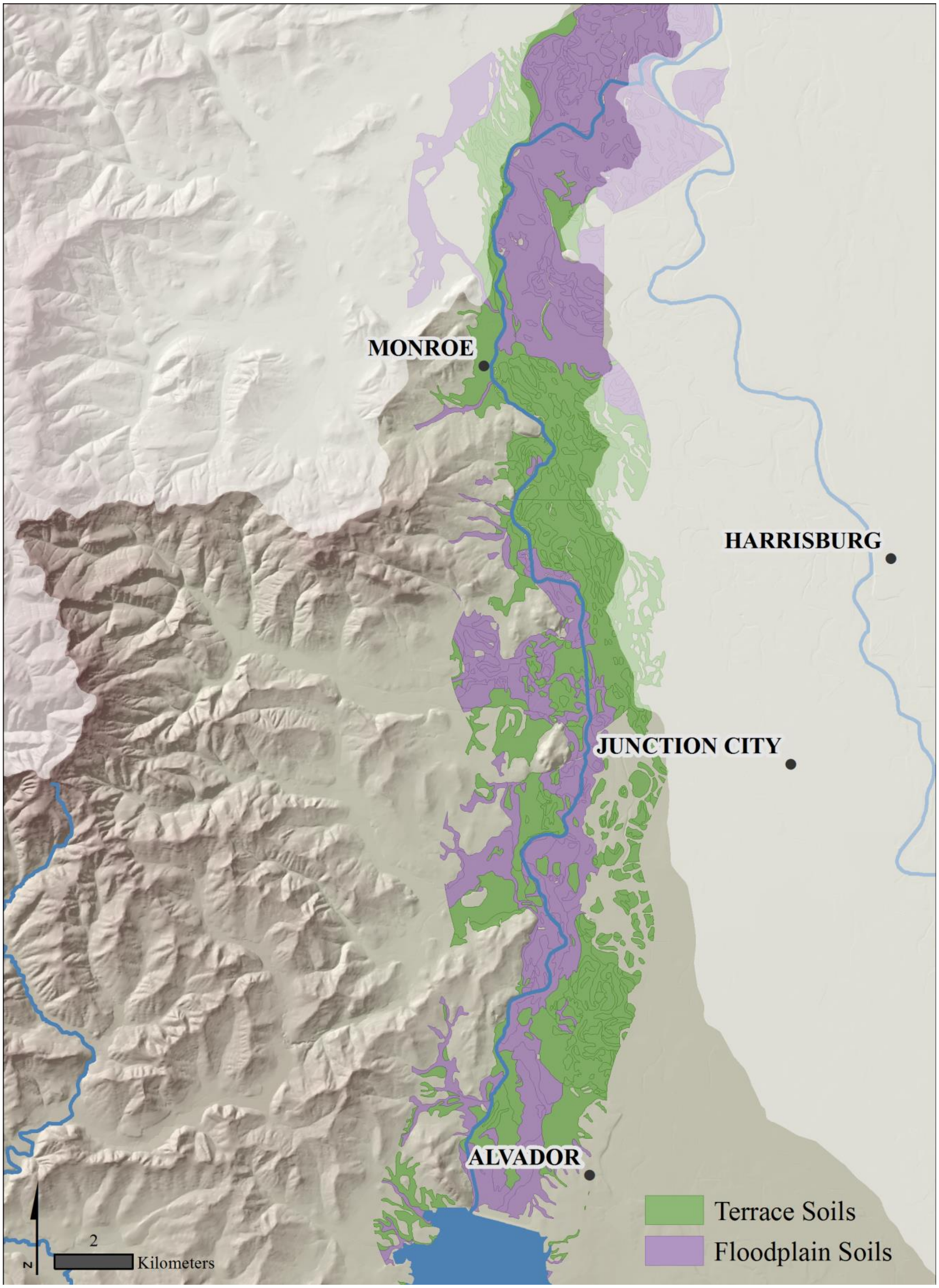


Figure 7: Map of the terrace and floodplain-derived soils classified by the author based on NRCS soil survey (Patching 1987, Fillmore 2009). The semi-transparent regions shown in grey are beyond the boundary of the modern Long Tom watershed.

Pre-channelization geomorphic conditions

Prior to channelization in the 1943-1951, the lower Long Tom River was primarily a single-thread channel with pronounced meander bends, varying sinuosity, and intermittent chutes. In a pre-channelization survey completed in 1944, the USACE mapped 28 chutes and meander neck cut-offs along 8 km of the main channel (USACE 1944). These individual chutes and cut-offs ranged in length from 60 m to more than 300 m. Some of the secondary channels had similar widths to the main channel and were likely actively passing flow throughout the year (Figure 8). This USACE survey shows that across the 20 km upstream of Monroe, the channel sinuosity was 1.9.

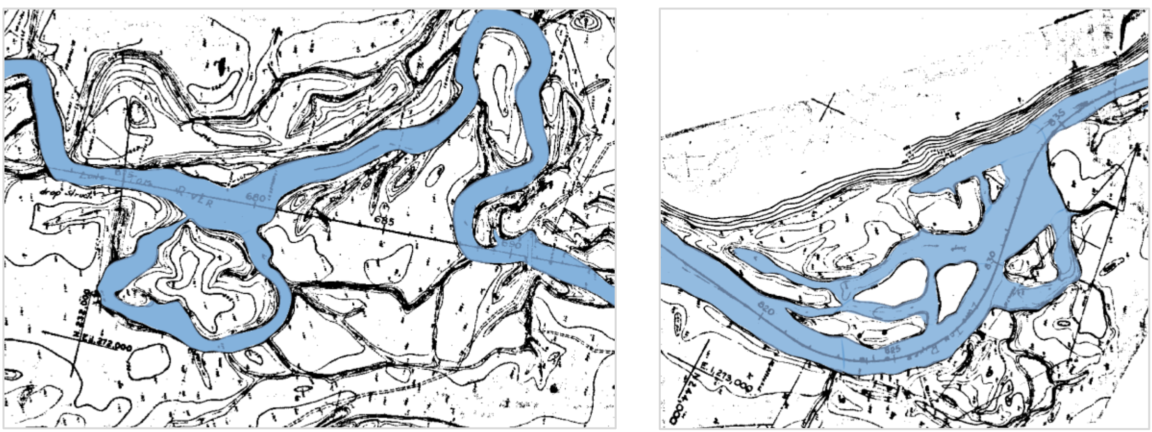


Figure 8: Examples of chutes and meander cut-offs from the USACE 1944 surveys with interpreted active channel highlighted by author.

The historical lower Long Tom River was a moderately low energy stream with a low channel slope. I used the 1944 USACE plan and profile surveys to estimate a channel slope of 0.077% and average channel width of 62 m near the city of Monroe (Appendix A Figure 1). Using the USGS Monroe stream gage data from 1920-1940, I estimate that the specific stream power was 29 W/m^2 at the 2-year flood discharge of 240 cms. To produce this estimate, I used the equation for specific stream power defined by Nanson and Croke (1992) and substituted channel slope for water surface slope due to the limited pre-channelization data.

According to Nanson and Croke's floodplain classification, a specific stream power of 29 W/m^2 suggests the historical Long Tom River had a medium-energy meandering floodplain (Class B3). However, Nanson and Croke observe that these floodplains are typically composed of unconsolidated gravels and the NRCS soil survey shows that the Long Tom's floodplains are composed of very fine grained, highly cohesive silty clay loam (Patching 1987, Fillmore 2009). This section of the Long Tom River appears to fall between Nanson and Croke's (1992) medium-energy non-cohesive floodplains (Class B) and low-energy cohesive floodplains (Class C). Nanson and Croke describe Class B floodplains as being in dynamic equilibrium with limited change during extreme flooding events. While they suggest that lateral migration may occur on cutbanks and concomitantly with point bars, they state that bank erodibility is a direct function of sediment texture for these type of streams. Given the fine-grained, resistant composition of the lower Long Tom's floodplain and banks, bank erosion would likely have occurred slowly over time and it would not have been a very laterally dynamic stream. Additional resources like the Bureau of Land Management's (BLM) General Land Office (GLO) maps from the 1840s show that the general location of the Long Tom River has not changed greatly, but the maps are not detailed enough to show whether or not individual meander bends have eroded or the channel has migrated within the floodplain (BLM 1853) (Appendix A Figure 2).

Both fluvial and pluvial (i.e. surface water) flooding would have been common along the lower Long Tom prior to channelization. As noted in the NRCS soils surveys, many of the floodplain and terrace soils were moderately to very poorly draining soils (Patching 1987, Fillmore 2009). The combination of clay-rich soils and very flat floodplains and terraces would have resulted in a relatively slow rate of infiltration probably causing water to pond at the surface. The GLO maps from the 1840s and 1850s show that the active channel was often directly surrounded by willow swamp and marsh that might have represented the active floodplain. Even beyond the boundary of the swamp and marsh, the GLO surveyors noted that the lowland prairie that was subject to inundation despite being setback from the main channel.

Post-channelization geomorphic conditions

The modern lower Long Tom River is a very straight, geomorphically simple channel with manmade levees lining the banks. The USACE's channelization and modifications in the 1940s and 1950s shortened the lower Long Tom River from 60 km to 39 km by realigning existing channel, cutting off existing meander bends, and creating new, straight bypass channels (Thieman 2000). The geomorphic complexity of the channel was diminished due to a reduction in sinuosity, reduction of channel width variability, removal of gravel bars, channel enlargement, decreased access of the stream to its floodplain, and extensive removal of riparian vegetation. In the 20 km upstream of Monroe, the channel sinuosity was reduced from 1.9 to 1.2 (Figure 9).

Figure 9: Photograph of the modern Long Tom River taken in 2015 by author. Along this reach, the levees are topped by gravel roads and there is limited riparian vegetation.

An example from the 1944 USACE construction plans (in Figure 10) shows that in order to increase the capacity of the lower Long Tom River, the USACE increased channel width and constructed levees along the banks (USACE 1944). The average levees in the Monroe area are 0.9 m above the adjacent floodplains or terraces and are commonly topped by gravel roads. The levees proposed in the USACE 1944 plans suggest that most were originally designed to be 4.6 to 4.9 m above the bottom of the channel. The bathymetric data collected for this thesis suggests a similar typical depth of 4.8 m below the levees and a typical width of 50.4 m between the Ferguson Creek confluence and the city of Monroe (Figure 1). This indicates that the modern average width to depth ratio is 10.4. The earthen levees at the edge of the channel reduced the floodplain connectivity of the Long Tom.

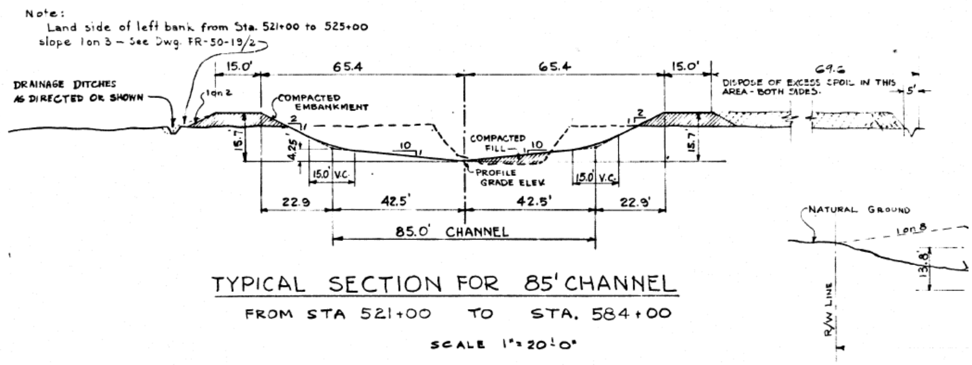


Figure 10: Construction diagrams from USACE (1944) show the plan to widen the historical channel (shown by the dashed line) to meet the current channel dimension (shown by the solid line) with the addition of levees on each bank.

Since no systematic geomorphic assessments have been completed on the lower Long Tom River, it is unclear how and at what rate the river has responded to channelization in the 1940s. Although no major lateral shifts or avulsions have been observed, the USACE has taken steps to minimize geomorphic change. At the time of channelization, the USACE chose to install drop structures to try to maintain the same channel grade despite dramatically shortening the length of the channel. Two of these drop structures, shown in Figure 11, create long areas of backwater in the channel which have not been shown to aggrade in the last decade (Bishop, pers. comm. 2016). However, USACE employees suggest that historically, in other sections of the lower Long Tom, dredging was necessary to maintain channel dimensions. The USACE records show that rock riprap was required at some locations to prevent bank erosion, indicating that localized erosion and deposition has occurred after channelization in the 1940s. In addition, historical aerial imagery and current field observations show that gravel bars are accumulating in the channel and minor to moderate bank erosion has started taking place. However, more research needs to be done to understand the geomorphic response to channelization and damming, to identify the spatial patterns of sediment erosion and deposition, monitor lateral and vertical channel change, and to quantify the available bedload.

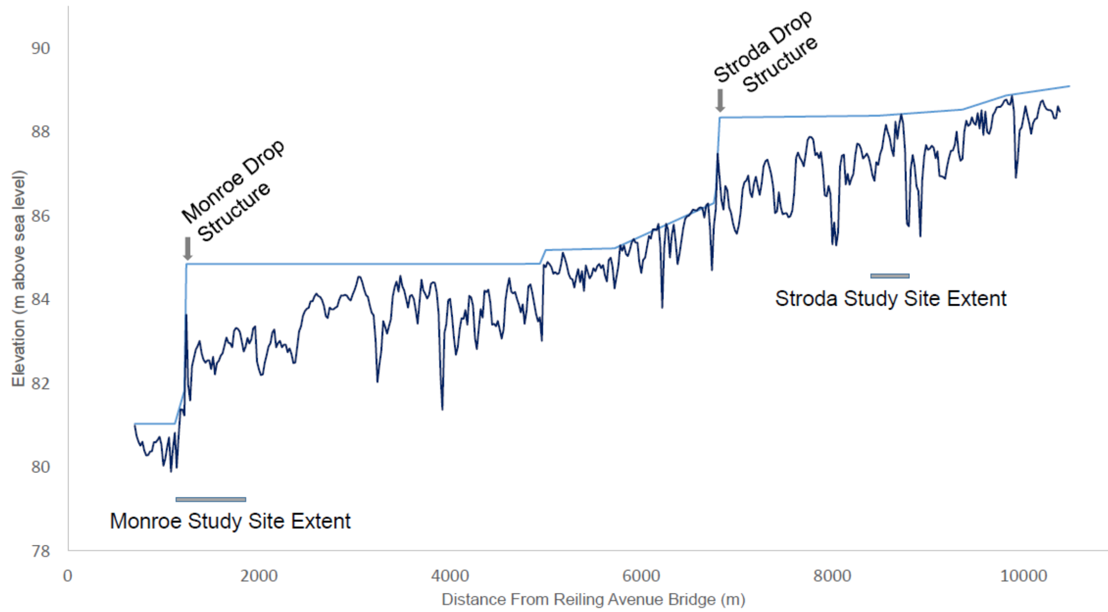


Figure 11: Longitudinal profile of the channel bed shows long areas of backwater during summertime low discharge and the uneven bed topography. The light blue line indicates the water surface elevation and the dark blue line shows the channel bed based on 20 m spaced points. The profile data are based on bathymetric and water surface elevations during this study.

Hydrology

The construction of Fern Ridge Reservoir and the channelization of the river also changed the hydrologic regime. As Magilligan and Nislow (2005) have documented, the impoundment and regulation of rivers often results in changes in the timing of flows, magnitude of peak events, and variability in flow depending on the goals of the flow regulation and storage capacity, the climatological regime, and the location of the river. In the case of the Long Tom River, a USGS gage in Monroe recorded the change in discharge between 1920 and the present.

Prior to damming and regulation in the 1940s, high flows typically began in early November, peaked in late-December, January or February, and then gradually transitioned into very low flow conditions that lasted from June through October (Figure 12). The modern hydrograph shows a similar overall pattern with two important changes. First, water is being released throughout the month of October in order to draw down the reservoir and create space for winter-time accumulation. Second, the period of highest flows is shorter and early than it was previously.

Not only has the timing of flows changed, the magnitude of peak flows has decreased after dam construction (Figure 13, Table 1). Both low and high frequency peak-flow events have been greatly diminished through regulation practices. This is, of course, intentional as the creation of the Fern Ridge Reservoir and channelization of the Long Tom River was intended to reduce flooding in the region. The USACE has indicated that the release from the dam should not cause the flow at Monroe to exceed 131.7 cms (4650 cfs) (USACE 2014).

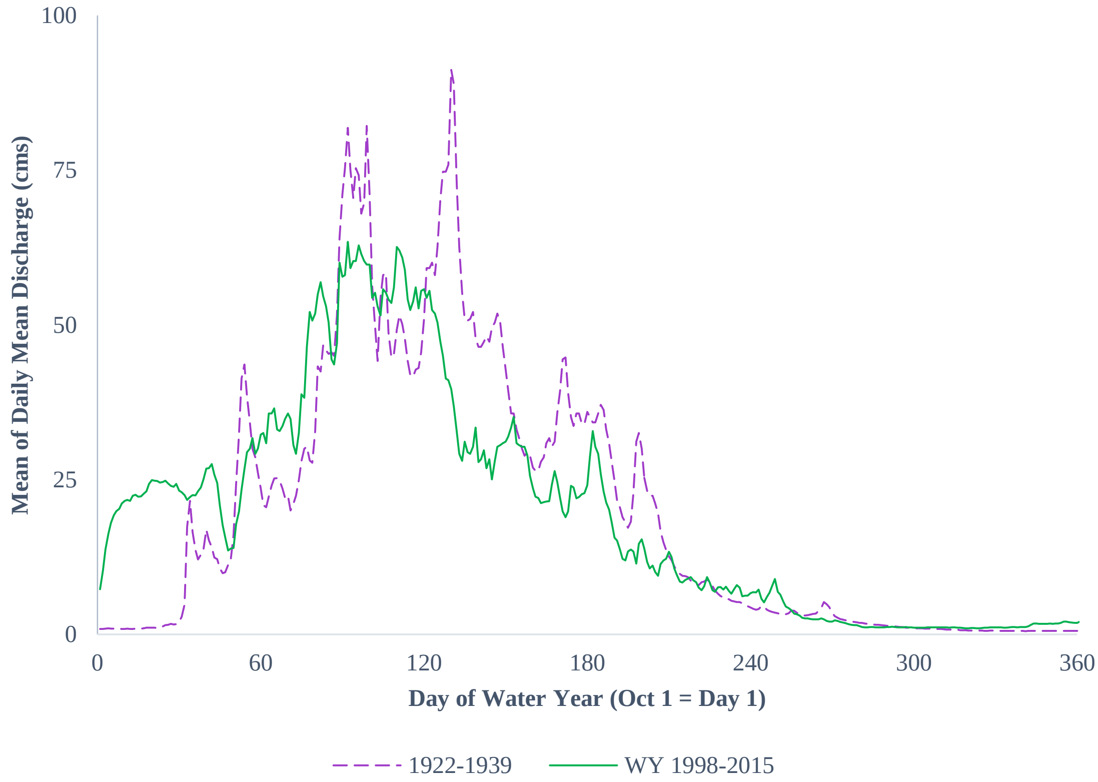


Figure 12: Two hydrographs of the average daily mean discharges for the Long Tom River at the Monroe USGS Gage (14170000) (USGS 2016).

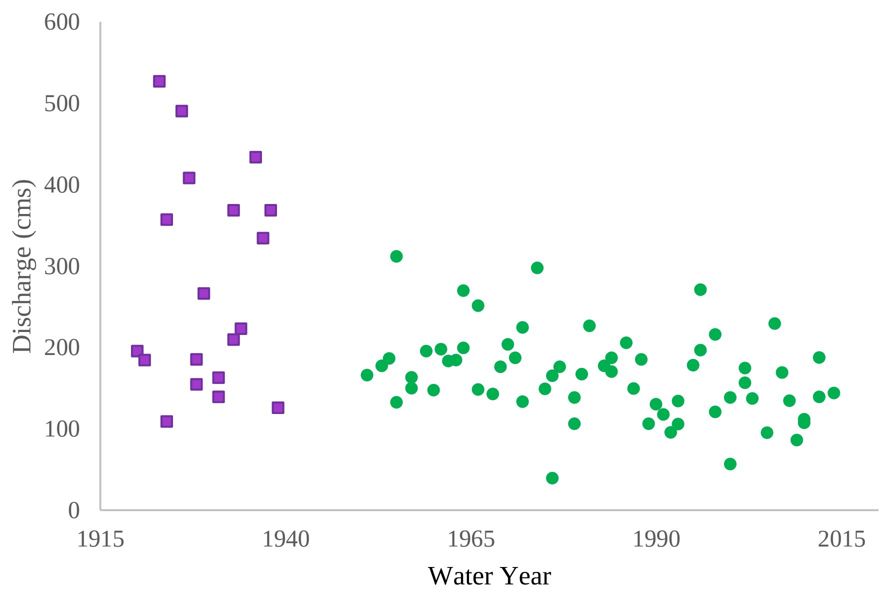


Figure 13: A comparison of the annual peak discharges from prior to dam construction (water year 1920 – 1939) and post-dam construction (water year 1951-2014) at the Monroe USGS Gage (14170000) (USGS 2016).

Table 1: Flood frequency analysis based on data collected at the Monroe USGS Gage (14170000) (USGS 2016). Southern study site values were calculated proportional to the difference in upstream drainage area.

Return Period(years)	1920-1940 Flood Discharge at Monroe (cms)	1951 - 2014 Flood Discharge at Monroe (cms)	1951 – 2014 Flood Discharge at Southern Study Site (cms)
1	81.32	58.08	57.63
2	240.16	162.25	161.01
5	362.58	211.67	210.05
10	451.75	238.35	236.52
25	572.88	266.68	264.63
50	668.96	284.63	282.44
100	770.24	300.35	298.05
200	877.07	314.31	311.90

Modern River Management Goals

There are two organizations actively managing the Long Tom Watershed. The first group is the Long Tom Watershed Council (LTWC). This organization was established in 1998 by a group of local residents concerned about the health of the Long Tom Watershed. Since its inception, the organization has taken steps to improve the health of the entire watershed by focusing on threats to aquatic species, water quality, and riparian and upland habitat. The LTWC is concerned that fish habitat is limited in the lower Long Tom River, that fish passage into the higher-order streams with high quality habitat is limited, and that stream temperatures are too high to sustain native aquatic species. The LTWC has expressed interest in reconnecting several of the disconnected, historical meander bends to the main stem of the Long Tom River. These historical meanders often have a higher concentration of tree cover, a wider riparian buffer, and much more instream wood than the adjacent main stem. The LTWC hopes that by increasing the channel length and complexity, these side channels may act as flood water storage, provide more aquatic and riparian habitat, slow the movement of water through the watershed, and potentially reduce stream temperatures.

The US Army Corps of Engineers is the second organization actively involved in Long Tom River management. As an agency, the USACE tries to reduce the risks of damage to human life and property associated with flooding of the Long Tom River. They control the flows coming out of Fern Ridge Reservoir, and maintain the channel and levees along the eroding banks of the channel. Erosion of the stream banks and constructed berms is a concern for the USACE, because it may directly damage private property or lead to increased areas of inundation. USACE employees have expressed an interest in understanding to what extent flood inundation will change if sections of the historical channel are reconnected and how the reconnections may change sediment storage and erosion.

River Restoration Potential

Historically, the Long Tom watershed provided aquatic habitat for many species including the coastal cutthroat trout (*Oncorhynchus clarkii clarkii*) and juvenile spring Chinook salmon (*Oncorhynchus tshawytscha*). However, installation of the Fern Ridge Dam and installation of drop structures reduced available habitat for both species by approximately 70% by prohibiting fish passage (Dedrick and Thieman 2005). Within the lower Long Tom River, the Monroe, Ferguson, and Stroda drop structures prevent juvenile trout and Chinook salmon passage and only allow for limited adult trout passage. In addition, the highly simplified channel morphology, minimal riparian vegetation, and lack of high quality off-channel habitat suggest that salmonid production may be limited. According the LTWC staff, it is important to allow for fish passage around the Monroe and Stroda drop structures in order to provide salmonids access to the higher quality habitat in the tributaries, such as Ferguson Creek (J. Kaul, personal communication, 2016).

As a result of creation and management of Fern Ridge Dam, habitat for native fish species has been degraded, water temperatures have increased, peak flows have decreased, and area regularly inundated by floods has diminished dramatically (Thieman 2000). However, many sections of historical channel still exist as ponds and lie adjacent to the current Long Tom River. These historical meander bends of the Long Tom are much more sinuous, contain more woody debris, and have more riparian vegetation than the current main stem and as such may provide much higher quality habitat. Stream side channels have been widely recognized to have much higher densities of juvenile salmonids than the adjacent, larger river main stems in the Pacific Northwest, particularly during high flows (Rosenfeld et al. 2008). In addition to providing refuges for fish during floods, strategically placed secondary channels have the potential to circumvent the fish passage barriers like the drop structures.

In undertaking this research, I seek to understand the impact of reconnecting the historical meander bends to the main stem of the Long Tom River. In addition, I want to understand how different types of historical channel connections will have potentially different impacts on the flood inundation boundary, fish habitat, and potential for bed sediment mobilization and deposition. I first propose to model one restoration scenario in which the historical channel is connected to the main stem by fish passable culverts. The costs and general impacts of culverts are well understood by the USACE and would allow for a controllable amount of flow to pass through between the main stem and historical channel. I also propose to model levee breach scenarios that would allow for sediment to move and water to flow unimpeded between the historical and main channel.

CHAPTER III

METHODS

Overview

In order to determine how salmonid habitat, flooding extent, and bed sediment mobilization will change with historical channel reconnection, this study utilized 2D hydraulic modeling to compare the current conditions to two restoration scenarios at the Monroe and Southern study sites. In the first restoration scenario, the historical channel was connected to the main channel by a series of large culverts, and in the second restoration scenario, the historical channel was connected to the main channel by breached levees. Using hydraulic modeling, I simulated a steady 1-year, 2-year, and 5-year flood flows for each scenario and recorded the inundation boundary, water velocity, water depth, and bed shear stress. I interpreted these model outputs by comparing the values to salmonid habitat requirements and critical shear stress mobilization threshold to assess the impact of the restoration as shown in Figure 14.

In the following sections, I describe the methods used to collect bathymetry on the historical channels; create a continuous terrain and modify it to show restoration conditions; calibrate, test, and run the models; and analyze model outputs. While my workflow and GIS methods are original to this thesis, the HEC-RAS modeling methods follow the guidelines written in the HEC-RAS 5.0 manual (Brunner 2016). Figure 14 shows a simplified schematic of the research methods.

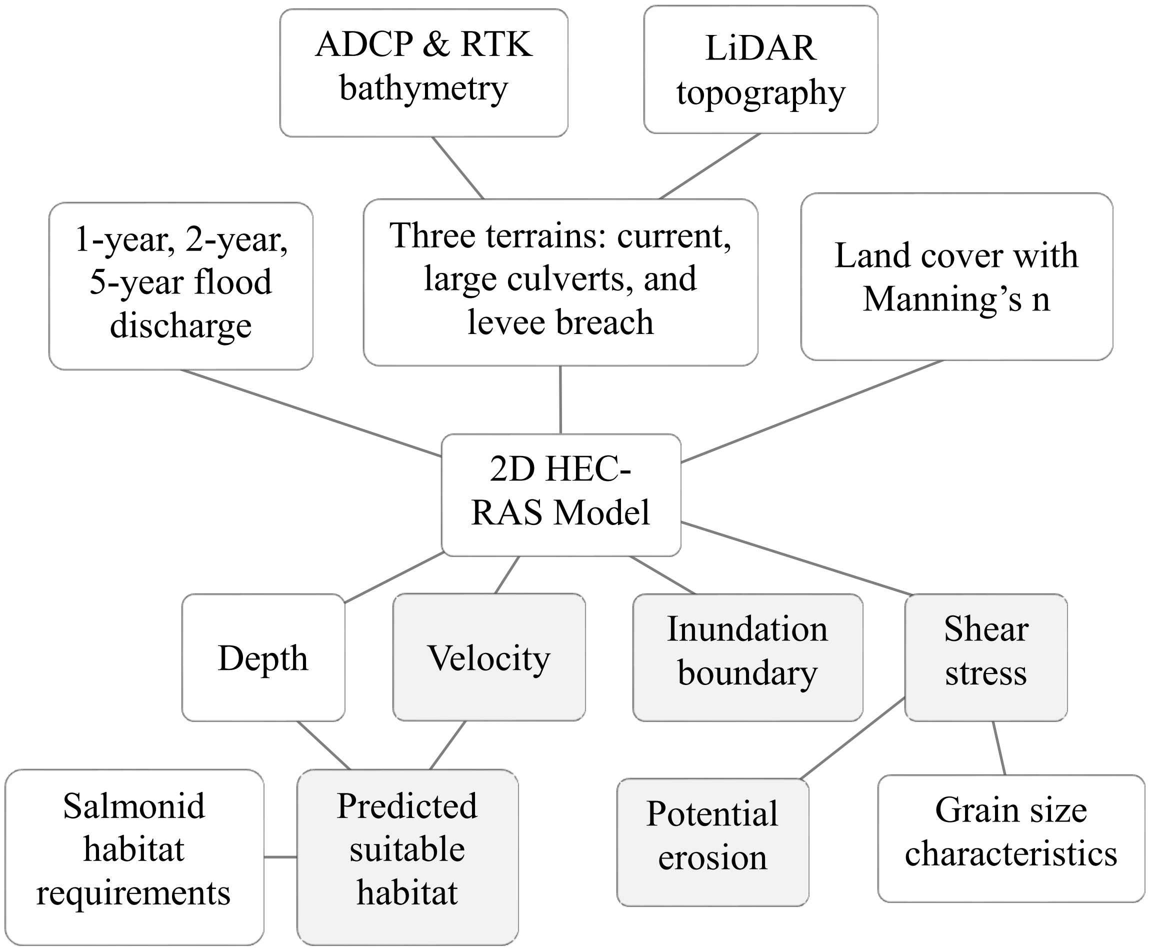


Figure 14: A simplified schematic of methods. Gray boxes indicate a map in the results section

Creating the Terrains

In order to run a fully 2D simulation, I had to create a continuous terrain or digital elevation model (DEM) that combined the current bathymetry and topography. While traditional LiDAR provides high-resolution topographic data, it cannot record accurate bathymetric elevations. For this study site, green LiDAR and bathymetry based on structure from motion were not an option due to high levels of turbidity. In addition, real time kinematic global positioning system (RTK-GPS) survey would be difficult to complete due to the fact that much of the main stem is too deep to be waded. Therefore, I used a combination of acoustic Doppler current profiler (ADCP) and RTK-GPS to collect bathymetry.

I first collected field data in the main channel and historical meander bends. Second, I converted water depths to bathymetric elevations above sea level and combined the bathymetry with LiDAR bare earth elevations. The 3-ft resolution LiDAR dataset was collected during August of 2008 and was provided by the Oregon Department of Geology and Mineral Industries (DOGAMI 2009). Third, I compared my terrain to a set of cross-sections that had been recorded by the USACE and, recognizing a minor errors from my data collection, I modified the terrain to account for these errors.

Field Data Collection

During July of 2015, I surveyed 10.8 km of the main stem of the lower Long Tom River from Ferguson Road bridge to the town of Monroe and collected more than 39,000 water depths. I used an ADCP to measure water depths between Ferguson Road Bridge and the town of Monroe. I collected data points along three longitudinal paths that were aligned along the right edge, left edge, and center of the active channel at approximately 1 m longitudinal spacing. I collected data using a SonTek RiverSurveyor S5 ADCP that was mounted to a Sontek HydroBoard that was towed behind a kayak. I used the average of four slant angle transducers to measure the depth of the channel with one point collect per second. Although the vertical resolution of the RiverSurveyor unit is 1 cm, the range of values of the four slant angle measurements was often close to 10 cm, which may be a better representation of the accuracy of an individual averaged depth. The horizontal location of each point was collected with the Sontek differential GPS that was mounted directly above the ADCP and had sub-meter accuracy and a HDOP range of 0.8 to 3.3. Although the ADCP had a built-in GPS unit, the vertical accuracy of the device was too low to be used to derive an accurate bathymetric depth. In order to establish a more accurate water surface elevation, I collected a series of points using a Topcon GR-3 and Topcon GR-5 RTK-GPS. I collected these elevations at strategic points to capture the water surface slope and to document the length of flat water behind the drop structures.

During August of 2015, I surveyed the historical meander bends of interest at the Monroe and Southern study sites using the same Topcon RTK-GPS. In Monroe, I collected 209 points of latitude, longitude, and elevation across an area of 26,590 m^2 (i.e. approximately one point every 5 m longitudinally). At the Southern study site, I collected 71 data points across an area of 7,120 m^2 (i.e. approximately one point every 5.25 m longitudinally). I surveyed these side channels from an inflatable raft. In addition, I collected elevations of the tops and bottoms of the drop structures at both study sites.

GIS Processing to Create the Initial Terrain

This research project followed a multi-step GIS process in order to create the initial terrain. As shown in Figure 15, the goals were to:

1. Create a continuous water surface elevation (WSE) raster for the main channel
2. Subtract my water depth points from the WSE raster to create a series of bathymetric points with elevations
3. Extract elevation values for the land surfaces from the LiDAR
4. Interpolate a continuous surface to create the initial terrain

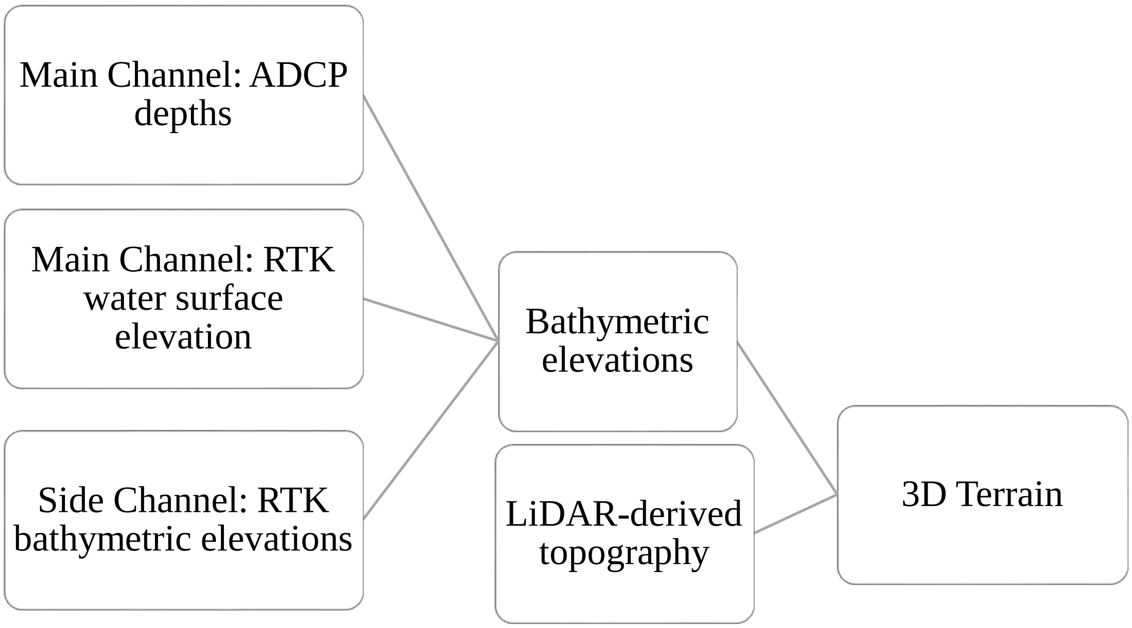


Figure 15: GIS workflow used to process data.

Step 1 & 2: Create a bathymetric elevation points dataset

First, I plotted my 8 WSE points on a longitudinal profile of the main stem of the Long Tom. Since the Long Tom's discharge was very similar on the day that the LiDAR data was collected and the day that I collected my main channel depths, I compared the LiDAR WSEs to my WSE points on the longitudinal profile. Since the known elevations matched very closely, I was able to add 8 additional points from LiDAR to my WSE dataset to capture several details lost in the field data collection process. The completed longitudinal profile with WSEs is shown in Figure 16.

Second, using the modified WSE profile, I generated a set of spatial points from the WSEs at 20 m interval stream stations. I employed a spline interpolation with active channel edges as the barrier to interpolation to create a water surface raster. The spline technique was appropriate in this situation since it forced the raster values to intersect my points exactly and it created a smooth surface that reflected the visibly flat water in the channel.

Third, after removing null and erroneous values from the ADCP depth dataset, I subtracted the water depths from the WSE raster to create a series of bathymetric points.

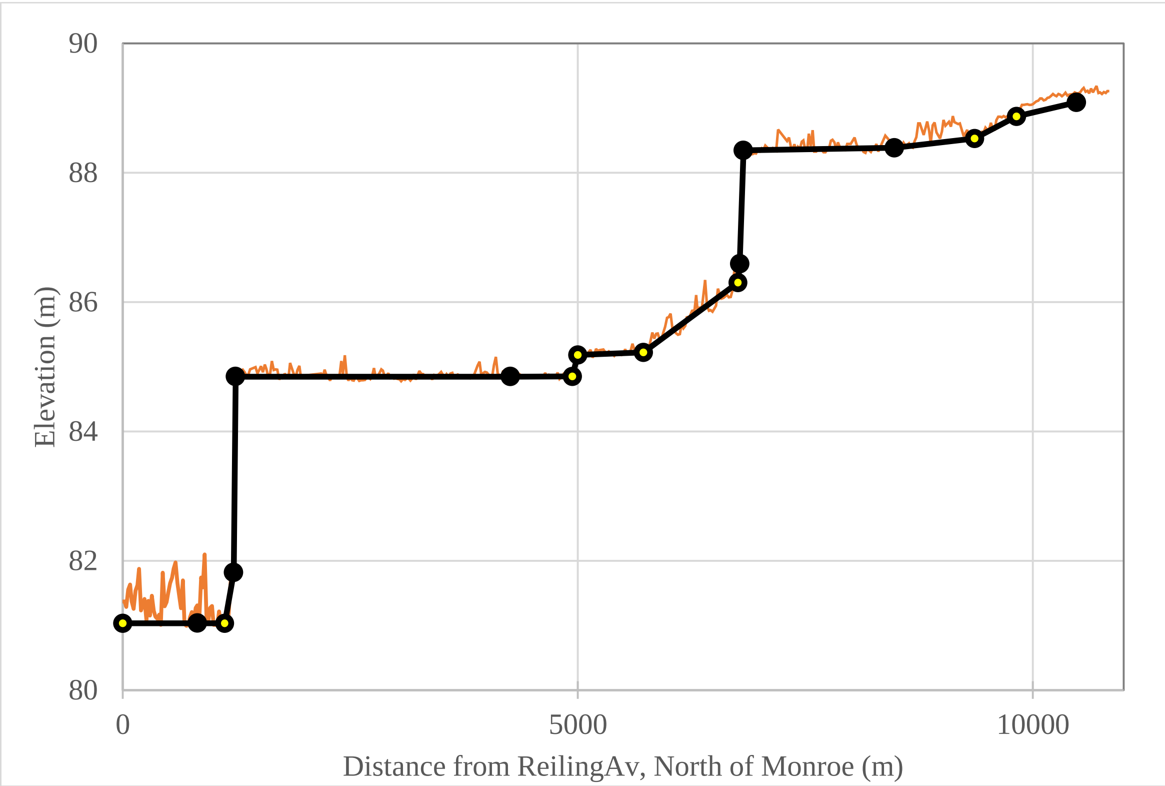


Figure 16: Stream surface profile from Monroe High School (~500 m) to Ferguson Bridge (~10,500 m). The orange line shows the LiDAR derived water surface profile, the black points show the measured water surface elevations, and the yellow points show the water surface elevations extract from the LiDAR.

Step 3: Extracting topography from LiDAR and modifying drop structure points

First, I digitized the active channel boundary from the August 2008 LiDAR DEM. Second, I extracted the topographic elevations to create a set of 0.91 m by 0.91 m spaced points by removing those point that were located in the active or historical channel. Third, I examined the point density at the drop structures and used the surveyed drop structure elevations to create a series of points along the tops of the drop structures so that the final terrain accounted for these abrupt changes.

Step 4: Triangulated Surface and DEM

After trying several types of interpolation, I used a triangulated irregular network (TIN) to combine the ADCP-derived main channel points, RTK-GPS survey side channel elevation points, and the LiDAR-derived topographic points into a continuous surface. I selected the TIN methodology based on the high density of points and the ease of use and modification. I converted the TIN to a raster format using the same 0.91 m by 0.91 m cell size that was used in the original LiDAR.

Terrain Validation and Correction

After creating my initial terrain, I compared my dataset to 18 USACE cross-sections that were collected in 1988 and 2013 by extracting my terrain values to the cross-section points in GIS. Despite potential channel changes over time, many of the cross-sections were well-aligned and the difference between my terrain and the cross-sections were typically less than 10 cm in the center of the channel. (See Figure 17) However, at the Monroe study site, one consistent difference between the datasets arose. In areas where the bank was steeply sloping and the ADCP data was collected more than 5 m from the edge of water, the terrain dataset underestimated the bathymetric depth at the channel’s edge. (See Figure 18). To rectify this error, I identified the areas in which the ADCP data was collected more than 5 m from the edge of water and I digitized a second point adjacent to the edge of water that had the same elevation as the closest

ADCP point. Effectively, this extended the recorded elevation further towards the edge of water and steepened the slope of the submerged bank.

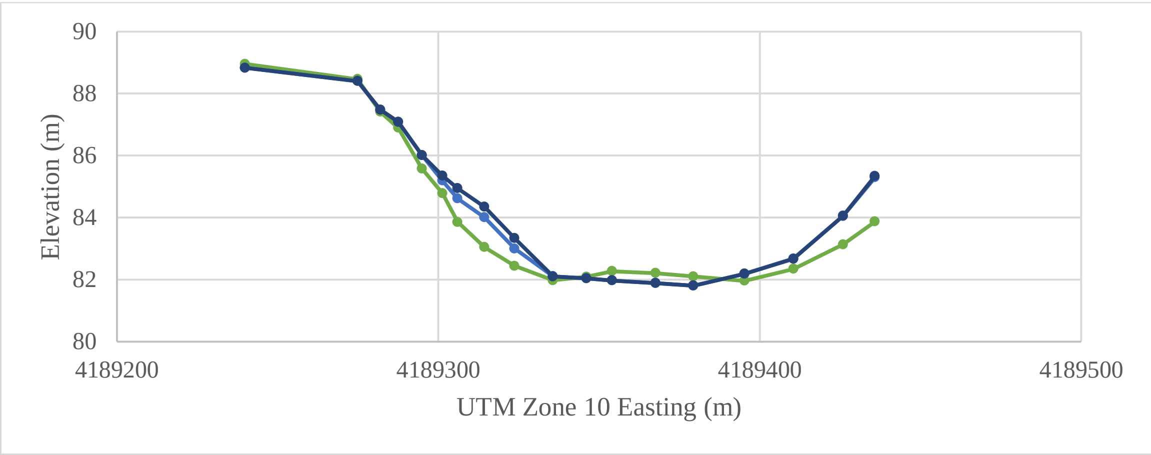


Figure 17: Comparison of cross sections at 1260 stream meters south of Reiling Avenue. USACE (2016) surveyed cross section (green line), author's uncorrected cross section (light blue), and author's corrected cross section (dark blue).

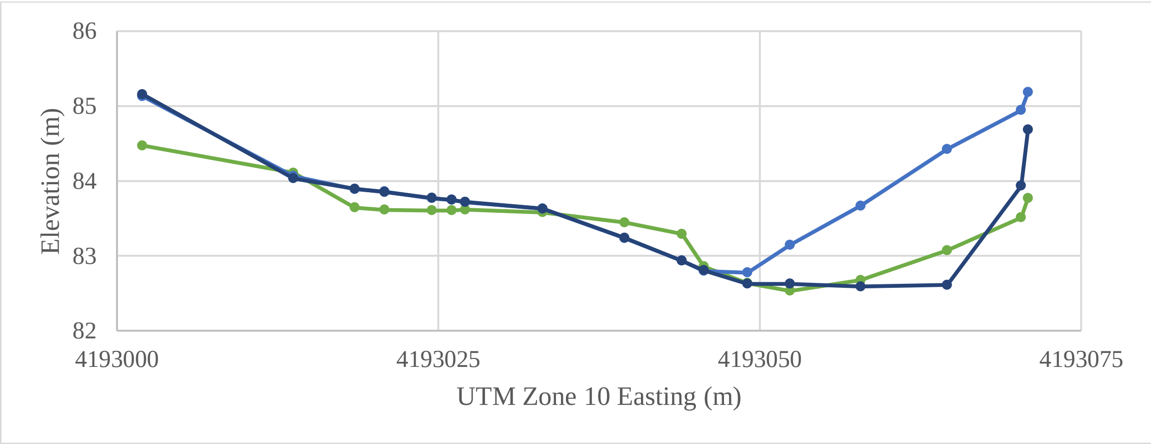


Figure 18: Comparison of cross sections at 3180 stream meters south of Reiling Avenue. USACE (2016) surveyed cross section (green line), author's uncorrected cross section (light blue), and author's corrected cross section (dark blue).

<u>Terrain Modification for HEC-RAS and Restoration Scenarios</u>

In order to use the HEC-RAS 5.0 software to model the current conditions, I made three more changes to the terrain to accommodate culverts. HEC-RAS 5.0 requires that the elevation of bottom of every culvert is higher than the cell to which it is connected.

Based on the current culvert dataset provided by the USACE (2015), the adjacent terrain cells were adjusted to reflect the bottom elevation of the three current culvert locations in Monroe. I did not include any culverts at the Southern study site under the current conditions and thus did not need to change the terrain further.

In order to model the large culverts restoration scenarios, I had to make further adjustments to the terrain. For the larger culvert model at the Monroe study site, I used the same terrain elevations at the culverts' ends from the current scenario model, built a set of steps into the terrain to replicate a riffle with fish passage, and adjusted the side channel to reflect removal of an earth and rock fill pile currently impeding side channel flow. For the larger culvert model at the Southern study site, I was able to reuse the current scenario model since it did not violate the HEC-RAS 5.0 terrain requirements. The size of the large culverts was based on a preliminary USACE culvert replacement report (2015).

For both of the levee breach models, I further modified the terrain to reconnect flow between the main and historical channel. I determined the dimensions of the levee breach based on the current width and depth of the historical channel at each site as shown in Tables 2 and 3. At the downstream end of the Monroe study site, I connected the higher side channel elevation to the main channel using the same series of steps that had been used in the large culvert scenario. Since there was fairly little change in elevation between the main channel and the historical channel at the Southern study site and at the upstream end of the Monroe study, I did not need to add additional grade modifications.

Table 2: Monroe levee breach widths used to create restoration terrain.

Location	Average width
Northern breach	16 m
Highway 99 breach	35 m
Southern breach	30 m

Table 3: Southern levee breach widths used to create restoration terrain.

Location	Average width
Eastern breach	36 m
Western breach	24 m

Flood Frequency Analysis

In order to determine which discharges to model, I performed a flood frequency analysis based on peak discharges for the 1951 to 2014 water year as recorded by the USGS Monroe streamflow gauge. As recommended by the U.S. Water Advisory Committee on Water Data (year), I fit the flood frequency curve using a Log-Pearson Type III distribution (Bedient and Huber 2002). Using the Monroe study site flood frequency curve, I estimated the flood discharges at the upstream Southern study site by measuring the drainage area upstream of the Southern study site and dividing it by the drainage area at the USGS Monroe gage. I multiplied the Monroe flood discharges by the drainage area proportion to calculate the flood discharges at the Southern study site. The results of the flood frequency analysis are shown in Table 4. I used the 1-year, 2-year, and 5-year flood discharges as inputs to the hydraulic model.

Table 4: Flood discharges and recurrence intervals at the Monroe and Southern study site

	Monroe Study Site		Southern Study Site	
Recurrence Interval (ys)	**Discharge (cfs)**	**Discharge (cms)**	**Discharge (cfs)**	**Discharge (cms)**
1	2050.90	58.08	2035.17	57.63
2	5729.91	162.25	5685.95	161.01
5	7475.21	211.67	7417.86	210.05
10	8417.23	238.35	8352.64	236.52
25	9417.74	266.68	9345.49	264.63
50	10051.50	284.63	9974.37	282.44
100	10606.81	300.35	10525.43	298.05
200	11099.87	314.31	11014.71	311.90

Land Cover

Another input to 2D HEC-RAS modeling is a classification of the area by Manning's n values. In ArcGIS, I classified the 2014 aerial imagery created by the National Agriculture Imagery Program (NAIP) by land cover type (see Figure 19 for cover types). I used the Oregon National Land Cover Database (NLCD) 2011 data as a reference, but given the 30 m resolution of the image, I wanted a finer scale classification that could only be acquired by hand digitization (Homer et al. 2015). I assigned each of the land covers a Manning's *n* estimate based on field observations, photographs, and, as recommended in the HEC-RAS Manual, the tables in Chow's 1959 book. As I will describe in the HEC-RAS section, I changed some of these Manning's *n*-values as a part of the calibration process. Adjustments were made incrementally and often yielded values that were still within the expected ranges (see Figures 19 and 20).

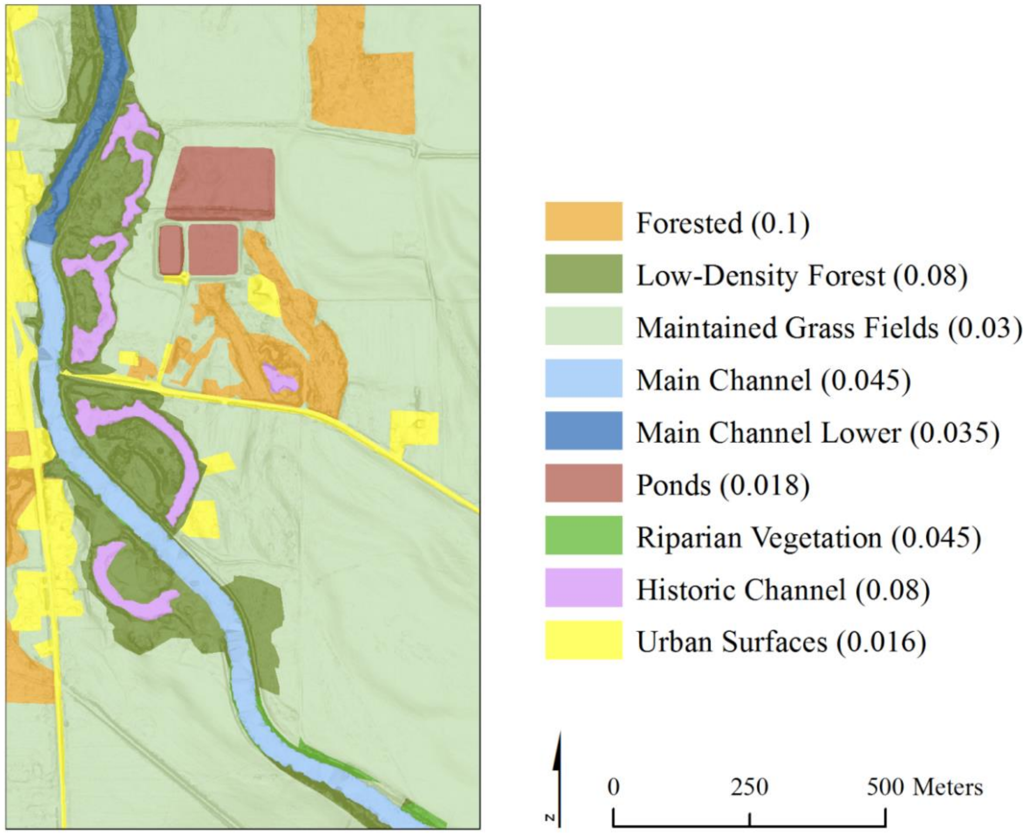


Figure 19: Land cover classification and Manning's n values at Monroe study site

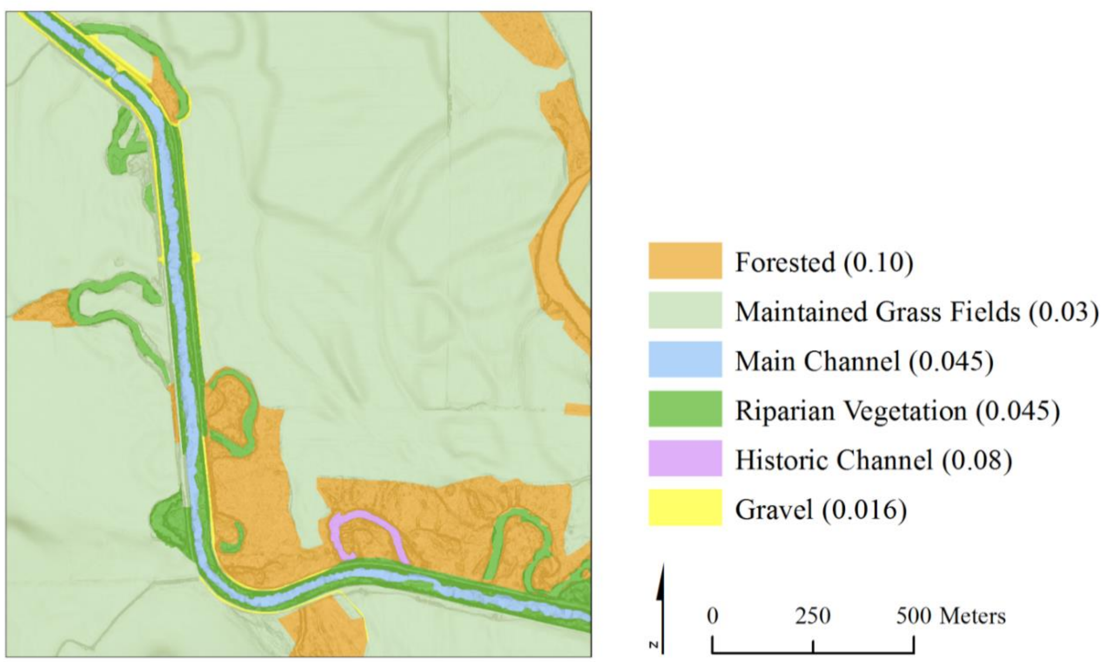


Figure 20: Land cover classification and Manning's n values at Southern study site

Grain Size Estimates and Critical Shear Stress

During the summer of 2015, I collected two sets of grain size measurements along the main stem of the Long Tom River. At each site, I measured the intermediate access of sediment grains along channel-spanning transects in the active channel, in the style of a Wolman pebble count (Woman 1954). I collected the first set of samples 120 m downstream from the confluence of Ferguson Creek and the Long Tom River, adjacent to a geomorphically active gravel bar. More than 200 clasts were measured at each site. These sites were selected based on their location adjacent to or directly upstream from the primary study sites and due to their accessibility based on depth. Since it was not feasible to collect a main channel gravel count at the Monroe study site, the gravel count at the Southern study site was used to estimate the main channel grain size distribution for both the Monroe and Southern study site for the remainder of this research project.

Based on the particle size distributions, I determined that the median grain size, the $D_{50,}$ for the Southern sample, is 19.3 mm (Figure 21.) Using the Shield's equation written below, I calculated that critical shear stress required to mobilize a grain of this size would be 14.07 N/m^2, assuming a dimensionless constant value *k* of 0.045 (Knighton 1998).

$$\tau_C = kg\,(\rho - \rho_s)\,D_{50}$$

τ_C is the critical shear stress (N/m^2), g is the gravitational constant of (9.8 m/sec), ρ is the density of the water (997 kg/m^3 at 25 deg. C from USGS), and ρ_s is the density of the sediment (2650 kg/m3 for quartz sediment from Wilcock and Southard 1988). This research used this single critical shear stress value of 14.07 N/m^2 as a threshold to calculate potential mobilization at both study sites.

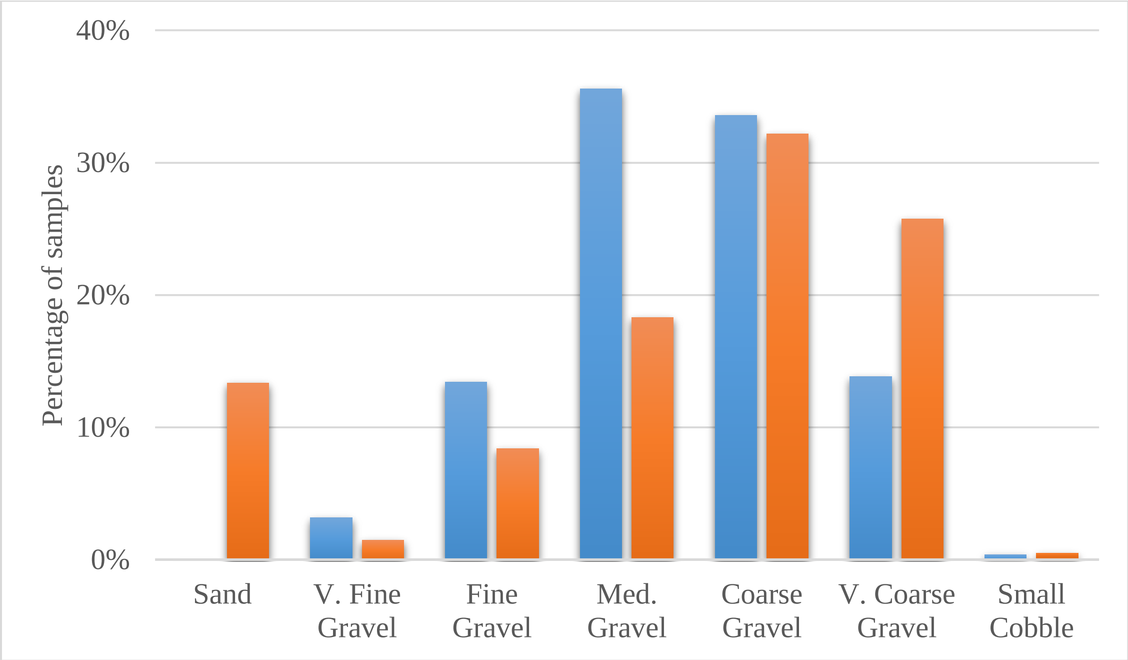


Figure 21: Grain size distributions excluding fine hard pan sediment. At the Southern study site, shown in orange, there were 202 clasts and 98 fine hard pan deposits observed. At the Ferguson Creek confluence, 253 clasts and three points of find hard pan were observed.

2D HEC-RAS Modeling

HEC-RAS v. 5.0.1 (Hydrologic Engineering Center – River Analysis System) is a publicly available piece of hydraulic modeling software that was produced by the U.S. Army Corps of Engineers. Unlike previous versions of this software, it is capable of performing 2-dimensional, unsteady flow analysis utilizing the Saint Venant equation or diffusion wave equation (Brunner 2016). Based on a user-generated grid, the software creates a computational mesh that can be used to calculate the volume of water in a given cell using an implicit finite volume algorithm. The software makes these calculations at specified time-steps and produces a detailed hydraulic table containing values for all cells and cell faces. These values can then be displayed using the RAS Mapper extension. One of the primary advantages of a 2D model is that it can produce detailed flood mapping based on high-resolution, continuous terrains and spatially variable roughness coefficients. For a summary of the model inputs, see Table 5.

In this study, I used HEC-RAS to model the changes in area of inundation, bed shear stress, velocity, and depth at the Monroe and Southern study sites across three different scenarios: the current conditions, the enlarged culvert restoration scenario, and the levee breach restoration scenario. As described above, I have created three terrains to simulate these different scenarios. Table 6, 7 and 8 show the additional inclusion of culverts in each scenario. Although the full Saint Venant's equation would have been the preferable method for my models (due to its inclusion of fully turbulent flow), running a single stable Saint Venant's-based model for my sites would have taken weeks, due to a limited available computing power. Instead, I opted to use the simplified Diffusion Wave equation. In order to capture the backwater behind the adjacent drop structures, I was required to create a model that included the drop structures. In addition, I modeled an area slightly greater than my final study site so that I was able to crop the final results to remove any errors that might occur along the edges of the model.

I determined the appropriate cell spacing at each site based on a set of sensitivity tests. I began with a 50 m cell resolution and ultimately used a typical cell resolution of 5 m on the floodplains and 2 m in the main and historical channels. While this resolution increased the computational time, it also reduced leaking of water between adjacent cells within the model, which is a common problem in the 2D HEC-RAS models. I enforced the smaller cell spacing using breaklines that I digitized from the terrain and aerial imagery in ArcGIS, and hand-edited the mesh points at the culvert locations. Based on the range of cell sizes and given the large size of my study site, I chose a computational interval of 1-second for all models. This value both produces a stable model and satisfies the time step recommendation in the HEC-RAS User's Manual based on the Courant number for the Diffusion Wave equation (Brunner 2016). As recommended in the HEC-RAS 2D Modeling User's Manual, I used many of the default computational mesh tolerance values (e.g. water surface elevation tolerance of 3 mm, 20 maximum iterations of equations, an implicit weighting factor of 1.0).

I calibrated this model by comparing the modeled water surface elevations and areas of inundation to the elevations I surveyed during a summer low flow discharge (0.82 cms), a near 1-year flood (52.39 cms) and a greater than 1-year flood (113.27 cms). Based on these comparisons, I adjusted the Manning's *n*-values and produced the final values shown in the previous Manning's *n* section. I also used the surveyed water surface profiles to determine the energy slope at the upstream end of the study site (0.0005 at the Southern study site and 0.00056 at the Monroe study site). I set friction slope at the downstream outlet of each study site based on the land slope in the vicinity of the study area (0.00066 at the Southern study site and 0.00115 at the Monroe study site).

I began each model run with a dry stream bed and gradually ramped up to the 1-year, 2-year, and 5-year flood discharges across 14 days at the Southern study site and 18 days at the Monroe study site using a hydrograph. Although the model was run in an unsteady mode, I simulated a steady-state flow for each of the flood discharges and allowed the water surface elevation in the model's main channel to reach a steady elevation before increasing it to the next flood level. I gradually increased the flow in the channel in order to avoid a rapid increase in water surface elevation that might induce leaking within the model.

Table 5: Model inputs and data sources for a 2D HEC-RAS 5.0 model

Hydraulic Model: HEC-RAS 5.0	
Model Inputs	Data Source
Terrain (topography and bathymetry)	2008 LiDAR and 2015 field data
Unsteady Discharge Values	Flood frequency analysis
Land cover with Manning's *n*	Digitized land cover and field estimates of Manning's *n*
Breaklines	Digitize from aerial imagery and terrain
Culvert characteristics	USACE communication

Table 6: Current culverts characteristics at Monroe study site (USACE 2015)

Culvert location	Culvert diameter	Culvert material and shape
Northern culvert	0.762 m	Circular, concrete pipe
Highway 99 culvert	1.067 m	Circular, concrete pipe
Southern culvert	0.305 m	Circular, concrete pipe

Table 7: Enlarged culverts characteristics at Monroe study site for restoration model (USACE 2015)

Culvert location	Culvert diameter	Culvert material and shape
Northern culvert	1.067 m	Circular, corrugated metal
Highway 99 culvert	1.067 m	Circular, concrete pipe
Southern culvert	0.61 m	Circular, corrugated metal

Table 8: Culverts characteristics at Southern study site for restoration model

Culvert location	Culvert diameter	Culvert material and shape
Eastern culvert	0.61 m	Circular, corrugated metal
Western culvert	0.61 m	Circular, corrugated metal

Data Analysis and Hypotheses

Once I ran the hydraulic models, I output the inundation boundary, bed shear stress, velocity, and depth values for the 1-year, 2-year, and 5-year floods. With the exception of the inundation boundary shapefile, the file outputs were 0.91 m resolution raster datasets. To analyze these outputs, I first used GIS to calculate the area of inundation from the inundation boundary shapefile. Second, I reclassified the velocity and depth datasets based on the rearing habitat requirements for juvenile and adult cutthroat trout and juvenile chinook salmon given in Table 9 and combined them into a set of suitable habitat maps. These habitat requirements were taken from the Washington Department of Fish and Wildlife's (WDFW) Instream Flow Guidelines (2004).

Third, I used the bed shear stress model outputs and reclassified these datasets into areas that fell below and exceeded the critical shear stress for the median grain size measured at the Southern study site (1.93 cm). Fourth, I subtracted the current shear stress values from each of the restored shear stress datasets to create maps showing the change in shear stress from restoration. Based on the habitat and shear stress maps, I calculated the areas of the suitable habitat and potential erosion.

Table 9: Analysis of HEC-RAS outputs (WDFW 2004).

HEC-RAS Output	Reclassification	Reclassification values
Maximum Inundation Boundary	N/A	
Velocity (m/s)	Does not exceed velocity for Spring Chinook Salmon	(< 1.097 m/s)
	Does not exceed velocity for Cutthroat Trout	(< 1.219 m/s)
	Exceeds velocity for Spring Chinook Salmon	(> 1.097 m/s)
	Exceeds velocity for Cutthroat Trout	(> 1.219 m/s)
Depth (m)	Does not fall below minimum depth for Spring Chinook Salmon	(> 0.137 m)
	Does not fall below minimum depth for Cutthroat Trout	(> 0.198m)
	Falls below minimum depth for Spring Chinook Salmon	(< 0.137 m)
	Falls below minimum depth for Cutthroat Trout	(< 0.198m)
Bed Shear Stress (N/m^2)	Exceeds critical shear stress	(> 14.07 N/m^2)
	Does not exceed critical shear stress	(< 14.07 N/m^2)

Given my research question, I will test the following hypotheses:

Area of Inundation

1. If either an enlarged culvert or a levee breach is constructed, the area of inundation will increase for the 1-year flood and 2-year flood.

2. If either an enlarged culvert or a levee breach is constructed, the area of inundation will not increase for a 5-year flood.

Physical Salmonid Habitat

1. If either an enlarged culvert or a levee breach is constructed, there will be an increase in the area of usable salmonid habitat based on a minimum depth and maximum velocity requirement at Q1 and Q2.

2. If either an enlarged culvert or a levee breach is constructed, the area of usable salmonid habitat based on a minimum depth and maximum velocity requirement will not increase for a Q5 flow. (The levees are currently overtopped during a Q5 flow and modifications to the levees will not have an appreciable impact on the area of usable habitat based on minimum depth).

Bed Sediment Mobilization

1. If either an enlarged culvert or a levee breach is constructed, the shear stress in the Southern side channels will not be high enough to mobilize the median grain size at the 1-year, 2-year, or 5-year flood.

2. If either an enlarged culvert or a levee breach is constructed, the shear stress in the Monroe side channel will not be high enough to mobilize the median grain size at the 1-year or 2-year flood, but it will be high enough to mobilize material during the 5-year flood.

CHAPTER IV

RESULTS AND DISCUSSION

Overview

In this section of the thesis, I present the results of modeling in the form of summary tables, graphs, maps, and written descriptions. First, I present the results based on the analysis of the Monroe study site; second, I present the results from the Southern study site; third, I compare the two sites to each other and make suggestions for future restoration work at each site. Finally, I present a critique of the methods, describe the limitations of the study, and give suggestions for the direction of future work.

Monroe Study Site

Area of Inundation

At the Monroe study site, the 2D hydraulic models show that the area of inundation changes inconsistently across the types of historical channel connection and flood discharge (as summarized Table 10). As may be expected, the levee breach scenario resulted in the greatest area of inundation at each modeled discharge (Figure 22 and Figure 23). However, as both figures show, the enlarged culvert scenario did not dramatically change the 1-year flood area of inundation from the current conditions and all three scenarios showed very modest differences at the 5-year flood flow. For both the 2-year and 5-year events, some areas inundated under the enlarged culvert scenario are not inundated under the levee breach scenario, and vice versa.

Table 10: Summary of differences in flooding extent at Monroe study site.

	Current: Small culverts	Restoration Scenario 1: Enlarged culverts	Restoration Scenario 2: Levee breach
1-year flood	Very minor floodplain inundation	Very minor floodplain inundation	Floodplain inundation
2-year flood	Minor floodplain inundation	Full floodplain inundation	Full floodplain inundation
5-year flood	Full floodplain inundation	Full floodplain inundation	Full floodplain inundation

I had initially hypothesized that during the 1-year and 2-year floods, both the restoration scenarios would have a greater area of inundation than the current scenario due to an increase in the volume of water in the historical channels. However, during the 1-year flood, the area of inundation for the enlarged culvert scenario was less than 1% greater than the current scenario. The levee breach scenario showed a modest 36% increase in area of inundation, all of it situated within the grass floodplains north and south of Highway 99. Despite the increase in flow in the secondary channels under restoration scenarios, the main channel appears to accommodate most of the 1-year flood flow.

During the 2-year flood, I observe the greatest difference between the scenarios in inundation boundary. As shown in Figure 22 and Figure 23, the enlarged culvert scenario floods an area 60% greater than the current scenario and the levee breach scenario floods an area 78% greater than the current scenario. The primary explanation for this pattern is that both the restoration scenarios show extensive flooding south of Highway 99. As a greater amount of water flows into the south end of the historical channel, the water appears to be trapped on the floodplain south of the highway. On the west side of the river, there is almost no difference in inundation from current conditions.

I also hypothesized that at the 5-year flood, the area of inundation values for all three scenarios would converge as the main channel flow overtopped the levees and water flowed freely across the floodplain. Although the models did not show the any of the levees being fully overtopped by the 5-year flood, the historical channel overtopped its banks in all three scenarios and occupied much of the floodplain south of Highway 99 and varying amounts of floodplain in the park north of the highway. Under these conditions, the enlarged culvert showed a 2% decrease in flood inundation area and the levee breach caused a 10% increase in the flood inundation area when compared to the current scenario.

The modeling results also show some of the potential impacts on infrastructure in Monroe. During the 1-year flood, the current and enlarged culvert scenarios show no impact on the baseball diamond or private access road south of Highway 99, but the levee breach scenario begins to impact both of these points. During the 2-year flood, the current and enlarged culvert scenarios again show no interaction with the baseball diamond, but the extensive flooding south of the highway would limit access to the private road and put structures at risk under both an enlarged culvert and breach levee scenario. In all three scenarios, there appears to be flooding of the northernmost waste treatment pond, but the pond's embankments post-date the topography used in this study and thus the suggested flooding in this area is dubious. More information on this subject can be found in the discussion of the model's limitations.

Overall, these model results show that there are relatively small differences in the area of inundation at the 1-year and 5-year floods for the different scenarios. They also show that an increase in the size of the connection between the historical channel and the main channel had the greatest impact on flood inundation at intermediate floods for this site.

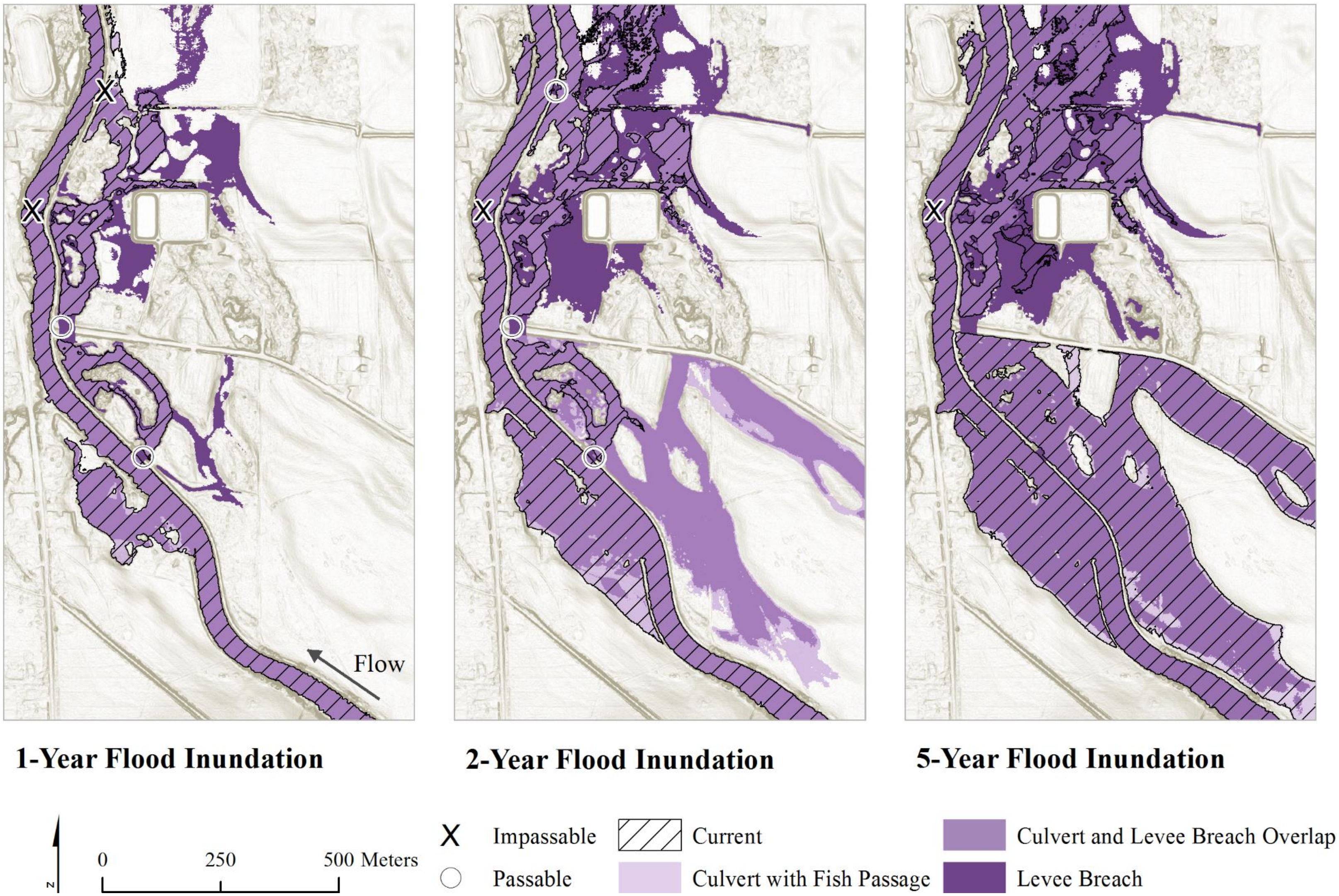


Figure 22: Map of difference in areas of inundation at Monroe study site for the 1-year, 2-year and 5-year flow events for current and two restoration scenarios.

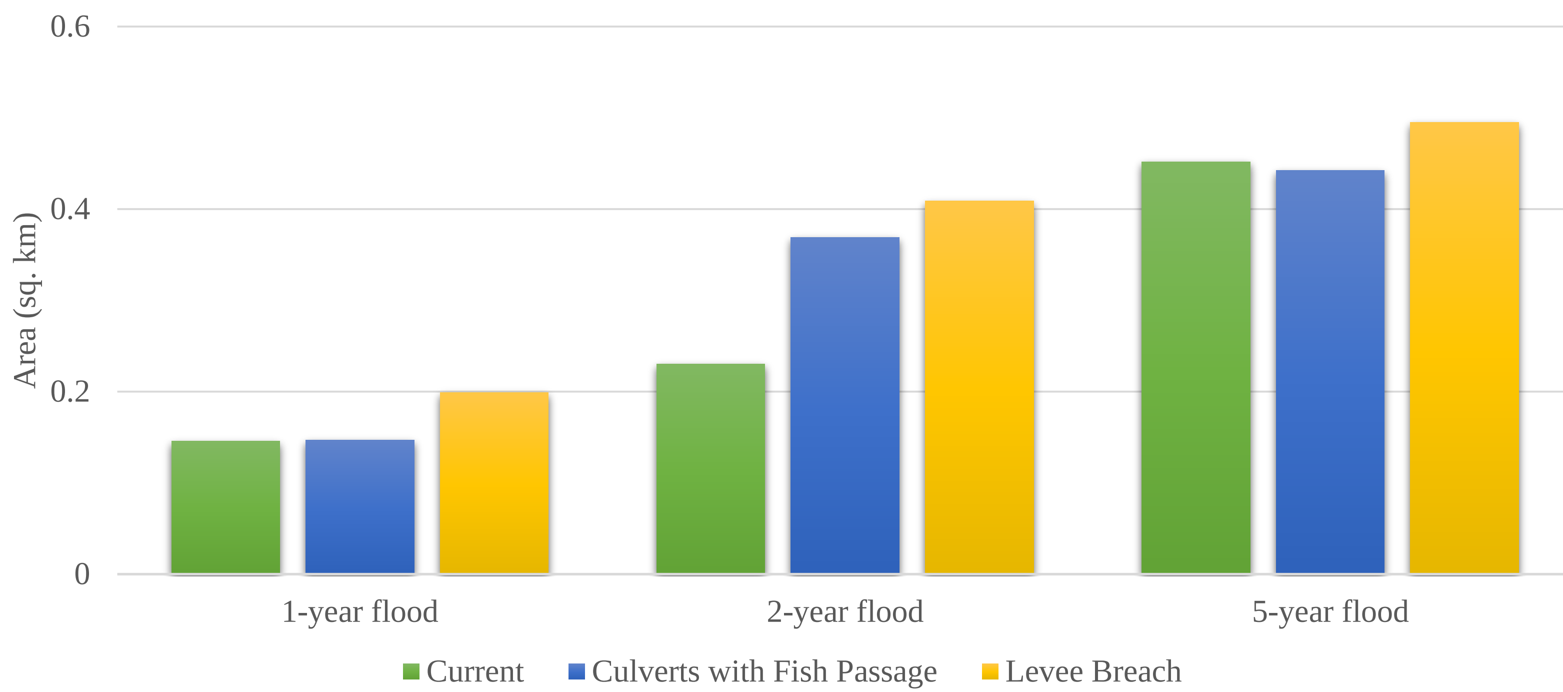


Figure 23: Areas of inundation at Monroe study site for the 1-year, 2-year and 5-year flow events for current and two restoration scenarios.

Suitable Fish Habitat

The historical channel provides a consistent source of suitable physical habitat for salmonids under all flood conditions and scenarios (as summarized in Table 11). While these salmonids do not currently have access to the historical channel below the drop structure due to a perched culvert, my model shows that if fish passage could be created, there would be a large increase in available habitat for salmonids (Figure 24). The models also show that usable habitat is quite limited in the main stem at higher discharge flows and that a larger area of inundation would produce a larger amount of available habitat.

Table 11: Summary of differences in available habitat at Monroe study site for main channel and side channels.

	Current: Small culverts	Restoration Scenario 1: Culverts with fish passage	Restoration Scenario 2: Levee breach
1-Year Flood	Main: Present	Main: Present	Main: Present
	Side: All habitat present but not accessible	Side: Present	Side: Present
2-Year Flood	Main: Limited by velocity	Main: Limited by velocity	Main: Mixed, partially limited by velocity
	Side: Present but not accessible	Side: Present	Side: Present
5-Year Flood	Main: Very limited by velocity	Main: Very limited by velocity	Main: Limited by velocity
	Side: Present*	Side: Present	Side: Present*

*Possibly limited access

Across all modeled flood levels and scenarios, the historical channel and floodplain provide the greatest quantity of potential habitat. In many of these areas, the water is both slow enough and deep enough to accommodate both juvenile and adult spring Chinook salmon and western coastal cutthroat trout. However, under the current scenario, salmonids have very limited access to these areas, and during the 2-year flood

78% of the potential habitat for both species is located in difficult to access areas off the main channel (Figure 24). As the area of inundation increases due to restoration, the area of suitable and accessible habitat also increases. For example, during the 2-year flood, the area of suitable habitat increases by 70% with enlarged culverts and by 92% with a levee breach when compared to the current conditions. The most common limiting factor in the secondary channel and floodplain habitat is that the water depth is too shallow. However, it is also important to observe that during the 2-year and 5-year flood, the levee breach scenario shows that at the northern, downstream channel outlet, an increase in velocity reduces the fish passage into the off-channel habitat.

While there appears to be abundant usable habitat at the 1-year flood in the main channel in all scenarios, main channel habitat is very limited during the 2-year and 5-year floods for the current and enlarged culvert scenarios (Figure 25, Figure 26, Figure 27). The vast majority of the main channel contains flow that has too high a velocity to provide suitable habitat for salmonids (Figure 28, Figure 29, Figure 30, Figure 31). In addition, the Monroe drop structure provides a complete barrier to fish passage under all modeled scenarios. However, by breaching the levee and reducing the volume of the water in the main channel, the models indicate that 2-year and 5-year flood velocities in the main channel between the upstream and downstream levee breaches will drop enough that the channel will become usable again by both species. Upstream and downstream of the levee breach reach, the main channel habitat remains too fast to accommodate spring Chinook salmon and cutthroat trout. If a levee breach is feasible in other locations along the Long Tom River, it may be the best option for reducing the velocity in the main channel and increasing both main stem and off channel habitat.

Overall, availability of suitable habitat changes with area of inundation and thus the scenarios that produced the largest areas of inundation, i.e. the restoration scenarios, showed the greatest promise for an increase in habitat. However, access to off-channel habitat is critical and the reconstruction of the perched culvert at the north end of the Monroe study site to allow for fish passage would lead to a large increase in fish passage. Similar to my area of inundation hypotheses, I had originally suggested that during the 1-year and 2-year flood, the area of habitat would be greater under restoration conditions. While the amount of accessible habitat increased greatly with restoration, the area of total potential habitat did not increase greatly at the 1-year discharge, but proportional to the increased area of inundation, it did increase with the 2-year flood. At the 5-year flood, my hypothesis that the areas of available habitat would be similar across all three scenarios was correct, although access to the habitat proved again to be a potential limitation in the current and levee breach scenarios.

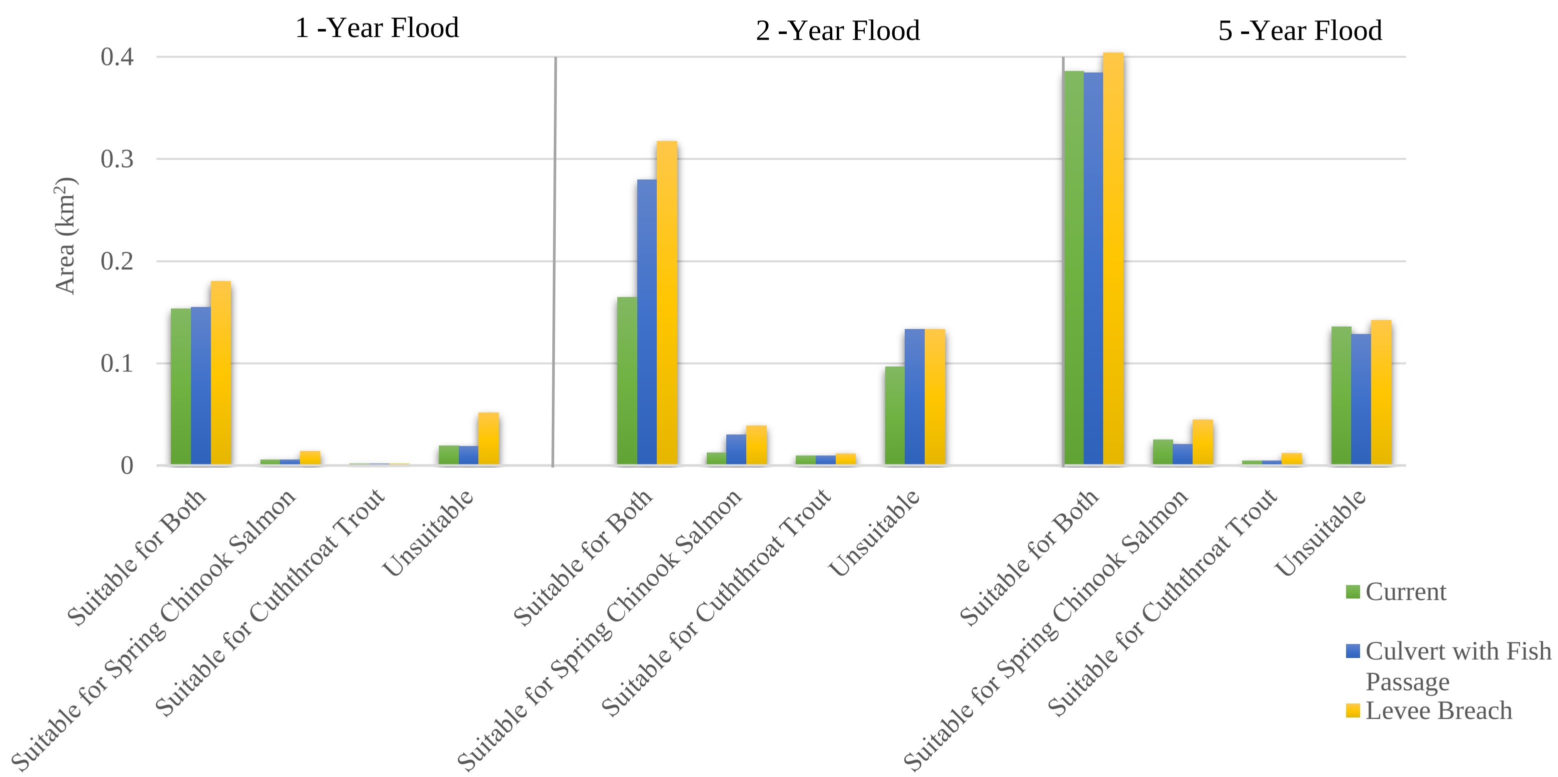


Figure 24: Area of suitable habitat at Monroe study site for the 1-year, 2-year and 5-year flood events for current and two restoration scenarios.

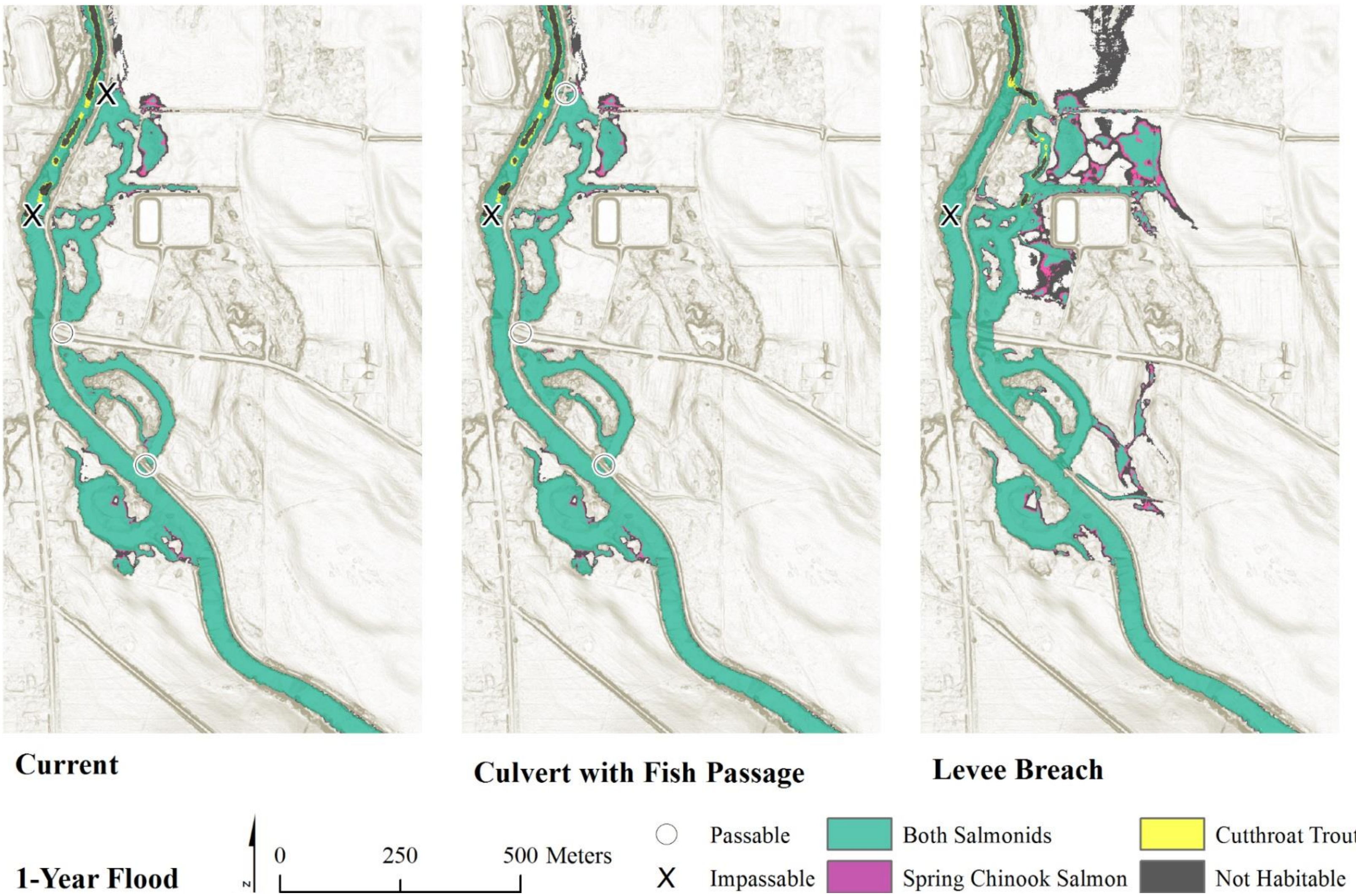


Figure 25: Maps of physical habitat for two fish species at Monroe study site for the 1-year flood event for current and two restoration scenarios.

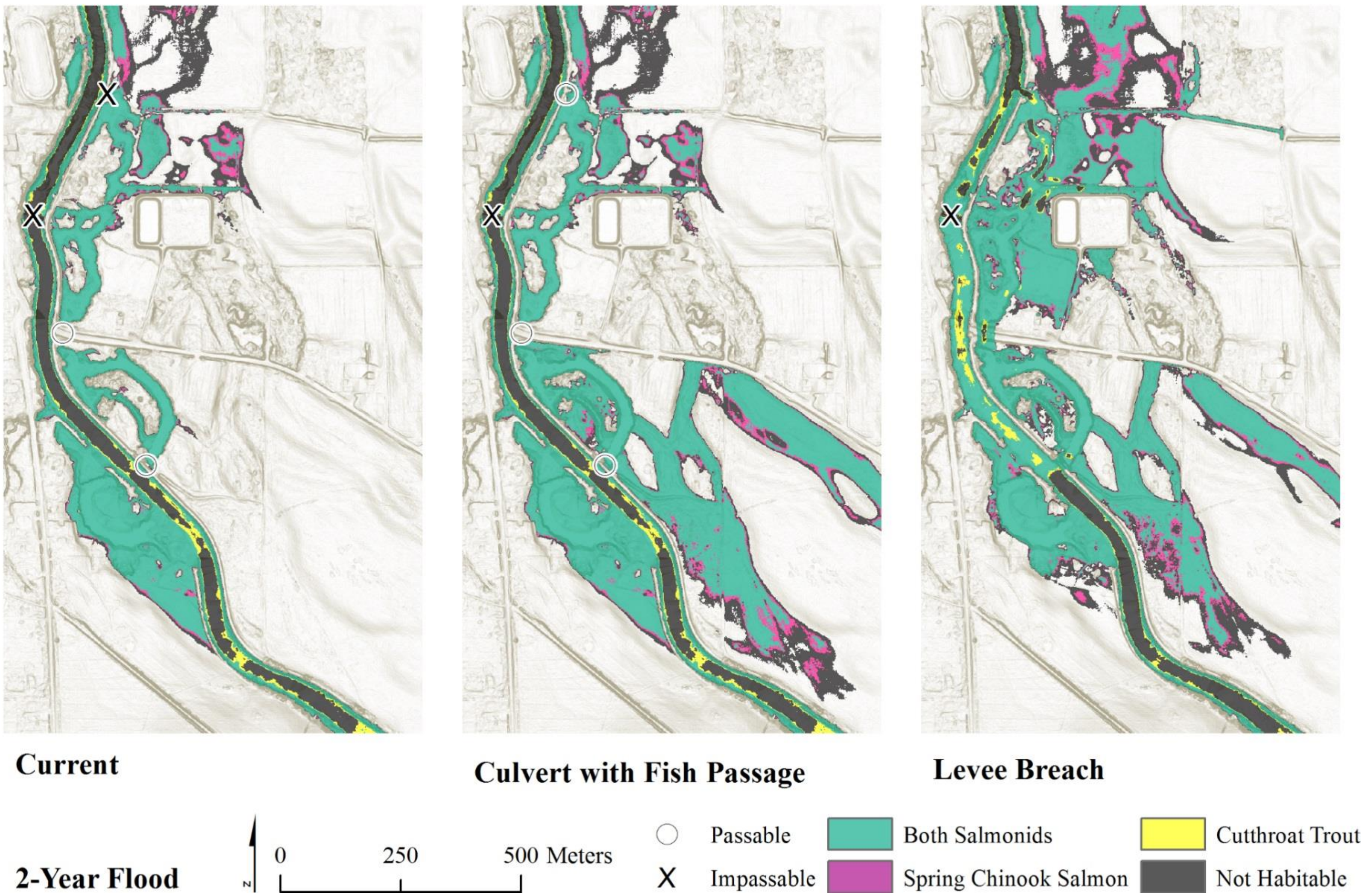


Figure 26: Maps of physical habitat for two fish species at Monroe study site for the 2-year flood event for current and two restoration scenarios.

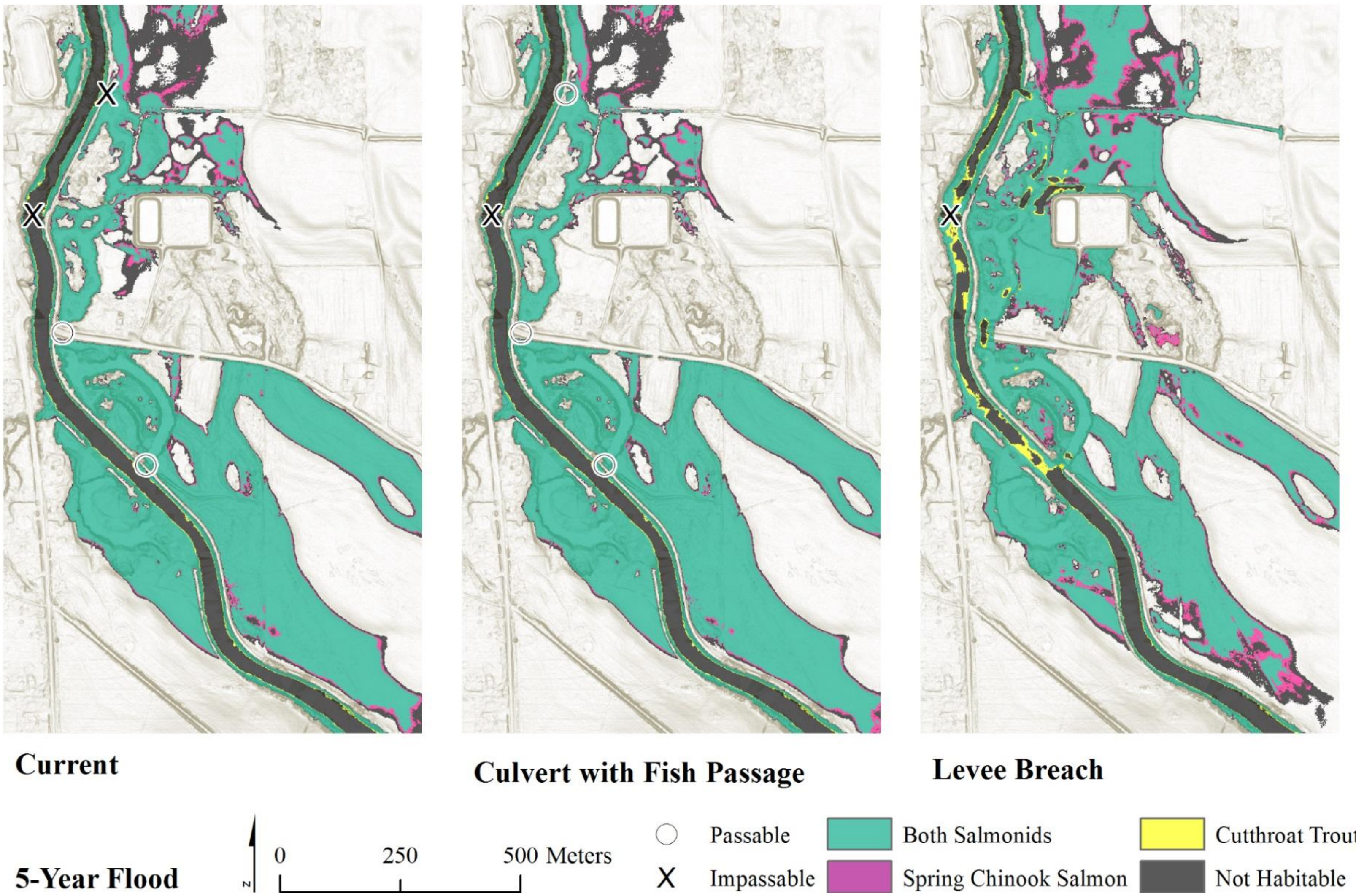


Figure 27: Maps of physical habitat for two fish species at Monroe study site for the 5-year flood event for current and two restoration scenarios.

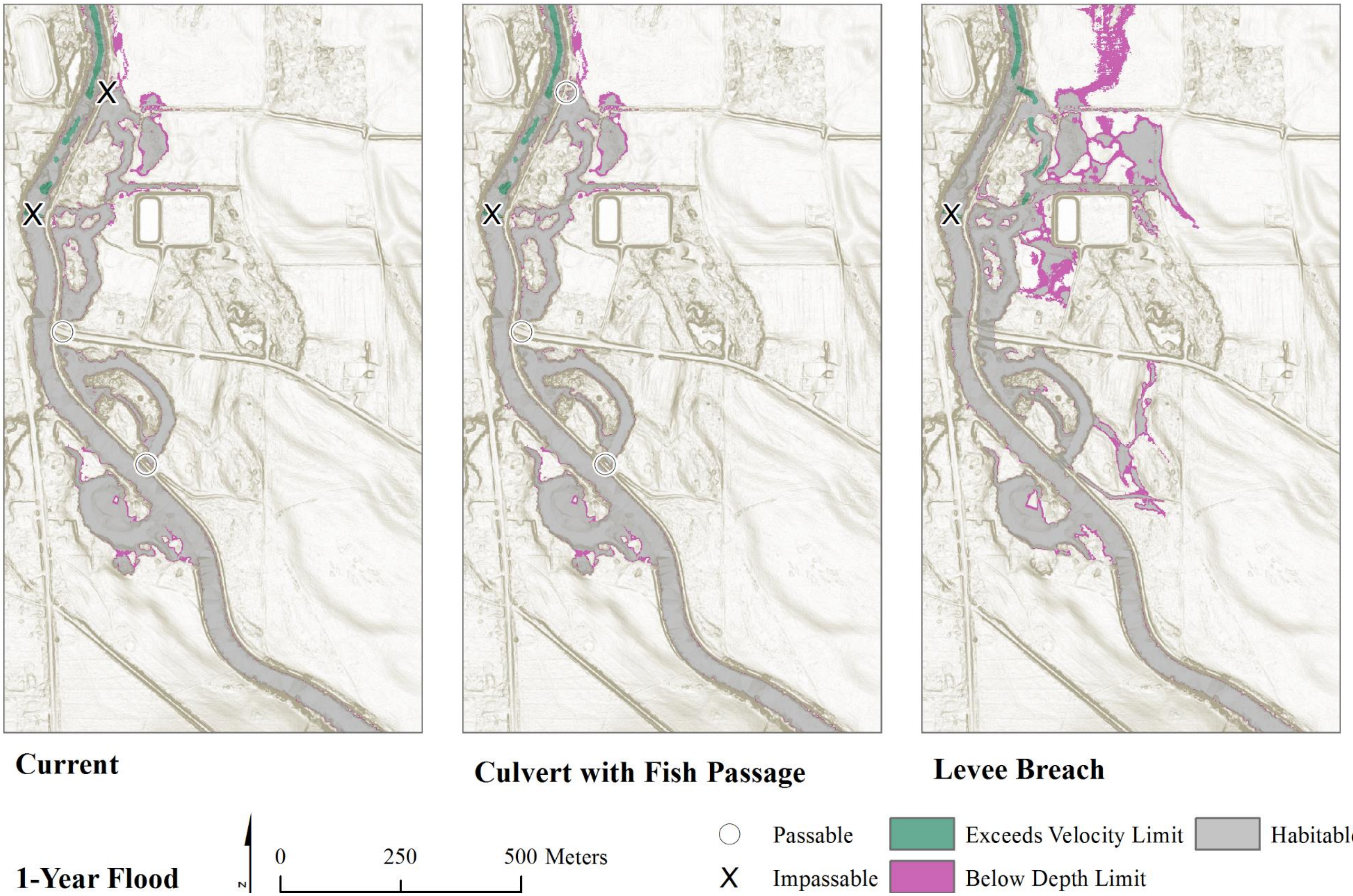


Figure 28: Maps of unsuitable habitat at Monroe study site for the 1-year flood event for current and two restoration scenarios.

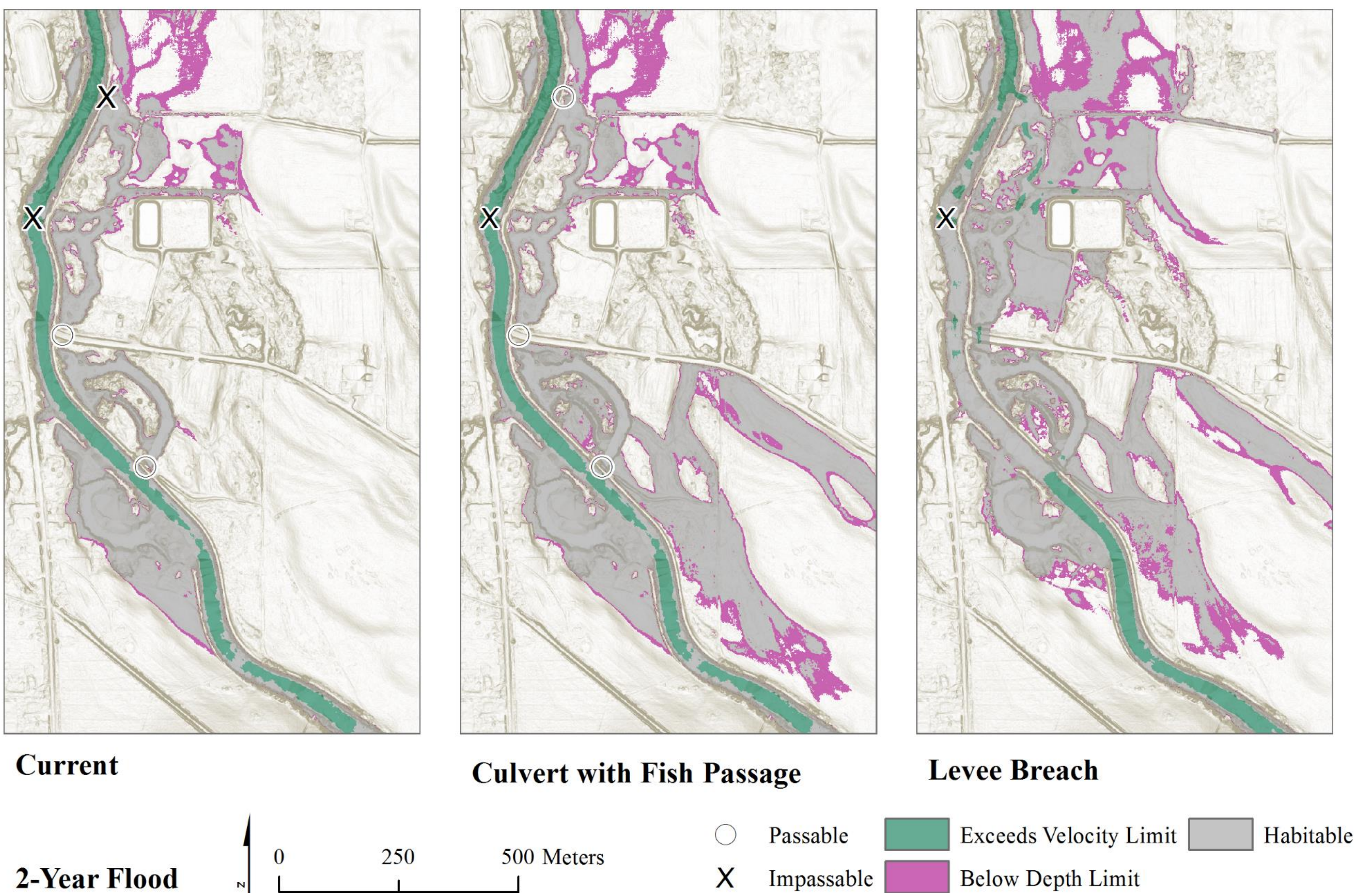


Figure 29: Maps of unsuitable habitat at Monroe study site for the 2-year flood event for current and two restoration scenarios.

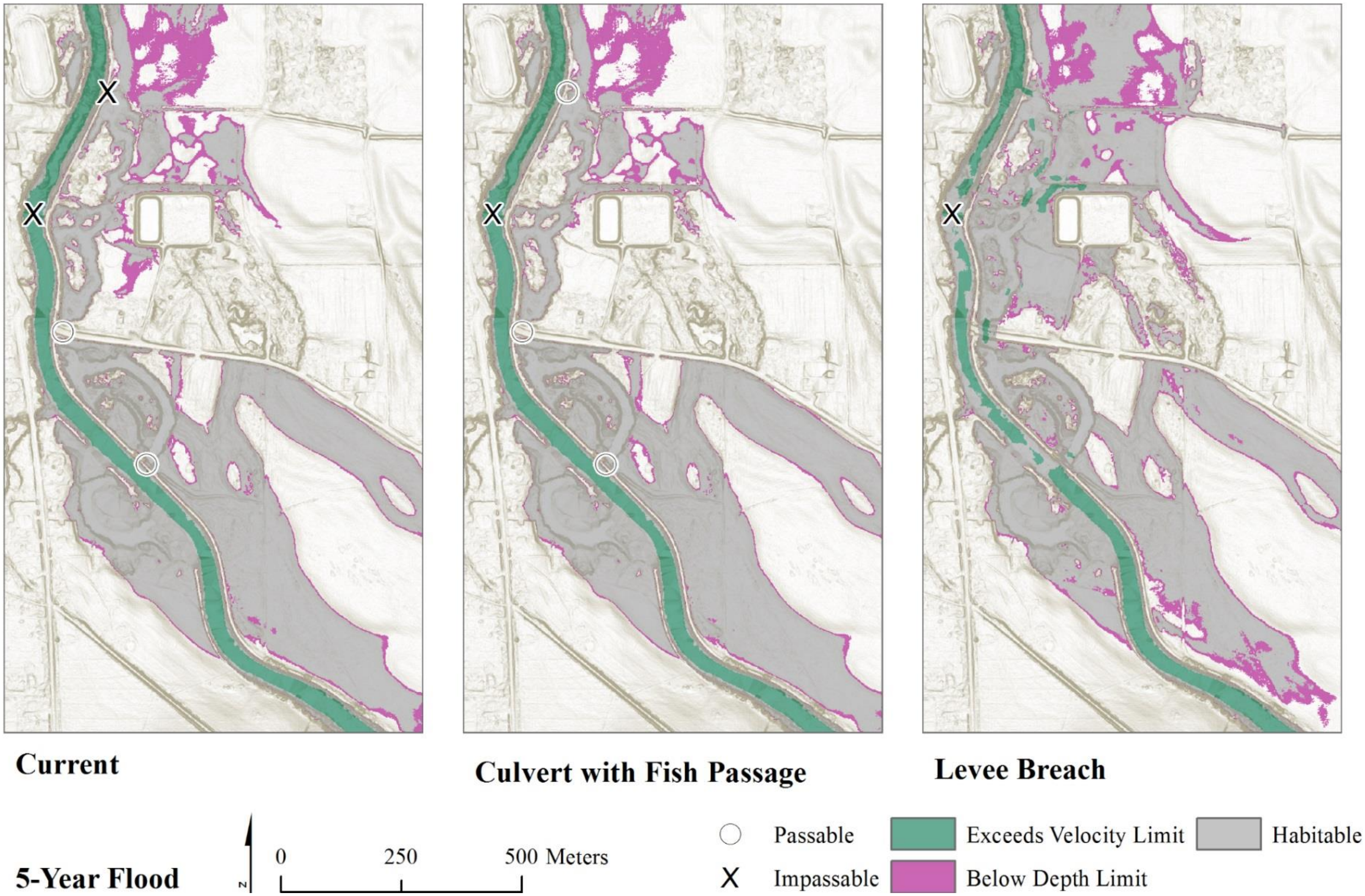


Figure 30: Maps of unsuitable habitat at Monroe study site for the 5-year flood event for current and two restoration scenarios.

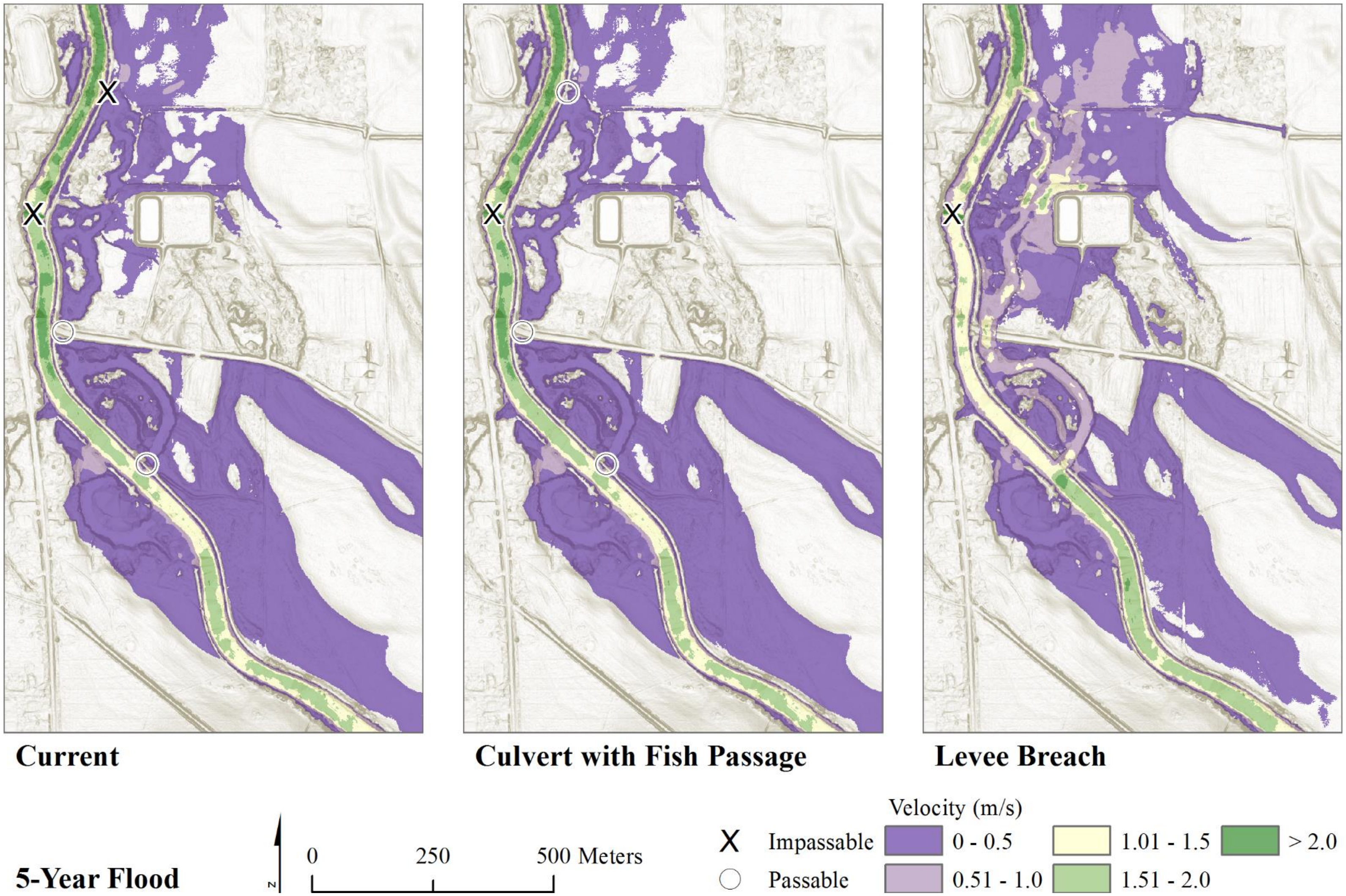


Figure 31: Maps of difference in velocity at Monroe study site for the 5-year flood event for current and two restoration scenarios.

Shear Stress and Potential Bed Mobilization

The modeling results do not specifically predict bed erosion. Rather, I determined the median grain size at one location at each site, and used a simple critical shear stress approach to indicate whether the median size would likely be mobilized. Analysis of sediment transport or a sediment budget was outside the scope of this study. This approach is intended to identify areas where bed erosion might potentially occur. My shear stress analysis suggests that the potential for erosion is greatest in the main channel under current and enlarged culvert conditions and in scattered areas along the historical channel under the levee breach scenario (as summarized in Table 12). Prior to this study, I incorrectly hypothesized that both the enlarged culvert and the levee breach would not

Table 12: Summary of potential bed mobilization and shear stress at Monroe study site for main and side channels.

	Current: Small culverts	Restoration Scenario 1: Culvert with fish passage	Restoration Scenario 2: Levee breach
1-Year Flow	Main: Immobile upstream of DS, some mobility downstream of DS	Main: Immobile upstream of DS, some mobility downstream of DS	Main: Immobile upstream of DS, some mobility downstream of DS
	Side: Immobile	Side: Immobile	Side: Some mobility in narrow sections
2-Year Flow	Main: Mobile	Main: Mobile	Main: Mixed, partially mobile
	Side: Immobile	Side: Immobile	Side: Mixed, some mobility in historical channel
5-Year Flow	Main: Mobile	Main: Mobile	Main: Mostly mobile
	Side: Immobile	Side: Immobile	Side: Mixed, some mobility in historical channel

mobilize historical channel bed sediments at the 1-year and 2-year flood flows, but that they would both mobilize sediment in the side channels during the 5-year flood. The modeling results show that the two restoration scenarios are quite different due to important differences in velocity.

During the 1-year flood, the current conditions and enlarged culvert scenarios show that the areas of highest of shear stress are downstream from the drop structure and that either deposition or no mobilization is likely in the historical channel. Alternatively, the levee breach scenario shows very little chance of erosion in the main channel and a greater potential for erosion in the historical channel along the most constricted channel widths (Figure 32).

The 2-year and 5-year flood models indicate that the shear stresses in the main channel of both the current and enlarged culvert scenarios are quite similar and that potential mobilization is likely throughout both modeled reaches. Again, deposition or no mobilization was predicted in the historical channel and along the floodplain for these scenarios. Unlike the culvert scenarios, the levee breach scenario shows the potential for bed mobilization across sections of the main and historical channel. Compared to the current and enlarged culvert scenarios, the shear stresses are much lower in the main channel and much higher in the historical channel (Figure 33 and 34).

Overall, there is very little change in shear stress between the current and enlarged culvert scenarios and a widespread change in shear stress between the current and levee breach scenarios as shown in Figures 35, 36, and 37. The levee breach consistently results in a reduction in shear stress in the main channel and an increase in the shear stress in the historical channel with minor increases also present on the floodplain. This pattern suggests that if the levees were breached, and if there were available gravels in the historical channel, there may be initial changes in bed or bank geometry unless grade control structures were installed.

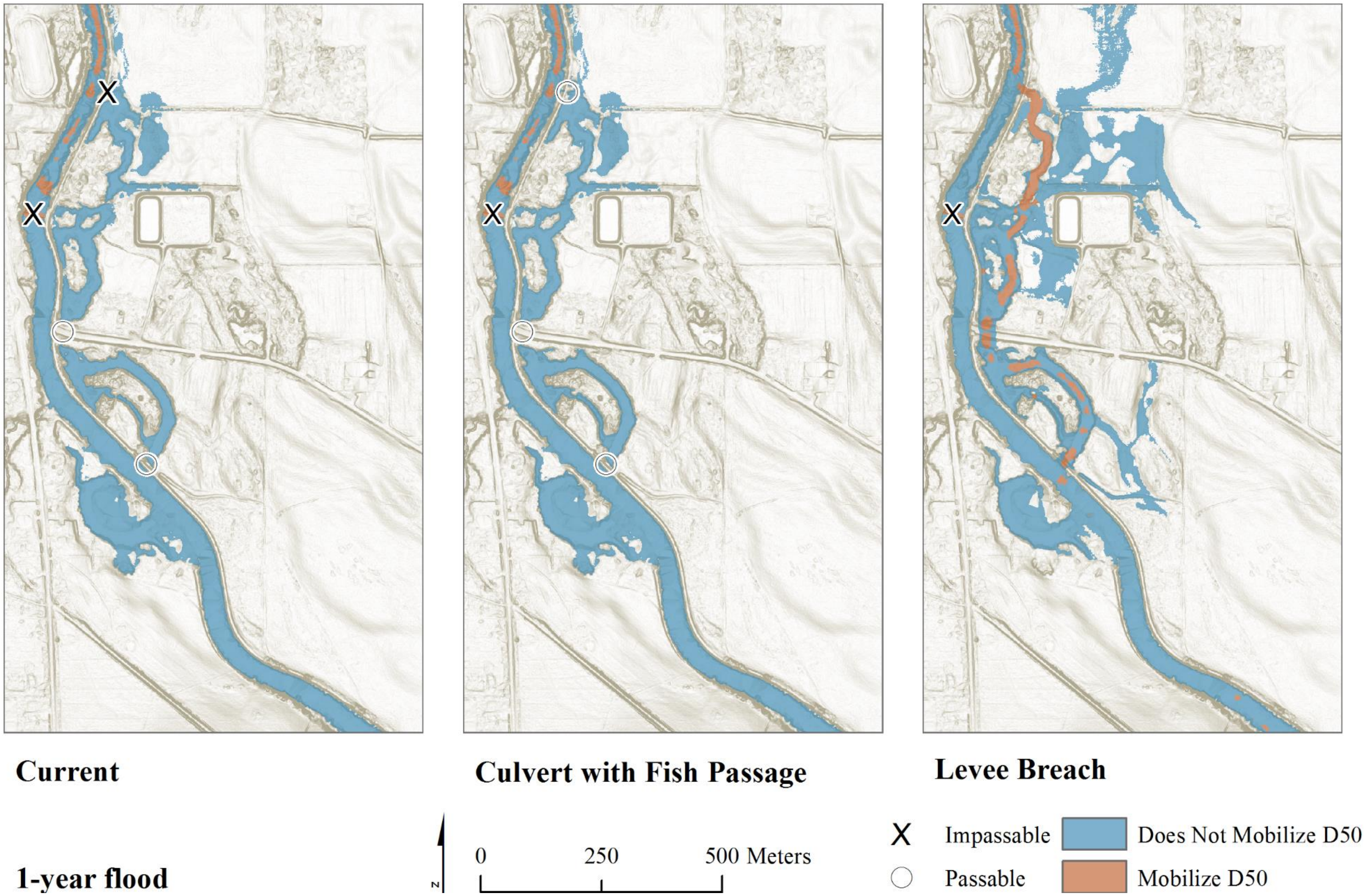


Figure 32: Maps of potential gravel mobility at Monroe study site for the 1-year flood event for current and two restoration scenarios.

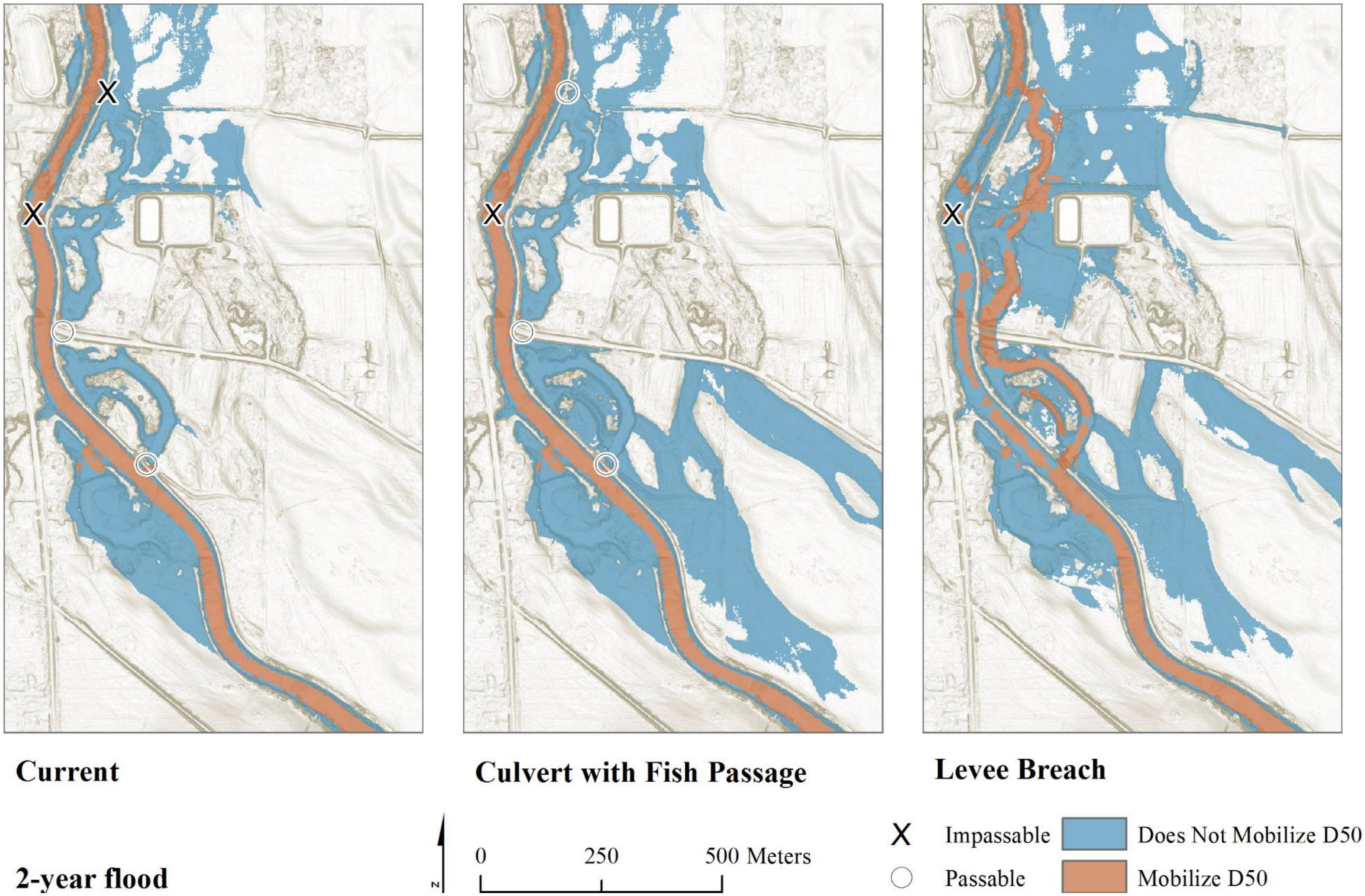


Figure 33: Maps of potential gravel mobility at Monroe study site for the 2-year flood event for current and two restoration scenarios.

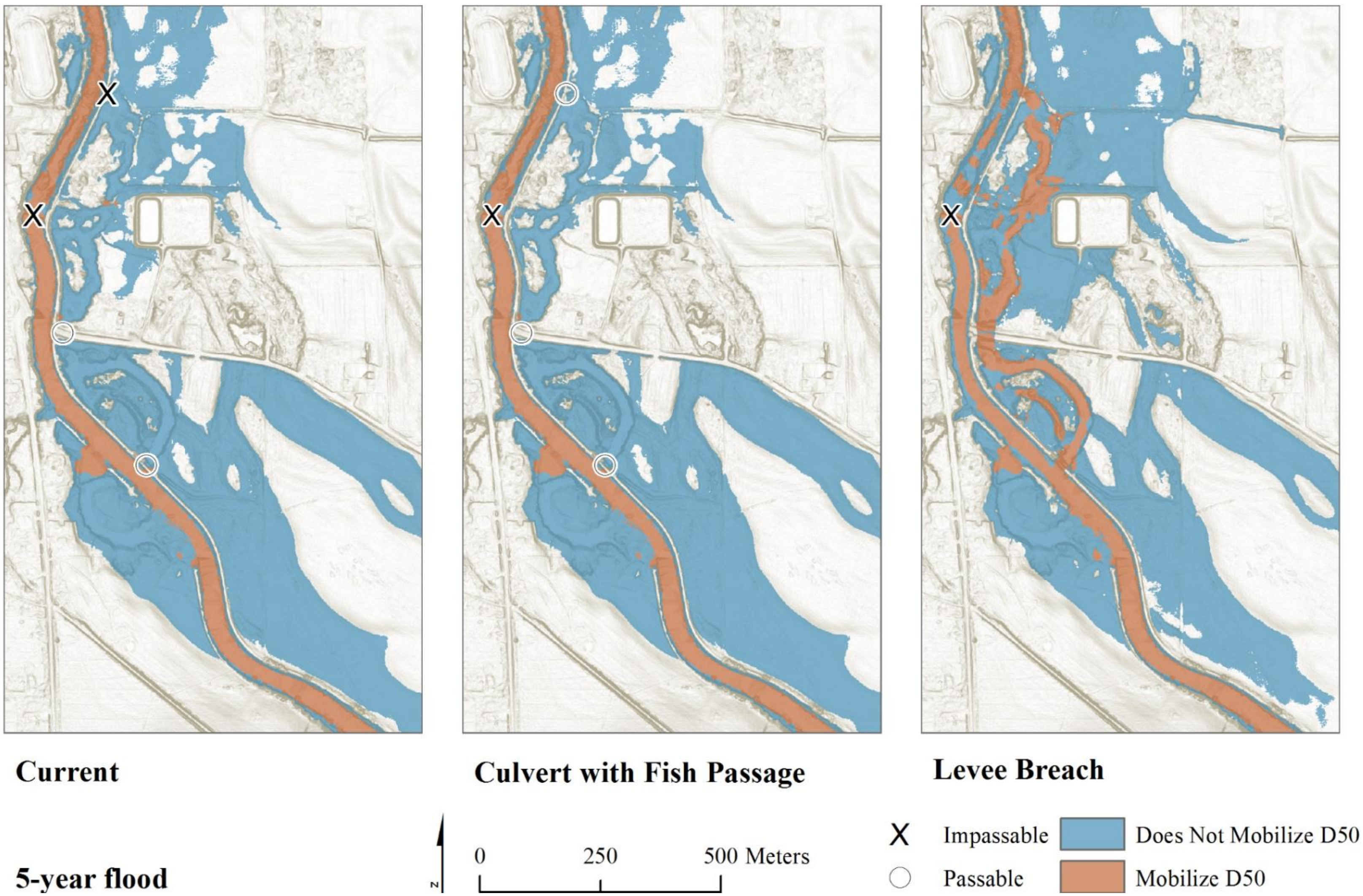
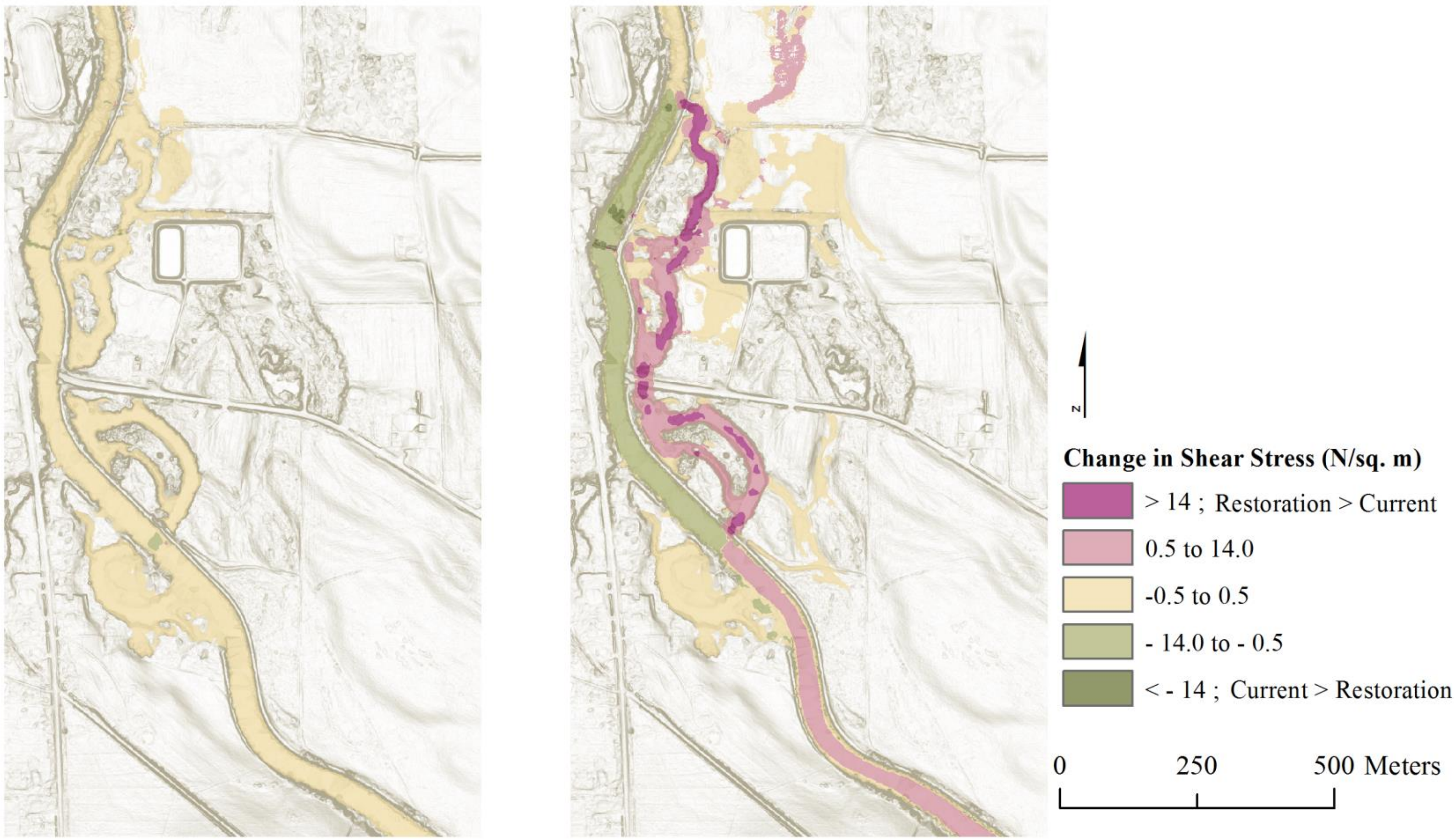


Figure 34: Maps of potential gravel mobility at Monroe study site for the 5-year flood event for current and two restoration scenarios.



1-Year Flood

Current -- Culvert with Fish Passage **Current -- Levee Breach**

Figure 35: Maps of difference in shear stress between current and restoration scenarios at the Monroe study site for the 1-year flood.

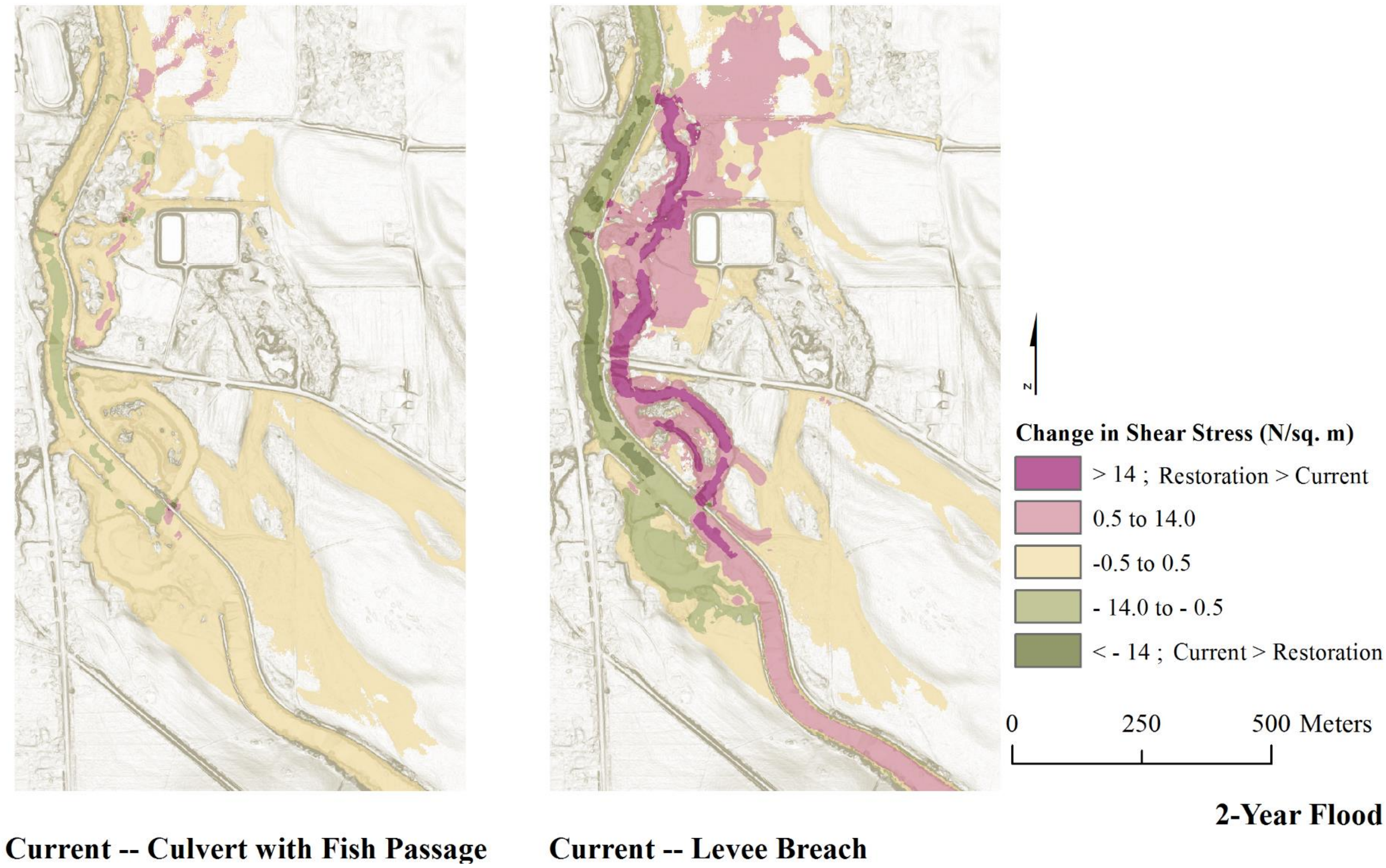


Figure 36: Maps of difference in shear stress between current and restoration scenarios at the Monroe study site for the 2-year flood.

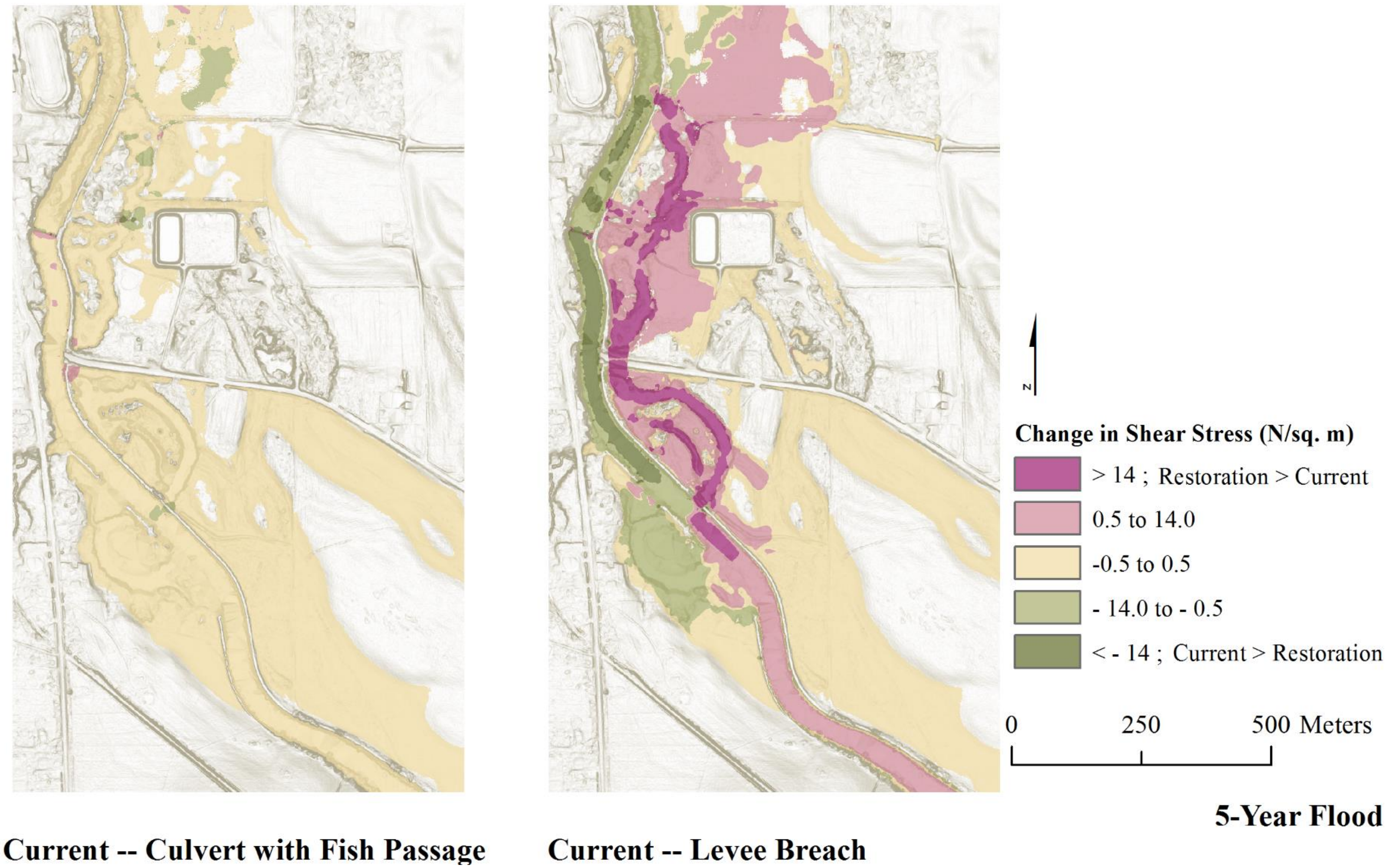


Figure 37: Maps of difference in shear stress between current and restoration scenarios at the Monroe study site for the 5-year flood.

Southern study site

Area of Inundation

The Southern study site shows a pattern of increasing inundation that is distinct from the Monroe study site (as summarized in Table 13). Unlike the Monroe study site, the Southern study site does not have structures like Highway 99 that prevent the water from moving downstream across the floodplain in accordance with the landscape topography. The models show that when the historical channel is reconnected and water inundates both the main channel and historical channel, the water in the historical meander overtops its banks. This first activates several north-south oriented swales. Progressively greater areas then become inundated – first, the other historical meander bends, then the open floodplain, and finally the historical terraces (Figure 38).

Table 13: Summary of differences in flooding extent at Southern study site

	Current: No culverts	Restoration Scenario 1: Culvert with fish passage	Restoration Scenario 2: Levee breach
1-Year Flood	Limited to main channel	Limited to main channel and historical channel	Limited to main channel and historical channel
2-Year Flood	Limited to main channel	Inundates one swale	Inundates swales and part of floodplain
5-Year Flood	Limited to main channel	Inundates swales and part of floodplain	Extensive floodplain inundation

At this site, current conditions do not allow consistent flow into the secondary historical channel and thus there is very little change between the 1-year, 2-year and 5-year flood inundation boundary (Figure 39). The model does show a small, slow seepage of water in the secondary channel during the 5-year flood, but given the quantity of water, this is likely a reflection of the model simulating a nearly overtopping levee.

My models do not support my first hypothesis that during the 1-year and 2-year flood flows the area of inundation for the restoration scenarios will be greater than the area of inundation for the current scenario. During a 1-year flood, there is very little difference in the area of inundation between the current and restored scenarios, because the 1-year flood discharge is not great enough to overtop the banks of the meander bend. The most significant difference in area of inundation is the new inundation of the historical meander bend. However, in the 2-year flood, the model shows that the area of inundation is significantly changed based on the amount of water flowing into the secondary channel. By connecting the historical channel to the main channel with culverts, the largest swale is inundated, resulting in a 70% increase in area of inundation. The levee breach scenario causes an inundation of several swales, historical meanders, and part of the floodplain which results in an inundated area 90% greater than under current conditions.

The models also do not support my second hypothesis that, by the 5-year flood, the water will overtop the levees and the area of inundation will be nearly equal for all scenarios. In fact, the models show that the greatest difference in areas of inundation occur at this flood level. While the culverts limit the amount of water in the historical channel, they still cause a 144% increase above current conditions in area of inundation. The levee breaches cause a full inundation of the floodplain and an increase in area of inundation by 313%.

In the 2-year and 5-year flood scenarios, the levee breach allows more water to flow into the secondary channel and causes inundation of the swales and floodplain at a lower discharge. As discussed in the Critique of Study section, this set of models did not include flooding due to rain, nor did it include flooding from other adjacent bodies of water or upstream sources of flooding. Under current conditions, the floodplain appears to be inundated during the 5-year flood (Kaul, personal communication, 2016) but the models show that those flood waters are not from overtopping levees within the study site. They are likely due to direct precipitation.

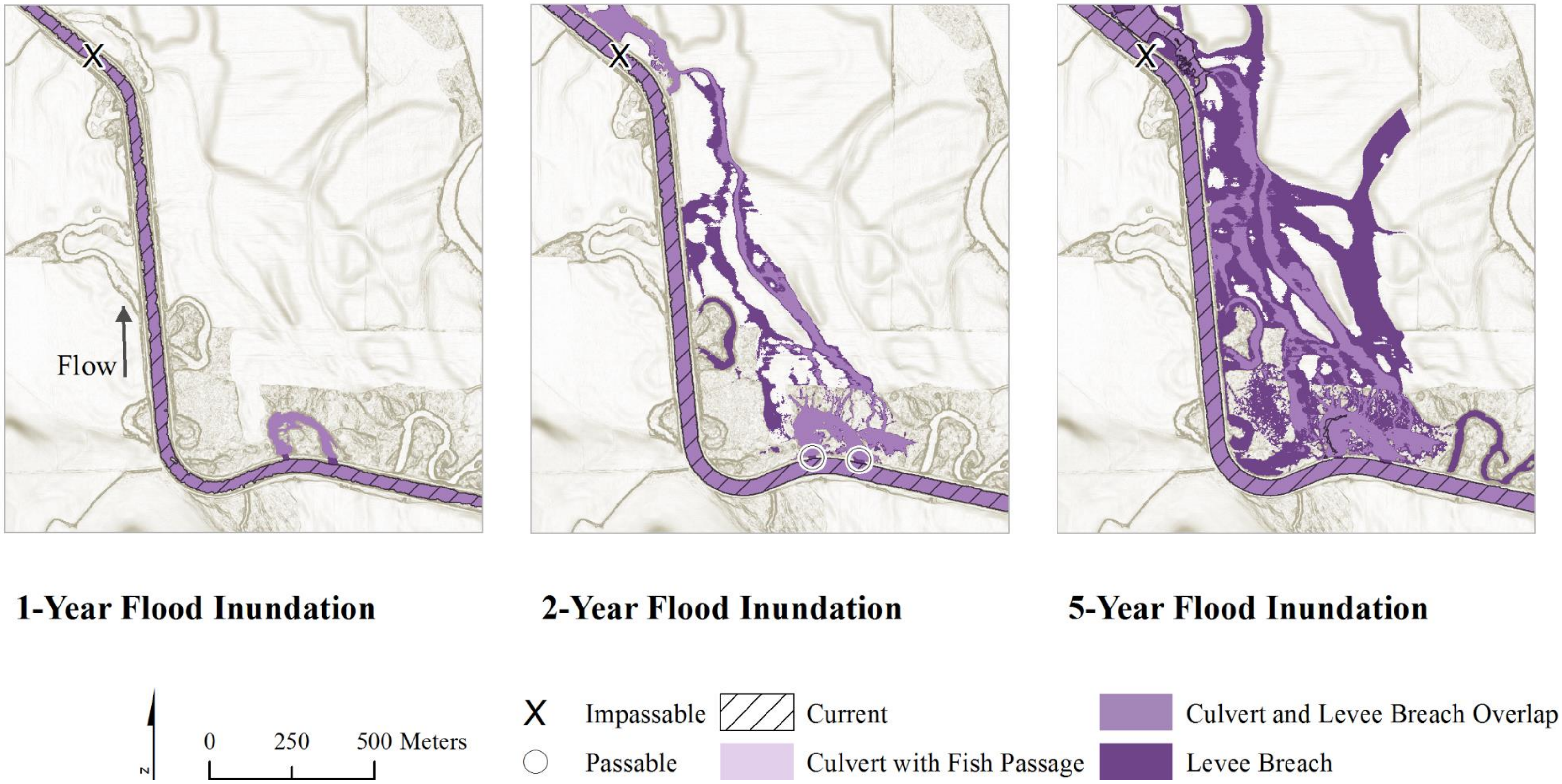


Figure 38: Map of areas of inundation at Southern study site for the 1-year, 2-year and 5-year flow events for current conditions and two restoration scenarios.

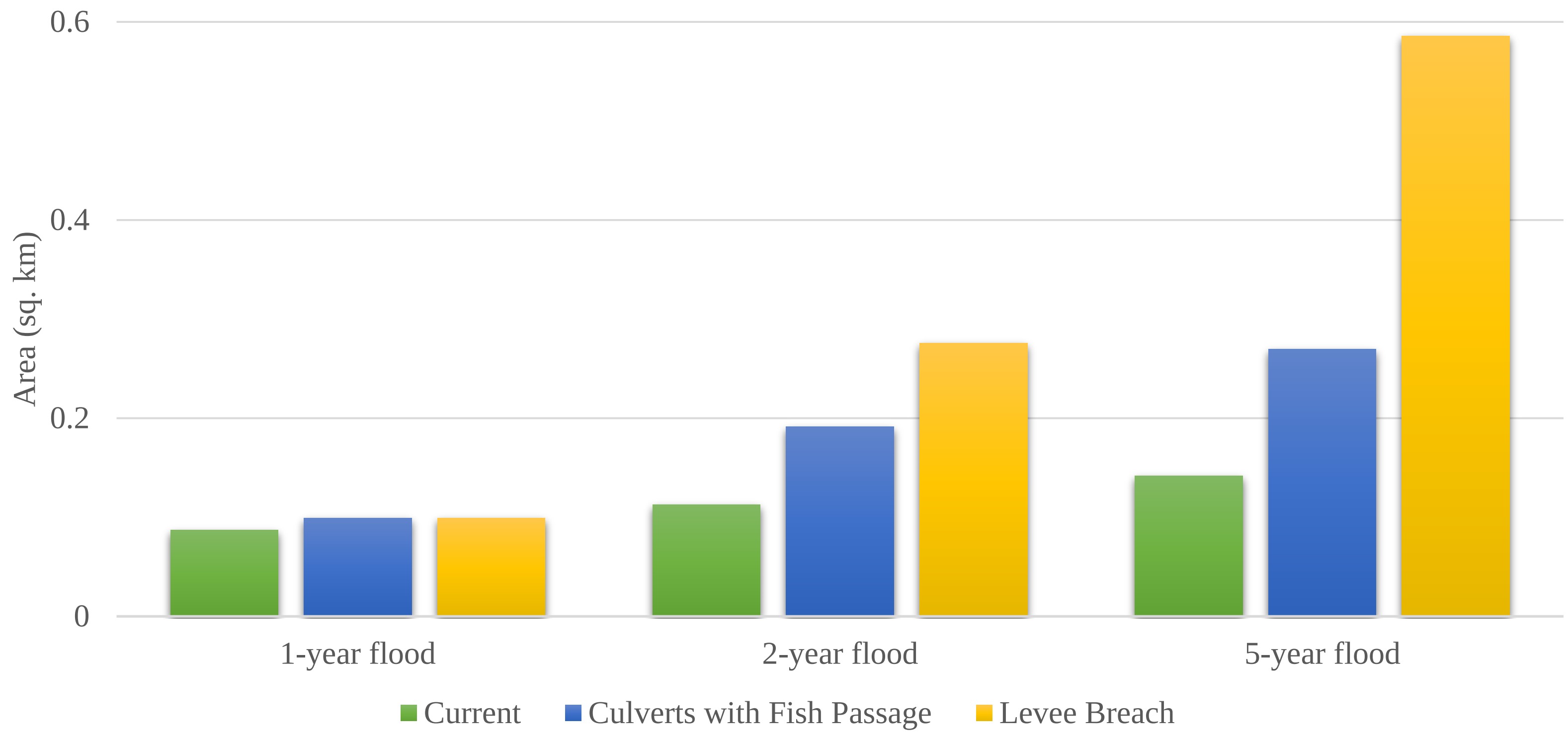


Figure 39: Areas of inundation at Southern study site for the 1-year, 2-year and 5-year flow events for current conditions and two restoration scenarios.

Suitable Habitat

Similar to the Monroe study site, the Southern study site shows limited habitat in the main channel and a greater abundance of off-channel habitat during higher flood flows (as summarized in Table 14). This study shows that if salmonids are provided with fish passage into the historical meander bend, there will be a large increase in the quantity of available habitat. While the investigation at this site focused on new available habitat in the side channel and floodplain upstream of the drop structure, the results of the modeling also demonstrate another opportunity for providing fish passage around the drop structure in the main channel by circumventing the drop structure along a secondary channel.

Table 14: Summary of differences in available habitat at Southern study site for main and side channels.

	Current: No culverts	Restoration Scenario 1: Culvert with fish passage	Restoration Scenario 2: Levee breach
1-Year Flood	Main: Present	Main: Present	Main: Present
	Side: None	Side: Present	Side: Present
2-Year Flood	Main: Limited by velocity	Main: Limited by velocity	Main: Limited by velocity
	Side: N/A	Side: Habitat in historical channel, limited habitat in swale by depth	Side: Habitat in historical channel, some habitat in swale that is limited by depth
5-Year Flood	Main: Limited by velocity	Main: Limited by velocity	Main: Limited by velocity
	Side: N/A	Side: Habitat in historical channel, some habitat in swale that is limited by depth	Side: Habitat in historical channel and throughout floodplain

Although I had hypothesized that there would be an increase in available habitat during the 1-year flood event, there was very little change in area between the current and the restored scenarios because of the limited change in inundation. All three models showed that at small, annual floods, the main channel provided a great deal of usable depths and velocities. Across all of these models, there were small pockets of water that moved too quickly and reduced the available habitat in the main stem (Figure 40, Figure 43).

I correctly hypothesized that there would be an increase in available habitat during the 2-year flood if the secondary channel was connected to the main stem by a pair of culverts or breached levees. Each of the modeled scenarios showed a dramatic decrease in the amount of available habitat in the main channel during a 2-year flood (Figure 41). This amount of discharge caused a universal increase in main channel velocities to speeds exceeding the tolerable limit for the target salmonids. The culvert and the levee breach models both show that the historical channels themselves provided ideal habitat and that as they overtopped their banks, they increased the area of habitat by 104% and 177% respectively. In both scenarios, water flowed north along a swale on the floodplain and eventually reconnected with flow adjacent to the drop structure. Based on the culvert scenario, the flow in the largest swale was not consistently deep enough to provide fish passage, but the levee breach scenario showed a continuous path of habitable water stretching across the floodplain (Figure 44). If the primary swale was connected to the main channel below the drop structure, the levee breach scenario could provide fish passage around the drop structure (Figure 41).

My final hypothesis incorrectly suggested that the amount of habitat would be the same across all scenarios at the 5-year flood. Both the area of inundation and the amount of habitat available for each scenario are quite different. All three scenarios show that the main channel has little available habitat due to intolerable flow velocities. In addition, the scenario with culverts shows an increase in available habitat of 177% above the current level (Figure 42). Much of that habitat is located in the meander bend and intermittent sections of the swales. The levee breach scenario shows that much of the swales, adjacent, disconnected side channels, and floodplain could increase the amount of habitat by 477% from the current area. The unintended consequence of this may be that fish which are able to move across the floodplain may become trapped in several of the older disconnected historical meander bends along the right bank (Figure 45). As a result, I would recommend the USACE consider breaching multiple levees in the area if possible. In addition, if the primary swale were connected to the main channel below the drop structure, either the levee breach scenario or the enlarged culvert scenario could provide fish passage around the drop structure.

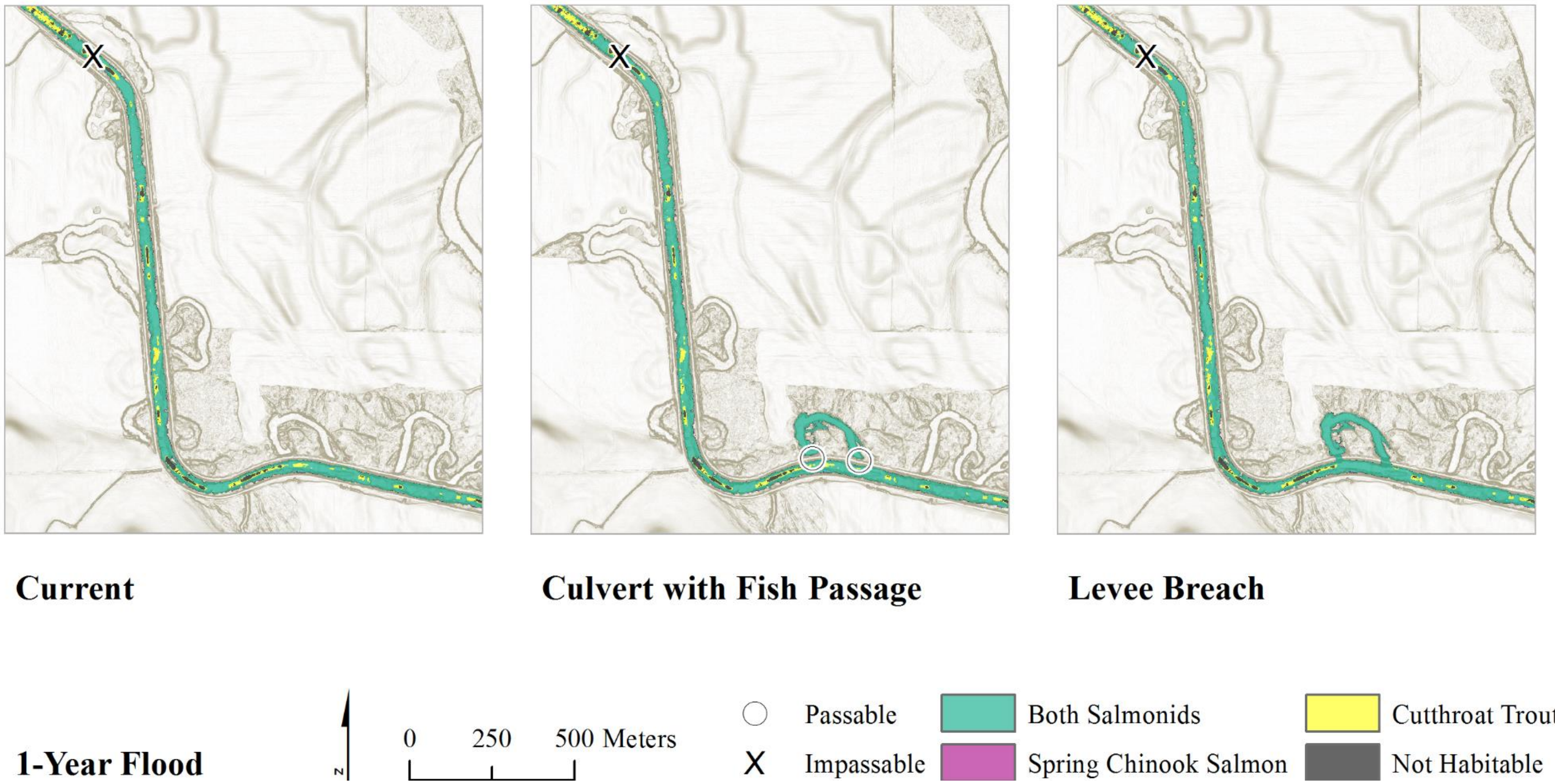


Figure 40: Maps of physical habitat for two fish species at Southern study site for the 1-year flood event for current conditions and two restoration scenarios.

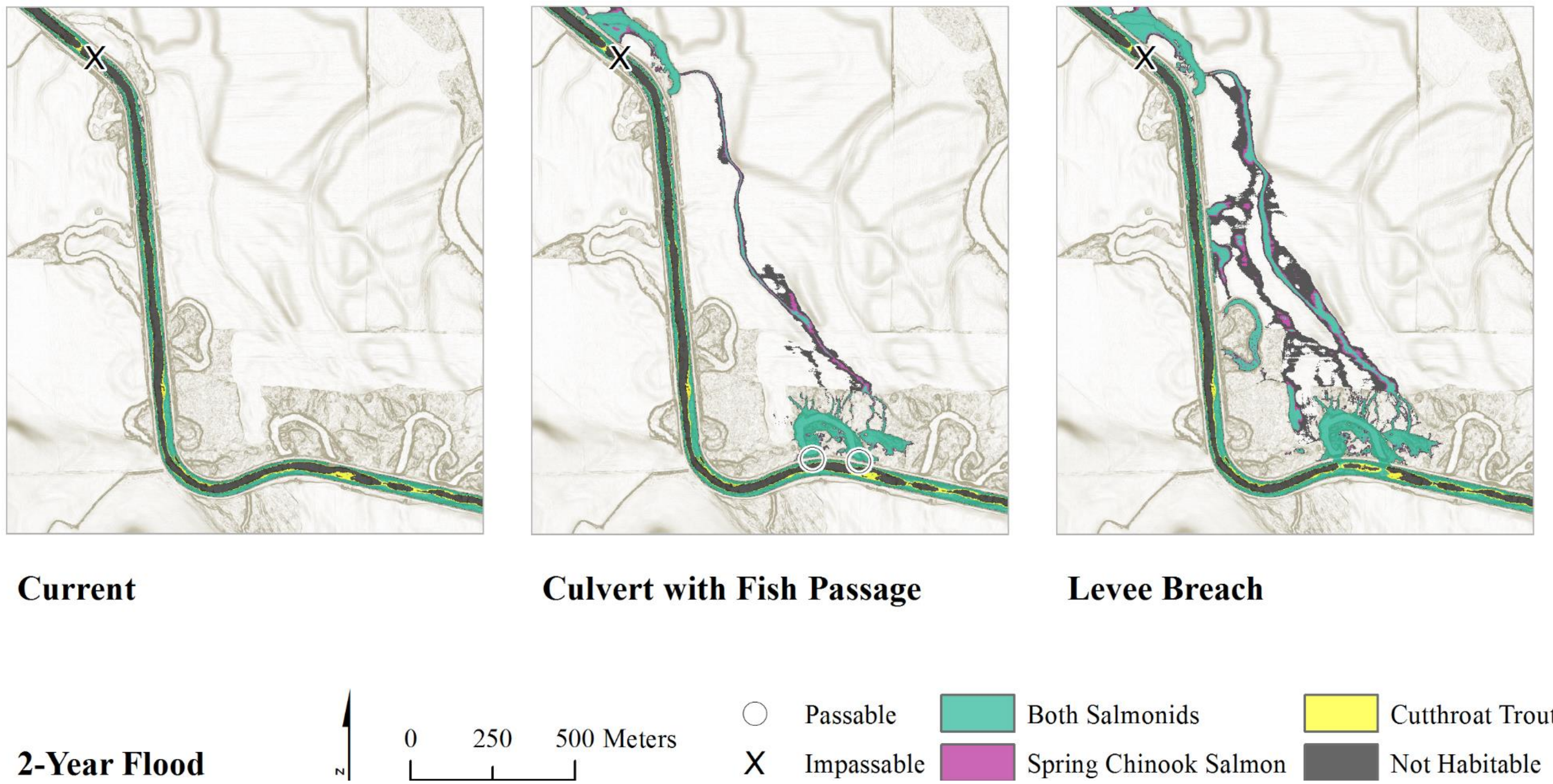


Figure 41: Maps of physical habitat for two fish species at Southern study site for the 2-year flood event for current conditions and two restoration scenarios.

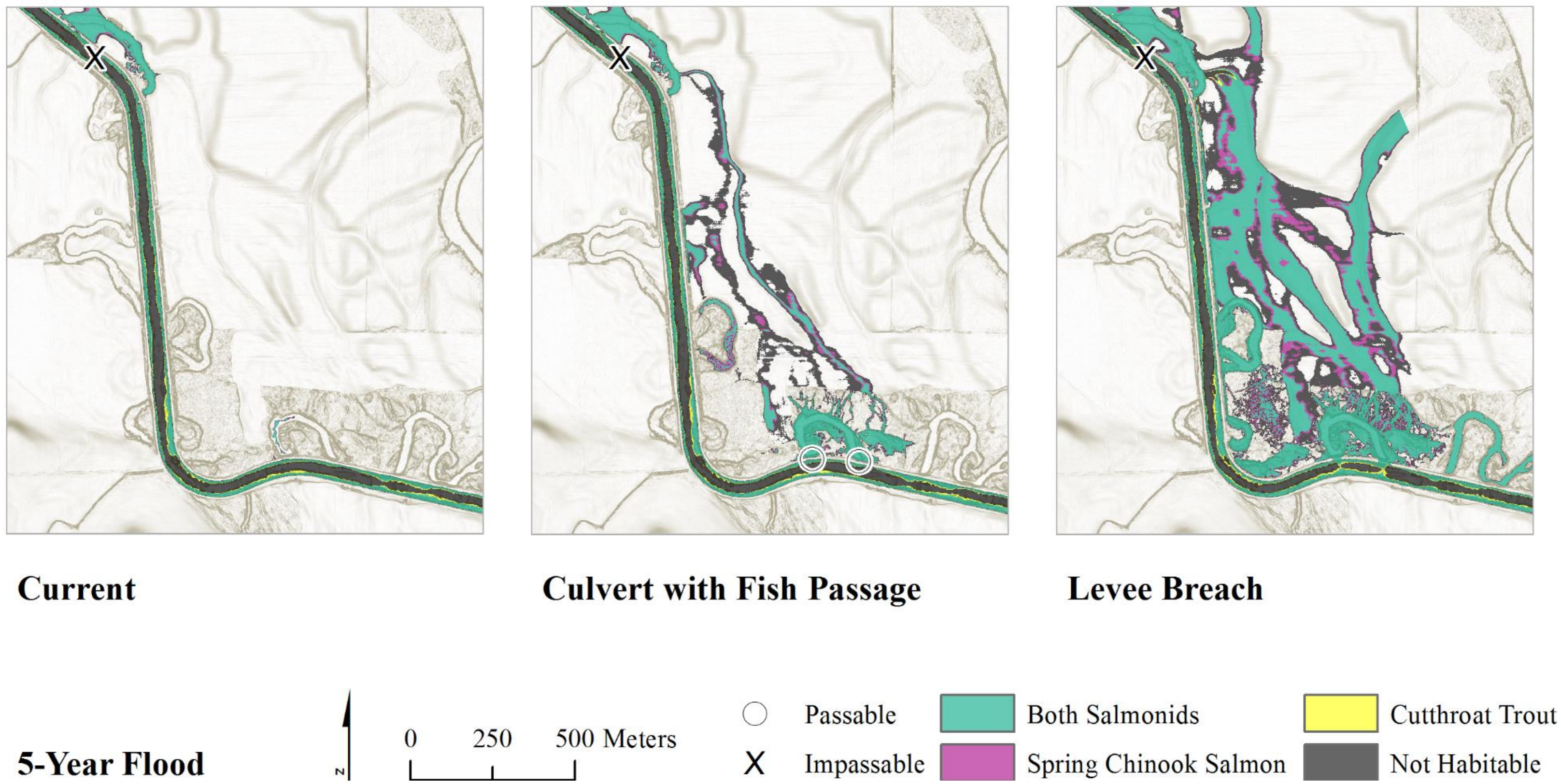


Figure 42: Maps of physical habitat for two fish species at Southern study site for the 5-year flood event for current conditions and two restoration scenarios.

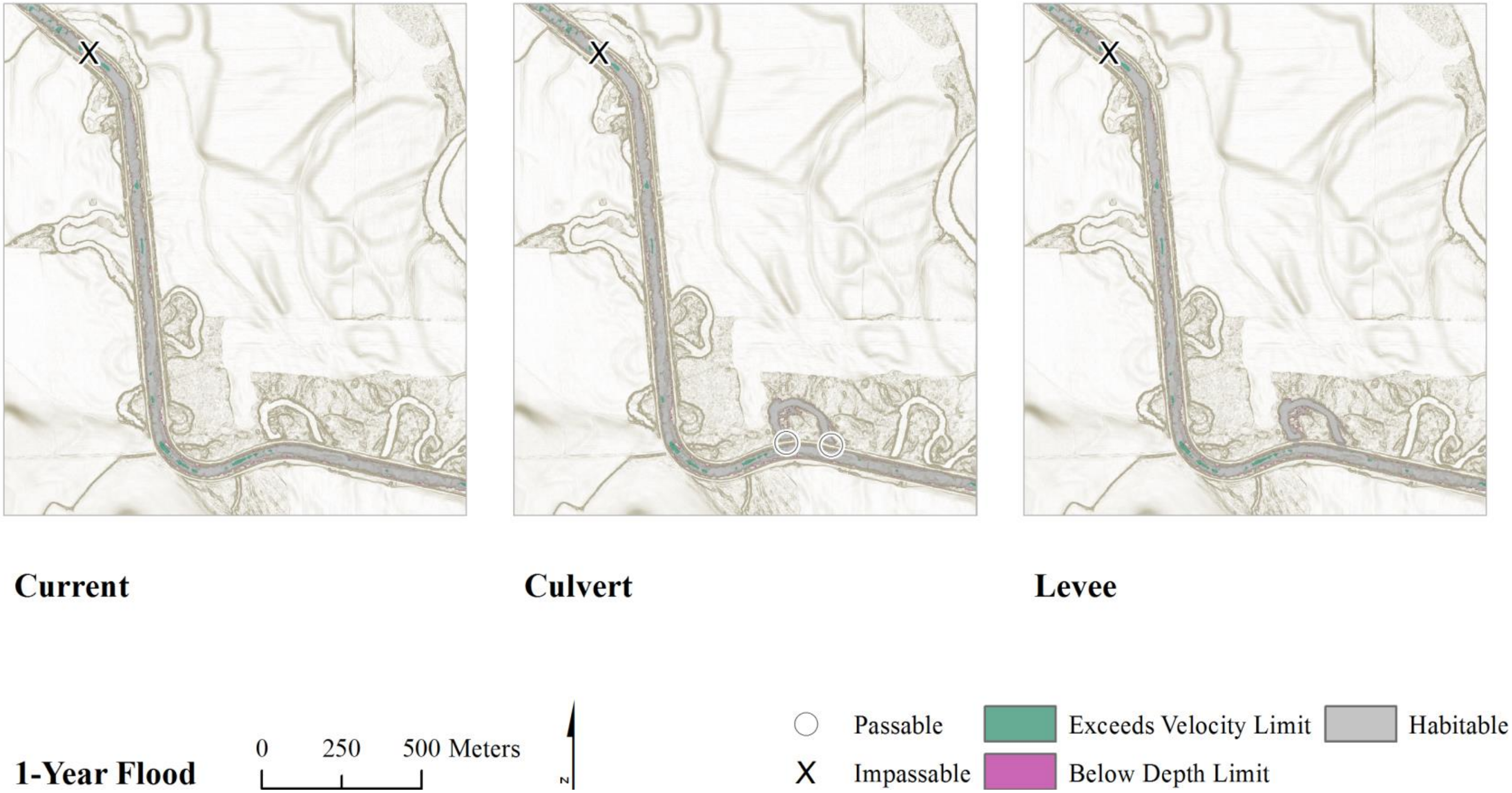


Figure 43: Maps of unsuitable habitat at Southern study site for the 1-year flood event for current conditions and two restoration scenarios.

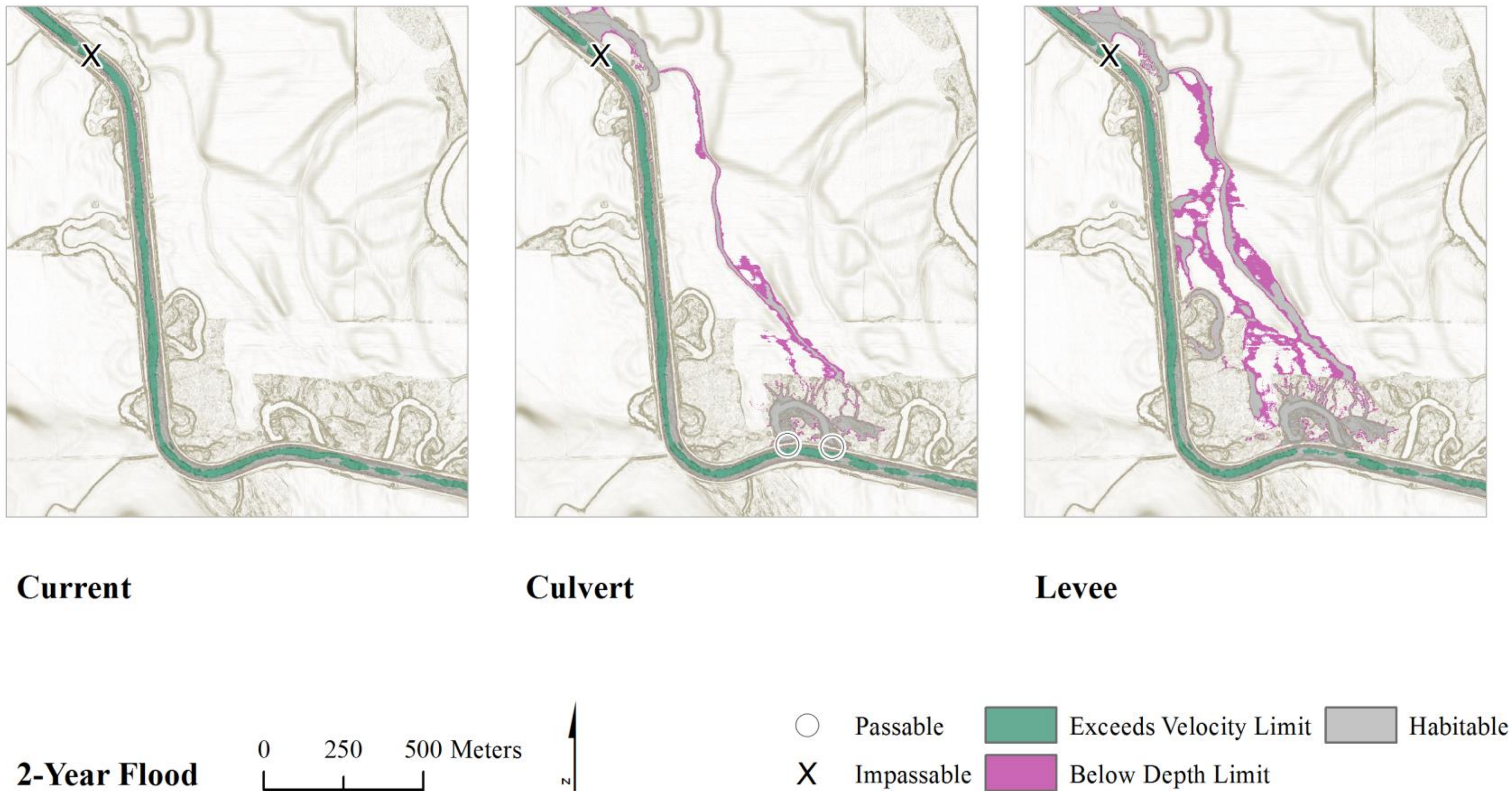


Figure 44: Maps of unsuitable habitat at Southern study site for the 2-year flood event for current conditions and two restoration scenarios.

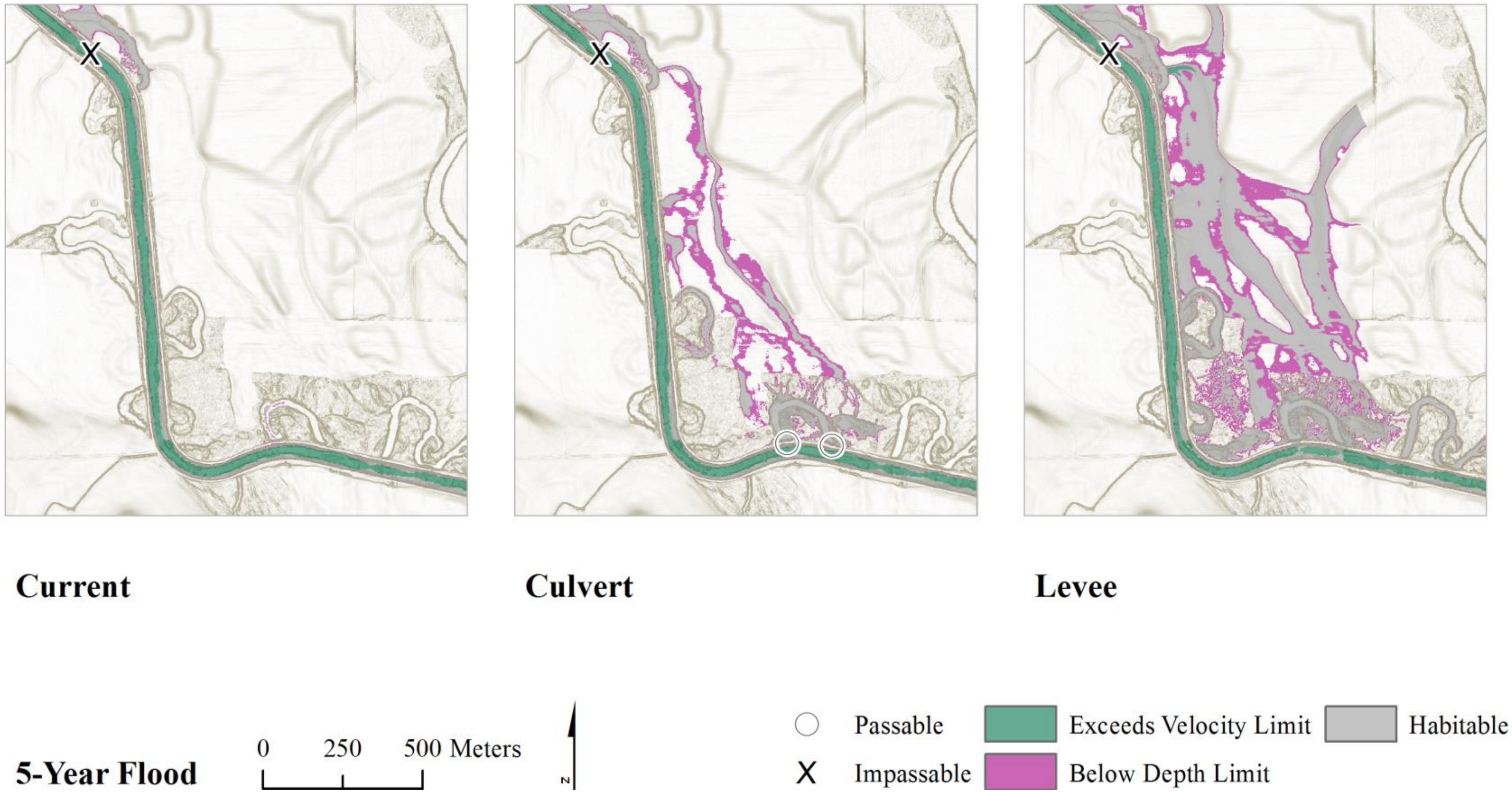


Figure 45: Maps of unsuitable habitat at Southern study site for the 5-year flood event for current conditions and two restoration scenarios.

Shear Stress and Potential Bed Mobilization

Similar to the Monroe Study Site, the Southern study site models showed a distinct difference in the erosion potential of the main channel as well as the historical channel and floodplain areas (as summarized in Table 15). In general, the main channel appears to be subjected to high bed shear stress that would be capable of mobilizing the median grain size, and the secondary channels and floodplains experience much lower shear stresses that would not mobilize or potentially deposit sediment that was the median grain size.

Table 15: Summary of potential bed mobilization and shear stress at Southern study site for main and side channels.

	Current: No culverts	Restoration Scenario 1: Culvert with fish passage	Restoration Scenario 2: Levee breach
1-Year Flood	Main: Partial mobilization	Main: Partial mobilization	Main: Partial mobilization
	Side: N/A	Side: No mobilization	Side: No mobilization
2-Year Flood	Main: Mobilization	Main: Mobilization	Main: Mobilization
	Side: N/A	Side: No mobilization	Side: No mobilization
5-Year Flood	Main: Mobilization	Main: Mobilization	Main: Mobilization
	Side: N/A	Side: No mobilization	Side: Very limited mobilization

During the 1-year flood, there are very similar quantities and spatial distribution of shear stress across the three scenarios. Figure 46 shows that the main channel is subjected to a mixture of bed mobilizing and non-mobilizing stresses while the shear stress in the historical channels is not great enough to mobilize material in either restoration scenario. This pattern was consistent with my initial hypothesis that the velocities associated with the 1-year flood would not be high enough to mobilize gravels in the side channel. Despite the similarity in mobilization potential, Figure 49 shows that, unlike the culvert restoration scenario, the levee breach both slightly increases the shear stress in the side channel and it decreases the shear stress in the main stem directly adjacent to the meander bend.

The 2-year and 5-year flood model results show similar trends in shear stress and potential mobilization (Figure 47, Figure 48, Figure 50, Figure 51). Under both flood levels, the main stem shows a consistently high potential for gravel mobilization and the historical channel and floodplains show a small increase in shear stress but a very low chance for gravel mobilization. Figure 51 shows that the levee scenario would result in a decrease in the main channel shear stress with increasing floodplain inundation. Overall, the floodplains show a much wider range of possible shear stresses and are the most likely area for sediment deposition.

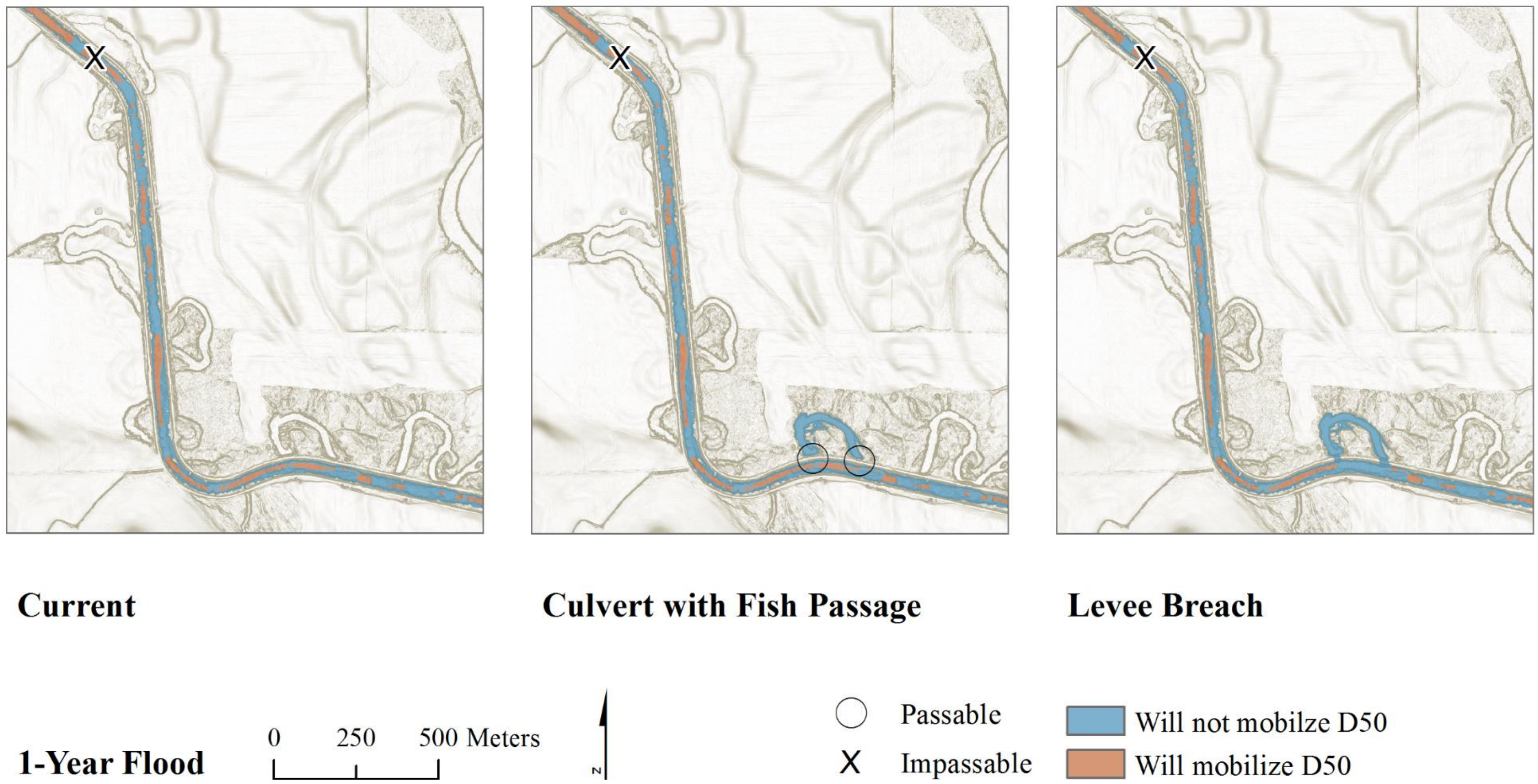


Figure 46: Maps of potential gravel mobility at Southern study site for the 1-year flood event for current conditions and two restoration scenarios.

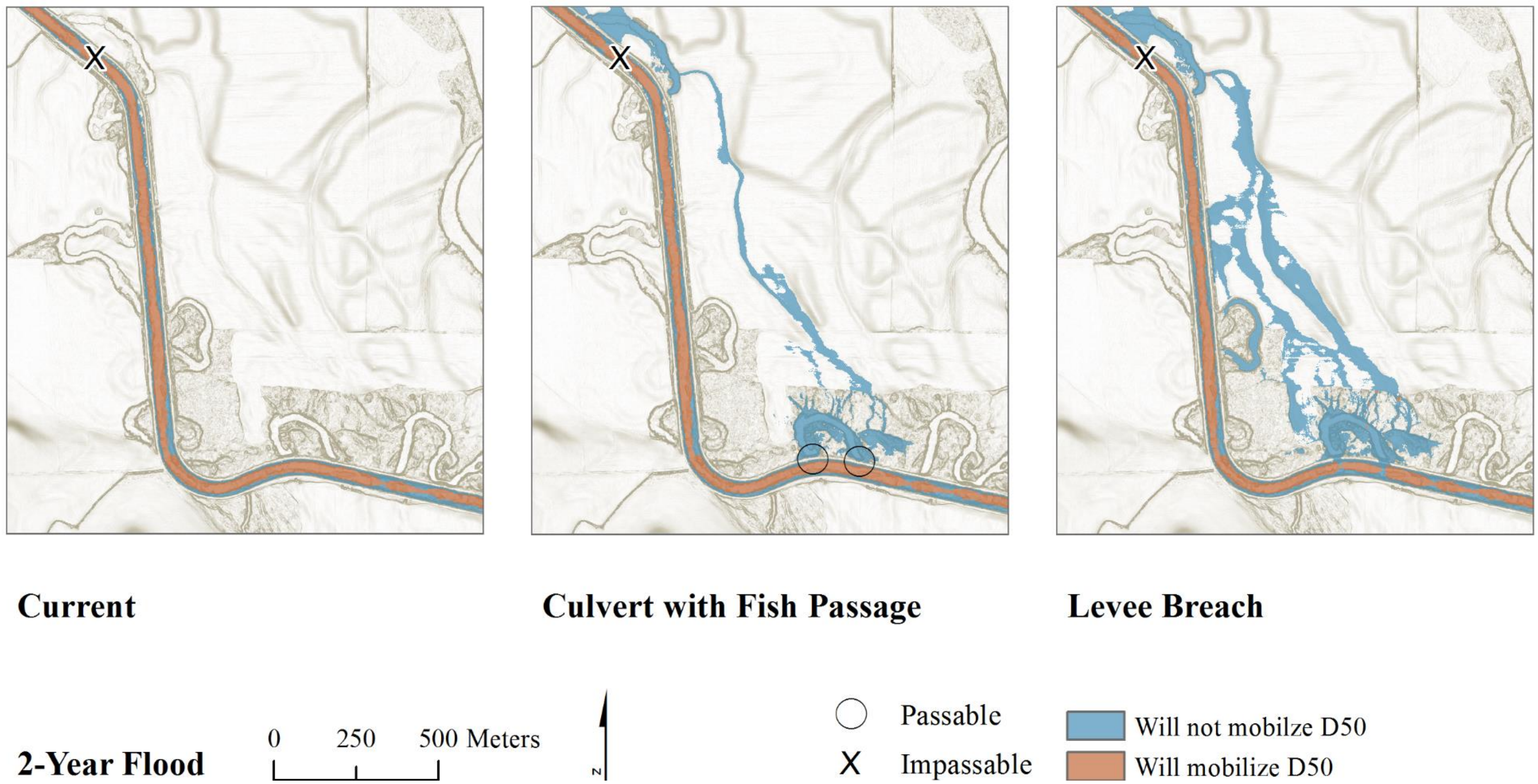


Figure 47: Maps of potential gravel mobility at Southern study site for the 2-year flood event for current conditions and two restoration scenarios.

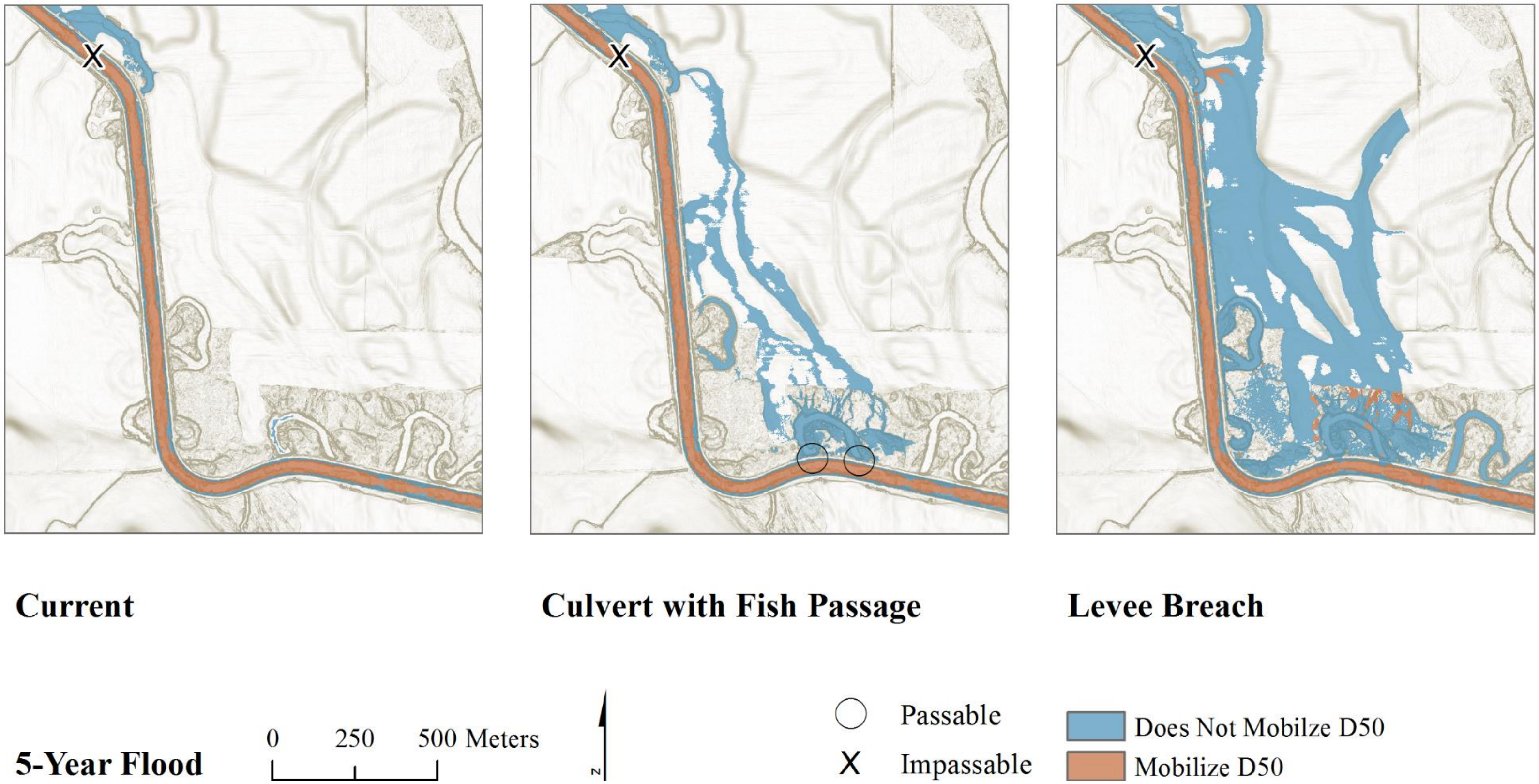
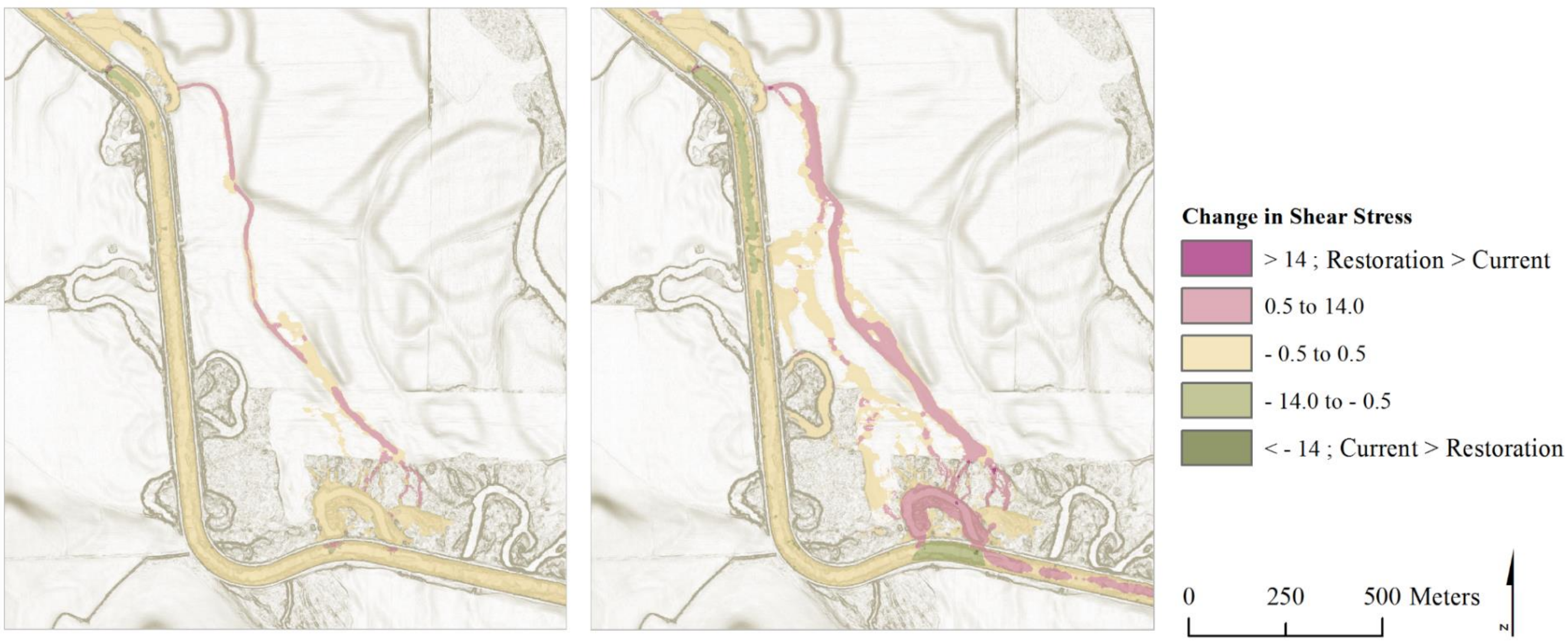


Figure 48: Maps of potential gravel mobility at Southern study site for the 5-year flood event for current conditions and two restoration scenarios.

Figure 49: Maps of difference in shear stress between current and restoration scenarios at the Southern study site for the 1-year flood event.



Current -- Culvert with Fish Passage **Current -- Levee Breach** **2-Year Flood**

Figure 50: Maps of difference in shear stress between current and restoration scenarios at the Southern study site for the 2-year flood event.

Figure 51: Maps of difference in shear stress between current and restoration scenarios at the Southern study site for the 5-year flood event.

Comparison Between Sites and Restoration Recommendations

My analysis of the two study sites shows that there are some similarities in channel responses to restoration and that several generalizations may be extrapolated from these models. Across both sites, the levee breach produces the largest area of inundation, the greatest abundance of suitable habitat, and the greatest likelihood of side channel bed mobilization while also reducing shear stress in the main channel. At both sites, the current conditions have the smallest quantity of suitable habitat at higher flows and often comparable or smaller areas of inundation. The current condition models showed high main channel bed shear stress values during the 2-year and 5-year floods, and those high values changed very little when large culverts were installed. For both sites, habitat in the main channel was typically limited by velocity and habitat in the historical channel and floodplain was typically limited by the minimum depth.

However, there are also important differences between the sites that limit the potential for generalizations. First, the current conditions in Monroe allow for water to pass through small culverts whereas the Southern site does not include any connection between the main channel and the historical channel. As a result, the Southern study site's current model shows no floodplain connection, which leads to much greater increases in area of inundation and habitat after restoration. While the Monroe study site appears to have similar areas of inundation across the different scenarios during the 5-year flood event, the Southern study site appears to have divergent areas of inundation. This is likely due to differences in channel geometries and floodplain connection. Second, the Monroe study site has multiple segments to the historical channel and the right bank floodplain is divided by the elevated highway, while the Southern site has only one historical meander bend of interest and water on the floodplain is able to follow the ground and historical terrace topography. Both of these differences in conditions begin to explain why the Monroe current condition model and enlarged culvert model often display similar patterns while the Southern current condition model and enlarged culvert model display very different patterns in inundation, habitat, and potential bed mobilization.

Given these differences between the models and topography, there are a few suggestions that I can make. First, since my modeling shows that potential habitat is quite limited in the main channel at 2-year and 5-year flood, I believe that providing consistent access to the historical channels for fish, regardless of the type of connection, would dramatically increase the amount of potential habitat. Reconnecting the historical channel by breaching the levees would provide the greatest amount of newly available habitat and improve conditions for fish within the main channel, but consideration should be given to the potential increase in area of inundation as well. Second, by reconnecting the Southern historical channel to the main stem, one would likely see an increase in the inundation and the presence of flow in the swale. I would suggest that, if this meander bend were reconnected or breached, arrangements be made so that the persistent inundation and potential loss of top soil in the adjacent field does not have a negative economic impact on local agricultural practices. One solution would be for a conservation organization to lease or purchase this area. If this land is set aside for conservation, a new plan to allow for fish passage around the drop structure through the secondary channel along the swale should be pursued.

Critique of Study and Opportunities for Future Work

Data collection

Although my work provided many useful insights into the restoration potential along the lower Long Tom River, there are several ways in which my work could be improved and expanded upon. First, I would recommend collecting more ADCP bathymetric data at the edge of the water in areas with steep banks. Although I was able to partially compensate for this missing data by modifying my terrain, it would be preferable if this data had been collected in the field. Since ADCPs are not frequently used to create bathymetric terrains based on longitudinal profiles, I would recommend collecting additional cross section surveys throughout the study area to determine how well the longitudinal profiles are capturing the channel geometry.

Second, this study could have been improved if I had been able to collect additional sediment samples for size analysis. In particular, I would like to sample the historical channel at both study sites and upstream of the drop structure at the main channel at the Monroe study site since this was not feasible during this study due to the water depth. Without more comprehensive sediment size data, I was forced to assume that the median grain size in the main channel at the Southern study site was representative of both study sites and the main and side channel. In order to collect a more complete dataset, a different sediment sampling method would need to be employed.

Third, I could improve my water surface elevation raster by surveying a greater number of elevations during bathymetric data collection. In this study, I was able to augment my data point collection by using the averaged LiDAR water surface elevations, but I would recommend collecting a greater number of points in future studies. Finally, I would recommend also collecting as many high-discharge water surface elevation points as possible to improve model calibration.

HEC-RAS Modeling

While HEC-RAS 5.0.1 has proven to be a tool well-suited to this study, I would recognize that there are many ways to improve these models in the future. First, I would rerun these models with the Saint Venant's equations instead of the diffusion wave equations if I had access to a greater computing power. Although models utilizing the Saint Venant's equations are prone to instability and require much shorter computational time-steps, these equations would allow me to incorporate fully turbulent flow into my model and account for the Coriolis effect which could change my modeling results.

Second, I think that more sensitivity testing and further calibration could also improve the accuracy of the model results. By running the same model under smaller computational time intervals, incrementally different Manning's n coefficients, and adjusted implicit weighting factors, I would be able to see which variables cause the greatest divergence in results or potentially could be used to create a range of possible flood characteristics instead of a single prediction.

Third, my models did not account for flooding due to the accumulation of rain. HEC-RAS is capable of modeling rainfall across a terrain and I would be interested in trying to simulate both flooding from the river flow and from rainfall.

Fourth, I would also like to use my models to determine the rate of floodwater recession under different restoration scenarios. While my models showed that a levee breach would typically result in a larger area of inundation than culverts, I believe that the increased connectivity with the main channel might also result in faster flood water recession in the levee scenario. This hypothesis could be tested using an unsteady HEC-RAS model and may influence the most desirable restoration scenario.

Fifth, my models all displayed the impact of flooding on a single, immobile terrain. While this provides a useful snapshot in time, it does not allow the terrain to adjust with different flood flows as would be expected in the real world. In the future, I could use a geomorphic change model to predict how the levee breach scenario would change during a 2-year flood event and use that modified terrain to make a more accurate simulation of larger flood conditions.

Sixth, I believe my models may have exaggerated flood inundation on the floodplain in Monroe south of Highway 99 because the model only allowed water to exit the floodplain by moving through the culvert or levee breach at Highway 99. It did not account for any water to exit through infiltration or additional culverts under Highway 99. Future studies should identify areas on the model where water may become trapped and closely examine the field site for addition flow exits.

Seventh, I would recommend making more 2D models for additional historical channel meander bends and different types of channel reconnections. More models would allow for greater comparison between sites and may help to identify priority historical meander bends to reconnect. If any of these historical channels are connected to the main stem, it would allow for model validation.

Additional Considerations

First, my ability to predict where sediment will erode or deposit is greatly limited by the limited understanding of sediment availability in the lower Long Tom River. At this time, no systematic research has been completed in order to account for the size, volume, or sources of sediment in or along the river bed and bars. While I observed fine-grained, cohesive materials in the bed and banks at both sediment sampling sites, no studies have been performed to understand how this material or the fill that was used to create the levees has responded to fluvial erosion.

In addition, no research exists showing how the channel has geomorphically changed since channelization and damming. More research must done in order to make better predictions and contextualize and test the erosion and deposition predictions made in this study.

Second, my models focused on a highly simplified measure of habitat. Additional physical habitat constraints like fish cover and water temperature should be accounted for in future studies. If additional habitat requirements are not met, my suggested usable habitat may be misleading. I did not consider whether or not salmonids would be attracted to the flow in the historical channel below the Monroe drop structure. If fish are unable to detect the historical channel flow, it will not provide the desired fish passage around the drop structure.

CHAPTER V

CONCLUSION

My work shows that by reconnecting the historical channel to the main stem, regional managers have the potential to dramatically increase the amount of accessible fish habitat when compared to the current conditions. During a 2-year or 5-year flood, the models indicate that the main channel velocities are too high for local cutthroat trout or juvenile spring Chinook salmon and that the historical channel and floodplain can provide far more suitable habitat. When comparing the two restoration scenarios, the models show that a levee breach would provide the greatest amount of fish habitat by increasing floodplain connectivity and increasing the total area of inundation, however it also shows the greatest potential to re-establish bed mobilization in the historical channel. If regional managers simply wish to provide the greatest amount of habitat and construct fish passage around drop structures, a set of levee breaches would be the recommended method. However, if the managers wish to control the flow in the side channel, limit the amount of floodplain flow, and reduce the chance of bed mobilization in the historical channel, I would recommend they install a set of culverts that fish can access and pass through.

This research demonstrates that river managers should consider modeling and potentially connecting other historical meander bends to the main channel throughout the lower Long Tom watershed in order to increase available habitat. Given that the local conditions at my study sites had important impacts on the change in flooding and potential habitat, I would recommend that further modeling is conducted in order to assess the potential for restoration throughout the watershed.

For example, in my work, I observed that features on the floodplain, like chutes and swales or raised highway barriers, had a direct impact on the area inundation. Depending on the local land use and threats to infrastructure, it may be important to use setback levees or work with local land trusts to lease vulnerable property for conservation purposes.

This study also showed some of the advantages and limitations of my methods and the use of 2D hydraulic modeling. Since 2D HEC-RAS models rely on a continuous terrain, they have the advantage of being able to incorporate high-resolution floodplain data derived from LiDAR that is increasingly widely available, but they also require high-resolution bathymetric data that can be difficult to obtain. In this study, I spent many hours collecting data and creating this complete terrain in GIS. I found that an inaccurate or incomplete bathymetric dataset could be an important source of error, and future studies should try to quantify and find ways to minimize this type of error. However, once the 2D model has been created, it is easily manipulated which allows the user to test different restoration scenarios and different flood flows. Nevertheless, at the scale used in this study, each model run was computationally intensive and each scenarios' model ran continuously for more than a week.

When managers create a long term strategy for restoration in the Long Tom watershed, it will be important for them to assess and consider two additional factors. First, there has not been a systematic study of the post-channelization geomorphic change in the lower Long Tom River and managers do not know the source or quantity of bedload sediment. Since I was unable to collect sediment samples in areas too deep to be waded, future geomorphic studies should seek to create a more comprehensive sediment size dataset by collecting additional sediment in the historical channel and in the backwatered areas behind the drop structures. By improving our understanding of current sediment sources, we will be able to make better predictions about the potential for erosion and deposition in both the main and reconnected historical channels. Second, we should seek to better understand the relationship between water quality, in particular water temperature, in the main and historical meander bends. If the dense, riparian vegetation along the historical channels effectively shades the channel and reduces the water temperature, historical channel reconnection may provide a source of cooler water in the main channel and further enhance restoration goals.

APPENDIX A

HISTORICAL MAPS AND SOIL SUMMARY TABLES

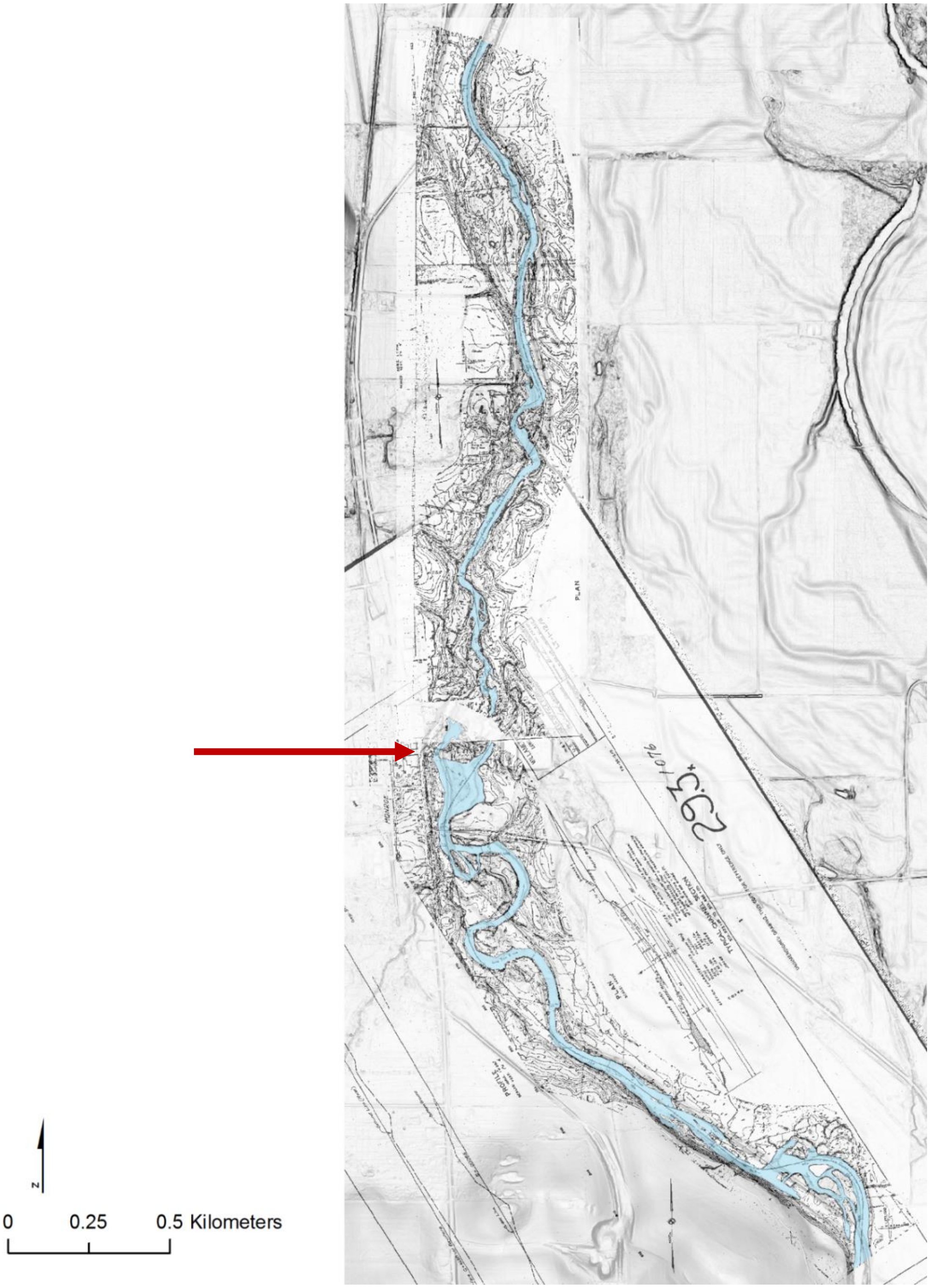


Figure 1: An example of the USACE 1944 survey in Monroe with a modern LiDAR-derived slope map as a basemap. Active channel has been interpreted and highlighted by author. The red arrow indicates the approximate location of the modern Monroe drop structure.

Figure 2: An example of the BLM 1853 GLO maps. The lower Long Tom River is shown by a dark line in the center of the map. The red arrow indicates the approximate location of the modern Monroe drop structure.

Table 1: Soil units that were classified as floodplain deposits by author based on the NRCS Soil Surveys (Patching 1987, Fillmore 2009)

Soil Unit Name	Type	Location Description	Lane Map Unit	Benton Map Unit	Typical Horizons	Either parent material or substratum description mentions: gravel, gravelly sand, gravelly clay
Abiqua	silty clay loam	"fans, terraces, and high flood plains"	1A	n/a	Ap, A12, B21, B3, C	Yes
Camas	gravelly sandy loam	"convex areas of flood plains"	22	28	Ap, A3, C	Yes
Chapman	loam	"floodplains" "low river terraces" "recent mixed alluvium"	24	35	Ap, A, BA, Bw, BC, C1, C2	Yes
Chehalis	silty clay loam	"on flood plains" "recent mixed alluvium"	26	n/a	Ap, A3, B21, B22, B3, C	No
Cloquato	silt loam	"well drained soil is on flood plains. It formed in recent mixed alluvium"	29	n/a	A11, A12, A13, C1, IIc2,	No
McAlpin	silty clay loam	"flood plains"	78	n/a	Ap, A12, B1, B21, B22, B3,	No
McBee	silty clay loam	"on flood plains"	79	118, 119	Ap, A3, B2, C	No
Natroy	silty clay loam	"in drainageways and other depressional areas on terraces and fans. It formed in mixed, fine-textured alluvium."	85	n/a	A11, A12, A13, C1, C2, C3,	Yes
Newberg	loam	"on flood plains and bottom lands. It formed in recent silty alluvium."	96	125, 127	Ap, AC, C1, C2, C3	Yes
Noti	loam	"in swales and drainageways on	98	n/a	A1, B2, C1,	Yes

		terraces. It formed in mixed alluvium"			IIC2, IIIC3,	
Waldo	silty clay loam	"This deep, poorly drained soil is in depressional areas on floodplains and low terraces"	130	n/a	Ap, B1, B21g, B3g	No
Wapato	silty clay loam	"bottom lands. It formed in mixed alluvium."	134	n/a	O1, A11, A12, B21, B22, C1g, C2g	No

Table 2: Soil units that were classified as terrace deposits by author based on the NRCS Soil Surveys (Patching 1987, Fillmore 2009)

Soil Unit Name	Type	Description	Lane Map Unit	Benton Map Unit	Typical Horizons	Either parent material or substratum description mentions: gravel, gravelly sand, gravelly clay
Awbrig	silty clay loam	"plane to concave areas on stream terraces and in drainageways"	5	n/a	Ap1, Ap2, IIB21t, IIB22t, IIB23t, IIC1	No
Coburg	silty clay loam	"low stream terraces"	31, 2025A	50	Ap, A3, B21t, B22t, B3t, IIC	No
Conser	silty clay loam	terraces	33	52	A1, B1, B2tg, IIC1g, IICg,	Yes
Dayton	silt loam, clay (glaciolacustrine) substratum	"in drainageways on broad stream terraces"	38	53	A, Eq, E2, 2Bt1, 2Bt2, 2BCt1, 2BCt2, 3C1, 3C2	No

Holcomb	silt loam	“terraces”	56	85	Ap, A, E, 2Btg, 2BCtg, 3C,	Yes
Linslaw	loam	“along drainageways dissecting old terraces and colluvial fans. It formed in old mixed alluvium	73	n/a	Ap, A12, B2t, B3, IIC1, IIC2	No
Malabon	silty clay loam	different descriptions for Benton (floodplains) vs Lane (valley terraces)	75, 2024A ,	110, 111	Ap, A3, B21t, B22t, B3t, IIC	Yes
Oxley	gravelly silt loam	“on terraces”	100	n/a	111, A12, A3, B2t, B3t, C	Yes
Salem	gravelly silt loam	“stream terraces”	118	139	Ap, B1, B21t, IIB22t, IIIC,	Yes

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