Hydraulic Modeling to Quantify Benefits of Floodplain Restoration

Zachary McBride

A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Landscape Architecture

University of Washington

2023

Committee:

Celina Balderas Guzmán

Ken Yocom

Program Authorized to Offer Degree:

College of Built Environments

University of Washington

Abstract

Hydraulic Modeling to Quantify Benefits of Floodplain Restoration

Zachary McBride

Chair of the Supervisory Committee:

Celina Balderas Guzmán
Department of Landscape Architecture

In rural areas, flood management is often achieved with large civic projects such as dams and levees. In contrast, the restoration of floodplain processes is done as a remediation or seen as a separate end. Restoring floodplain processes into the flood management toolbox will be essential for the health and safety of people living in flood prone areas. The Chehalis watershed of Southwestern Washington is indicative of the changing philosophy behind water management. This case study examines how restoration is being studied as a viable alternative to continued levee and dam construction. Previous research has focused on small-scale interventions or broad watershed-wide statistical aggregation of sites. There exists a gap in research towards the mid-scale, reach-based, restoration. In this work, I quantify the reach-scale benefits of three floodplain restoration techniques: side channel creation, in-channel modifications, and flood-able basins. I use HEC-RAS modeling software to simulate the flood attenuation benefits of these interventions compared to a control landscape that emulates the South Fork of the Chehalis River. The resulting simulations show that the floodplain restoration strategies increase floodplain area inundation by 38% and delay the passage of floodwater by 22-44%. These findings demonstrate that floodplain restoration techniques can be effective in floodplain management. They can not only hold water on the landscape but encourage processes such as groundwater recharge associated with inundated soils. When the tertiary benefits are considered, such as habitat creation and increased tourism, restorative floodplain management should be viewed as a viable alternative to traditional flood mitigation strategies.

Table of Contents

Table of Figures

Restorative Floodplain Solutions

Site Selection and Characteristics

Site Exploration

Modeling with HEC-RAS

Intervention Typology

Characteristics of Landscape after Strategies

Overview

Opportunities for Future Study

Appendix A, B, C

1 - Introduction

Floodplain Management

Floodplains are a confluence of many forces, including the conflict between human development and the natural environment. It is estimated that 13 million United States residents live within a designated flood hazard area (FEMA 2023; Crowell et al. 2010). This area is expected to expand on two fronts: human populations continue to grow, encroaching deeper into flood-prone areas, and the effects of climate change will expand flooding areas, frequency, and severity (OAR US EPA 2016; Mallakpour and Villarini 2015).

Flood management traditionally centers around artificial physical changes to the landscape. These take the form of engineered solutions such as levees, ditches, canals, weirs, and dams. Levees are earthen embankments that help protect cordoned areas from rising water levels. These embankments are made from earthen fill and require regular maintenance. Ditches, canals, and other diversionary structures help increase the flow capacity of a landscape. Their primary purpose is to transport floodwater to selected destinations. Dams and weirs are both used to regulate the flow of water. They capture and build up a reservoir upstream. They often feature gates that can release water at metered levels to optimize flow for downstream flood management systems. The engineered graywater solutions to flooding offer relief from flood damage to local areas, yet their use often comes with significant drawbacks.

These solutions are now under scrutiny as catastrophic failures in this infrastructure regularly result in massive amounts of loss (Freitag et al. 2009). Katrina, the costliest disaster in U.S. history, caused $161 billion dollars in damages (Knabb, Rhome, and Brown 2023). The 1993 Mississippi River floods caused $15-20 billion in damages, followed by the 2008 floods which caused $9.6 billion dollars in damage (Freitag et al. 2009; US Army Corps of Engineers 2008). As seen with Katrina, these events frequently concentrate damages upon the marginalized within communities (Benevolenza and DeRigne 2019). Marginalized groups are not only at a higher risk of damages but are also more frequently subjected to this damage (Fielding 2012; Poussard et al. 2021).

Furthermore, the World Commission on Dams published a 2020 report calling for greater consideration to be given to the placement of dams and levees. They found that there is a great disparity between the displacement of harm caused by dam construction and the return of benefits (World Commission on Dams 2020). These factors include not only the human element but also the disruption to natural systems that frequently provide similar benefits to flood mitigation. Climate will have long-lasting effects on the hydrological regimes seen in the Pacific Northwest. It will change the patterns of precipitation and temperature that dictate the time and quantity of water within the watersheds. As snow accumulates at high latitudes, the watershed that receives snowmelt accumulates a bank of water at high elevations. That snow develops through the winter months and then slowly releases as meltwater. Water from meltwater can slowly parse itself through the soil substrates, allowing for a steady release of moisture through the warm part of the year. This is accelerated by periods of warm rainfall or elevated temperatures. With climate change, the stream regimes that relied on snowmelt may feel the greatest effects of climate change. It is expected that elevated temperatures will reduce the quantity of snow accumulation throughout the Pacific Northwest. This will then shift the hydrological patterns from a snowmelt-dominated system towards a rain-dominated system. Climate change will cause a major fluctuation in flood patterns, though the exact result is unpredictable (Freitag et al. 2009). This uncertainty requires floodplains to not only increase capacity to handle flood water but also be fundamentally resilient to disruptions.

The management of human response to these disruptions falls upon various political agencies. Their control involves a complex network of policies, regulations, and practices. They must also manage the human psychology associated with disruption. In a 2009 study, Healy and Malhotra found that public perception rewards disaster relief over disaster preparedness, encouraging elected officials to be responsive instead of proactive towards environmental dangers. This despite every dollar towards preparation and resilience being worth fifteen times that of response (Healy and Malhotra 2009). These forces are understandably at odds between encouraging and discouraging human settlement on floodplains. The Federal government subsidizes settlement in high-risk areas through The National Flood Insurance Program (NFIP). While requiring some modifications to structures to qualify, it nonetheless results in the development of neighborhoods that are sometimes leveled by flood events (Oliver 2017). The NFIP does, however, encourage state and local governments to enact regulations and plans for public safety. To qualify for NFIP, local governments often require setbacks from waterways, different building regulations within flood hazard zones, zoning regulations, and subsidies for desired behaviors (Freitag et al. 2009). While these are often effective, many urban areas continue to spread into floodplains, thus increasing the conflict between human development and natural cycles.

The two primary forms of floodwater management can be classified as grey and green infrastructure. Grey infrastructure is traditional stormwater and flood infrastructure in the built environment. These include levees, drains, pipes, dams, and other architectural-based approaches. Green infrastructure contrasts with this. It calls for the creation of

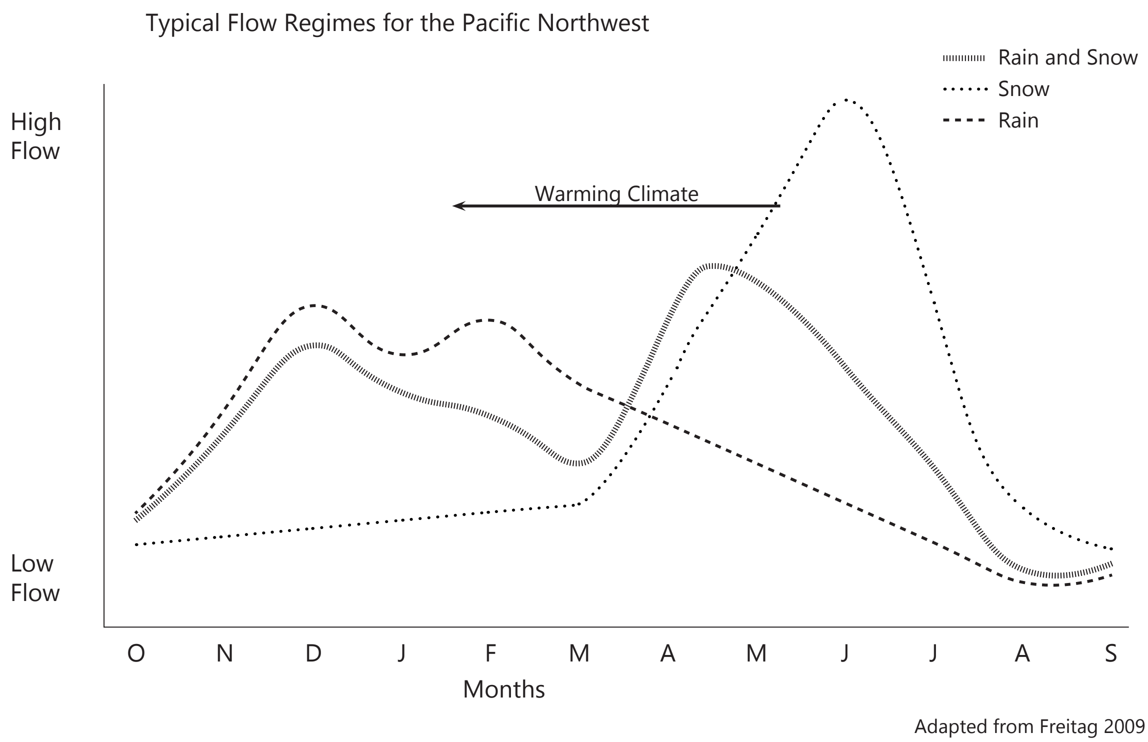


Figure 15 - Flow Regimes

Flow regimes differ based on the source of the water. Snow holds water at high elevations and is then released slowly during preiods of melt. Rain flows out of the system much faster. A warming climate scenario would create more rain events earlier in the season compared to the common flow patterns seen in the past.

ecologically based systems to replace, mimic, restore, or enhance existing infrastructure (ORD US EPA 2022). Alternatives to grey infrastructure solutions are increasingly being explored globally. A key emerging concept is that of harnessing the ability for nature-based systems to replace or complement existing management strategies. Nature-based solutions (NBS), as defined by the European Commission, are "solutions to societal challenges that are inspired and supported by nature… nature-based solutions must benefit biodiversity and support the delivery of a range of ecosystem services" (Directorate-General for Research and Innovation (European Commission) and Vojinovic 2020 p.5.). Designs featuring ecological systems as a central theme help realize a multitude of benefits from projects. They often provide improvements to water quality, air pollution, human health, habitat, aesthetics, resilience, and recreational opportunities. The expansive and interwoven quality of natural systems allows for a multitude of benefits to be felt as side effects of their primary purpose.

The exploration of incorporating natural systems into design is often seen in small-scale urban interventions. These interventions find opportunities in projects of limited scope to create regenerative landscapes that are multi-faceted in their benefits to the plural demands placed on urban space. Small interventions are also more easily funded by communities that do not wish to place importance on centralizing green solutions. They also mitigate the primary challenges felt by nature-based solutions, that of complexity. Just as they can provide a multitude of benefits, they are also challenging to implement correctly. They are highly location-specific and are not appropriate in all settings. Their effectiveness is also dispersed, so the immediate effects are hard to quantify (Directorate-General for Research and Innovation (European Commission) and Vojinovic 2020).

However, the recognition of the value of ecological services is growing. The world's floodplains continue to be a focal point of research and economic evaluation (Chee 2004; Farber, Costanza, and Wilson 2002; Turner et al. 2000). Their flows of energy through water, nutrients, and sediment are foundational to many human and natural systems. They are understood to possess great value as habitat and are used by fish (Nakahashi et al. 2023; McKinney, Charpentier, and Wigand 2009), amphibians (Duke 2014), and birds (Gomez-Sapiens, Soto-Montoya, and Hinojosa-Huerta 2013; Kitazawa et al. 2019). Wetlands have been explored for their ability to remove harmful contaminants. Their use has been encouraged to manage stormwater runoff pollution (Destandau, Imfeld, and Rozan 2013; Liquete et al. 2016), ambient pollution in waterways (Wu et al. 2020; Mitsch 1992), and as replacements for wastewater treatment (Hammer 1989; Mitsch 1992). Wetlands are critical sources of carbon sequestration. Despite only occupying 5-8% of the total land area, they store 30% of the total carbon held by soils (Nahlik and Fennessy 2016). With carbon emissions becoming a daily talking point, their importance cannot be overstated (Carr et al. 2018; Yoo et al. 2022; Zang 2019).

Recent discussions around the value of wilderness in human health have inevitably turned to the role of these important zones. Floodplains, which are subject to damaging flood events, are used as an example of how humans can increase their resilience through deepening connections to the natural environment (Sutton-Grier and Sandifer 2019). Public health proponents point out that watershed and wetland health is often overlooked when quantifying the benefits of wetlands (Dale and Connelly 2012; Horwitz and Finlayson

2011). Water is the most basic human need, so the health of ecosystems that rely on water is directly tied to human health (Cools et al. 2013).

The majority of large-scale NBS/RFP implementation has been done in the European Union. The Dutch serve as the archetype for these projects. Their riverine flood management strategies are innovative by necessity, as 60% of the Netherlands is subject to flood danger (Netherlands Water Partnership 2023). In 2001, a new policy was introduced by the Dutch government that shifted strategy from levees to "making more room for rivers" (Klijn et al. 2013). The result was 39 projects that centralized solutions that worked in concert with natural systems and spatial quality. These projects have already been successful in reducing flood damages and increasing ecological function (van Buuren 2019; Urry 2016).

The restoration of the Laojie River in Taoyuan, Taiwan, also serves as a landmark implementation. This 2011 project, which remediated 37 km of the Laojie river waterfront, is a successful large-scale restoration project. The project allowed the region to drastically reduce damages from the 2012 flood that ravaged the rest of the island. It reduced the amount of flood-prone land by 192,500 square meters, contributed to a 73% reduction in waterborne pollution, and revitalized the surrounding economy (Sustania 2018).

The Washington State Department of Ecology, working with engineering firm Natural Systems Design, apply these benefits to the concept of floodplain management in the Puget Sound. They use the term Restorative Flood Protection (RFP) in this application of NBS. In the 2019 Newaukum report, RFP is explained as reconnecting as much of the river as possible to the full extent of its floodplain. This will restore the natural system's

Figure 17 - Hutt River Restoration, The Netherlands

(Kay 2022)

ability to slow, store, and filter floodwaters while also increasing habitat, improving water quality, and reconnecting fish and wildlife populations (Abbe et al. 2019). The Newaukum report quantifies the costs and benefits of NBS implementation, and their results suggest that these systems are cost-competitive with conventional gray infrastructure projects (Abbe et al. 2019).

Floodplain management is a complex issue involving multiple factors such as human settlement, climate change, and the need for resilient solutions. Traditional gray infrastructure solutions have drawbacks and can result in catastrophic failures. Nature-based solutions, or green infrastructure, are emerging as a promising approach to flood management. These solutions harness the benefits of ecological systems to provide multiple benefits such as improved water quality, habitat restoration, carbon sequestration, and human health. While the implementation of nature-based solutions can be challenging and site-specific, successful examples from around the world demonstrate their effectiveness in reducing flood damages and enhancing ecosystem function. The shift towards incorporating

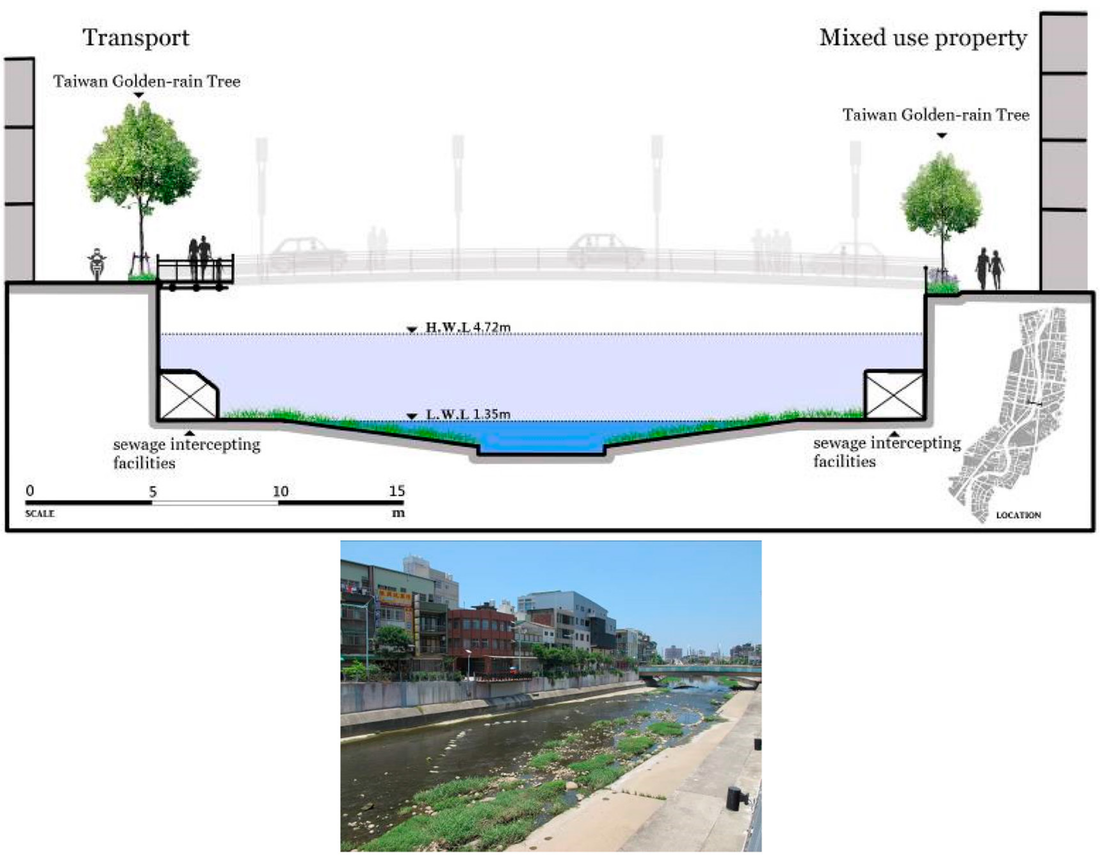


Figure 18 - Laojoie River Restoration, Taiwan

(Chou 2016)

nature-based solutions in floodplain management is gaining traction, as seen in initiatives like Restorative Flood Protection (RFP) in Washington State.

The application of ecological design concepts to floodplain management, specifically fluvial agricultural landscapes, is the topic of this thesis. Previous research has concentrated on the aggregated effect of small-scale interventions. These interventions are the most common, as their implementation has the lowest cost, least maintenance, are less complex, easily studied, and often prioritized in urban areas (Directorate-General for Research and Innovation (European Commission) and Vojinovic 2020). Study of large interventions is limited. This project explores the flood mitigating impact of reach-scale nature-based interventions to floodplains.

Objectives

This thesis tests the flood mitigating potential of landscape alterations informed by restorative ecological practices and provides quantitative evidence of their benefits. Its objectives are: to analyze and assess an existing landscape for flood mitigating potential, to emulate this landscape within hydrological modeling software, to make alterations to this landscape within the simulation, and to evaluate the resulting data using relevant metrics to flood attenuation and ecological health.

Methodology

The project begins with the examination of the Chehalis Watershed flood management as a case study. The landscape of the Chehalis watershed is an archetype mirrored by much of the riverine land in Cascadia. The rivers cascade down the mountains and slow into the meandering fields of cropland that end only at the Pacific Ocean. The Puget Sound is characterized by large floodplains and marsh land situated between glacial drumlins. The Chehalis area also characterizes the metropolitan/agricultural/silvicultural nexus and therefore can be used to examine the typical human use of the area. The Chehalis Watershed has many characteristics that exemplify this area. This far-reaching applicability makes it an excellent area to study methods that can then be applied broadly.

The Chehalis case study brings forward a proposal for alternative strategies to greywater solutions to floodplain management. The political management of flooding in the basin also serve as typical; the conflict continues between many interest groups. A recent report serves as an example of this and examines the conflict between grey and green management strategies. Commissioned by the Chehalis Basin Strategy with the Department of Ecology, the report explores the feasibility of restoration-based solutions within the Newaukum drainage of the Chehalis River (Abbe et al. 2019). This proposal highlights the goals and feasibility of restorative floodplain solutions that inform this project's trajectory. It also provides an in-depth analysis of the floodplain's past and present.

The results of this study are expanded upon in this paper. This project will quantify and explore the benefits of restorative landscape modifications. This requires discrete metrics to be defined and explored. To accomplish this, hydrological modeling of a landscape is used as a tool for evaluation. The Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS) software is employed to this end (Hydrologic Engineering Center 2022). This software was first developed in 1995 and allows users to "perform one-dimensional steady flow hydraulics; one and two-dimensional unsteady flow river hydraulics calculations; quasi unsteady and full unsteady flow sediment transport-mobile bed modeling; water temperature analysis; and generalized water quality modeling" ("Forward" G. W. Brunner, Ackerman, and Goodell 2023). The two-dimensional unsteady river flow hydraulic modeling capability is used to compare and contrast the performance of water as it flows over a selected landscape.

The first metric is flow. This is based on the cubic feet per second of flow at predetermined cross-section transects along the selected river reach at given points in time. With control over the amount of water input into the model, we can examine the time that it takes that water to move to the designated outlet of the simulated system. The second metric measures the total area of inundation beyond 0.1mm of surface depth. This metric is used to roughly quantify the ability of the landscape to engage with natural processes that require interaction with water. A comparison of the surface area will help to explore the differing health of a floodplain. While these metrics are highly simplified, their generality will benefit the anticipated outcomes of the project, which hopes to show a causal relationship in a highly controlled environment.

The landscape selected is based on an actual reach of the Chehalis River tributary: the South Fork of the Chehalis River. This will allow for realistic parameters to be the baseline, as they are taken from actual phenomena from observations. The reach landscape simulation is calibrated for this project, and benchmark measurements are taken. The results are then compared to the same flows through a modified landscape. This modified landscape embodies the suggested changes proposed within nature-based solutions. The goal of these modifications is to affect the changes to the flow rate and floodplain engagement and are informed by nature based and restorative practices. The landscape modifications are subjected to the same flow simulations as the unmodified landscape and data between these two treatments are compared to determine the results and effects of this terrain modification.

The outcomes determine the effectiveness evaluation of the landscape modifications. If the flow of water at the outlet is moderated over a longer period with less volume of flow, then treatments were successful in holding the water on the landscape for longer. If the maximum surface area of the water is increased after the treatments, then the landscape within the simulation engages at a broader range than the control environment. These two metrics allow an assumption about the effectiveness of the modifications to the simulated landscape. With increased engagement with the landscape, ecological processes will increase and with increased attenuation, flood waters are alleviated downstream.

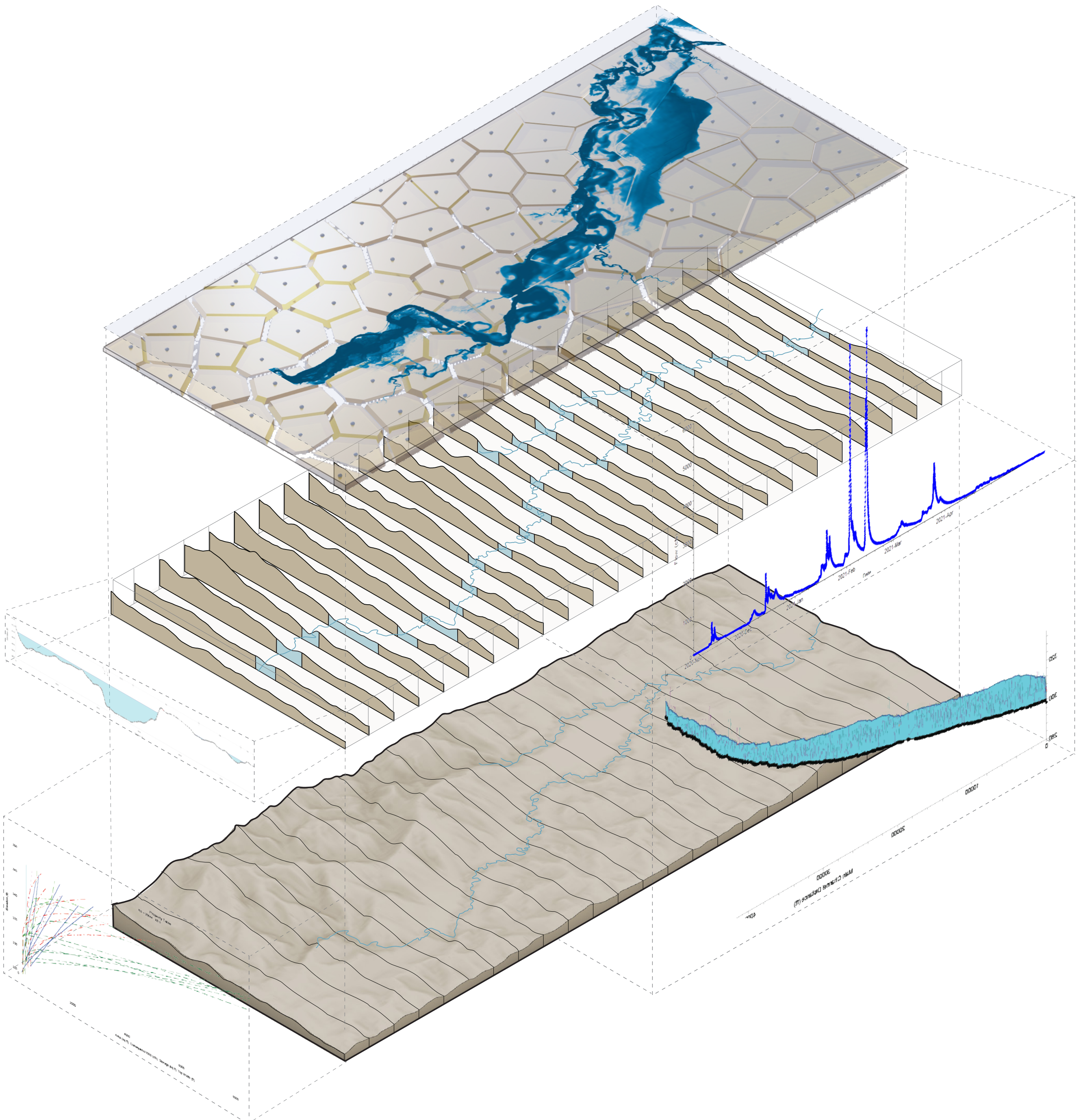


Figure 26 - “The Origin of Methodology”
Artistic interpretation of methodological approaches.

2 - Case Study

Chehalis, Washington


Seattle
Tacoma
Olympia
Chehalis River Watershed
South Fork of the Chehalis River

Figure 30 -

The State of Washington & Chehalis River Basin

Chehalis River

The Chehalis River basin is currently undergoing a thorough review process to address the challenges posed by seasonal flooding. Recent and historical floods have prompted collaboration among lawmakers, engineers, and residents to find effective solutions. Since the 1900's, grey retaining and defensive structures have been utilized to mitigate flood damage in the river valley. However, with the proposal for a new dam near Pe Ell, Washington, alternative ideas are being explored. The Aquatic Species Enhancement Plan (ASEP) and the Local Actions Non-Dam Alternative (LAND) proposals are part of ongoing efforts to assess the impact of a comprehensive flood mitigation plan across the entire watershed. These plans aim to improve habitat conditions and restore historical channel characteristics to promote habitat improvement and nature-based flood damage mitigation through green infrastructure.

While the LAND and ASEP plans incorporate various tools to restore habitat and influence flows along the river corridor, it has become evident that restoration and habitat improvement alone will not fully address the flooding challenges in the valley (Abbe et al. 2019, WA. DoE 2023). It is increasingly recognized that a combination of traditional flood mitigation structures, strategies, and policies, along with environmentally restorative techniques, may offer the most effective solution for the Chehalis basin. Advocating this approach could mark a significant milestone in floodplain management strategies in the United States, as it harnesses natural processes to achieve desired outcomes. This comprehensive plan also necessitates changes in land use practices in the surrounding valley. Since approximately half of the developed land near the Chehalis River is located within a mile of the stream, engaging with landowners and stakeholders is crucial (Chehalis Flood Authority 2010). Much of this land is conventionally managed agricultural land, which exerts a substantial influence on water flow due to its extensive coverage of the floodplain.

Agricultural land often exacerbates flood damage issues by significantly altering natural processes and topography. Current outreach efforts regarding flood damage reduction in farmland focus on three main categories: products to protect production infrastructure against water damage, water conveyance products/techniques, and riparian buffers. However, this toolbox is limited, with only one option providing ecological improvements to the farm. Finding flood damage mitigation with nature based solutions that simultaneously enhance farm productivity would greatly facilitate compliance with government strategies aimed at reducing flood damage.

Chehalis Watershed

The Chehalis watershed is located in Southwest Washington State and is the second largest watershed in the state, second only to the Columbia River basin. It covers an area of 2,700 square miles and begins near Pe Ell, collecting over 3,300 linear miles of streams and rivers before flowing west into the Pacific Ocean at Grays Harbor (WA. Dpt. of Ecology, n.d.). The watershed is bounded by the Olympic Mountains to the north, the Deschutes River Basin to the east, and the Cowlitz River Basin to the south. It traverses three distinct eco-regions: Cascade, Puget Lowland, and Coast Range. The outlet at Grays Harbor serves as an important estuary habitat (Harma 2023).

Within the basin, eight species are currently listed as threatened or endangered under the Federal Endangered Species Act (Harma 2023). The rivers in the basin support spawning chinook, chum, and coho salmon, while pink and sockeye salmon are rarely observed. Factors limiting salmon return include disruptions to stream morphology, physical barriers, and degraded water quality resulting from agriculture and industry. Logging activities have also impacted gravel beds, reducing their recharge and filtration capacity. Deforestation has led to streambed scouring, removing the necessary riffle and flow patterns for salmon. The Department of Fisheries hatchery on the Satsop River attempts to supplement the rivers' fish populations, but the number of returning fish remains low, with fewer than 40 observed per year (WA. Dpt. of Ecology, n.d.).

The location of the Chehalis watershed has influenced human activities in the area. The City of Aberdeen, situated near the river's outflow into the Pacific Ocean, relies on the river for industrial processing and shipping. The fertile floodplain soils support agricultural uses throughout the basin. Tributaries originating from steep hills descend to the river plain, with elevation ranging from approximately 400 feet to 1,500 feet in the mid-ranges. These areas have been extensively used for silviculture, similar to other parts of the coastal range.

The watershed's proximity to major urban centers like Portland, Seattle, and surrounding cities has fueled development and maintained a stable population in the area, despite economic shifts. The watershed is home to over 200,000 residents and spans seven counties (Harma 2023). However, the seasonal fluctuations in flow pose challenges to contemporary land users. In 2022, major flood events caused damages ranging from $13.7 to $20 million in Lewis, Thurston, and Grays Harbor counties alone. Although only 11 percent of the basin's total land is developed, the development is concentrated along the river channel, placing human activities largely within the floodplain (Chehalis Flood Authority, 2010).

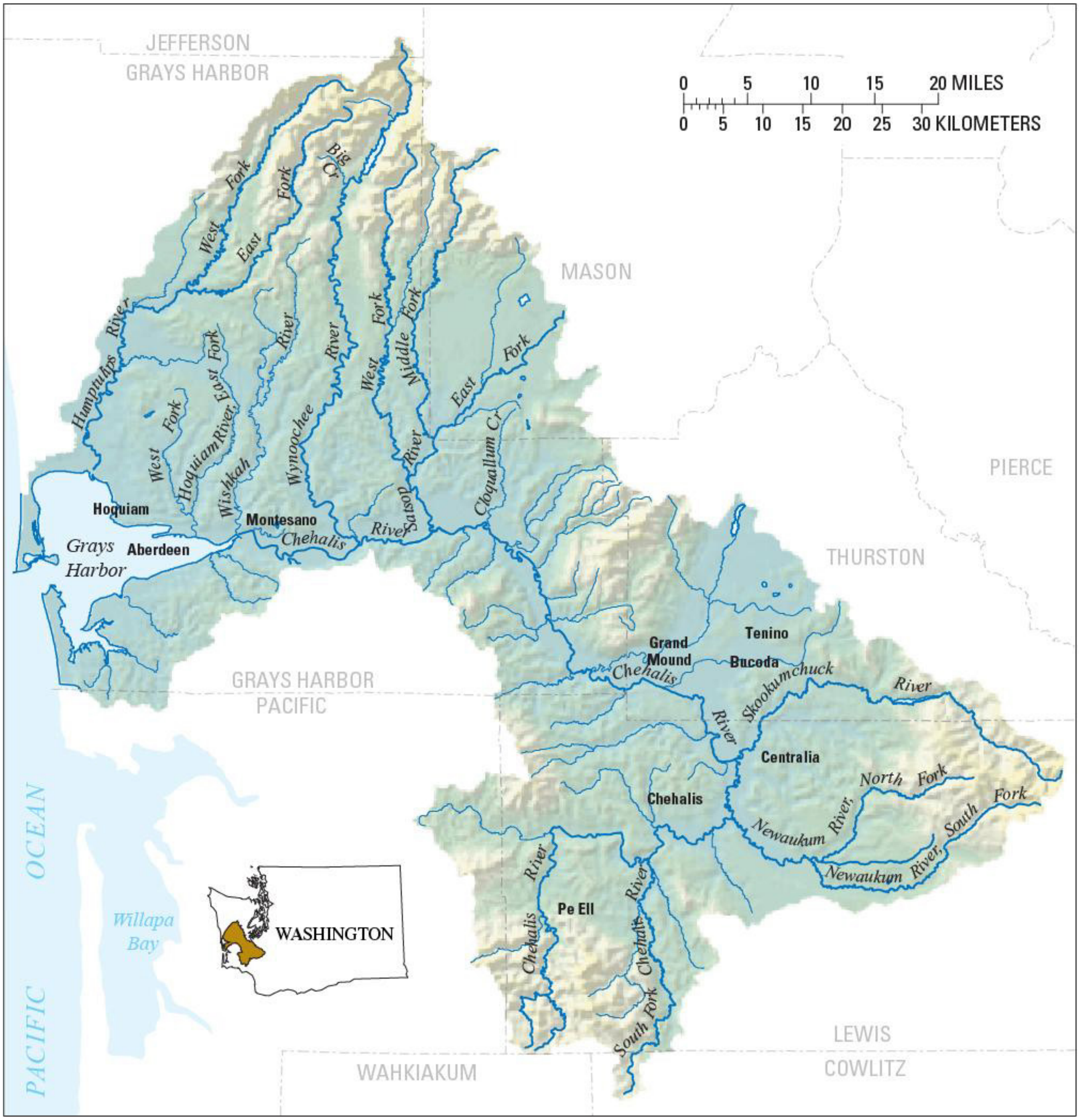


Figure 34 - Map of the Chehalis Watershed

(Washington State Department of Natural Resources)

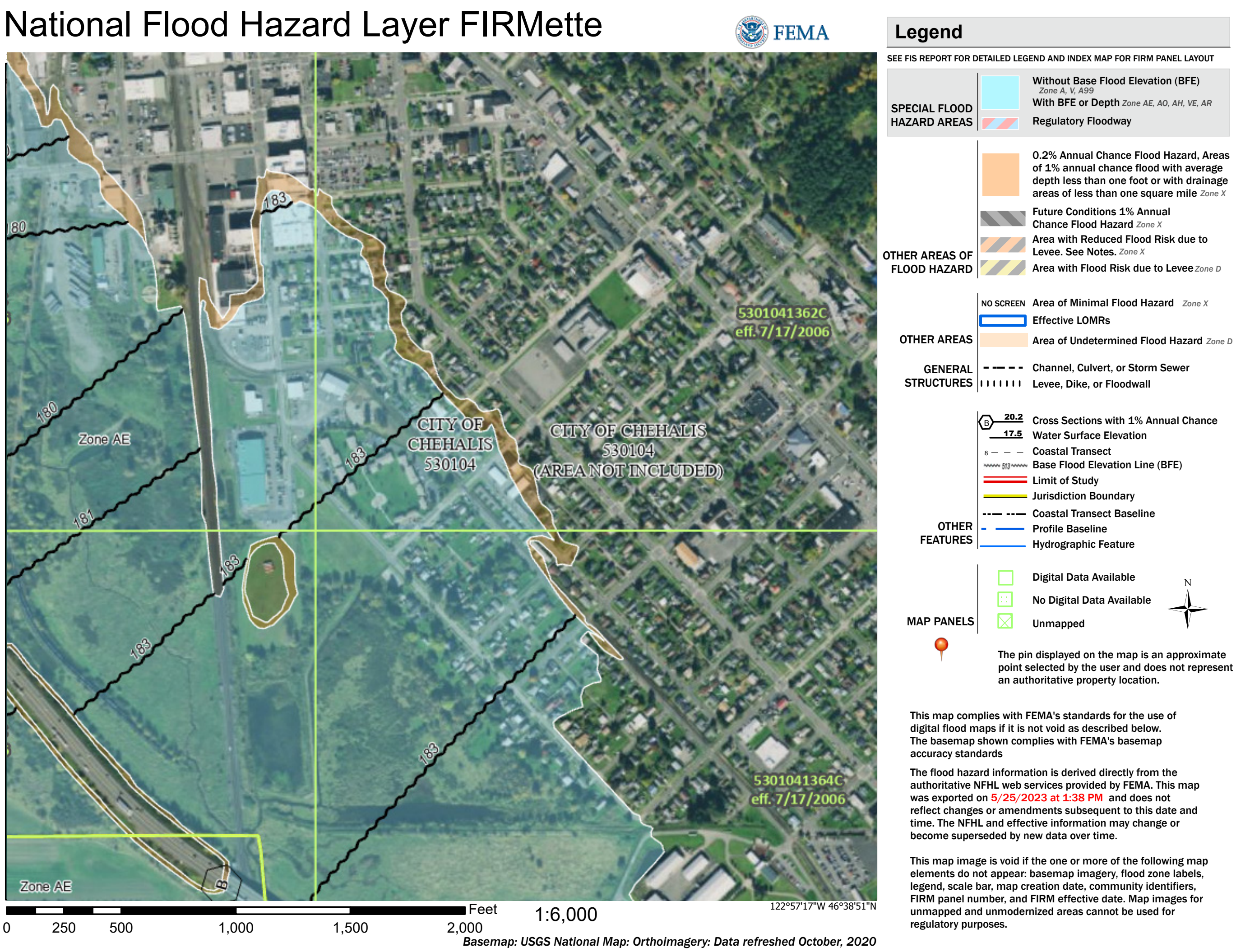


Figure 35 - Chehalis WA, FEMA FIRM Map

This map shows an area of Chehalis WA and the anticipated extent of flooding during a 100-year flood event. Substantial portions of the city are at risk for flood damage.

(FEMA 2006)

Figure 37 - 1933 Chehalis Flooding

This photograph from an unknown author shows flooding of the Chehalis area.

(Chehalis Historical Museum)

Flood Information

A flood, as defined by the Federal Emergency Management Agency, is the inundation of normally dry land with water (FEMA 2020). This generally corresponds to the level of water of a riverine system cresting the hydrologic floodplain, or the bankfull elevation. Flooding of the Chehalis River basin is a natural yearly occurrence. The seasonal shifts of the Pacific Northwest from summer drought to winter monsoon cause vast fluctuations in the flow of the river. The drastic, yet predictable, shift in flow leads to dynamic changes in the landscape. This region of the Pacific Northwest undergoes a drought and monsoon cycle that helps shape the biological landscape. Chehalis demonstrates a drastic precipitation shift because of this. November, often the wettest month of the year, averages 8.4 inches of accumulated rainfall. Contrasting to this is July's 0.8 inches on average ("Chehalis

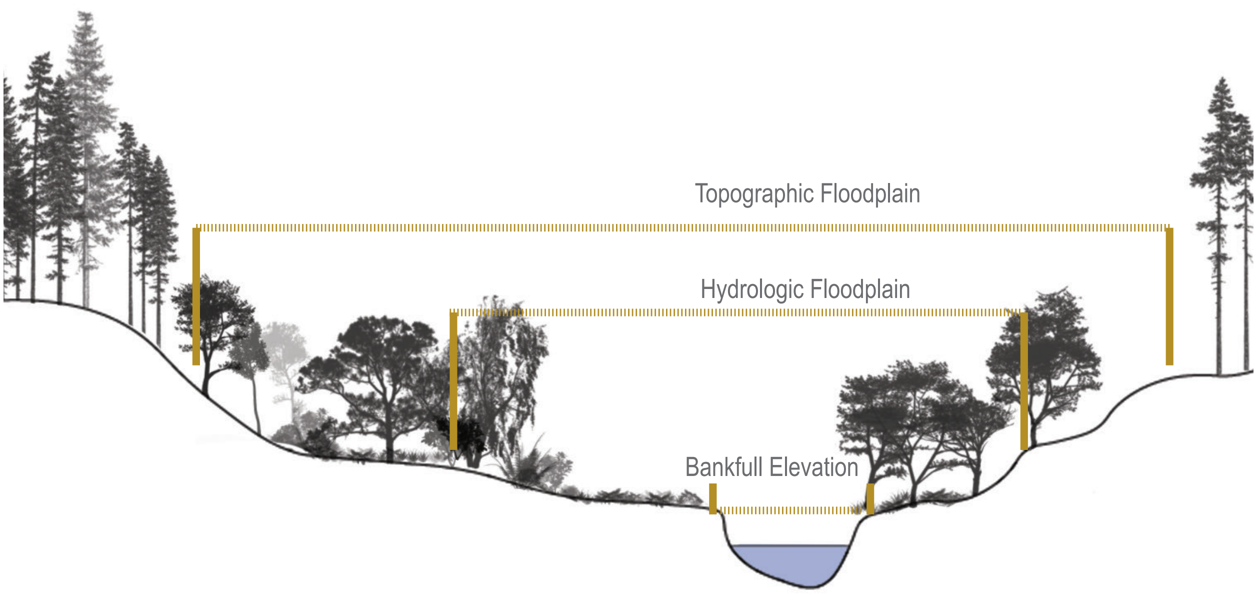


Figure 38 - River Stages

Climate" 2023). This causes a seasonal swelling in the watersheds. Normal summer flow for the Doty River gauge is 225 gallons per second. Normal non-floodstage winter flow for the nearby Porter gauge could be up to 57,000 gallons per second (Dept of Ecology 2023). The water year begins in October and ends in April, reflecting the end of the drought and the start of the monsoons. Floods occur during the peak of the monsoon season through the winter.

Both the Cowlitz and Chehalis Nations have histories of cataclysmic floods in the area. The flood reported in Cowlitz history was so severe that only the peak of *Lawelatla* (St. Helens) remained visible above the water and was mistaken for a canoe. The Chehalis Nation relate their origin to a particular flood event, which caused a cathartic exchange of spirits between humans and animals (McDonald and Fund 2017). Flooding has been a recurrent thematic element in many of the stories and histories of the indigenous people in the area (Washington State Department of Ecology 2020). The seasonal flooding influenced local Native American migration and food sources. Often, summer grounds or camps were flooded by river waters during the wet season. This would cause a migration to higher grounds where other food sources were in season.

Witten records by Euro-American settlers also track floods in the basin. Newspaper articles from 1887 described a flood: “Between Centralia and Chehalis, nearly the whole country was under water” (McDonald and Fund 2017). Major floods of the early Euro-American occupation of the area reported some loss of life, but primarily the disruptions were to railroad and livestock. As use and density of the area increased, so did the efforts taken to control the flooding and reduce damage. Concerted efforts began in 1931, when the Army Corps of Engineers released the first of three reports. These reports assessed the feasibility of flood management on the river. The Corps found flood control too costly to consider. It was only in 1954, with the installation of the new interstate highway, that large-scale construction on flood control was economically viable. The resulting 11 miles of levees, completed during with the highway’s construction, have not alleviated flood damage, but have been inundated with every major flood event in the area (Godwin 2020).

Major floods are those that, with statistical analysis, occur in 1% of all years. In the past 50 years, the Chehalis River has recorded floods of this magnitude in 1972, 1975, 1986, 1990, 1996, 2007, 2009, and 2022. In the past twenty years, four 100-year floods have occurred (Poor 2008). Of these dates, 1996 and 2007 qualify as catastrophic, where water is flowing at more than 75,000 cfs. Catastrophic events are frequently labeled as “500 year” storms. This implies that, in any given year, an event of this magnitude has a 0.2% chance of occurring. Philip Mote, out of the Office of Washington State Climatologist, draws into question designating these floods as “500 year”. He states that there is not enough known about the historical statistics of the past 500 years, and that there are too many assumptions about the hydrology of the area to make such a claim on their frequency (Mote 2008). Regardless, the trend of higher and more frequent floods is apparent. Nat

Kale with the Washington State Department of Ecology recently provides estimates using University of Washington Climate Impacts Group data (Chehalis Basin Strategy 2022; Sexton 2022). He offered that the basin currently experiences 14 major flood events a year. Under a moderate climate change scenario, that amount may increase to 33 by 2080. Additionally, the Chehalis basin will experience 25% more peak stream flows by 2080. This will culminate in the potential for major floods to have a 50% likelihood of occurring every year by the end of the century.

Ecological Functionality and Restoration Benefits

The ecological benefits of restoring a floodplain ecosystem are extensive (Williams and Reeves 2006). The consequences of restoration can positively impact habitat, economic outcomes, recreation opportunities, flood mitigation and countless more features of their systemic connections. They are frequently difficult (but not impossible) to measure. Moreover, they are nearly impossible to capture in one metric. Using a monetary equivalency is one of the only languages we can use to express the value of an object (Matzek and Wilson 2021; Good 2020; McElwee 2017; Schröter et al. 2014; Benayas et al. 2009). We can use fiat to compare it on the same metric to other disparate phenomena. There is benefit to this, as it provides an easily digestible and universal currency to the value of any one thing. The current value of a US dollar is widely understood on a global scale, easing the conversations around the cost/benefit analysis of ecological and economic factors. Application of US dollar language to natural phenomenon help to translate between the two value systems.

Ecological systems are inherently complex and interconnected. This is demonstrated frequently as continued research and observation uncovers new knowledge to explain the world. The benefits of ecological systems are not transactional or discernable in a point of sale. Urban ecologist Robert Costanza states: “A large part of the contributions to human welfare by ecosystem services are of a purely public goods nature. They accrue directly to humans without passing through the money economy at all. In many cases, people are not aware of them. Examples include clean air and water, soil formation, climate regulation, waste treatment, aesthetic values, and good health…”(Costanza et al. 1997 p.257). Ecosystems shift constantly; they migrate, transform, and fluctuate based on immeasurable factors. In attempting to evaluate the broadest set of factors to assess benefits, Costanza conducted a comprehensive analysis of various biomes in a 1997 paper. He attempted to factor in the wide-ranging and often invisible benefits provided by ecosystems. For example, Lakes and Rivers were estimated to provide yearly benefits of $17,154.84 per hectare, Floodplains/Swamps at $39,525.97, and Agricultural land at $185.72 per hectare (adjusted for USD 2023) (Costanza et al., 1997).

Another challenge in assessing ecological benefits is the issue of scale (Apostol et al., 2006). While the impact of planting a riparian buffer on water temperature is insignificant when measured on a small scale, the cumulative effect of restoration efforts across a 100-

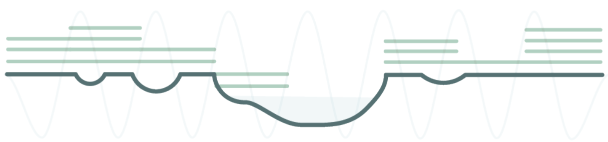
mile stream within a watershed may result in discernible changes. However, within this 100-mile stretch, numerous other changes may have occurred, making it difficult to isolate the specific effects of the restoration. The complexity of riparian systems has long been a challenge, and it was only in the late 1990s that science acknowledged the linkages between terrestrial and aquatic systems after an ambitious experiment (Nakano, Miyasaka, and Kuhara, 1999). Shigeru Nakano isolated a segment of stream using greenhouse-style netting. The isolated sections reduced the number of surrounding inputs and outputs on the stream's functions and allowed for simplification of tests to record results. In the context of the Chehalis River, the watershed is too large to isolate, so the economic effects of restoration may manifest as increased salmon recovery in Alaska.

Furthermore, the effects of habitat restoration may occur over a timescale that is difficult to quantify, control, or predict. Environmental changes operate on a longer timescale and are interconnected with larger events, making it challenging to isolate the specific benefits of restoration efforts. With climate change impacting the environment and human landscapes, quantifying environmental benefits from habitat restoration becomes even more complex. Aaron W. Jenkins' 2010 paper incorporated estimates from speculative carbon regulations. Jenkins estimates the current value of wetland services at $70/hectare. But with future carbon sequestration government buybacks predicted giving $4.20 for a ton of carbon dioxide gas removed from the atmosphere, that figure increases to a speculative $1035/hectare (Jenkins et al. 2010). A wide range of speculative quantities. Possibly because of the above reasons, evaluation metrics of ecosystem benefits vary greatly.

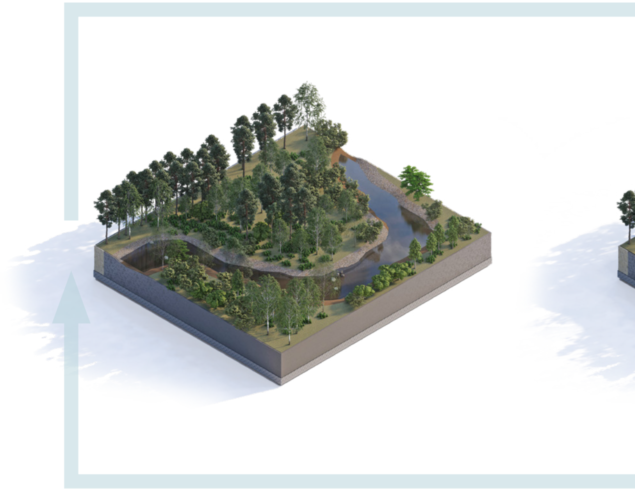
The ecological benefits of restoring floodplain ecosystems are extensive and interconnected, influencing habitat, economics, recreation, flood mitigation, and more. However, these benefits are challenging to measure and capture in a single metric. By using monetary equivalencies, such as the US dollar, we can provide a universal language to express the value of ecological systems and facilitate cost-benefit analyses. Nevertheless, the complexity and scale of ecological systems pose significant challenges in quantifying and isolating the specific effects of restoration efforts. The impacts of habitat restoration may occur over long timescales and are intertwined with broader environmental changes, such as climate change. Despite these complexities, recognizing the invaluable contributions of ecosystems beyond the realm of transactional value is essential for fostering a sustainable and harmonious relationship between humans and the natural world. Continued research, observation, and interdisciplinary collaboration will be key to better understanding and appreciating the intricate benefits of floodplain restoration and ecological systems as a whole.

Figure 43 - Fluvial Processess and Ecological Flood Mitigation

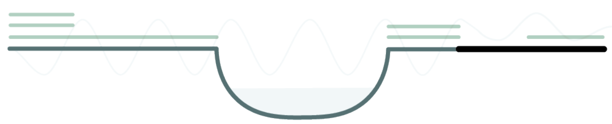
Ecologically Functioning Floodplain



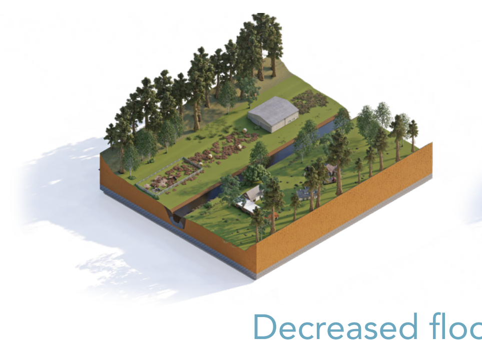
In constant flux, an ecologically functioning fluvial system engages the entire floodplain. It actively fills and dredges new channels, encourages water to interact with soils, and pulls organic material into the channel.



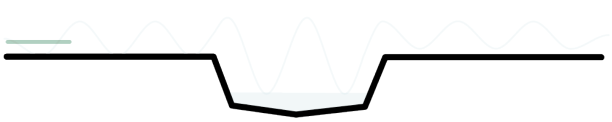
Transitional Degredation/Rehabilitation



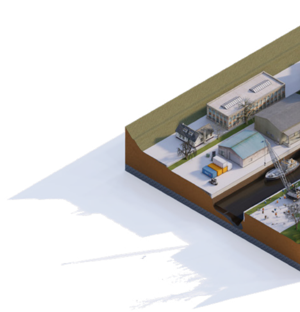
Altering the environment of the watershed influences the characteristics of the river's flow. Straightened channels increase flow speeds and entrench the streambed. Less water is held in organic materials and soils, causing flooding downstream.



Limited Ecological Processes



A fully developed waterway uses the built environment to convey water quickly through the landscape. This reduces local flooding, but exacerbates downstream conditions as water volume is concentrated and displaced.



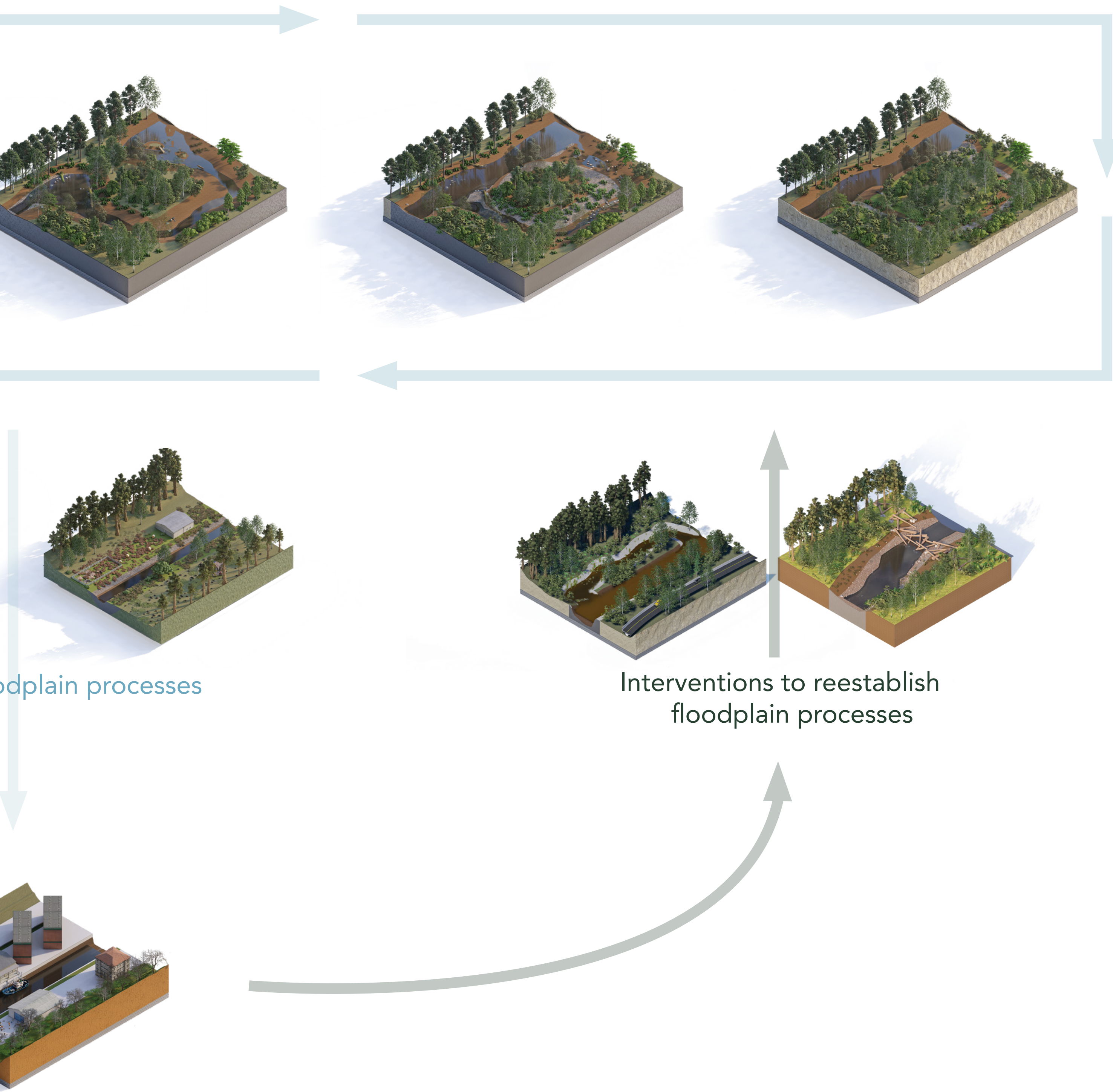

dplain processes
Interventions to reestablish
floodplain processes

Figure 45 - Ecological Functionality Example: Oxbow Formation 1

Oxbow Formation

An oxbow is a curving meander of a river and freqently results in a lake bearing the same name. These lakes offer excellent habitat, increase floodplain width, and also store water during seasonal floods.

Conditions

Oxbow formation is most common in flat areas that are rich in silt. The silt deposits when the water is calm, yet is still able to be swept away during periods of high flow.

Vegetation

Fast growing species that enjoy high sun and disturbance thrive in dynamic floodplains. Species such as Alnus rubra , Populus balsmifera, Rubus spectabilis, and Carex obnuta are common.

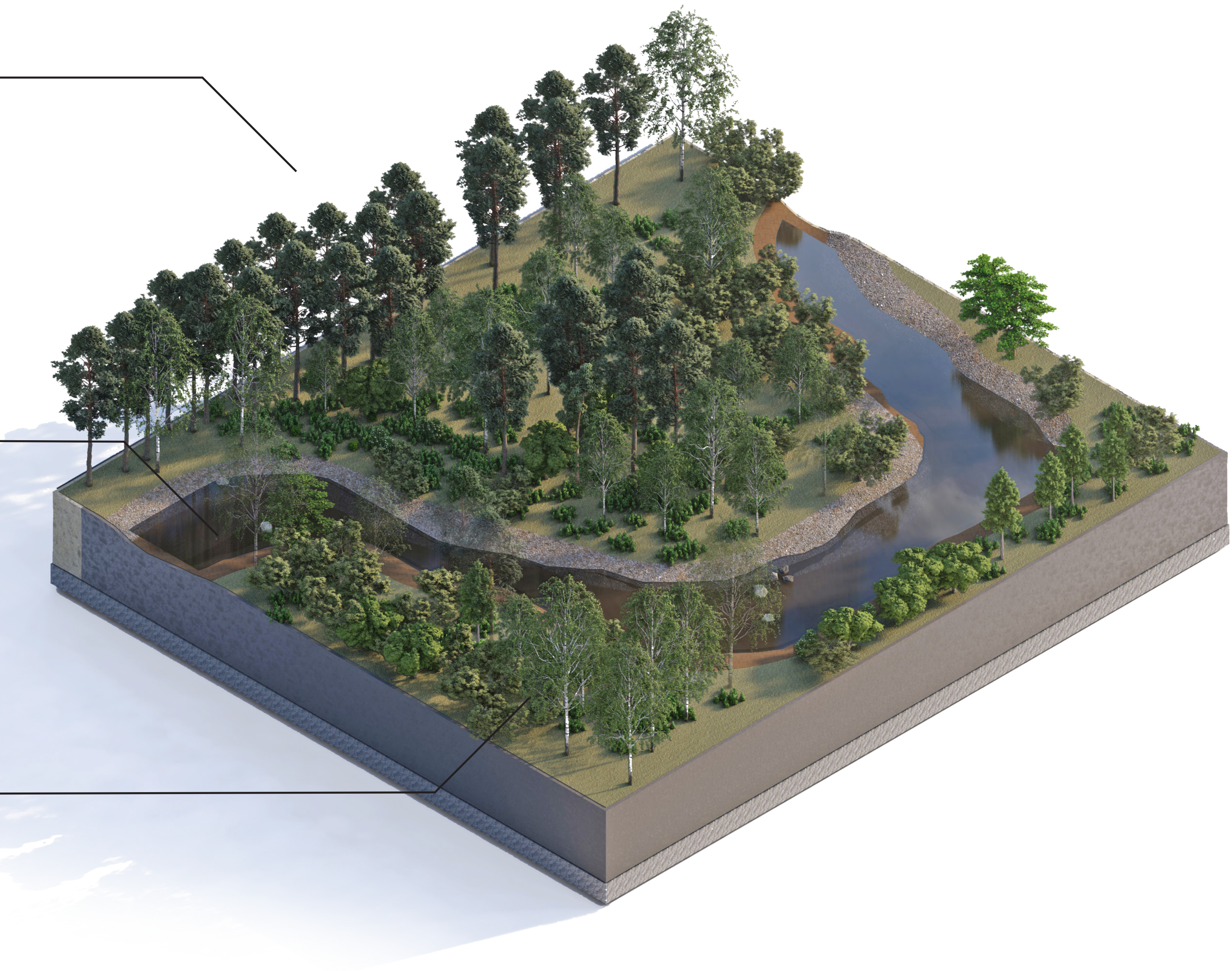


Figure 47 - Ecological Functionality Example: Oxbow Formation 2

Dynamic Events

Periods of intense rain increase the erosive energies in the floodplain. While they often take tens of years to cycle, extrodrinary rain events will rapidly accelerate these shifts.

Silt Deposition and Erosion

As silt is removed from areas of high energy, it is deposited as water slows in pools. These areas of low energy allow the sediments in the water to drop

Primary Channel

The primary channel still serves as a thoroughfare for water, but water no longer flows through it without difficulty.

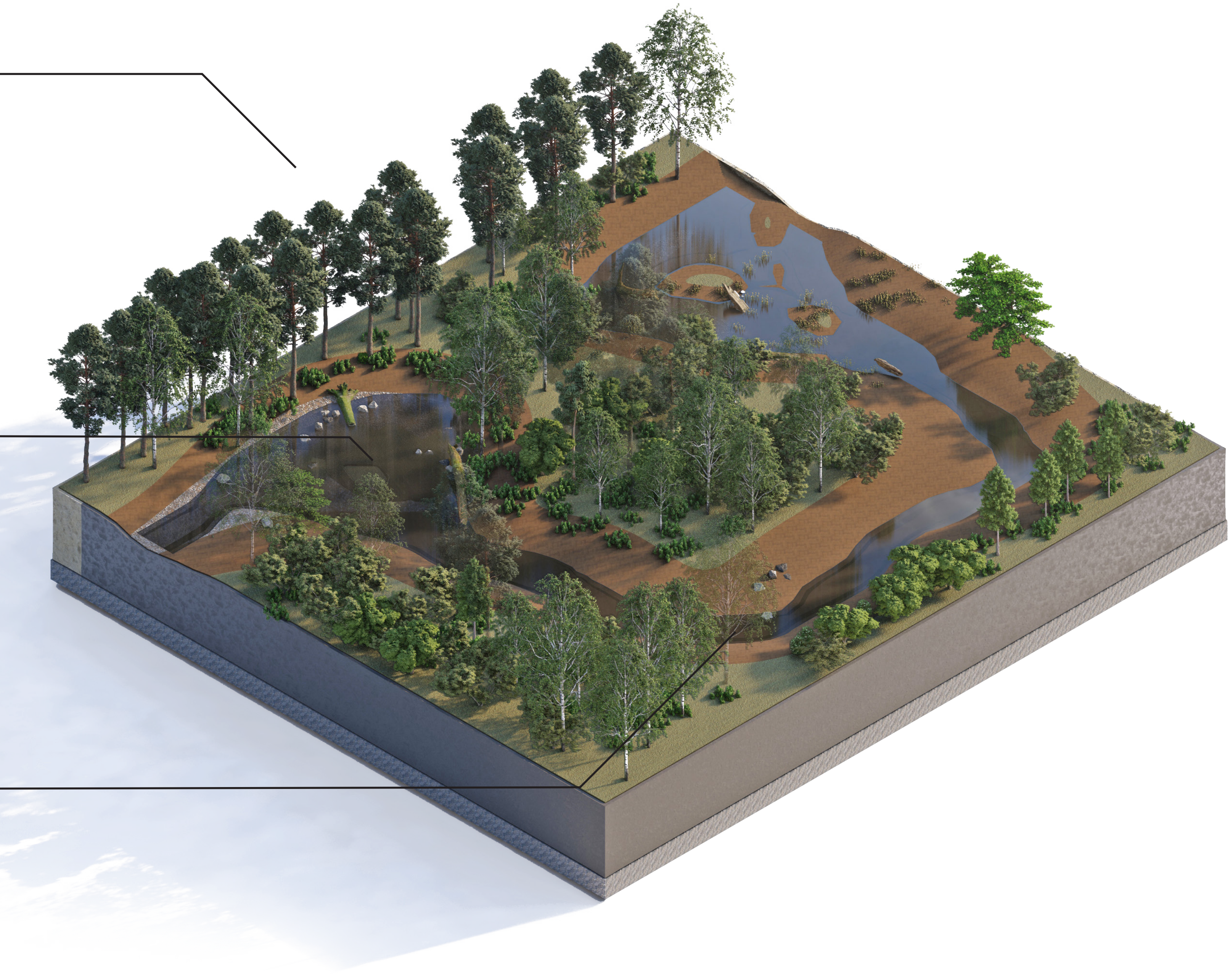


Figure 49 - Ecological Functionality Example: Oxbow Formation 3

Stable Banks

Stream banks lined with mature vegetation is more resistant to erosion. The roots of large trees hold soil in place. These banks do erode, however, and provide recruitment of large woody debris, a critical ingredient in river proceeesses.

Breaching a New Channel

Eventually, water will crest over the bank and follow the shortest path downhill. The breach widens as more water flows over and through it. Eventually, a new channel is formed.

Marsh Lake

The flow through the side channel reduces drastically as the new channel matures. The flow of water may only reach this area during seasonal high flows. This change in hydrolic cycles causes a shift in the vegetation and habitat on the side channel.

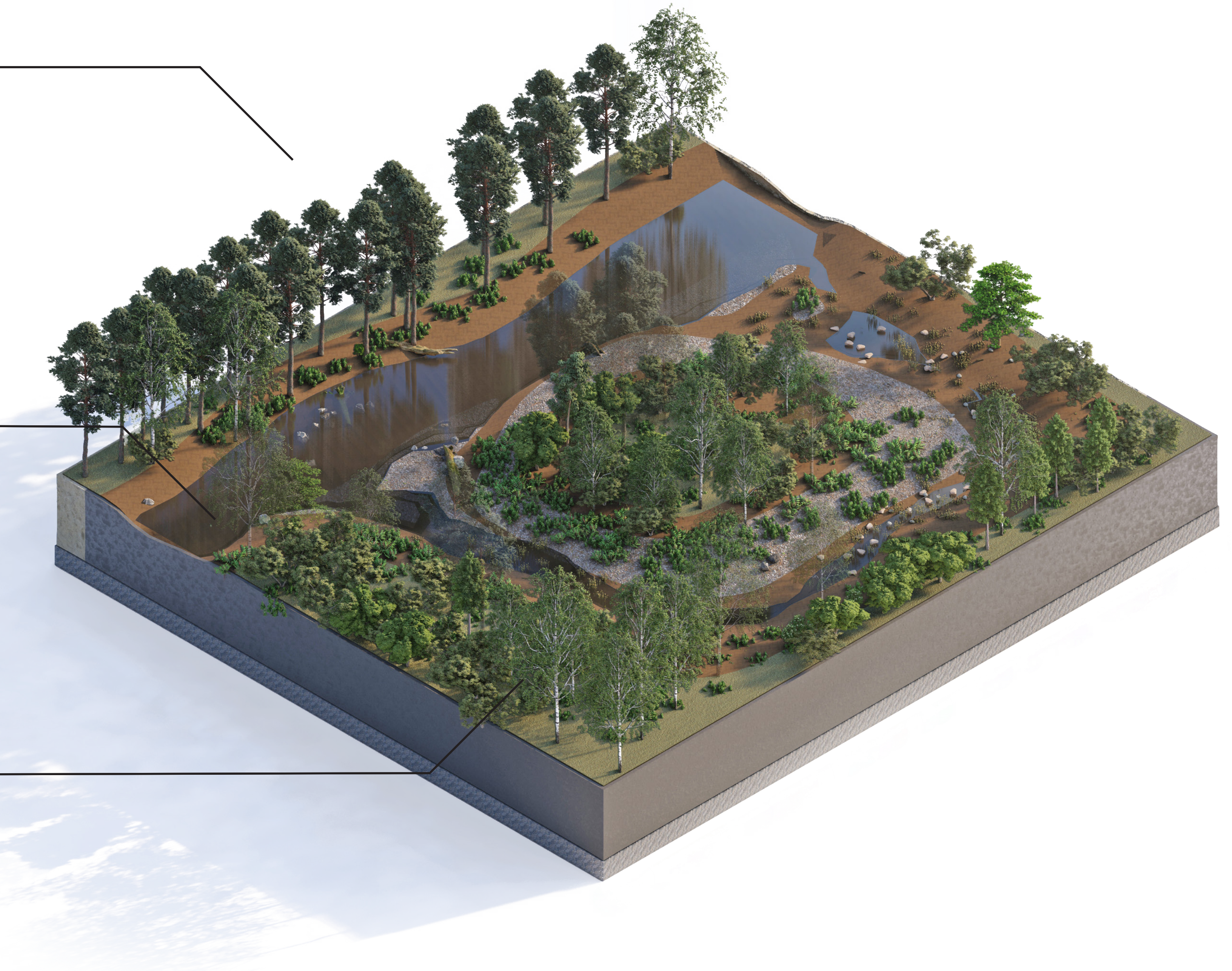


Figure 51 - Ecological Functionality Example: Oxbow Formation 4

Oxbow Formation

This cycle will continue as long as the river is allowed to roam its floodplain. Often, it is triggered by land slides or a large tree falling into the channel.

Vegetation Fills

The vegetation will continue to mature successionally. Eventually, large tree species adapted to wet conditions will take root. More often, however, the river will return to this section and remove many of the trees established here.

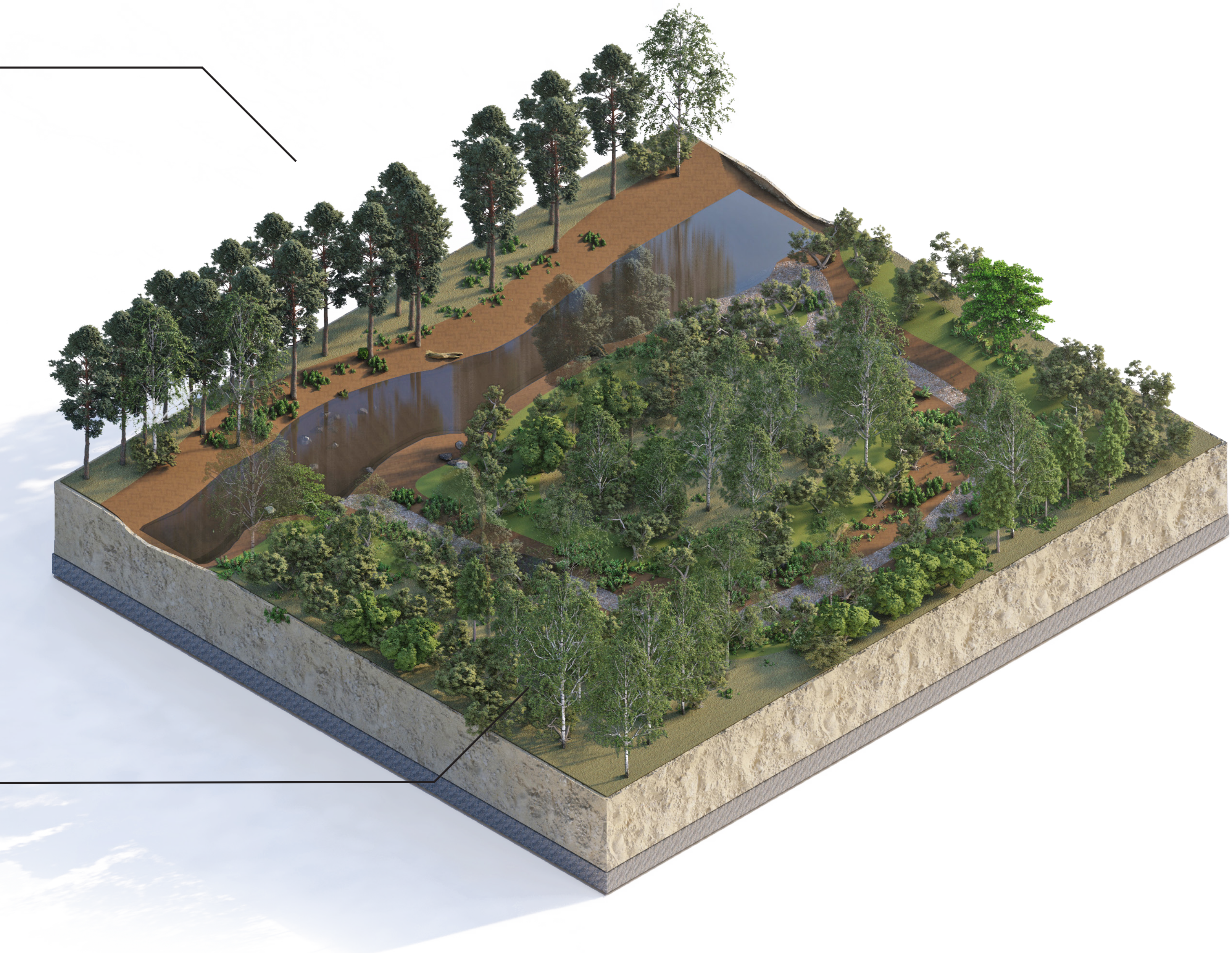


Figure 53 - Fluvial Processess and Ecological Flood Mitigation

Oxbow Formation on the South Fork of the Chehalis River

These series of satelite images show the formation of an Oxbow curve in the river. A series of major rain events occured between 2006 and 2008, causing the most dramatic shift.

1990 **2006** **2012**

2014

2017

2021

N

200 ft.

(NOAA, LANDSAT, COPERNICUS, GOOGLE)

Proposed Flood Management Strategies

Proposals are being examined by the local authorities to fund new systems of flood mitigation. These proposals are being led by the Washington State Department of Ecology's Chehalis Basin Board and explore a broad range of strategies. The Chehalis Basin Board is a task force within the Department of Ecology and was formed in 2016 as an expansion of the Chehalis Basin Work Group (Chehalis Basin Strategy 2016). The Board represents a broad array of local interest groups ranging from government officials to tribal leaders and is responsible for soliciting and evaluating these proposals before their implementation.

Two primary proposals characterize the changing thought processes of flood management strategies. The first is a water retention dam and levee expansion, which illustrates the conventional paradigms in grey flood mitigation strategies. The grey infrastructure strategy is sponsored by the US Army Corps of Engineers and the Chehalis Basin Flood Control Zone District [sic]. The second, known as the LAND alternative, is an approach which integrates riparian restoration strategies with conventional, though less intensive, structures than the proposed dam. The LAND alternative, while including alternatives to heavy dam construction, still relies on the expansion of a large levy network. This alternative allots only a third of its $1.9 million budget towards direct restoration. Additional funds for larger land modifications fall under part of its conveyance budget, which accounts for another third of the cost. Direct funding towards levees are the final third of the budget (Dept of Ecology 2023). These funding allotments show that only a third of the budget for the greener alternative goes directly towards restorative practices that would alleviate the causes of flooding. A full two thirds of the mindset is driven by engineering solutions that would shift impacts elsewhere in the floodplain.

Such strategies will have a substantial impact on the livelihood of those living and working in the watershed. If no action is taken, then flooding will persist at current levels and will become increasingly severe due to predicted climate change effects. With repeated damage exceeding the tens of millions of dollars and predictions of flood waters rising, action to alleviate these issues is a high priority (Office of Chehalis Basin 2018). Management of the watershed will determine the future flooding characteristics. A levee can block the erosive energy of water, but not dissipate this energy. If the energy and amount of water is maintained, then the only effect is the displacement of its impact. In an artificial system, the displacement then becomes a choice of where to send the impact.

Conventional tools can control displacement of these effects but not reduction. A dam can control the flow, but not the total amount of water that must be addressed.

Flood Management and Social Justice

Marginalized communities have shouldered the burden of environmental degradation throughout the colonial history of the Pacific Northwest. This is a global phenomenon, as indigenous communities are frequently identified at being at the highest risk for damages from climate change (Laduzinsky 2019; "Conference on Indigenous Peoples and Climate Change" 2008; OAR US EPA 2022). These groups have felt this burden even as their agency over floodplains decreases. Indigenous peoples have managed the environment and floodplains since time immemorial and hold deep knowledge of natural systems and how humans can modify them (Mann 2006).

A recent study of indigenous Nigerian flood control methods found that their methods were 63% effective in flood damage risk reduction (Obi et al. 2021). Studies like this help to highlight the legitimacy of indigenous responses to land management that run parallel to western science-based solutions. A study of Pacific Northwest indigenous

Figure 57 - Levees on the Chehalis River

(Chehalis Basin Flood Control Zone District)

opinions by Floodplains by Design interviewed tribal land managers. A prevalent theme to their interviews was that Western management centered around the protection of property, as opposed to the general health of the landscape or the cultural significance of human relationships with the river: "[the] respondents felt that [Floodplains by Design]'s grant program prioritized human property over salmon recovery, and thus resources are disproportionately allocated to those who have continued to develop in the floodplain, further degrading habitat" (Zimmerman 2022).

Increasing urbanization and density of land use has made this choice a highly political issue for several reasons. The choice of harm displacement implies that there will be parties that benefit more than others. Likely, even, parties that suffer for the changes enacted in the floodplain. In the past, the negative externalities of dominant society's choices have been absorbed by marginalized groups and the environment. A dam which disrupts national sovereignty, natural systems, and historical ties to the landscape would be judged as worthwhile because those affected do not hold value in the dominant social hierarchy (World Commission on Dams 2020). The proximity to urban centers places a spotlight on the politics of these decisions. It draws in diverse interest groups and subjects the project to scrutiny that a smaller or less expansive project may not feel. Increased political power

Figure 58 - Restoration on the Chehalis

(Chehalis Basin Lead Entity)

given to marginalized groups by the relatively progressive Washington State government has allowed more agency to the natural world and Tribal Nations.

The watershed's future requires a confluence of voices in the outcomes of these new flood management strategies. The Chehalis River has historically been challenging in this sense—our conventional politics, outreach, and flood management strategies have been inherently biased. This has led to perpetual conflict between interest groups in the valley. If the conventional flood abatement strategies are those of harm displacement, then the only tools available to mitigate flooding are implemented with social bias. Expansion of the proposed restorative alternatives to the dam have a chance to disrupt these patterns. Restoration of floodplains must incorporate multiple voices and centralize the experiences of the indigenous keepers of the land (Zimmerman 2022; IUCN 2014; Robinson et al. 2021). Within the Chehalis watershed, the Confederated Tribes of the Chehalis Reservation and the Quinault Indian Nation have already engaged in the dialogue of flood control. Empowering these communities to influence the outcomes of managing the Chehalis River is essential in a just outcome.

Proposed Flood Damage Reduction Project

With increased pressure on flood control infrastructure, the leading proposal to alleviate these issues is a series of grey infrastructure projects. The largest of these is a Flood Damage Reduction Project (FDRP) near the town of Pe Ell. This retention facility will store floodwater in a valley during periods of excessive rain. The water would be held behind a dam and accumulate up to 65,000 acre-feet of volume. The temporary reservoir would stretch 5 miles upstream, filling a drainage basin. Over the following month this water could be released at a determined rate, allowing a temporary abatement of the surge of stormwater down the valley. The structure itself would be 1,500 feet long and 270 feet high. When not in use, the facility would open conduits and allow the river to flow at standard volumes (Chehalis River Basin Flood Control Zone District 2019).

The dam would help mitigate events that are expected to occur at 7-year recurrence intervals. The rate of flow to trigger its use would be a measurement of 38,800 cubic feet per second at the Grand Mound river gauge. It would be able to release water at a rate of 6,500

Figure 62 - Render of Proposed FDRP Near Pe Ell, WA

(WA DNR)

cfs. when safe to do so, allowing for a drawdown of downstream surface water elevation. (Chehalis River Basin Flood Control Zone District 2019). The plan also incorporates a fish passage feature and expanded levees in other areas of the floodplain. The resulting dam and flood control projects would have significant benefits to flood damage reduction downstream. Estimates to the effects show significant positive improvement to flood attenuation throughout areas that previously had issues with flooding. With catastrophic flood scenarios, all the area downstream of Pe Ell to the confluence with South Fork of Chehalis would no longer inundate—a water depth reduction of up to 8'. Within the City of Chehalis areas that had previously been inundated in extreme scenarios would see water reduced by 3 to 5'. This would reduce the number of structures inundated from almost 3,000 in the non-action alternative to 1,280 in the FDRP (WA Dpt. of Ecology 2020). These estimates are conclusive for the positive impacts that the project would have on the human environment.

The construction of the retention dam, while providing benefits to downstream flood damage reduction, will cause significant ecological and cultural damage (WA Dpt. of Ecology 2023). As a requirement for considering the proposals, the project must undergo regulatory review. Federal law under the National Environmental Policy Act (NEPA) requires an environmental impact statement (EIS) to be prepared. The EIS contains a

Figure 63 - Site of Proposed Dam Near Pe Ell, WA

(Crosscut)

summary of the project, the anticipated environmental and cultural impact of the project, and possible alternatives. This process also accompanies a system of public review that can comment on the project and is concluded with the issuance of a Record of Decision that summarizes the agency's decision and any modifications to the plan needed (US EPA 2013). The federal EIS for the dam project was completed by the U.S. Army Corps of Engineers. The state of Washington requires similar reporting under the State Environmental Policy Act (SEPA). This process is administered by the Washington State Department of Ecology. In February of 2020 the SEPA draft environmental impact statement for the Flood Damage Reduction Project was released. This plan outlined the project, potential impacts, and mentioned proposed alternatives as required by SEPA. Enumerated in the SEPA, the anticipated negative effects of the FDRP are as follows:

- Removal of 90% of trees over 600 acres in the retention area.
- Elimination of 11 acres of wetland, 333 acres of wetland buffer, 441 acres of stream buffers and 17 miles of streams.
- Severe and lasting modification of the preceding 13.8 miles of Chehalis River headwaters.
- Significant changes to sediment transport and substrate in the river.
- Significant negative impact on the aquatic species in the area through changes in water temperature (2° to 9° F), dissolved oxygen reduction, increased turbidity during storm events, reduction of suspended organics, and super nitrification of water.
- The construction of the concrete structure would emit 123,439 metric tons of greenhouse gasses (WA Dept. of Ecology 2020). That amount according to an EPA greenhouse gas emissions equivalencies calculator, would require an offset of two million trees allowed to grow for ten years (OAR US EPA 2015).
- Removal of recreation from almost 14 miles of the resulting landscape.
- Reduce opportunities for recreational fishing and hunting throughout the watershed.
- The inundation area would affect areas culturally sensitive to local tribes. Nine identified archaeological sites would come under stress from inundation, increased erosion, burial beneath sediment, and accelerated deterioration (Washington State Department of Ecology 2020).

The Chehalis River Basin Flood Control Zone District (CFCZD) will comply with the Washington State Department of Ecology requirement that there be no net loss of ecological function. Their strategy for compliance with this requirement is through remediation opportunities throughout the watershed. In a memorandum on the topic, the CFCZD stated that "… mitigation is technically feasible, and sufficient mitigation opportunities are available to mitigate for the anticipated project impact to aquatic and terrestrial habitats and species" (Kleinschmidt Group 2021 p.6). To do this, the CFCZD will:

- Reforest 924 acres of riparian buffer area.
- Conserve 100 acers of upland, implement 34 channel habitat enhancements.
- Place 50 log structures.
- Replace 5 barriers to fish movement.

This assessment is based on judgements made to estimate the scope of interventions needed to achieve "ecological lift" in mitigation areas (Kleinschmidt Group 2021). Reviewing the accompanying documents, some concerns should be noted. The planting plan proposed by HDR Engineering relies heavily on the quick growing Alnus rubra to repopulate the deforested area behind the dam and in mitigation areas. Red Alder has benefited from human expansion. Previously localized to areas of geologic disturbance, alder often uses its ability to thrive in disturbed areas to benefit from logging activities. Studies have shown that overpopulation of Alnus species in the Pacific Northwest have led to a super nitrification of waters. This over nitrification is having adverse effects on riparian ecosystems (Rucker and Kangas 1974; Fidler and Miller 1994; Kovac, Pleizier, and Brauner 2022). The use of Alnus deliberately as a replacement species for the mitigation efforts is an example of simplifying and reducing complex ecological systems- a practice which often leads to unintended consequences. The planting plan does not consider the potential for climate change to affect the growing conditions of the mitigation areas. The planting plan and plant selection is based on traditional "native plant restoration" ideals that have been used in the past decades.

The proposal of this dam in 2019 created expected controversy. Proponents of the project believe that the immediate and direct benefits from its construction would provide safety and continuity to people living in the downstream area. They see the impacts of the construction as a necessary and acceptable tradeoff to ensure effective flood control measures. Proponents can point to the fact that only 10 spring salmon spawned in the area last year ergo, a 100% loss of salmon run would be 10 fish. (Godwin 2020). Opponents stress that the social, environmental, and financial costs of the project are not worth the benefits (Sexton 2022). Tribal members and representatives fear that the creation of the dam will cause irreparable cultural damage and continue the trend of alienation and disenfranchisement that they have been subjected to for centuries (Zimmerman 2022; Quinalt Indian Nation 2022).

After increasing tension between groups, the Governor of Washington, Jay Inslee, issued a letter of direction to Laura Watson and Kelly Susewind, directors of the State Department of Ecology and Fish and Wildlife respectively. This ordered the halt to progress on the dam and an expansion of the scope of the project to incorporate more alternatives to the dam. Specifically, it required more involvement of Tribal agencies and partners (Inslee 2020; Ryan 2020). With this order, the Chehalis Basin Strategy formed a sub-group called the Local Actions Non-Dam alternatives (LAND). This group's goal was to develop a holistic approach to flood management in the watershed to provide a contrasting voice to the leading dam strategy. Key to the approach was a recommendation report from a Seattle based firm – Natural Systems Design (NSD). NSD explored the concept of using ecological systems to provide flood mitigation throughout the watershed. This culminated in the presentation of a 2019 report that imagined that resulting landscape and simulated it using hydrologic software (Abbe et al. 2019). The changes proposed to that plan were called restorative floodplain strategies.

Restorative Floodplain Solutions

In 2016, the Chehalis Basin Partnership contracted with the riparian restoration and engineering firm Natural Systems Design. The lead hydrological engineer for the firm, Timothy Abbe, and a team produced a strategy, named “the Newaukum Report”, for restoration-based flood control through restoring ecosystem functionality throughout the watershed. The Restorative Flood Protection strategy, or RFP, was finalized in 2019 as part of the Advanced Feasibility Evaluation for the Chehalis Basin Strategy. This study evaluated the benefits of using RFP to solve issues of flooding within the basin. Restorative Flood Protection, as defined by Abbe, is an alternative approach to flood damage reduction that seeks to connect as much land as possible to the natural processes of the original river’s floodplain. Its goals, as stated in the Advanced Feasibility Evaluation, are threefold: to eliminate future flood damages and liabilities for subject areas, to decrease and delay downstream flood peaks, and the restoration of aquatic and riparian habitat within the treatment area (Abbe et al. 2019).

Ultimately, the study area of the Chehalis floodplain offered a disappointing outcome. It was found that the implementation of prescribed RFP techniques would only provide a reduction of 10-24% to annual flooding. Because of this, the RFP settled on two primary actions. The first action is the relocation of people and land use to higher ground. The second action is to restore the “natural hydraulic roughness and flood storage” of the valley. This will attenuate the speed of water returning through the watershed, reducing the acute height of the potential flood water (Abbe et al. 2019). Ecosystems that are functioning in complex ways slow and use the water throughout its journey through the floodplain. This works in the precise opposite way of conventional stormwater management, which seeks to convey the water as quickly as possible to its end point.

There are four engineered treatments proposed by the Newaukum Report in the Chehalis Basin. These elements work towards the goal of reducing peak inundation areas and slowing down floodwater. They achieve this by increasing the “roughness” of the landscape regarding the passage of water. Without obstructions, water passes through the landscape quickly, increasing its kinetic energy potential and reducing its time to contact the ground for infiltration. Slowing the flow of water throughout the watershed will allow more time for the dissipation of that water as it flushes through the streams, channels, and river basins.

Log Structures

Engineered log structures reintroduce large woody debris into the floodplain and stream channel. Recent practices have prioritized the removal of woody debris to increase channel throughput. When present, these logs perform many functions in the processes of the stream channel. As defined by the Stream Habitat Restoration Guidelines, large woody debris is considered by the state of Washington as having at least 10cm for 2m of their length (Cramer 2012). The large woody debris creates a barrier within the flow of water. It shelters and provides refuge for creatures of all types. This barrier not only slows water but serves to catch and recruit additional barrier elements. The slowed water is forced downward by the obstruction and has much greater intrusion into the ground at these areas. This helps to promote a healthy hyporheic area by creating “lateral hydraulic gradients’’ and recharges the groundwater table (Abbe et al. 2019).It also has the added benefit of cooling the water in the stream, which is artificially warm due to human interventions. Previous management of the watershed encouraged the removal of woody debris to aid the flow of water and navigability of the channel. This was brought about by logging, agriculture, splash damming, road building, urbanization, and flood control (Cramer 2012).

Grade Control Structures

Grade control structure, or incision treatments, seek to reestablish the historical floodplain braiding. These treatments are suggested to be used on areas like the Chehalis River basin that have had significant modification by humans. These modifications often concentrate the flow and create a scouring effect, trenching the river and discouraging meander (Cramer 2012). By placing sediment collecting structures across the span of the river, the incision present in the channel slowly fills with deposited materials. As it slows, water also backs up at these locations. This encourages overtopping of banks as the distance between the channel bottom and the bank edge decreases (Abbe 2016). The Stream Habitat Restoration Guidelines caution, however, that this approach is highly variable in its outcomes: “Structures are frequently designed and placed as fixed, static elements with outcomes that may achieve an initial function but that become inappropriate or even harmful to habitat as conditions change. This is particularly problematic given the continual successional changes that biological communities experience”.

Riparian Buffers

Reestablishing buffer areas of trees and shrubs along the river valley is important to continue to slow the flow of water along the drainage. Since the 1800’s, the Pacific Northwest has seen a 50-90% reduction in riparian habitat (Cramer 2012). This habitat offers critical benefits to ecosystems. As water rises, it inundates habitat that is usually dry. This habitat has a multitude of obstructions that block, detain, and absorb flood water (Abbe et al. 2019). Floodplains, as they are used now, are largely devoid of thick growth. The mechanical farming methods used by American farmers preclude the rough tangle that would benefit flood mitigation efforts. Farms offer little to slow the flow of water during flood events. They present flat, large, open areas of very limited vegetation. At most, crops such as corn stalks provide some amount of slowing to waters. But most crop fields are fallow during the flooding months of winter. They offer bare soil to be swept away by floodwaters. Buffers of riparian vegetation are generally thick and dense with woody stalks. Plants such as willow line banks of the pacific northwest thrive during flood events, which allow them to propagate from broken branches. Vegetation also serves to refresh log and other debris obstructions in the stream channels. Trees and fallen logs are carried into the stream channels, providing large woody debris. Restoration efforts are likely to fail unless the underlying cause of the environmental degradation is removed (Cramer 2012).

To further address the issues of flooding to agriculture, RFP proposes a series of flood protective practices to be established in floodplains of the Chehalis. Floodwater removes sediment from the farms that are devoid of retaining vegetative roots. This causes extensive erosion and subsequent deposition of this sediment elsewhere. Many farms extensively use chemicals to promote crop success. These chemicals are also swept away by floodwater, causing negative side-effects to natural systems. RFP suggests that farms in flood-prone areas use crops with woody and resilient structures, laid out the crops in such a way as to provide protection to itself and the surrounding soil, and use plants that are adapted to inundation events (Abbe et al. 2019). The study finds that the practice of agroforestry incorporates elements of flood-resilient agriculture design. Agroforests, it states, promotes the use of perennial crops, creates a vertical or layered structure of plant growth, and incorporates more than one crop type.

Critiques/Challenges

Revegetation efforts as described in the RFP are new to the practice of land management. In 2011, Susan Wall conducted a review of 1,340 projects in the inland Pacific Northwest to determine how successful revegetation was to the goal of restoration. Wall confronted substantial difficulties in finishing the assessment. Only 11% of those projects actually monitored the resulting sites after implementation. And of these 151 cases that were monitored, only 36 of these projects were able to furnish the data to Wall. Wall was able to shift the study to find commonalities of success and failure between projects. She interviewed and discussed these projects with land managers. This resulted in several summary findings. Wall discovered that successful revegetation projects included a thorough assessment of the site conditions and subsequently appropriate plant selection. Factors such as herbivory, plant competition, moisture, erosion/flooding/scour, and coarse substrate

Figure 71 - In Stream Structure

An engineered obstruction is inserted in the stream. The logs or posts serve to create habitat and to slow the flow of water. They also serve to catch or "recruit" additional woody debris, increasing their effectiveness.

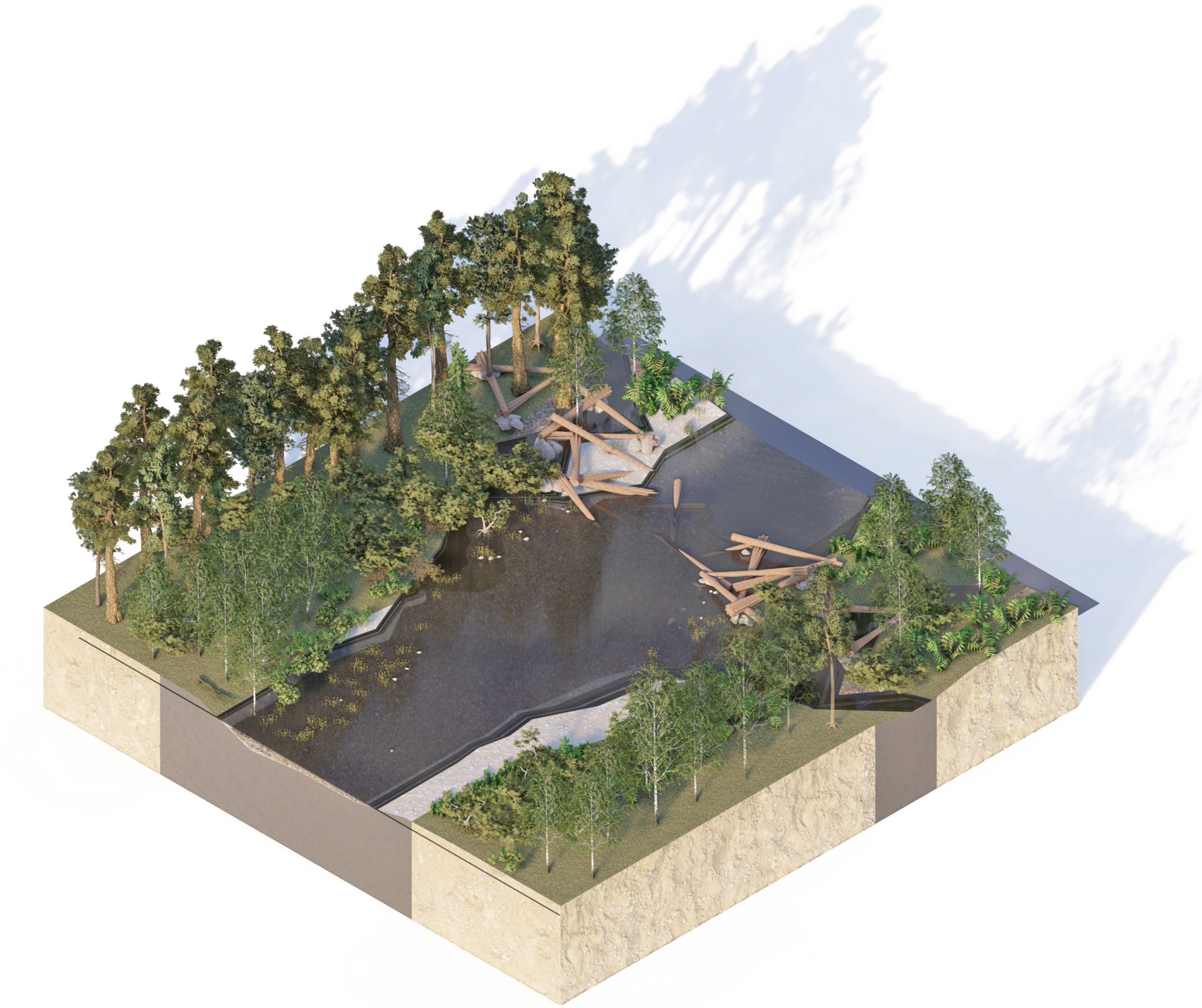


Figure 72 - Slowing Flow

The structure obstructs and slows the flow of water, simulating the natural pooling that occurs in rivers. Sediment deposits on the stream bed as the water slows, reducing freeboard and ensuring increased floodplain interaction.

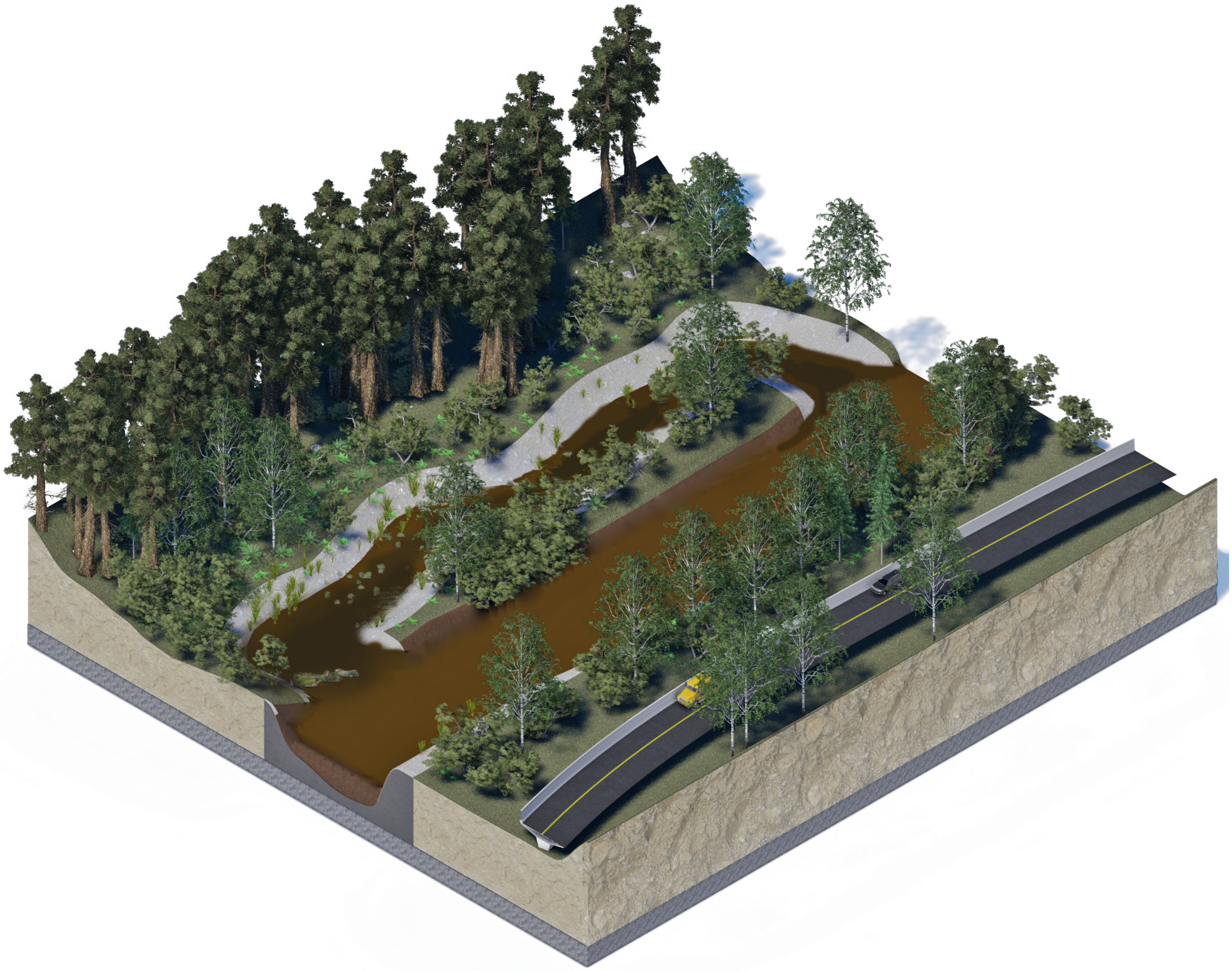


Figure 73 - Side Channel Creation

Engineered side channels allow for increased habitat and floodwater storage. They also increase the potential for marshland, one of the most carbon-dense and beneficial ecosystems.

contributed to the site conditions that needed to be considered before a planting inventory was developed. Furthermore, the interviews with practitioners resulted in a list of variables that they felt most contributed to success and failure. Those factors were: sufficient budget for vegetation installation, interdisciplinary approaches to the site plan, conducting an in-depth assessment of site conditions, integrating ecological concepts from past studies of revegetation, and taking a watershed scale approach to the revegetation (Wall 2011).

Basing their 2020 study on synthesis of fluvial modeling, Christos Theodoropoulos cautions against the current trajectory of river restoration. He sees that many efforts to design restoration projects use a "trial and error" approach. This, in his view, is doomed to failure and has substantial consequences due to the high cost of restoration projects. He found that benefits from restoration only occur with very specific species life stages, and only during near-dry flows in the river channel. The net positive benefits were small and deemed not worth the high costs of installation. Theodoropoulos suggests that implementing very restrained use of in-stream installations would produce better results. Additionally, these installations must be very specifically designed for target species. He implies that the high cost and specificity of these structures must be targeted towards species that will make the most impact to mitigate the future ecological impacts of climate change (Theodoropoulos et al. 2020).

Looking at the RFP in light of the advice from Wall, we can see that Abbe and the Chehalis Basin Restoration Plan must have taken these considerations seriously. The RFP conducted extensive interdisciplinary studies of the area, starting with background research into historical conditions. Multiple social factors, such as cultural heritage and contemporary land use were identified alongside traditional engineering site considerations. As stated previously, continual efforts in the basin reexamined the environment of the watershed due to the prevalence of flood damage. They took these assessments and compiled them into a comprehensive study of past conditions. Abbe and team found the previous geomorphology of the Chehalis River's meander and analyzed the resulting historical changes of vegetation (Abbe et al. 2019). Included in the report is also the synthesis of this information into guidance for planting under various conditions. The guidance on planting advises location, soil types, and other growing conditions to optimize success in revegetation efforts.

3 - Hydrologic Modeling

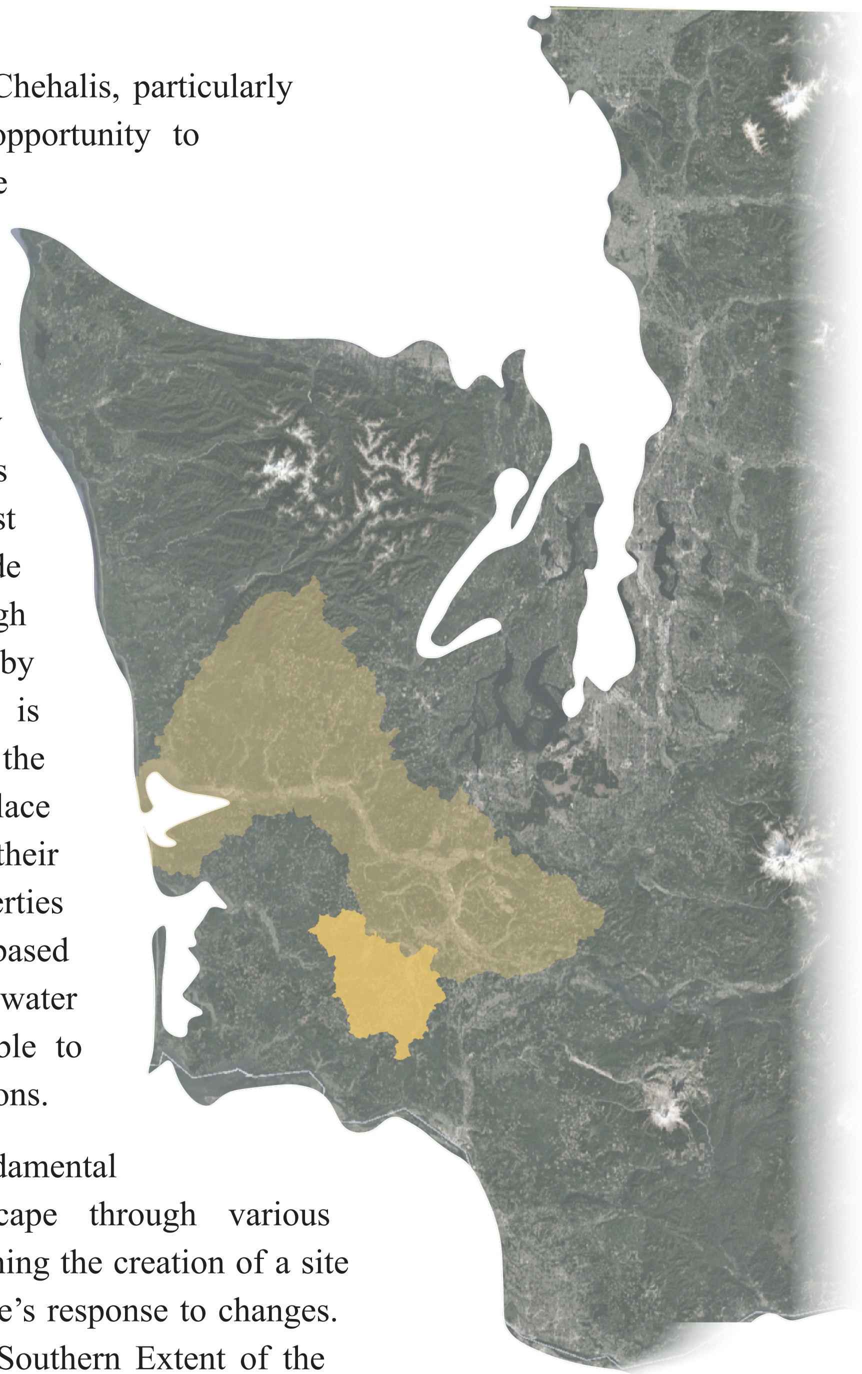
Overview

Testing of natural or ecologically based solutions to floodplain management has previously been limited to small scale interventions or region wide simulations. The European Commission found that more research into reach-scale projects would be beneficial to furthering nature-based solutions as common practice. Massive efforts are underway to find creative solutions to flooding in the Chehalis area. The 2019 Newaukum study found the effectiveness of nature-based solutions carried out in aggregate has some effect on mitigating low and moderate levels of flooding (Abbe et al. 2019). The Newaukum drainage, unlike the South Fork of the Chehalis, was notably more urbanized and had more stakeholders. Land managers will undoubtedly be looking for alternatives that provide similar benefits seen by the compounding small interventions proposed by Natural System Design.

The South Fork of the Chehalis near Boistford is a good candidate to explore aspects of the ultimate solution and examine under-explored reach-scale interventions. As part of a larger watershed, the South Fork of the Chehalis offers a landscape that is not urbanized and has relatively few parcel owners. Its land use is vital, though not immutable by government incentives. Through careful and deliberate analysis, interventions can be strategically placed to optimize their performance. As opposed to greywater interventions, which seek to control the landscape, nature-based solutions must be responsive to current, past, and future conditions. Various strategies for uncovering the essential characteristics of the landscape will be explored. These phenomena and processes will inform the subjective and objective creation of a site model to simulate the landscape's response to changes.

This thesis models the Southern Extent of the South Fork of the Chehalis and institutes landscape modifications at a reach wide scale. It discusses the concepts learned from the analysis of the site and subsequent observation of data. Finally, it synthesizes this analysis into succinct and tangible results. It shows that these modifications are effective in providing flood mitigation through attenuating peak flow, and that they increase the interaction between soil and water – thus increasing natural processes that benefit floodwater reduction.

The testing of natural or ecologically based solutions for floodplain management has traditionally been limited to small-scale interventions or regional simulations. However, the European Commission recognizes the need for research on reach-scale projects to advance nature-based solutions as common practice. In the Chehalis area, significant efforts are underway to find innovative flood management solutions. The 2019 Newaukum study demonstrated that aggregated nature-based solutions have some effectiveness in mitigating low and moderate levels of flooding. The study examined the larger watershed and tributaries, even breaking the areas into reach sections. The reach-level breakdown was limited to the Newaukum drainage area. Land managers in the region are likely seeking alternatives throughout the watershed that can provide similar benefits to the cumulative effect of smaller interventions proposed by Natural System Design on the Newaukum (Abbe et al. 2019).



The South Fork of the Chehalis, particularly near Boistford, presents an opportunity to explore various reach-scale interventions and aspects of future solutions. Compared to the more urbanized Newaukum drainage, the South Fork of the Chehalis has relatively fewer parcel owners and is less developed. Less divergent interest in the area provides more latitude for interventions. Although land use can be influenced by government incentives, it is crucial to carefully analyze the landscape and strategically place interventions to optimize their performance. Conflicting properties may conflict with this. Nature-based solutions, unlike traditional greywater interventions, must be adaptable to current, past, and future conditions.

This project will the fundamental characteristics of the landscape through various strategies and processes, informing the creation of a site model to simulate the landscape's response to changes. I focus here on modeling the Southern Extent of the

South Fork of the Chehalis and implementing landscape modifications at a reach-wide scale. I then explore the insights gained from the site analysis and data observations, synthesizing them into concise and tangible results. The findings demonstrate that these modifications effectively mitigate flooding by attenuating peak flow and enhancing the interaction between soil and water, thereby promoting natural processes that contribute to floodwater reduction. By presenting these outcomes, the thesis contributes to the broader understanding and implementation of nature-based solutions for floodplain management on a reach scale.

Site Selection and Characteristics

The South Fork site was selected to use as a case study for the implementation of various green flood mitigation properties. This reach would serve to provide a practical backdrop for the theoretical implementation of the solutions. Reach selection was important. An appropriate site would be vital to the project's methodological framework. Building on previous reports (LAND 2023, Abbe et al. 2019), the project aims to explore the feasibility and impact of green alternatives. By selecting a site with generalizing qualities, the findings can be extrapolated to other sites within the region. Additionally, the chosen site should be practical for implementing these strategies and possess favorable characteristics for restoration. It must exhibit generalizability to similar sites in the watershed while satisfying a set of specific criteria:

Free of Major Constraints

The site must not have any unusual or major constraints. Throughout the watershed, the river passes through, around, and under countless reminders of the impact of the built environment. All of these things must be considered for their necessity to the current environment. Both for the structures and systems that now rely on them and for the political or social importance of the features. Other features, such as a driveway, do not carry such high costs and are more mutable.

Agriculture is Significant

Agriculture should be abundant and typical of regional practices. Site selection is contingent on the presence and quantity of agricultural development. Green strategies require the space to grow and flourish, which is provided by the wide open spaces of agriculture. Additionally, the current farming practices feature crops that provide little benefit to the watershed's roughness and ability to slow the flow of flood water. The South Fork of the Chehalis River features a floodplain that is primarily used for agricultural purposes. Less than 25% of its flow is forested, with the majority being occupied by agriculture or turf (Abbe 2016).

Practical for Implementation of Design Strategies

The site must also be practical in size, scope and qualities that would allow for implementation of green strategies. The reach a total of 1033 acers in area. It runs for 18,520 ft. along the valley bottom with an average width of 2000ft. This ample width allows for several property parcels to be active in the floodplain, allowing several options for property acquisition for future planning and strategy implementation.

Stream Gauges Available

Stream gauge information must be available for study and use. To quantify the data used for hydrological simulations, sufficient historical measurements are necessary. The United States Geological Survey and Washington State Department of Ecology operate and monitor 29 stream gauges within the Chehalis River Basin. This limits the reach selection for the monitoring study to reaches that have measurable flow inputs. The station at the South Fork of the Chehalis River near Wildwood, WA has been active since 1996 and data easily available online. This river gauge captures the flow from the Southern reaches of the South Fork of the Chehalis River and enters an agricultural reach at approximately the location of the town of Wildwood.

Accessible

Wildwood road runs the length of the reach, often paralleling the river course. This road would provide moderate difficulty to relocate. It services residents, agriculture, and provides a major southern connection to Washington State Highway 506. Most of the surrounding hillsides are used for silviculture, and having access to the road is important to resource extraction at various times.

Landscape Heavily Modified by Humans

The Chehalis River and its tributaries border a major metropolitan area in Washington. Major human developments envelope it throughout and major roads parallels its flow. Some of these artefacts, such as I-5, possess a lot of political and economic inertia. In a report estimating the costs of I-5 closure during flood events, it was estimated that I-5's economic value to the region is $1.1 million dollars a day (Hallenbeck, Goodchild, and Drescher 2014; "Technical Advisory Group Meeting 6 Summary" 2021).

History of Floodplain Conditions

The Chehalis River, and its flooding, is present in several indigenous oral history accounts (McDonald and Fund 2017). The South Fork of the Chehalis was surveyed by the General Land Office during the major surveying of the area. Investigating reports and

Figure 84 - Scenes from the South Fork of the Chehalis River - Near Wildwood WA.

(GOOGLE STREET VIEW)

surveys from 1874 provides information on the character of the landscape at the time. The reports indicate many areas of marsh and an active floodplain (Berry 1874).

Not in a Previously Simulated Area

The 2019 report created by Natural Systems Design thoroughly simulated flood conditions throughout the Chehalis River basin. More detailed simulations were created of the Newaukum drainage system (Abbe et al. 2019). These detailed simulations included tests of landscape modifications that have inspired this project. Continued simulation of the Newaukum drainage system would provide diminished return.

Subject to Seasonal Flooding and Typical Qualities of Pacific Northwest Floodplain

The Chehalis River receives rainfall typical of the climate in which it is situated. It is comparable in character to many of its tributaries of similar orders. Additionally, the qualities are all general and typical for many of the rivers throughout the lowland Salish Sea.

Site Challenges

Despite meeting the requirements for several of the features, the site still had some qualities that will add challenge to the project. First, the average bank height is 12.1 ft. This indicates that the river is highly scoured due to concentrated flow in an established channel. The strategy to convey water as quickly as possible through a landscape causes that water to be concentrated into a specific channel. This channel gets a disproportionate amount of force exerted upon it from all this water. Over time, sediment is removed, and the river is entrenched into a deep channel. Most of the substrate below the river is exposed bedrock due to these forces. This does much to decrease the channel roughness. The majority of the South Fork Chehalis is scoured to this extent.

At 12ft. below the flood plain, a great elevation that must be overcome if the water is to make contact with the surrounding areas. The bankfull height of the stream is 4.6ft, leaving 7.5ft of freeboard to the floodplain in most locations. This is problematic for restorative practices, as it limits the treatment sites to those that are at specifically low areas. If that is not possible, then the creation of sediment beds through various means would be needed to decrease the difference in height between the floodplain and the channel bottom. This level of incision requires significant excavation to invite water into floodable areas. This

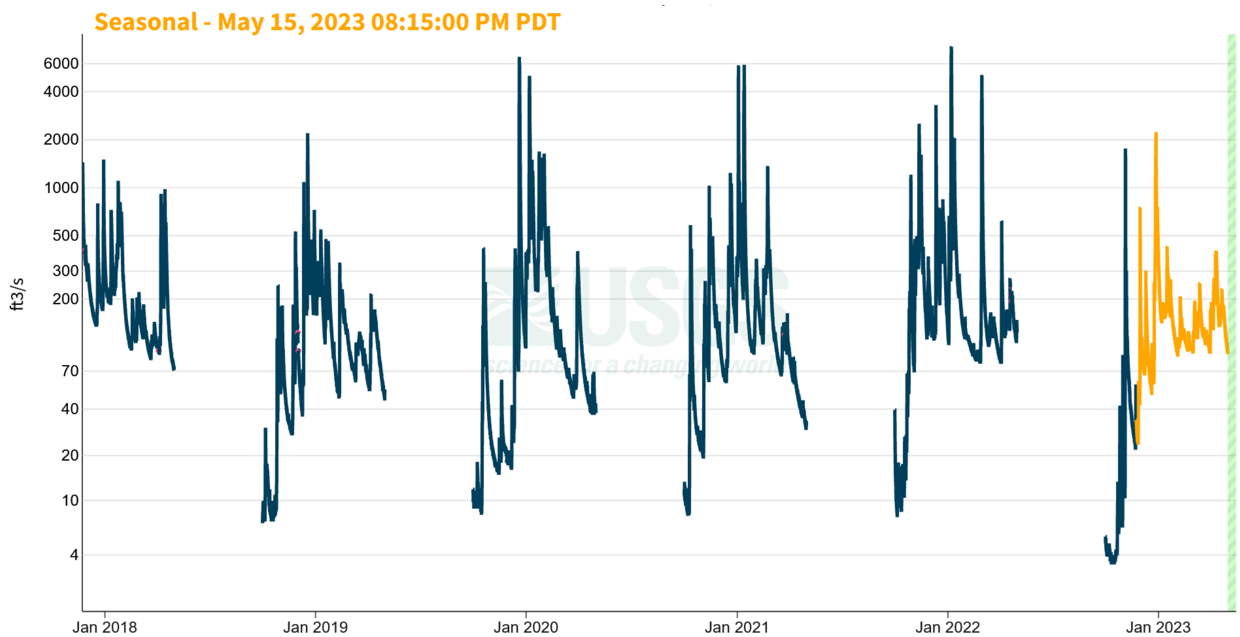


Figure 86 - USGS Stream Gague 12020900 Near Wildwood WA

Seasonal flow recordings for Wildwood, WA 2009-2023. Predicted quantities in yellow. (USGS)

level of incision also is indicative of a space that could be drastically improved by incision techniques that reduce bank confinement.

The location of the stream gauge at Wildwood is good for parsing out the flow rates at the mid-range area. The major drawback to the reach, however, is that there is not another stream gauge between the lower extents of the reach and the next major confluence. The next stream gauge is located after the South Fork of the Chehalis and the main Chehalis river meet near Millburn, WA. This limits the ability to calibrate the flow measurements against real time data or comparable realistic flow measurements.

3 - H


Google Earth
Dryad
RAINBOW FALLS STATE PARK
Ceres Hill
Ceres
Chehalis River
Bunker
Millburn
Adna
Littell
Claquato
Airport
Water Tank
Landing Strip
Curtis
Klaber
Boistfort
Prairie
Stillman Creek
Lost Valley
Halfway Creek
Beaver Creek
Stearns Creek
West Fork Stearns Creek
Crego Hill
Radio Tower
Buckhorn Hill
Radio Facility
Sam Henry Mountain
POWERLINE
Deep Creek
Lake Creek
Joy Mountain
Lookout
Boistfort Peak
Round Knob
Sure Shot Mtn
Little Mtn
Wildwood
RAILROAD
Clinton Knob
Ferris Peak
North Fork
Cougar Flat
LEWIS CO
LEWIS CO
COWLITZ CO
WAHKIAKUM CO
COWLITZ CO
Stillwater
Ryderwood
Pumphrey Mtn
6km
N

(L) Figure 88 - USGS Topographic Map of South Fork of the Chehalis River
(USGS)

Site Exploration

A landscape's natural inclination is to express itself as a manifestation of the systems that influence it. An area subjected to seasonal wetness will have specific types of soil, vegetation, geology, and so on. An area that is on a steep hillside will have deep rooted vegetation, small streams, and its vegetation will be highly influenced by its aspect. Landscape is always in flux, so these characteristics and attributes are subject to change, often in the form of long cycles. Humans, however, can interrupt, isolate, and overpower these relationships.

Information of past conditions is vital to the planning for future land use (Williams and Reeves 2006; Cramer 2012). For example, if a developer wants to build a shopping mall, they must figure out what kind of soil conditions would be right for that land use. Shopping malls enjoy a high soil acidity content and therefore are frequently located on top of historical bogs with peat deposits. These deposits could have been built over centuries while a wetland was developing dense mats of moss and vegetation. If the land conditions are not immediately apparent, this knowledge may be gleaned from several sources. The investigation of the South Fork of the Chehalis requires investigation into the conditions. Implementing design strategies centered around natural systems requires a deep knowledge of surrounding conditions. These conditions on every scale are expressed on the landscape and will have tangible effects on outcomes to any intervention.

General Land Office Surveys

Historical records can often inform restoration decisions (Williams and Reeves 2006; Cramer 2012). An excellent source of information comes from the United State's Government's General Land Office (GLO). The GLO was created in 1812 with the design to survey public lands owned by the Federal Government. The end objective was to take stock of the parcels owned by the Federal Government and sell them to smaller interests or agencies. Within 200 years the GLO created survey maps that spanned 1.5 billion acres ("Beyond Land Surveys" 2015). These maps show many areas of the West before major European-American occupation. At this time, the landscape was not yet modified by an industrialized force, and was under the stewardship of the native American tribes who managed the resources. These tribes used techniques that were often less invasive then their

European-American counterparts and the landscape is more likely to express a naturalistic affectation because of this.

To create the GLO maps, surveyors would start from a known point and create a measured grid, marked with stakes. They would then measure and mark the boundaries of the area and begin documenting its layout. The surveyors would then walk transects across the area, connecting the grid intersections to one another at one mile between intersections. As they walked, they would document the notable features of the terrain. These centered around natural resources such as streams, trees, mineral deposits, and more. Once a comprehensive survey of the landscape was completed, they would then document the results and produce a measured and certified map ("About the Public Land Survey System" n.d.).

The reports completed by Natural Systems Design for the Washington Department of Natural Resources features GLO reports in an early draft (Abbe 2016). Their report transcribes the notes, which are often pixelated and difficult to read. The South Fork of the Chehalis occupies two townships on maps created by the GLO surveyors between 1873-1874. The surveyors recorded several observations on the area, including that "The South Fork is a beautiful stream of crystal clear water averaging about 100 links [66 ft.] in width and from 6 to 18 in. of depth in shoals during September, which is the month of lowest water. The stream is capable of floating saw logs during nine months of the year" (Berry 1874). Additional comments noted that the timber, which is represented by white on the map, was 88% conifer. The river valley was said to be excellent for cultivation, and coal deposits were noticed on a sandstone outcropping (Berry 1874; Abbe 2016).

Relative Elevation Modeling

To further visualize the selected reach, I utilized a process of representation called Relative Elevation Modeling (REM). In this style of visualization, the elevation baseline is determined by the height of the water above the floodplain at any given point. This is indicated in another term used to define them: "height above river" representations. This differs from traditional depictions of landforms which are usually depicted in relation to elevation above sea level. This immobile baseline contrasts landforms against the relative height of surrounding areas, but cannot adapt to the subtle changes in topography on a smaller scale. The river, being on a persistent grade, is continually sampled in REM for elevation to reevaluate the relief representation of the surrounding area.

REMs are an excellent tool for uncovering fluvial processes and historical geomorphology. A leading proponent of the technique, Daniel Coe, cartographer with the Washington State Division of Geology and Earth Sciences states: "subtle elevation changes in relation to the river surface enable the delineation of fluvial features that would otherwise have been difficult to discern using photos or a DEM (digital elevation model)" (Coe 2016). Using the REM, the South Fork of the Chehalis River's character comes into more focus. We are able to see where the stream's meander has taken it over time. This is influenced by soil conditions, terrain height, water flow, natural obstacles, and human interference. Because we an infer the cause of previous deviations, we are able to gain insight as to the influences on the flow patterns of the river in a specific location.

The digital elevation model allows us to see straight sections of the river contrasted with winding areas. Its line is consolidated, and the coloration of the stream is solid. This indicates that there is little geomorphic deviation in the surrounding bed relative to the water height. Much of the South Fork of the Chehalis is deeply incised in this way. Because of the incision, this is a typical representation of many rivers. Additionally, the land surrounding the river has been tilled, graded, and manipulated for human use. This often erases evidence of the subtle changes in topography we see in meanders. Evidence of meandering shows that the river has been there in the past, and is indicative of specific fluvial soil types, lower elevation, and lower elevations. These areas are valuable for restoration due to these qualities. Evidence of past ecosystems indicates that there is potential for the insertion of similar ecological communities.

The Chehalis River, coincidentally, is the subject and catalyst for initial REM mapping techniques. The extensive surveying and mapping in response to the flooding of the area has poured resources into the data collection and representation of the area (Slaughter and Hubert 2014; Olson et al. 2014). The Chehalis is also near the state's center for geologic information, The Washington Division of Geology and Earth Resources in Olympia. These two factors have lead to an abundance of information available for the Chehalis Basin. Washington State's LIDAR database is bolstered by this effort. The Chehalis Basin Strategy has enlisted professionals to gather and use this information to

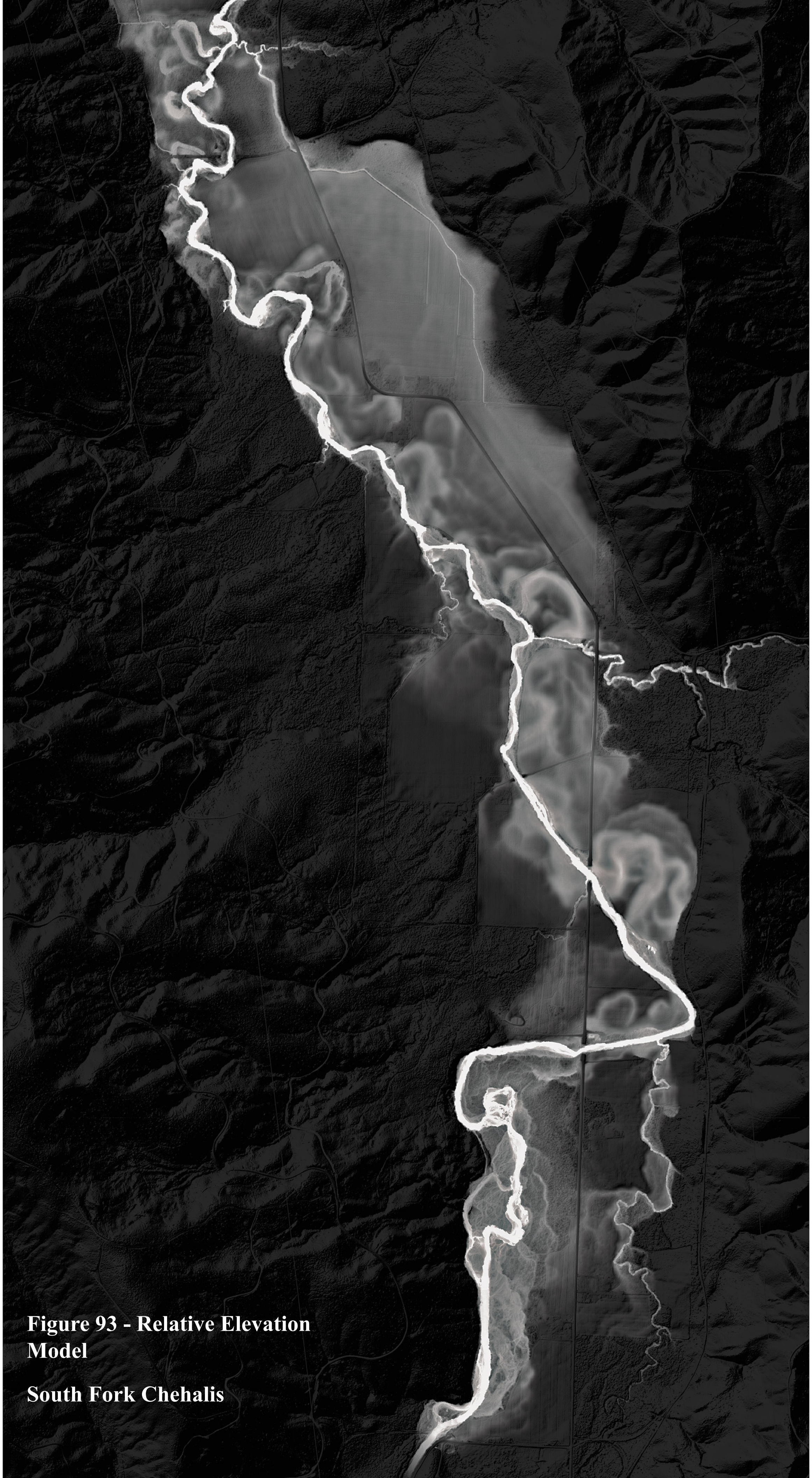


Figure 93 - Relative Elevation Model

South Fork Chehalis

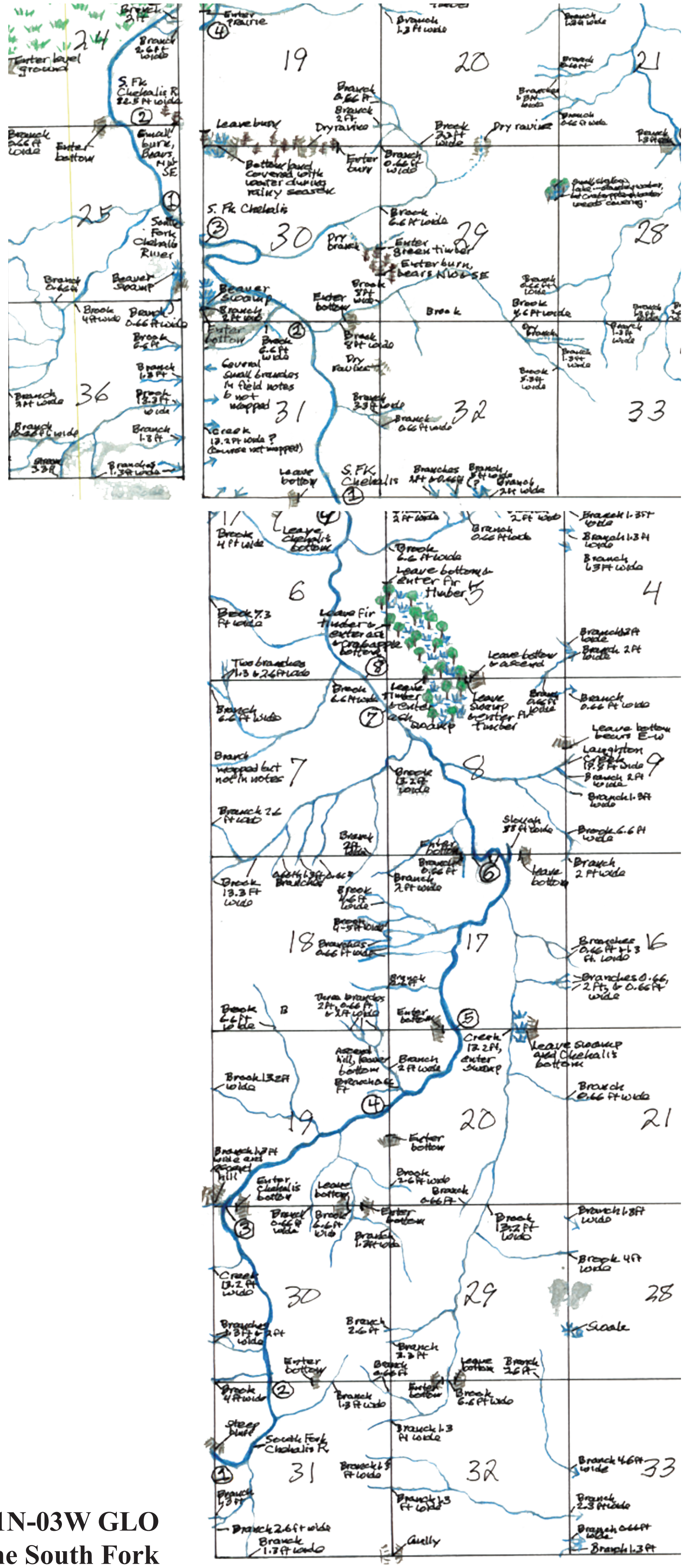


Figure 94 - 11N-03W GLO Survey Map of the South Fork of the Chehalis River

(James T. Berry 1875)

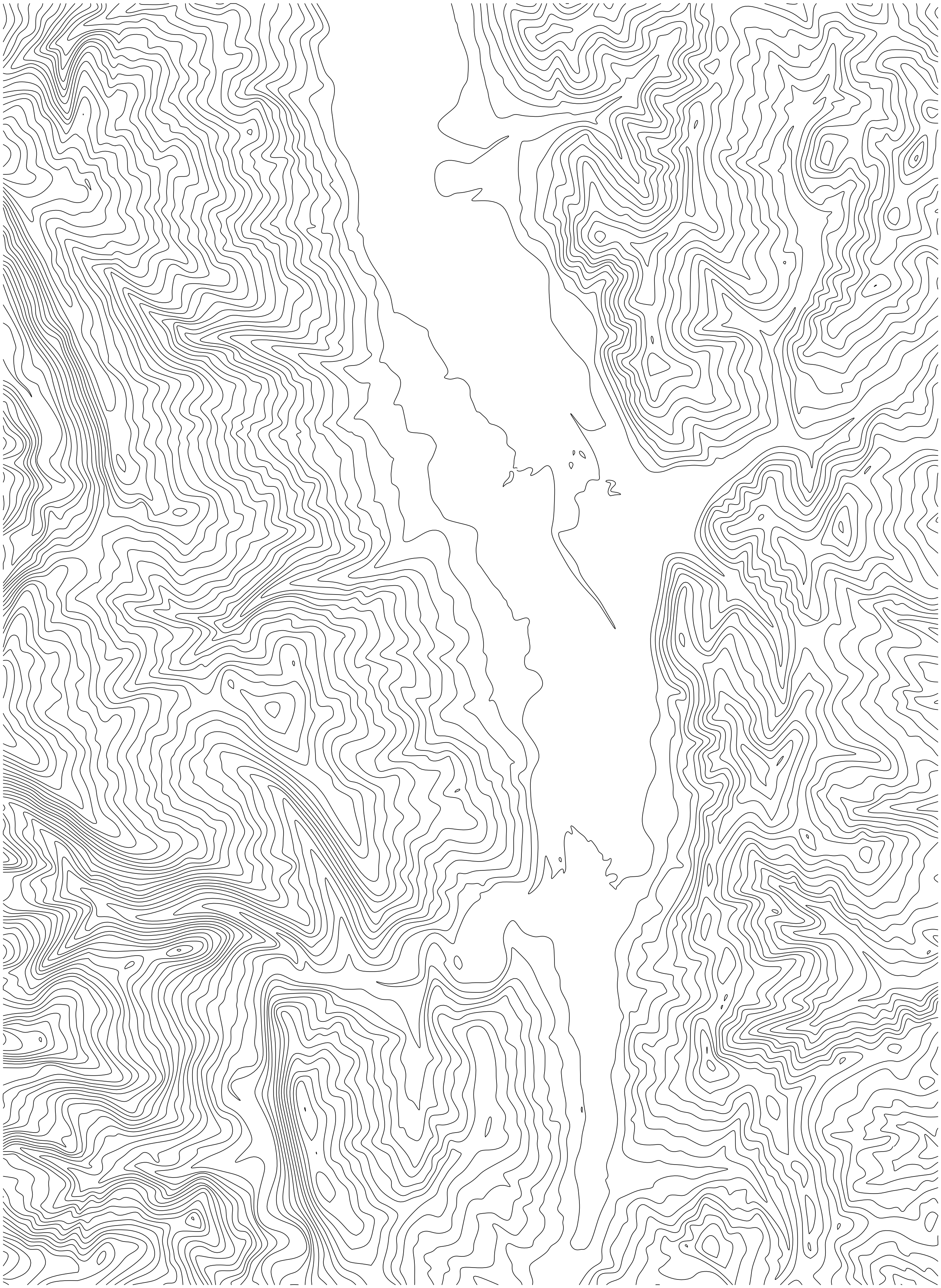


Figure85 - 2' Topography Lines

These contour lines were extracted from a DEM so do not correspond to sea level benchmarks. They are useful, however, for illustrating the reach's topography.

help understand the nature of flooding issues in the basin. This has produced many of the reports used throughout the paper.

To create the REM of the South Fork of the Chehalis, I followed the process as described by the Daniel Coe (Coe 2017). This process used GIS data to process elevation models. The data from this mapping and other aspects of this thesis are collected from public data sources such as Federal and State Agencies, Lewis County. The primary LIDAR source for the area is the 2017 Southwest Washington Foothills survey. I used the Quantum GIS program to modify the data collected from public sources (QGIS Dev Team 2022, n.d.).

The process of creating a REM model of the floodplain was time intensive and laborious in comparison to traditional mapping techniques, which provide ready-made examples. Of the several methods to create REM's, I chose to use the Inverse Distance Weighted (IDW) method. This method weighs sample points with reducing value as it gets further away from a specified point. In this case, the specified point is the river's water surface elevation at any given point. Taking the elevation data, I created a IDW interpolation of that DEM for every 1 meter distance of the river's flow, tracing its path manually for the entire length of the area (Macho 2018; Jurgiel 2022). I then extracted the elevation data from each of those points for the IDW interpolation. Using a comparison of the elevation data produced by the IDW interpolation and the existing DEM data, I was able to layer and construct a visualization of the relative elevation of the channel as it moved through the landscape (Coe 2017).

Modeling with HEC-RAS

Simulation Landscape Generation

To measure the flow of water through the site, I utilize the HEC-RAS (Hydrologic Engineering Center-Hydrologic River Analysis System) software from the U.S. Army Corps of Engineers (Hydrologic Engineering Center 2022). This software uses input parameters such as elevation, channel width, flow rates, and Manning's coefficients to simulate the flow of liquid water through a simulated environment. By running these simulations, I determine the base level flow of existing conditions and then compare that flow level to green flood solutions and modifications to the environment. If the flow is attenuated through increased holding capacity of the reach, it would be indicative of successful flood mitigation properties by the implemented strategies. The area of the model covered or inundated by flood water visualizes the interactions between the water and soil. These natural processes are assumed to occur throughout the floodplain, though in real situations, their effectiveness would be strongly tied to environmental conditions. Those environmental conditions only strongly affect the developed areas of the site, which are negligible for this level of accuracy.

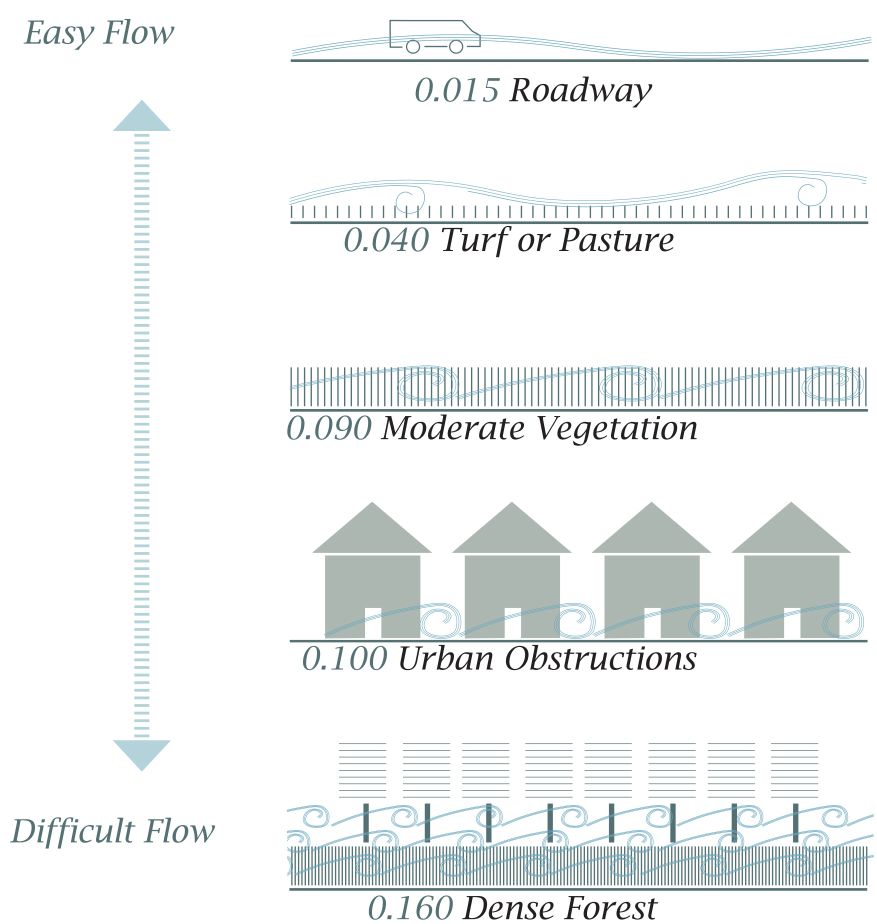
To generate the model, HEC-RAS requires data inputs and parameters to create the terrain simulation. The base of this representation is the digital elevation model that depicts the elevation of the terrain in two dimensional format, the same information used to create the REM. The HEC-RAS software interprets the terrain data from imported DEM files and uses it for the base of the simulated flows. Height interpolation maps provide a layer of elevation information for the program to use as a parameter. A boundary is established around the subject area to further specify the area of computation.

The program develops a mesh overlay on top of this computation area. To create the mesh, a geometry calculation uses elevation data and Manning coefficients for its baseline models. Refining this to come closer to actual site conditions takes iterative modifications. The mesh is aligned with the surface topography to increase its accuracy. The HEC-RAS program uses polygon geometry similar to GIS programs to communicate these "breaks" in topography and mesh. Polylines are drawn over any notable site features. These include stream banks, stream centerlines, ditches, forest edges, walls, buildings, road prisms, ramps, etc. The aligned mesh better represented the landscape and increased the fidelity of the calculation cells. Without refining this layer, the model would generate less accurate and slower results.

Manning's Values

The software requires the specification of zonal parameters for its calculations. These zones inform the calculations used by the mesh layer. One of the most important layers of information is the Manning's Value (n). This value represents the level of landscape friction that water encounters as it flows over the site. The values here are derived from several sources related to hydrologic simulation and engineering (Cippa 2022; "Manning's n Values" n.d.; Brunner, Ackerman, and Goodell 2023; Karpack and Butler 2019). I selected the values from these sources that most closely resembled the landscape of the simulated reach. High n numbers, such as 0.9n, represent areas of almost impenetrable friction. These are typically buildings, walls, and water-blocking infrastructure. Most values of the metric

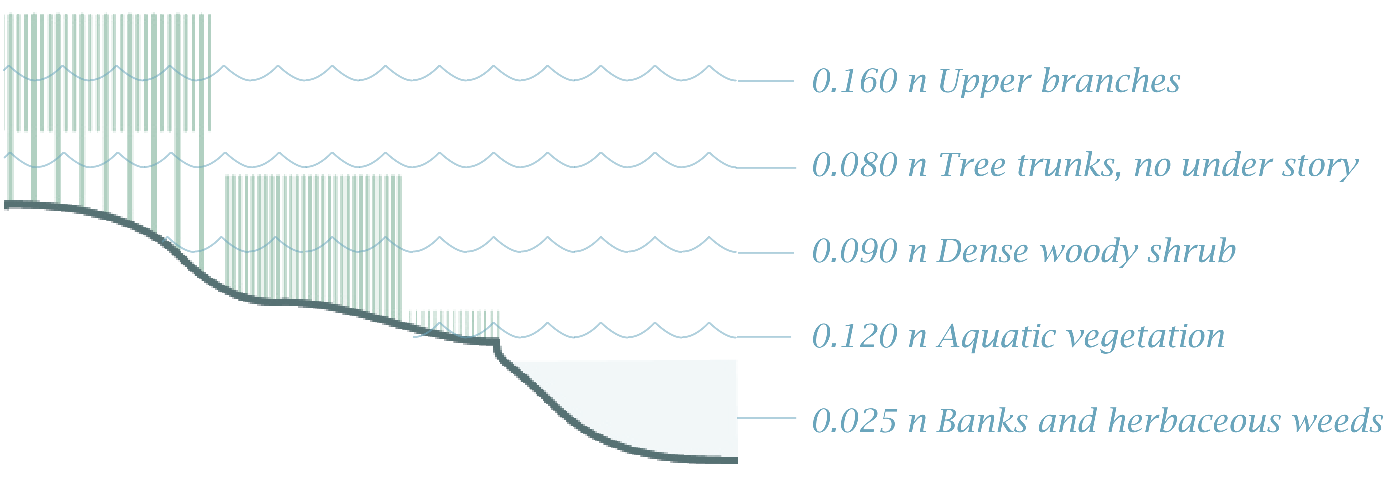
Figure 99 - Manning's Values



are below 0.5n. Areas with dense woody stems, such as thickets of willow along stream banks, receive high numbers: 0.2n. Mowed lawns would receive negligible values such as 0.01n.

Previous simulations of the Chehalis generalized the n values of the floodplain. They attributed a general value to each bank that summarized the conditions on each side (Karpack and Butler 2019; Elliot and Karpack 2014; Elliot, Tschetter, and Karpack 2019). This provided economy for the large-scale simulations or tests, but did not allow for high resolution accuracy for site conditions. For the purposes of this study, I create a zonal arrangement of n values initially based on the US Multi-Resolution Land Characteristics (MRLC) data set (United States Geological Survey 2009). This dataset attributes categories to landscape features based on satellite data. It then creates a group of inferences from this data, such as the general characteristics of vegetation on agricultural land versus that of roadway. The MRLC data set served as a foundation for further calibration and honing of the n value layer. From there I used various survey inputs such as soil conditions, building information, bank information, and satellite imagery to compose a more finely tuned layer. I compared the base layer provided by the MRLC to the data provided by other sources. I then made a judgement as to what category

Figure 100 - Vertical Changes in Roughness



(L) Manning's values are based on the friction that water encounters as it moves across the landscape. Dense areas of forest offer greater resistence than open agricultural fields.

(R) This value also changes with flood stage and water depth. Trees, for example, have low n values for a grove of trunks. Their canopies have much higher n values.

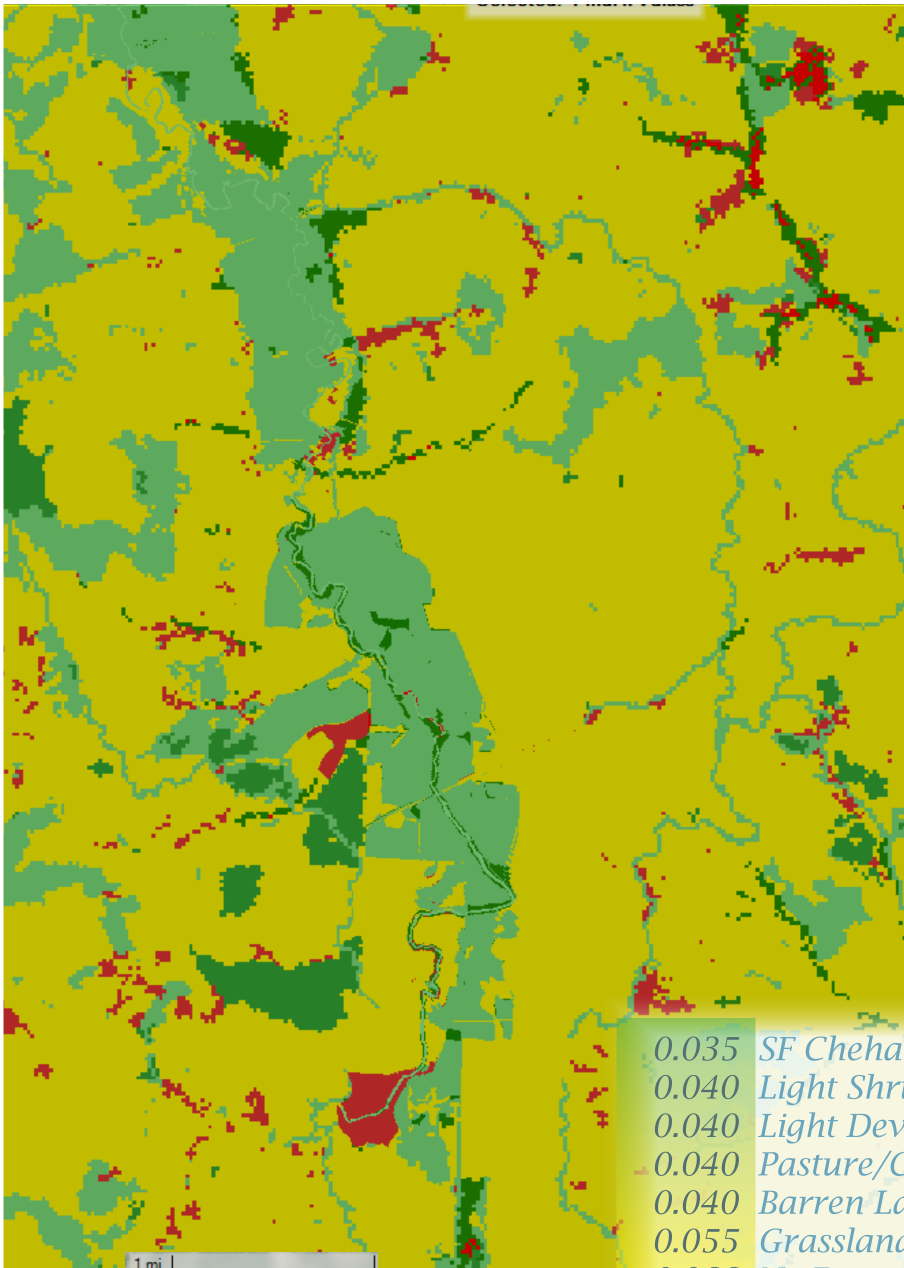


Figure 101 - Manning's n Values on the South Fork of the Chehalis

A depiction of the USGS Land Use Dataset from 2019. These polygons were imported into the model and assigned n values. This provided a base for the tuning of future variables.

Manning's n values adapted from: USFS Corvallis Forestry Sciences Laboratory; Karpack and Butler 2019; Elliot, Tschetter, and Karpack 2019

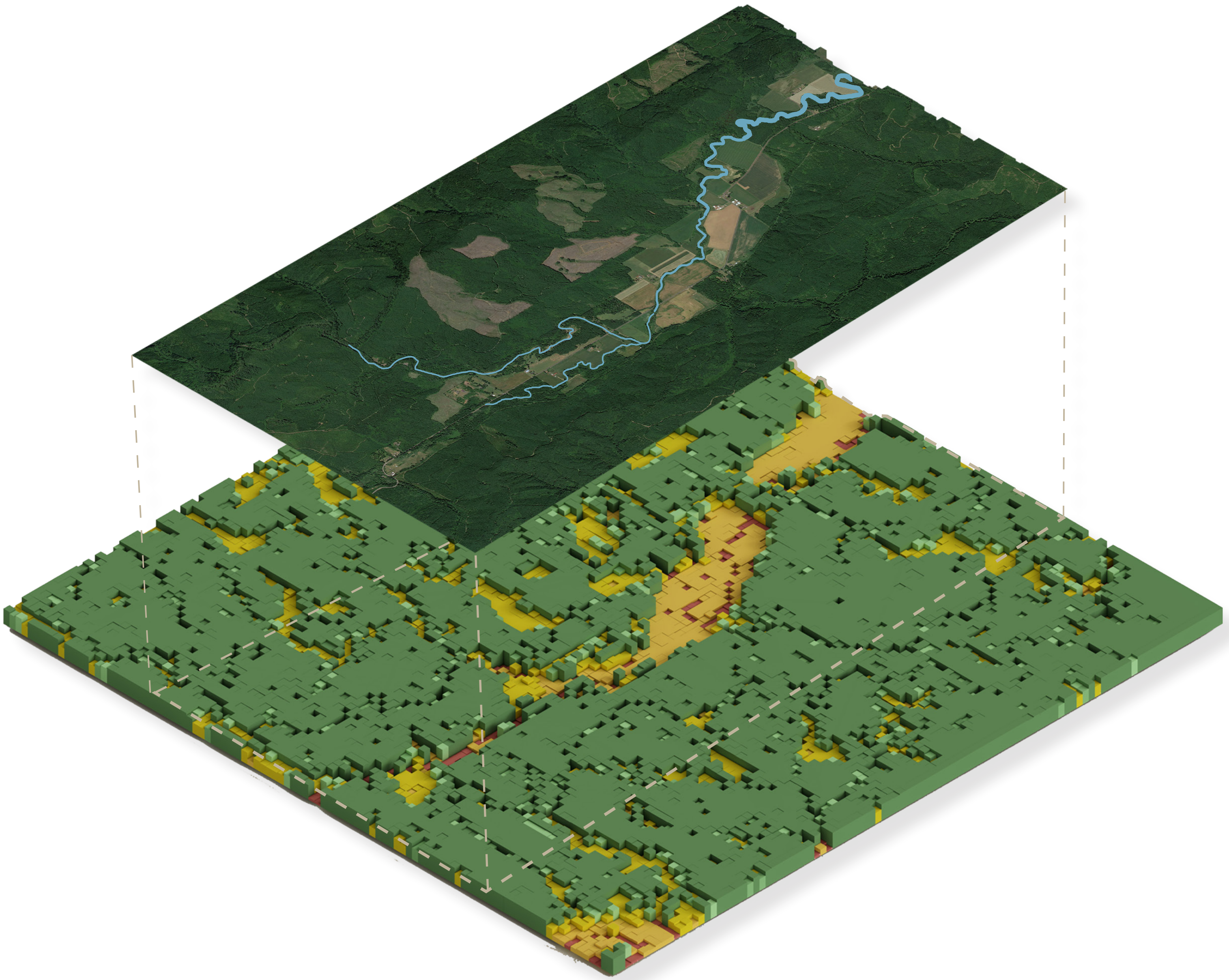


Figure 102 - Land Use and Roughness

Height and coloration of this rendering correspond to the n values attributed to the area. The aireal image is overlaid to provide context.

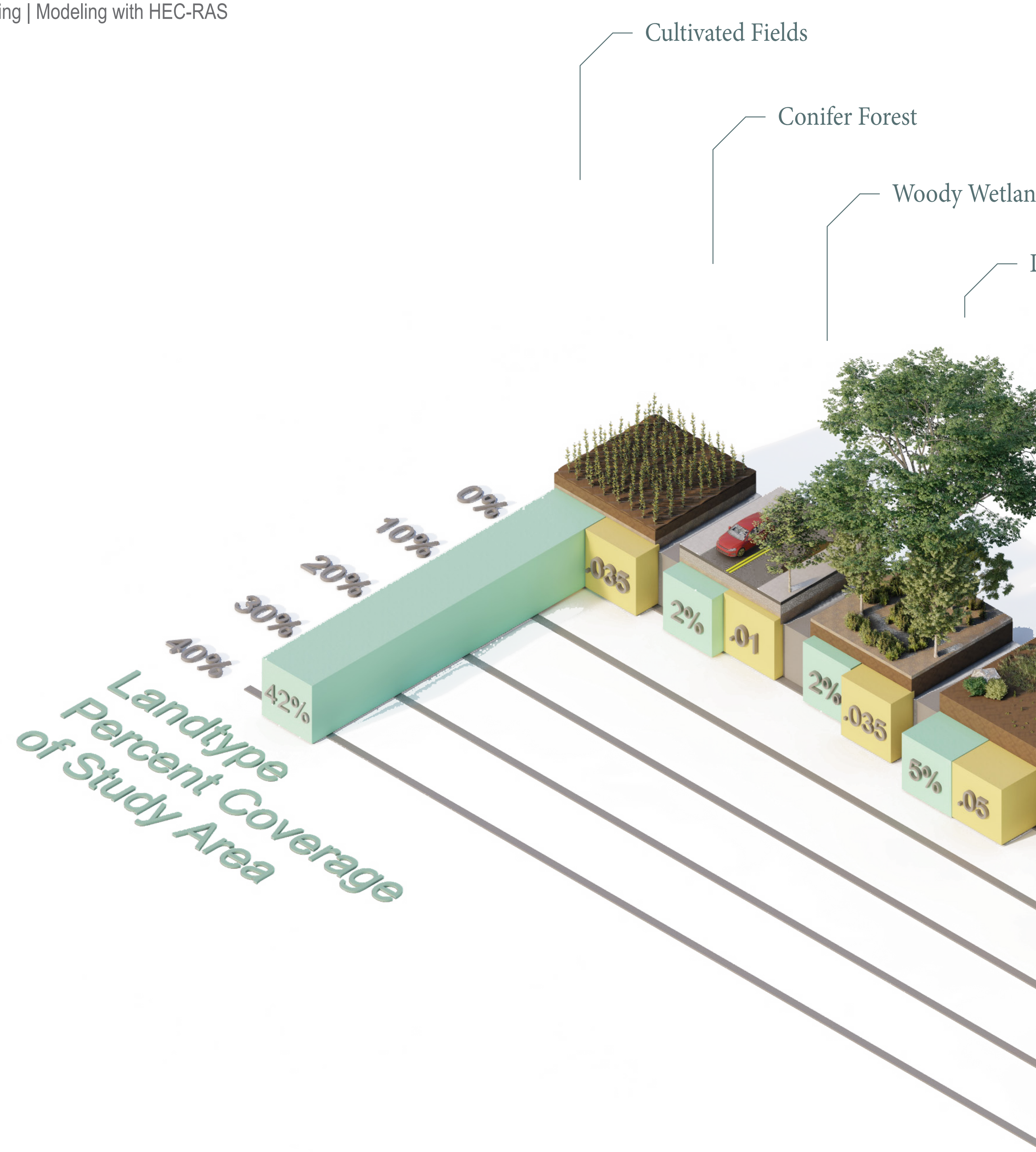


Figure 103 - Relative n Values

This graphic depicts the relative values and total land coverage of various land types used in the model.


d
Deciduous Forest
Light Shrub
Heavy Shrub
Asphalt and Developed
Grass and Pasture
Wetland
.07
.20
23%
.14
.16
.04
0.00
0.10
0.20
0.30
0.40
n Manning Values
(Roughness)

Figure 105 - Representation of Vertical Zone Vegetation Complexity

of n value I should attribute to the landscape. The result was a high-accuracy patchwork of polygons that accurately represent the site conditions throughout the landscape.

Next, fields of flow are defined to specify areas for simulation. For the initial trial and calibration of the landscape, I use the simplest form of mesh creation, which is an automated process within the software. It produces a uniform layer that is only influenced by terrain height. Later iterations will refine this layer with ‘break’ lines. Flow parameters and geographic locations are defined. Line boundaries are drawn and given attributes of an entrance for water and an outflow for water. The inflow requires information about the time of flow simulation and the cubic feet per second flow rate at any given time. For the flow rate, data was taken from the USGS stream gauge at Wildwood, Washington (“USGS Current Conditions for USGS 12020800” Various). Other data inputs for the

model included manual entry of channel geometries and bank lines, stream bed sediment characteristics, soil infiltration rates, evapotransmission rates, bridges, culverts, landscape features, buildings, wind, precipitation, and model input flow rates. These came from several sources, such as GIS layers from Lewis County, Washington State, and the Federal Government. The completed model reached an expansive level of complexity and became increasingly unstable as more layers were added. Though this also increased its accuracy. The stopping point came from the implementation of precipitation on the model, which caused calculations to be created for the entire area of the simulation. This caused the simulation speeds to severely decrease and was abandoned. The models are not simulated with precipitation, only flow rates inferred from that precipitation.

Establishing Sampling Cross Section Nodes

Cross sections are used within the program to achieve multiple ends. They are used by HEC-RAS calculating algorithms to interpolate terrain conditions between given transects. The elevation is established on any given cross section and used as a terrain benchmark for these calculations. They are also used as checkpoints to gather data as it is calculated along the flow. This data is available in a wider and more accessible range than data collected across the general area of the model. In addition to the cross sections established to create the model, certain checkpoints are specified to act in a comparative capacity. This was started at series B, test 6 as the model was determined subjectively to have fidelity enough to start to make numerical measurements.

In total eight cross sections were selected for closer examination. The cross sections were determined by the primary objective of collecting comparable data, but secondary qualities such as the features they captured was also considered. The sections used for interpolating terrain data are limited to a transect of approximately 1000ft. across the flood plain and perpendicular to the river flow. To capture additional data, secondary cross sections that spanned the breadth of the floodplain perpendicular to the channel were also created. This wider section will allow visualization of flow data beyond the immediate area of the channel and help to capture secondary channels and interesting characteristics of the floodplain.

Starting upstream, cross sections were named by their sequence and relative station to the study area. For example, “XS 4 W” is at station 39281. It is 6800ft. in length and runs across the drainage valley and up into a side channel for about 2000ft. of its length. The trajectory was selected because it crosses the main channel at a bridge location, which acts as a bottleneck to water movement. It also crosses the secondary channels of Cedar creek in four locations, allowing for visualizations of flow coming from that tributary.

“XS 1 W” and “XS 2” cross the channel at the southern end of the study reach zone. They are selected due to the simple, unbraided nature of the channel. They are slightly set back from the areas that spawn the flow, to allow some area to smooth out any irregularities generated from the flow creation by the software. The initial benchmarks will help for

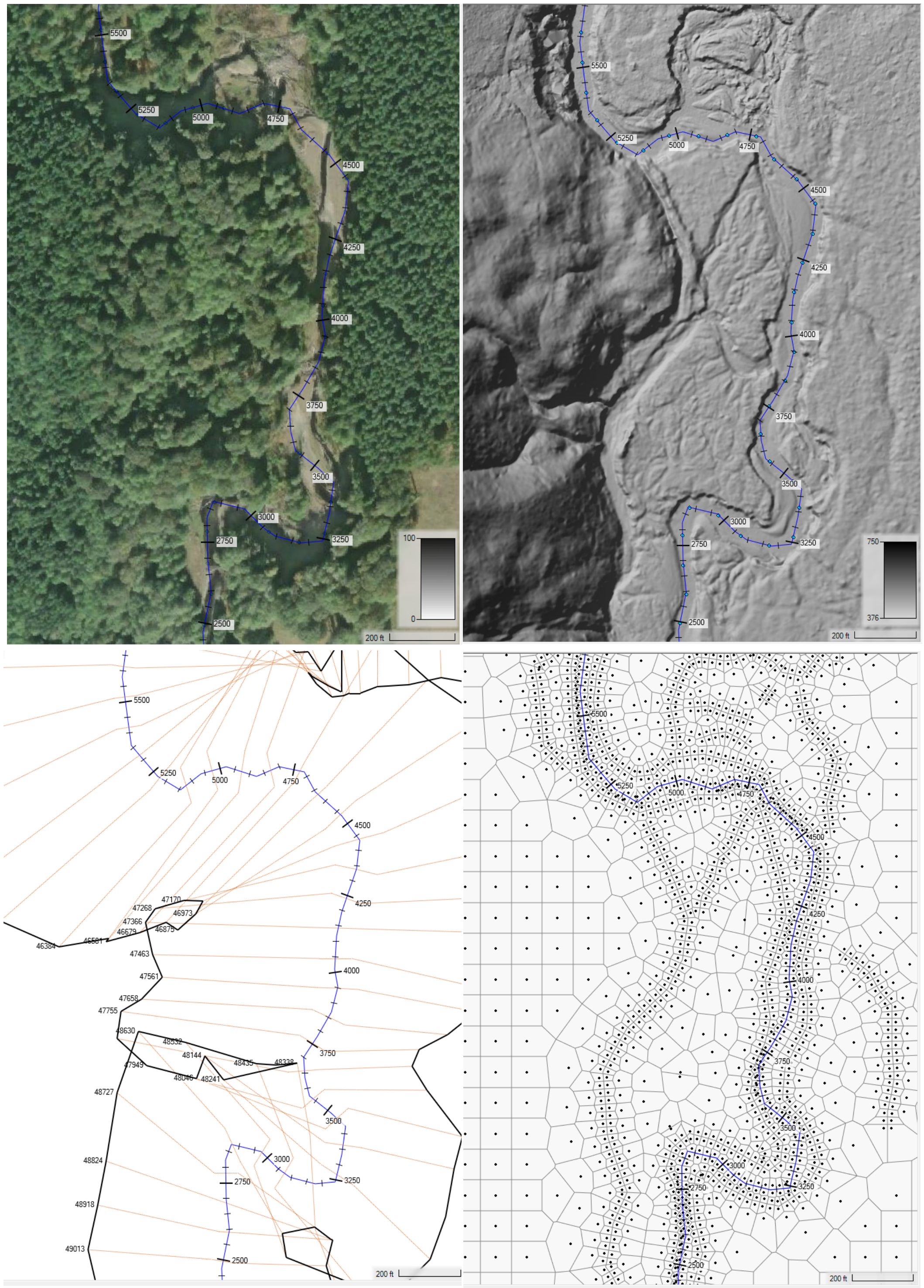
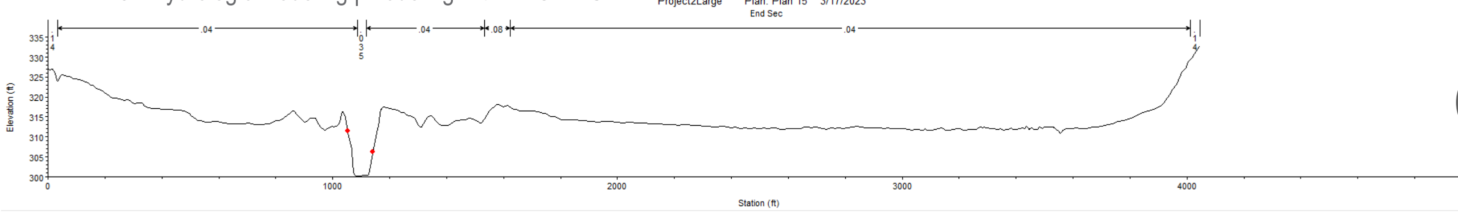
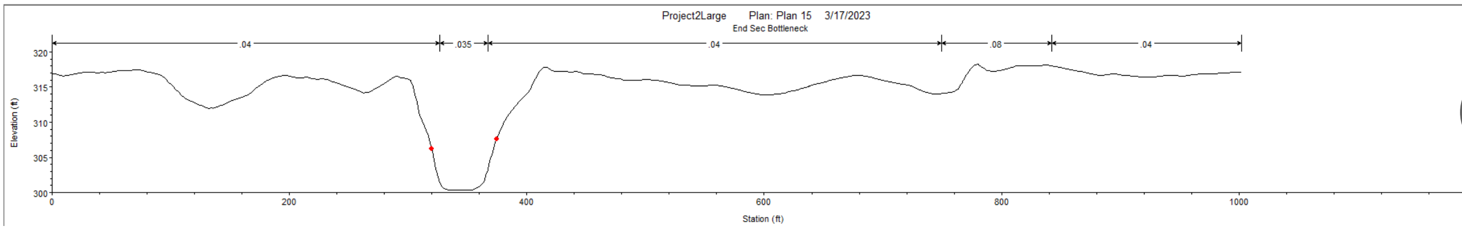


Figure 108 - Layers of Information

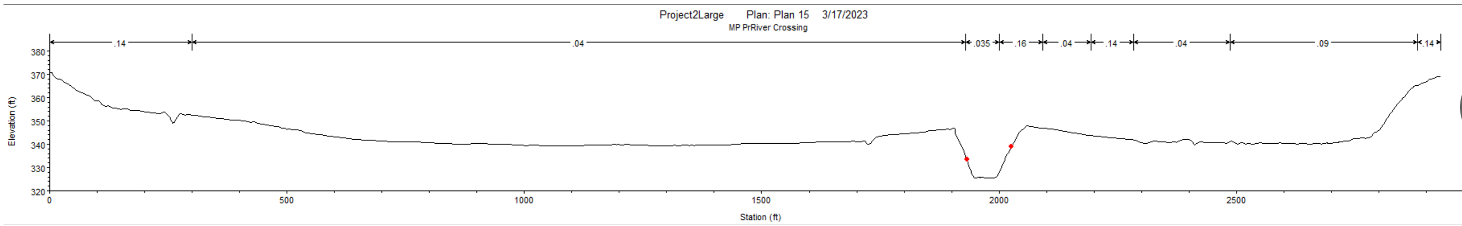
(TL) - Establishing centerline polygon based on satellite data.
(TR) - Tuning the centerline with LIDAR data
(BL) - Establishing sections for calculation and observation
(BR) - Developing a calculation mesh



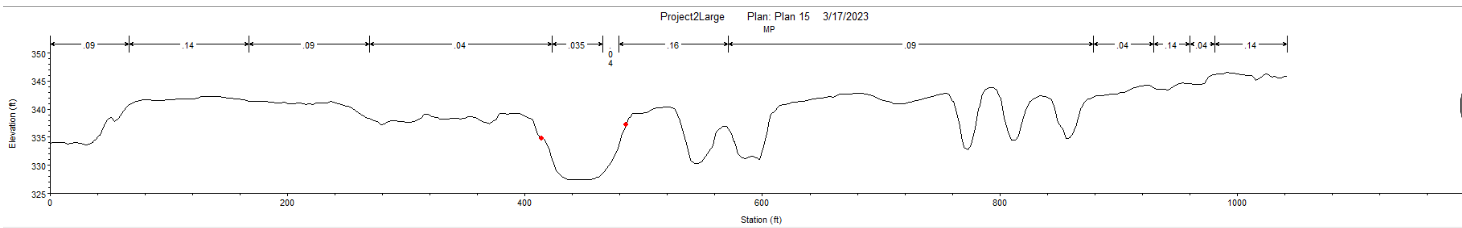
XC 1



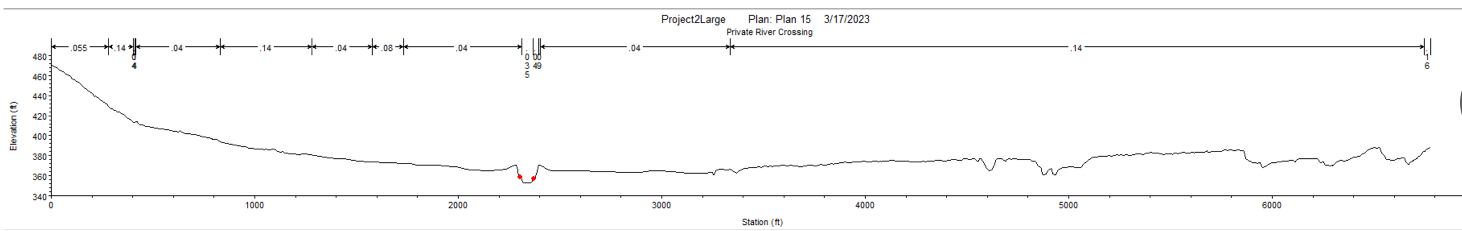
XC 2



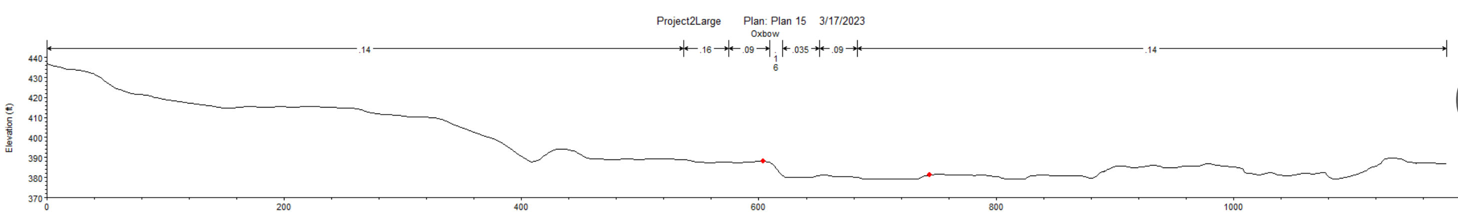
XC 3



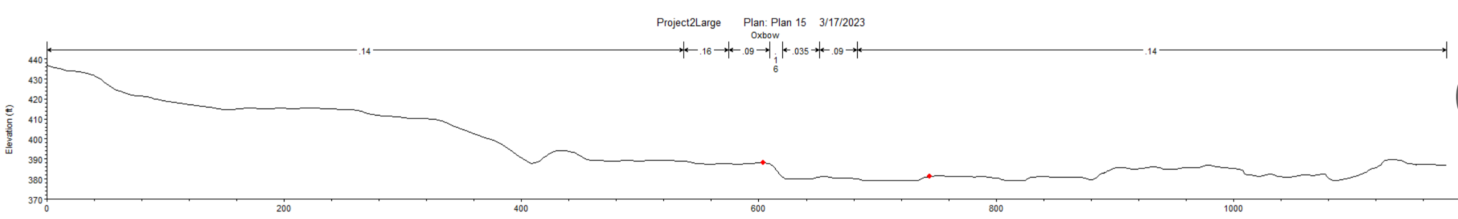
XC 4



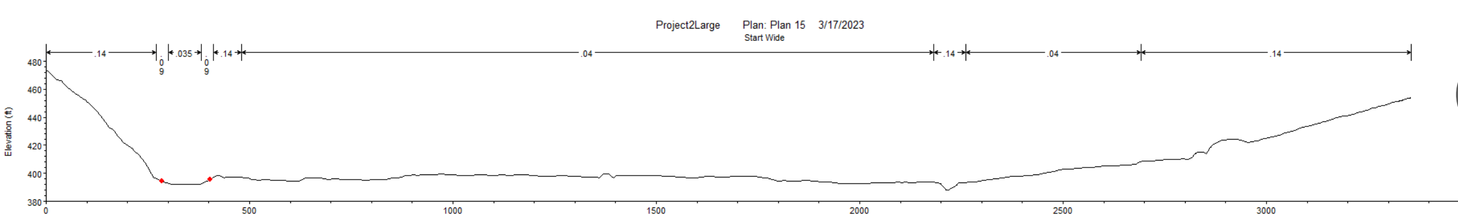
XC 5



XC 6



XC 7



XC 8

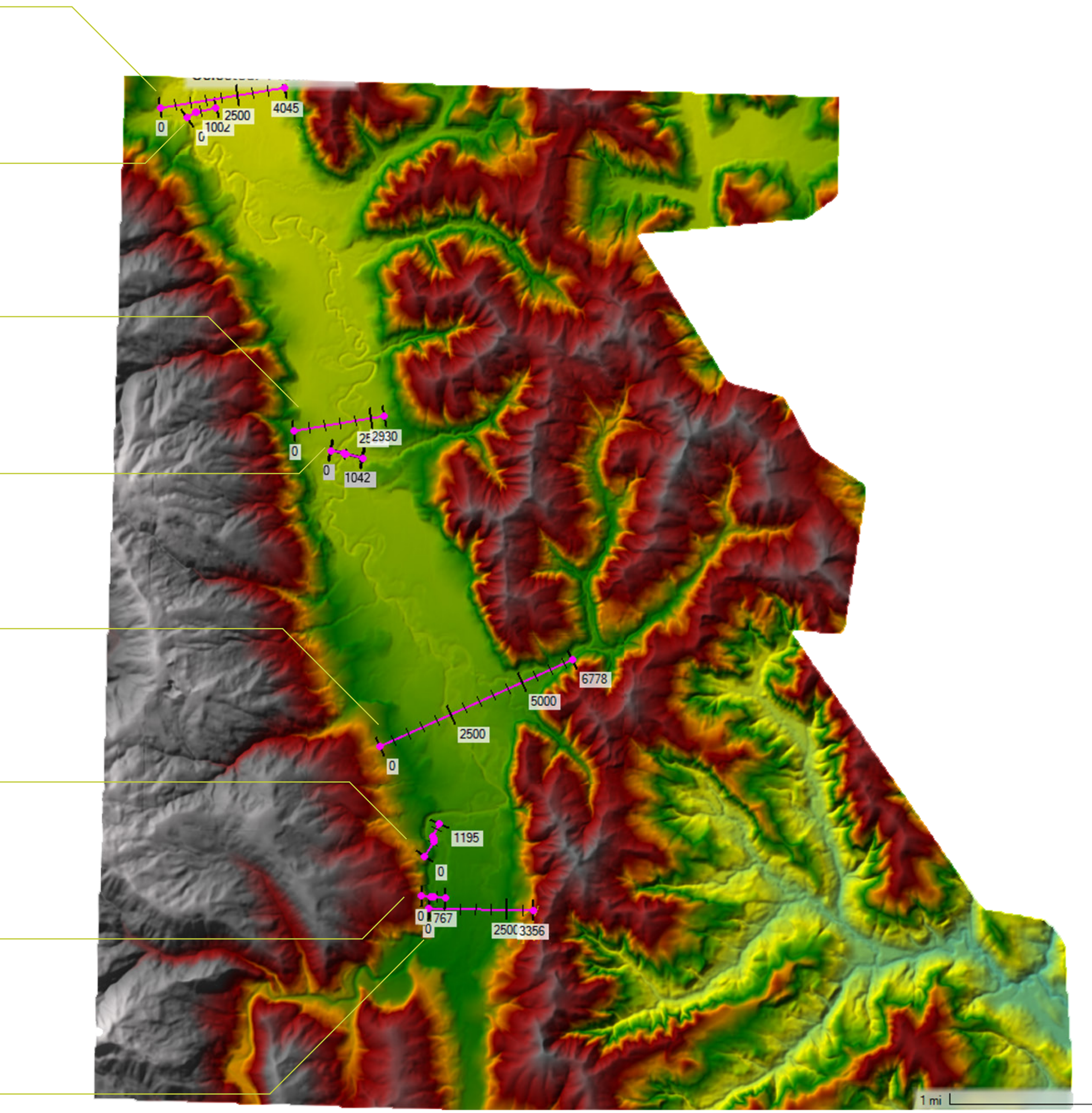


Figure - 110 Monitoring Cross Sections

This harlequin map displays cross sections established for benchmark measurements. These cross sections will remain the same for both the modified and unmodified landscapes. This will provide continuity for metrics gathered from them.

comparison for input vs output through the model. The two cross sections differ very little in placement, and their only variation is in their width.

"XS 3" captures an interesting feature at station 46581. It moves roughly SW to NE across the channel and then enters soil being fragmented and wasted by water flow. The cross section bisects an oxbow that is actively being created and will result in interesting information.

"XS 4 W" is the longest cross section at 6820ft. in length. It crosses the South Fork Chehalis at the location of a private road, which uses a road span to cross between two ramped embankments. It then follows the drive to the intersection with Wildwood Road. From there it continues NE up the Cedar Creek drainage. Cedar creek is a major tributary of the South Fork Chehalis, draining eight square miles of hillside to the river's East. The transect crosses the creek in four locations as it meanders down the hill.

"XS 5" and "XS 6 W" cross at the midpoint of the study area and will provide a middle checkpoint for flow monitoring. "XS 5" was placed at a point that crosses an old oxbow on the river's West flank. It then crosses the undulating path of Sears Creek to the East of the channel. It ends within the prism for Wildwood Road. "XS 6 W" captures a bottleneck at a road crossing. This will hopefully provide a consistent and consolidated flow output for measurement.

The study area exits to the North with "XS 7" and "XS 8". The two cross sections capture an area set back about 500ft. from the study boundary to reduce abnormalities associated with computation edges. The cross sections also try to capture areas of consolidated channel width.

Calibration Outcomes

The result of the creation of the simulated South Fork of The Chehalis within the modeling program HEC-RAS was exciting. The river behaved as it was subjectively supposed to. The flow rates of input roughly matched the anticipated rates of flooding. To objectively assess the performance of the model it is compared to realistic or historic indicators. If the flow of the water in cubic feet per second roughly matched the stage, or height of the river as recorded at similar rates, then it is assumed that the model has sufficient accuracy. As stated previously, there are no ideal stream gauges to measure this numerically. Instead, I rely on maps drafted by the National Flood Insurance program. These maps indicate areas that are prone to flooding and subsequently assign different insurance rates and requirements to properties in those areas. One of the key benchmarks that the National Flood Insurance maps use is the 100-year flood mark. I compared the location of the 100-year floodplain delineation to the inundation extent within the simulation (FEMA FIRM Map No. 530102 0440, 1981). Once the simulation's inundation reached the geographic location indicated to be the 100-year flood stage by the Insurance maps, I noted the amount of water being introduced into the model at that time.

The calibration or baseline model reached 100-year flood stage when a rate of 7,200 cfs. of flow was introduced for prolonged periods. I used this as an origin for the subsequent rates of flow to test the models. The model tests were performed in five trials that will be carried out with the unmodified and modified model landscape. The trials were four fixed rate flows and one simulated water year. The fixed rate flows all performed with similar patterns. The models would start at an arbitrary date, as the duration of the flow was the only important temporal metric. Starting with a preexisting flow of 200 cfs. for three days (not recorded in results), the flow would then increase over a period of two weeks to the top flow rate. Once hitting the top flow rate, the flow would taper back to 200 cfs. over the course of one week. The simulations were a total of three weeks long. The flow rates would throttle consistently, but the amount that the flow rate had to change would determine the rate of this change. The increase from 200 cfs. to the top rate of 1,000 cfs. would have a slower increase than the ramp up to 15,000 cfs. This was necessary for practical implementation of the simulations.

The second type of trial is the simulated 2020-2021 water year. Using actual data recorded from the Wildwood, WA stream gauge, I use the input to create a flow model that is updated hourly within the simulation ("USGS Current Conditions for USGS 12020800"). This simulation ran from October 1st, 2020 to April 30, 2021. Within this data, the flow rate is typical for an average year for the reach. The flow rate sees steady increases through the fall, and steady decreases during the spring. The rates are most dynamic during the winter. On January 2nd, a rain event caused a brief peak of 5,500 cfs. Again on January 13, the stream gauge recorded 4,000 and 5,800 cfs. spikes for a few hours.

The tests of these types of flow data place the models under two different stressors. The fixed rate flows will primarily test the capacity of the system to hold volumes of water. They also can create unrealistic scenarios to explore the extremes of performance. The flow parameters based on the water year, however, simulate a longer and steadier scenario. This demonstrates the extent to which the water spreads across the landscape. This type also shows in more detail the ability of the landscape to convey the water as it decreases.

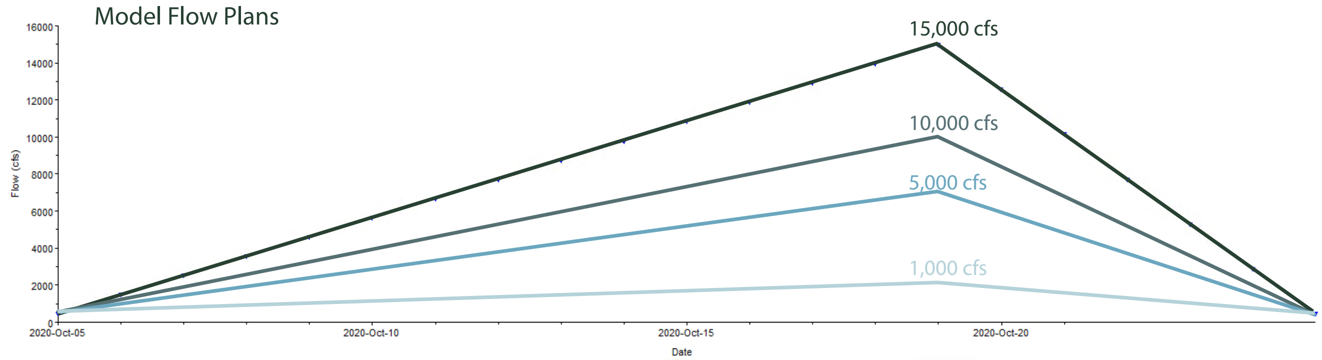


Figure 114a - Fixed Rate Flow Hydrographs

This graph depicts the flow rate of the fixed rate test inputs. The quantity of water increases for fourteen days, hits a peak, then decreases over a week.

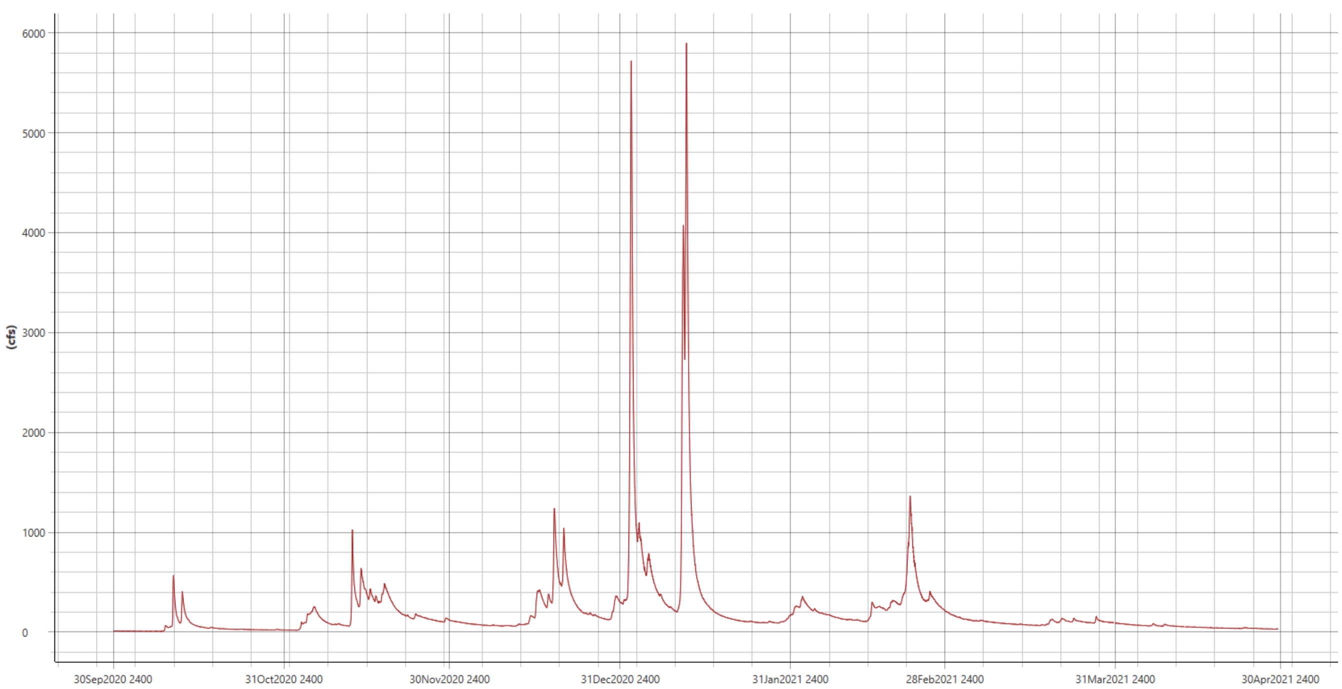


Figure 114b - Realistic Rate Flow Hydrographs

This graph depicts the flow rate of the realistic flow rate scenarios. This rate is derived from the October 2020-April 2021 water year. The flow input recorded at the Wildwood stream gague is input into the model at hourly integers.

Benchmark Unmodified Flow Results

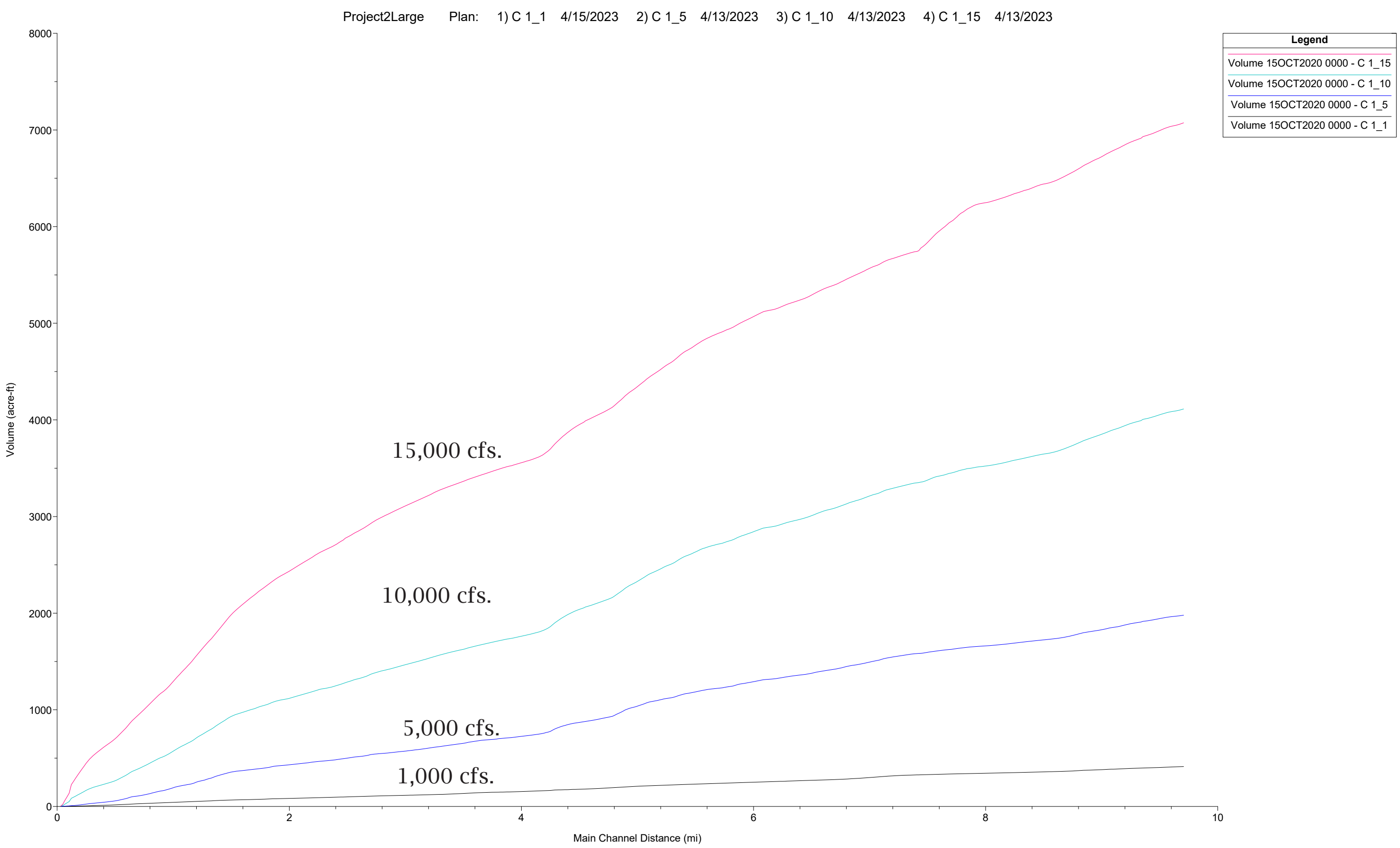


Figure 115- Area Inundated

Comparison of area inundated during fixed rate flows. October 15 represents approximately half of the maximum flow. E.g. the flow for 5000 cfs. max is at 2500 cfs. at the time of this sample.

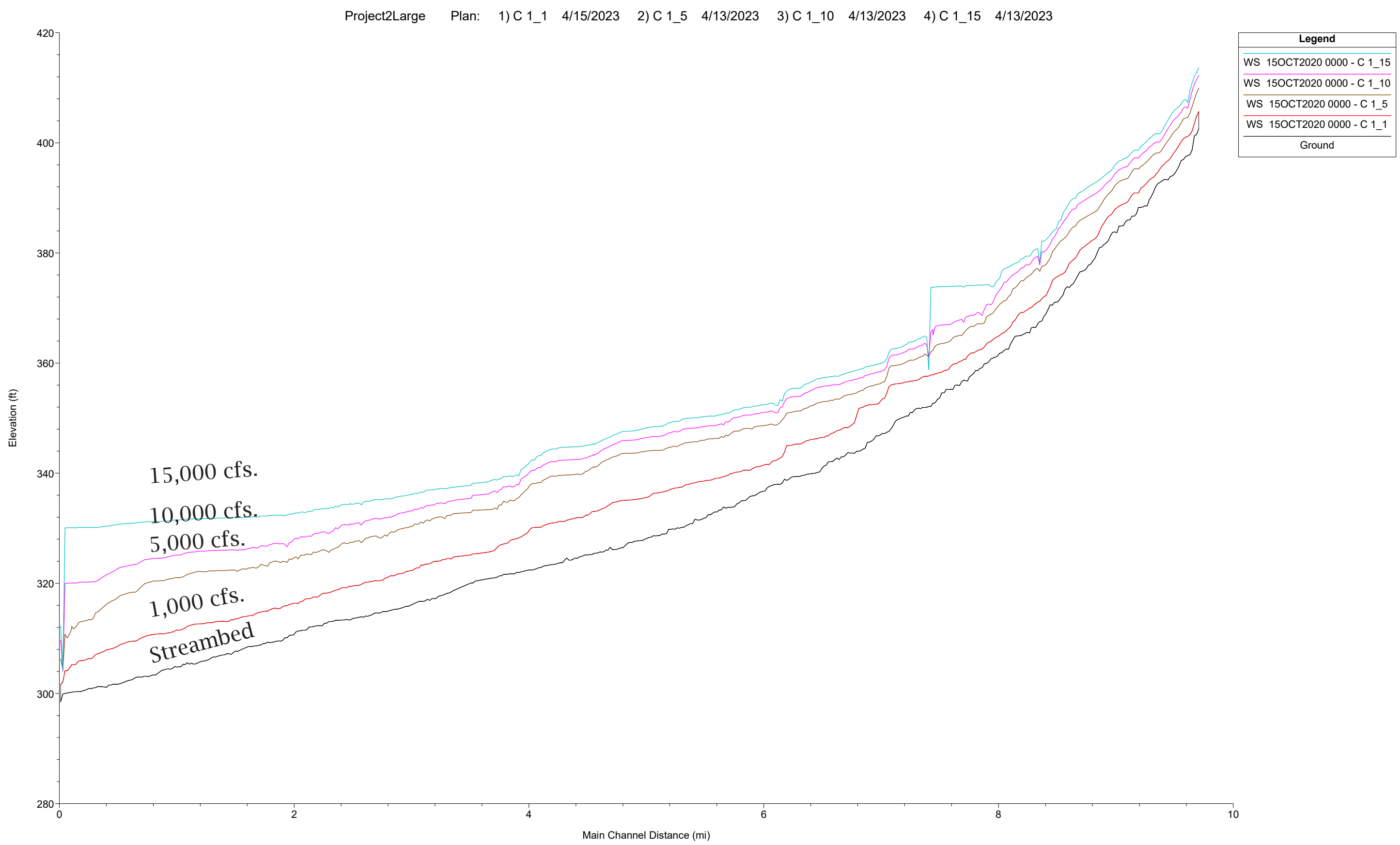
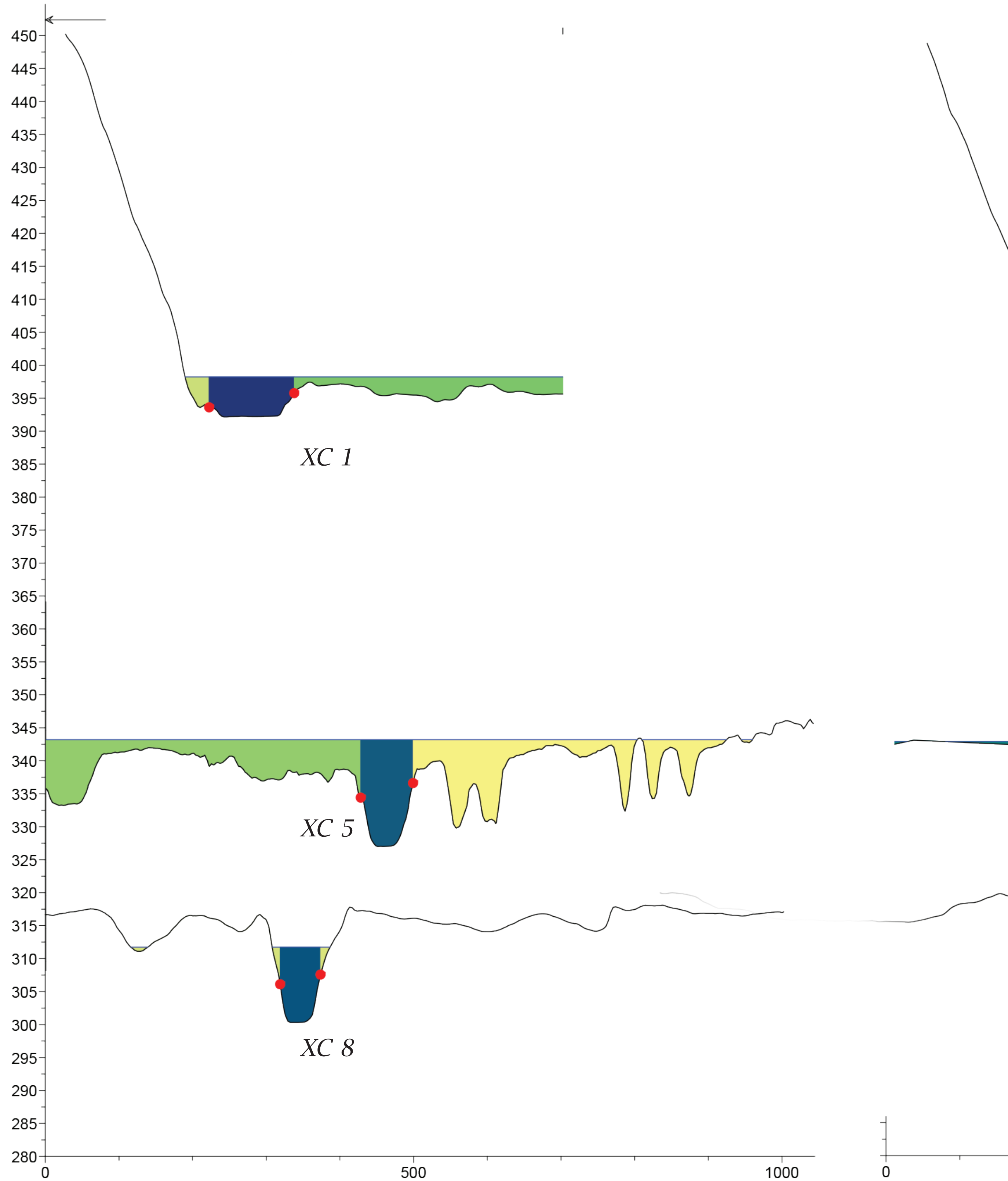


Figure 116 - Fixed Rate Depth Profile

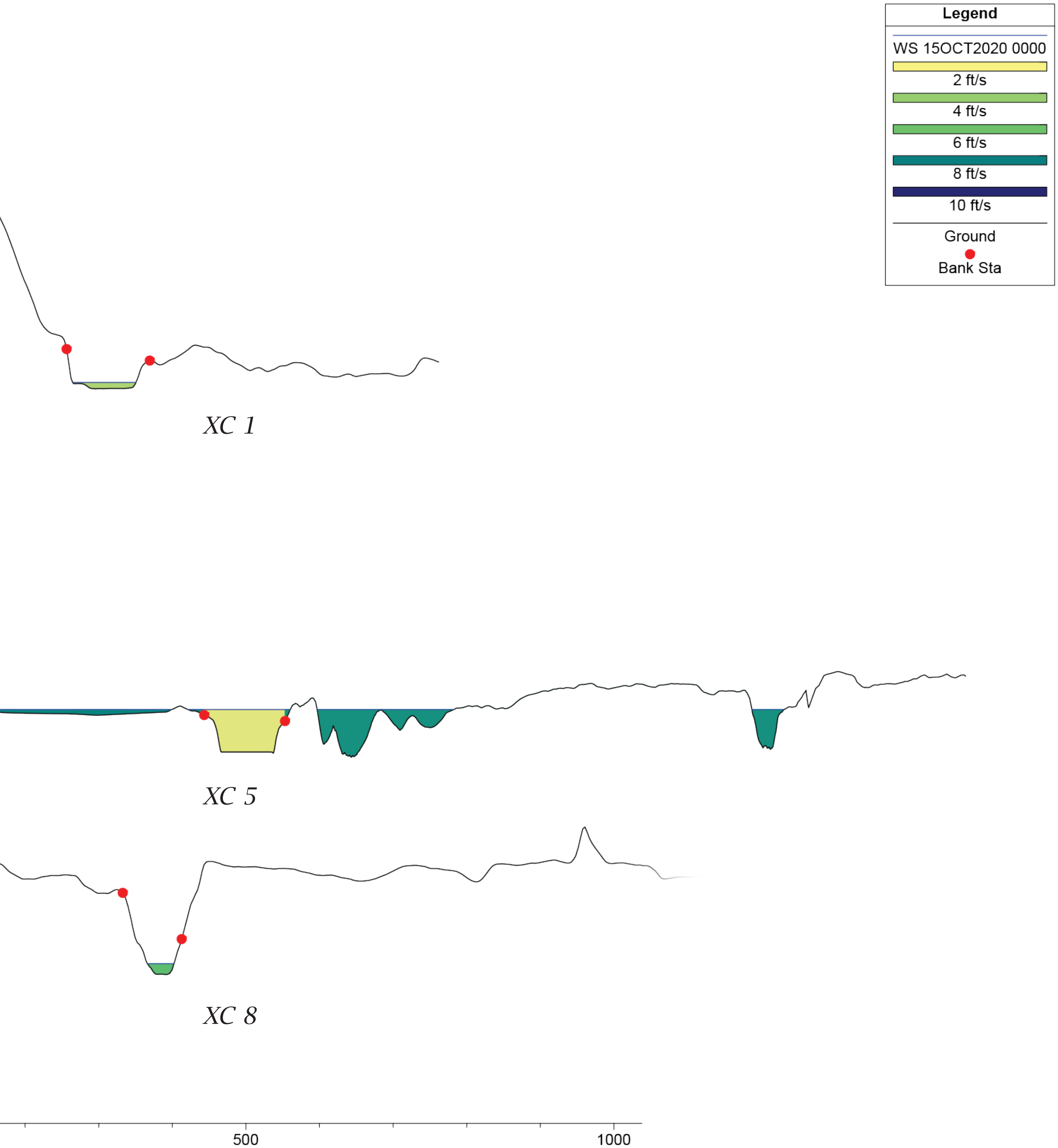
Depth at peak flows for fixed rate tests. On this chart, the left side is North or downstream. The lines represent the water depth above center channel at different rates of flow.



) Elevation and (x) Channel Distance in Feet

Figure 118 - Sections - Rate of Flow and Depth Comparisons

Cross sections illustrate the rate of water flow and their depth. Sections compare 10000cfs. (L) and 5000cfs. (R) test flows. Middle cross section is approximately the same geographic location.



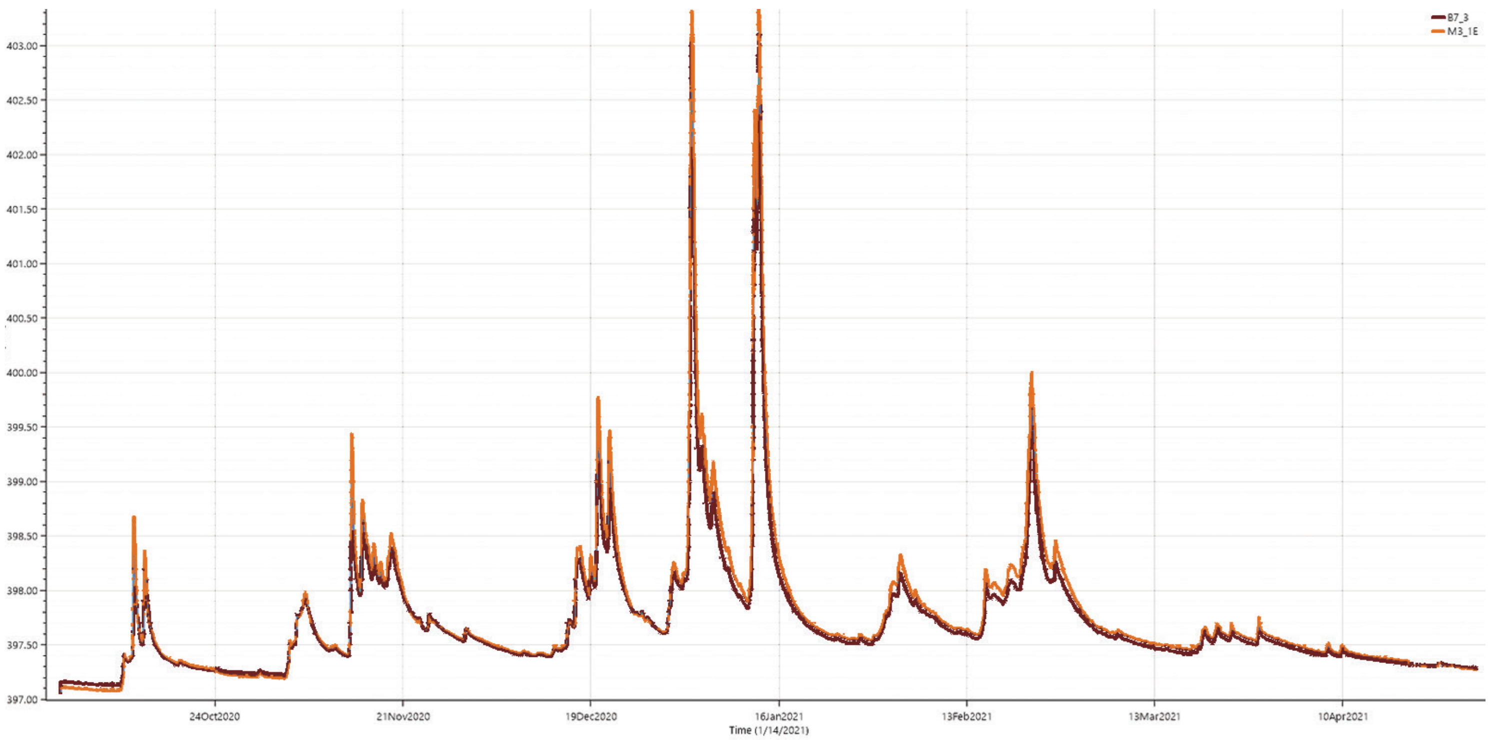


Figure 119- Water Surface Elevation

Water surface elevation (above sea level) for realistic water year at XC 8. Note the close similarity to the input cfs levels (Fig. 106b), indicating little floodwater attenuation.

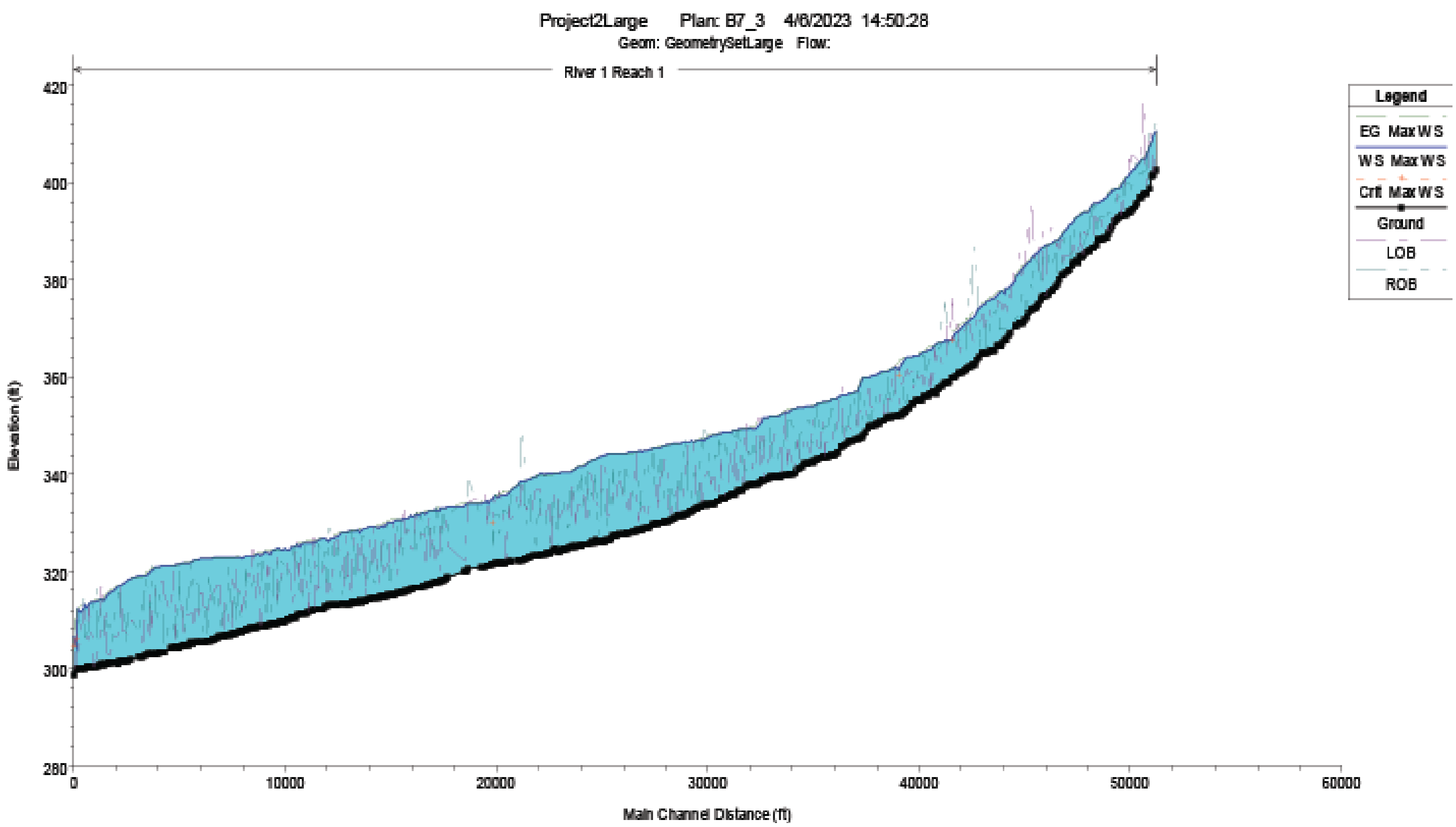


Figure 120 - Channel Depth Profile

Depth of water on landscape at peak flow for realistic water year tests. On this chart, left side is North/Downstream.

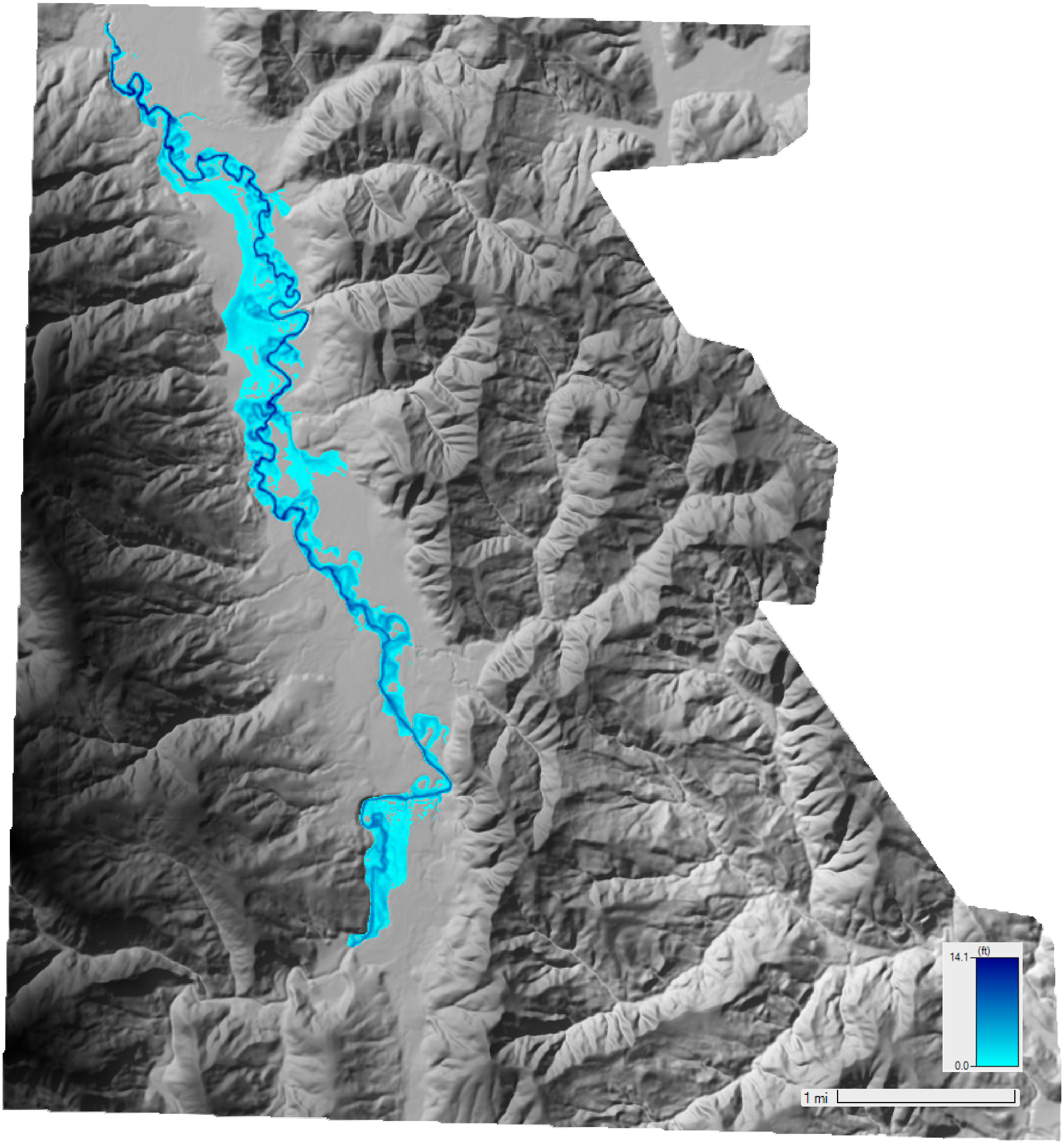


Figure 121- Extend Inundated at 7,000 cfs.

Total surface area inundated by >0.01 ft. of water at 7000 cfs. flow rate. Taken from 10,000 cfs. fixed rate test. This is at the cusp of becoming a 100-year flood event, which happens at 7,200 cfs. on this model.

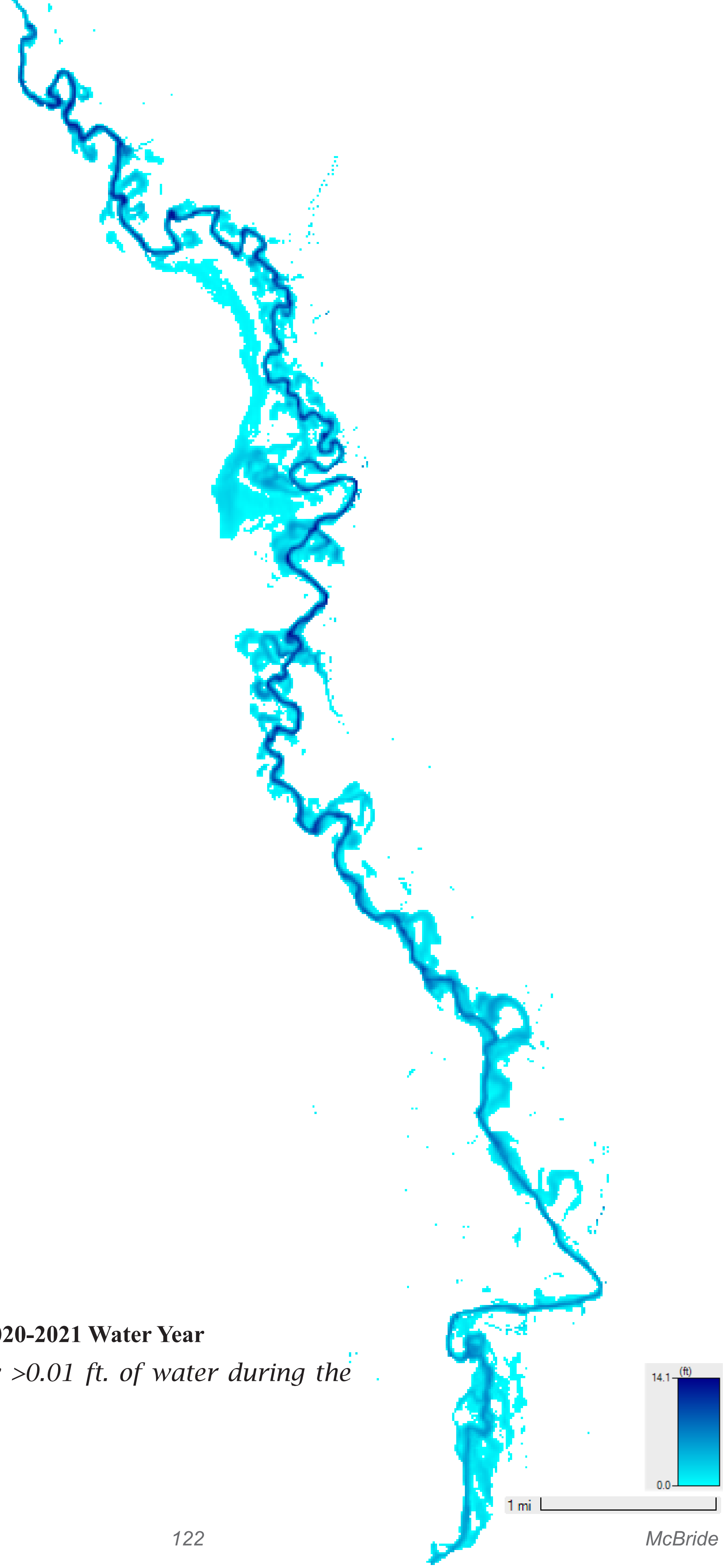
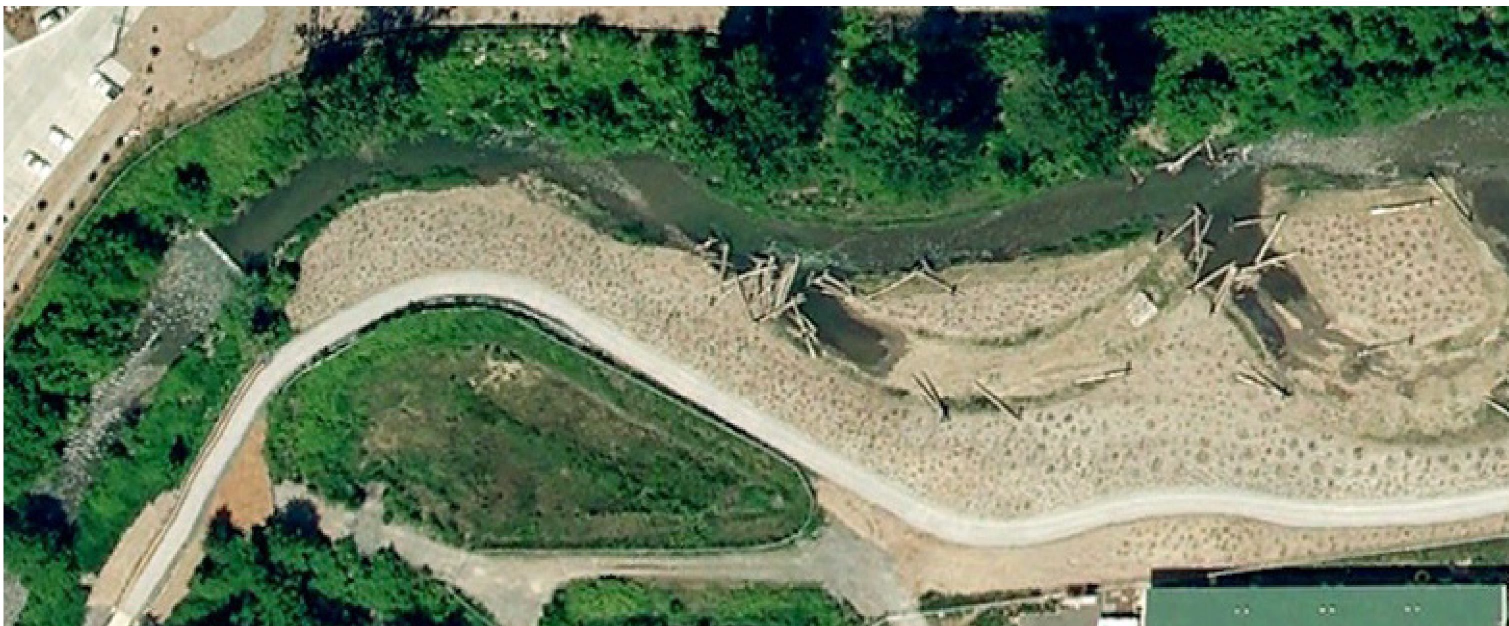


Figure 122 - Extent Inundated During 2020-2021 Water Year

Total surface area inundated by >0.01 ft. of water during the realistic flow tests.

Intervention Typology

To make the interventions, decisions were made as to what their forms and shapes could be. A major source of inspiration for this project is the 2015 renaturalization of the River Aire in Geneva by Atelier Descombes Rampini. The project on the Aire River reestablished a natural flow process. The designers chose to initiate the restoration by cutting polygonal geometric forms into the streambed, which eroded over time into organic forms. Within the first year, only remnants of the initial design persisted in the landscape (Atelier Descombes Rampini 2015). While this was an artful use of natural process, my interventions needed



to have immediate results based on probable end-form functions. The interventions needed to have organic appearances and be immediately mature in their morphology. Similar projects, such as the 1999-2006 restoration sites on Whatcom Creek by the City of Bellingham (Forester 2010), devised similar forms to those used here. The designers of this restoration project used natural forms such as holding basins and arcs to form its language. While it wasn't guided by geometric aesthetics to the same extent as the ADR site, it sets a precedent for this project. The interventions there take shape using natural forms for their inspiration. River geomorphology often has a fluid, sinuous, curling

Figure 124 - Examples of Restoration Sites

(T) Whatcom/Cemetary Creek Confluence Restoration Project (City of Bellingham 1999)

(B) River Aïre, Geneva (ADR 2015)

(USGS, Google)

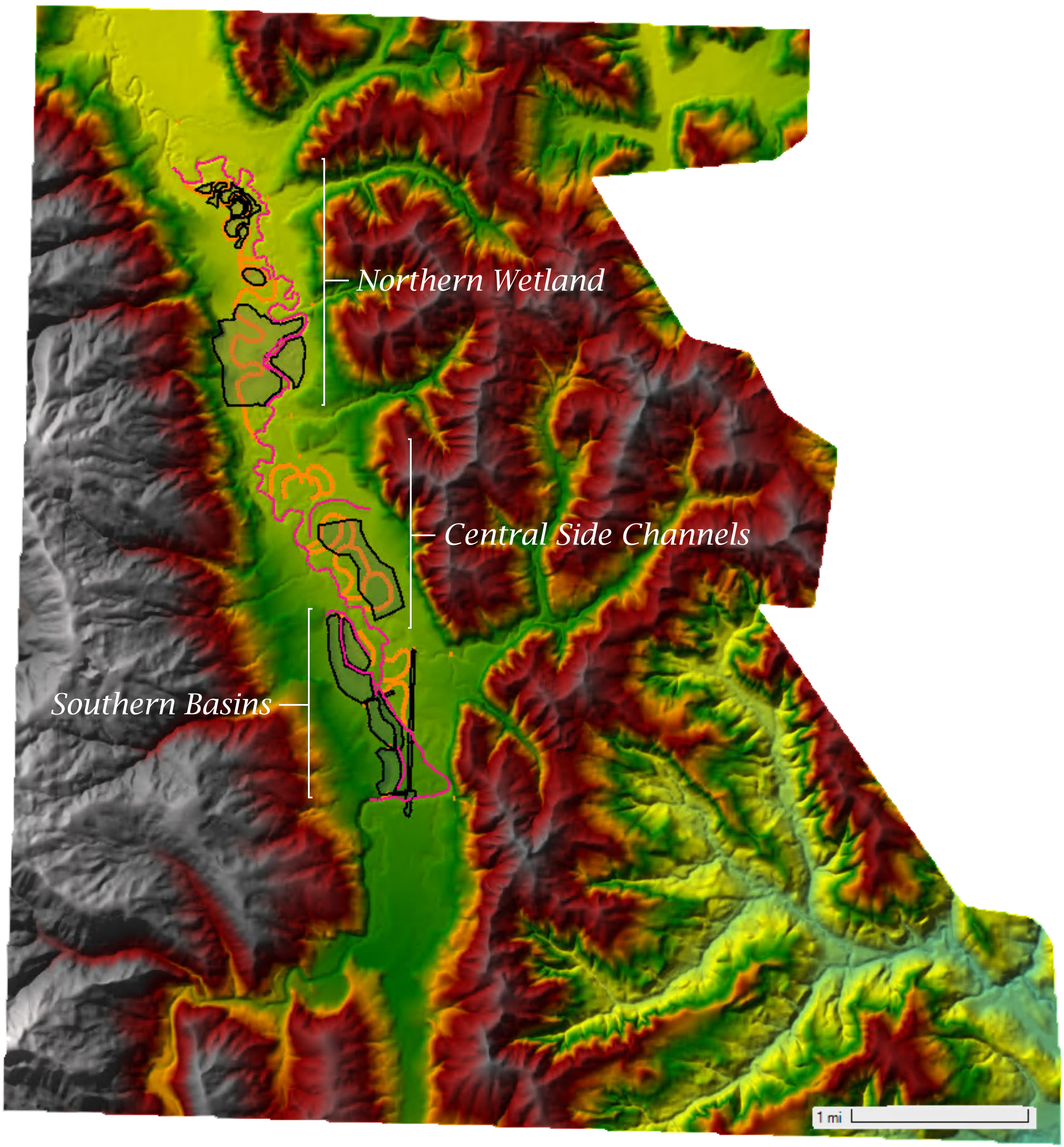


Figure 125- Primary Intervention Site Locations

Fill

Cut

Areas of basins or broad cut/fill modifications shape. This leads to the oxbows, bends, thalwegs, braids, and other evolving features. These are the shapes that were influential in the creation of the interventions. These shapes are proven, by their existence within the physical landscape, to be effective in the processes and goals that this project seeks to replicate. While engineered forms may produce different results, they are not thoroughly evaluated due to time limitations.

The tools used in the creation of the landscape have a large impact on their appearance and function (Hansen 2011). The interventions are be inherently artificial, and therefore influenced by human process and technology. The tool HEC-RAS is designed to be intuitive to people familiar with GIS processing software. The software uses polygons and lines as its language, and therefore must be conversed with in similar human geometry. The program is unable to use curvilinear forms, arcs, ellipses, and other graceful representation. The resulting hieroglyphs are angular and blocky—clearly geometric and artificial. This language greatly influenced the outcome of the project. The resulting landscape of modifications is alien and strange. The implementation of this design may embrace the geometric forms, seeing them soften over time. Or the geometry could be softened by designers to produce more curvilinear and pre-eroded forms.

Streambed Elevation

The artificial raising of the base stream bed height proved invaluable to the implementation of all other strategies in the landscape. It is a method to mitigate the effects of a common problem within many human managed streams: incision. As a stream increases velocity through straightening, obstacle removal, and bank modifications its conveyance and wasting exceed the input of sediment from upstream. This creates a sediment deficit that leaves the streambed scoured- more sediment is leaving the system than is deposited. The South Fork of the Chehalis River is no exception to this, having banks that are often twelve to fifteen feet above the streambed. The streambed itself is frequently reduced to bedrock, having conveyed all the available sediment downstream. This creates a common challenge for restoration efforts that seek to enlarge the floodplain engagement: the floodplain is two dozen feet above the water. With an average slope of 0.0034%, the South Fork of the Chehalis would have to travel 4,400 ft. to change 15 ft. of elevation. That would require almost a mile of diversionary channels from upstream to account for that discrepancy. These channels would be counterproductive to the goals of restoration and impractical. Thus, streambed rehabilitation becomes a key component to the restoration of rivers. Streambed treatments such as logjams and instream-structures help to slow the flow of water, allowing the deposition of sediment and the rebuilding of soils underneath the stream flow. This in

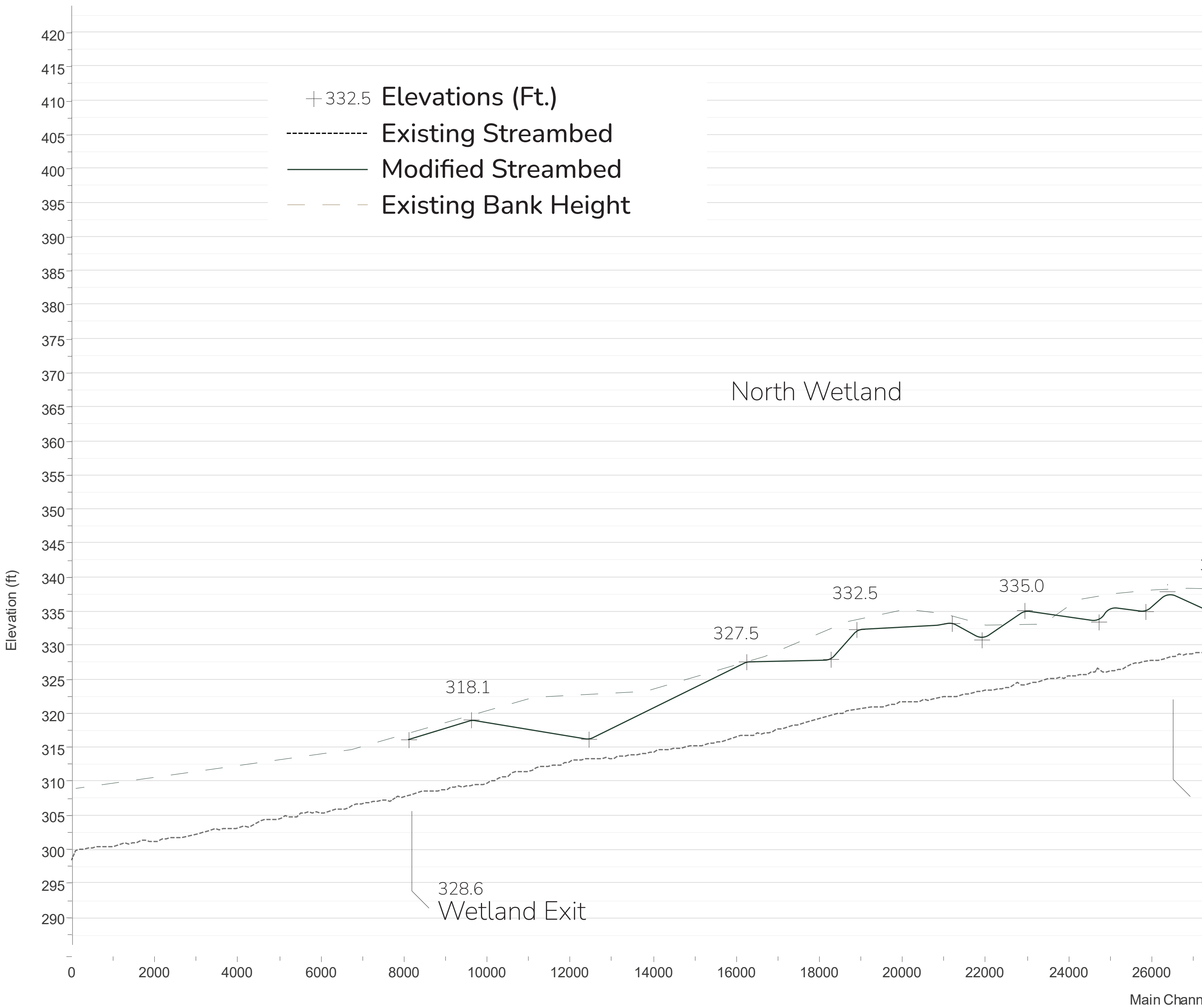
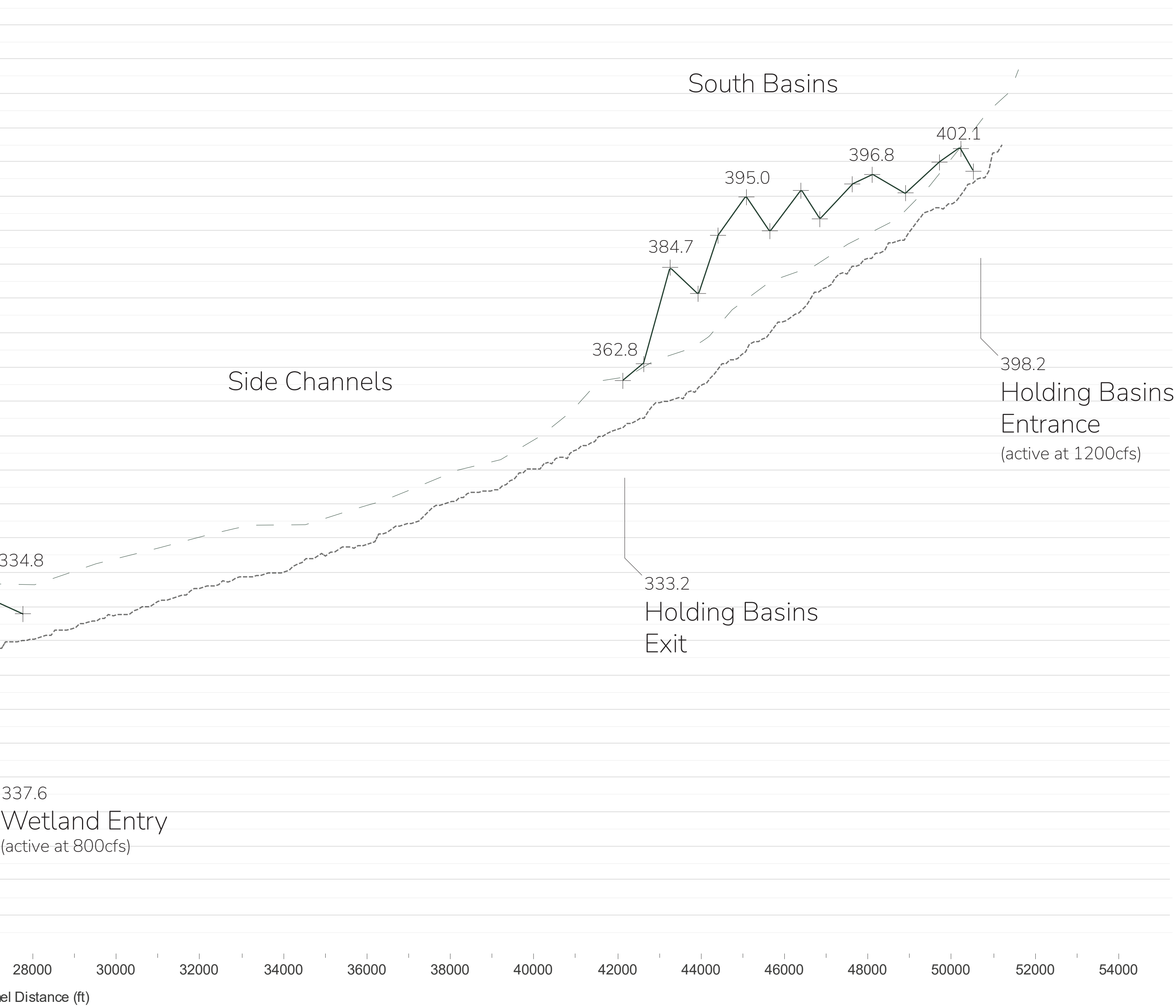


Figure 127- Elevation Profile with Modifications

This diagram was used for planning the entry and exit heights of the channel modifications. The bank elevation was important, as it roughly corresponds to the 100 year flood stage. It also was important to consider the bank threshold to prevent or encourage spillover into the floodplain. The section line does not represent the lowest point of the landscape, just the entry and exit thresholds.


South Basins
402.1
396.8
395.0
384.7
362.8
Side Channels
398.2
Holding Basins
Entrance
(active at 1200cfs)
334.8
333.2
Holding Basins
Exit
337.6
Wetland Entry
(active at 800cfs)
28000
30000
32000
34000
36000
38000
40000
42000
44000
46000
48000
50000
52000
54000
el Distance (ft)

turn decreases the freeboard of the banks, allowing water to breach the stream banks with less volume.

The difference in freeboard creates challenges with diverting water from the path of flow to interventions. A mile of lead-up channels would have to be used before any water could enter a holding area or side channel. The minimum water surface elevation would need to be very high before passing the elevation threshold needed to enter these structures. If the entrance to a holding basin was at ten feet above stream bed, then there would have to be more than ten feet of water before it would flow into the basin. This leads to the first intervention: for the entirety of the site, the base channel bed elevation was raised by five to six feet. This halved the freeboard throughout and drastically reduced the barrier to engagement with the surrounding floodplain. Now the stream would only have to raise its surface elevation by less than six feet to start engaging with the surrounding area. Entries to basins and side channels could start recruitment of water at a much lower stage, allowing for a broader range of intervention options.

In engineered structures, a key component is a disruption of the flow of water using obstructions. In log jams, this is not only large woody debris, but also the detritus that gets caught within the wood tangle. In engineered structures, logs or manufactured pylons are used to simulate this effect. The result is a permeable damming of the flow of water that is common throughout rivers. The HEC-RAS modification to terrain that best emulates this is a raised weir or spillway within the channel. This weir elevates the streambed another four feet for a total of nine feet over existing bed elevation. The weir extends for forty linear feet in the channel with 45-degree banks integrating it into the topography. Weirs were included periodically throughout the channel bed modification.

The geometry of the weir was largely arbitrary and primarily designed to be proportional to the landscape. It was designed to emulate the riffle and pool character that is prescribed for rivers like the South Fork of the Chehalis. In this classification, there are a series of blockages that leads to a pooling of water at intervals along the path of flow. These are characteristics of waterways that are less than 2% in grade, moderately flowing, and have limited supplies of silt. (Buffington and Montgomery, 2013). While it was not used in this way, the elevation of the weir heights could be modified to better control the surface elevation of water that is held behind it.

The real-world implementation of this modification would require extensive engineering and the filling of specialized soils. It would drastically impact biological, fluvial, and countless other processes in cataclysmic ways. The gradual buildup of sediment

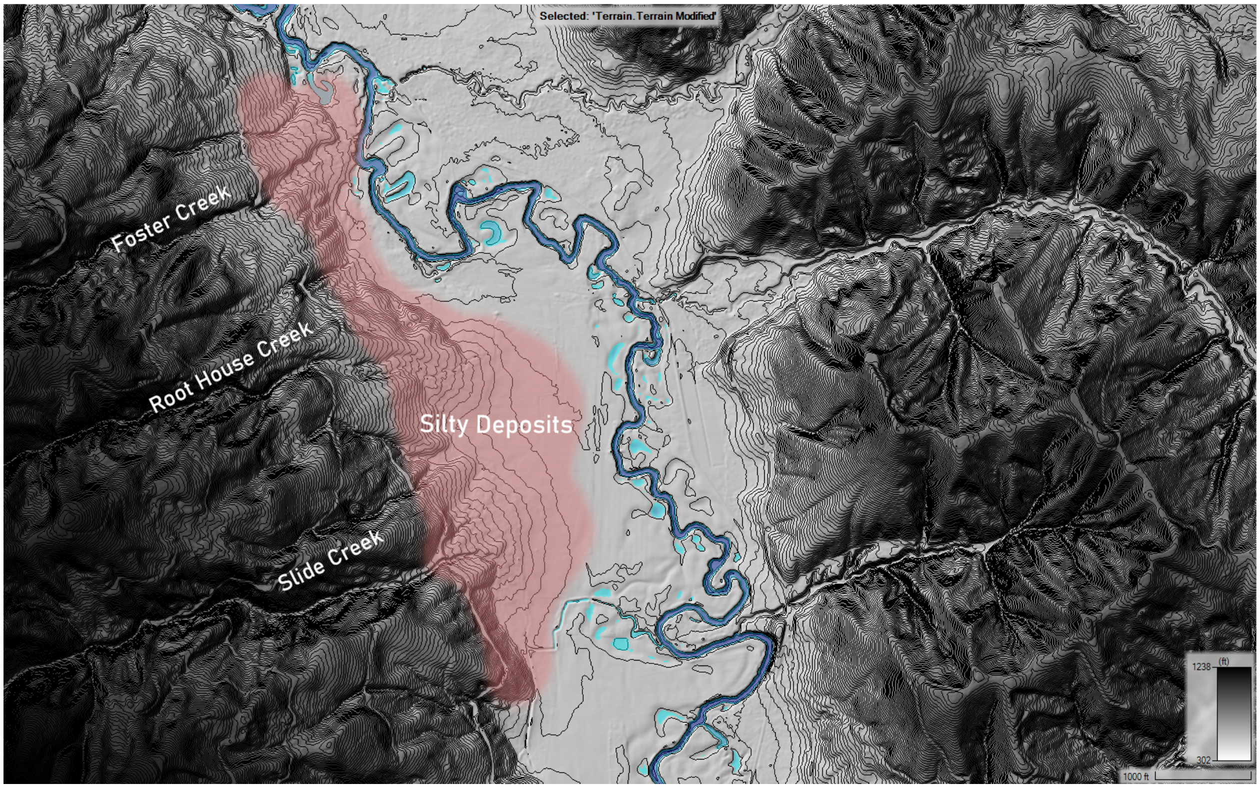


Figure 130 - North Wetland Design Constraints

The Northern Wetland location is influenced by the fluvial silt deposits. The silt deposits created a gentle slope at the end of nearby creeks leading down into the basin. The design took advantage of this to imagine availability of fill once the basins were excavated. It also forced the modifications to be close to the center of the basin.

through natural sediment transportation processes, however, would achieve similar results in a way that would enrich the river's overall health. Furthermore, much of the harm to this natural sedimentation process is from upstream influences. Logging the surrounding valley hillsides robs the stream of critical woody debris and disrupts sediment transport. While this project does not address these concerns, it works under the assumption that the surrounding conditions are addressed in such a way as to allow for the site to function as intended.

Holding Basins

To directly address the need to hold water on the landscape for longer periods of time, a series of holding basins were implemented. The objective of the holding basins was to fill with water at specific flood stages, and hold that water to infiltrate into the landscape.

Outflows allowed sufficiently high flows to use the holding basins as diversionary channels, ensuring that the flow would not overbank and disrupt other areas. The size and shape of the basins were determined by the constraints of the landscape. They were designed to balance and minimize the terrain modification needed to implement them. They were also designed to fit within specific sub-areas that allowed for opportunities for ingress and egress. For example, the Northern Wetland area's entrance branches off from a sharp curve in the river and entered through a historical oxbow channel. This allowed it to use the existing landscape conditions to enhance the ability of the inflow point to perform in diverting water. The exit to the wetland uses an existing drainage channel to join back with the main flow. Using the existing topography will theoretically encourage the resilience of the systems, as they work with the same flows of energy that have expressed themselves.

To implement these changes within HEC-RAS, several techniques were used. First, a meandering channel of 40-60 feet was cut across the area that would hold the cluster of modifications. This channel established the whole system's inlet and outlet heights. It also ensured that the water would flow through the system if overwhelmed by water. The entry height was dictated by the desired level of flood stage that the system would activate. The exit height was dictated both by the streambed height at outlet and the outlet height of the last holding basin. The exit must be below the height of the last basin's outlet threshold. Once the general flow was established by the channel, the basins were constructed within that curvature and placed on the landscape. A central low point was established, and the maximum depth was calculated so as not to exceed 15% slope at any time. The decision for 15% was arbitrary, but based on the assumption that the typical soil type would be silt. This would be well below the required angle of repose needed to hold that soil in place. Additionally, the low grade would increase the longevity of the landform modifications. The inlets and outlets between basins were determined by the height of the surrounding floodplain. The goal was to reduce perched basins of holding water whenever possible. The inlets and outlets of the basins were used to change elevation to match the surrounding height. This could not be done at the settling basins, as the change in elevation between inlet and outlet would also reduce their holding capacity. Maximizing the holding capacity of the basin system would come at the cost of diverging from the natural grade of the river. The low point elevation was then expanded within the basin as much as possible to maintain the 15% slope on the banks and work within the elevations needed of the inflow and outflows. For example, if the basin allowed water into the holding area at an elevation

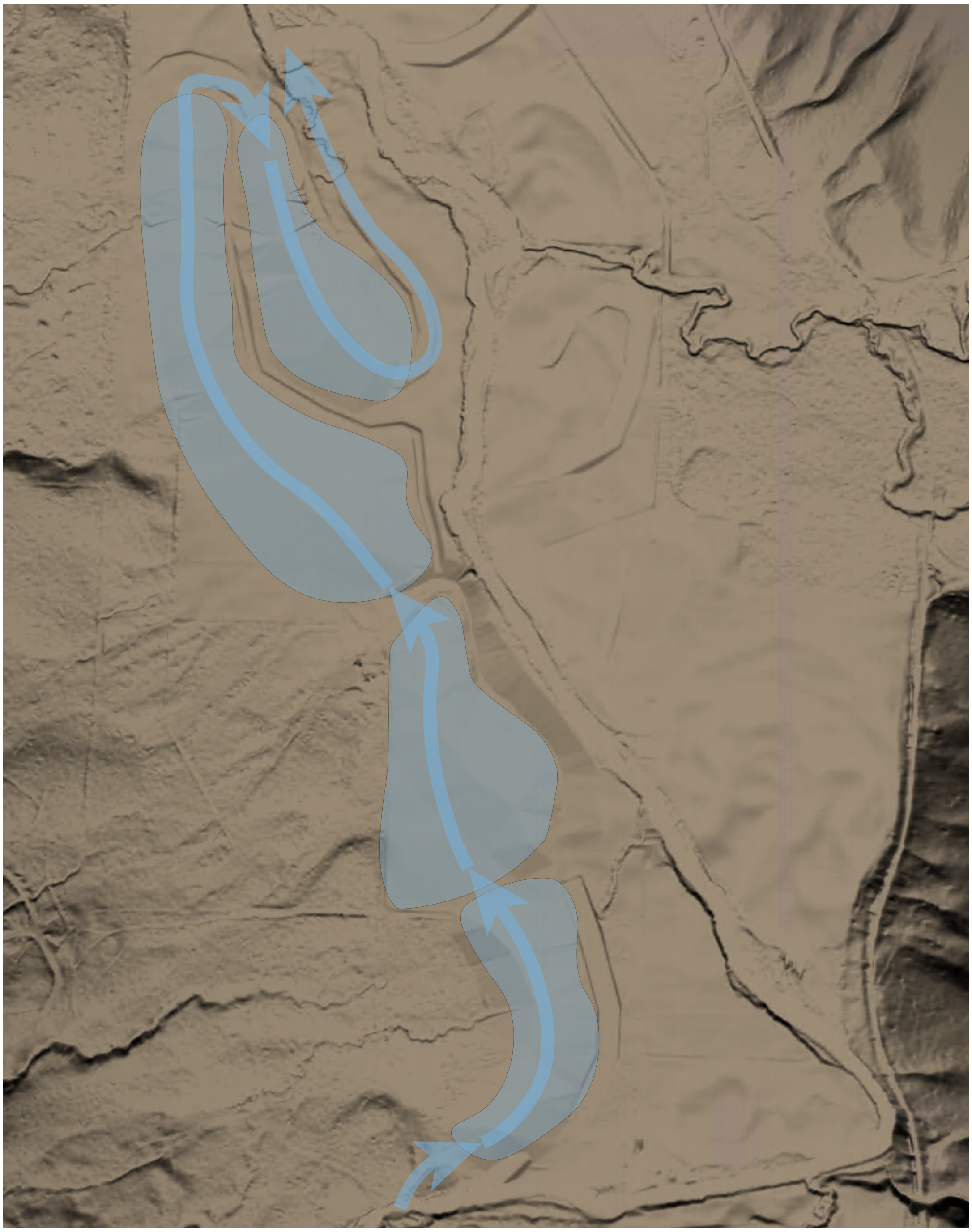


Figure 132- Site Modification - Holding Basins

Figure 133a - Site Modification: Side Channels

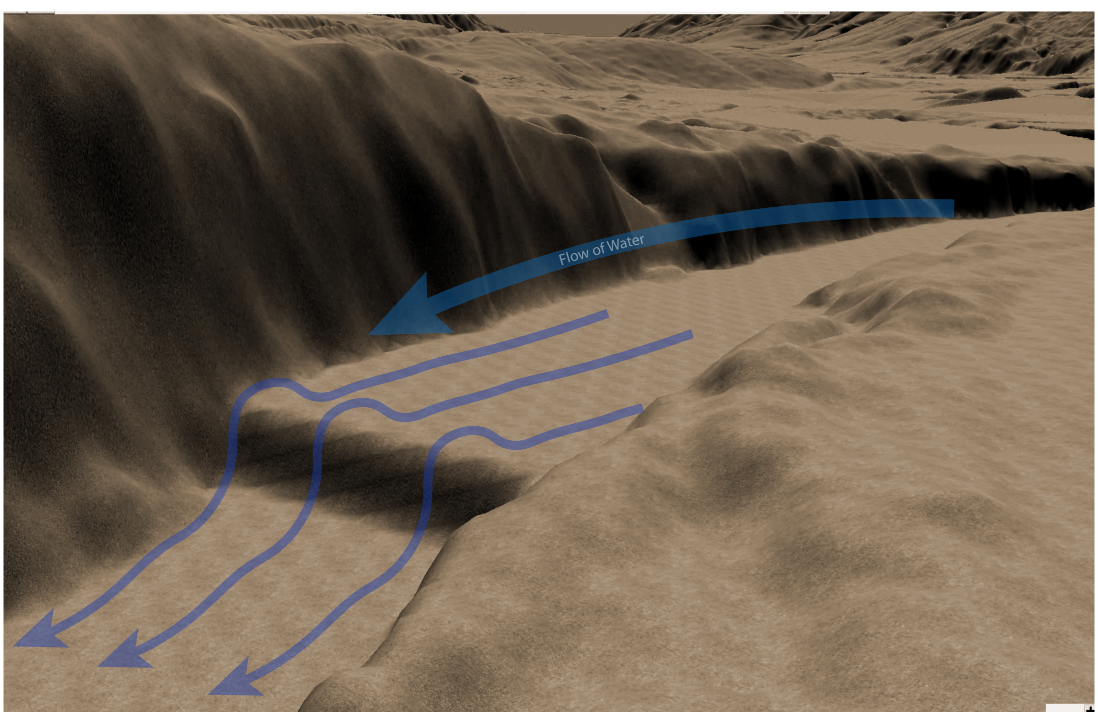


Figure 133b - Site Modification: Instream Treatment of 100ft. and outflow at 99ft., then the bottom of the basin could be no closer than 6.6 ft. to the rim of the outlet.

The basins are designed to sequentially flood as water levels rise. The Southern Basin area requires the first basin to fill before the second basin, which is connected to the outlet of the first, engages. The same mechanism is employed for the remaining basins, which fill only if the preceding basin is at capacity.

The inflow height of the channels decided the anticipated nature of the basin areas themselves. Some of the basins were designed to hold water at a low flood stage. These would fill during times of heavy rain or high seasonal flows and help to recharge aquifers and engage with water-soil processes. They would also be able to sequester higher volumes of water at times of need. Other basins were designed to allow the inflow of water during major flood events. But as the water reached a certain elevation, these basins would inundate with water, increasing the landscape's capacity to hold and retain floodwater. These basins would slowly drain through the soil, plants, and evapotransmission as water receded below the outlet threshold and pooled in storage areas.

The ephemerality of the holding basin would dictate the vegetation and microclimatic conditions. The basins that engage at high stream flows would take on characteristics of riverine benches, which flood regularly with seasons. The basins that engage in major flood events would be populated by upland forest plants and soil. These would tolerate occasional flooding but would convert to a different profile if the flooding occurred too frequently. Using the Southern Basin system as an example, the first basin would be characterized by vegetation that enjoys or requires seasonal flooding. The second basin would hold vegetation that tolerates inundation but does not require cyclical wetting. The third and fourth basins are anticipated to rarely see floodwater, so they would hold vegetation that is typical of upland forests.

Staggering the availability and frequency of basin use allows for flexibility within the floodplain system. It would encourage resilience within the landscape's ability to adapt to changing water levels. Furthermore, it would allow for malleability for larger trends within climate change. The basins that were developed for use during major year floods could express changes in soil and vegetation as they were flooded at more regular intervals. Unlike major engineered structures such as dams, the basins emulate the existing typologies of floodplains. Because of this they also take on the plastic characteristics of these systems.

Side Channels

The side channels took shape in a similar way to the holding basins. Their key difference, however, was their objective. While holding basins sought primarily to retain water at certain flood stages, the side channels' primary focus was to increase the surface area of water interaction with the flood plain. The side channels, therefore, did not have to be deep or concern themselves with water elevations for engagement. The inspiration for the side channel form came from the oxbow and braiding dendric meanders evident in the DEM examination of the historical landscape. As part of the evolution of an oxbow, the stream creates a new channel and eventually seals it off from the main flow. The layers of this create a complicated assemblage of flood channels. This transformation from main channel into a seasonally flooded wetland was a key inspiration for the design of the side channels. The form also accomplished the goal of being labyrinthine, allowing water to inundate the area slowly as lungs draw breath from trunk to alveoli. This pattern helps to maximize the surface area of inundation and creates a diverse landscape of microclimates.

The site constraints of the side channel locations were much less than those of the basins. The side channels require a relatively flat landscape. This flat landscape is easily found in the floodplain. The channels are also flexible with changes in elevation. They are designed to be at least seasonally inundated, so do not need to differ greatly from the normal elevation of water flow. They also do not need to engage in successional programing with the flow of water. They can adapt to changing conditions and will encourage vegetation that fits that niche. The primary zone for side channels were situated between the basin systems that were established within their demanding constraints. Their placement filled the gaps between the other interventions and focused on expanding the channel's interaction with the surrounding floodplain. The entrances to the side channels started at elevations near to the streambed, allowing for continuous seasonal inundation. The side channels often have secondary channels at similar elevations, or at gradually increasing elevations that encourage water interaction at increasing flood stages. These side channels expand the wetland inundation areas and provide more area for habitat.

Characteristics of Landscape after Strategies

Northern Wetland

The Northernmost intervention is a retaining wetland and natural area. It is designated as "Northern Wetland" and its goal is a combination of increasing the interaction with the floodplain and attenuating peak flows through retention. The wetland takes the form of basins with channels throughout to accomplish these dual goals. The channels are designed to either convey water through the landscape or provide complexity for the floodplain to fill and create side channels or wetlands.

The site is characterized by a meandering oxbow channel which dances around the basins that occupy the interiors and exteriors of the curves. It runs in line with the existing stream bed, offering a water diversion once the stream height reaches a bankfull depth. The total length of the intervention is 8430 ft. and has a grade of 0.004%, matching the channel elevation. The channel that offers the main path through the intervention offers points for the water to spill into these basins periodically to be held as they permeate into the soil over time. The basins hold this water by maintaining a higher rim elevation on the downstream side than the channel as it passes through the area.

The site is divided into two distinct and independent sections. The Southern section is smooth and integrated into the landscape. It allows water to start flowing into the system at a stage of 3 ft. of depth. This stage occurs during flows of 300 cfs. or higher. This low entry height would allow for frequent flooding throughout the wet season. The area it occupies is essentially flat, used for generations for agriculture. This flatness allows for the gentle changes in elevation. The northern section has more dynamic and obvious cuts into the landscape. It is designed in response to the silty alluvial deposits of Foster, Root House, Slide, and Water creeks that occupy the area West of the channel. The deposited sediment from the hillside creates a steepness to the terrain that necessitates harder elevation cuts to make transitions. The Northern portion of the Northern Wetland would only allow water at levels of 8.5 feet above stream bed which occurs at 5700 cfs. of flow. This section would only engage with higher flows that threaten to otherwise overbank throughout the floodplain. Using the 2020 realistic flow data, this would only occur twice in that year.

Central Side Channels

The center intervention is informed by the goals of engaging the floodplain by increasing the total surface area of its interaction with the landscape. It consists of a series

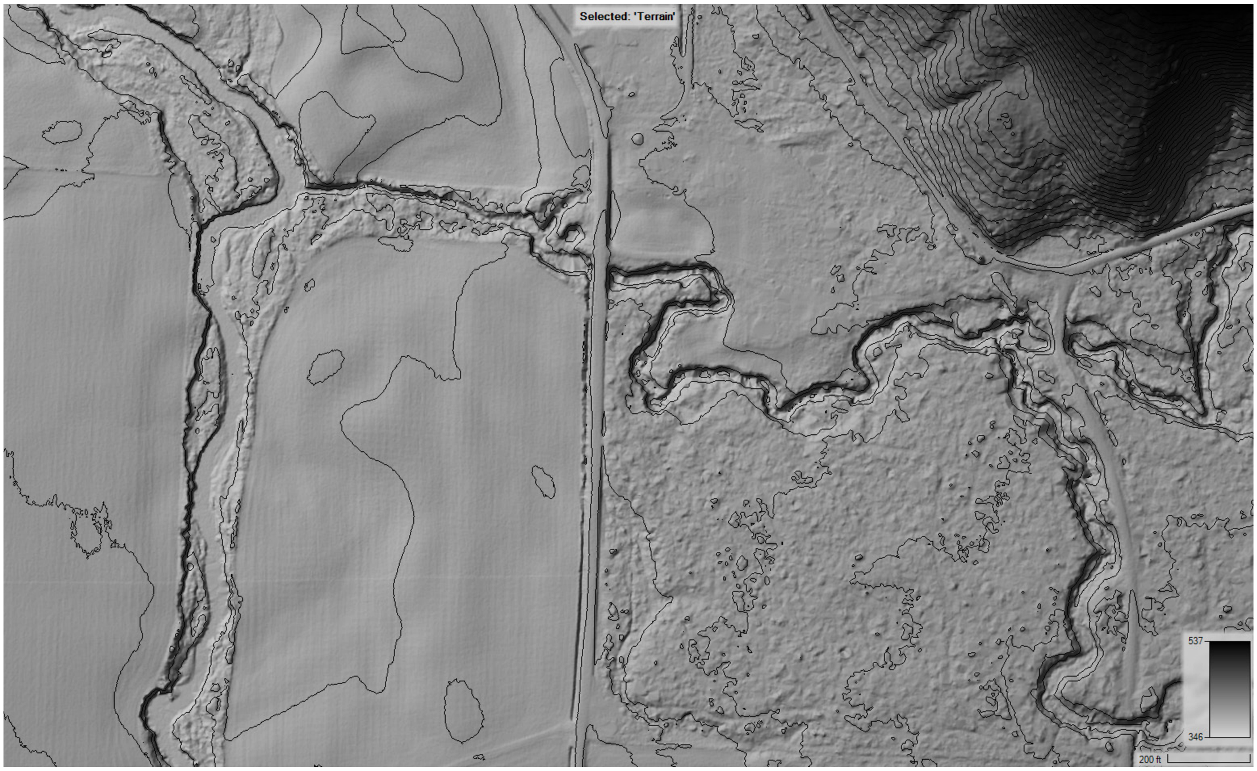


Figure 139 - Unmodified Landscape Near Cedar Creek Confluence

of overlapping oxbow forms, emulating the oxbow side channels that express themselves during normal floodplain processes. The section runs for 8760 ft. on the Eastern bank of the river. It encourages the collection of water from the confluence of Cedar and Laughlin Creeks. The area selected for this modification expressed a history of oxbow formation activity when examined with the REM maps. Recreating this typology was appropriate due to this characteristic. The side channels engage with the flow of water at very low stages. Many of the entrances breach the bank at stream bed elevation, allowing any flow of water to start pooling into the wetland forms. These channels increase at a gentle grade towards their apex, which is the highest point of the side channel. This allows water to flow in gradually into the system. Many of the side channels have secondary branches that network together with other forms to create a complex canal system of side channels. The frequent inundation of these areas encourages the growth of wetland and aquatic species.

Southern Holding Basins

By far the most aggressive intervention, the Southern Holding Basins work towards retaining water and allowing slow percolation and recharge of ground water. The site's

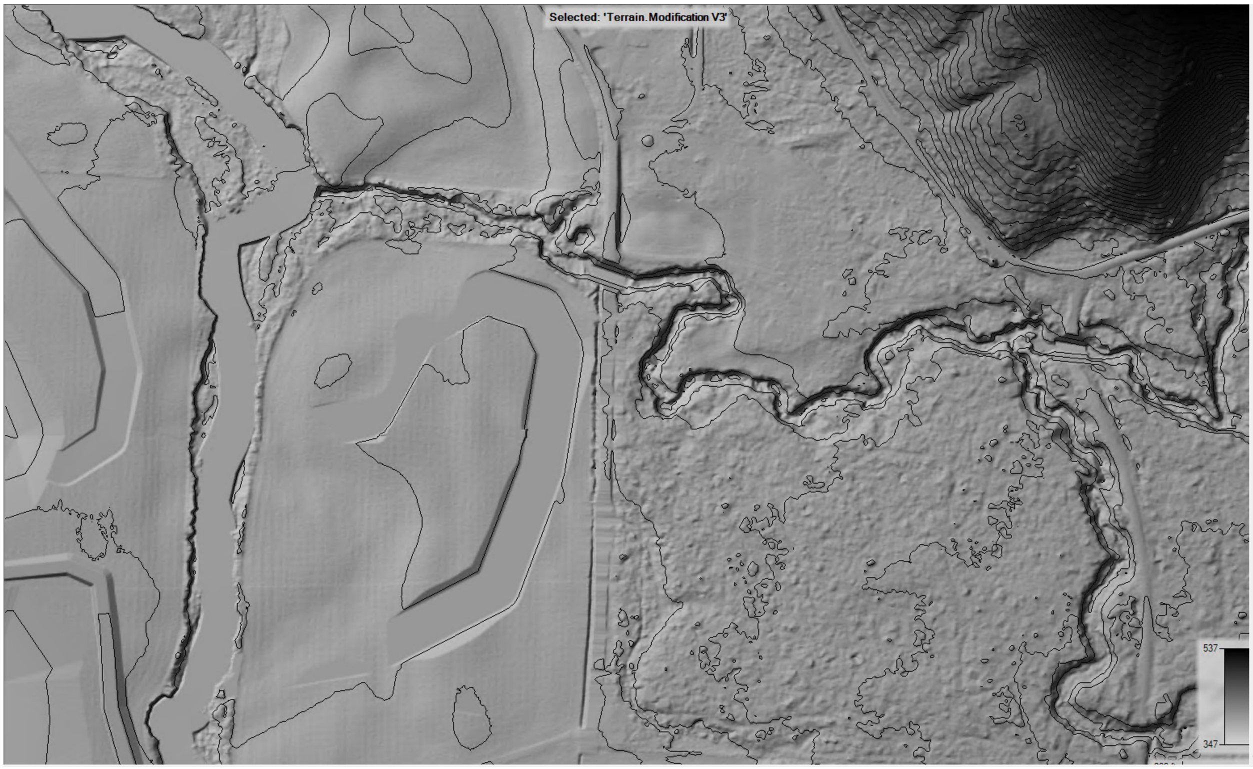


Figure 140 - Modified Landscape Near Cedar Creek Confluence

topography was the determining influence on their creation. The hillside to the West of the stream starts climbing towards the floodplain walls. The gradual climb is steeper at the Southern end of the site and becomes shallow as it continues North. This is perfectly suited for a terraced system of holding basins to run parallel to the flow of water. The basins are a series of catchments sequentially situated and joined together with small breaching canals. These canals are at specific heights to allow water to flow onto the next basin only when the previous basin is full. Water flowing out of the system through the spillway and back into the main channel would only occur when all the basins were completely full. This system engages at the first basin once flow levels reach 7 ft. of height. The system is designed to be a modification of the hillside, not necessarily the floodplain. The intent is that the basins will rarely flood, so that the hillside can function as a mature forest for much of its lifetime.

Reach Scale Modifications

The totality of the landform modifications occupies and drastically alters a great expanse of the floodplain's 3000 acres. Heavy modifications, such as the holding basins, use 9% (275 acres). Moderate modifications, such as canals, streambed raising, and side channels would take 14% (441 acres) of land. It would require the elimination of existing

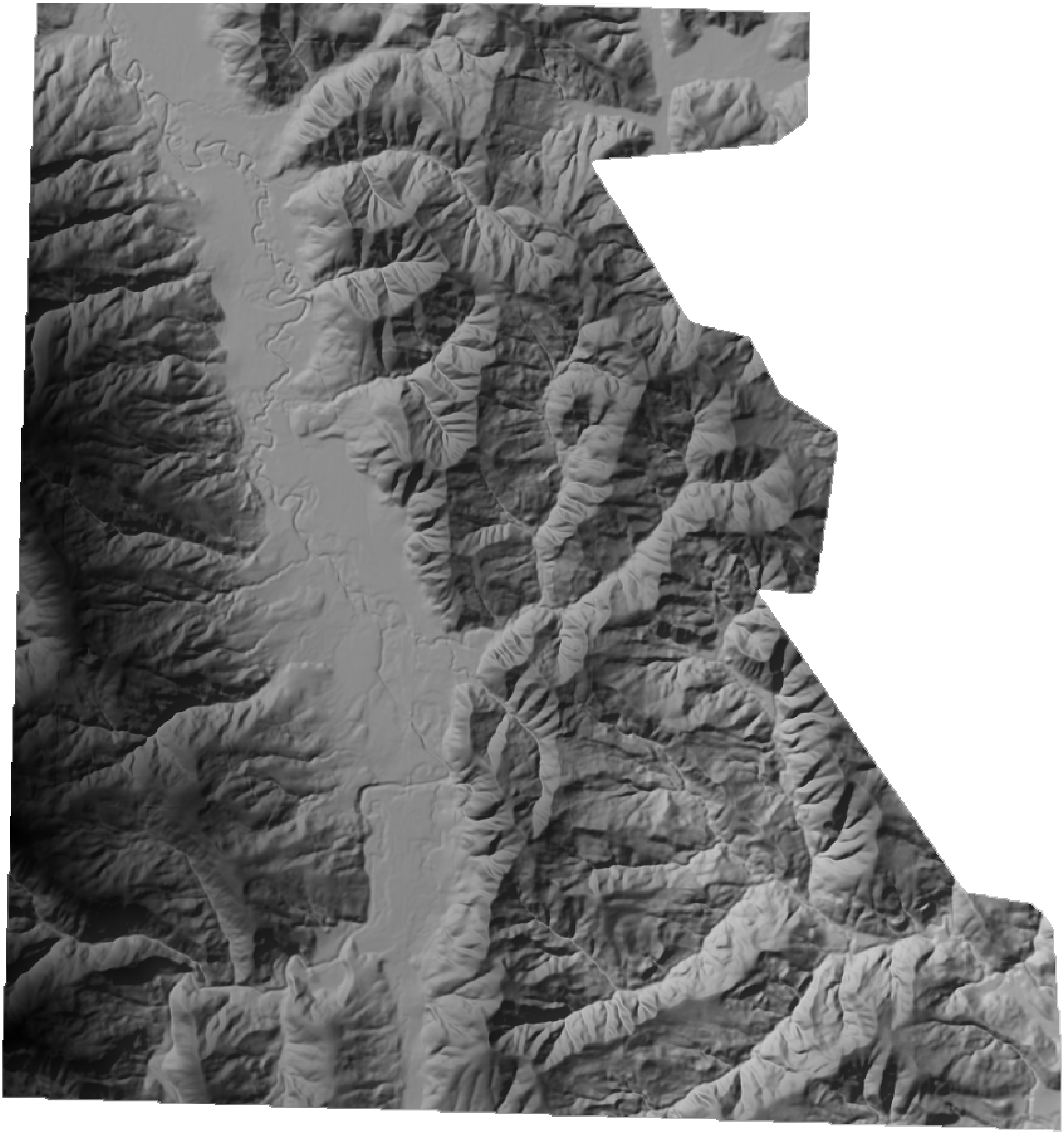


Figure 141 - Landscape Comparison

Comparison of landscape (L) before and (R) after landscape modifications.


1 mi

human structures. These include culverts that alter the flow patterns of surrounding creeks and levees that carry roads through the landscape. The culverts and levees greatly alter the flow patterns of the stream, often blocking large swaths of the landscape like a dike.

The modifications not only change the terrain, but the resulting changes in hydrology and microclimates will change the vegetation of the landscape. This is assumed to be a result of successful restoration efforts which are not explored in depth in this project. With the modifications, new Manning's values were used to reflect these changes. The n modifications were determined by the anticipated relationship the area would have with water. Areas that were frequently flooded were assigned values for woody wetlands, and areas that were on the hillside and above the floodwaters given values associated with forests. Vegetation of varying density was placed in clusters and forms that emulated the natural growth within a healthy floodplain. Whereas in the unmodified landscape, much of the channel banks were vegetated in a narrow buffer area, the modified landscape drastically increases the friction that water experiences as it travels through the floodplain.

The South Fork of The Chehalis is reinvigorated in this potential future. Before, the stream occupied and interacted with less than 1% of the landscape. With modifications, the stream regularly interacts with 35% (1105 acres) of the surface area of the floodplain. This drastic improvement not only increases floodplain biologic processes but restarts the geomorphology that has been hampered by past modifications to the landscape. Human involvement with the floodplain is drastically revised. Previous use of the floodplain for monocrop agriculture and pasture is no longer feasible. People can live in specific areas of the floodplain basin itself but are frequently cut off from easy access due to flood water. These people will need to be temporarily relocated as the modifications to the landscape take place. As envisioned by the Newaukum report, human occupation is easily accommodated

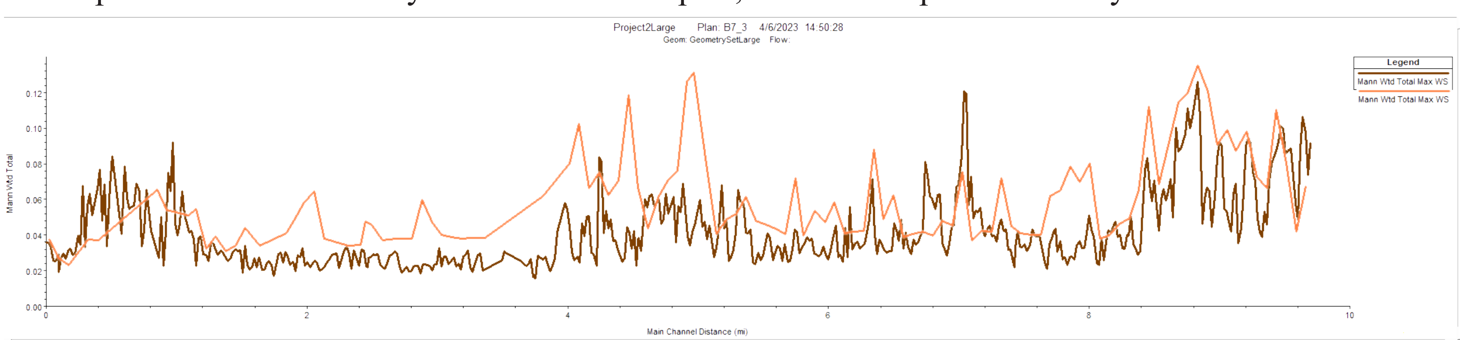


Figure 143 - Averaged n Values of Reach

Unmodified
Modified

on the gentle grades surrounding the floodplain. With the modifications, there is now more than 500 acres remaining that featured slopes from 5-10%. These areas may accommodate human use with careful consideration on how human occupation may affect ecological processes.

Flow Modeling in Altered Landscape

With modifications completed on the landscape, the next step is to run the same series of tests that were conducted for the unmodified control landscape. The modified landscape is subjected to flows of 1000, 5000, 10,000, and 15,000 cubic feet per second of steady input rates. Then they are simulated with the 2020-2021 water year. Results and data are collected from the same areas of the terrain as before. Overall, the flows across the landscape appear to interact with the features as anticipated. The wetlands and basins flood at approximately the anticipated times. Some errors of flow such as gaps or angular artefacts are present, but not to an alarming extent (Price 2019). The process of running the models produced a concerning number of errors. While efforts were are to reduce the errors, it is concluded that the errors do not cause meaningful deviations from the results and were limited to a few recidivist cells repeatedly failing calculations.

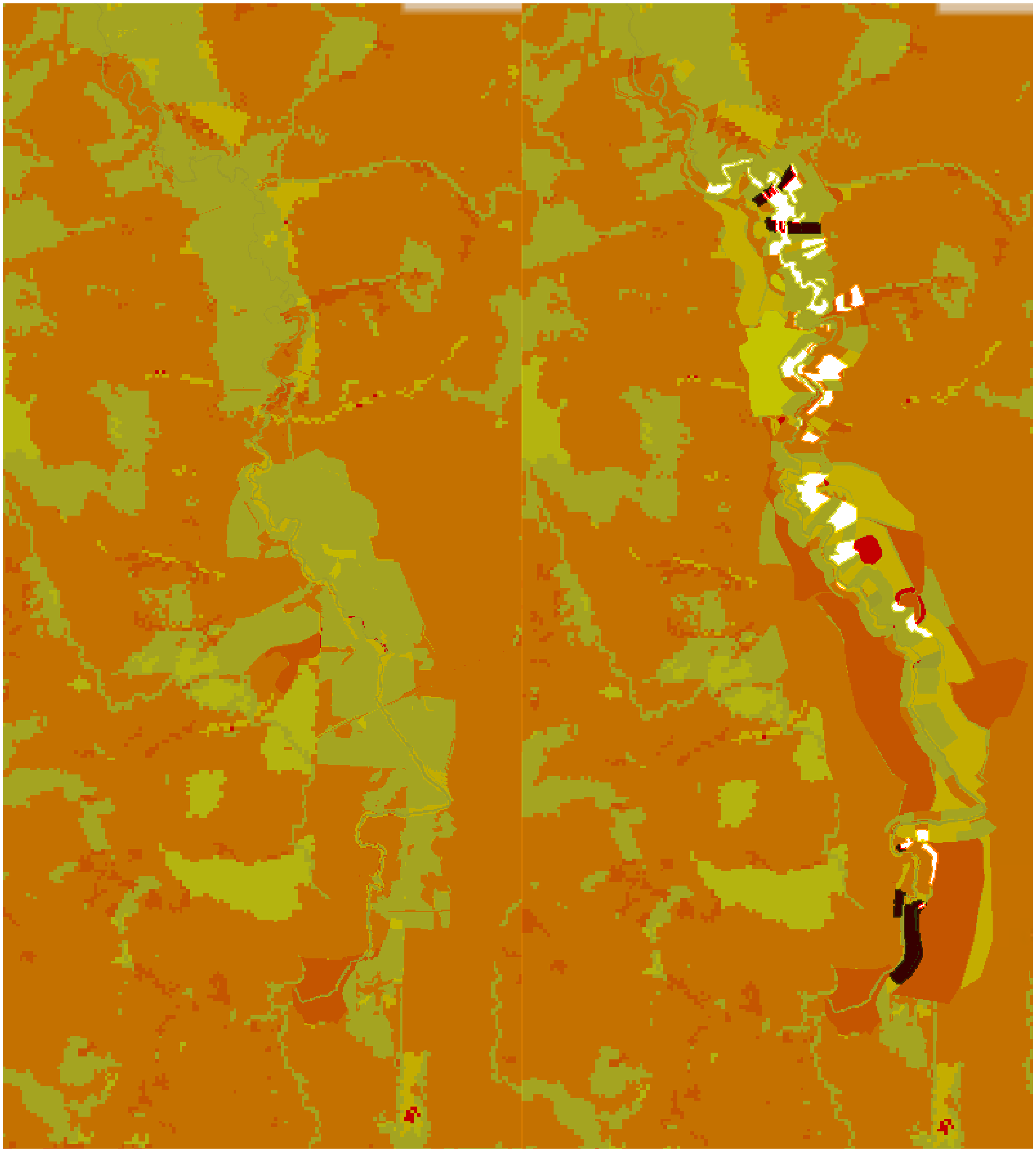


Figure 145 - Manning's Values

Comparison of Manning's Values (L) before and (R) after landscape modifications. Areas of white on modified landscape are errors and defaulted to the average value of the site (n 0.06).

4-Results

Overview

Overall, the site’s performance exceeds expectations. Almost the entire basin bottom touches water throughout the 2020-2021 water year. Inundation is concentrated to planned areas. Unanticipated overbanking is drastically reduced from the unmodified landscape. These parameters, however, are difficult to compare or place value judgement upon for the performance of the landscape. Multiple changes to the landscape occured at once, so isolating the impact of any one strategy is impossible using this method. Taken

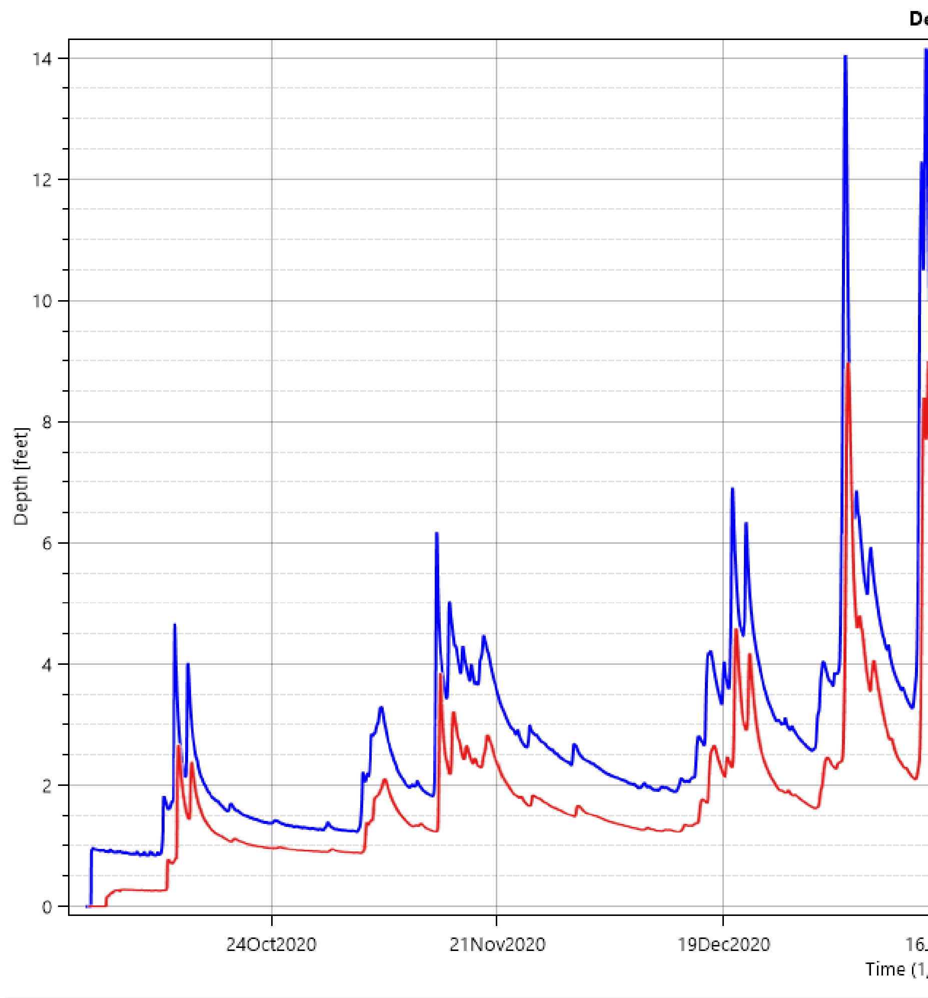
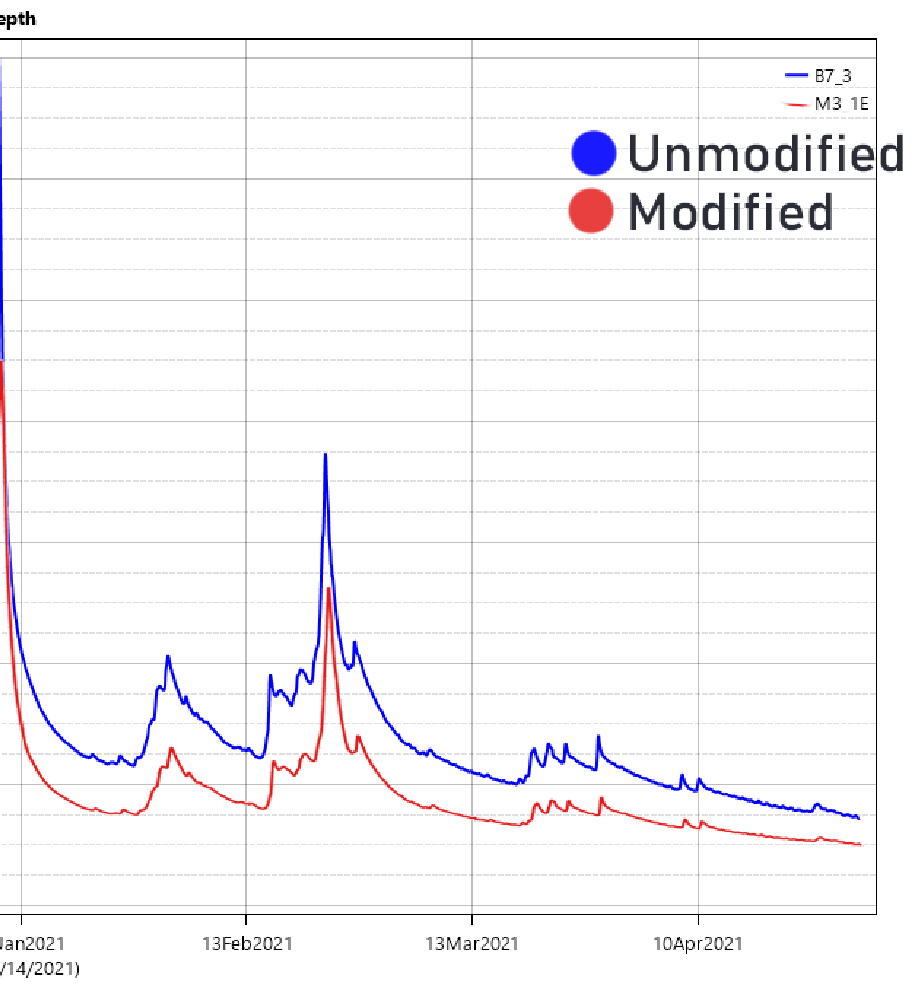


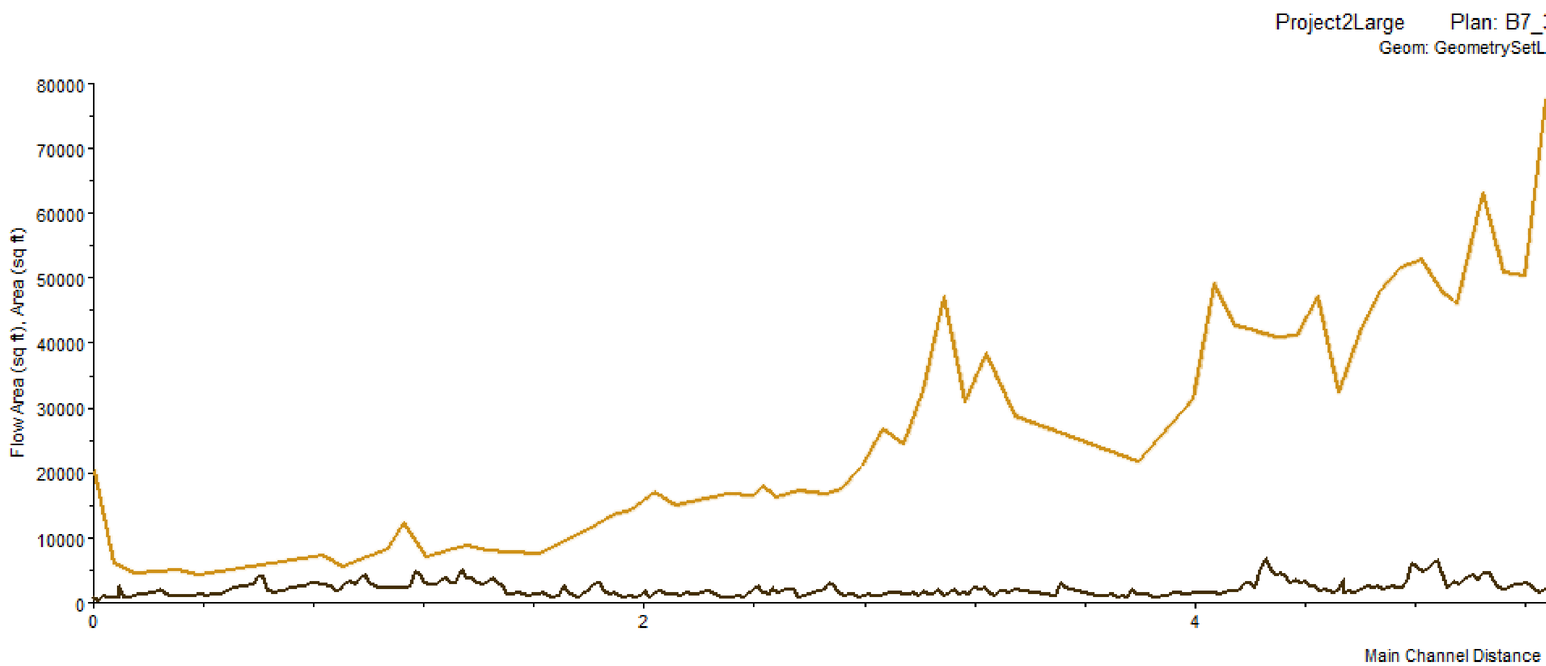
Figure 149 - Depth at Mid-Point Sample Node

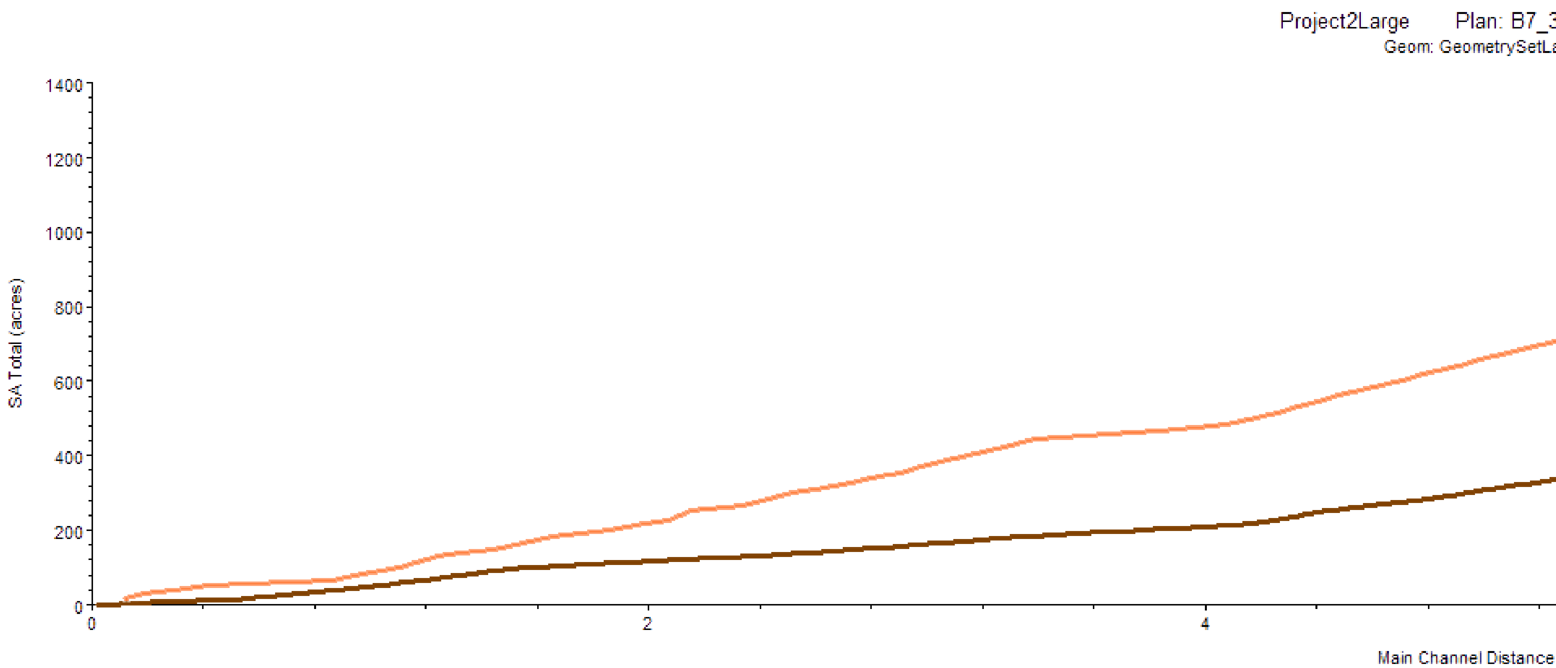
Flow comparison between realistic flow scenarios
Reduced depth of water is apparent throughout.

as aggregate, however, the changes are striking. Analysis concentrates on the 2020-2021 water year flows. The steps of steady flows do not show the details of the relationship between the water and the landscape as much as the variable flow. The fluctuations within the variable flow help to highlight the behavior of the water on the landscape as it oscillates between small increases and decreases within larger trends.



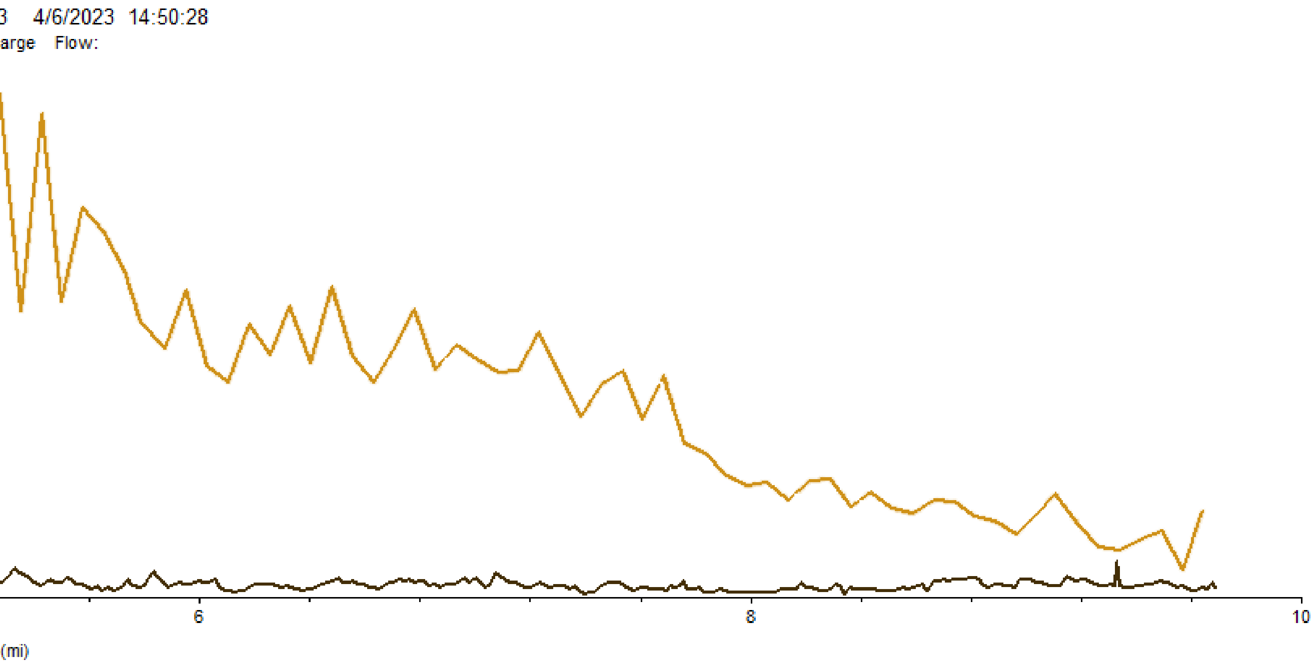
. Flow speed attenuation is present at the peak flows.

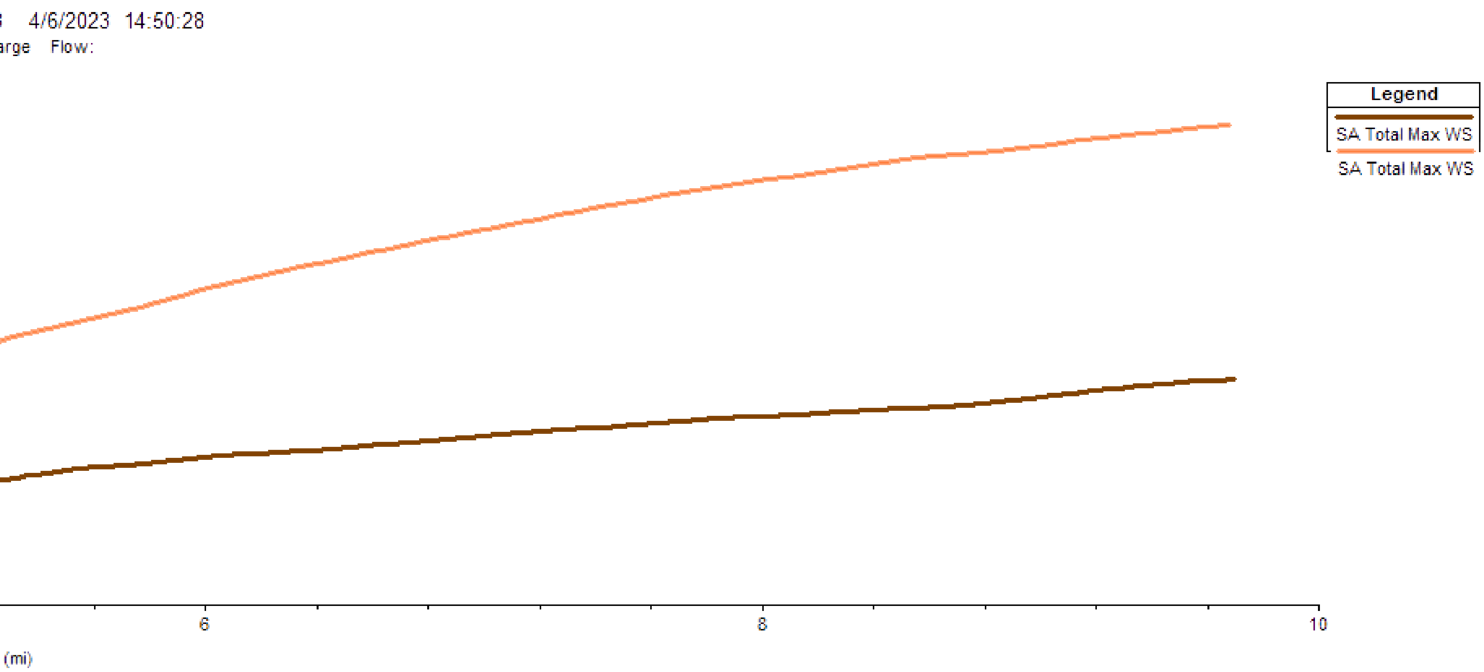




(T) Figure 151 - Area of Active Flow

As expected, the area of active flow drastically increased after landscape modifications. This increase in area will allow more infiltration and exchange between surface and groundwater.





(B) Figure 152 - Total Water Surface Area

Even at higher rates of flow, when the unmodfied landscape still had widespread inundation, the modified landscape has much more surface area.

Unmodified
Modified

Recorded at peak flow during realistic scenario.

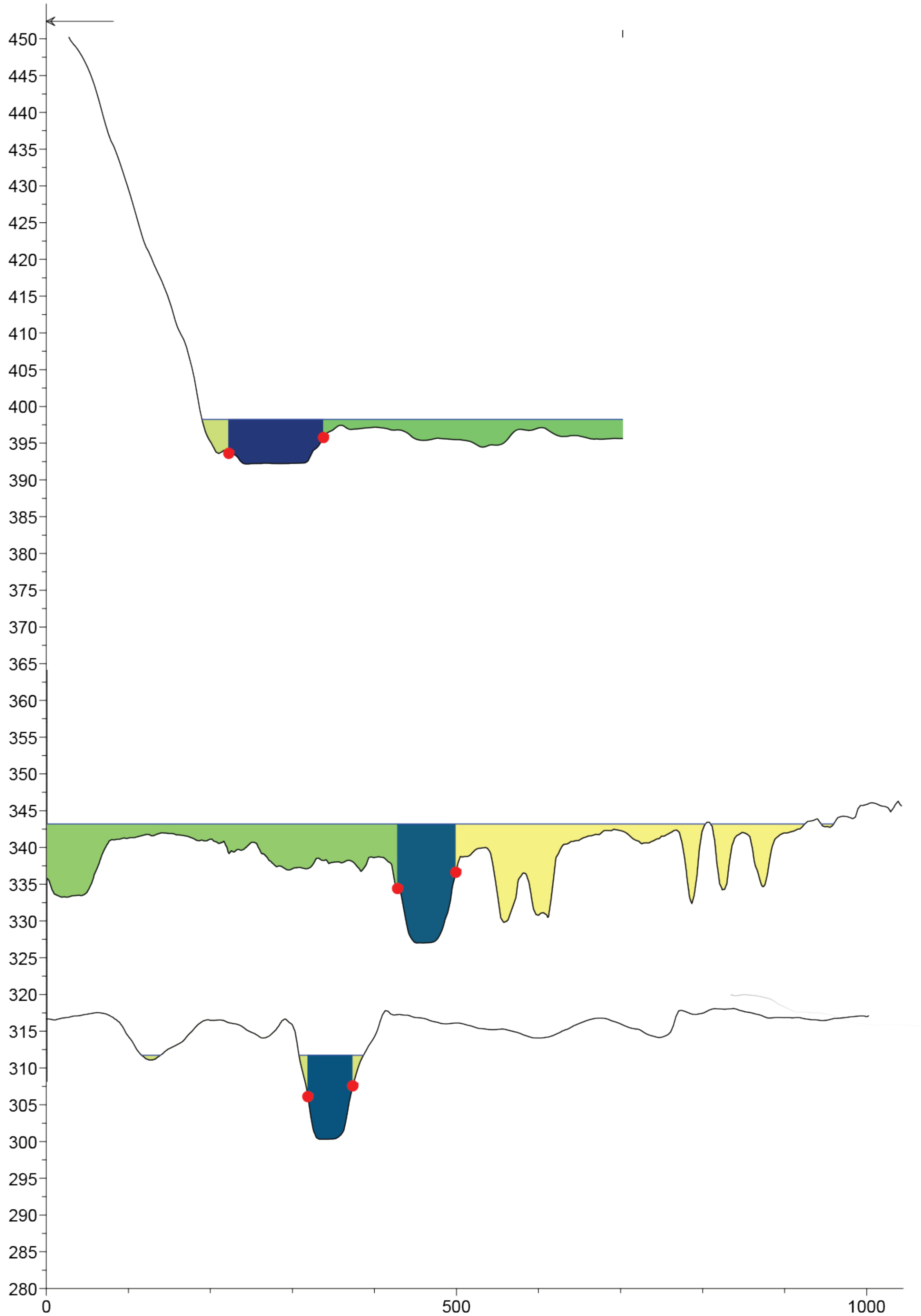
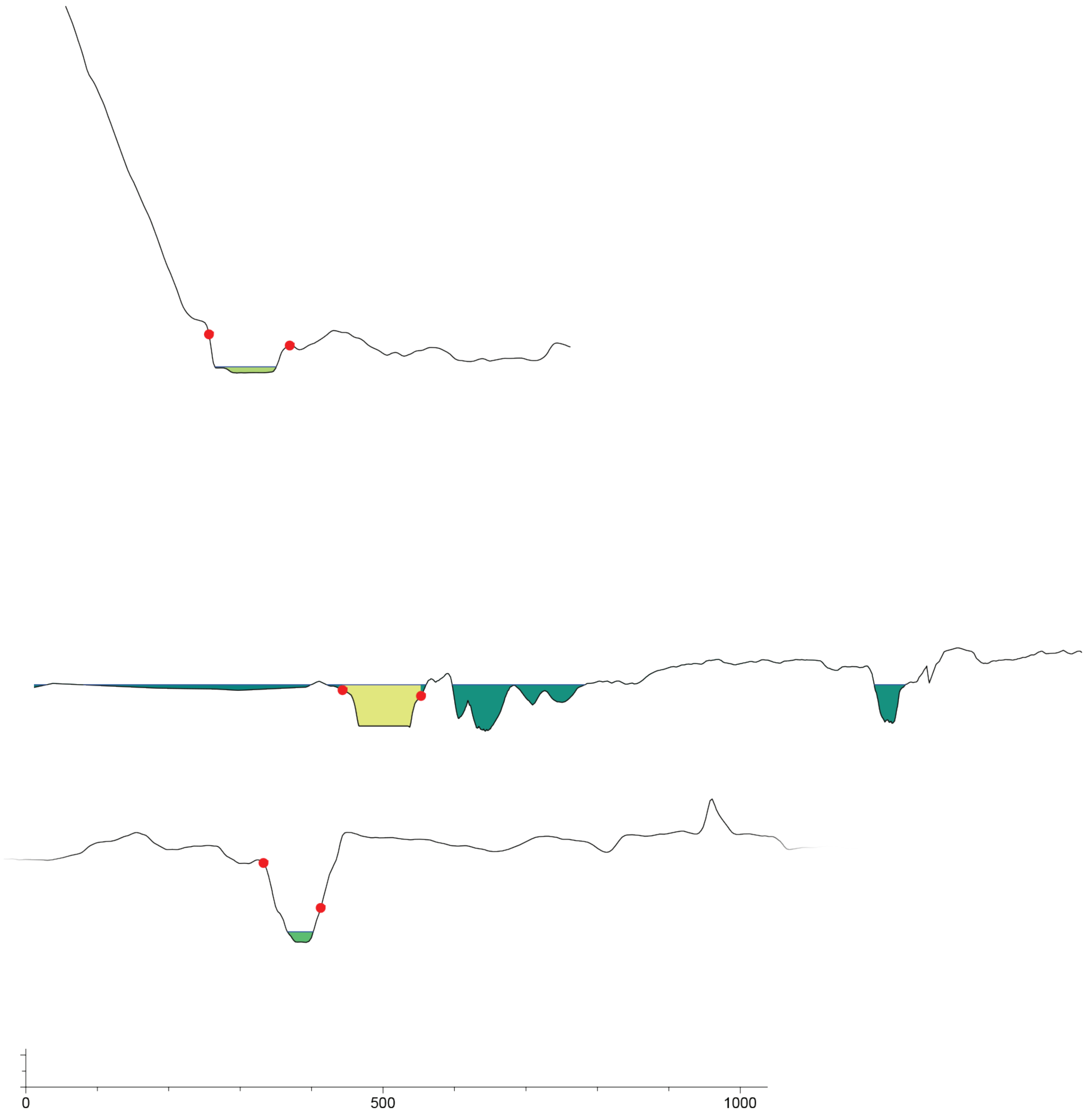


Figure 153 - Unmodified - Depth at XC 1, 5, 8 at 5k cfs.

Flow comparison between 5k cfs. flow scenarios. These charts compare the water depth and n values at sampled cross sections.

Recorded at peak flow.



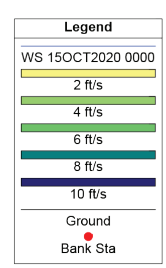


Figure 154 - Unmodified - Depth at XC 1, 5, 8 at 5k cfs.

Flow comparison between 5k cfs. flow scenarios. These charts compare the water depth and n values at sampled cross sections.

Recorded at peak flow.

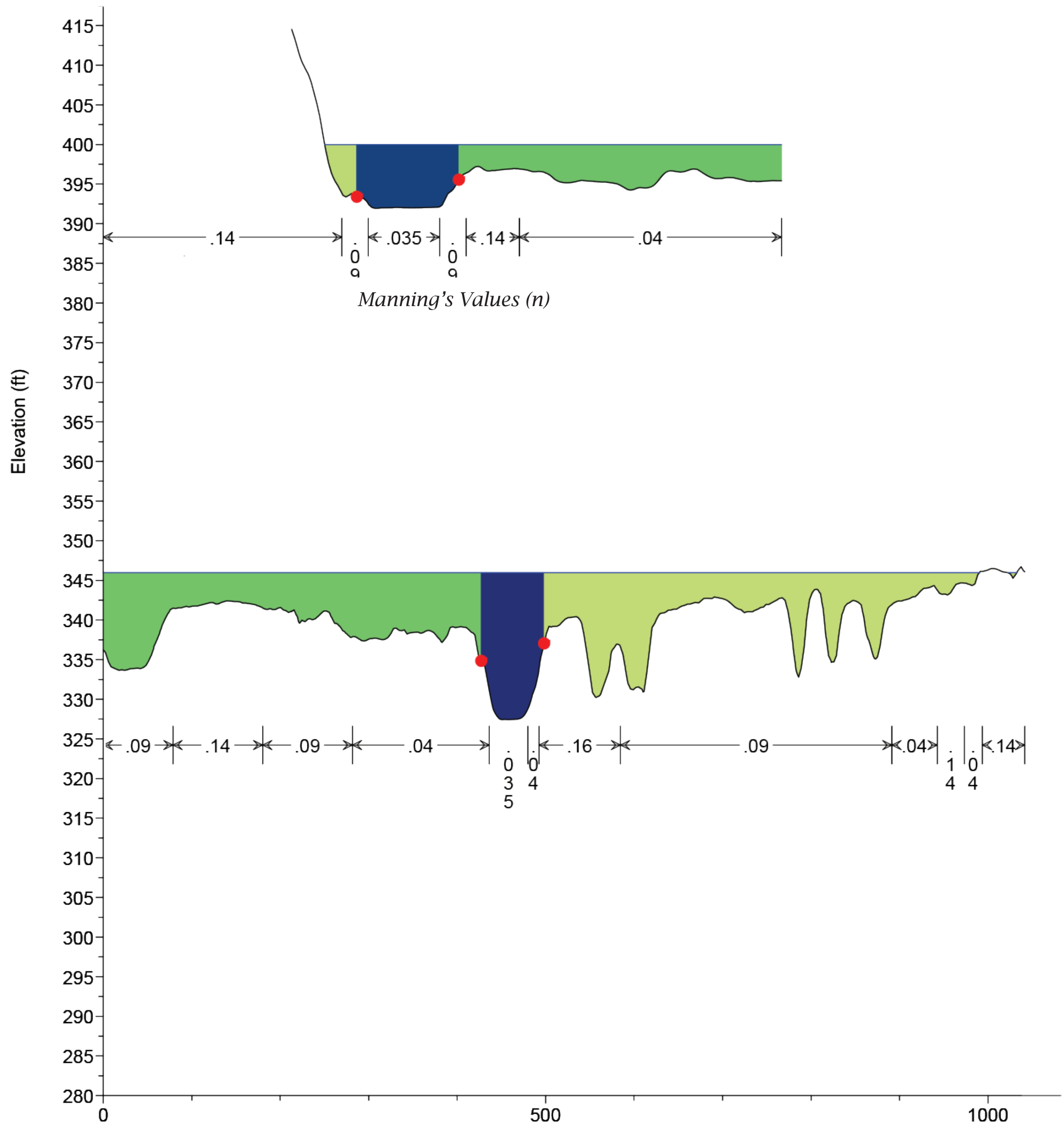


Figure 155 - Unmodified - Depth at XC 1 & 5 at 10k cfs.

Flow comparison between 10k cfs. flow scenarios. These charts compare the water depth and n values at sampled cross sections. Velocity measurements for unmodified terrain only.

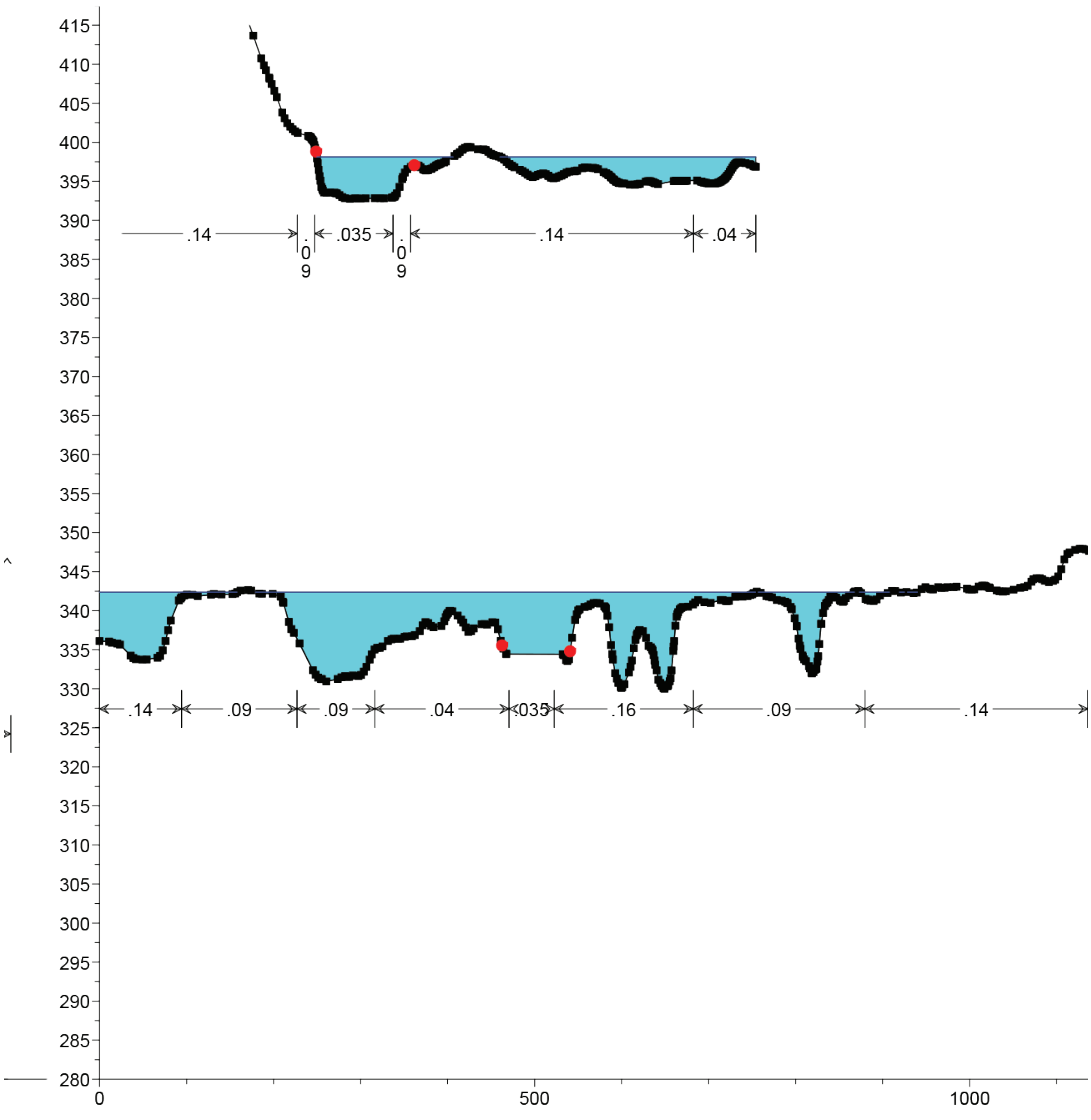


Figure 156 - Modified - Depth at XC 1 & 5 at 10k cfs.

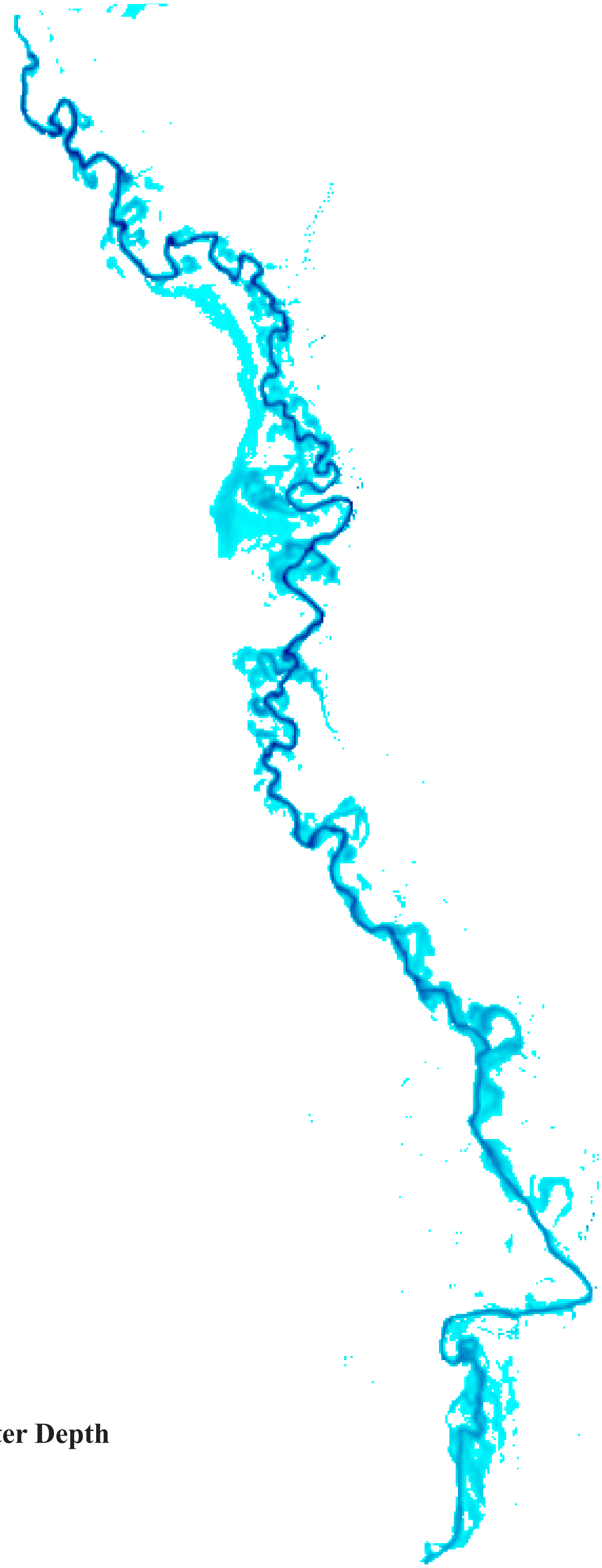


Figure 157 - Maximum Water Depth

(L) - Unmodified
(R) - Modified
Recorded at peak flow during realistic scenario.


(ft)
14.1
0.0
1 mi

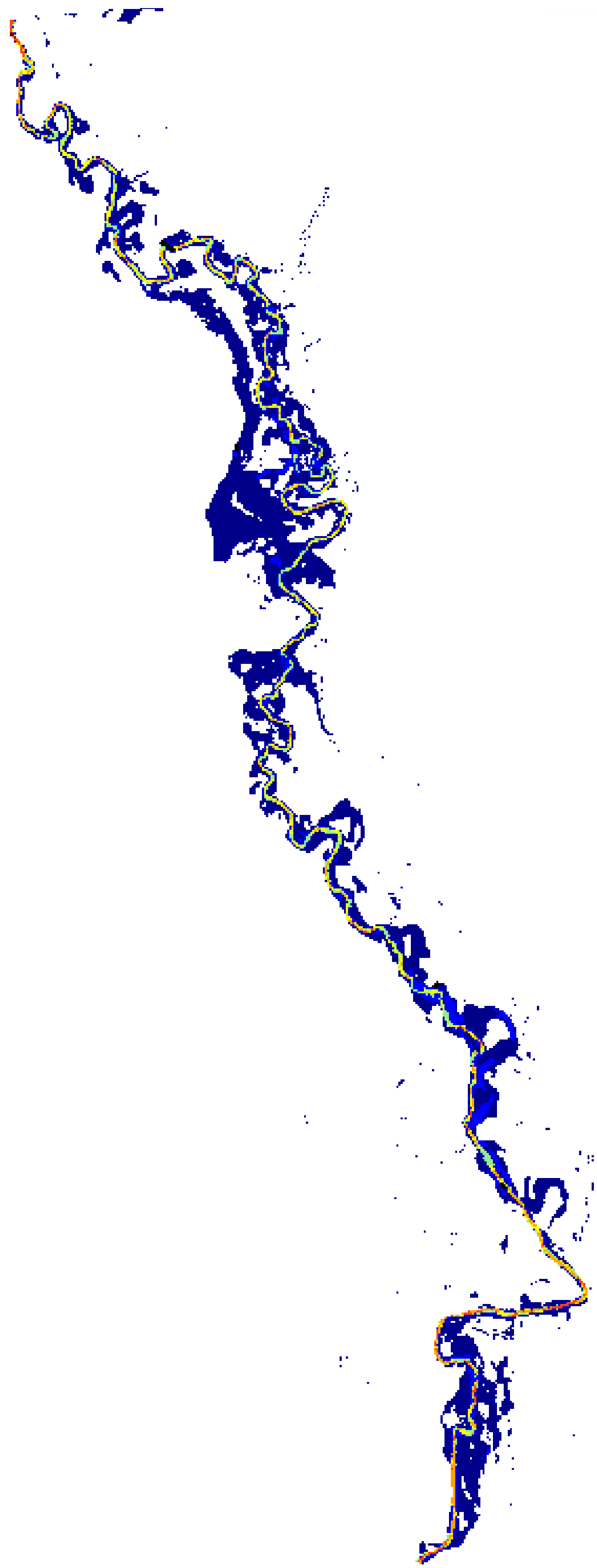
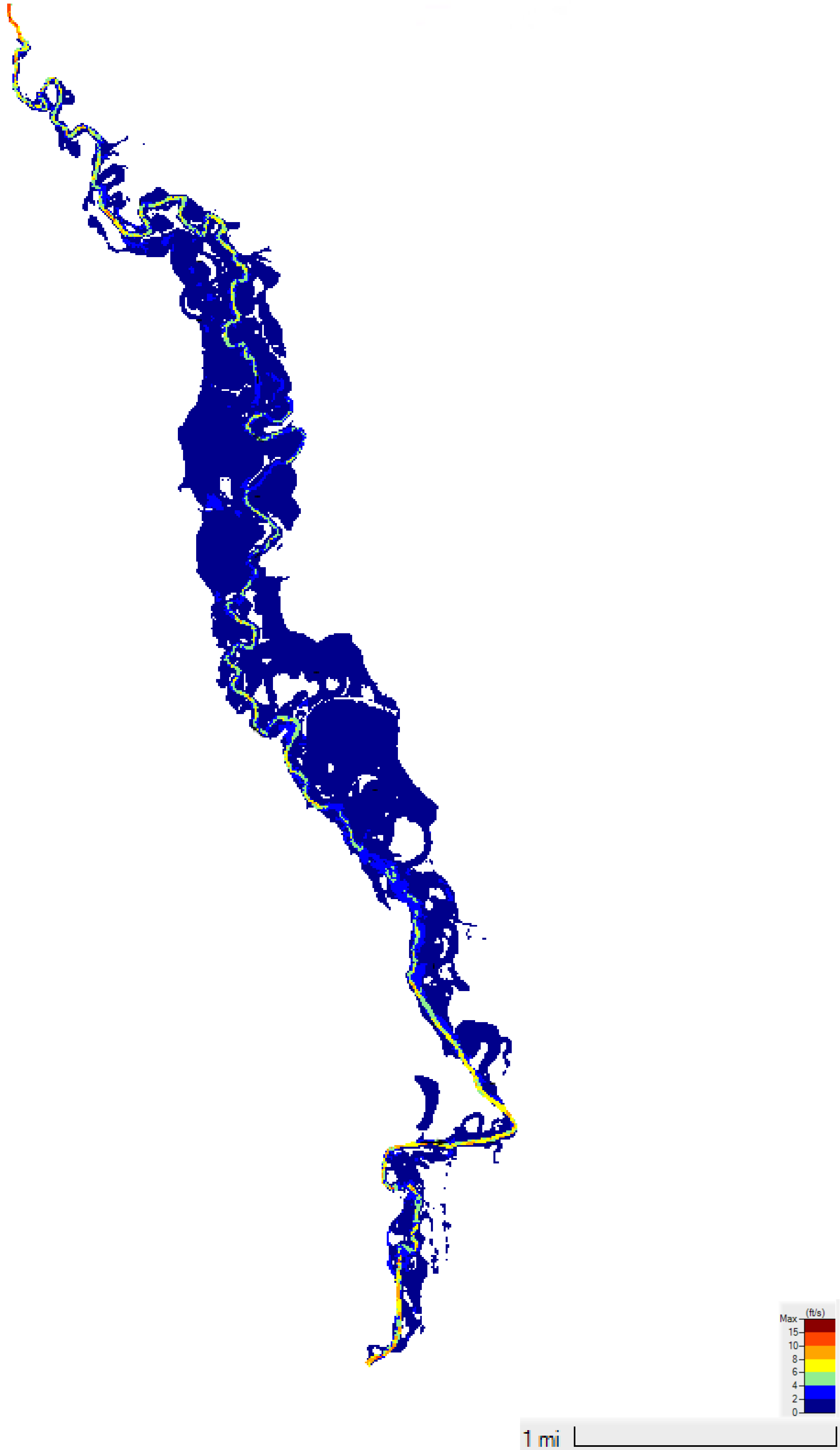


Figure 159 - Flow Velocity

(L) - Unmodified
(R) - Modified
Recorded at peak flow during realistic scenario.


(ft/s)
Max
15
10
8
6
4
2
0
1 mi

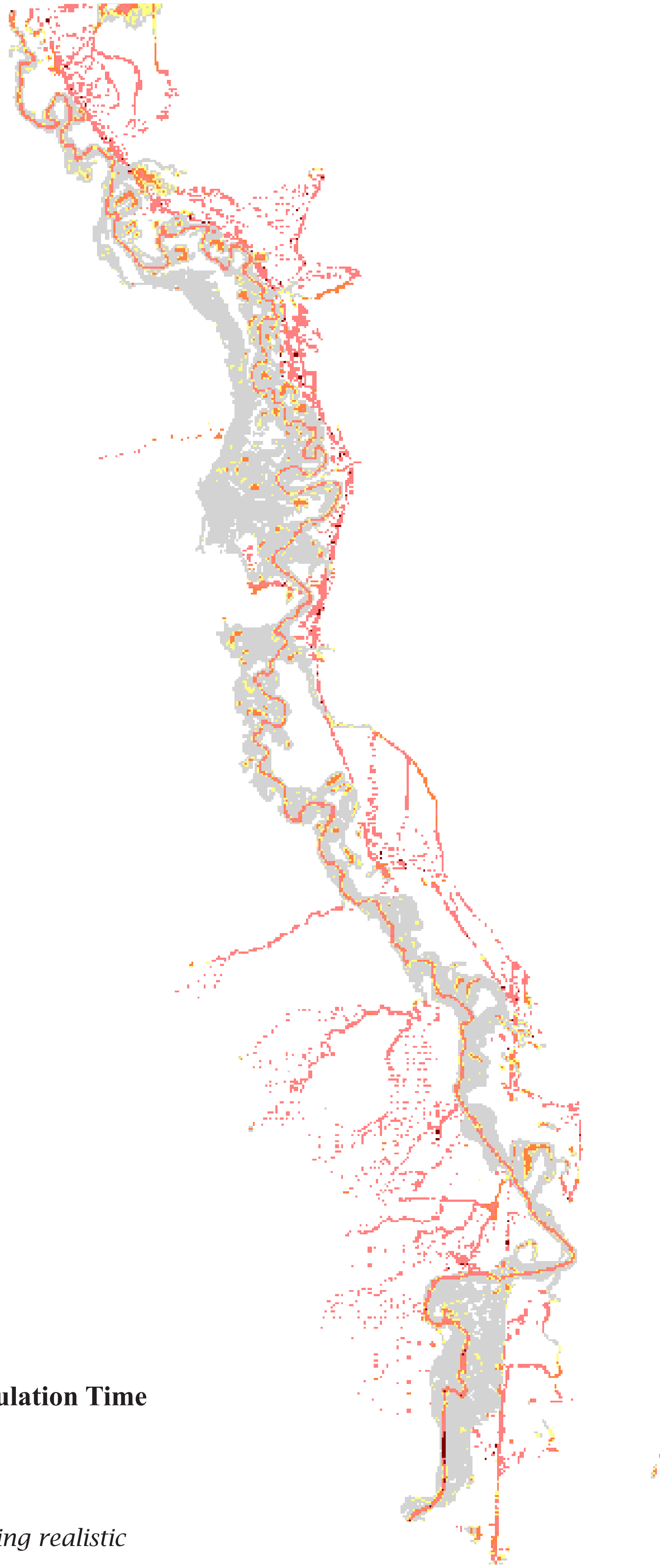
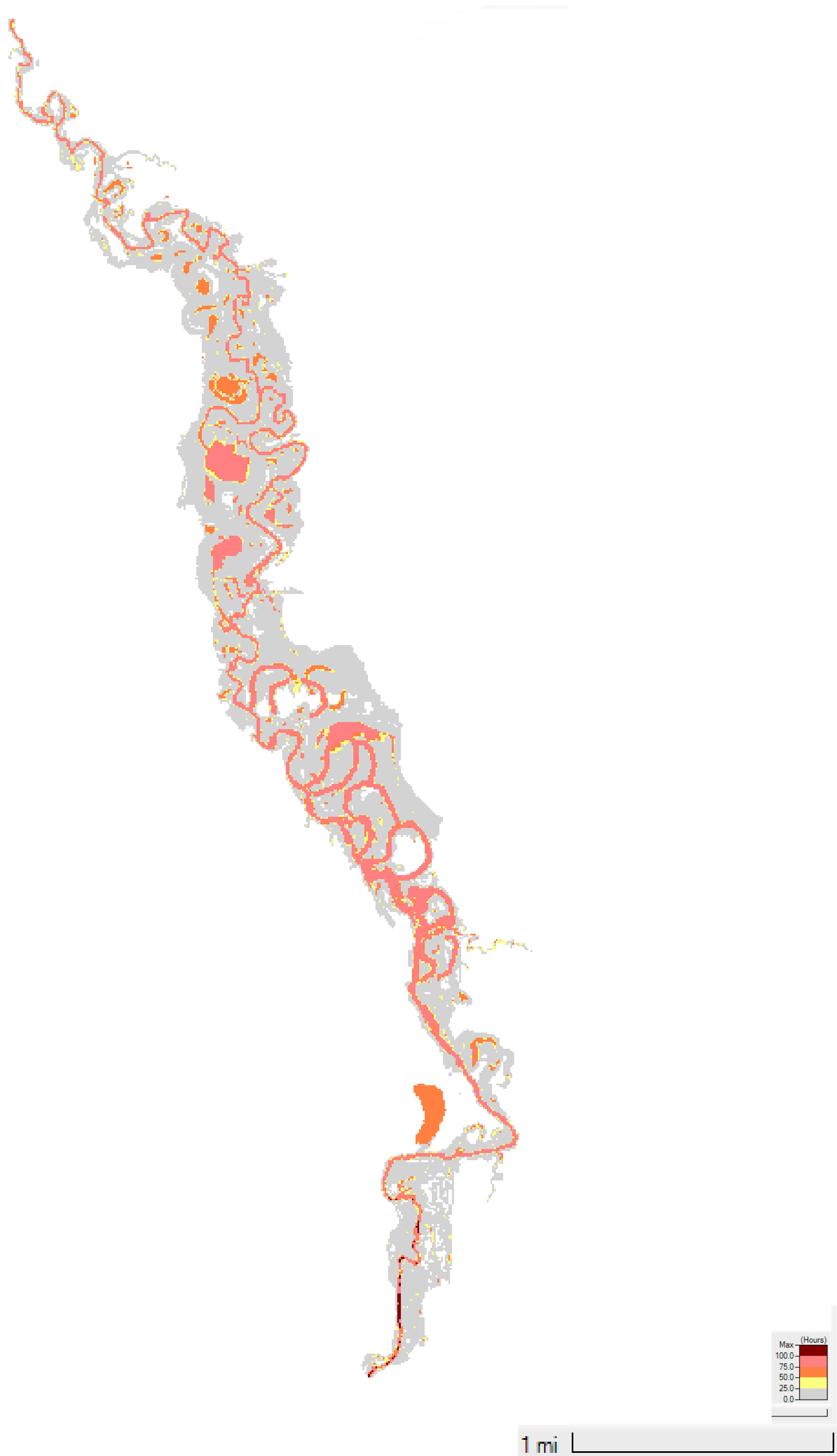


Figure 161 - Percent of Simulation Time Inundated

(L) - Unmodified
(R) - Modified
Recorded at peak flow during realistic scenario.
Note evidence of rainfall on unmodified terrain, this rainfall was untenable with the modified landscape.


Max (Hours)
100.0
75.0
50.0
25.0
0.0
1 mi

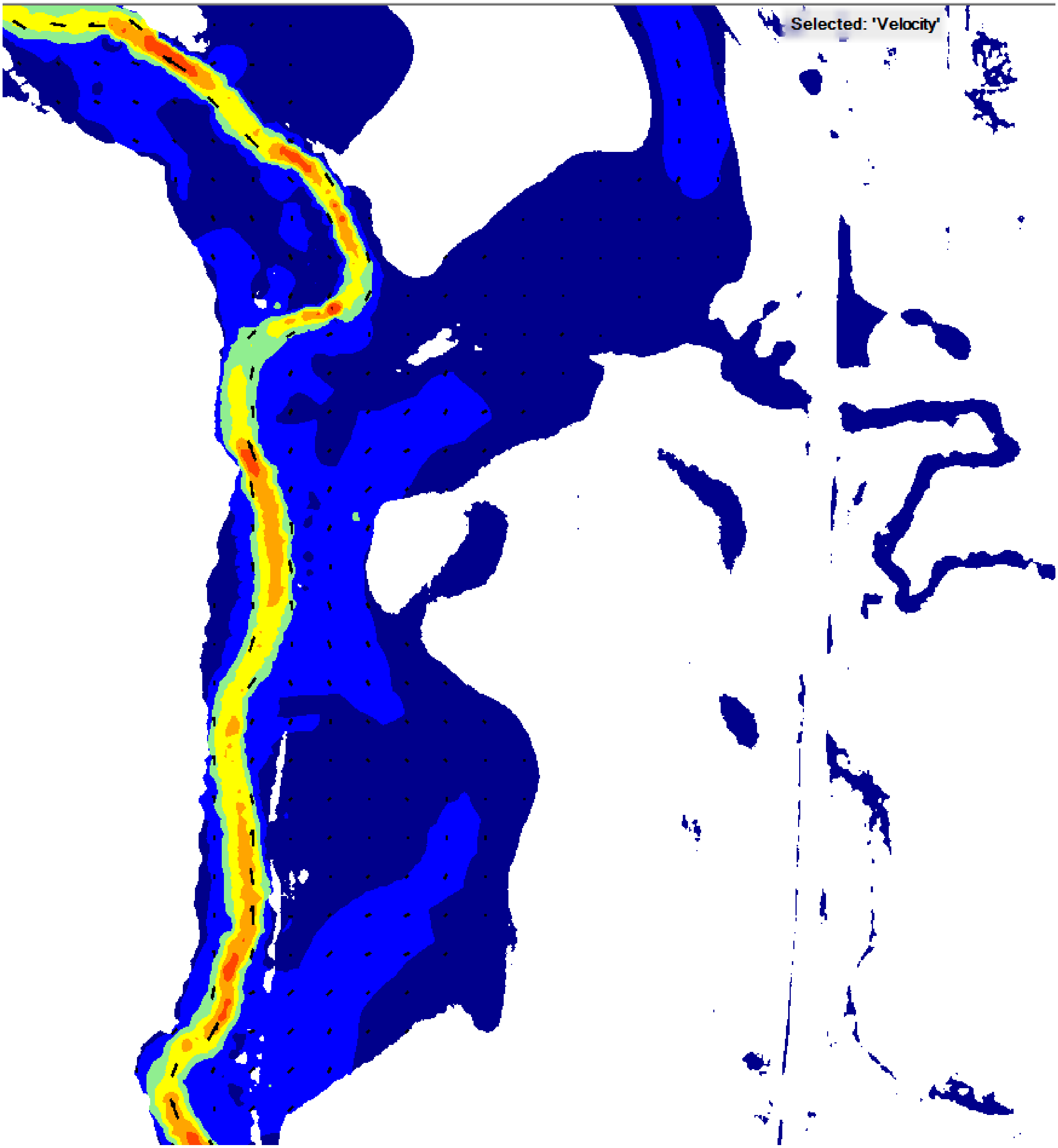
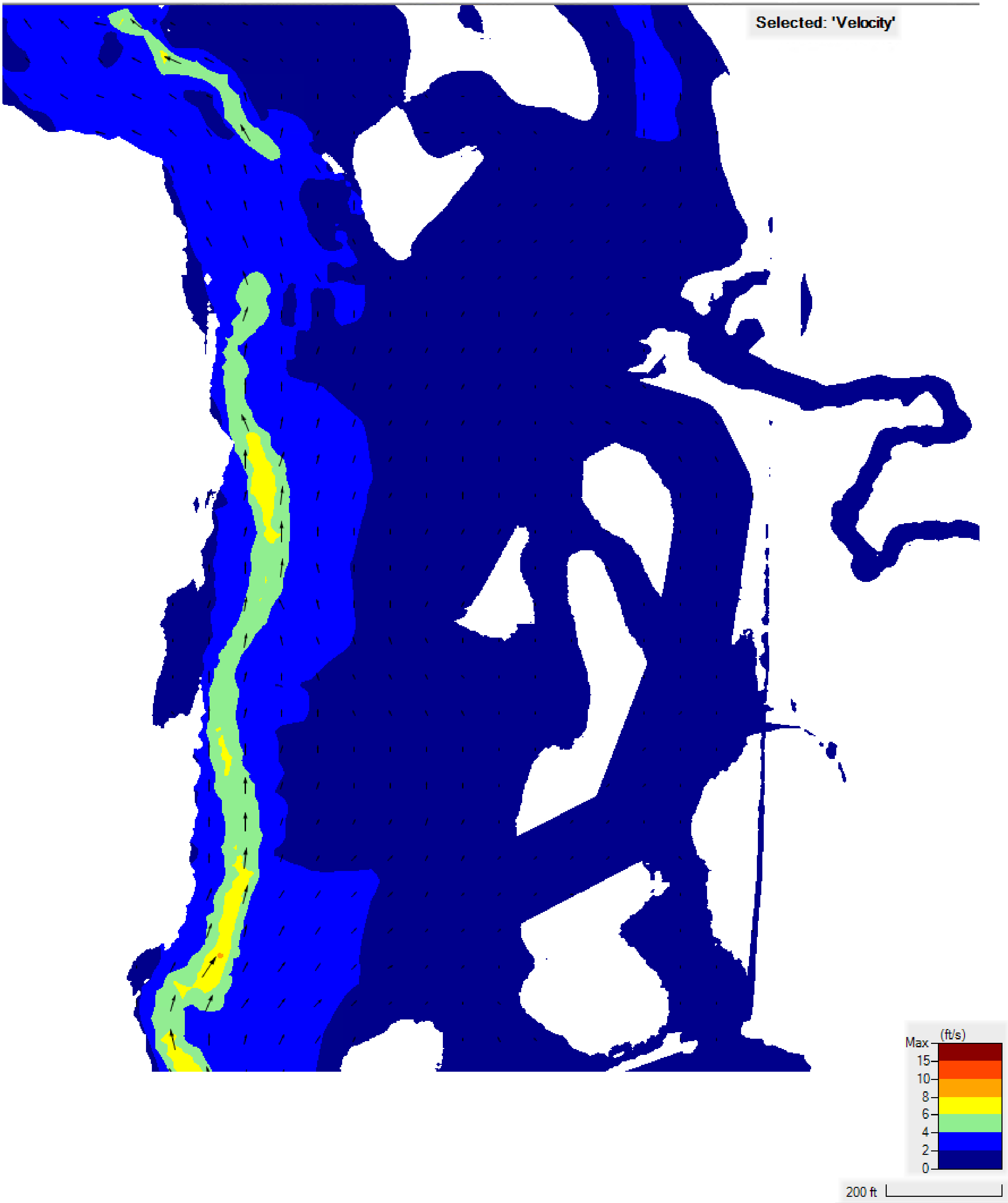


Figure 163 - Water Velocity

Midpoint Sample Area
(L) Unmodified (R) Modified
Recorded at peak flow during realistic scenario.



Selected: 'Velocity'
(ft/s)
Max
15
10
8
6
4
2
0
200 ft

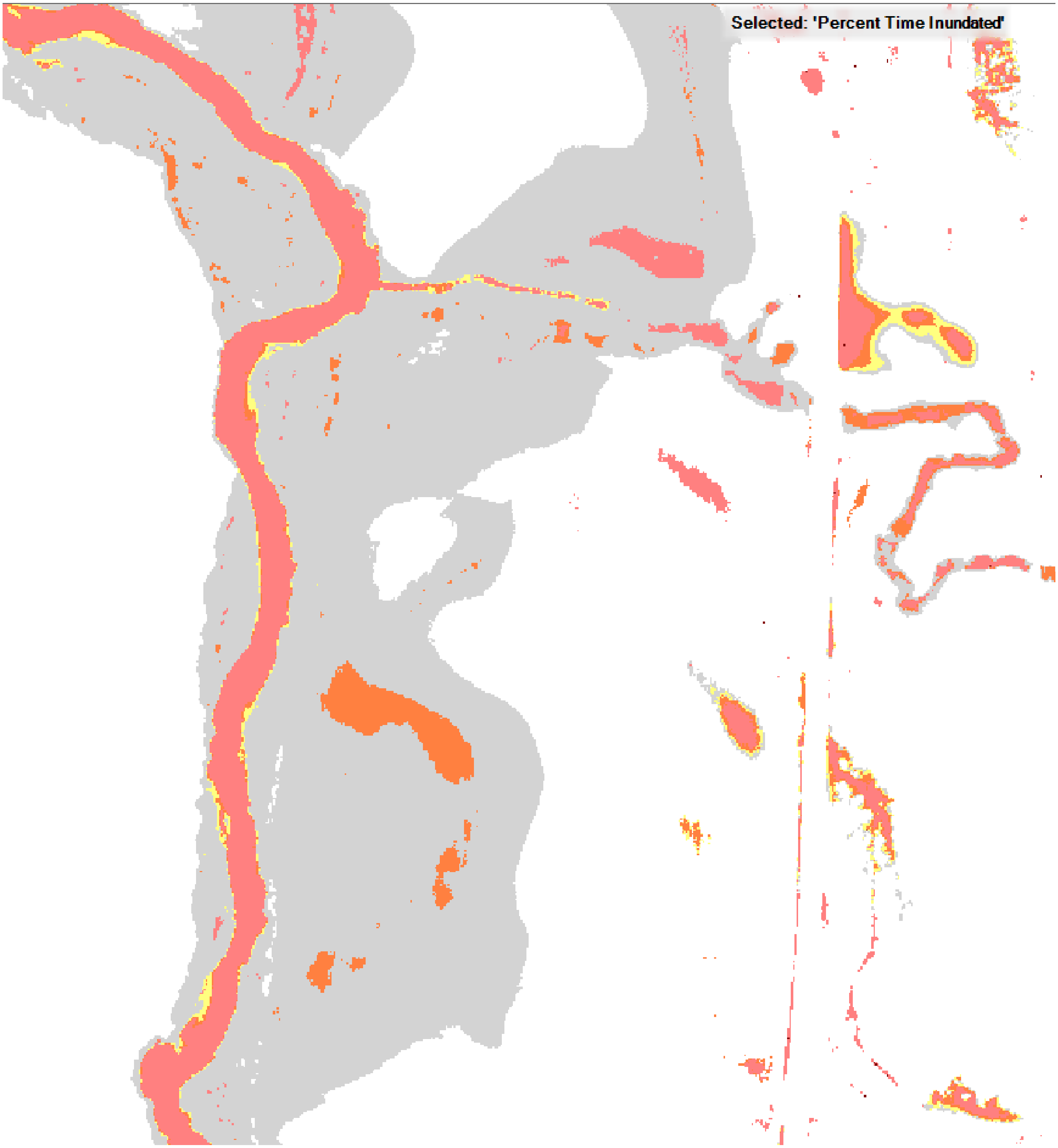
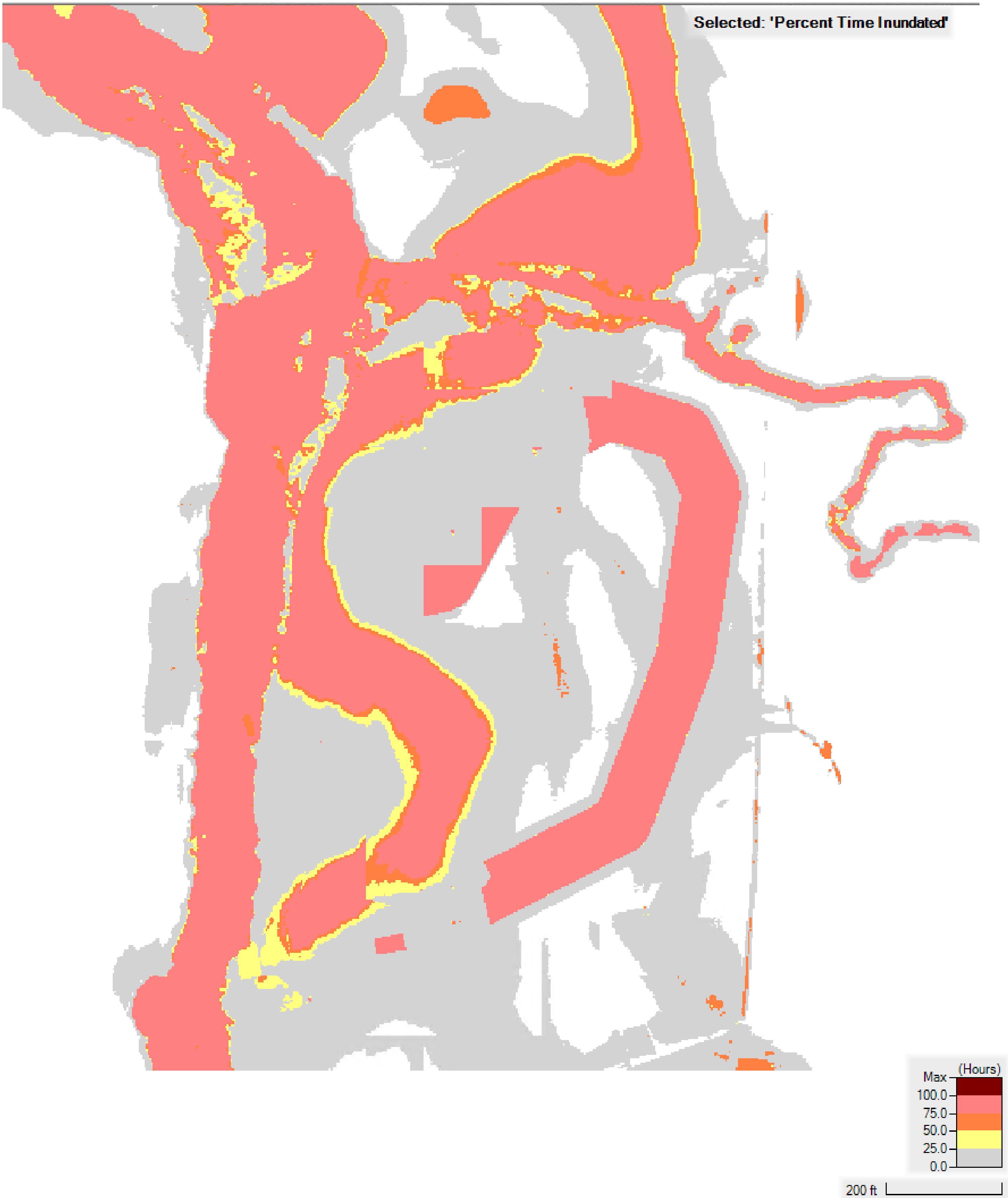


Figure 165 - Percent of Simulation Time Inundated

Midpoint Sample Area
(L) Unmodified (R) Modified
Recorded with realistic scenario.


Selected: 'Percent Time Inundated'
(Hours)
Max
100.0
75.0
50.0
25.0
0.0
200 ft

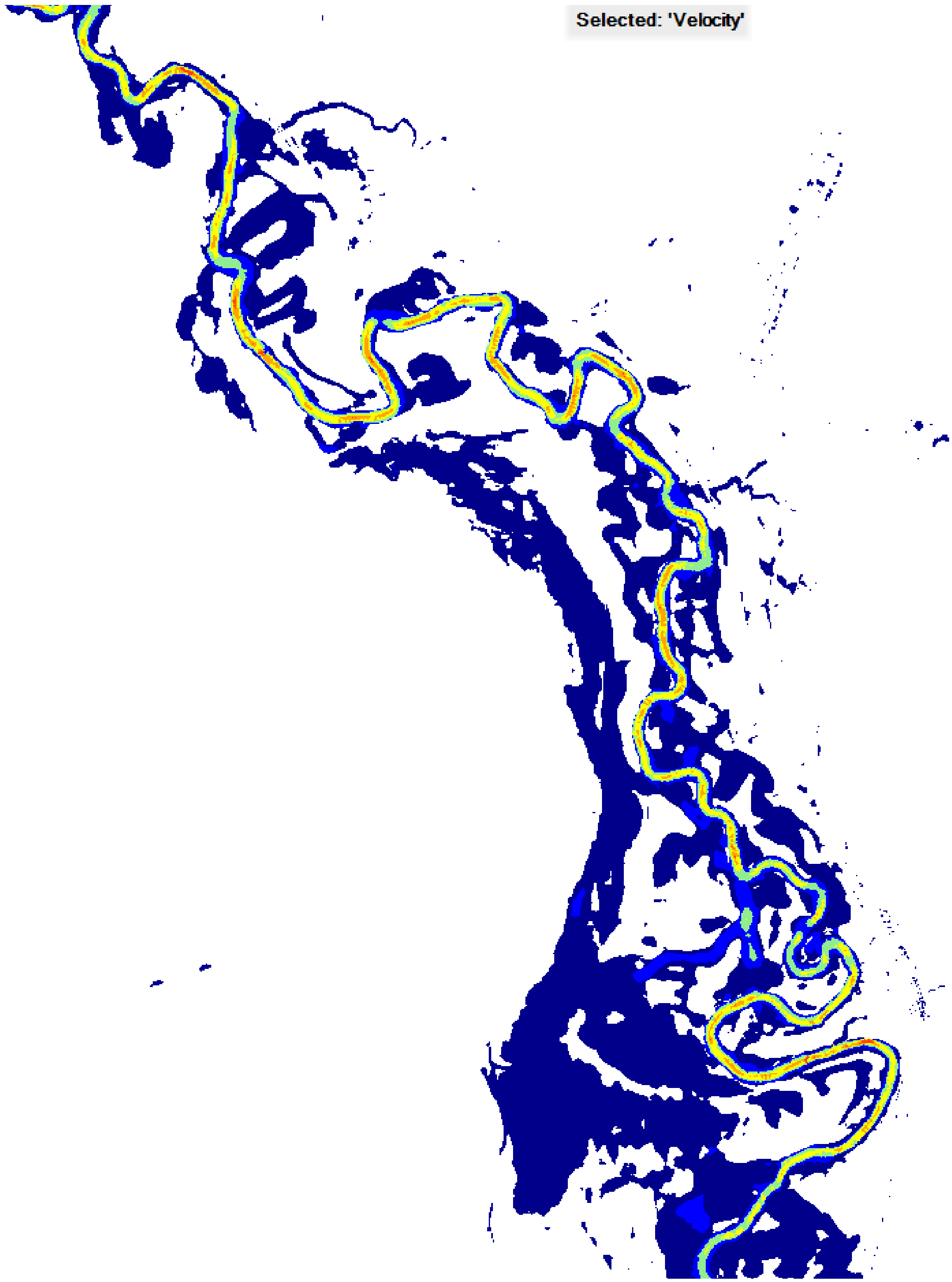
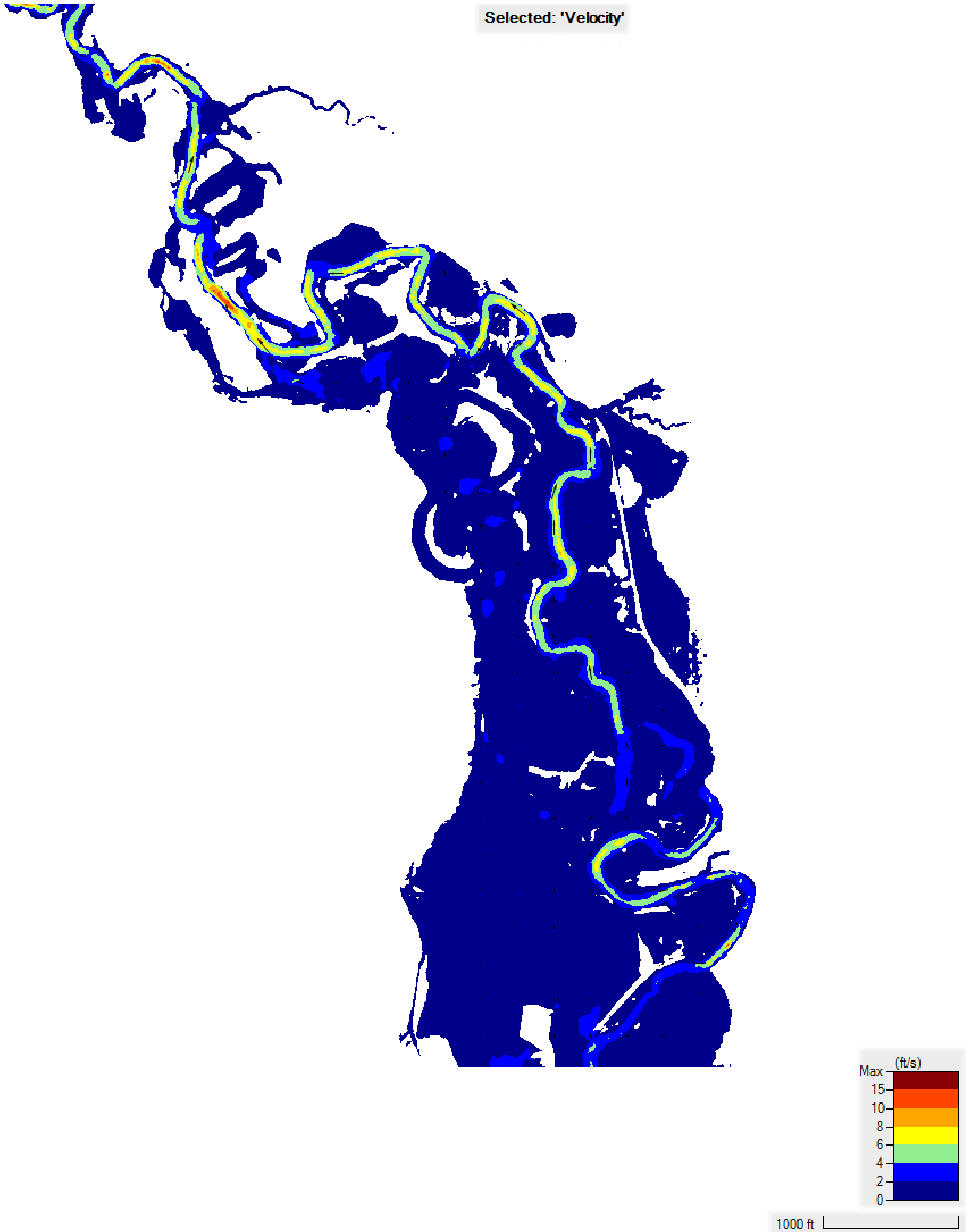


Figure 167 - Water Flow Velocity

Northern Wetland Area
(L) Unmodified (R) Modified
Recorded at peak flow during realistic scenario.



Selected: 'Velocity'
(ft/s)
Max
15
10
8
6
4
2
0
1000 ft

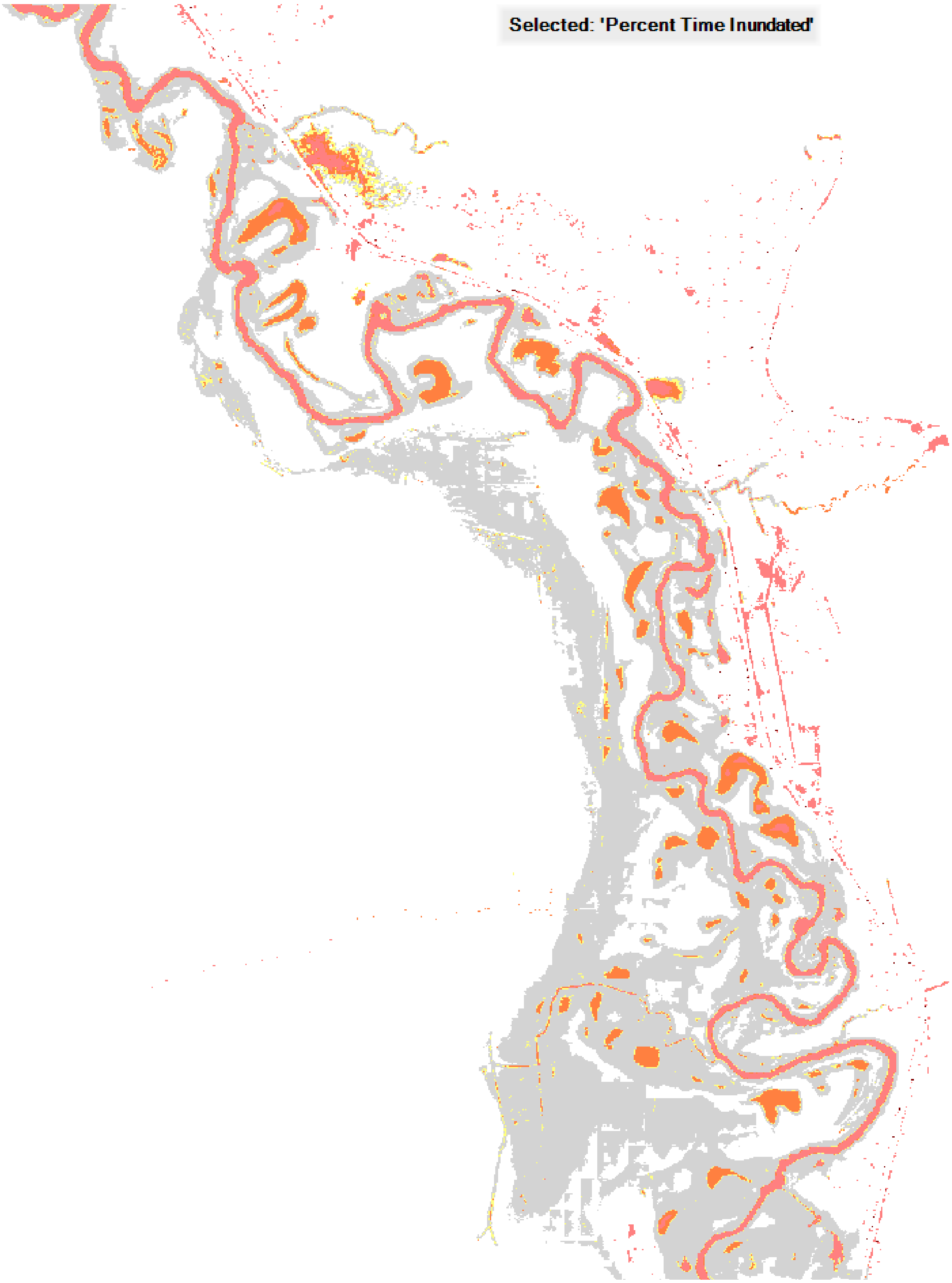


Figure 169 - Percent of Simulation Time Inundated

Northern Wetland Area
(L) Unmodified (R) Modified
Recorded with realistic scenario.


Selected: 'Percent Time Inundated'
(Hours)
Max
100.0
75.0
50.0
25.0
0.0
1000 ft

Discussion

Incision Repair

The goal of the incision repair is to reduce the freeboard from the stream bed to the bank height. The main channel is active throughout the flow and is still given priority when designing the alternative routes of travel for water. Velocities of water flow drastically reduce along the entire length of the channel. Areas that peaked at 15ft/s of flow previously now reduce to 7ft/s. Despite adding six feet to the entire length of the streambed, the displacement of over nine million cubic feet of conveyance space still results in reduced flow speeds at comparative volumes of throughput. An interesting unanticipated outcome of the modification is that the remnants of the oxbows present in the landscape are recruited into use. Whereas before they only inundated by major floods that breach the banks, reducing the freeboard allows them to engage with much less water needed.

Northern Wetland

The Northern Wetland is the most responsive of the treatments in regard to the modulations in river flow. This is expected with the minimal changes in elevation of the Southern area of the plot. This area maintains water in its basins during most of the water year. These water basins also fluctuate in height within their holding areas as the water flowed in and out of them, always maintaining connection with the overall stream height. This contrasts with the Northernmost area which has more dramatic changes within the landscape. This area begins to flood when the flow rate passes 3,600cfs. This occurs only twice during the 2020-2021 water year. On February 22 the stream rose to 1,300cfs. and shows the system initially filling and almost reaches the activation threshold before backing off. The Northern area retained water at the bottom of its basins after becoming inundated with water for the first time on January 12th.

Central Side Channels

The side channels maintain water throughout the 2020-2021 season. This works as anticipated and causes a major increase in the total water surface area in the landscape. The oxbows fill with water and respond as the overall height of the river fluctuates. Water velocity remains very low throughout the inundation periods, never surpassing 1.5ft/s of flow. This indicates that the areas can harbor wetland ecosystems and assist in the deposition of sediment form upstream sources. They also provide valuable habitat functions for many of the species in the region.

Southern Holding Basins

The Southern holding basin engages only once during the entirety of the 2020-2021 water year. On time marker January 13, 2021 water reaches 6,000cfs of flow. This water never continues to the second basin yet comes within a foot of the spillway into the second basin. At its peak, the basin holds 231,910 cubic feet of water to be slowly infiltrated through the landscape. During the 10,000cfs. test, the Southern basins fill almost completely. In this test the first basin starts to spill into the second at 5,100 cfs. of introduced flow. They continue to flow and increase held volume until the third basin fills with 1.5 feet of water and recedes. The third basin only engages with the maximum test flow of 10,000cfs. The basin system engages, therefore, only in cataclysmic conditions. While this is the intent of the design, modifications can be made to refine this. I believe that a system like this should engage at the 100 year flood stage, which on this model is at 7,200cfs. The overfilling of the area can be designed to top the final spillway and reenter the main channel at a 150-year flood stage. This ensures that the landscape modification is effective in flood attenuation during the worst events and not inundates during lesser and more common events. This benefits species that are not flood tolerant, such as Pseudotsuga menziesii and Acer macrophyllum.

Overall, the landscape modifications completely change the dynamics of the floodplain. The unmodified terrain suffers from frequent flooding but only in isolated areas of agricultural land. The modified landscape frequently floods over broad stretches of the landscape. As per the design of both landscapes; the agricultural landscape seeks to concentrate the flow of water and to place the overflow into less valuable areas.

Manning’s Values

The changes in the ecotones within the landscape and subsequent representation through Manning’s value polygons create a measurable change within the calculation mesh. Overall, the roughness of the path of flow increases in value and more water encounters that additional roughness. This change has several impacts on the simulated flows. A landscape with less roughness can convey water more quickly through the landscape. When viewing graphs of the flow rates, that appears to be a curve that is flattened and offset slightly. This represents that more water is held on the landscape upstream and that the water that does come through arrives later. Both landscapes have similar roughness values for the channel and the proximal banks. Vegetation is maintained on the existing river banks in alignment with current Lewis County Code which requires a 150 ft. buffer around the South Fork of the Chehalis (LCC 17.38.270 2023). Within this buffer, the vegetation is unmanaged and is dense weeds or native shubs. Beyond this buffer, however, the unmodified agricultural landscape has drastically reduced roughness in comparison to the modified landscape.

Peak Flow Attenuation

Peak flow attenuation is a critical component to measuring the performance of the landscape. Flood mitigation strategies use different methods to retain water on the landscape as long as possible. This reduces the quick rush of water that is characteristic of conveyance models of flood management. Upon viewing the charts that compare the two terrains in the 2020-2021 water year, the trend towards retaining water mass on site is illustrated.

Many of the peaks of flow are offset when comparing the two terrain models. This indicates a slowing of the flow of water through the site. During periods of low to moderate seasonal flows the modified landscape increases this transit time up to five hours. This amount decreases as the flow rate increases. At the peaks of flow, the transit time difference is less than two hours. This is consistent with the idea that the landscape intervention forms are only effective at slowing flows up to a certain water surface elevation height. The landscape modifications that are designed for slowing the flow of water are at low elevation differences from the main channel. On average, it takes water a total of nine hours to traverse the main channel of the unmodified site. The modified landscape increases this by 44% during low flows and 22% during high flows. This is a dramatic increase in the ability of the landscape to slow the flow of water and reduce surges in downstream infrastructure. Comparing the models, benchmarks for the 100 year flows are estimated. The unmodified terrain overbanks (which is considered roughly 100 year flood stage) at an input flow of 7200cfs. Modified Terrain overbanks at 8300cfs. To establish these flow rate benchmarks, the FEMA FIRM maps are used to determine the geographic extent of the flooding needed to constitute a 100 year flood stage (Federal Emergency Management Agency 1981). Once the unmodified simulated landscape's inundation footprint meets the geographic area shown in the FIRM Maps, the current water volume input is noted. On the modified landscape, the location of comparison was in an unmodified area.

Volume of Water

Similar to the reduction of peak flow, the reduction of water volume is indicative of a landscape that mitigates harmful flooding. The flow curve is not only elongated to illustrate the length of time water is on site, but the depth of water at any given point is also reduced. The reduction in the volume of water draining out of the site is apparent in the measured graphs at the simulation outlet. Measured at the outlet, the modified terrain holds a depth of water measuring 2.38 ft. and a maximum depth of 9.16 ft. The original landscape's average depth is 2.05 ft. and had a maximum depth of 10.06 ft. (both maximum depths occurred on January 13/2021 between 05:00 and 06:00). The average difference between the two during the 2020-2021 water year is 0.03 ft.

Water depth results show that the modified landscape has a lower water depth during the highest flows, but on average has a higher water depth during moderate and low flows. This is possibly because the modified landscape spreads the depth of the highest flows across the whole floodplain yet has a reduced main channel capacity. The largest difference between the two numbers comes after the major peaks. For example, 19 hours after the max depths recorded for the sample site is also the time of greatest difference (0.52 ft.). Similarly, other peak flow periods are followed by the largest differences between the depths of the two models.

In summary, the largest differences in flow volume are occurring immediately after heavy flow periods in which the modified landscape hosts a greater water depth than an unmodified landscape. It is unclear what is causing the largest differences in flow to occur during periods when the modified landscape holds more water than the unmodified landscape.

Floodplain Area Engagement

The altered landscape of the floodplain uses many techniques to spread the flow of water across the terrain. Channels divert water into wide basins and add complexity to the channel network. The modifications increase the surface area of the water flow during normal and severe flow periods. The altered landscape was so effective that it was challenging to make comparisons between the two floodplains. The altered landscape modeled a braided geometry where the flows of water are dispersed throughout the area. HEC-RAS software is oriented towards measuring concentrated flows within channels, not wide and shallow areas. The breadth of the inundation both accomplished the goal of increasing inundation and also made quantifying flows more challenging by fundamentally altering the character of the floodplain.

The modified landscape holds an average depth of water of 1.84 ft. during the 2020-2021 water year compared to the original landscape's 2 ft. The control landscape's peak flood inundation area during the realistic flow scenario is 426 acres. This increased by 38% in the modified landscape to 691 acres. This demonstrates that the modified landscape holds a higher volume of water at any given time-- the water is spread broadly. However, the surface area of that average depth differs. The average depth of the modified landscape is spread over a thin surface area, whereas the original landscape is largely constrained to the channel.

Challenges

Throughout the processes, various concessions are made to ensure the completion of the model simulation. Data inputs are based on satellite images, federal datasets, local datasets, past studies, and the experience of the researcher. This provides a fidelity of creation appropriate for the model and frequently surpasses the accuracy demonstrated or suggested by professionals instructing on HEC-RAS. It should be noted, however, that there are approximations throughout the process. Much of the data that populates the input sets is gleaned from calculated or inferred knowledge. Topographic resolution is approximately one meter. While this is commonly sufficient for most tasks, small abnormalities may drastically impact the outcomes of flow modeling.

Model Creation

The creation of the model is based on coordinate reference systems (EPSG:2927 NAD83 / WA South (ftUS)). The placement of many data layers is based on matching coordinates and provides a precise application. Other layers, such as river prisms and Manning's Values, are applied by hand using polygons based on the information provided in the georeferenced layers. Furthermore, the modifications to the landscape are applied by hand using polygons to alter the topography. Abnormalities and artifacts are present and have potential to influence flow calculations. When found they are addressed, though some are sure to remain on the modified model. Calibration and iteration can identify and palliate many issues. The lack of stream gauges, as discussed previously, ensure that the model could be only self-referential. While the model shows many metrics (such as 100-year flood stage) that correspond to observable data, it is still imprecise.

Existing Landscape

While terrain and conditions on site are thoroughly evaluated and considered, little attention is given to the human emotional element of the landscape. About two dozen households and several businesses occupy the study reach. The town of Boistfort, with a population of 300, is immediately to the North ("U.S. Census Bureau QuickFacts: Chehalis City, Washington"). These people have created homes and attachment to the landscape.

Furthermore, the reach is on the traditional homelands of the Chehalis, who have had, and continue to have, a relationship with the area since time immemorial.

These communities potentially hold deep knowledge in their lived experience of the South Fork of the Chehalis. This knowledge uncovers insight that cannot be discovered through remote research and site visitations. Accounting for this local agency is not done by this study and would benefit from it. Furthermore, this project ignores the political and legal landscape. These families and businesses need to be relocated and fairly compensated within our existing political system. Here, modifications to the landscape are not constrained by parcel lines or zoning requirements.

Modifications

The modifications are made without consideration to cost or impact on the landscape. The disruption to the landscape would be complete. While the existing landscape is already completely modified by human interventions, the vegetation and soil structures provide immediate benefits to the ecology and economy of the region. Modifications are made with only their result informing decisions. Existing site conditions that are not an immediate benefit to the treatments that would occupy that space are not considered. A project of the scale proposed needs monumental imperative to be considered.

Assumptions

The project relies on the assumptions that inundated areas necessarily produce ecologically beneficial results. This is not necessarily true. It radically simplifies the legion of ecological processes that are present in floodplains. Consideration must be given to a broad range of phenomena and invite many specialists to contribute to the informed design of floodplain projects. The study site is isolated from the larger world. It removes the connections between the South Fork of the Chehalis and its contextual placement. Beyond the boundaries of the heightmap and polygon mesh, the model has a void of data where the actual river has a network of infinitely complex connections to the surroundings.

In real floodplains, the restoration of a reach or section provides no benefit if the surrounding conditions that caused that state to exist in the first place are not addressed. The study focuses on the immediate area's transformation into a conveyance channel and agricultural landscape. But the study does not address the impacts of logging on the surrounding hillsides, which occur frequently and with regularity. This logging has adverse impacts on the presence of large woody debris (Winkler et al. 2010; Bisson et al.

1987), healthy sedimentation processes (Merten et al. 2010; McEachran et al. 2021; Olsen, Wagenbrenner, and Robichaud 2021; Grant 2008), and subsequent rates of flow (Zhao, Boll, and Brooks 2021).

Statement of Positionality

The individual conducting this survey must also be considered. The researcher has a privileged background of being an economically, culturally, racially, educationally, bodily, and socially advantaged white cisgender heterosexual male. While this may not be immediately necessary to research for declaration, it should be considered when accounting for the methodology and interpretation of the data.

Opportunities for Future Study

Throughout the process of this project, several opportunities arise to pursue topics tangential to the focused objectives. While many of these topics can become sections within the scope here, some could have become large projects. Continued research into the field of riparian restoration is essential as conditions shift on the landscape and the effects of climate change come into focus.

Climate Change

Climate change is a major topic of uncertainty and should be further explored in this context. While many predictive models are coalescing into a single agreed upon narrative, there is much left to speculation (NOAA 2013; Hausfather 2019). Research within the field of restoration is frequently being conducted using climate change as a primary lens (Estenoz and Bush 2015; Griffiths 2013; Veloz et al. 2013; Mallakpour and Villarini 2015; NOAA 2013). The field of riparian restoration would benefit in several ways from continued exploration of future uncertainties.

The plant selection for the FDRP dam and levee, and to a lesser extent within the planting choices of the Aquatic Species Restoration Plan, do not sufficiently take climate change into account. Their plant selection is based on historical choices (Office of Chehalis Basin 2019; WA Dpt of Ecology 2023). The plant selection proposed within these would offer immediate results, but as climate change worsens, it is important to select plant species that are prepared for climate change. Recent studies focus on the transition of ecosystems due to climate change and subsequent migration of plant species (Estenoz and Bush 2015; Richardson et al. 2009; Olson et al. 2007; Fremout et al. 2022; Abbe et al. 2019; WA Dpt of Ecology 2023). A quick assessment with the "Seedlot Selection Tool" shows that plant species for the South Fork of the Chehalis should come from Northern California (St.Clair et al. 2022). This tool suggests plant groupings that would be appropriate for the future conditions after climate change. Further study can explore the changing plant palettes that should be used with Pacific Northwest riparian restoration and integrate them into hydrological modeling.

Shifting hydrologic profiles

A key aspect of plant selection is also the availability of water. This drives many of the changes to be seen in future flood management. As rain patterns shift, the snow/

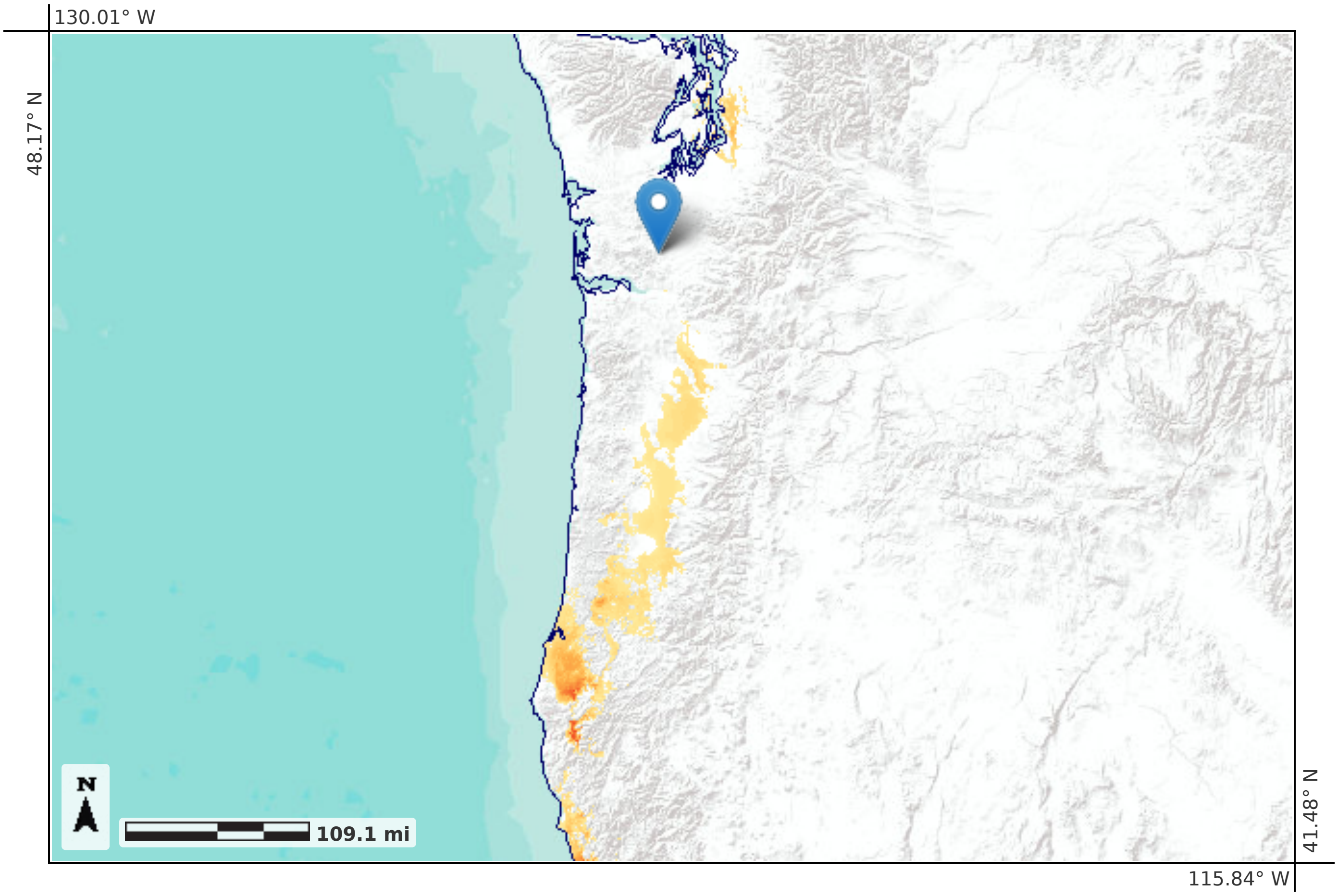


Figure 182- Future Seedlots

This map from the "Seedlot Selection Tool" shows areas in orange of appropriate future seedlots for the South Fork of the Chehalis. The model shows data for 2070 at a moderate climate change scenario.

(St.Claire, et. al 2022)

water and accumulation/melt will be upturned (Freitag et al. 2009; Li et al. 2019). This changes the duration, frequency, and severity of water that travels across the landscape throughout the year (Griffiths 2013; C. H. Luce, Abatzoglou, and Holden 2013; Vano, Nijssen, and Lettenmaier 2015; Tohver, Hamlet, and Lee 2014; Salathé et al. 2023; Hamlet and Lettenmaier 2007). Current landscape conditions are adapted to the Pacific Northwest drought/monsoon system that is characteristic of the area. Changes in water patterns will result in widespread disruption to every system in the region. A primary concern to riparian areas is the effects of climate change on water temperatures, which are primary drivers in many ecological processes (Isaak et al. 2012; C. Luce et al. 2014). Incorporating future conditions will drastically shift the 100-year benchmark that many agencies use as a benchmark. This will have long-lasting implications on policy and human interaction with floodplains. This study uses existing benchmarks and past flow patterns to analyze objectives. Additional tests with the same models can be conducted with revised or expected flow patterns.

Intervention Typology

As explained by the European Commission report, the existing field of research is largely concerned with the small-scale interventions placed in urban areas. These interventions are related to stormwater or urban streams (Directorate-General for Research and Innovation (European Commission) and Vojinovic 2020). This offers a few opportunities for research. With decentralized interventions and treatments, cumulative effects are hard to measure. Future simulations can address this by creating networks of small interventions to see the effects of decentralization in restoration. Additionally, the scale of the interventions can be modified. Variations in size, centralization, and complexity of these networks can yield results that were important to realistic conditions. Often, land available for restoration is patched together among other parcels or placed within interstitial spaces around structures. This practice will decrease and project size increase as the economics of restoration become favorable.

As these are the most common forms of restoration, it is a high priority to study these variables in restoration efforts. The result of the LAND study enforces the idea that green infrastructure is not seen as a primary flood control method, and only compliments the more concrete projects favored by engineers (WA Dpt of Ecology 2023). Simulation and demonstration of the integration of green and grey solutions can explore this relationship. Furthermore, synergies between these two approaches are beneficial to identify and exploit.

Intervention Temporality

The landscape constructed within HEC-RAS is static. The program has capacity to explore the deposition and removal of sediment, though that was not used in this study. Floodplains are the antithesis of a static landscape. Future study should be conducted to any typology proposed on the long-term durability or mutability of the restoration interventions. The entirety of the intervention's life cycle should be understood. Particularly with the thresholds to engagement with interventions. As the landscape shifts, will these thresholds remain durable to the flow intended? Or do they need to be constructed out of permanent materials? The vegetation intended in these areas will also shift with the changing landscape and engagement with water. Future studies should incorporate the shifts within time and space to portray a truer landscape.

Humans

The study does not consider human needs within the landscape when constructing the interventions. For restoration efforts to be practical, they must provide some economic benefit. Without that imperative, restoration for the intrinsic value of natural life will not be a sufficient argument for modifications. Further tests should incorporate the human element into the landscape. It should create limitations and controls that would ensure economic viability within the planning process. For example: how much agricultural land must be maintained within the floodplain? Are there alternatives? How many residences must be in the area?

The ideas, methods, traditions, and culture of indigenous voices should be incorporated into the design process. Two emerging cultures within restoration that honor indigenous agency are the Indigenous Peoples' Restoration and Environmental Justice Restoration movements. These movements help to shift the lotus of restoration away from the landscape as seen by European-Americans and "expand the circle of people involved in environmental policy" (Tomblin 2009)p. 186). Incorporating non-Western scientific principles that build partnerships and acknowledge the history, place, and connection of indigenous people to ecologic understanding will enrich the outcomes for all individuals (Hall et al. 2021).

5-Conclusion

The modified landscape provides evidence that modifications to the landscape are effective in many areas of floodplain management. From broad observations it shows that the water behaves dramatically differently. In the original state, the watershed consolidates the water into the channel. During times of peak flows it overbanks into areas that are actively used by residents. This landscape is not resilient to the future challenges faced by watersheds as anticipated by climate change models. The landscape also underperforms as an ecologically viable space. Modifications to the landscape show distinct and observable results. These results are measured by the total volume and timing of water flows. Flood management is principally centered around allowing water to move through an area without damage. The attenuation of peak flows allow downstream water systems to spread the peak impact of the flows over a longer period.

It is also valuable to compare the amount of surface area that allows for water to come into contact with floodplain soils. The interaction between soil and water helps engage ecological processes, hyporheic exchange, and groundwater recharge. Each of these alone is a valuable contribution to a healthy ecosystem. The data collected by modeling changes in the South Fork Chehalis floodplain explores these changes and illuminates measurable differences. The models show the following:

Modifications to landscape informed by restorative floodplain methods are effective at reducing output flow volumes and reduce peak flows in simulated floodplains.

The modifications lower the peak flow volumes by allowing more of the water to spread across the landscape. The channels throughout the landscape are complex and create a long linear network of canals that the water can flow through. This greatly increases the exposure of the water flow to more friction in both quantity and quality. This results in an increase of up to 44% in the time it takes water to flow through the site.

Catch basin landscape modifications are effective at retaining water during simulations.

The catch basins are effective at storing large volumes of water throughout the floodplain. The first basin alone holds 230,000 cubic feet of water. At a 100-year flood event level, that single basin could absorb the entire outflow of the river for twenty-seven seconds. Coupled with a dispersed network of basins, this effect taken in aggregate could provide effective peak flow attenuation comparable to graywater projects.

Furthermore, these systems can be engineered to engage at specific flow levels and frequencies. Unlike greywater systems that need mechanical gates, this is achieved by simple grading of the topography. A holistic approach to activating different catchment systems has potential to increase their effectiveness even more.

Side channel landscape modifications are effective at increasing total inundated area.

Replicating the processes of a naturally functioning floodplain environment demonstrates that areas can be engineered to recreate similar benefits. This process is highly dependent on planting plans and management strategies, as the vegetation that infills these areas will be the catalyst for the positive externalities.

Modification placement should be influenced by present and historical conditions at multiple scales.

The existing topography of the landscape should be carefully considered while planning the placement. The landscape modifications work together as the water flows across the landscape, primarily influenced by the soil around and underneath it. The existing soil and vegetation will further dictate its success and are key to the success of the intervention's objectives.

Stream bed incision must be addressed before other treatments become available.

The scouring of channels is a common hurdle for restoration efforts and a common indication of success for past floodplain management efforts. The design and integration of landscape modifications must consider the existing channel bed elevation and freeboard. With freeboards extending tens of feet below the floodplain, the movement of water away from the incised channel becomes prohibitive. Implementation strategies should first consider methods to reduce this freeboard. This may require instream modifications to mature for many years before wider floodplain modifications can begin successfully.

Many modifications are temporarily ineffective at high flows, though provide benefit as water level recedes.

Modifications should be designed to be resilient to many stages of flood height. Shallow modifications become less effective as their topography, and therefore benefits, were overwhelmed by water volume. This may be incorporated into positive design elements, allowing the landscape to perform different functions based on the demand of water volume placed upon it.

Using landscape restoration strategies in tandem with restrained engineering projects provide an opportunity to redefine floodplain management to provide a more just outcome for all parties involved. Ecological based approaches to flood mitigation will create the ability to not only mitigate water's negative impact on human use, but to harness water's inherent positive and restorative qualities.

This project concentrates on the agricultural floodplain areas of the larger non-dam alternative strategy. Agricultural interests have seen flood reduction strategies proposed by the non-dam alternatives as contrary to their livelihoods and bottom line. Often, residents and farmers believe that their current priorities are opposed to those of restorative actions. Strategies of using ecological systems provide far-reaching, though subtle benefits. Attention can be brought to these practices in a sympathetic way that provides the agricultural owners with a broad range of options. Solutions can be developed and presented to those living with the river that would prove mutually beneficial to the goals of ecological and economic development. These proposals show the intimate connection between the river's health and the health of human communities.

Bibliography and Works Cited

Abbe, Tim, Mike Hrachovec, and Steve Winter. 2018. "Engineered Log Jams: Recent Developments in Their Design and Placement, with Examples from the Pacific Northwest, USA." Reference Module in Earth Systems and Environmental Sciences. Netherlands: Elsevier. Https://Doi. Org/10.1016/B978-0-12-409548-9.11031-0, Accessed August 7: 2020.

Abbe, Timothy. 2016. "Preliminary Scientific and Technical Assessment of a Restorative Flood Protection Approach for the Upper Chehalis River Watershed."

Abbe, Timothy, Cynthia Carlstad, Danielle Devier, Dickerson-Lange Susan, Julia Jay, Megan Nelson, Embertson Leif, et al. 2019. "Chehalis Basin Strategy Restorative Flood Protection Advanced Feasibility Evaluation."

Acreman, M., and J. Holden. 2013. "How Wetlands Affect Floods." Wetlands 33 (5): 773–86. https://doi.org/10.1007/s13157-013-0473-2.

Aguiar, Terencio R., F. R. Bortolozo, F. A. Hansel, K. Rasera, and M. T. Ferreira. 2015. "Riparian Buffer Zones as Pesticide Filters of No-till Crops." Environmental Science and Pollution Research 22 (14): 10618–26. https://doi.org/10.1007/s11356-015-4281-5.

Åhlén, Imenne, Peter Hambäck, Josefin Thorslund, Andrew Frampton, Georgia Destouni, and Jerker Jarsjö. 2020. "Wetlandscape Size Thresholds for Ecosystem Service Delivery: Evidence from the Norrström Drainage Basin, Sweden." Science of The Total Environment 704 (February): 135452. https://doi.org/10.1016/j.scitotenv.2019.135452.

Åhlén, Imenne, Josefin Thorslund, Peter Hambäck, Georgia Destouni, and Jerker Jarsjö. 2022. "Wetland Position in the Landscape: Impact on Water Storage and Flood Buffering." Ecohydrology 15 (7): e2458. https://doi.org/10.1002/eco.2458.

Álvarez, Manuel, Jeronimo Puertas, Enrique Peña González, and María Bermúdez. 2017. "Two-Dimensional Dam-Break Flood Analysis in Data-Scarce Regions: The Case Study of Chipembe Dam, Mozambique." Water 9 (June): 432. https://doi.org/10.3390/w9060432.

Ameli, Ali A., and Irena F. Creed. 2019. "Does Wetland Location Matter When Managing Wetlands for Watershed-Scale Flood and Drought Resilience?" JAWRA Journal of the American Water Resources Association 55 (3): 529–42. https://doi.org/10.1111/1752-1688.12737.

Apostol, Dean, Warren Warttig, Bob Carey, and Ben Perkowski. 2006. "Landscape and Watershed Scale." In Restoring the Pacific Northwest, 319–50. Society for Ecological Restoration International and Island Press.

Atelier Descombes Rampini. 2015. "Renaturation of the River Aire, Geneva." Landezine (blog). June 30, 2015. http://landezine.com/renaturation-of-the-river-aire-geneva/.

Benayas, José M. Rey, Adrian C. Newton, Anita Diaz, and James M. Bullock. 2009. "Enhancement of Biodiversity and Ecosystem Services by Ecological Restoration: A Meta-Analysis." Science 325 (5944): 1121–24. https://doi.org/10.1126/science.1172460.

Benevolenza, Mia A., and LeaAnne DeRigne. 2019. "The Impact of Climate Change and Natural Disasters on Vulnerable Populations: A Systematic Review of Literature." Journal of Human Behavior in the Social Environment 29 (2): 266–81. https://doi.org/10.1080/10911359.2018.1527739.

Berry, James T. 1874. "11N-03W GLO Survey." General Land Office Survey. South Fork Chehalis. https://glorecords.blm.gov/details/survey/default.aspx?dm_id=398935&sid=3kne2fpi.urj#surveyDetailsTabIndex=1.

Bisson, Peter A., Robert E. Bilby, Mason D. Bryant, Andrew C. Dolloff, Glenn B. Grette, Robert A. House, Michael L. Murphy, K Victor Koski, and James R. Sedell. 1987. "Large Woody Debris in Forested Streams in the Pacific Northwest: Past, Present, and Future." In Streamside Management: Forestry and Fishery Interactions: Proceedings of the Symposium.

Brander, Luke M., Raymond J. G. M. Florax, and Jan E. Vermaat. 2006. "The Empirics of Wetland Valuation: A Comprehensive Summary and a Meta-Analysis of the Literature." Environmental and Resource Economics 33 (2): 223. https://doi.org/10.1007/s10640-005-3104-4.

Brandt, Patric, David J. Abson, Dominick A. DellaSala, Robert Feller, and Henrik von Wehrden. 2014. "Multifunctionality and Biodiversity: Ecosystem Services in Temperate Rainforests of the Pacific Northwest, USA." Biological Conservation 169 (January): 362–71. https://doi.org/10.1016/j.biocon.2013.12.003.

Brunner, Gary, dir. 2021. HEC-RAS 2D Class 1.1 - Overview of 2D Unsteady Flow Modeling. https://www.youtube.com/watch?v=97BXt4sxgKE.

Brunner, Gary W., Cameron T. Ackerman, and Chris R. Goodell. 2023. "HEC-RAS User's Manual." HEC-RAS User's Manual. 2023. https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/foreword.

Buffington, John M., and David R. Montgomery. 2013. "Geomorphic Classification of Rivers." Treatise on Geomorphology Vol 9: 730–67.

Bunzel, Katja, Matthias Liess, and Mira Kattwinkel. 2014. "Landscape Parameters Driving Aquatic Pesticide Exposure and Effects." Environmental Pollution 186 (March): 90–97. https://doi.org/10.1016/j.envpol.2013.11.021.

Bureau of Land Management. 2020. "About the Public Land Survey System." 2020. https://mlrs.blm.gov/s/article/PLSS-Information.

Buuren, Arwin van. 2019. "The Dutch Delta Approach: The Successful Reinvention of a Policy Success." In Great Policy Successes, edited by Paul 't Hart and Mallory Compton, 0. Oxford University Press. https://doi.org/10.1093/oso/9780198843719.003.0011.

Carino, Joji. 2022. "Indigenous Voices at the Table: Restoring Local Decision-Making on Protected Areas." October 20, 2022. https://www.culturalsurvival.org/publications/cultural-survival-quarterly/indigenous-voices-table-restoring-local-decision-making.

Carr, Edward W., Yosef Shirazi, George R. Parsons, Porter Hoagland, and Christopher K. Sommerfield. 2018. "Modeling the Economic Value of Blue Carbon in Delaware Estuary Wetlands: Historic Estimates and Future Projections." Journal of Environmental Management 206 (January): 40–50. https://doi.org/10.1016/j.jenvman.2017.10.018.

Castelle, Catherine Conolly, Michael Emers, Eric Metz, Susan Meyer, Michael Witter, Susan Mauermann, and Terrell Erickson. 1992. "Wetland Buffers: Use and Effectiveness DNR." Washington State Department of Natural Resources.

Chee, Yung En. 2004. "An Ecological Perspective on the Valuation of Ecosystem Services." Biological Conservation 120 (4): 549–65. https://doi.org/10.1016/j.biocon.2004.03.028.

Chehalis Basin Strategy, dir. 2022. Future of Flooding in the Chehalis Basin. https://www.youtube.com/watch?v=z2eHSdyY8Lk.

Chehalis Flood Authority. 2010. "Chehalis River Basin Comprehensive Flood Hazard Management Plan." Chehalis River Basin Flood Authority.

Chehalis River Basin Flood Control Zone District. 2019. "Chehalis River Basin Water Retention Facility and Levee Improvements - Project Need, Purpose, and Description." Chehalis River Basin Flood Control Zone District.

Chou, Rung-Jiun. 2016. "Achieving Successful River Restoration in Dense Urban Areas: Lessons from Taiwan." Sustainability 8 (11): 1159. https://doi.org/10.3390/su8111159.

Chronicle, The. 2020. "Flood Authority Endorses Dam As Part of Chehalis Basin Strategy." The Daily Chronicle. May 1, 2020. http://www.chronline.com/stories/flood-authority-endorses-dam-as-part-of-chehalis-basin-strategy,3899.

Chronicle, The.2023. "Chehalis Basin Group Unveils Four Non-Dam Flood Prevention Proposals; Asks for Public Input." The Daily Chronicle. January 30, 2023. http://www.chronline.com/stories/chehalis-basin-group-unveils-four-non-dam-flood-prevention-proposals-asks-for-public-input,308225.

Cippa, Andrea, dir. 2022a. HEC-RAS Part 6/10, Insert the Land Cover and Manning's Coefficients with HEC-RAS 6.1. https://www.youtube.com/watch?v=MwMomA3jPgI.

Cippa, Andrea dir. 2022b. HEC-RAS Part 9/10, Display and Discuss the Results of the Simulation with HEC-RAS 6.1. https://www.youtube.com/watch?v=aT7xBgwCSU0.

ClimateData.org. 2023. "Chehalis Climate." Climate Data.Org. 2023. https://en.climate-data.org/north-america/united-states-of-america/washington/chehalis-15538/.

Coe, Daniel E. 2016. "Floodplain Visualization Using Lidar-Derived Relative Elevation Models." Washington State Geologic Survey.

Coe, Daniel E. 2017. "Creating REMs in QGIS with the IDW Method." Dan Coe Carto. 2017. https://dancoecarto.com/creating-rems-in-qgis-the-idw-method.

Coe, Daniel E, S L Slaughter, and I J Hubert. 2016. "Chehalis River Flood Plain and Channel Patterns." WASHINGTON STATE GEOLOGY NEWS (blog). February 24, 2016. https://washingtonstategeology.wordpress.com/2016/02/24/chehalis-river-flood-plain-and-channel-patterns/.

Cools, J., M. Diallo, E. Boelee, S. Liersch, D. Coertjens, V. Vandenberghe, and B. Kone. 2013. "Integrating Human Health into Wetland Management for the Inner Niger Delta, Mali." Environmental Science & Policy, Management of wetlands in river basins: the WETwin project, 34 (December): 34–43. https://doi.org/10.1016/j.envsci.2012.09.011.

Costanza, Robert, Ralph d'Arge, Rudolf de Groot, Stephen Farber, Monica Grasso, Bruce Hannon, Karin Limburg, et al. 1997. "The Value of the World's Ecosystem Services and Natural Capital." Nature 387 (6630): 253–60. https://doi.org/10.1038/387253a0.

Cramer, Michelle L. (ed.). 2012. "Stream Habitat Restoration Guidelines." 2012. https://wdfw.wa.gov/publications/01374.

Crowell, Mark, Kevin Coulton, Cheryl Johnson, Jonathan Westcott, Doug Bellomo, Scott Edehnan, and Emily Hirsch. 2010. "An Estimate of the U.S. Population Living in 100-Year Coastal Flood Hazard Areas." Journal of Coastal Research 26 (2): 201–11.

Cumbria Strategic Flood Partnership. 2018. "Natural Flood Management Measures: A Practical Guide for Farmers." Cumbria Strategic Flood Partnership. https://www.preventionweb.net/publication/natural-flood-management-measures-practical-guide-farmers.

Dale, P. E. R., and R. Connelly. 2012. "Wetlands and Human Health: An Overview." Wetlands Ecology and Management 20 (3): 165–71. https://doi.org/10.1007/s11273-012-9264-4.

Destandau, François, Gwenaël Imfeld, and Anne Rozan. 2013. "Regulation of Diffuse Pesticide Pollution: Combining Point Source Reduction and Mitigation in Stormwater Wetland (Rouffach, France)." Ecological Engineering 60 (November): 299–308. https://doi.org/10.1016/j.ecoleng.2013.07.030.

Directorate-General for Research and Innovation (European Commission), Harriet Bulkeley, Sandra Naumann, Zoran Vojinovic, Carlo Calfapietra, Kym Whiteoak, Tiago Freitas, Sofie Vandewoestijne, and Tom Wild. 2020. Nature-Based Solutions: State of the Art in EU Funded Projects. LU: Publications Office of the European Union. https://data.europa.eu/doi/10.2777/236007.

Directorate-General for Research and Innovation (European Commission), and Zoran Vojinovic. 2020. Nature-Based Solutions for Flood Mitigation and Coastal Resilience: Analysis of EU Funded Projects. LU: Publications Office of the European Union. https://data.europa.eu/doi/10.2777/374113.

Dpt of Ecology. 2023. "Office of Chehalis Basin." 2023. https://ecology.wa.gov/About-us/Who-we-are/Our-Programs/Office-of-Chehalis-Basin.

Dpt of Ecology. n.d. "Chehalis Basin Water Resource Inventory Areas 22 & 23." WIRA Report. Washington State Department of Ecology.

Duke, J.R. 2014. "Assessing the Effectiveness and Values of Wetland Habitat Created for Amphibians in the Nantahala National Forest in NC." https://www.proquest.com/docview/1531329598?pq-origsite=primo&parentSessionId=ZUeFFJGE%2BO92oZ%2FVTbcH9en0gO61D1jf2POryXTrO%2B8%3D.

Dumax, Nathalie, and Anne Rozan. 2021. "Valuation of the Environmental Benefits Induced by a Constructed Wetland." Wetlands Ecology and Management 29 (6): 809–22. https://doi.org/10.1007/s11273-021-09811-x.

Earth Resources Observation and Science Center, and United States Geological Survey. 2018. "National Land Cover Database."

Elliot, Bob, and Larry Karpack. 2014. "Development and Calibration of Hydraulic Model Memorandum."

Elliot, Bob, Tim Tschetter, and Larry Karpack. 2019. "Chehalis River Existing Conditions RiverFlow2D Model Development and Calibration Memorandum." Chehalis Basin Strategy.

Espeland, Erin K., and Karin M. Kettenring. 2018. "Strategic Plant Choices Can Alleviate Climate Change Impacts: A Review." Journal of Environmental Management 222 (September): 316–24. https://doi.org/10.1016/j.jenvman.2018.05.042.

Estenoz, Shannon, and Eric Bush. 2015. "Everglades Restoration Science and Decision-Making in the Face of Climate Change: A Management Perspective." Environmental Management 55 (4): 876–83. https://doi.org/10.1007/s00267-015-0452-x.

Farber, Stephen C., Robert Costanza, and Matthew A. Wilson. 2002. "Economic and Ecological Concepts for Valuing Ecosystem Services." Ecological Economics 41 (3): 375–92. https://doi.org/10.1016/S0921-8009(02)00088-5.

Federal Emergency Management Agency. 1981. "FEMA FIRM Map." Flood Insurance Rate Map. Community Panel No 530102 0440 B: Federal Emergency Managment Agency.

Federal Emergency Management Agency. 2020. "FEMA Flood Risk Communication Toolkit." FEMA.

FEMA. 2006. "FEMA FIRM Map 5301041364C." FIRM Maps. Chehalis WA: Federal Emergency Managment Agency. https://msc.fema.gov/portal/search?AddressQuery=chehalis%20wa#searchresultsanchor.

Fidler, L.E., and S.B. Miller. 1994. "British Columbia Water Quality Guidelines for Dissolved Gas Supersaturation." BC Ministry of Environment Canada Department of Fisheries and Oceans Environment Canada.

Fielding, Jane L. 2012. "Inequalities in Exposure and Awareness of Flood Risk in England and Wales." Disasters 36 (3): 477–94. https://doi.org/10.1111/j.1467-7717.2011.01270.x.

Flitcroft, Rebecca L., William R. Brignon, Brian Staab, J. Ryan Bellmore, Jonathan Burnett, Paul Burns, Brian Cluer, et al. 2022. "Rehabilitating Valley Floors to a Stage 0 Condition: A Synthesis of Opening Outcomes." Frontiers in Environmental Science 10. https://www.frontiersin.org/articles/10.3389/fenvs.2022.892268.

Forester, Brenna. 2010. "Whatcom Creek Restoration Project Report: 2009." Bellingham, Washington: The City of Bellingham Environmental Resources Department.

Foster, Stephen, Ricardo Hirata, Daniel Gomes, Monica D'Elia, and Marta Paris. 2002. Groundwater Quality Protection. The World Bank. https://doi.org/10.1596/0-8213-4951-1.

Freitag, Bob, Susan Bolton, Frank Westerlund, and J.L.S. Clark. 2009. Floodplain Management: A New Approach For a New Era.

Fremout, Tobias, Evert Thomas, Hermann Taedoumg, Siebe Briers, Claudia Elena Gutiérrez-Miranda, Carolina Alcázar-Caicedo, Antonia Lindau, et al. 2022. "Diversity for Restoration (D4R): Guiding the Selection of Tree Species and Seed Sources for Climate-Resilient Restoration of Tropical Forest Landscapes." Journal of Applied Ecology 59 (3): 664–79. https://doi.org/10.1111/1365-2664.14079.

Godwin, Mandy. 2020. "When the Chehalis Floods Again, Who Pays the Price?" Crosscut, May 13, 2020, sec. Environment. https://crosscut.com/2020/05/when-chehalis-floods-again-who-pays-price.

Gómez Martín, Eulalia, María Máñez Costa, and Kathleen Schwerdtner Máñez. 2020. "An Operationalized Classification of Nature Based Solutions for Water-Related Hazards: From Theory to Practice." Ecological Economics 167 (January): 106460. https://doi.org/10.1016/j.ecolecon.2019.106460.

Gomez-Sapiens, Martha M., Eduardo Soto-Montoya, and Osvel Hinojosa-Huerta. 2013. "Shorebird Abundance and Species Diversity in Natural Intertidal and Non-Tidal Anthropogenic Wetlands of the Colorado River Delta, Mexico." Ecological Engineering, Colorado Delta Wetlands, 59 (October): 74–83. https://doi.org/10.1016/j.ecoleng.2013.03.004.

Good, Anthony. 2020. "Three Essays on Non-Market Valuation: Valuing the Billy Frank Jr. Nisqually National Wildlife Refuge." Ph.D., United States -- Virginia: George Mason University. https://www.proquest.com/docview/2470052260/abstract/DC1338A9A2DC4721PQ/1.

Goodell, Chris. 2013. "Stabilizing a Dynamic Unsteady HEC-RAS Model - Kleinschmidt." The RAS Solution (blog). October 8, 2013. https://www.kleinschmidtgroup.com/ras-post/stabilizing-a-dynamic-unsteady-hec-ras-model/.

Grant, Gordon. 2008. Effects of Forest Practices on Peak Flows and Consequent Channel Response : A State-of-the-Science Report for Western Oregon and Washington. General Technical Report PNW ; GTR-760. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Research Station.

Graziano, Michael P., Amanda K. Deguire, and Thilina D. Surasinghe. 2022. "Riparian Buffers as a Critical Landscape Feature: Insights for Riverscape Conservation and Policy Renovations." Diversity 14 (3): 172. https://doi.org/10.3390/d14030172.

Griffiths, Jennifer Rhiannon. 2013. "Climate Change and Geomorphic Evolution in an Alaskan Watershed and Implications for Salmon Production." Thesis. https://digital.lib.washington.edu:443/researchworks/handle/1773/22567.

Hall, Monique Mae, Priscilla M. Wehi, Hēmi Whaanga, Erana T. Walker, Jonni Hazeline Koia, and Kiri Joy Wallace. 2021. "Promoting Social and Environmental Justice to Support Indigenous Partnerships in Urban Ecosystem Restoration." Restoration Ecology 29 (1): e13305. https://doi.org/10.1111/rec.13305.

Hallenbeck, Mark, Anne Goodchild, and Jerome Drescher. 2014. "Travel Costs Associated with Flood Closures of State Highways Near Centralia/Chehalis, Washington." Research Report WA-RD 832.1. Washington State Department of Transportation.

Hamlet, Alan F., and Dennis P. Lettenmaier. 2007. "Effects of 20th Century Warming and Climate Variability on Flood Risk in the Western U.S." Water Resources Research 43 (6). https://doi.org/10.1029/2006WR005099.

Hammer, DA. 1989. Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural Chattanooga, June 1988.

Hansen, Andrea. 2011. "From Hand to Land: Tracing Procedural Artifacts in the Built Environment." Scenario Journal.

Harma, Kiersten. 2023. "Chehalis Watershed." 2023. https://chehalisbasinpartnership.org/chehalis-watershed/.

Hausfather, Zeke. 2019. "The High-Emissions 'RCP8.5' Global Warming Scenario." Carbon Brief. August 21, 2019. https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario/.

Hay, Christopher H., Benjamin D. Reinhart, Jane R. Frankenberger, Matthew J. Helmers, Xinhua Jia, Kelly A. Nelson, and Mohamed A. Youssef. 2021. "Frontier: Drainage Water Recycling in the Humid Regions of the U.S.: Challenges and Opportunities." Transactions of the ASABE 64 (3): 1095–1102. https://doi.org/10.13031/trans.14207.

HDR Engineering. 2021. "Plant Replacement Plan Memorandum." Technical Memorandum. Chehalis Basin Flood Control Zone District.

Healy, Andrew, and Neil Malhotra. 2009. "Myopic Voters and Natural Disaster Policy." The American Political Science Review 103 (3): 387–406.

Hey, Donald L. 1995. "Flood Reduction through Wetland Restoration," Restoration Ecology, 3 (1): 4–17.

Hiscock, Kevin M., and Victor F. Bense. 2014. Hydrogeology - Principles and Practice. 2nd ed. John Wiley & Sons.

Horwitz, Pierre, and C. Max Finlayson. 2011. "Wetlands as Settings for Human Health: Incorporating Ecosystem Services and Health Impact Assessment into Water Resource Management." BioScience 61 (9): 678–88. https://doi.org/10.1525/bio.2011.61.9.6.

Hydrologic Engineering Center. 2022. "HEC-RAS River Analysis System." Davis, CA: U.S. Army Corps of Engineers.

Inslee, Gov. Jay. 2020. "Inslee Letter to Agencies Chehalis Basin," July 22, 2020. https://www.documentcloud.org/documents/7002731-Inslee-Letter-to-Agencies-Chehalis-Basin-7-22-20.

Isaak, D. J., S. Wollrab, D. Horan, and G. Chandler. 2012. "Climate Change Effects on Stream and River Temperatures across the Northwest U.S. from 1980–2009 and Implications for Salmonid Fishes." Climatic Change 113 (2): 499–524. https://doi.org/10.1007/s10584-011-0326-z.

IUCN. 2014. "New Social Compact." International Union for the Conservation of Nature. https://www.worldparkscongress.org/.

IWGIA. 2008. "Conference on Indigenous Peoples and Climate Change." Meeting Report E/C.19/2008/CRP. 3. Permanent Forum on Indigenous Issues. Copenhagen: International Work Group for Indigenous Affairs.

Jadidoleslam, Navid. 2D Flow Modeling Using HEC-RAS 5.0. 2016. Youtube.

Jeffres, Carson A., Jeff J. Opperman, and Peter B. Moyle. 2008. "Ephemeral Floodplain Habitats Provide Best Growth Conditions for Juvenile Chinook Salmon in a California River." Environmental Biology of Fishes 83 (4): 449–58. https://doi.org/10.1007/s10641-008-9367-1.

Jenkins, W. Aaron, Brian C. Murray, Randall A. Kramer, and Stephen P. Faulkner. 2010. "Valuing Ecosystem Services from Wetlands Restoration in the Mississippi Alluvial Valley." Ecological Economics 69 (5): 1051–61. https://doi.org/10.1016/j.ecolecon.2009.11.022.

Jensen, Mark, dir. 2021. HEC-RAS 2D Class: 1.6 - Mesh Generation. https://www.youtube.com/watch?v=tbNxsgKQz6E.

Jha, Manoj. 2020. "Impacts of Landscape Changes on Water Resources." Water 12 (August): 2244. https://doi.org/10.3390/w12082244.

Jurgiel, Borys. 2022. "Point Sampling Tool."

Karpack, Larry, and Colin Butler. 2019. "Chehalis River Basin Hydrologic Modeling Memorandum." Chehalis Basin Strategy.

Kay, Tom. 2022. "Making Room for Rivers." Forest and Bird. June 22, 2022. https://www.forestandbird.org.nz/resources/making-room-rivers.

Keddy, Paul A. 2023. Causal Factors for Wetland Management and Restoration: A Concise Guide. Cham, SWITZERLAND: Springer International Publishing AG. http://ebookcentral.proquest.com/lib/washington/detail.action?docID=7192863.

Keesstra, Saskia, Joao Nunes, Agata Novara, David Finger, David Avelar, Zahra Kalantari, and Artemi Cerda. 2017. "The Superior Effect of Nature Based Solutions in Land Management for Enhancing Ecosystem Services." Science of The Total Environment, August. https://doi.org/10.1016/j.scitotenv.2017.08.077.

Kitazawa, Munehiro, Yuichi Yamaura, Masayuki Senzaki, Kazuhiro Kawamura, Masashi Hanioka, and Futoshi Nakamura. 2019. "An Evaluation of Five Agricultural Habitat Types for Openland Birds: Abandoned Farmland Can Have Comparative Values to Undisturbed Wetland." Ornithological Science 18 (1): 3–16. https://doi.org/10.2326/osj.18.3.

Kleinschmidt Group. 2021. "Commitment to No Net Loss of Aquatic Habitat Function." Memorandum. Chehalis Basin Strategy.

Klijn, F., Dick Bruin, Maurits Hoog, Sjef Jansen, and Dirk Sijmons. 2013. "Design Quality of Room-for-the-River Measures in the Netherlands: Role and Assessment of the Quality Team (Q-Team)." International Journal of River Basin Management 11 (September): 287–99. https://doi.org/10.1080/15715124.2013.811418.

Knabb, Richard D., Jaimie R. Rhome, and Daniel P. Brown. 2023. "Tropical Cyclone Report Hurricane Katrina." Tropical Cyclone Report. National Hurricane Center - National Oceanic and Atmospheric Administration.

Kovac, Anthony, Naomi K. Pleizier, and Colin J. Brauner. 2022. "The Effect of Total Dissolved Gas Supersaturation on Gas Bubble Trauma in Juvenile Rainbow Trout (Oncorhynchus Mykiss), Juvenile Kokanee (Oncorhynchus Nerka), and Two Age Classes of White Sturgeon (Acipenser Transmontanus)." Canadian Journal of Fisheries and Aquatic Sciences 79 (2): 249–56. https://doi.org/10.1139/cjfas-2020-0448.

Kubo, Josh, Michael Thai, Kollin Higgins, and Beth leDoux. 2019. "Synthesis of Riparian Buffer Best Available Science: Informing Variable-Width Buffers in the Lower Snoqualmie Valley." King County Department of Natural Resources and Parks.

Laduzinsky, Paige. 2019. "The Disproportionate Impact of Climate Change on Indigenous Communities." KCET. December 19, 2019. https://www.kcet.org/shows/tending-nature/the-disproportionate-impact-of-climate-change-on-indigenous-communities.

LCC 17.38.270. 2023. "Lewis County Code Title 17 Land Use and Development Regulations." Lewis County Washington. https://www.codepublishing.com/WA/LewisCounty/#!/LewisCounty17/LewisCounty1738.html.

Li, Dongyue, Dennis P. Lettenmaier, Steven A. Margulis, and Konstantinos Andreadis. 2019. "The Role of Rain-on-Snow in Flooding Over the Conterminous United States." Water Resources Research 55 (11): 8492–8513. https://doi.org/10.1029/2019WR024950.

Liquete, Camino, Angel Udias, Giulio Conte, Bruna Grizzetti, and Fabio Masi. 2016. "Integrated Valuation of a Nature-Based Solution for Water Pollution Control. Highlighting Hidden Benefits." Ecosystem Services, Integrated valuation of ecosystem services: challenges and solutions, 22 (December): 392–401. https://doi.org/10.1016/j.ecoser.2016.09.011.

Liu, Xingmei, Xuyang Zhang, and Minghua Zhang. 2008. "Major Factors Influencing the Efficacy of Vegetated Buffers on Sediment Trapping: A Review and Analysis." Journal of Environmental Quality 37 (5): 1667–74. https://doi.org/10.2134/jeq2007.0437.

Luce, C. H., J. T. Abatzoglou, and Z. A. Holden. 2013. "The Missing Mountain Water: Slower Westerlies Decrease Orographic Enhancement in the Pacific Northwest USA." Science 342 (6164): 1360–64. https://doi.org/10.1126/science.1242335.

Luce, Charles, Brian Staab, Marc Kramer, Seth Wenger, Dan Isaak, and Callie McConnell. 2014. "Sensitivity of Summer Stream Temperatures to Climate Variability in the Pacific Northwest." Water Resources Research 50 (4): 3428–43. https://doi.org/10.1002/2013WR014329.

Macho, Werner. 2018. "QChainage."

Mallakpour, Iman, and Gabriele Villarini. 2015. "The Changing Nature of Flooding across the Central United States." Nature Climate Change 5 (3): 250–54. https://doi.org/10.1038/nclimate2516.

Mann, Charles C. 2006. 1491: New Revelations of the Americas Before Columbus. Vintage.

Martinez-Martinez, Edwin, A. Pouyan Nejadhashemi, Sean A. Woznicki, and Bradley J. Love. 2014. "Modeling the Hydrological Significance of Wetland Restoration Scenarios." Journal of Environmental Management 133 (January): 121–34. https://doi.org/10.1016/j.jenvman.2013.11.046.

Matzek, Virginia, and Kerrie A. Wilson. 2021. "Public Support for Restoration: Does Including Ecosystem Services as a Goal Engage a Different Set of Values and Attitudes than Biodiversity Protection Alone?" PLOS ONE 16 (1): e0245074. https://doi.org/10.1371/journal.pone.0245074.

Mayer, Paul M., Steven K. Reynolds Jr., Marshall D. McCutchen, and Timothy J. Canfield. 2007. "Meta-Analysis of Nitrogen Removal in Riparian Buffers." Journal of Environmental Quality 36 (4): 1172–80. https://doi.org/10.2134/jeq2006.0462.

McAlpin, Tate O., Jeremy A. Sharp, Stephen H. Scott, and Gaurav Savant. 2013. "Habitat Restoration and Flood Control Protection in the Kissimmee River." Wetlands 33 (3): 551–60. https://doi.org/10.1007/s13157-013-0412-2.

McDonald, Julie, and Edna Fund. 2017. "From Native American Legends to 2007: A History of Flooding in the Chehalis River Basin." The Chronicle, December 6, 2017.

McElfish, James, Rebecca Kihslinger, and Sandra Nichols. 2008. Planner's Guide to Wetland Buffers for Local Governments | Environmental Law Institute. Environmental Law Institute. https://www.eli.org/research-report/planners-guide-wetland-buffers-local-governments.

McElwee, Pamela. 2017. "The Metrics of Making Ecosystem Services." Environment and Society: Advances in Research 8 (August): 96–124. https://doi.org/10.3167/ares.2017.080105.

McKinney, Richard A., Michael A. Charpentier, and Cathleen Wigand. 2009. "Assessing the Wildlife Habitat Value of New England Salt Marshes: II. Model Testing and Validation." Environmental Monitoring and Assessment 154 (1): 361–71. https://doi.org/10.1007/s10661-008-0403-6.

Miles, Edward L., Amy K Snover, Alan F Hamlet, Bridget Callahan, and David Fluharty. 2000. "Pacific Northwest Regional Assessment: The Impacts of Climate Variability and Climate Change on the Water Resources of the Columbia River Basin1." JAWRA Journal of the American Water Resources Association 36 (2): 399–420. https://doi.org/10.1111/j.1752-1688.2000.tb04277.x.

Miller, Dale, and Peter Skidmore. 2003. "Establishing a Standard of Practice for Natural Channel Design Using Design Criteria." In Restoration of Puget Sound Rivers, edited by David R. Montgomery, University of Washington, and Society for Ecological Restoration. Seattle, WA: Center for Water and Watershed Studies in association with University of Washington Press.

Miller, Jerry R., and R. Craig Kochel. 2013. "Use and Performance of In-Stream Structures for River Restoration: A Case Study from North Carolina." Environmental Earth Sciences 68 (6): 1563–74. https://doi.org/10.1007/s12665-012-1850-5.

Milligan, Dorothy A. 1985. "The Ecology of Avian Use of Urban Freshwater Wetlands in King County, Washington." University of Washington.

Mitsch, William J. 1992. "Landscape Design and the Role of Created, Restored, and Natural Riparian Wetlands in Controlling Nonpoint Source Pollution." Ecological Engineering 1 (1): 27–47. https://doi.org/10.1016/0925-8574(92)90024-V.

Montgomery, David R., University of Washington, and Society for Ecological Restoration, eds. 2003. Restoration of Puget Sound Rivers. Seattle, WA: Center for Water and Watershed Studies in association with University of Washington Press.

Muenz, Tara K., Stephen W. Golladay, George Vellidis, and Lora L. Smith. 2006. "Stream Buffer Effectiveness in an Agriculturally Influenced Area, Southwestern Georgia." Journal of Environmental Quality 35 (5): 1924–38. https://doi.org/10.2134/jeq2005.0456.

Nahlik, A. M., and M. S. Fennessy. 2016. "Carbon Storage in US Wetlands." Nature Communications 7 (1): 13835. https://doi.org/10.1038/ncomms13835.

Nakahashi, Honoka, Taihei Yamada, Nobuo Ishiyama, and Futoshi Nakamura. 2023. "Ecological Value of Gravel Pit Ponds for Floodplain Wetland Fish." Freshwater Biology 68 (2): 340–48. https://doi.org/10.1111/fwb.14029.

Nakano, Shigeru, Hitoshi Miyasaka, and Naotoshi Kuhara. 1999. "Terrestrial–Aquatic Linkages: Riparian Arthropod Inputs Alter Trophic Cascades in a Stream Food Web." Ecology 80 (7): 2435–41. https://doi.org/10.1890/0012-9658(1999)080[2435:TALRAI]2.0.CO;2.

National Research Council. 2013. Levees and the National Flood Insurance Program: Improving Policies and Practices. Washington, D.C.: National Academies Press. https://doi.org/10.17226/18309.

Navid Jadidoleslam, dir. 2016. 2D Flow Modeling Using HEC-RAS 5.0. https://www.youtube.com/watch?v=R795eunWB_E.

Netherlands Water Partnership. 2023. "Flood Management | NWP." 2023. https://www.netherlandswaterpartnership.com/expertise/climate-resilience/flood-management.

Nicholson, Alexander Robert. 2014. "Quantifying and Simulating the Impact of Flood Mitigation Features in a Small Rural Catchment." Thesis, Newcastle University. http://theses.ncl.ac.uk/jspui/handle/10443/2382.

NOAA. 2013. "Climate Model: Temperature Change (RCP 4.5) - 2006 - 2100." Science On a Sphere. November 17, 2013. https://sos.noaa.gov/catalog/datasets/climate-model-temperature-change-rcp-45-2006-2100/.

Northern Instutute of Applied Climate Science. n.d. "Adaptation Workbook: A Climate Change Tool for Land Management and Conservation." Accessed January 19, 2023. https://adaptationworkbook.org/niacs-strategies/ag.

Obi, Rachael, Maxwell Umunna Nwachukwu, Donald Chiuba Okeke, and Uloma Jiburum. 2021. "Indigenous Flood Control and Management Knowledge and Flood Disaster Risk Reduction in Nigeria's Coastal Communities: An Empirical Analysis." International Journal of Disaster Risk Reduction 55 (March): 102079. https://doi.org/10.1016/j.ijdrr.2021.102079.

Office of Chehalis Basin. 2019. "Chehalis Basin Strategy Aquatic Species Restoration Plan." Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/1913002.html.

Oliver, John, dir. 2017. "Floods." Last Week Tonight. HBO. https://youtu.be/pf1t7cs9dkc.

Olsen, Will H., Joseph W. Wagenbrenner, and Peter R. Robichaud. 2021. "Factors Affecting Connectivity and Sediment Yields Following Wildfire and Post-Fire Salvage Logging in California's Sierra Nevada." Hydrological Processes 35 (1): e13984. https://doi.org/10.1002/hyp.13984.

Olson, Barry. 2021. "A Closer Look at Engineered Stream Structures for Habitat Restoration." March 7, 2021. http://northwestfishingreports.com/Articles/Details/1028.

Olson, Deanna H., Paul D. Anderson, Christopher A. Frissell, Hartwell H. Welsh, and David F. Bradford. 2007. "Biodiversity Management Approaches for Stream–Riparian Areas: Perspectives for Pacific Northwest Headwater Forests, Microclimates, and Amphibians." Forest Ecology and Management, Biodiversity Management in Pacific Northwest Forests: Strategies and Opportunities., 246 (1): 81–107. https://doi.org/10.1016/j.foreco.2007.03.053.

Olson, Patricia L., Nicholas T. Legg, Timothy Abbe, Mary Ann Reinhart, and Judith Radloff. 2014. "A Methodology for Delineating Planning-Level Channel Migration Zones." 14-06-025. Washington State Department of Ecology.

Oregon State University. 2015. "Beyond Land Surveys." Institute for Natural Resources. August 21, 2015. https://inr.oregonstate.edu/hvmp/beyond-land-surveys.

Oregon State University. n.d. "Manning's n Values." Accessed February 28, 2023. https://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm.

Otis, David L., William R. Crumpton, David Green, Anna Loan-Wilsey, Tom Cooper, and Rex R. Johnson. 2013. "Predicted Effect of Landscape Position on Wildlife Habitat Value of Conservation Reserve Enhancement Program Wetlands in a Tile-Drained Agricultural Region." Restoration Ecology 21 (2): 276–84. https://doi.org/10.1111/j.1526-100X.2012.00898.x.

Page, Ken, Arthur Read, Paul Frazier, and Nick Mount. 2005. "The Effect of Altered Flow Regime on the Frequency and Duration of Bankfull Discharge: Murrumbidgee River, Australia." River Research and Applications 21 (5): 567–78. https://doi.org/10.1002/rra.828.

Pattison-Williams, John K., John W. Pomeroy, Pascal Badiou, and Shane Gabor. 2018. "Wetlands, Flood Control and Ecosystem Services in the Smith Creek Drainage Basin: A Case Study in Saskatchewan, Canada." Ecological Economics 147 (May): 36–47. https://doi.org/10.1016/j.ecolecon.2017.12.026.

Phiri, W.K., Davide Vanzo, Kawawa Banda, Edwin Nyirenda, and Imasiku Nyambe. 2021. "A Pseudo-Reservoir Concept in SWAT Model for the Simulation of an Alluvial Floodplain in a Complex Tropical River System." Journal of Hydrology: Regional Studies 33 (February): 100770. https://doi.org/10.1016/j.ejrh.2020.100770.

Pollock, Michael, Timothy Beechie, Joseph Wheaton, Chris Jordan, Nick Bouwes, Nick Weber, and Carol Volk. 2014. "Using Beaver Dams to Restore Incised Stream Ecosystems." BioScience xx (March): 1–12. https://doi.org/10.1093/biosci/biu036.

Potter, KW. 1997. "Estimating Potential Reduction Flood Benefits of Restored Wetlands." Water Resource Update 97: 34–38.

Poussard, Clémence, Benjamin Dewals, Pierre Archambeau, and Jacques Teller. 2021. "Environmental Inequalities in Flood Exposure: A Matter of Scale." Frontiers in Water 3. https://www.frontiersin.org/articles/10.3389/frwa.2021.633046.

Price, Kray, dir. 2019. HEC-RAS Basics Part 1 of 8: Download and Install HEC-RAS with Tips and Tricks for Getting Started. https://www.youtube.com/watch?v=BUjF_MGcxYQ.

QGIS Dev Team 2022. n.d. "Quantum GIS." Hannover. Open Source Geospacial Foundation Project. https://qgis.osgeo.org.

Quartenary Research Center, Geomorphological Research Group. 2016. "Puget Sound River History Project." 2016. http://riverhistory.ess.washington.edu/glo.php.

Quin, Andrew, and Georgia Destouni. 2018. "Large-Scale Comparison of Flow-Variability Dampening by Lakes and Wetlands in the Landscape." Land Degradation & Development 29 (10): 3617–27. https://doi.org/10.1002/ldr.3101.

Quinalt Indian Nation. 2022. "Chehalis Dam Comments." Chehalis Dam DEIS Quinault Comments. 2022. https://chehalisdeisquinaultcomments.squarespace.com/fczd.

Rehfeldt, Gerald E., Nicholas L. Crookston, Marcus V. Warwell, and Jeffrey S. Evans. 2006. "Empirical Analyses of Plant Climate Relationships for the Western United States." International Journal of Plant Sciences 167 (6): 1123–50. https://doi.org/10.1086/507711.

Richardson, David M., Jessica J. Hellmann, Jason S. McLachlan, Dov F. Sax, Mark W. Schwartz, Patrick Gonzalez, E. Jean Brennan, et al. 2009. "Multidimensional Evaluation of Managed Relocation." Proceedings of the National Academy of Sciences 106 (24): 9721–24. https://doi.org/10.1073/pnas.0902327106.

Robinson, Jake M., Nick Gellie, Danielle MacCarthy, Jacob G. Mills, Kim O'Donnell, and Nicole Redvers. 2021. "Traditional Ecological Knowledge in Restoration Ecology: A Call to Listen Deeply, to Engage with, and Respect Indigenous Voices." Restoration Ecology 29 (4): e13381. https://doi.org/10.1111/rec.13381.

Roni, Phil, Karrie Hanson, and Tim Beechie. 2008. "Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques." North American Journal of Fisheries Management 28 (3): 856–90. https://doi.org/10.1577/M06-169.1.

Rucker, Robert R., and Paul M. Kangas. 1974. "Effect of Nitrogen Supersaturated Water on Coho and Chinook Salmon." The Progressive Fish-Culturist 36 (3): 152–56. https://doi.org/10.1577/1548-8659(1974)36[152:EONSWO]2.0.CO;2.

Ryan, John. 2020. "Inslee Puts Proposed Chehalis River Dam on Hold, Calls for Non-Dam Options." July 24, 2020. https://www.kuow.org/stories/inslee-puts-proposed-chehalis-river-dam-on-hold-calls-for-non-dam-options.

Salathé, Eric P., Adrienne Beggs, Chris McJunkin, and Satveer Sandhu. 2023. "The Relative Warming Rates of Heat Events and Median Days in the Pacific Northwest from Observations and a Regional Climate Model." Journal of Climate 36 (8): 2471–81. https://doi.org/10.1175/JCLI-D-22-0313.1.

Scarsbrook, Mike R., and Jane Halliday. 1999. "Transition from Pasture to Native Forest Land-use along Stream Continua: Effects on Stream Ecosystems and Implications for Restoration." New Zealand Journal of Marine and Freshwater Research 33 (2): 293–310. https://doi.org/10.1080/00288330.1999.9516878.

Schröter, Matthias, Emma H. van der Zanden, Alexander P.E. van Oudenhoven, Roy P. Remme, Hector M. Serna-Chavez, Rudolf S. de Groot, and Paul Opdam. 2014. "Ecosystem Services as a Contested Concept: A Synthesis of Critique and Counter-Arguments." Conservation Letters 7 (6): 514–23. https://doi.org/10.1111/conl.12091.

Semlitsch, Raymond D., and J. Russell Bodie. 2003. "Biological Criteria for Buffer Zones around Wetlands and Riparian Habitats for Amphibians and Reptiles." Conservation Biology 17 (5): 1219–28. https://doi.org/10.1046/j.1523-1739.2003.02177.x.

Sexton, Owen. 2022. "'More Floods and Worse Floods' in the Chehalis Basin: Officials Discuss Potential Effects of Climate Change." The Daily Chronicle. October 21, 2022. http://www.chronline.com/stories/more-floods-and-worse-floods-in-the-chehalis-basin-officials-discuss-potential-effects-of,302137.

Slaughter, S L, and I J Hubert. 2014. "Geomorphic Mapping of the Chehalis River Floodplain, Cosmopolis to Pe Ell, Grays Harbor, Thurston, and Lewis Counties, Washington." Washington Division of Geology and Earth Resources Information Circular 118.

St.Clair, John Bradley, Bryce A. Richardson, Nikolas Stevenson-Molnar, Glenn T. Howe, Andrew D. Bower, Vicky J. Erickson, Brendan Ward, Dominique Bachelet, Francis F. Kilkenny, and Tongli Wang. 2022. "Seedlot Selection Tool and Climate-Smart Restoration Tool: Web-Based Tools for Sourcing Seed Adapted to Future Climates." Ecosphere 13 (5): e4089. https://doi.org/10.1002/ecs2.4089.

Stroud Water Research Center. 2023. "Model My Watershed." Model My Watershed. 2023. https://modelmywatershed.org/analyze.

Sustania. 2018. "Taoyuan: River Remediation Protects and Beautifies Land." Global Opportunity Explorer (blog). June 27, 2018. https://goexplorer.org/taoyuan-river-remediation-protects-and-beautifies-land/.

Sutton-Grier, Ariana E., and Paul A. Sandifer. 2019. "Conservation of Wetlands and Other Coastal Ecosystems: A Commentary on Their Value to Protect Biodiversity, Reduce Disaster Impacts, and Promote Human Health and Well-Being." Wetlands 39 (6): 1295–1302. https://doi.org/10.1007/s13157-018-1039-0.

Sweeney, Bernard W. 1993. "Effects of Streamside Vegetation on Macroinvertebrate Communities of White Clay Creek in Eastern North America." Proceedings of the Academy of Natural Sciences of Philadelphia 144: 291–340.

Sweeney, Bernard W., Thomas L. Bott, John K. Jackson, Louis A. Kaplan, J. Denis Newbold, Laurel J. Standley, W. Cully Hession, Richard J. Horwitz, and M. Gordon Wolman. 2004. "Riparian Deforestation, Stream Narrowing, and Loss of Stream Ecosystem Services." Proceedings of the National Academy of Sciences of the United States of America 101 (39): 14132–37.

Sweeney, Bernard W., and J. Denis Newbold. 2014. "Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review." JAWRA Journal of the American Water Resources Association 50 (3): 560–84. https://doi.org/10.1111/jawr.12203.

"Technical Advisory Group Meeting 6 Summary." 2021. Online.

"The Engineering ToolBox." n.d. Accessed February 28, 2023. https://www.engineeringtoolbox.com/.

Theodoropoulos, Christos, Anastasios Stamou, Leonidas Vardakas, Christina Papadaki, Elias Dimitriou, Nikolaos Skoulikidis, and Eleni Kalogianni. 2020. "River Restoration Is Prone to Failure Unless Pre-Optimized within a Mechanistic Ecological Framework | Insights from a Model-Based Case Study." Water Research 173 (April): 115550. https://doi.org/10.1016/j.watres.2020.115550.

Tohver, Ingrid M., Alan F. Hamlet, and Se-Yeun Lee. 2014. "Impacts of 21st-Century Climate Change on Hydrologic Extremes in the Pacific Northwest Region of North America." JAWRA Journal of the American Water Resources Association 50 (6): 1461–76. https://doi.org/10.1111/jawr.12199.

Tomblin, David C. 2009. "The Ecological Restoration Movement: Diverse Cultures of Practice and Place." Organization & Environment 22 (2): 185–207. https://doi.org/10.1177/1086026609338165.

Turner, R. Kerry, Jeroen C. J. M. van den Bergh, Tore Söderqvist, Aat Barendregt, Jan van der Straaten, Edward Maltby, and Ekko C. van Ierland. 2000. "Ecological-Economic Analysis of Wetlands: Scientific Integration for Management and Policy." Ecological Economics 35 (1): 7–23. https://doi.org/10.1016/S0921-8009(00)00164-6.

United States Department of Agriculture. 2023. "Managing Water for Increased Resiliency of Drained Agricultural Landscapes." 2023. https://transformingdrainage.org/.

United States Geological Survey. 2009. "Multi-Resolution Land Characteristics (MRLC) Consortium." Data Set. https://www.mrlc.gov/contact-us.

Urry, Allan. 2016. "After the Floods: York and Nijmegen - a Tale of Two Cities." BBC News, February 9, 2016, sec. England. https://www.bbc.com/news/uk-england-35472936.

US Army Corps of Engineers. 2008. "Upper Mississippi Comprehensive Plan." Main Report. US Army Corps of Engineers. https://www.mvr.usace.army.mil/Missions/Flood-Risk-Management/Upper-Mississippi-Comprehensive-Plan/.

US Census Bureau. 2022. "U.S. Census Bureau Chehalis City, Washington." 2022. https://www.census.gov/quickfacts/fact/table/chehaliscitywashington#.

US EPA, OAR. 2015. "Greenhouse Gas Equivalencies Calculator." Data and Tools. August 28, 2015. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

US EPA. 2016a. "A Closer Look: Land Loss Along the Atlantic Coast." Reports and Assessments. June 27, 2016. https://www.epa.gov/climate-indicators/atlantic-coast.

US EPA. 2016b. "Climate Change Indicators: River Flooding." Reports and Assessments. July 1, 2016. https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding.

US EPA. 2022. "Climate Change and the Health of Indigenous Populations." Overviews and Factsheets. March 21, 2022. https://www.epa.gov/climateimpacts/climate-change-and-health-indigenous-populations.

US EPA, OP. 2013. "National Environmental Policy Act Review Process." Overviews and Factsheets. July 31, 2013. https://www.epa.gov/nepa/national-environmental-policy-act-review-process.

US EPA, ORD. 2022. "Green and Gray Infrastructure Research." Overviews and Factsheets. January 5, 2022. https://www.epa.gov/water-research/green-and-gray-infrastructure-research.

USGS. Various. "USGS Current Conditions for USGS 12020800." Various. https://waterdata.usgs.gov/nwis/uv?site_no=12020800&legacy=1.

USGS. n.d. "USGS Current Conditions for Washington_ Streamflow." Accessed February 21, 2023. https://waterdata.usgs.gov/wa/nwis/current/?type=flow.

Vano, Julie A., Bart Nijssen, and Dennis P. Lettenmaier. 2015. "Seasonal Hydrologic Responses to Climate Change in the Pacific Northwest." Water Resources Research 51 (4): 1959–76. https://doi.org/10.1002/2014WR015909.

Veloz, Samuel D., Nadav Nur, Leonardo Salas, Dennis Jongsomjit, Julian Wood, Diana Stralberg, and Grant Ballard. 2013. "Modeling Climate Change Impacts on Tidal Marsh Birds: Restoration and Conservation Planning in the Face of Uncertainty." Ecosphere 4 (4): art49. https://doi.org/10.1890/ES12-00341.1.

Vidon, Philippe G., and Alan R. Hill. 2006. "A Landscape-Based Approach to Estimate Riparian Hydrological and Nitrate Removal Functions1." JAWRA Journal of the American Water Resources Association 42 (4): 1099–1112. https://doi.org/10.1111/j.1752-1688.2006.tb04516.x.

WA Dpt of Ecology. 2023. "Washington State Department of Natural Resources GIS Open Data." 2023. https://data-wadnr.opendata.arcgis.com/.

WA Dpt of Ecology. "Draft SEPA for Proposed Chehalis River Basin Flood Damage Reduction Project." Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/2006002.html.

WA Dpt of Ecology. 2023. "LAND Preliminary Alternatives Summary." https://www.chehalisbasinland.com/.

WA Dpt of Ecology. n.d. "Flow Monitoring Network Application." Flow Monitoring Network. Accessed February 21, 2023. https://apps.ecology.wa.gov/continuousflowandwq/.

Wall, Susan. 2011. "Efficacy of Riparian Revegetation Projects in the Inland Pacific Northwest." Graduate Student Theses, Dissertations, & Professional Papers, January. https://scholarworks.umt.edu/etd/365.

Walters, Kelli M., and Meghna Babbar-Sebens. 2016. "Using Climate Change Scenarios to Evaluate Future Effectiveness of Potential Wetlands in Mitigating High Flows in a Midwestern U.S. Watershed." Ecological Engineering 89 (April): 80–102. https://doi.org/10.1016/j.ecoleng.2016.01.014.

Washington State Department of Ecology. 2020. "SEPA Cultural Resources Discipline Report."

Watson, Keri B., Taylor Ricketts, Gillian Galford, Stephen Polasky, and Jarlath O'Niel-Dunne. 2016. "Quantifying Flood Mitigation Services: The Economic Value of Otter Creek Wetlands and Floodplains to Middlebury, VT." Ecological Economics 130 (October): 16–24. https://doi.org/10.1016/j.ecolecon.2016.05.015.

Wheaton, Joseph, Stephen Bennett, Nick Bouwes, Jeremy Maestas, and Scott Shahverdian. 2019. Low-Tech Process-Based Restoration of Riverscapes: Design Manual. Version 1.0. https://doi.org/10.13140/RG.2.2.19590.63049/2.

Williams, David B. 2021. Homewaters: A Human and Natural History of the Puget Sound. 1st ed. University of Washington Press.

Williams, Jack E., and Gordon H. Reeves. 2006. "Stream Systems." In Restoring the Pacific Northwest, 298–318. Society for Ecological Restoration International and Island Press.

Winkler, R., R. Moore, Todd Redding, D. Spittlehouse, and Brian Smerdon. 2010. "The Effects of Forest Disturbance on Hydrologic Processes and Watershed Response, Chapter 7." In Compendium of Forest Hydrology and Geomorphology in Briticsh Columbia, 179–212.

World Commission on Dams. 2020. "Dams and Development: A New Framework for Decision-Making." World Commission on Dams. https://archive.internationalrivers.org/resources/dams-and-development-a-new-framework-for-decision-making-3939.

WS-DOT. 2014. "Chehalis River Basin I-5 Flood Protection Near Centralia and Chehalis." WS-DOT.

Wu, Haiming, Jian Zhang, Peizhi Li, Jinyong Zhang, Huijun Xie, and Bo Zhang. 2011. "Nutrient Removal in Constructed Microcosm Wetlands for Treating Polluted River Water in Northern China." Ecological Engineering 37 (4): 560–68. https://doi.org/10.1016/j.ecoleng.2010.11.020.

Wu, Yanfeng, Guangxin Zhang, Alain N. Rousseau, Y. Jun Xu, and Étienne Foulon. 2020. "On How Wetlands Can Provide Flood Resilience in a Large River Basin: A Case Study in Nenjiang River Basin, China." Journal of Hydrology 587 (August): 125012. https://doi.org/10.1016/j.jhydrol.2020.125012.

Yoo, Jaeyoung, Jinhyun Kim, Jaegeun Kim, Jeongcheol Lim, and Hojeong Kang. 2022. "Soil Carbon Storage and Its Economic Values of Inland Wetlands in Korea." Ecological Engineering 182 (September): 106731. https://doi.org/10.1016/j.ecoleng.2022.106731.

Yuan, Yongping, Ronald L. Bingner, and Martin A. Locke. 2009. "A Review of Effectiveness of Vegetative Buffers on Sediment Trapping in Agricultural Areas." Ecohydrology 2 (3): 321–36. https://doi.org/10.1002/eco.82.

Zang, Zheng. 2019. "Analysis of Intrinsic Value and Estimating Losses of 'Blue Carbon' in Coastal Wetlands: A Case Study of Yancheng, China." Ecosystem Health and Sustainability 5 (1): 216–25. https://doi.org/10.1080/20964129.2019.1673214.

Zedler, Joy B. 2003. "Wetlands at Your Service: Reducing Impacts of Agriculture at the Watershed Scale." Frontiers in Ecology and the Environment 1 (2): 65–72. https://doi.org/10.1890/1540-9295(2003)001[0065:WAYSRI]2.0.CO;2.

Zhang, Jian, Chunling Zhang, Wanli Shi, and Yicheng Fu. 2019. "Quantitative Evaluation and Optimized Utilization of Water Resources-Water Environment Carrying Capacity Based on Nature-Based Solutions." Journal of Hydrology 568 (January): 96–107. https://doi.org/10.1016/j.jhydrol.2018.10.059.

Zhang, Xuyang, Xingmei Liu, Minghua Zhang, Randy A. Dahlgren, and Melissa Eitzel. 2010. "A Review of Vegetated Buffers and a Meta-Analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution." Journal of Environmental Quality 39 (1): 76–84. https://doi.org/10.2134/jeq2008.0496.

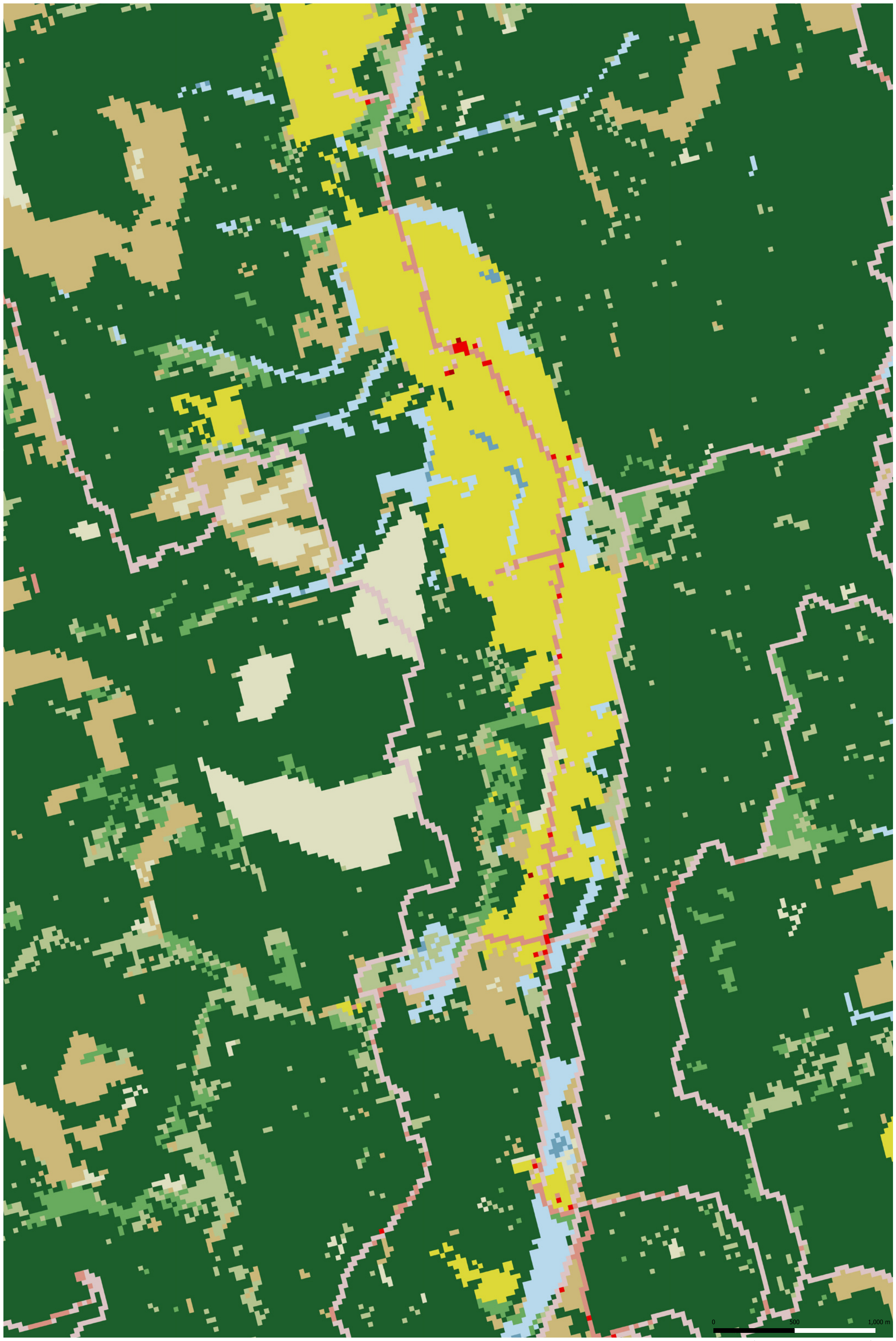
Zhao, Mengqi, Jan Boll, and Erin S. Brooks. 2021. "Evaluating the Effects of Timber Harvest on Hydrologically Sensitive Areas and Hydrologic Response." Journal of Hydrology 593 (February): 125805. https://doi.org/10.1016/j.jhydrol.2020.125805.

Zimmerman, Olivia. 2022. "Floodplains for Whom?" ArcGIS StoryMaps. June 23, 2022. https://storymaps.arcgis.com/stories/1f3b040033a24e10bb14eabb9e6d6a1a.

Zimmerman, Olivia. 2022. "Centering Indigenous Perspectives in Floodplain Management." Nwcasc.Uw.Edu. Accessed April 28, 2023. https://nwcasc.uw.edu/science/project/centering-indigenous-perspectives-in-floodplain-management/.

Appendix A

South Fork of the Chehalis River
Site Information



(NLCD 2019)

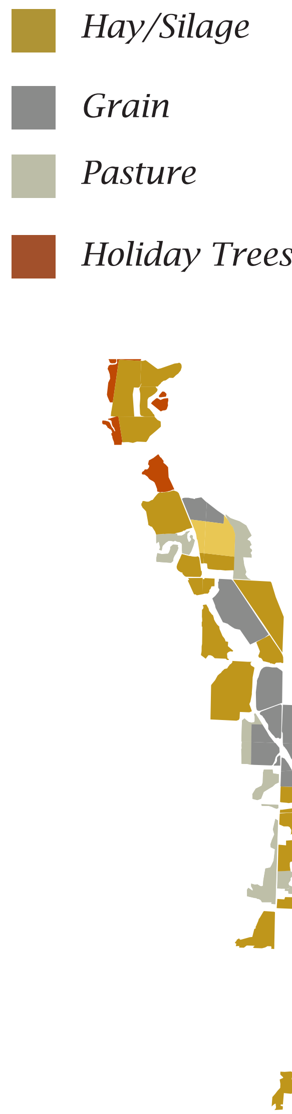
Figure 207 - National Land Cover Data of Site

Agriculture	*Light Vegetation*	*Developed Area*
Cleared Forest	*Dense Vegetation*	*Road*

Figure 208 -

(L) Erosion Hazard **(R) Crops**

(WA DNR)



(WA DNR)

Figure 209 -

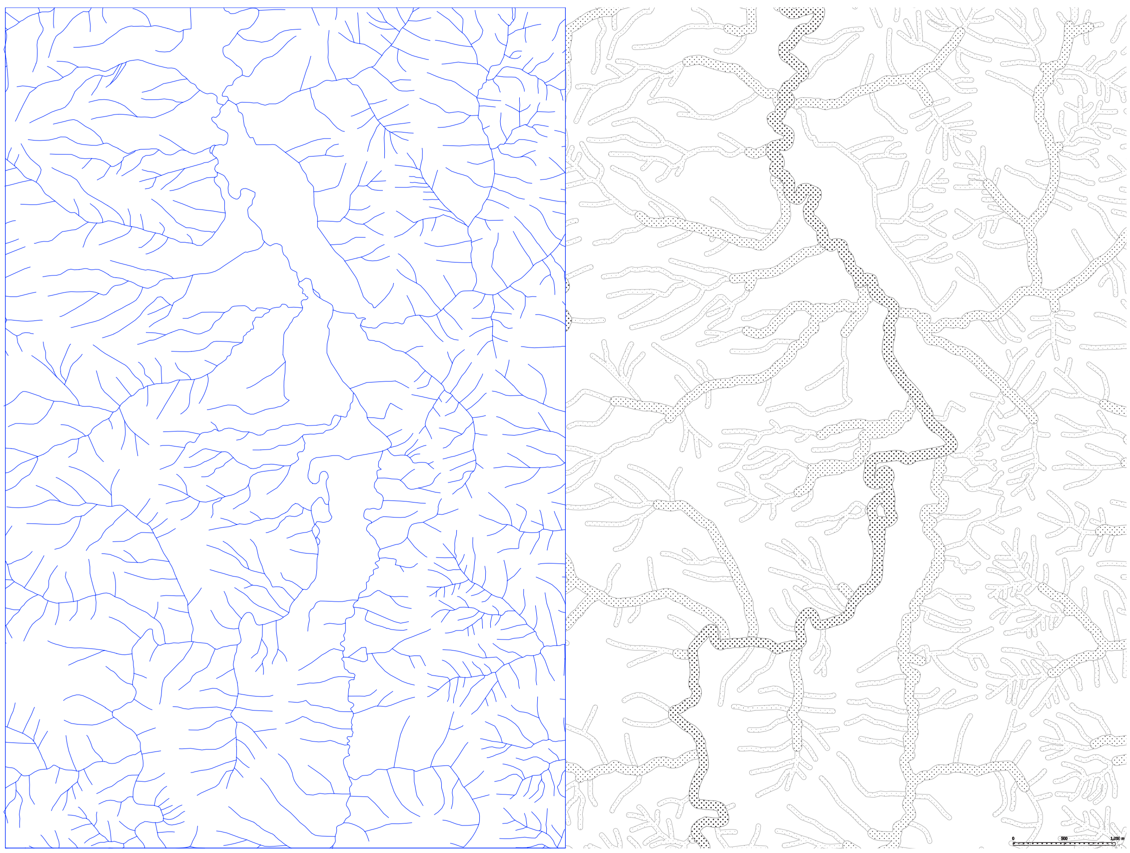
(L) **Watercourses**

(R) **Hydrological Buffers**

75' Non-Fish

150' Fish

150' Shoreline



(WA DNR) *(Lewis County)*

Figure 210 -

(L) **Soil Permeability**

High

Moderate

Low

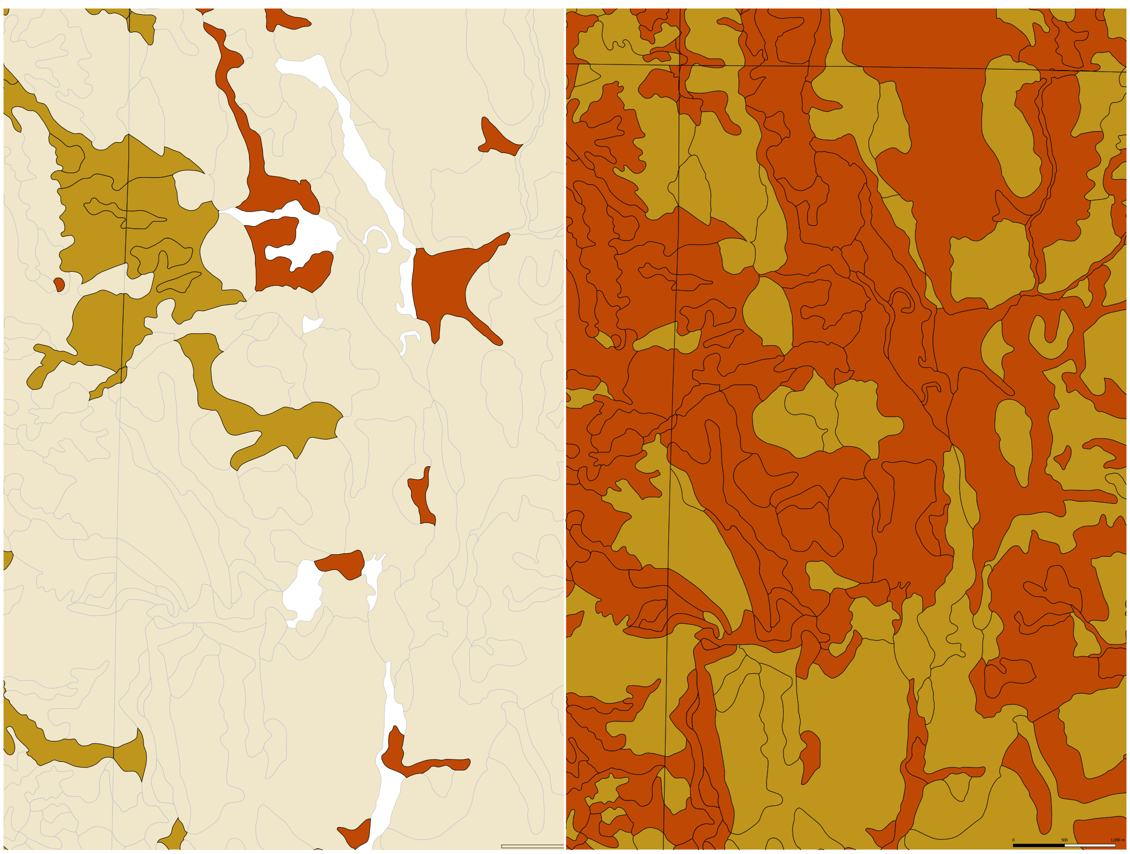
Very Low

(R) **Soil Texture**

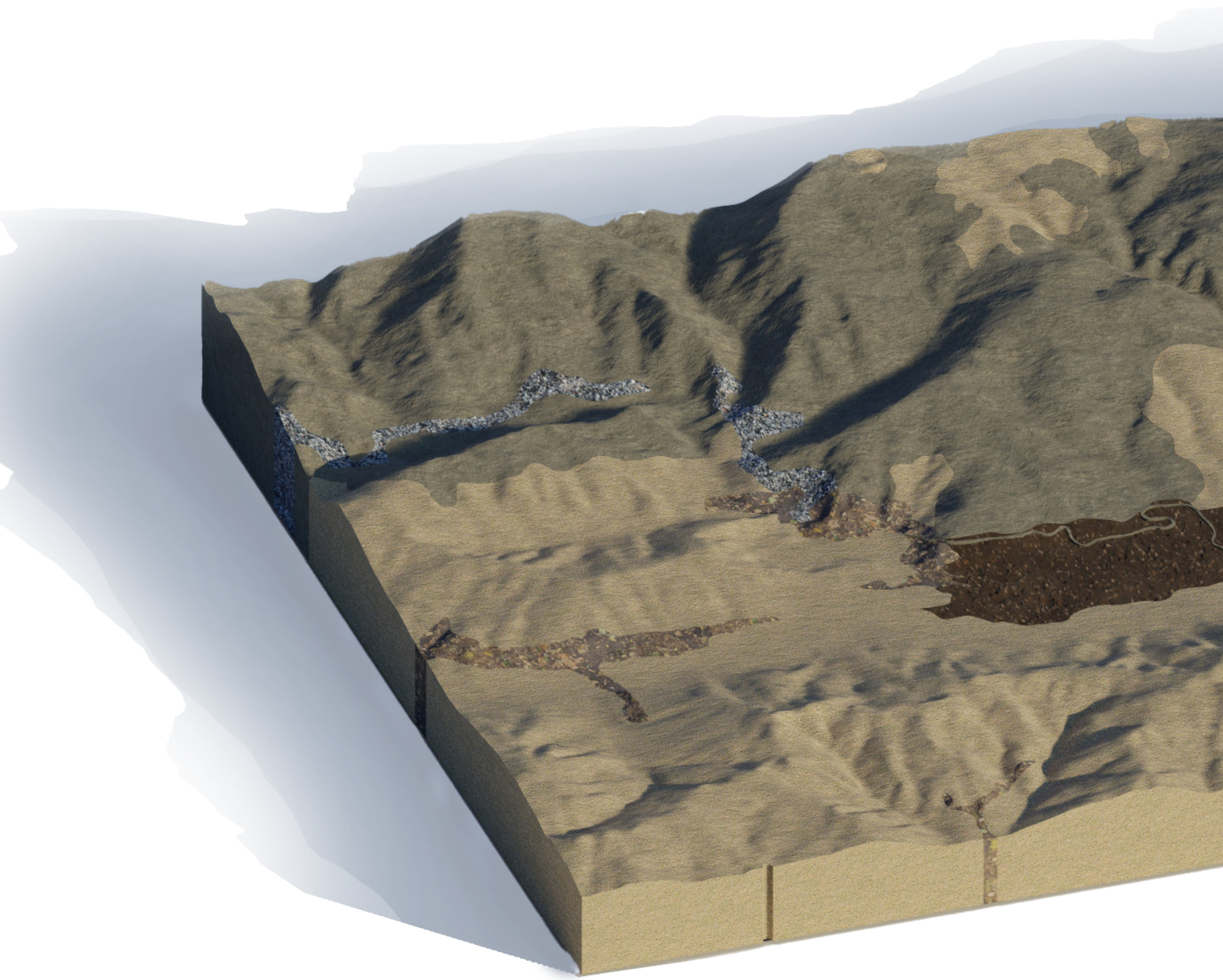
Silt

Clay

Gravel, sand, and loams are present in negligible amounts.



(WA DNR) *(WA DNR)*



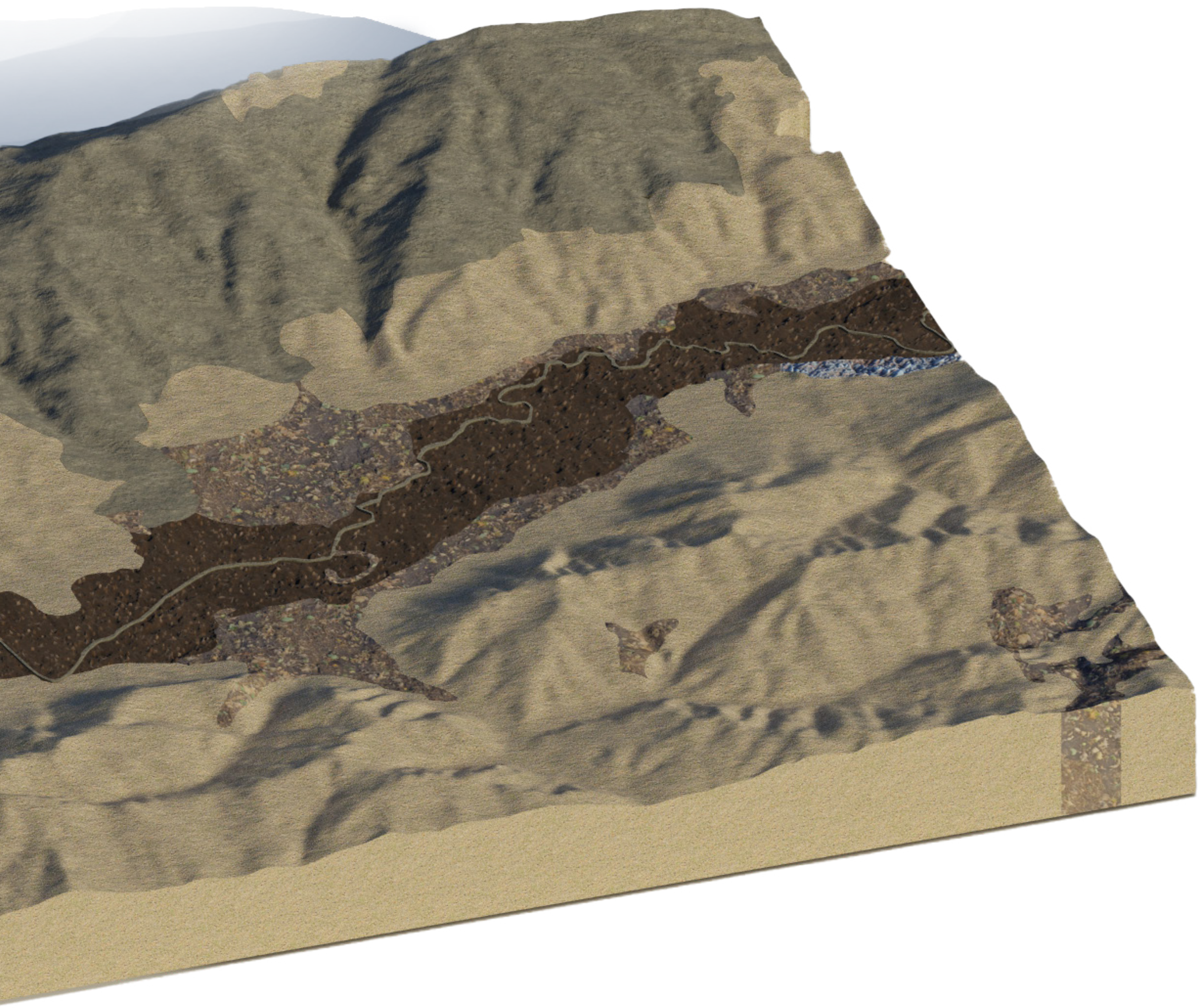


Figure 212 - Soil Types

This graphic depicts the soil types on site. Different textures and colors correspond to soil series.

Appendix B

Additional HEC-RAS Modeling Data

Figure 215 - Satellite Imagery of Reach

Visual imagery such as this helped to define the model. Data was frequently input, modified, or cross-referenced with several layers of information.
(USGS)


'LCLayer2'
1 mi

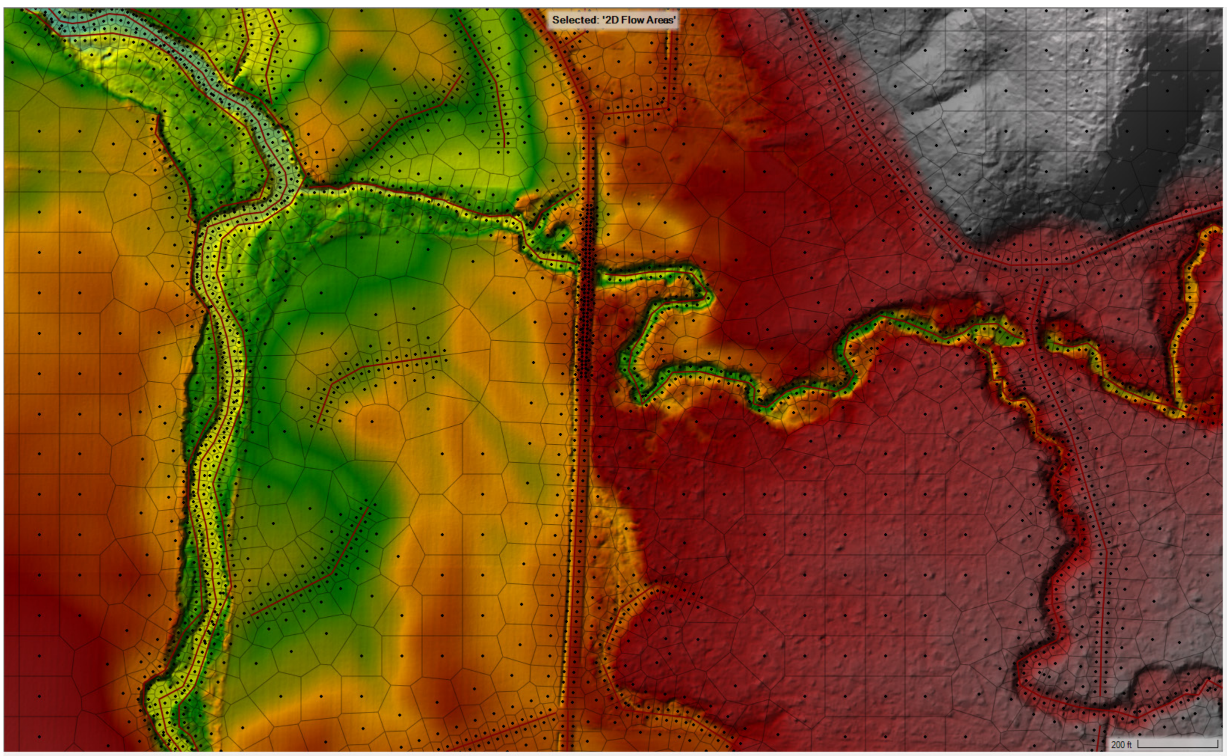


Figure 217 - Breakline and Mesh Modification

Example closeup of area on site where the breaklines modify the calculating mesh. Note how the regularity of the mesh is disrupted by the red lines, which represent the breaklines.

Figure 218 - Breakline Modifications

This demonstrates the manually-input breaklines in the HEC-RAS model. These breaklines disrupt and tune the calculation mesh on the landscape.

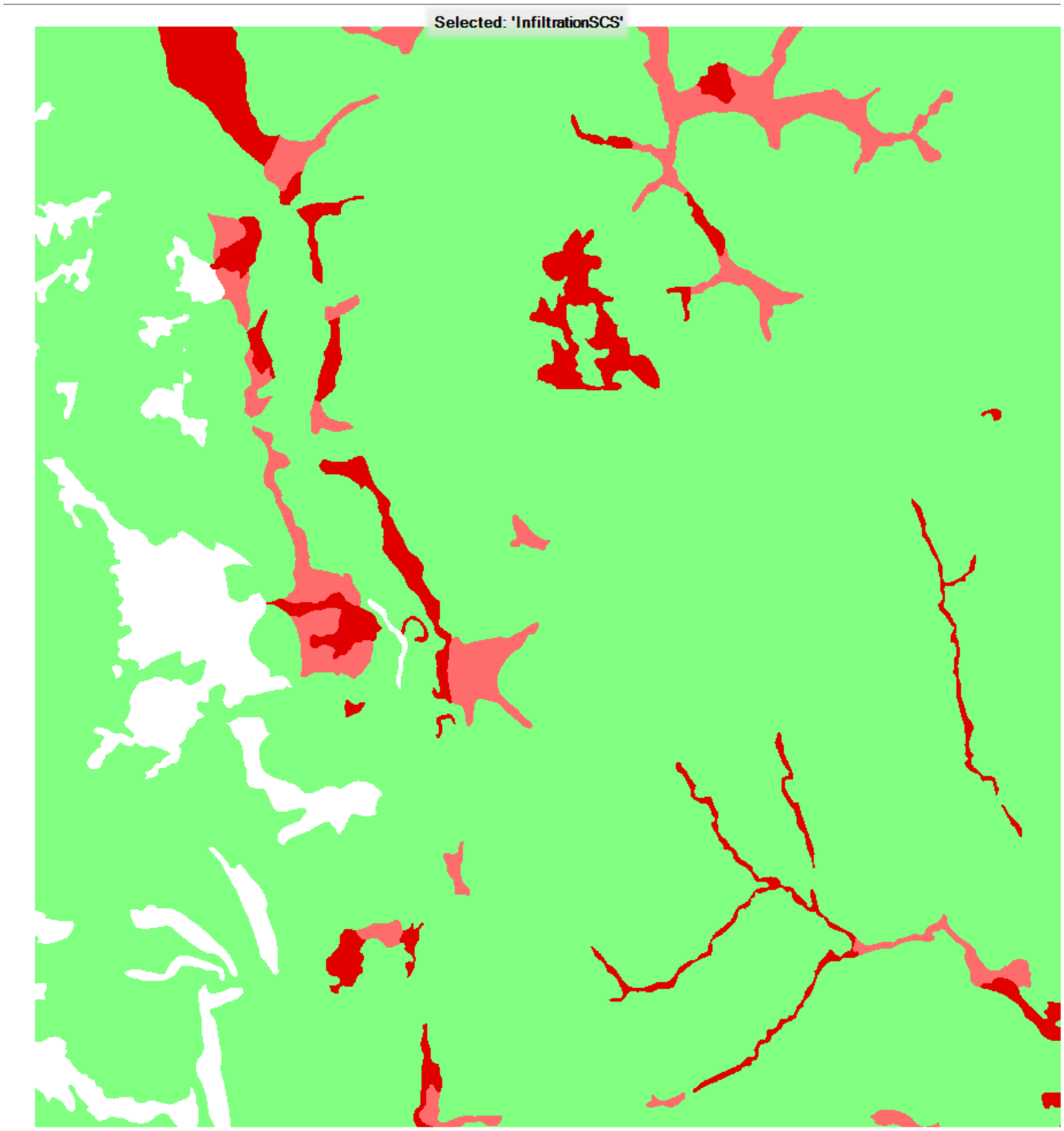


Figure219 - National Land Cover Data of Site

Soil Infiltration rates were based on the USGS soil data. On this map, areas of high rates or "good" infiltration are green, where red hues are areas of poor infiltration.

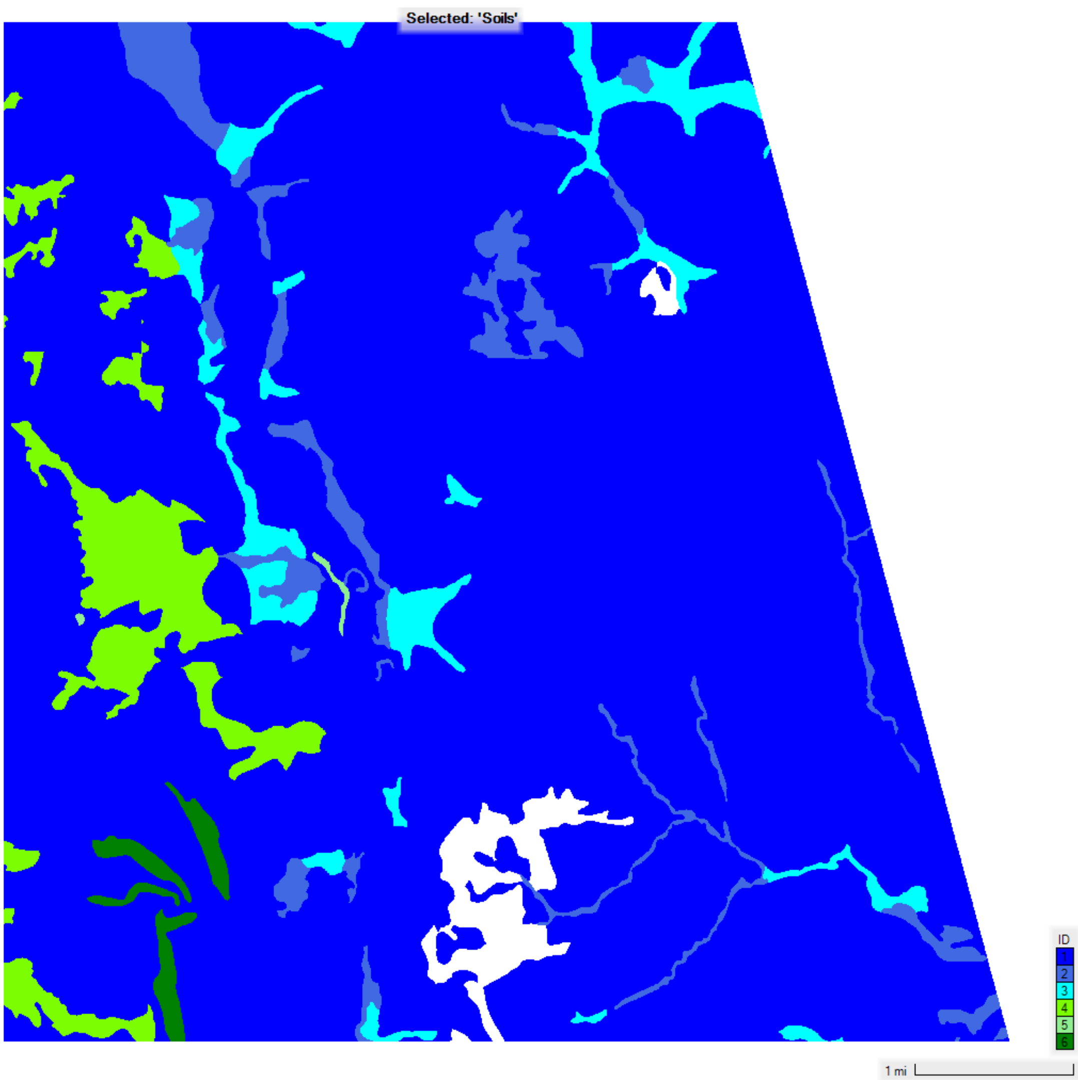


Figure 220 - Soil Types

GIS data from USGS on soil types within the area. This data was used to modify soil performance parameters within the model.
(USGS)

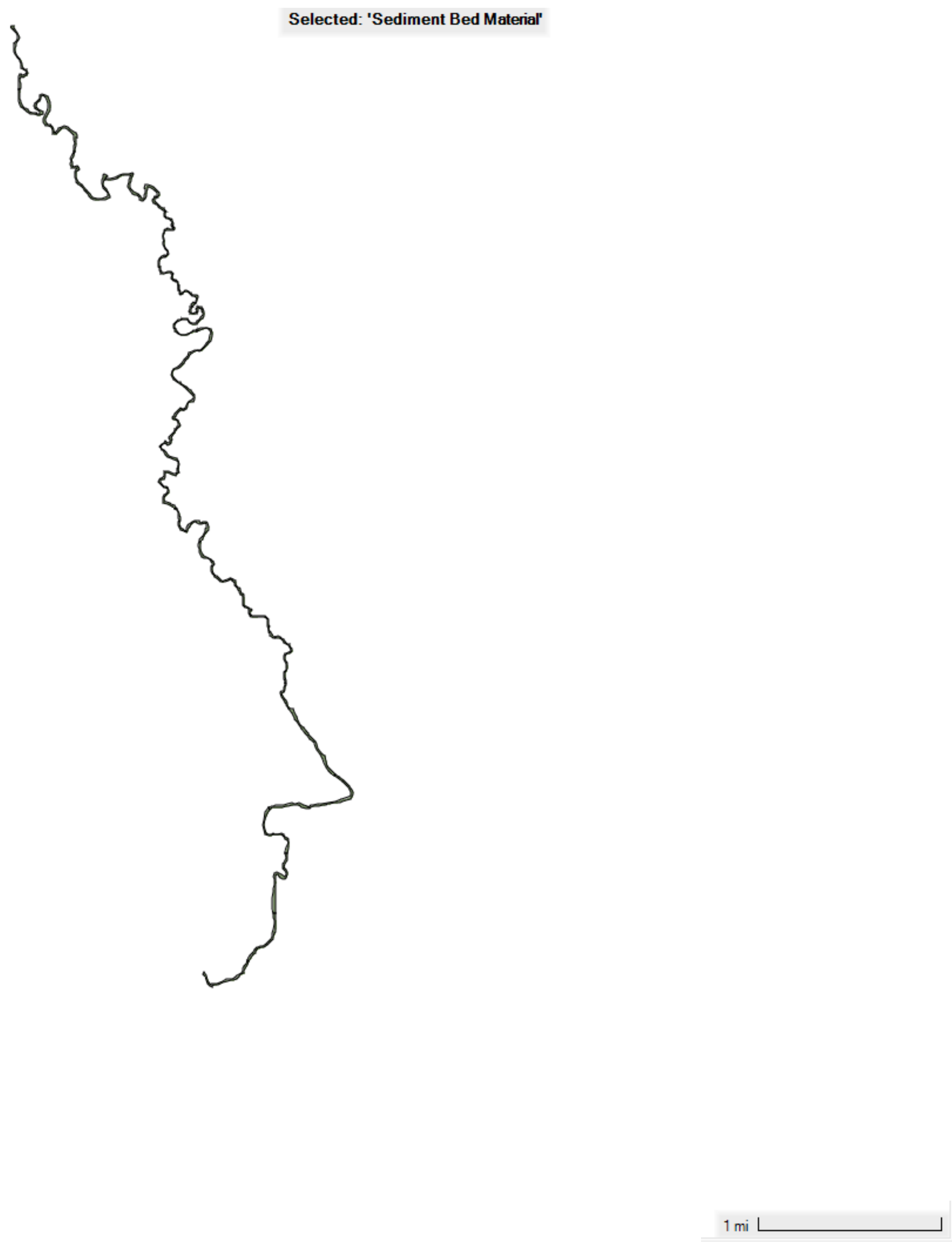


Figure 221 - Sediment Bed Material

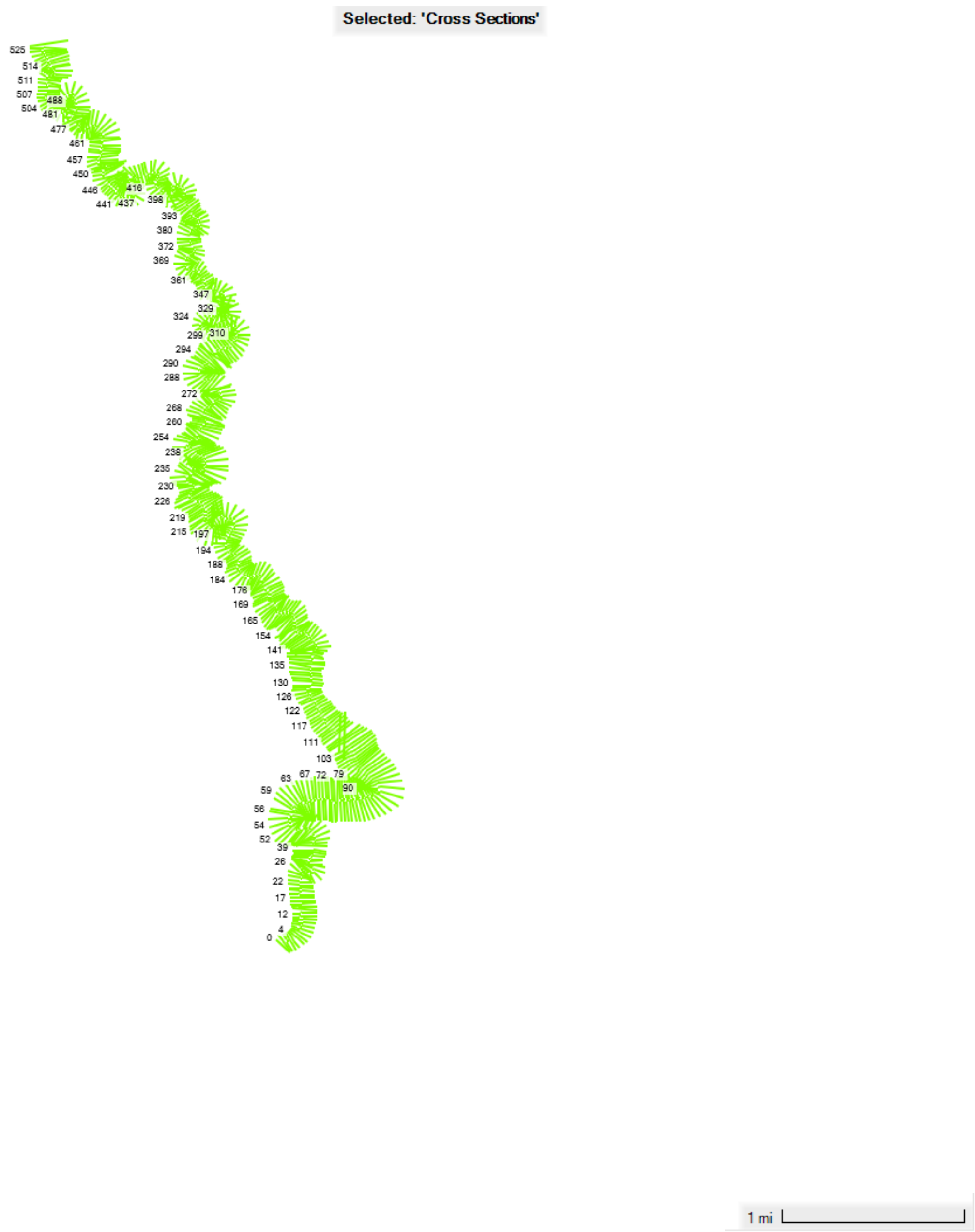


Figure 222 - Total Cross Section Illustation

The model used cross section of the river to help calculations within the primary channel. It interpolated the terrain characteristics between the cross section transects. There were a total of 525 generated cross sections.

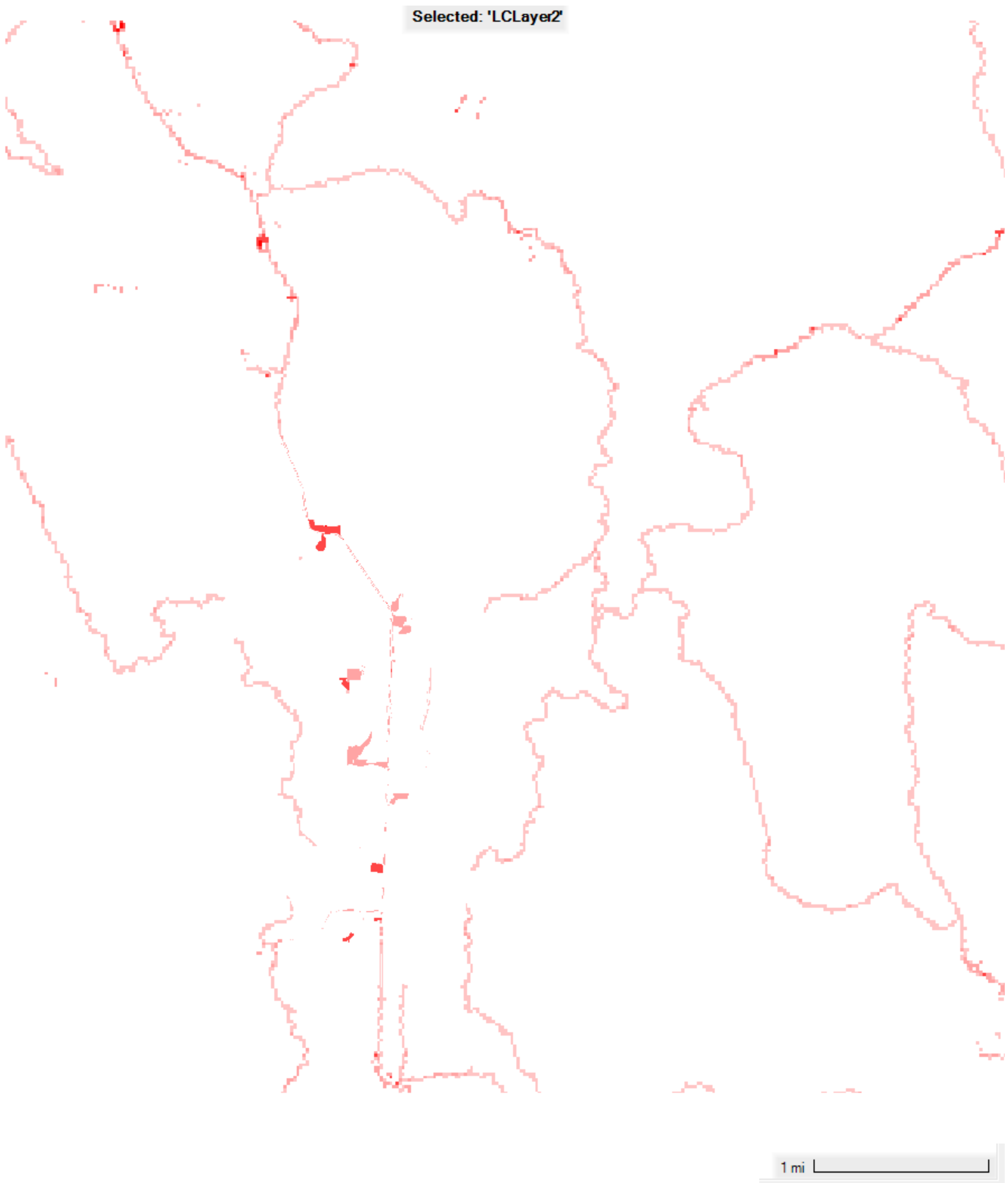


Figure 223 - Impervious Surfaces

National Land Cover Data of site informed the attribution of impervious areas. While it was not significant in this area, urban areas would demonstrate higher levels of imperviousness.

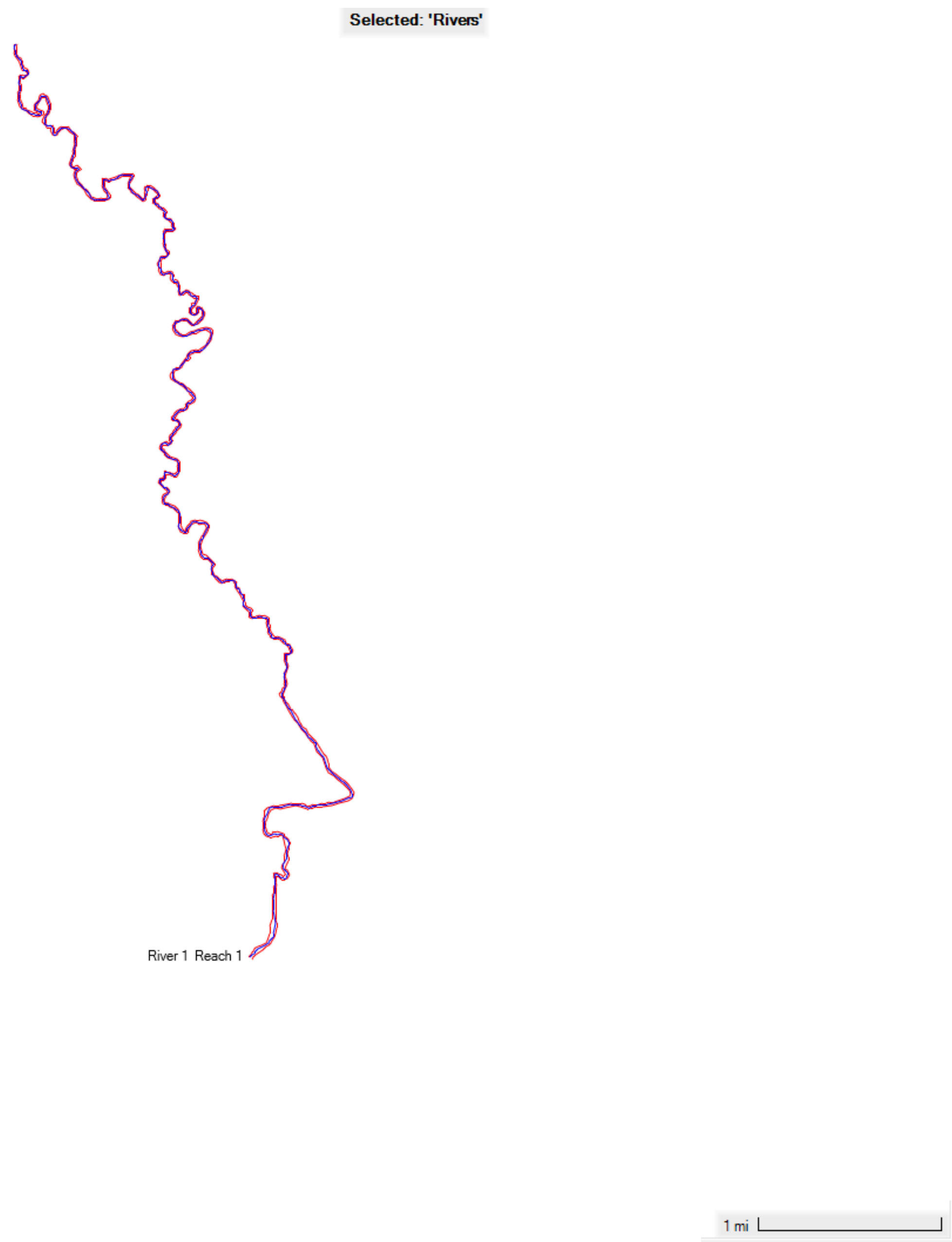


Figure224 - River Channel Polygons

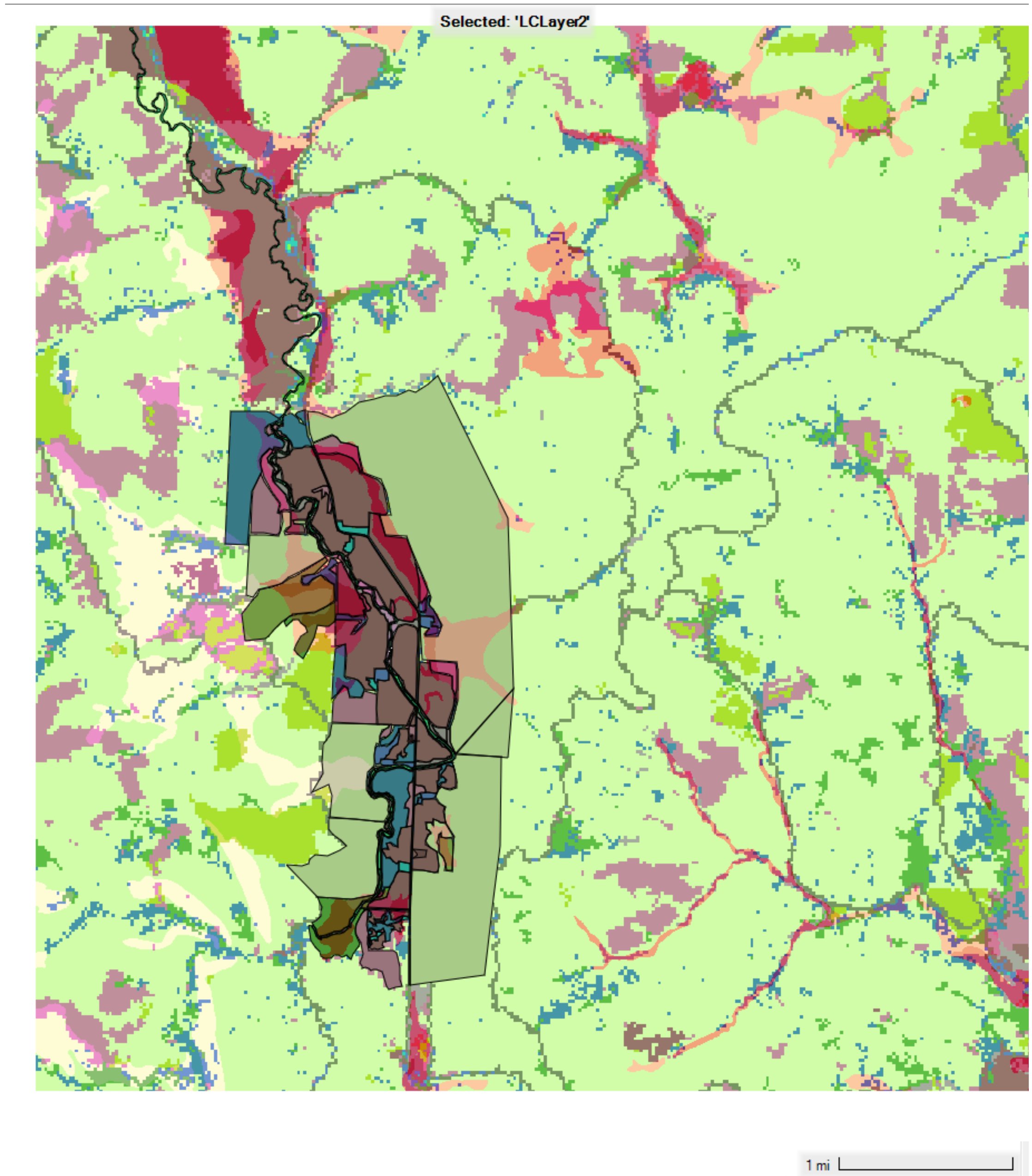


Figure 225 - Manning's Values Colored by Land Use Type

The data for Manning's Values are based on the land use and character of the site. This was determined by GIS mapping, satellite data, and manual entry.

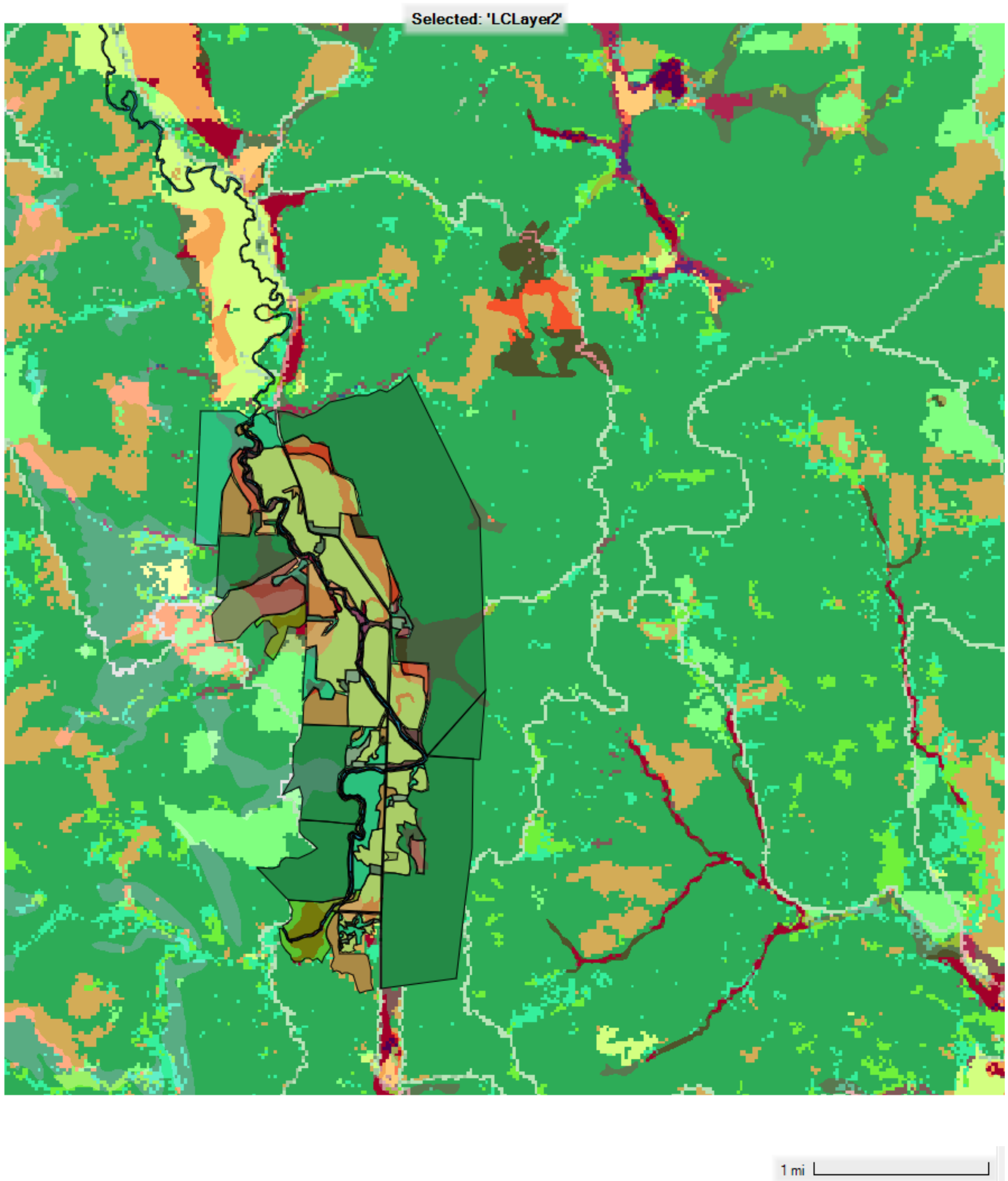


Figure 226 - Manning's Values Colored by n value

Manning's values are displayed here in a spectrum from green to red. Green being areas of high roughness, and red being areas of low roughness. The polygons in the reach area are areas of modificiation from the interventions.

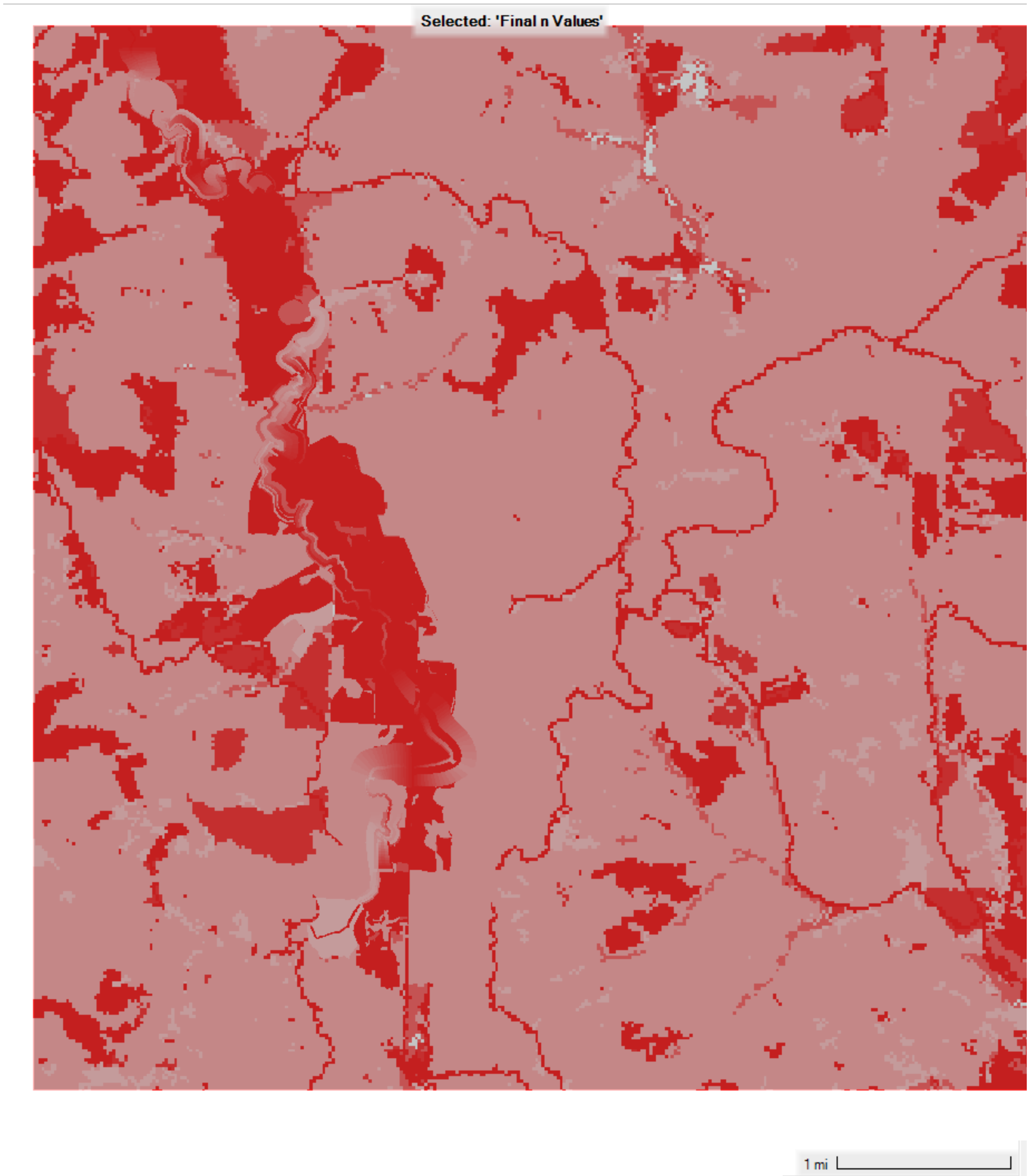


Figure 227 - Manning's Values - Monochromatic

Monochromatic mapping allows for generation of heightmaps using software such as Rhino.

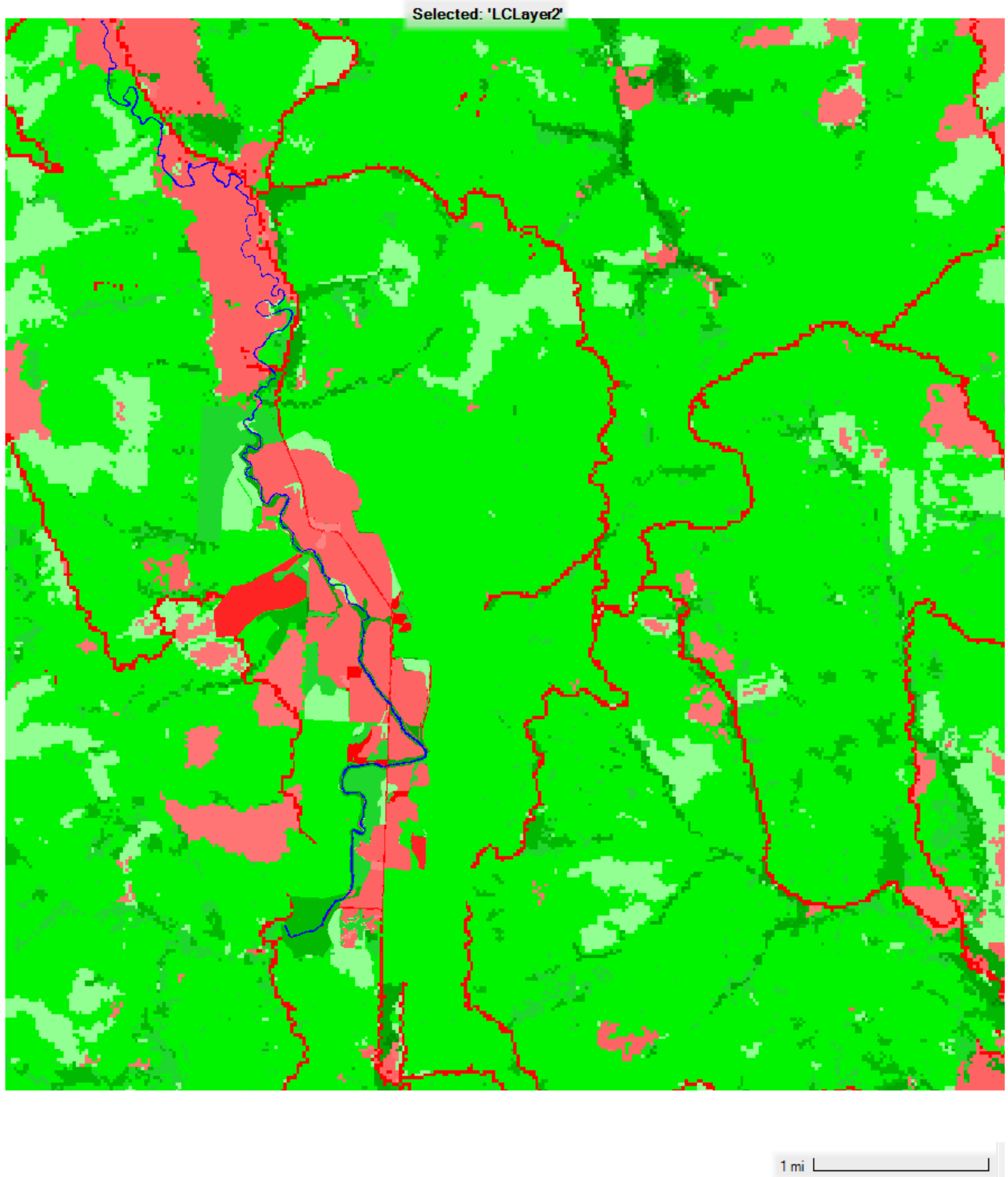
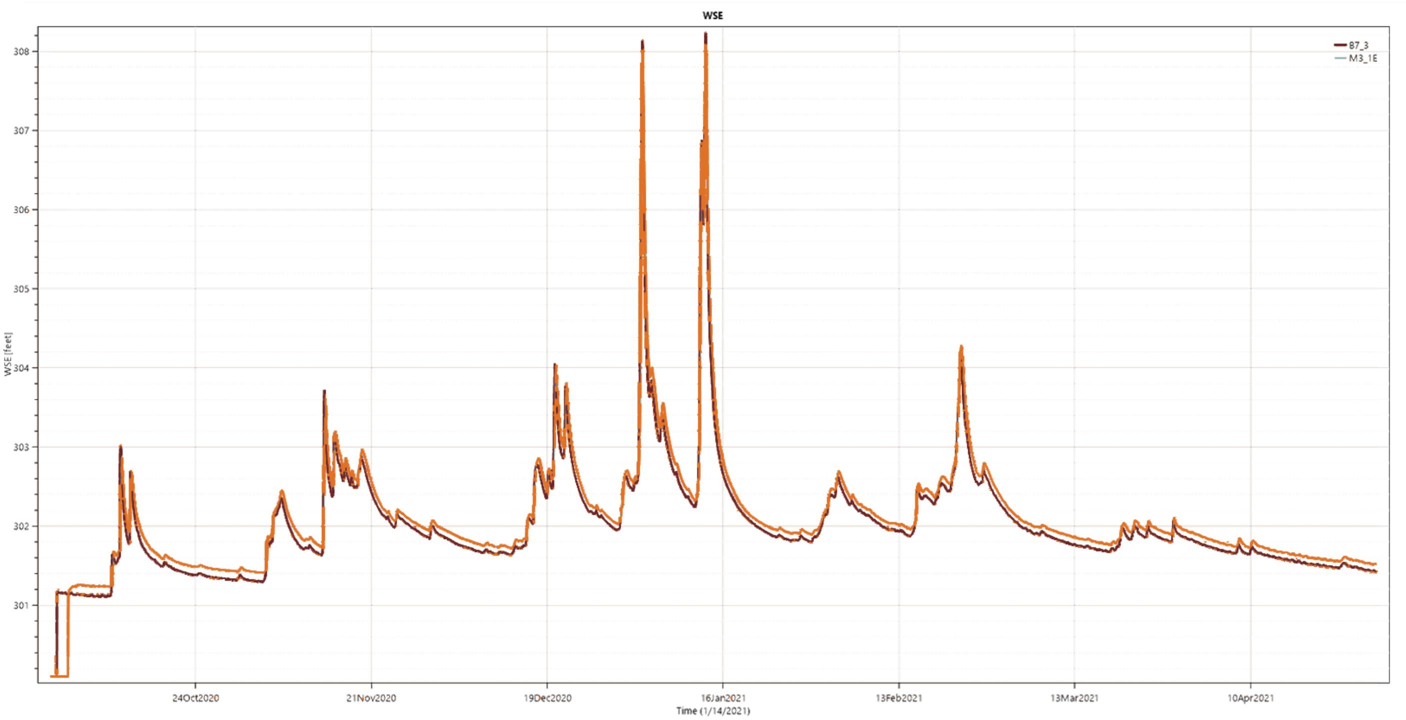


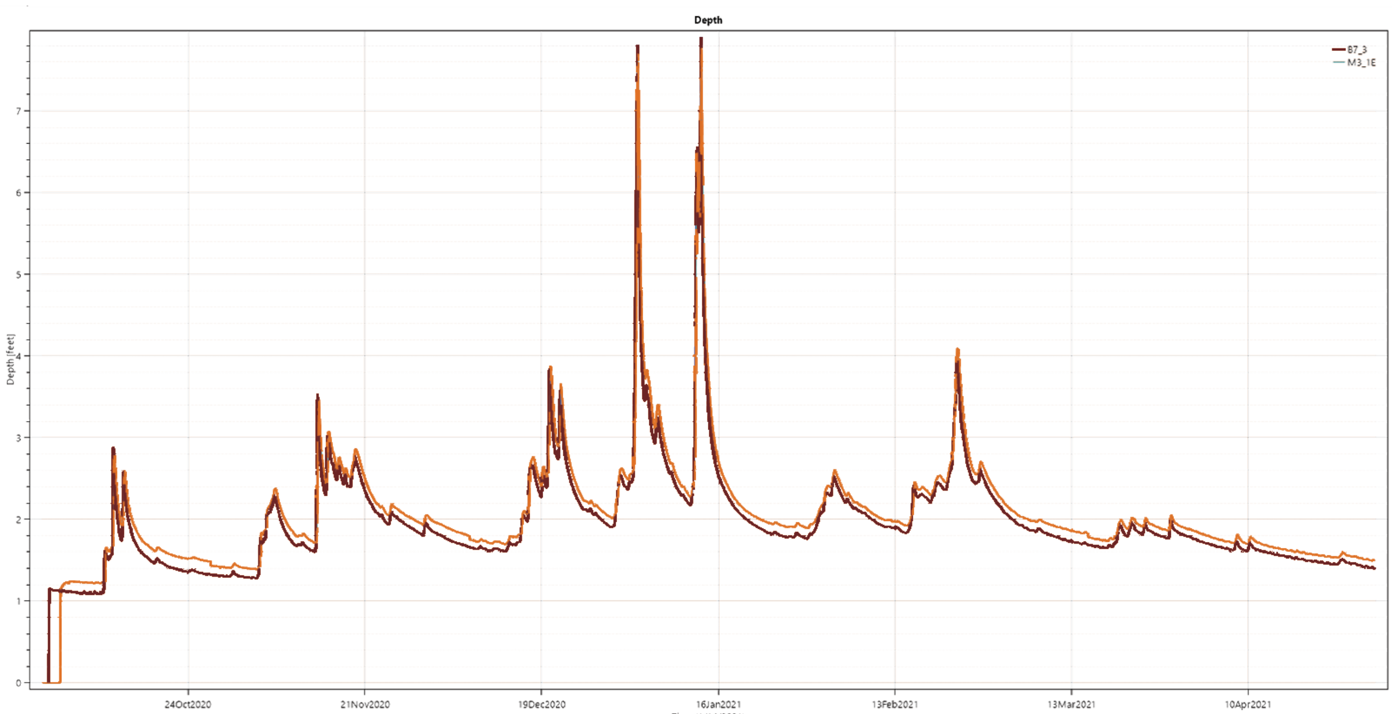
Figure 228 - Manning's Values - Two Colors

Appendix C

Additional HEC-RAS Example Results

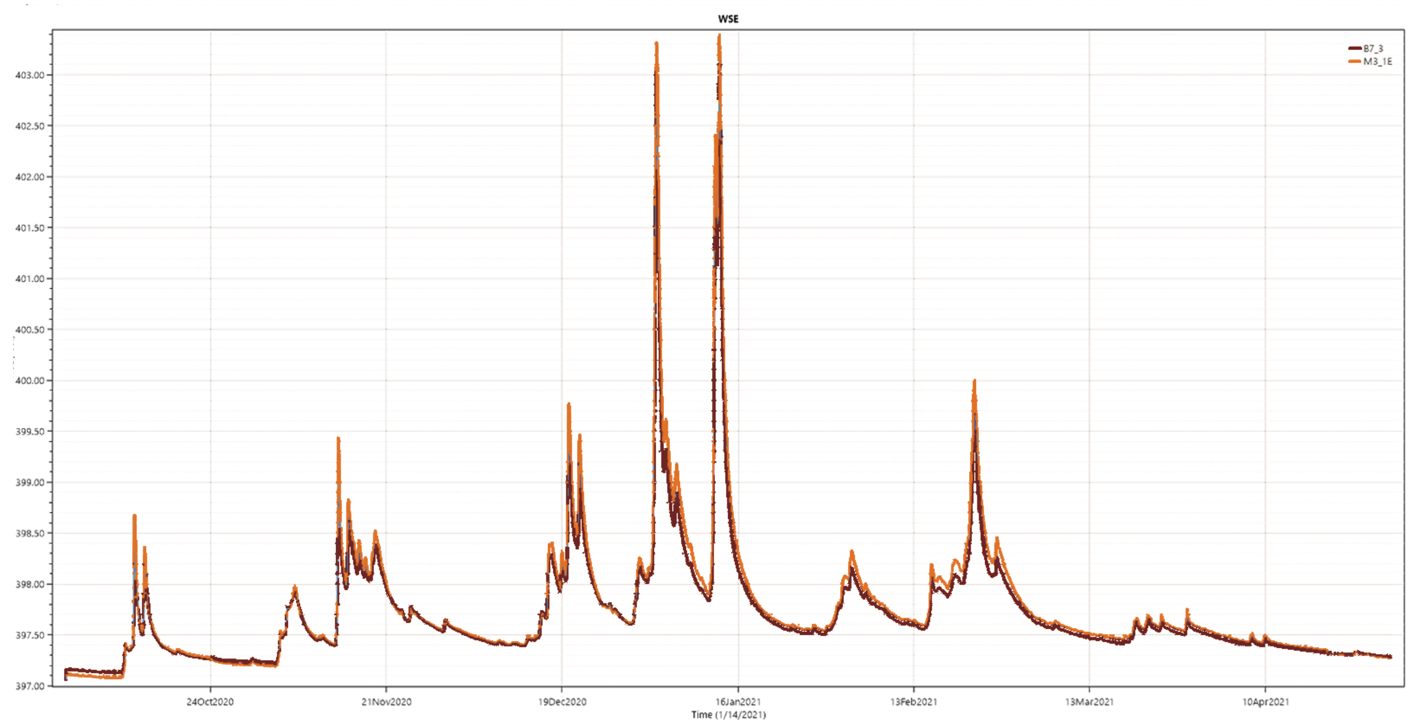


Water Surface Elevation - XC 8

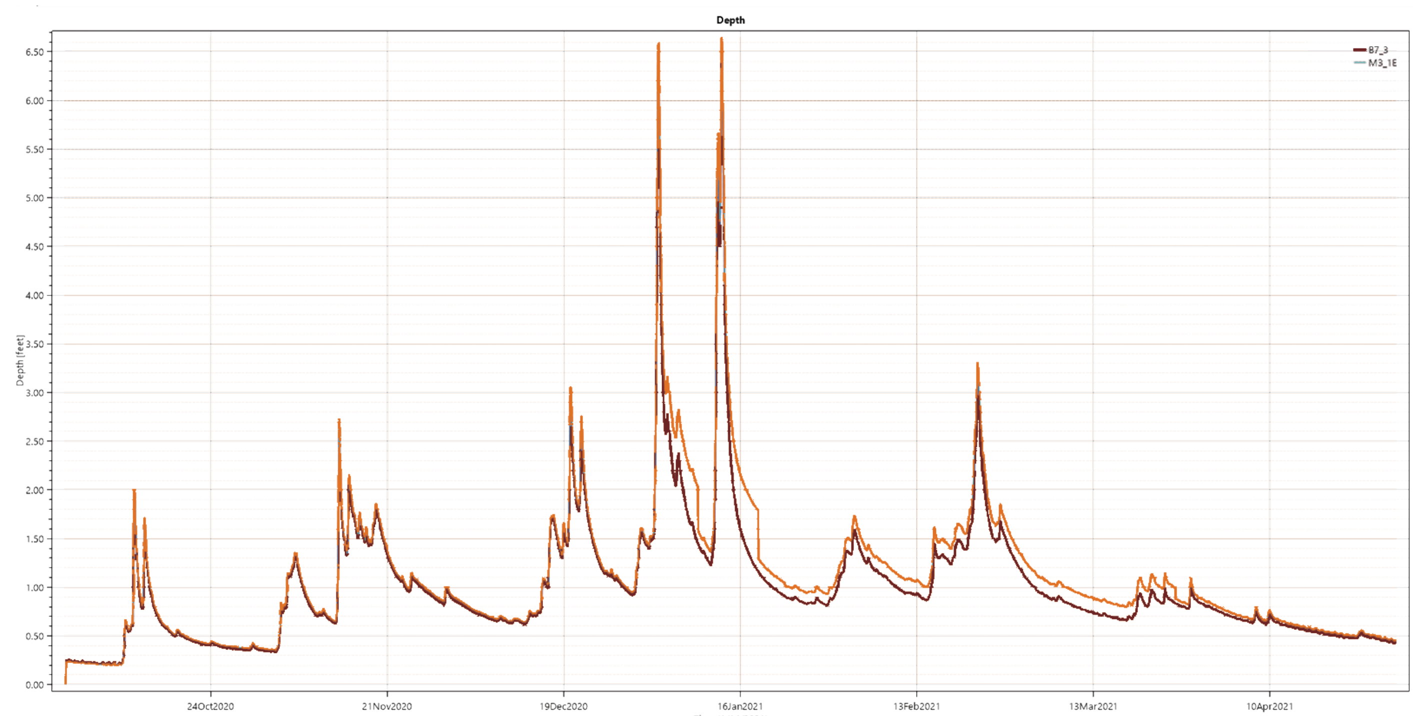


Water Depth - XC 8

Unmodified
Modified



Water Surface Elevation - XC 1



Water Depth - XC 1

Unmodified
Modified

Ordinate	Time and Date	Stage- M 4_1 Elevation (ft)	Flow- M 4_1 Flow (CFS)	Stage- M 4_5 Elevation (ft)	Flow- M 4_5 Flow (CFS)	Stage- M 4_10 Elevation (ft)	Flow- M 4_10 Flow (CFS)	Stage- M 4_15 Elevation (ft)	Flow- M 4_15 Flow (CFS)
0	29Sep2020 2400	403.4	500	403.4	500	403.4	500	403.4	500
1	30Sep2020 0100	405	500	404.12	500	404.12	500	404.12	500
2	30Sep2020 0200	401.74	500	402.04	500	402.04	500	402.04	500
3	30Sep2020 0300	403.29	500	401.35	500	401.35	500	401.35	500
4	30Sep2020 0400	403.25	500	404.19	500	404.19	500	404.19	500
5	30Sep2020 0500	403.18	500	405.63	500	405.63	500	405.63	500
6	30Sep2020 0600	402.77	500	411.46	500	411.46	500	411.46	500
7	30Sep2020 0700	402.26	500	402.7	500	402.7	500	402.7	500
8	30Sep2020 0800	401.23	500	403.35	500	403.35	500	403.35	500
9	30Sep2020 0900	402.9	500	403.93	500	403.93	500	403.93	500
10	30Sep2020 1000	403.31	500	402.34	500	402.34	500	402.34	500
11	30Sep2020 1100	406.72	500	401.34	500	401.34	500	401.34	500
12	30Sep2020 1200	411.7	500	401.82	500	401.82	500	401.82	500
13	30Sep2020 1300	404.62	500	408.51	500	408.51	500	408.51	500
14	30Sep2020 1400	406.12	500	406.48	500	406.48	500	406.48	500
15	30Sep2020 1500	403.06	500	403.9	500	403.9	500	403.9	500
16	30Sep2020 1600	409.87	500	404.13	500	404.13	500	404.13	500
17	30Sep2020 1700	404.13	500	408.17	500	408.17	500	408.17	500
18	30Sep2020 1800	403.16	500	403.04	500	403.04	500	403.04	500
19	30Sep2020 1900	402.19	500	402.81	500	402.81	500	402.81	500
20	30Sep2020 2000	402.33	500	402.05	500	402.05	500	402.05	500
21	30Sep2020 2100	402.55	500	402.24	500	402.24	500	402.24	500
22	30Sep2020 2200	401.95	500	402.98	500	402.98	500	402.98	500
23	30Sep2020 2300	403.45	500	403.03	500	403.03	500	403.03	500
24	30Sep2020 2400	408.37	500	407.54	500	407.54	500	407.54	500
25	01Oct2020 0100	404.11	500	402.23	500	402.23	500	402.23	500
26	01Oct2020 0200	404.73	500	406.37	500	406.37	500	406.37	500
27	01Oct2020 0300	403.5	500	407.93	500	407.93	500	407.93	500
28	01Oct2020 0400	404.18	500	402.86	500	402.86	500	402.86	500
29	01Oct2020 0500	402.17	500	407.64	500	407.64	500	407.64	500
30	01Oct2020 0600	403.64	500	401.48	500	401.48	500	401.48	500
31	01Oct2020 0700	408.46	500	404.95	500	404.95	500	404.95	500
32	01Oct2020 0800	403.76	500	404.81	500	404.81	500	404.81	500
33	01Oct2020 0900	404.88	500	404.31	500	404.31	500	404.31	500
34	01Oct2020 1000	410.1	500	409.27	500	409.27	500	409.27	500

Figure 233 - Example of Data Output

This table excerpt shows the measured depth of water mid-channel during the various measured flow scenarios at every cross section on the model.

Figure 234 - Example of Data Output

This table excerpt shows the measured depth of water mid-channel during the realistic flow scenario. Results like this are typical for the data pulled from HEC-RAS.

		Depth at XS 8		
CFS Input	Time	Un-modi-fied	Modi-fied	Differ-ence
2270	1/3/2021 13:00	6.744	7.629	0.885
2271	1/3/2021 14:00	6.486	7.362	0.876
2269	1/3/2021 12:00	7.045	7.903	0.858
2272	1/3/2021 15:00	6.268	7.091	0.823
2513	1/13/2021 16:00	6.614	7.416	0.802
2512	1/13/2021 15:00	6.867	7.647	0.78
2514	1/13/2021 17:00	6.402	7.177	0.775
2268	1/3/2021 11:00	7.407	8.181	0.774
2273	1/3/2021 16:00	6.075	6.842	0.767
2511	1/13/2021 14:00	7.139	7.887	0.748
2515	1/13/2021 18:00	6.22	6.944	0.724
2274	1/3/2021 17:00	5.892	6.615	0.723
2275	1/3/2021 18:00	5.711	6.406	0.695
2510	1/13/2021 13:00	7.436	8.13	0.694
2516	1/13/2021 19:00	6.058	6.736	0.678
2267	1/3/2021 10:00	7.815	8.475	0.66
2276	1/3/2021 19:00	5.559	6.217	0.658
2517	1/13/2021 20:00	5.888	6.542	0.654
2277	1/3/2021 20:00	5.407	6.048	0.641
2518	1/13/2021 21:00	5.729	6.364	0.635
2509	1/13/2021 12:00	7.784	8.39	0.606
2519	1/13/2021 22:00	5.603	6.199	0.596
2278	1/3/2021 21:00	5.309	5.849	0.54
2492	1/12/2021 19:00	7.665	8.195	0.53
2493	1/12/2021 20:00	7.459	7.984	0.525
2520	1/13/2021 23:00	5.491	6.011	0.52
2266	1/3/2021 9:00	8.258	8.775	0.517
2279	1/3/2021 22:00	5.22	5.713	0.493
2508	1/13/2021 11:00	8.161	8.653	0.492

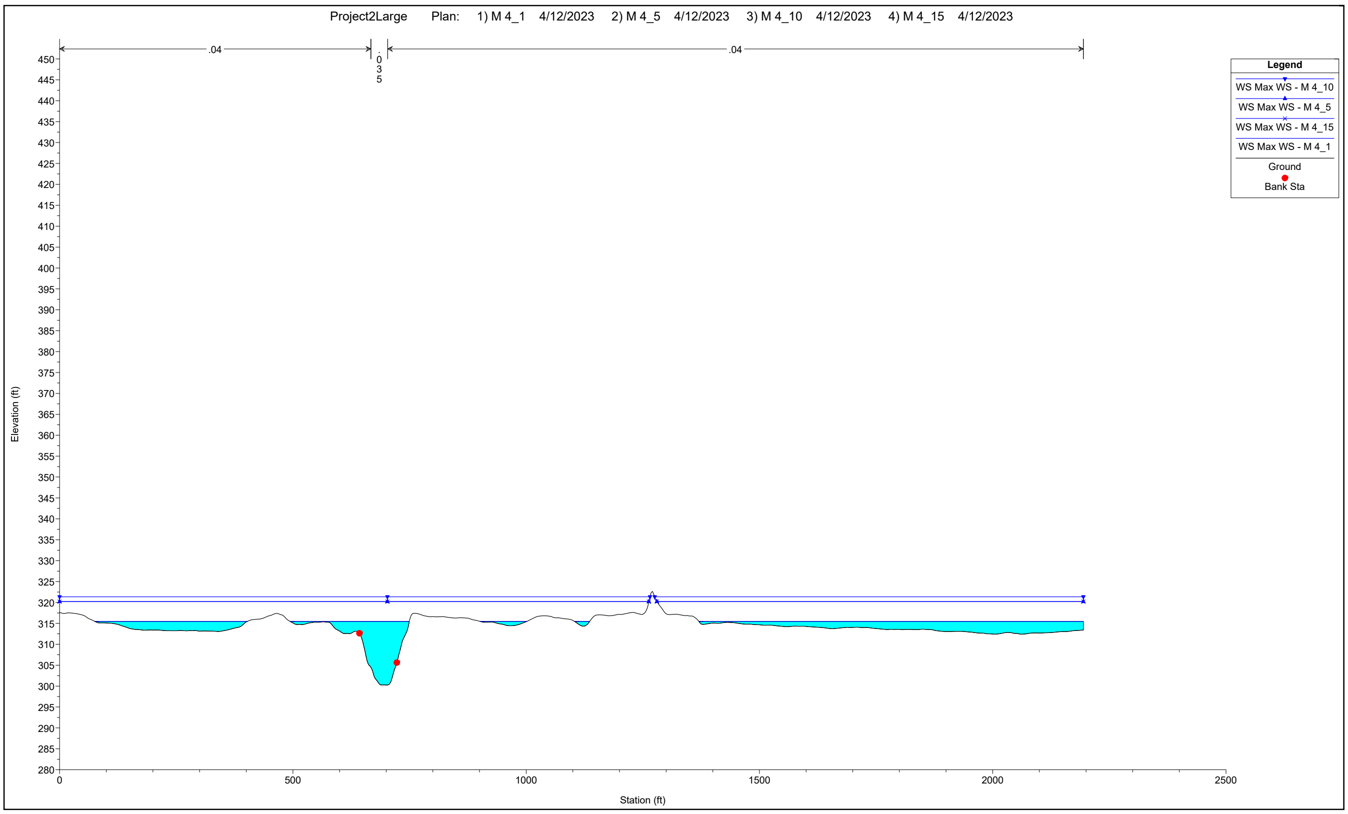


Figure 235 - Section of XS 4

This cross section of XS 4 shows the peak water depth at different measured flow stages.

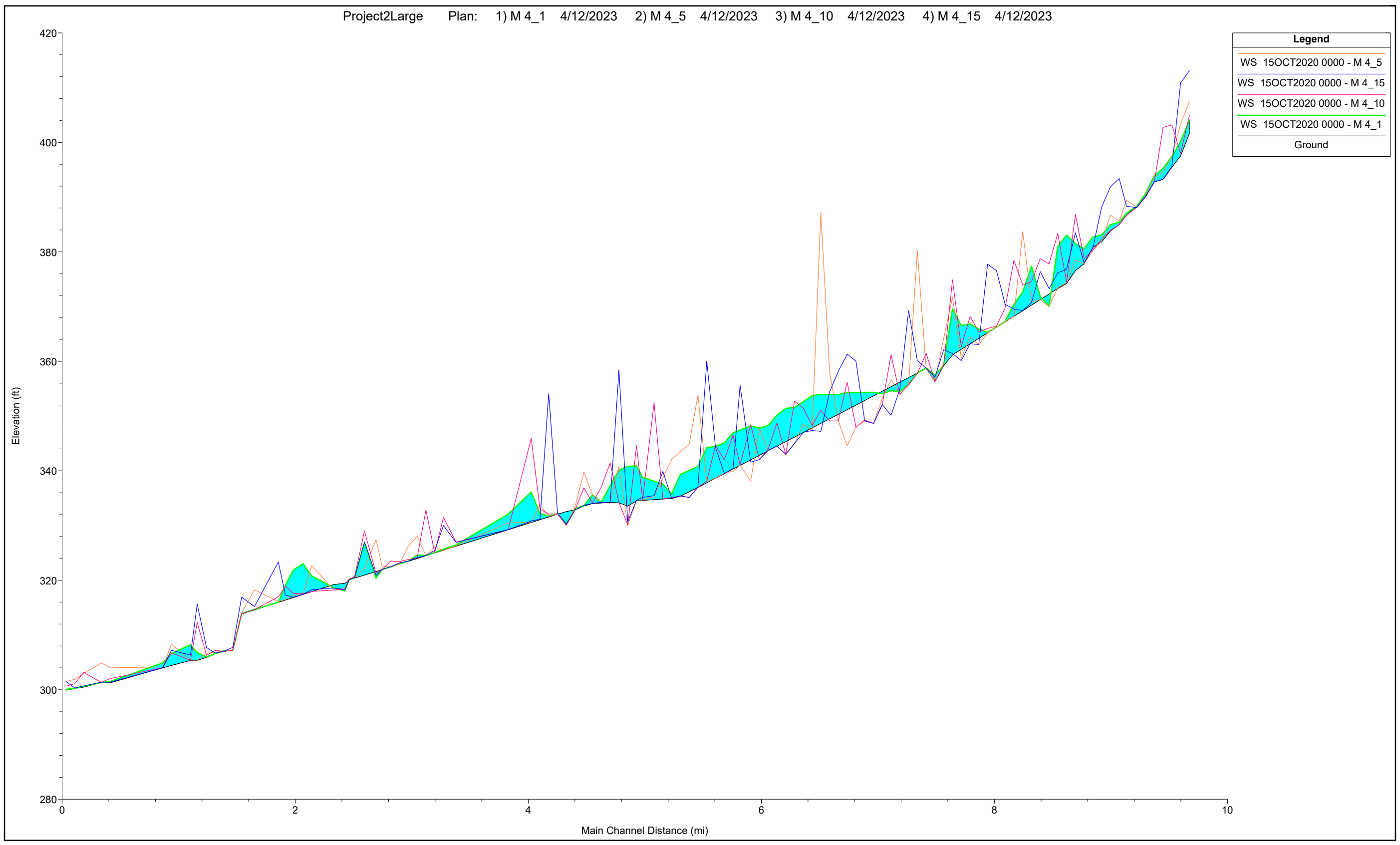


Figure 236 - Modified Landscape Profile

This profile shows the depth at various points on the modified landscape model running measured threshold tests.

Hydraulic Modeling to Quantify Benefits of Floodplain Restoration

Zachary McBride

Master of Landscape Architecture
University of Washington

2023

Committee:

Celina Balderas Guzmán

Ken Yocom