Vegetation Recruitment Assessment on Gravel Shadows of Engineered Log Jams in the Lower Satsop River After a Single Hydraulic Cycle

by

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ABSTRACT

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Catherine A. Harris

Rivers are dynamic features of landscapes, transporting large quantities of water and sediment downstream each year. Rivers naturally cause erosion and flooding and are often close to human activity which can impact these functions. Portions of the Chehalis River Basin are being restored because riverbank erosion, channel migration, and regular flooding are impacting essential public infrastructure, property, farmland, and fish habitat. On the Lower Satsop River, engineered log jams were installed to divert flow away from farmland and roads and toward natural floodplain areas downstream. For this thesis vegetation data was collected over eleven weeks on the gravel shadows of recently installed engineered log jams. Data collected within quadrats included the number of species present, percent cover, vegetation heath, and substrate type. These results demonstrated that one of the gravel shadows had the highest percent cover, vegetation health, and presence of the native species Sitka willow (*Sitka sitchensis*) by the final week of data collection. This gravel shadow had higher inundation levels earlier during the study, and the sustained moisture likely contributed to the more extensive and healthier vegetation observed there relative to the other sites. Substrate type may have influenced the presence of Sitka willow, however variables that were not measured such as moisture content, elevation of the gravel shadow, and a historic heat wave early in the study may have also had an influence on willow establishment. A generalized linear mixed effects model was constructed to further examine the factors contributing to Sitka willow presence. Results suggest that a combination of substrate type and differences in site (presumably including moisture availability and nutrient availability) may have had an effect on the presence of Sitka willow on the gravel shadows. Future engineered log jam installation projects may consider the placement of log jams to create gravel shadow conditions with ideal substrate type, moisture content, and nutrient availability. This will create optimal growing conditions for native riverine species such as willow and cottonwood, enabling them to establish in great numbers. Native species provide habitat for terrestrial and aquatic species. Further, their root structures could help stabilize gravel shadows and improve the longevity of installed log jam structures.

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I. Introduction

In the Pacific Northwest, healthy riparian zones benefit many species including the keystone species: salmon (Deur & Chocktoot, 2021). However, many rivers have been altered and as a result ecosystem services have been degraded. The development of prairies and forested areas across the United States into agricultural land has drastically altered riparian habitat. Furthermore, land development pressures to accommodate urban sprawl continue habitat decline alongside rivers (David Allan, 2004). Riverine degradation was spearheaded by the removal of large woody debris in rivers in the 19^{th} century to allow for steamboat transportation and land development (Wohl, 2014).

In recent decades the reintroduction of large woody debris has been recognized as an important technique to restore channel function, diversity, and provide more diverse habitat conditions (Abbe et al., 1997), (Abbe et al., 2018). Large woody debris affects rivers in many ways including the creation of pools and increased sediment deposition, which creates new spaces for vegetation to colonize (Bertoldi et al., 2015). Furthermore, they can be used to create ideal shelters for juvenile and spawning salmonids and as vectors to divert flow away from valuable farmland and roads (Abbe et al., 2018).

Stream restoration efforts have begun focusing on installing engineered log jams, and this provides opportunities to study the impacts they pose on the environments they are placed in. Once installed, gravel shadows form behind engineered log jams, with vegetation colonizing over the first growing season. The species that colonize could affect the stability of the gravel shadow and provide habitat for terrestrial and aquatic species (Caponi et al., 2020). Robust plant communities on gravel shadows can also influence hydraulics, bank erosion, and channel pattern (Caponi et al., 2020).

Species such as *Salix* (willow) or *Populus* (cottonwood) are native to riparian habitats in the Pacific Northwest and have the potential to colonize on gravel shadows (Amlin & Rood, 2002). These fast-growing species can quickly stabilize gravel shadows with their roots and provide shade and habitat for terrestrial and aquatic species within the river system (Hall et al., 2011). The natural recruitment of native plants would be ideal for any restoration project and by pre-planning the set-up of an engineered log jam to allow for the establishment of these species on newly formed gravel shadows, future projects could save money by avoiding costly revegetation efforts. Robust early establishment of vegetation could also lead to a higher project success in terms of overall log jam structural stability, reduced erosion downstream of the log jam, and habitat benefits to native fish and wildlife species (McHenry et al., 2007).

This research project sought to examine the growth of vegetation on gravel shadows behind engineered log jams by examining vegetation health, percent cover, and/or number of species present. Furthermore, this project examined whether substrate size would make a difference in these vegetation parameters. As engineered log jams are still relatively new in riparian restoration efforts, how they alter the physical environment and vegetation patterns is worth exploring. Engineered log jams have been used to improve stream habitats but are also seen as an effective way to divert river flow and reduce erosion.

Meandering of rivers and high flows naturally cause erosion and flooding, but anthropogenic activity often occurs on or near river floodplains. This is true in the Chehalis River Basin which is one of the largest drainage basins in Washington State at 2,700 square miles and contains diverse land use (Gendaszek, 2011). The Chehalis River Basin is home to the anadromous salmon species coho salmon (Oncorhynchus kisutch), Chinook salmon (O. tsha-wytscha), steelhead (O. mykiss), and chum salmon (O. keta) (Beechie et al., 2021). One of the main tributaries in the Chehalis River Basin is the Satsop River, which contains the study site for this project, a stretch of river in which erosion is affecting agricultural land and man-made infrastructure. The Satsop River originates in the Olympic Mountains and flows south, eventually joining the Chehalis River and emptying into the Pacific Ocean through Grays Harbor (Montgomery et al., 1996).

Due to issues caused by the steady and persistent erosion by the Lower Satsop River in Montesano, Washington, the Lower Satsop Restoration and Protection Program (LSRPP) was formed in 2017 (Lower Satsop Restoration & Protection Program, 2021). Portions of the Lower Satsop River are being altered to divert river flow away from public roads and privately owned farmland by the LSRPP. The LSRPP is interested in protecting public and private property but is also interested in improving riparian habitat on the Lower Satsop River.

The LSRPP is a collaboration between Grays Harbor County, The Chehalis River Basin Flood Authority and The Washington Department of Fish and Wildlife (WDFW), among others (Lower Satsop Restoration & Protection Program, 2021). The WDFW is interested in protecting and restoring fish and wildlife habitat, while Grays Harbor County (with support from the Chehalis River Basin Flood Authority) is interested in protecting Keys Road (downstream of the Lower Satsop River) and representing and helping landowners (whose farmland and homes are adjacent to the Lower Satsop River). The protection of Keys Road is preventative as the river has not yet eroded sections of the road, however it is getting increasingly close to doing so. Sections of farmland have already begun experiencing erosion by the Lower Satsop River, such as the property downstream of the study site for this project, which is what prompted the need to divert river flow away from that property (Lower Satsop Restoration & Protection Program, 2021).

The LSRPP has included the reintroduction of large woody debris into their restoration projects through several variations including the installation of engineered log jams. Phase I, completed in 2020, included installing engineered log jams in the Lower Satsop River to improve fish habitat and deflect river flows from property and infrastructure. River flow needed to be diverted to control further erosion of privately owned farmland alongside the river as well as public land downstream of the river alongside Keys Road. Several engineered log jams were placed in order to have a large-scale impact on river flow direction (Aquatic Species Restoration Plan, Satsop River RM 2.5 to 5.0, 2021).

This research project gathered vegetation data on newly formed gravel shadows behind engineered log jams installed during Phase I of the Lower Satsop Restoration and Protection Program. Research questions were focused on what vegetation health, percent cover, and/or number of species present would be on gravel shadows and whether or not substrate size would make a difference in these parameters. Quadrats were placed randomly on the gravel shadows behind three engineered log jams and one naturally occurring log jam. Vegetation data was recorded from June through August 2021, which included the number of plant species present in each quadrat as well as species identification, percent cover, vegetation health and substrate size.

Results could inform future restoration projects using engineered log jams on the ideal conditions for native species to colonize on gravel shadows in robust numbers after project completion. Natural recruitment of native vegetation helps stabilize log jams and gravel shadows through plant roots and provides habitat for terrestrial and aquatic species. Having vegetation naturally accrue also prevents the need for costly planting projects, and the stabilization quickly provided by plant roots strengthens log jams. Engineered log jams are generally secured with log posts driven into the earth and bolted connections to hold the structure in place, however, the log jam will eventually fail (T. Abbe et al., 2018). Early root establishment by vegetation could help lengthen the lifespan of engineered log jams. This is increasingly important as changes in climate cause more extreme events such as flooding. This is a global issue, and restoration projects that can be used on rivers around the world should strive to keep up with and adapt to environmental changes.

II. Literature Review

Introduction

In reviewing the literature for this study, substantial research has been done pertaining to river system functions, including gravel bars, log jams and vegetation. The following literature review will firstly go over natural log jam function in a river system, including different types of log jams and how the creation of pools and movement of sediment by log jams influence river systems. Engineered log jams will then be discussed as a restoration technique to emulate the benefits natural log jams provide to river systems. This will be followed by gravel bar function in a river, including different types of gravel bars and their influence on sediment distribution and vegetation placement in rivers. Lastly, vegetation growth on gravel bars will be reviewed, specifically key native species in the Pacific Northwest which establish quickly, stabilizing gravel bars and providing habitat for terrestrial and aquatic species.

The installation of engineered log jams on the Lower Satsop River created gravel shadows, which are defined as sediment accrual behind log jams, on which vegetation data was collected.

Gravel shadows differ from gravel bars because gravel bars form in different parts of a river, such as on a bend or in the middle of a channel. For this literature review, vegetation establishment and growth has been determined to be similar on gravel bars and gravel shadows due to the proximity of both to the river. Gravel bars and gravel shadows parallel each other when it comes to their functions, such as providing growing space for vegetation, stabilizing sections of rivers and reducing erosion of riverbanks (McHenry et al., 2007), (Abbe et al., 2003). However, they are also different from each other in many ways. The placement of engineered log jams in a river dictates the placement of gravel shadows, whereas gravel bars may form wherever an opportunity for sediment accrual exists (Bywater-Reyes et al., 2018). Sediment distribution may be different due to the presence or absence of a log jam, the velocity of river flow, or proximity to the bank. Vegetation distribution may also vary depending on sediment distribution, shade provided by log jams, or seed distribution via wind or water.

This study focuses on vegetation establishment on gravel shadows. The majority of published research has focused on vegetation establishment on gravel bars rather than gravel shadows. As such, this literature review points out for the reader whether a study was conducted on gravel bars or gravel shadows. More research on the impacts that engineered log jams and the gravel shadows that form behind them have on river systems should be conducted and added to the literature in the future.

Natural log jam function in a river

Large woody debris (LWD) are natural components of river systems which are capable of redirecting flow and changing channel planform (Abbe et al., 2018). During the 19^{th} century in the United States, there were massive efforts to clear rivers of large snags and logjams to allow for steamboat transportation and land development. Subsequent and continued land development has eliminated many sources of LWD to rivers across the country (Wohl, 2014). With the disappearance of large wood in rivers, the importance of its role in many fluvial systems was lost until the late 20th century. Restoration projects began to focus on the role of wood in salmon habitat and there was some reintroduction of wood into streams. However, it wasn't until 1995 that an engineered log jam (ELJ) made up of LWD was installed to help control bank erosion in the Upper Cowlitz River (Abbe et al., 2018).

Log jams naturally occur in rivers when large trees or logs get stuck or jammed into banks or shallow and narrow parts of the river. These LWD trap smaller pieces of wood and debris as they float down the river and as the log jam accumulates more and more material, its structure and size begin to influence the movement of sediment, and affect species diversity, organic matter retention, and physical form of the channel (Bilby & Ward, 1989). A stable log jam will alter the physical form of the channel by slowing and re-directing flow, cause pool scours and sediment accumulation which leads to gravel bar formation (Abbe & Montgomery, 2003). In the North Fork Stillaguamish River in Washington State, natural log jams historically stabilized gravel bars which allowed vegetation to take hold and create in-channel islands, further adding to the diverse channel network of the system (Abbe et al., 2003).

Waterfalls formed by LWD allow for sediment to flow through and be slowly transported by low energy areas downstream. The low energy areas also facilitate sediment retention (Bilby & Ward, 1989). The formation of pools that LWD creates are ideal places for salmon and trout species to take cover. Juvenile salmon use these pockets to feed and seek shelter from predators, and adult salmon use them as places to rest from the fast-moving currents of the main river as they make their way upstream to spawn (Bilby & Ward, 1989). In a study by Fausch &

Northcote (2011), sections of a stream that had LWD removal and sections that did not were compared for juvenile salmonid presence and health. Results indicated that the presence of LWD had a critical role in creating and maintaining pools that provide habitat for juvenile salmonids. Sections with LWD present had larger pools and larger populations of salmonids. The salmonids found were also larger in size in the sections with LWD than those that had LWD removal.

In examining the patterns and processes of wood debris accumulation in the Queets River basin, Abbe & Montgomery (2003), describes many types of wood debris jams. A few have been selected for discussion because they show an array of different log jams commonly found in rivers. The bar-apex jam was also selected because it is a common type of engineered log jam installed to divert river flow and was used in the Lower Satsop River site for this study. The first log jam presented by Abbe & Montgomery (2003) is *In situ*, consisting of around three boles that have fallen and remained where they fell, and are large enough to inhibit downstream transport during high flows. These jams can develop into *Combination jams*, which form when the boles from in situ debris trap smaller driftwood and obstruct a channel. One example of a combination jam is a *Valley jam*, which occurs when wood accumulation that forms from the in situ jam gradually widens to a width greater than bankfull channel over several decades (Figure 1). Another type of combination jam is a *Flow-deflection jam*, whose initial fallen boles also remain where they fell, but accumulated material does not span the width of the channel (Figure 1). Accumulated material then deflects the flow of the river around a Flow-deflection jam. Besides In situ jams there are *Transport jams*, which are composed of material that has been fluvially transported. One type of transport jam is a *Bar-Apex jam*, which has a main log parallel to the river flow with an attached rootwad facing upstream. These jams initiate the formation of a bar in the thalweg or accelerate the growth of a pre-existing bar (Figure 1).

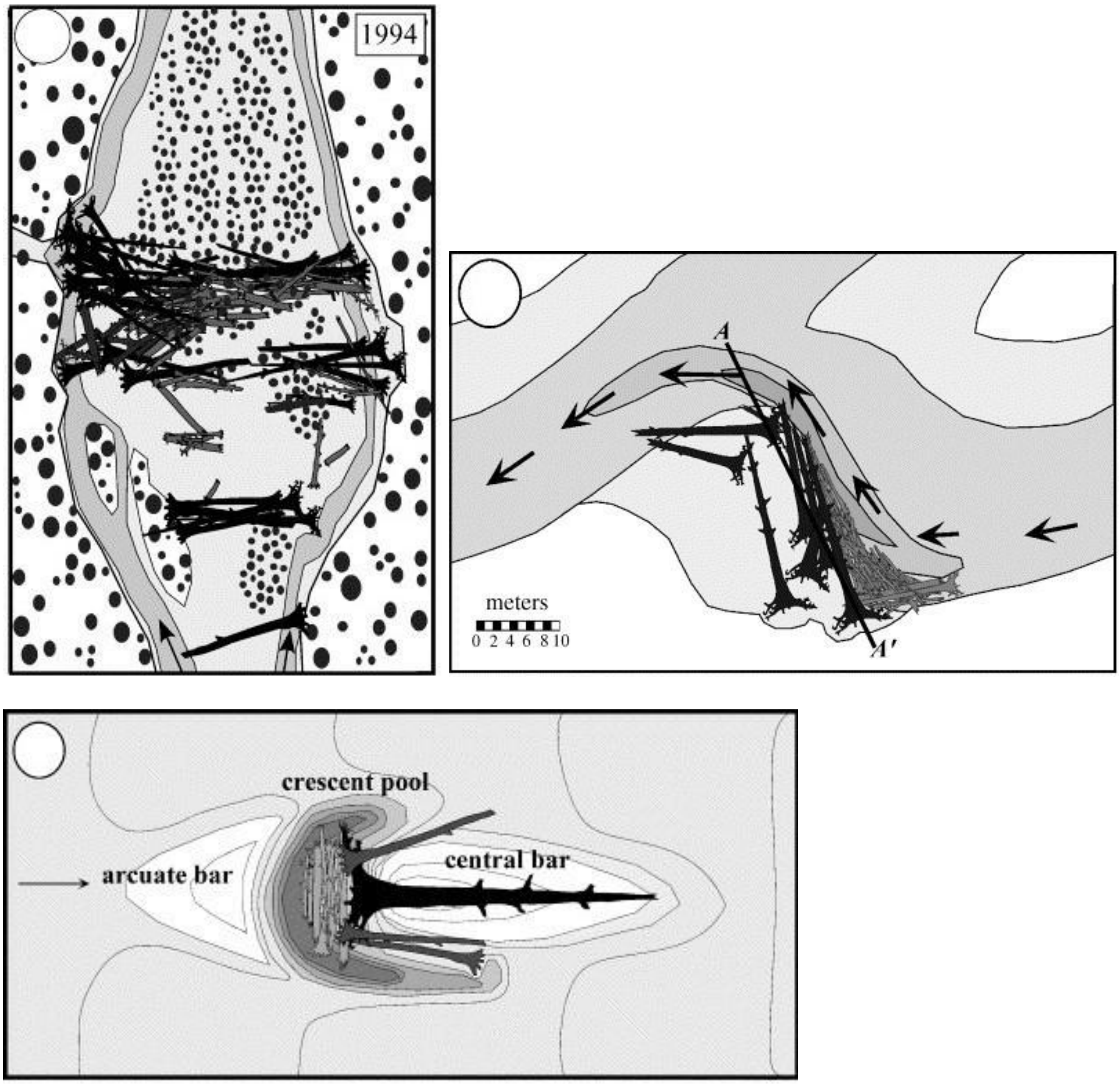

Figure 1: Examples of a Valley jam (top left), Flow-deflection jam (top right), and Bar-apex jam (bottom) (T. B. Abbe & Montgomery, 2003).

Restoration projects that plan to use engineered log jams often turn to the types of natural log jam structures to use as guides. The type of restoration project being implemented might call for a particular structure to be used. For example, if channel incision is the goal, a *valley jam* could be used. For channel migration, *flow-deflection jams* may be used for bank protection and *bar-apex jams* may be used for flow diversion and erosion control (Figure 2).

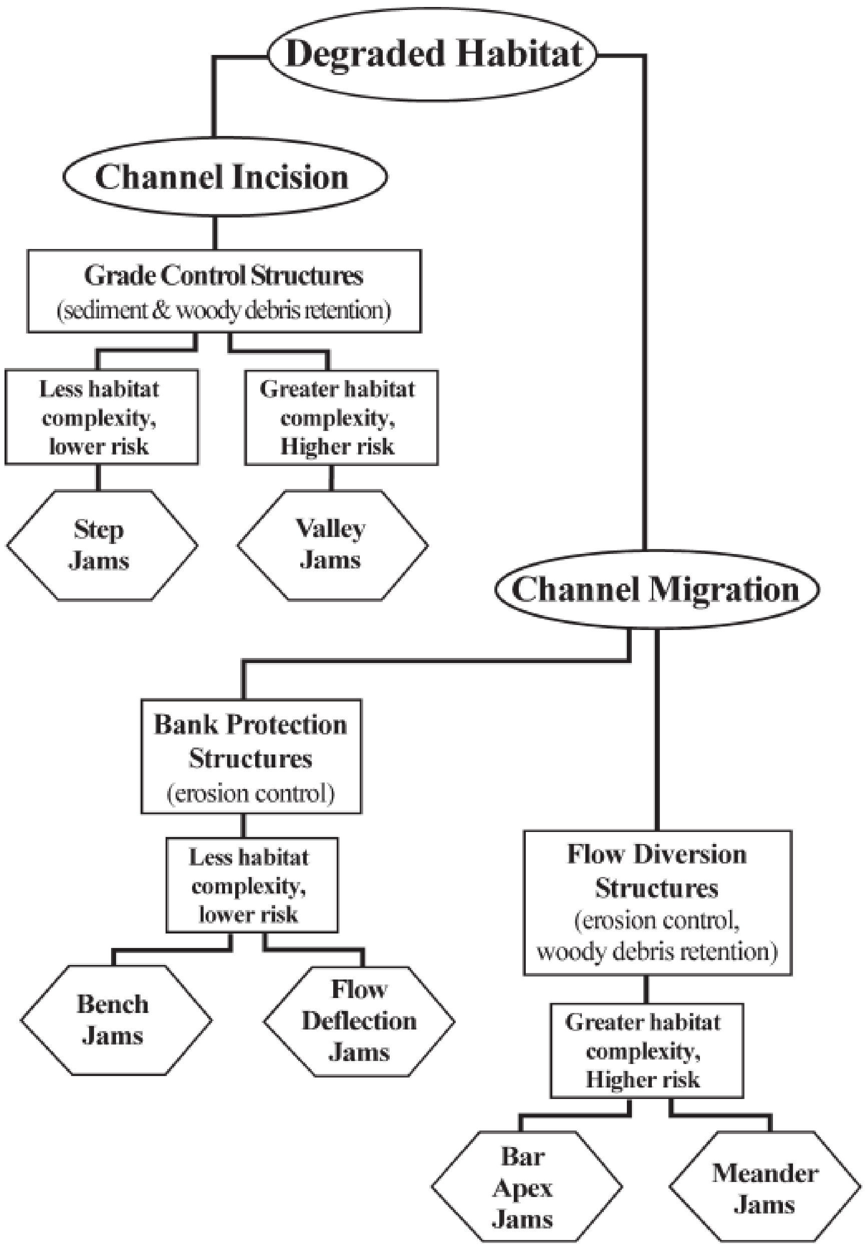

Figure 2: Engineered log jams appropriate for treating habitat degradation. Categories include Channel Incision (vertical treatment) and Channel Migration (lateral treatment) (Abbe et al., 2003)

Engineered log jams (ELJs)

An engineered log jam (ELJ) aims to emulate the functions of naturally occurring log jams to restore riverine geomorphic, hydraulic and sediment transport processes using calculations on wood stability, longevity, and function. ELJs obstruct flow and control channel planform, and in doing so they can connect secondary channels and wetlands within the floodplain to the mainstem channel (Abbe et al., 2003). Many ELJs have been installed to improve salmon habitat, but an increasing number are being installed specifically for bank protection and restoring riverine physical processes (Abbe et al., 2018).

No artificial materials are necessary to construct an ELJ. Native trees at the site can be used if the size and shape meet design specifications, however most projects will import trees to the site to preserve existing riparian trees (Abbe et al., 2003). The size, shape, and placement of initial logs in a ELJ is critical to ensuring stability of the log jam. The design life for engineered log jams is 50-100 years (Abbe et al., 1997), however some fail before reaching that goal (Addy & Wilkinson, 2016). Over time, stability will increase on the ELJ with additions of woody debris during flood events, as well as the growth of trees on the ELJ, whose roots help hold the structure together and size help weigh it down (Abbe et al., 2003). The accumulation of smaller woody debris is also an important function of natural log jams and ELJs, because smaller debris decays more rapidly and provides food sources for microorganisms and invertebrates (Abbe & Brooks, 2011). These food sources benefit salmonids and enhance the food web in riparian ecosystems.

On the North Fork Stillaguamish River in Washington State, five ELJs were installed in 1998, four of which were meander type jams and one which was a bar-apex jam (Abbe et al., 2003). The structures were effective at trapping woody debris, and all stayed intact after fourteen flood events occurred between late 1999 and early 2000. Pool frequency increased after construction from 1 pool/km to 5 pools/km and remained at that level. Adult Chinook salmon utilize deep pools within river systems, and prior to construction on the North Fork Stillaguamish, Chinook mostly congregated in one available deep pool. After construction, Chinook redistributed throughout the treatment reach, utilizing the increase in available pools (Abbe et al., 2003).

Engineered log jams have also been installed in the Elwha River in Washington State, and physical and biological effects were reviewed in a report published by the U.S. Fish and Wildlife Service. They found that the log structures changed the dominant sediment size in the river from mostly cobble to various class sizes of gravel. (McHenry et al., 2007). This provided more suitable spawning habitat for local salmon species. Sediment storage also increased after ELJ installation, with a 60% increase in sediment stored in gravel bars over the five-year study (McHenry et al., 2007).

A ten-year project installing log jams on Finney Creek in Washington State found that the ELJs increased the complexity of the channel with more stable gravel bars and slower movement of sediment downstream (Nichols & Ketcheson, 2013). The initial goal for this project was to minimize sediment delivery to streams by stabilizing eroding hillslopes and roads. This was followed by log jam installations in 1999 which progressed downstream until 2010. Continued monitoring of the site showed increases in scouring pools and more diverse aquatic habitat overall, as well as an expansion of riparian vegetation onto stable gravel bars and behind log jam structures (Nichols & Ketcheson, 2013).

Gravel bar functions in a river

Although this study looked at vegetation on gravel shadows, the majority of the literature describes gravel bars. Differences between the two will be pointed out when necessary. Gravel bars are key components of gravel-bed rivers and are highly dynamic, subject to seasonal erosion and deposition during flood events (Gilvear et al., 2007). Further, there are many different types of gravel bars. Sediment that builds up in wide, slow-moving rivers can form islands in the middle of the channel. These islands are referred to as mid-channel bars or braid bars in braided rivers. Point bars, often referred to as gravel bars, are common in meandering rivers and occur along bends where sand or gravel is deposited due to a decrease in sediment transport capacity on the inside of the bend (Kalníková et al., 2018). Mid-channel bars may develop into relatively stable islands with mature vegetation, causing unstable braided rivers to develop into stable anabranching rivers (Li et al., 2014).

After a gravel bar initially forms in a river, it reaches its total thickness (height) within the first few years and soon after approaches its equilibrium length. Continued growth occurs mainly by lateral accretion (width) consistent with the flow of the river and could take over a century to reach equilibrium width (Church & Rice, 2009). Gravel bar formation is followed by vegetation recruitment, which can influence the morphology of rivers in many ways including hydraulics, bank erosion, and channel pattern. These effects vary depending on vegetation distribution on bars, whether that be individually or in clusters, as well as vegetation height and stem flexibility (Bywater-Reyes et al., 2018). On the Lower Satsop River, vegetation colonized on newly formed gravel bars behind engineered log jams. Recording what vegetation colonizes is of interest because established vegetation could help stabilize the gravel shadow and log jam structures and increase their longevity. Establishment of native vegetation would be beneficial to salmonids by providing shade (Martin et al., 1986) and hosting invertebrate populations which salmon may feed on (Flory & Milner, 1999). Robust plant communities on gravel shadows can also influence hydraulics, bank erosion, and channel pattern (Caponi et al., 2020).

Unvegetated gravel bars in early successional stages provide an opportunity for species to establish in an environment free from the competition of established plants. In a study by Janssen et al., (2020), the effect of fine-grained sediment availability on vegetation establishment on gravel bars on the Rhone River was measured. It was determined that the moisture content and nutrient availability in fine grained sediments allowed for ruderal species to establish and thrive before more stress tolerant perennial species became widespread. In the Lower Satsop River fine and sand particles have the opportunity to be deposited on gravel shadows behind engineered log jams (Zimmerman & Winkowski, 2021a), (Kalníková et al., 2018), providing nutrients for vegetation to quickly establish.

The upstream end of a gravel bar is referred to as the bar head and usually has coarse sediment, while the downstream end is referred to as the bar tail and usually has fine sediment such as sand (Bluck, 1971). As the river slows down, heavier coarse sediments are deposited first (bar head), while lighter fine sediments remain suspended in the water until the river is almost still (Bluck, 1971). In a study by Li et al. (2014), mid-channel bars were measured by sediment distribution and vegetation on the bar surface and found that finer sediments were deposited on the bar tail, while sediment deposits became coarser along the bar until the head was reached. Vegetation was dense on the bar tail and bare on the gravel bar head with shrubs growing in the middle of the bar, indicating upstream growth along the gravel bar. Vegetation first established on fine sediments at the bar tail and continued to establish towards the upstream (bar head) end of the bar. Due to continued scouring and deposition of coarse sediment (depending on upstream sources of erosion) the bar head usually has minimal vegetation growth (Li et al., 2014). This type of sediment distribution is typical of gravel bars; however, gravel shadows may differ. Vegetation can be affected by flood frequency and magnitude, as well as sediment type, bar elevation above the normal water level and ground water table, surface temperature and moisture, and light availability (Kalníková et al., 2018), however the degree to which each affects vegetation growth may also differ on gravel bars versus gravel shadows. For example, gravel shadows behind engineered log jams may experience differences in scouring and sediment deposition during floods due to the anchored log jam presence in front of the gravel shadow. More fine sediments may have the chance to be deposited on gravel shadow tails as coarse sediment interacts with the log jam. Engineered log jams may also offer protection to vegetation on gravel shadows during flooding events due to the log jam absorbing some of the high intensity flows (McHenry et al., 2007).

Vegetation growth on gravel bars

In the Pacific Northwest, the native plant species most likely to establish on gravel bars are in the cottonwood (*Populus*) and willow (*Salix*) group (Amlin & Rood, 2002). Both are members of the Salicaceae group or willow family and can reproduce by producing roots when robust stems are placed in wet ground (Hall et al., 2011). In this way, branches that break off during storm events can be transported downstream and take root if they end up stuck in a muddy riverbank. This adaptive behavior allows fast growing willows and poplars to become established in dynamic river environments. The more common method of plant establishment in the willow family is through seed dispersal. Prolific seed producers, willows are pollinated by insects and in some cases, wind pollinated (Gage & Cooper, 2005).

In Western Washington, the heavy precipitation and flood season occurs from late October to mid-March (Neiman et al., 2011). After high flow events, water levels decline and in late spring and early summer, germinating seeds and seedlings are found in great numbers on point bars and other moist, exposed substrates in alluvial floodplains (Stettler et al., 1995). Seedlings need open space with plenty of light which gravel bars provide, and seedlings on gravel bars are also not as susceptible to the scouring that can wash away seedlings attempting to establish on riverbanks (Stettler et al., 1995). In a study by Merritt & Wohl (2002), predictive models of patterns of seed dispersal were determined after constructing an experimental flume in which three hydrologic regimes were used. Color coded seeds were released in replicated trials in which relationships between dispersal phenology and hydrologic regime were examined. Results showed the highest concentrations of seeds were deposited on eddies, areas of flow expansion, slackwater areas, and pool margins. These areas have reduced flow velocity where fine sediments and organic material tend to be deposited, offering soils with higher water retention and nutrient availability, ideal conditions for seed germination and the survival of seedlings (Merritt & Wohl, 2002). A study by McBride & Strahan (1984), looked at factors influencing the establishment and survival of seedlings on the gravel bars of Lower Dry Creek in California. They observed that cottonwood seedlings germinated first, with willow germinating a few weeks later. Willow was found to prefer areas where surface sediment size was less than 0.2 centimeters. Drought-induced seedling mortality was observed in the third week of July on sites that were more elevated above the stream.

Cottonwood seedlings are intolerant of drought but do tolerate 3-4 weeks or more of water inundation (Stettler et al., 1995). These periods of inundation eliminate competitors and allow cottonwood plants to fully establish by keeping recruitment zones open. Seedlings need to establish long root structures in order to survive when water levels drop. Generally, this occurs during dry summer months, when roots grow down deeper in the soil in search of water. In the study by McBride & Strahan (1984), cottonwood seedling roots were often three times as long as willow seedling roots by the end of summer, indicating that cottonwood seek to establish deep roots early on in life.

Another native plant species that will likely establish on gravel bars is red alder (*Alnus rubra*). According to Harrington (2006), red alder is a pioneer species that favors high light conditions and exposed mineral soil. It is a lowland species found on disturbed sites, with the best stands found on deep alluvial soils in river and stream flood plains. Seeds are produced in great numbers and are primarily dispersed by wind, and sometimes by water. Once established, red alder form extensive root systems, and when flooded, form adventitious roots which continue to grow down and anchor the plant once the soil is drained. Red alder also has root nodules that fix atmospheric nitrogen as the nodules have a symbiotic relationship with an actinomycete (*Frankia spp.*) (Harrington, 2006). This is especially valuable to a riparian habitat, as red alder establishes on disturbed sites, stabilizing the soil and adding nitrogen so that other species may establish and benefit as well. As a pioneer species, red alder stands create canopy cover to make way for conifer and understory species to establish. In some cases, salmonberry, thimbleberry or vine maple form a dense shrub canopy that conifers cannot penetrate, expanding rapidly by vegetative reproduction as space becomes available (Harrington, 2006). Before conifer trees establish, red alder is an important snag tree for cavity nesting birds, and promotes understory plant growth and species richness, which in turn creates habitat for small mammals, birds, and fish in freshwater streams (Hanley et al., 2006).

Vegetation establishment on gravel bars depends on ideal growing conditions for seeds to germinate. Once plants are established, their survival then depends on drought events and the frequency and severity of flooding events. During flooding their ability to withstand uprooting from powerful flow or burial from increased sediment load is key to survival (Caponi et al., 2020). In a study by Caponi et al. (2020), the above and below ground traits of plants were evaluated based on their ability to interact with hydromorphological processes and cope with disturbances. They found that plants did not typically survive on migrating gravel bars, because the disturbance was too great, but on steady gravel bars where plants were able to establish over a few years with less disturbance, the chance of survival was higher. Plants that did the best on stable gravel bars were those that grew quickly above and below ground. Greater above-ground biomass growth allowed plants to resist burial from transported sediment during flooding events, and fast-growing roots stabilized plants so they wouldn't be uprooted during high water flows. Deeper root structures also allowed plants access to groundwater during drought conditions, ensuring survival during low flow periods.

Conclusion

Log jams, gravel bars and vegetation are essential components of riverine and riparian ecosystems. Often these components are degraded due to human influence. Restoration projects are more frequently installing engineered log jams as part of river restoration efforts. These projects serve to divert river flow, control erosion, and increase scour and pools within the river to provide essential habitat to salmon species. On the Lower Satsop River, engineered log jams were installed and vegetation data was collected on newly formed gravel shadows. Vegetation recruitment on gravel shadows could help to stabilize gravel shadows and log jam structures as adventitious roots anchor native willow, cottonwood, and alder trees during high and low flow events. Robust native plant communities will also provide shade and habitat for terrestrial and aquatic species. Vegetation data was collected to shed light on the ideal conditions for native plants to establish and flourish on gravel shadows. If engineered log jams can encourage these conditions after installation, there will be greater project success in terms of log jam stability and habitat benefits for salmon. This research aims to highlight the importance of vegetation recruitment on gravel shadows so that it may be included in future measurements of engineered log jam success.

III. Methods

Site Description

The study area is on the Lower Satsop River in Southwest Washington State. The area of interest is the portion of the Satsop River that meets up with and drains into the Chehalis River (Figure 3). The Chehalis River has a drainage basin of 2,700 square miles and contains diverse land use within the system (Gendaszek, 2011). The section of the Satsop River where the study area occurred has been experiencing riverbank erosion, extreme channel migration and flooding, prompting the formation of the Lower Satsop Restoration and Protection Program (LSRPP). The LSRPP's main goals are to address impacts to public infrastructure and private property and improve habitat along this portion of the river. Figure 4 shows the Lower Satsop River with areas of erosion highlighted in red.

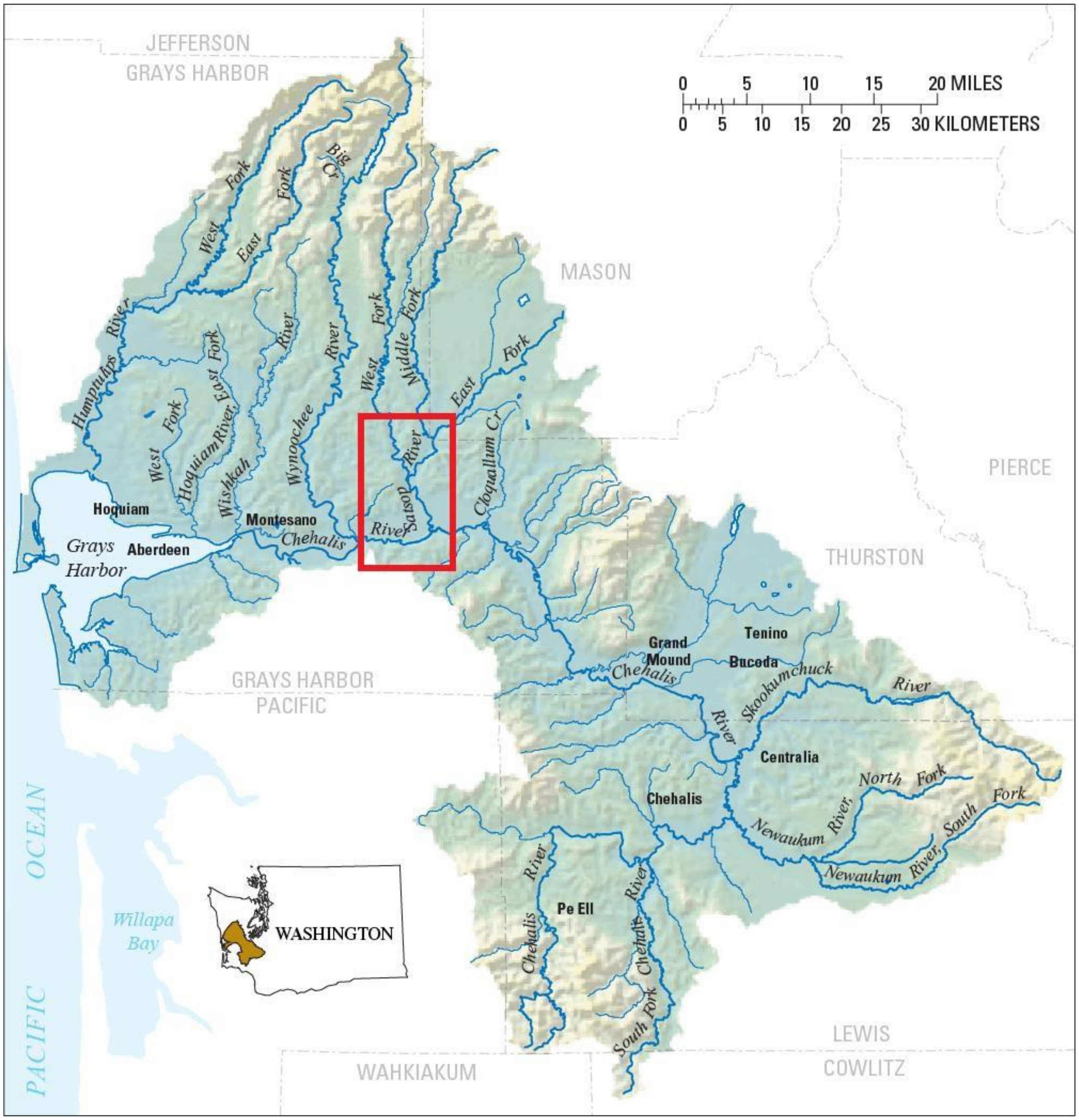

Figure 3: The Chehalis River Basin with the Satsop River study area highlighted in red (Chehalis Basin - Washington State Department of Ecology, n.d.).

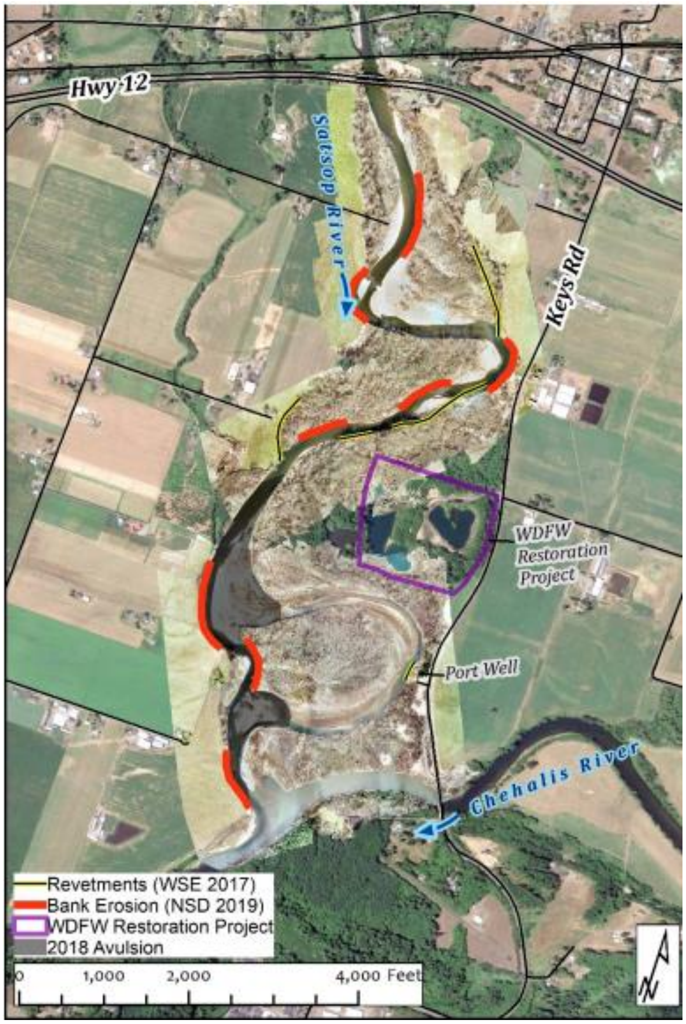

Figure 4: The Lower Satsop River draining into the Chehalis River. Problem areas with erosion needing to be addressed are highlighted in red *(Lower Satsop Restoration & Protection Program, 2021).*

The LSRPP is a collaboration between Grays Harbor County, The Chehalis River Basin Flood Authority and The Washington Department of Fish and Wildlife (WDFW), among others. Restoration projects have been approved and portions of the restoration plan have been carried out. One of the earlier project goals was to establish a buffer along Keys Road and deflect river flow away from privately owned agricultural land by installing engineered log jams upstream of these sites. Figure 5 shows the projects completed in Phase 1 of the LSRPP in 2020. The topmost yellow section that is highlighted shows engineered log jams that were installed and is the location of data collection for this project. This particular section includes engineered log jams installed under the guidance of the WDFW, who were interested in the log jams providing habitat for fish species in the Lower Satsop River.

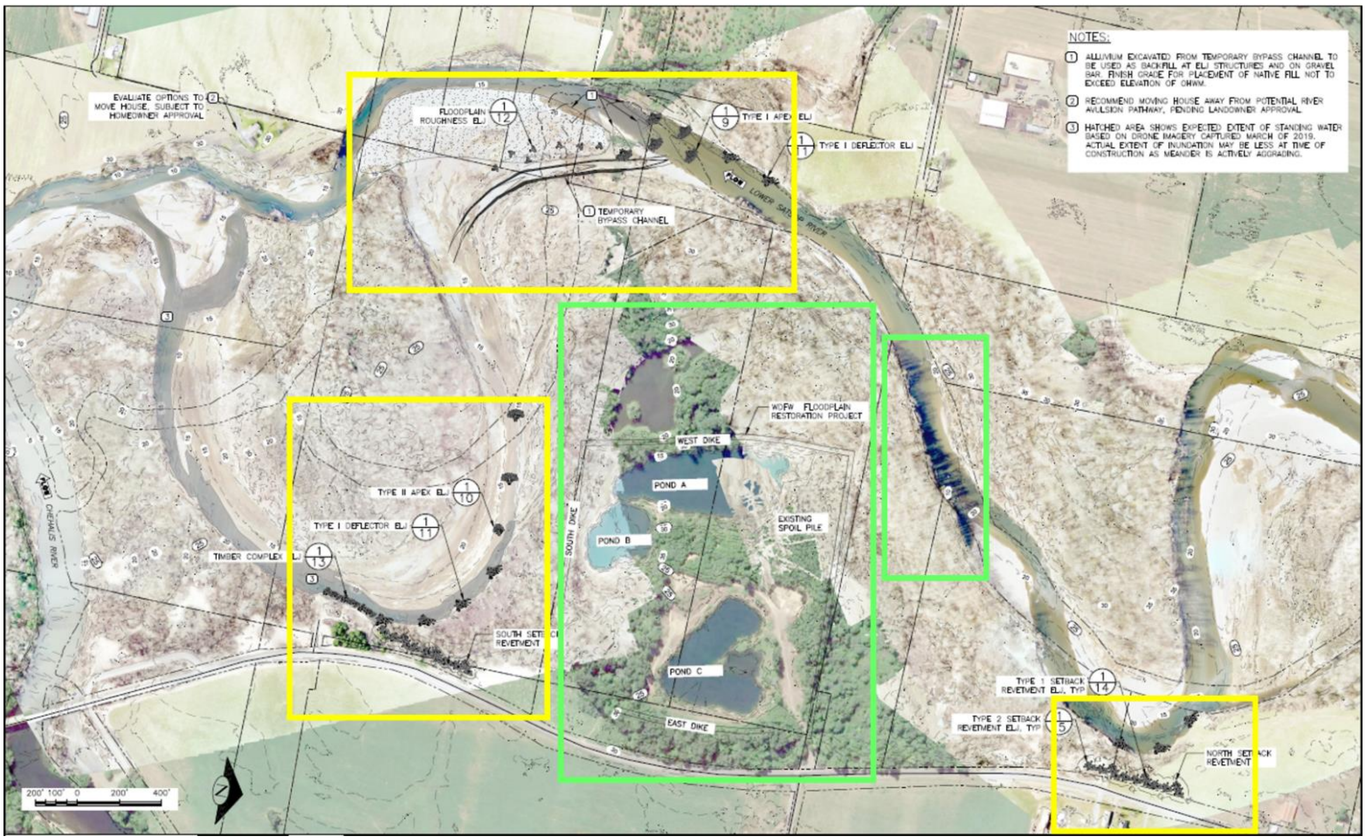

Figure 5: Restoration projects completed on the Lower Satsop River by the LSRPP in 2020. The topmost yellow section is the study site for this thesis *(Lower Satsop Restoration & Protection Program, 2021).*

After the installation of the engineered log jams, gravel shadows formed behind the structures (McHenry et al., 2007). This provided an opportunity to research the vegetation growth on the gravel shadows over the first growing season. For this project, vegetation was sampled on the gravel shadows behind three of the engineered log jams and one naturally accrued log jam within the site (Figure 6). Two of the engineered log jams were apex log jams, and one was an apex log jam with floodplain roughness structures. Naturally accrued apex log jams are composed of material that has been transported fluvially. For example, a bar-apex jam occurs when a main log parallel to the river flow with an attached root wad facing upstream will collect smaller material which floats downstream (Abbe & Montgomery, 2003). The added floodplain roughness structures to one of the engineered apex log jams are smaller blockades downstream of the log jam which curve in the desired direction of flow and are designed to guide river flow further away from previously eroded areas. The naturally accrued log jam in this study was chosen as a control to see if there were any stark differences in the gravel shadows which formed due to the man-made and installed engineered log jams.

Research questions before data collection began were focused on assessing the presence of key pioneer species (Sitka willow specifically), vegetation health of all plants, percent cover, and the number of species present on the gravel shadows and assessing whether substrate type influences those vegetation parameters.

Figure 6: Study site aerial imagery showing gravel shadows where vegetation data was sampled (tan polygons). Labeled log jams are as follows: 1 – FR1: Apex jam with floodplain roughness structure, 2 – N1: Naturally accrued log jam, 3 – A1: Apex jam, 4 – A2: Apex jam. The river flows downstream towards farmland opposite of log jam 2. Drone footage of the site captured by Mike Ruth, July 2021.

Field Sampling Layout and Materials

Data collection was completed once a week over eleven consecutive weeks from June 18th to August 27th, 2021. Each week, vegetation data was collected on the gravel shadows of three engineered log jams, and one naturally accrued log jam. A transect line was first placed at the center of the back of the log jam and stretched straight down to the end of the gravel shadow using a tape measure (Figure 7).

One of the engineered log jams measured had floodplain roughness structures behind it and was labeled as FR1. FR1 had a gravel shadow that was 110 feet long. The other two engineered log jams were apex log jams and were labeled as A1 and A2. Both A1 and A2 had gravel shadows that were 90 feet in length. The final log jam measured was the naturally accrued log jam, labeled as N1. N1 had a gravel shadow that was 90 feet long.

After the transect line was stretched along the length of the gravel shadow, a quadrat was placed on either side of the transect line every 10 feet. This first occurred at the 10-foot mark because at zero feet the transect line was at the base of the log jam before there was any gravel shadow to collect data on. Thus, starting at the 10-foot mark the quadrat was randomly tossed to the left of the transect line towards the left outside edge of the gravel shadow, and to the right of the transect line towards the right outside edge of the gravel shadow, placing quadrats at random distances from the transect line. This continued to the left and right of the 20-foot mark, 30-foot mark, 40-foot mark, etc. until the end of the gravel shadow was reached. Thus, with two quadrats measured every 10 feet along the transect line, FR1 had a total of 22 quadrats and A1, A2 and N1 had 18 quadrats (Figure 8).

Figure 7: Photos of gravel shadow A1 with transect line (top) and gravel shadow N1 with transect line and quadrat (bottom). Photo of A1 taken on June 18th, 2021. Photo of N1 taken on July 9th, 2021.

Figure 8: Aerial photo of the sampled gravel shadows (tan polygons) and the location of each quadrat (yellow dots). Exact quadrat locations were obtained using a GPS Trimble device. Drone footage of the site captured by Mike Ruth, July 2021.

Quadrat locations were chosen randomly via tossing from the transect line during the first week on June 18th, 2021. As each quadrat location was determined, a flag marker was placed in the top left corner of the quadrat with the log jam and quadrat number written on each flag. During subsequent weeks of data collection, quadrats were placed in the same spot by placing the quadrat with the flag marker in the top left corner every time. The quadrat square measured 2 feet by 2 feet once assembled. After assembly, orange mason twine was strung through drilled holes to create a grid of 16 equally sized squares within the quadrat (Figure 9).

On the A2 gravel shadow (labeled '4' in Figure 8), there was initially inundation on the lower half of the gravel shadow which slowly receded after the third week of data collection. This began in the first week of July, and by the last week of July only a small patch of water remained on the gravel shadow. The water was shallow, and the holes drilled in the quadrat frame allowed for the quadrat to sink and be measured in the same spot each week. Photographs were taken from above the quadrat each week and any small vegetation was recorded, although not much grew in those quadrats until the water receded (Figure 10). Substrate was not affected as the water was pooled and stagnant by the time data collection began in week 1. No other gravel shadows measured in this study experienced inundation.

Figure 9: Photo of the constructed quadrat during data collection. The quadrat flag marker is in the top left corner.

Figure 10: Inundated quadrat A2Q18 on July 2nd, 2021. Water was shallow enough for data collection and more vegetation was able to colonize as the water receded by August 27th, 2021 (last week of data collection).

Data collection

Data collected within each quadrat included substrate type, number of plant species present, plant species identified, overall vegetation health, and percent vegetation cover within each quadrat. Data was collected using the ArcGIS Survey123 app and also transcribed into an excel spreadsheet. However, for the purposes of this thesis, rather than discussing all plant species identified, only Sitka willow (*S. sitchensis*) will be discussed due to its prolific establishment and its importance as an early establishing native species.

Substrate type

Substrate type for each quadrat was determined during the first week of data collection and was assumed to remain unchanged over the eleven weeks due to low flow of the river and lack of mobility of the substrate during the duration of sampling. Substrate sampling guidelines were taken from Bunte & Abt, (2001). The substrate size classifications used were fine (< 0.63 mm), sand (0.63 – 2.0 mm), gravel fine (2.0 – 16.0 mm), gravel coarse (16.0 – 64.0 mm), cobble (64.0 – 256.0 mm), and boulder (> 256.0 mm). Within each quadrat each substrate size classification was recorded if present, so multiple substrate types could be recorded within each quadrat frame. Substrate type was not numerically quantified; rather, size class was recorded if observed. Presence was determined by measuring substrate within the quadrat that could be seen looking straight down at the quadrat from above. Within the surface layer substrate was recorded as falling under one of the six size classifications listed above. The surface layer was not tampered with within quadrats to preserve seeds and leave young vegetation undisturbed.

Vegetation measurements

During each week of data collection there were several vegetation measurements recorded in every quadrat. The first was the number of species present in the quadrat, which was recorded on site. Species' names that could be correctly identified were also recorded, and pictures of each quadrat were taken to reference and further identify plants outside of the field. Not all species were able to be identified, and due to the high numbers of Sitka willow (*S. sitchensis*) establishment, this native species was focused on during data analysis.

Overall vegetation health was also determined on site on a scale of 1-5. The number was determined by looking at the health of all plants within the quadrat and determining how healthy they collectively looked. Table 1 shows an example of vegetation health distribution on the gravel shadow A2 from July 9th, 2021. Plants were assigned either a 1: Near Death (not fully dead but close), 2: Poor (yellow leaves, plants look like they are dying), 3: Fair (some yellow leaves), 4: Good (slight signs of distress such as yellowing on the edge of leaves), or 5: Excellent (no signs of distress, peak health). Quadrats with no vegetation were assigned a 0: No vegetation. Lastly, the percent vegetation cover within each quadrat was determined. This was mostly determined outside the field using the pictures taken of each quadrat. Pictures were taken from above and centered, to show the quadrat square and the vegetation within each quadrat. By using the string that divided up the quadrat into 16 equal squares, the vegetation cover was determined by looking at a quadrat picture and determining that vegetation covered, for example, 1.5 squares, which then was divided by 16 to get a percent vegetation cover of 9%.

Vegetation Health						
July 9th, 2021						
	No Veg (0)	Near Death (1)	Poor (2)	Fair (3)	Good (4)	Excellent (5)
A2Q1						
A2Q2						
A2Q3						
A2Q4						
A2Q5						
A2Q6						
A2Q7						

A2Q8						
A2Q9						
A2Q10						
A2Q11						
A2Q12						
A2Q13						
A2Q14						
A2Q15						
A2Q16						
A2Q17						
A2Q18						

Table 1: Vegetation health distribution among quadrats from the engineered log jam A2 on July 9th, 2021

Statistics

Descriptive statistics were first conducted to determine the mean, standard deviation, median, and range of key variables measured on the gravel shadows of different types of log jams. Percent cover, vegetation health and substrate combinations were examined first. For data analysis, the last week of data collection was focused on because it was the most representative of plant health conditions at the end of the growing season. This would be most meaningful in assessing vegetation recruitment during the first year of log jam installation. Using the program R Studio, data was tested to see if there were differences in variables of interest across the gravel shadows. After testing the variables for normal distribution using a Shapiro-Wilk normality test, all parameters were not normally distributed, (i.e., percent cover had a right sided skew and vegetation health and substrate had left sided skews). Percent cover was arcsin-square root transformed and tested again for normality, this time passing the test ($W = 0.963$, $p = 0.049$). A one-way ANOVA was then performed using the percent cover dataset. Vegetation health and substrate were also transformed but did not pass the Shapiro-Wilk test, therefore non-parametric Kruskal-Wallis tests were performed on those datasets instead.

Given the importance of Sitka willow (*S. sitchensis*) as an early establishing native species, one objective of data analysis was to model willow presence on gravel shadows as a function of several independent variables. To do so, we developed a generalized linear mixed effects model using the lme4 package in R Studio (Bates et al., 2015). Potential explanatory for willow presence included site location, distance from log jam, and substrate type. To understand how site (and log jam type) differ depending on location, we modeled site as a random variable. Variables that seemed to impact willow presence and were not measured were moisture level and gravel shadow elevation, which differ among sites and are therefore also considered to fall under the random site variable. Distance from log jam and substrate type were modeled as fixed variables because they were determined to be unchanging after the first week of data collection. Substrate type was re-categorized into 3 groupings in order to have enough quadrats in each category while analyzing data. For example, there were a few quadrats with only fine substrate, which is not enough to model so fine and sand substrates were combined into one category. The combinations included one that had quadrats with only fine, only sand, or a combination of fine and/or sand with gravel fine, gravel coarse and cobble. The second combination excluded quadrats with fine substrate, and the third combination excluded quadrats with fine or sand substrates (Table 4).

IV. Results

<u>*Percent Vegetation Cover*</u>

Percent cover of vegetation in individual quadrats of gravel shadows range from 0% cover (experienced on all gravel shadows) to 99% cover in A2 over the course of eleven weeks (Table 2). Gravel shadow A2 had the highest mean percent cover of 18.0 ± 24.9%, followed by A1 (12.0 ± 11.2%). N1 had the lowest percent cover values (8.0 ± 14.0%) (Table 2). Although FR1 experienced some high percent cover, by the final week percent cover decreased overall, compared to A1 & A2 (Figure 11).

Percent cover values are shown from the first week of data collection with the last week of data collection in Figure 11. Overall percent cover decreased by the last week for the log jams FR1 and N1. However, percent cover increased by the last week for A1 and especially for A2. The 'x' within each boxplot on Figure 11 represents the mean. There is a slight increase for the means of A1 (9% in week 1 and 14% in week 11), but for A2 there is a more drastic increase in the means (9% in week 1 and 26% in week 11).

In order to see if percent vegetation cover on different gravel shadows was significantly different from each other by the end of the study period (week 11), a one-way ANOVA was performed using only week 11 data. There were significant differences between the log jams in terms of percent vegetation cover ($F = 6.118$, $p = 0.001$, $df = 3$). In order to compare the differences between each log jam, a post-hoc Tukey test was performed. This was a multiple pairwise comparison between the means of the log jams. The output showed that the difference between percent vegetation cover on the gravel shadows of FR1 and A2 ($p = 0.004$, 95% C.I. =

[-0.50, -0.07]) and N1 and A2 (p = 0.001, 95% C.I. = [-0.55, -0.01]) were significant. All other gravel shadow pairings were not significantly different from one another. The gravel shadow A2 had a much higher mean than FR1 and N1 by the last week of data collection (Figure 11).

	Mean	Standard deviation	Median	Range
FR1	10.0	16.3	2.0	0-75
N1	8.0	14.0	4.0	0-68
A1	12.0	11.2	8.0	0-48
A2	18.0	24.9	8.0	0-99

Table 2: Percent vegetation cover in quadrats on the gravel shadows of log jams FR1, N1, A1 & A2. Percent cover mean, standard deviation, median & range values are depicted for each log jam. Measurements were taken every Friday and averages were determined using data from each week over the course of eleven weeks of data collection.

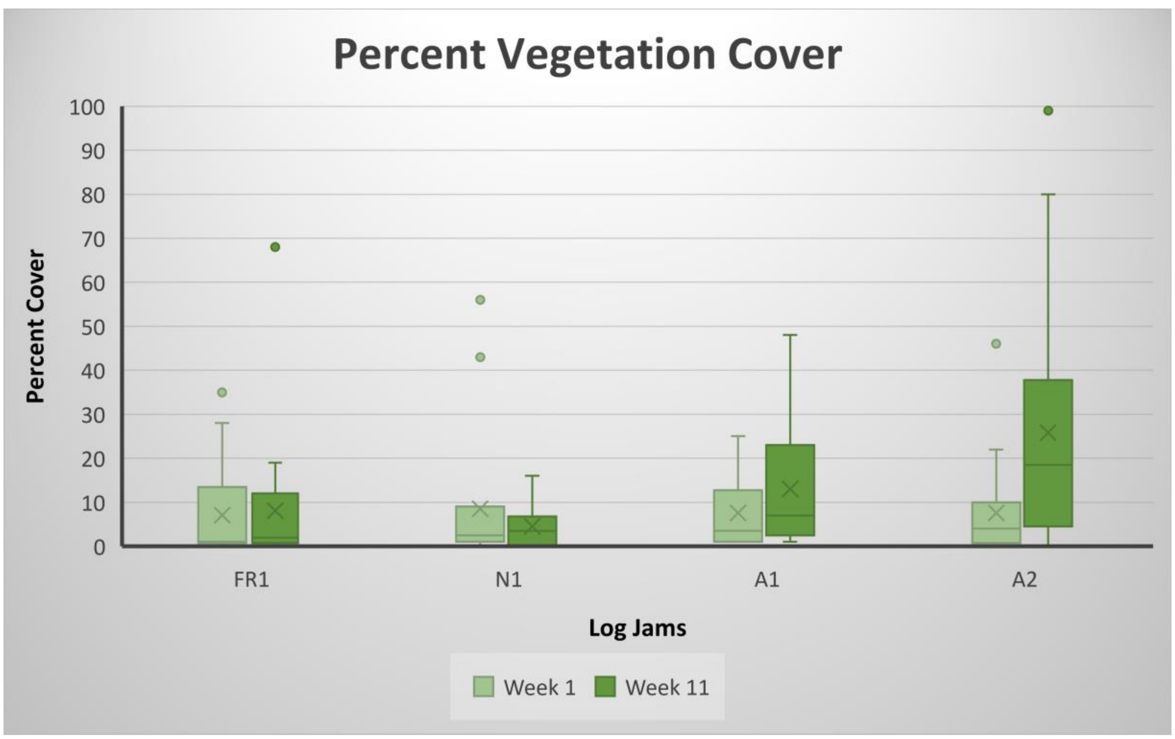

Figure 11: Boxplot of percent vegetation cover differences on log jams on the first week of data collection vs. the last week. The x on each boxplot represents the mean and dots represent any outliers in the data.

Vegetation Health

Vegetation health showed similar trends. For example, A2 had the highest mean percent cover and also a high mean vegetation health of 4.3 ± 1.0 (Table 3). A1 also had a high mean vegetation health of 3.8 ± 1.0, whereas N1 was the least healthy (3.5 ± 1.1), although FR1 also indicated lower vegetation health. Vegetation health in individual quadrats of gravel shadows range from near death (1) to excellent (5) on all gravel shadows.

Overall vegetation health measured in quadrats is shown on the first week vs. the last week in Figure 12. All gravel shadows experienced a decrease in vegetation health, however FR1 and N1 had more drastic decreases than A1 and A2. Due to a heat wave occurring right around Week 3 with temperatures reaching over 100 degrees Fahrenheit, all gravel shadows experienced record heat, but the gravel shadows on river left (FR1 & N1) experienced high temperatures without the moisture benefits that river right had (A1 & A2).

To see if gravel shadows differed from one another in terms of vegetation health on the final week (week 11), a one-way ANOVA was again considered. However, upon testing the normality of the dataset, vegetation health had a left sided skew that would not resolve with a transformation of the dataset. Therefore, the non-parametric Kruskal-Wallis test was conducted instead of a one-way ANOVA. There are significant differences between vegetation health on different gravel shadows ($\chi^2 = 14.275$, $p = 0.003$).

The Kruskal-Wallis test did not conclude which log jams in this study had gravel shadows with significant differences in vegetation health, so pairwise comparisons using Wilcoxon rank sum test with continuity correction were performed. The pairwise comparison showed that there were significant differences between the gravel shadows A1 & A2 ($p = 0.015$), A2 & FR1 ($p = 0.010$), and A2 & N1 ($p = 0.010$). This shows that A2 had differences in vegetation health than all the other gravel shadows, and with A2 having the highest mean by the final week, we can conclude that A2 was significantly healthier than all other gravel shadows tested.

	Mean	Standard deviation	Median	Range
FR1	3.6	1.2	4.0	1-5
N1	3.5	1.1	4.0	1-5
A1	3.8	1.0	4.0	1-5
A2	4.3	1.0	5.0	1-5

Table 3: Vegetation health in quadrats on the gravel shadows of log jams FR1, N1, A1 & A2. Measurements were recorded using a health index from 1-5. The index goes as follows: 1: Near Death (not fully dead but close), 2: Poor (yellow leaves, plants look like they are dying), 3: Fair (some yellow leaves), 4: Good (slight signs of distress such as yellowing on the edge of leaves), or 5: Excellent (no signs of distress, peak health). Vegetation health mean, standard deviation, median & range values are depicted for each log jam. Measurements were taken every Friday and averages were determined using data over the course of eleven weeks of data collection.

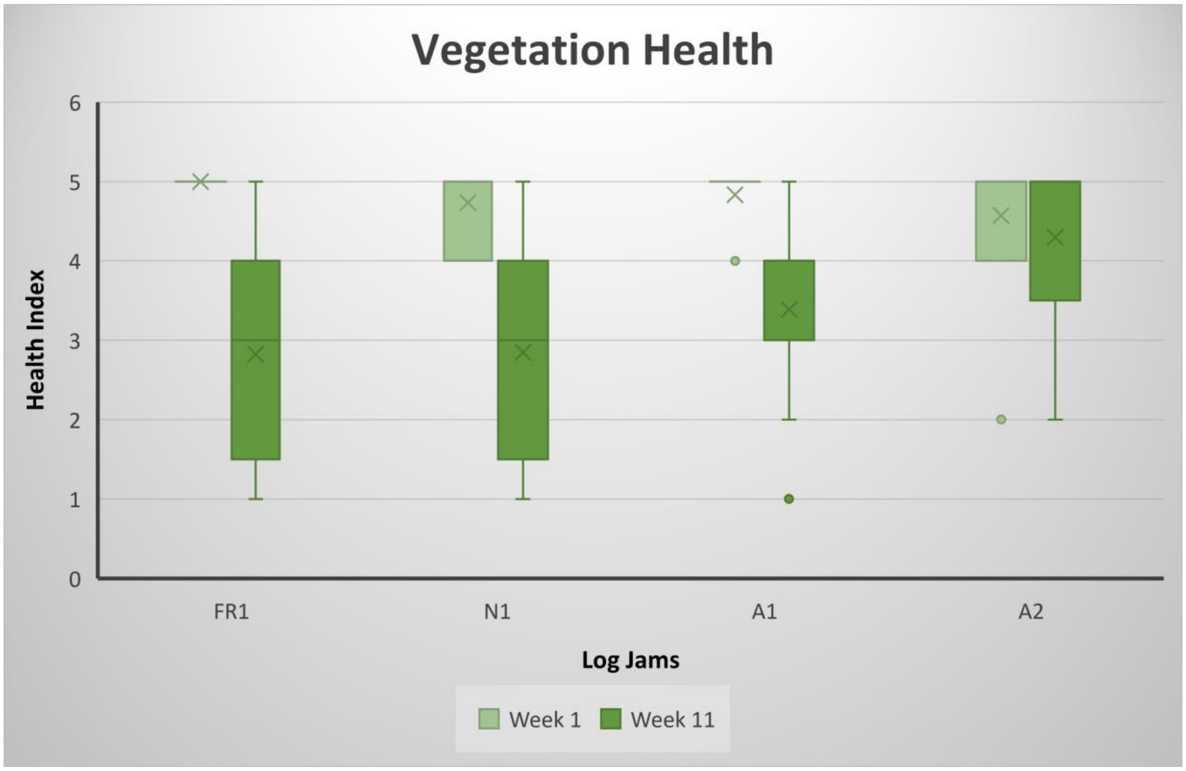

Figure 12: Boxplot of vegetation health differences on log jams on the first week of data collection vs. the last week. Vegetation health was recorded using a health index ranging from 1-5. The x on each boxplot represents the mean and dots represent any outliers in the data.

<u>*Substrate Type Combinations*</u>

Substrate type in individual quadrats of gravel shadows range from values of 1 (Fine, Sand, and/or Gravel fine/Gravel coarse/Cobble) to 3 (Gravel fine/Gravel coarse/Cobble only) (Table 4). A1 had the highest mean value of 2.1 ± 0.8 meaning that on average quadrats did not contain fine substrate. N1 had the lowest mean value of 1.3 ± 0.5 meaning that on average quadrats always contained fine or sand or both in combination with each other or with gravel fine, gravel course and/or cobble.

In order to determine if gravel shadows differed from one another in terms of substrate, a one-way ANOVA was considered. However, a left-sided skew in the data did not meet the required ANOVA assumption of normal distribution. Instead, the non-parametric Kruskal-Wallis rank sum test was performed, which showed significant differences between gravel shadows ($\chi^2 =$ 9.618, p = 0.022). Pairwise comparisons using Wilcoxon rank sum test with continuity correction were performed. The pairwise comparison showed that only A1 & N1 were significantly different from each other (p = 0.016). These results are similar to those observed from Table 5, where A1 had the highest mean with quadrats that on average did not contain fine substrate, whereas N1 had the lowest mean with quadrats generally containing fine or sand substrates.

Substrate type combinations: F=Fine, S=Sand, G/C=Gravel Fine, Gravel Coarse, and/or Cobble		
Combination 1	F, S, F+S+G/C, F+G/C	
Combination 2	S+G/C	No F
Combination 3	G/C	No F or S

Table 4: Substrate type combinations. Key located in the top row. All quadrats were categorized into one of the three combinations based on the substrate present within the quadrat.

	Mean	Standard deviation	Median	Range
FR1	1.8	0.8	2	1-3
N1	1.3	0.5	1	1-2
A1	2.1	0.8	2	1-3
A2	1.6	0.9	1	1-3

Table 5: Substrate type in quadrats on the gravel shadows of log jams FR1, N1, A1 & A2. Measurements were recorded during the first week and remained unchanged due to minimal disturbance over the weeks of data collection. Substrate type mean, standard deviation, median & range values are depicted for each log jam.

Sitka Willow (S. sitchensis) Presence

Sitka willow (*S. sitchensis*) presence in individual quadrats of gravel shadows range from zero quadrats in N1 to twelve quadrats in A2. A2 had the highest mean presence of 9.7 ± 1.6, followed by A1 (7.3 ± 1.3). N1 had the lowest willow presence of 1.2 ± 1.3 (Table 6). By the final week of data collection, the gravel shadow with the most quadrats with willow was A2, with 12 out its 18 quadrats containing willow (Figure 13).

	Mean	Standard deviation	Median	Range
FR1	1.6	0.7	2	1-3
N1	1.2	1.3	1	0-4
A1	7.3	1.3	7	6-9
A2	9.7	1.6	10	8-12

Table 6: Sitka willow (S. sitchensis) presence in quadrats on the gravel shadows of log jams FR1, N1, A1 & A2. Willow presence mean, standard deviation, median & range values are depicted for each log jam. Averages depict the average number of quadrats that contained Sitka willow on each log jam. Measurements were taken every Friday and averages were determined using data over the course of eleven weeks of data collection.

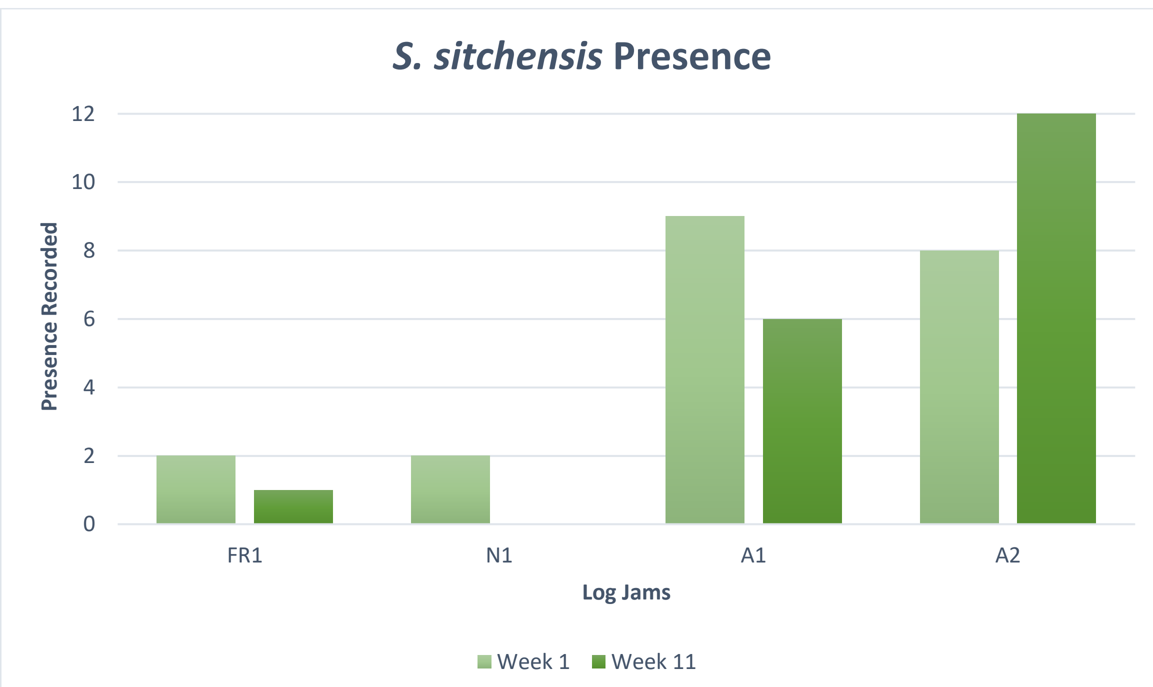

Figure 13: Bar graph comparing Sitka willow (S. sitchensis) presence on the gravel shadows of each log jam on the first and last weeks of data collection. Presence indicates that S. sitchensis

was present in a quadrat. For example, for the first week on the gravel shadow of FR1, willow presence was recorded in 2 quadrats.

Generalized Linear Mixed Effects Model

The differences in Sitka willow (*S. sitchensis*) presence across gravel shadows was compelling so further analysis of the data including willow presence was explored using generalized linear mixed effects modeling in R Studio using the package 'lme4'(Bates et al., 2015). The Kruskal-Wallis test on substrate showing significant differences between gravel shadows A1 and N1 led to the speculation that substrate may have influenced the increased numbers of willow on A1 and A2. Differences in site location of the gravel shadows such as moisture content and elevation were not measured but were observed to influence willow recruitment as well.

A GLMM allows for measured variables and unmeasured (random) variables to be used in the same model (Bolker et al., 2009). In this way, significant effects may be observed and/or controlled for (due to random variables that were not measured) while the significance of fixed effects can still be evaluated. For this modeling effort, the response variable used was Sitka willow (*S. sitchensis*) presence (1) or absence (0). Models with different combinations of the independent variables site, as a random effect, as well as distance from the log jam (transect line placement) and substrate type (combinations 1, 2, or 3) as fixed effects, were created and assessed using the Akaike information criterion (AIC) for model selection.

The best supported model with the lowest AIC, and an AIC weight of 0.61 included substrate as a fixed effect (but not distance from transect) and site as a random effect (see Table

7). However, there was also some support (AIC weight of 0.29) for the model with substrate as an additional fixed effect (Table 7). The simplest model (with a random effect of site) had no weight in the AIC ranking. Meanwhile, models with the most parameters (which included estimating regression coefficients for the effects of distance separately for each site) also had little support (Table 7). The use of GLMMs for this dataset should be considered preliminary, however, the fixed effects variables collected for this project (substrate and distance from transect) appeared to have an effect on willow presence/absence while controlling for the different sites.

Model	K	AIC	AIC Weight
Substrate + Site (random)	4	56.58	0.61
Distance + Substrate + Site (random)	5	58.03	0.29
Substrate + Distance | Site (random)	6	61.18	0.06
Substrate + Distance + Distance | Site (random)	7	62.25	0.04
Site (random)	2	70.31	0.00
Intercept-only (null model)*	1	87.47	0.00

Table 7: GLMM models used in the AIC calculation to determine the best-supported model (lowest AIC). The AIC weight is the proportion of the total amount of predictive power provided by the full set of models contained in the model being assessed. The highest AIC weight determines the best-supported model, here model 2 contains 61% of the total explanation that can be found in the full set of models (Bevans, 2022).

*The intercept-only model was calculated using glm() rather than glmm() and is reported for comparison of AIC only.

V. Discussion

After comparing the gravel shadows of log jams in terms of substrate, vegetation health and percent cover of vegetation, differences between gravel shadows were found. Specifically, A2 contained significantly healthier vegetation, and had a higher percent cover relative to the other sites. Further, it contained more Sitka willow (*S. sitchensis*) than the other sites. By the final week of data collection (week 11), percent vegetation cover was the highest at A2 relative to other gravel shadows and had the highest increase from week 1. Furthermore, there were significant differences between A2 and FR1 & N1. This is consistent with A2 having the highest percent cover mean and N1 having the lowest, followed by FR1. Similar findings occurred for vegetation health.

Although data collection took many variables into account, other factors which may have affected vegetation growth on gravel shadows were observed in the field. A heat wave during week 3 (July 2nd, 2021) led to temperatures above 100 degrees Fahrenheit and made it clear that gravel shadows that had less moisture availability would have decreases in vegetation health and percent cover. This was true of FR1 and N1, which were located on river left. High flows during rainy seasons led to gravel shadow formation behind those log jams, however river flow had decreased by the summer months and the channel concentrated towards river right. This left the FR1 and N1 gravel shadows with less sustained moisture to aid vegetation during high temperatures. On river right, A1 and A2 were parallel to the downstream flow of the river. A1 was next to the river and therefore it can be speculated that vegetation received more moisture to combat the heat wave during week 3 relative to gravel shadows which were farther away from river flow. However, the gravel shadow on A1 was observed to have a higher elevation in places which likely caused some vegetation to suffer during higher temperatures due to separation from the water table (Figures 7 & 15). The same drought-induced seedling mortality was observed in a study by McBride & Strahan (1984), on sites that were more elevated above Dry Creek in California. The only gravel shadow with substantial moisture levels was A2, which was in fact partially inundated during week 1 due to a side channel which allowed river water to backflow water around the A1 gravel shadow and submerge the lower half of A2 (Figure 14). The end of A2 was observed to be at a lower elevation which allowed for water to cover the shallow half of the gravel shadow. River flow decreased by week 3, and the channel was cut off, leaving the inundated portion of the A2 gravel shadow to slowly recede over the summer months (Figure 15).

The heat wave that led to temperatures over 100 degrees Fahrenheit was unusual for the region (Wang et al., 2022). Had temperatures reached their normal highs over the summer of 2021, vegetation decline on some of the gravel bars may not have been so steep. Vegetation health got worse over the weeks following the heat wave, especially on N1 and FR1, and also the elevated portion of A1. This unusual event may have been the reason for such widespread declines in vegetation health on some gravel shadows.

An increase in vegetation percent cover and overall health on the gravel shadows A1 and A2 correlated with an increase in willow presence (*S. sitchensis*) on those gravel shadows. Willow seeds are commonly pollinated via insects or wind and transported via wind and/or water (Gage & Cooper, 2005), so seeds most likely came to the gravel shadows in great numbers from parent trees upstream. Earlier germination of cottonwood seedlings followed by willow a few weeks later was observed in the study by McBride & Strahan (1984), with germination ending by mid-July. The germination of willow seedlings in this study points to the fact that there were parent trees upstream as well as perhaps a preferred timing of seed dispersal for willow over cottonwood. Germination of most willow seedlings in this study occurred in early to mid-July, which is later than cottonwood would have been dispersed (McBride & Strahan, 1984). Willow seedlings that came in on the inundated portion of A2 germinated even later into August as the water level slowly dropped. Cottonwood was only observed a handful of times in and around quadrats on the gravel shadows of this study, so cottonwood seedlings may not have had favorable conditions to germinate earlier in the season, or there were not enough seedlings that made it to the gravel shadows from parent trees observed upstream.

The inundation and/or continual moisture of the A1 and A2 gravel shadows likely allowed for Sitka willow (*S. sitchensis*) seeds to successfully germinate in great numbers. This is reflected in Figure 11, because high numbers of *S. sitchensis* show an increase in percent cover of A1 and A2 by the final week, while drier conditions, die-offs of other vegetation, and lower *S. sitchensis* populations on FR1 and N1 show a percent cover decrease by week 11. The complete inundation of over half of the gravel shadow A2 slowly receded over the course of the summer (Figure 16). This likely allowed for vegetation to survive the heat wave and thrive in more dense populations. The highest willow presence was on A2, and this was the only gravel shadow to increase in the number of quadrats with willow by the final week of data collection. This increase occurred because willow began to sprout later in the summer after water levels dropped and seeds germinated in the previously inundated section of the A2 gravel shadow (Figure 17).

Figure 14: June 18th, 2021 (Week 1 of data collection). Log jams A2 (left) and A1 (right) surrounded by water flowing in from the Lower Satsop River. Most of the A2 gravel shadow was flooded during the first week of data collection.

Figure 15: July 2nd, 2021 (Week 3 of data collection). Log jam and gravel shadow of A1 shown behind Megan Tuttle (WDFW). Water has receded and the connection has been severed between the gravel shadow of A2 (left, not shown) and the Lower Satsop River (right).

Figure 16: July 2nd, 2021 (Week 3 of data collection). Log jam A2 and the A2 gravel shadow with the transect line extending to the end of the gravel shadow a bit before the orange tape measure. Quadrats extend back to the log jam (pink flags), but many are inundated with standing water after the back-flow of water over the first week. The channel connecting the gravel shadow to river water has been cut off by this week (see Figure 15).

Figure 17: Photos showing the A2 gravel shadow as water receded and vegetation established. Top photo was taken on July 30th, 2021 (Week 7 of data collection). Bottom photo was taken on August 20th, 2021 (Week 10 of data collection).

The high concentrations of Sitka willow (*S. sitchensis*) on the lower half of gravel shadow A2 were clearly connected to the early summer inundation and sustained moisture as the water receded. Willows grow along riverbanks and their seeds travel downstream to be deposited on moist, exposed soil (Stettler et al., 1995). As the water receded, new willow seedlings germinated on A2 by the last week of data collection (Figure 17). The jump in willow concentration also caused the percent cover of quadrats on A2 to increase by the final week. The healthy new seedlings increased the vegetation health index for A2 above all other gravel shadows. High moisture was a contributing factor in willow recruitment and sustained health on A2, and assisted vegetation on A1, however the observed higher elevation of that gravel shadow possibly led to lower survival rates overall. High temperatures and droughts can cause plant mortality by reducing soil moisture and pore water availability for root uptake (Caponi et al., 2019). Gravel bars typically have coarse sediments at the bar head and fine sediments at the bar tail (Li et al., 2014). With the presence of an engineered log jam in front of a gravel shadow, scouring occurs and slows flow, allowing for fine sediment to be deposited on gravel shadows (McHenry et al., 2007).

Substrate is another factor that can influence the establishment of vegetation on gravel shadows. Coarser sediments have larger pore spaces which can drain water more quickly than fine sediments. Fine sediments tend to have more moisture availability and nutrients due to organic matter buildup (Kalníková et al., 2018). Nutrient availability in fine sediments is beneficial to the recruitment of fast-growing plants along with sustained moisture availability (Kalníková et al., 2018). On the A2 gravel shadow, the inundated section that receded by the last week was made up of mostly fine sediment. This gave way to prolific willow germination in a matter of weeks (Figure 17). McBride & Strahan (1984), observed that willow seedlings preferred sediment sizes less than 0.2 centimeters in their study. This was consistent with the substrate measured in this study on the A2 gravel shadow. The categorized substrates of fine and sand were both less than 0.2 centimeters in size and were both found in substrate combination 1, with sand also found in substrate combination 2. The A2 gravel shadow had a mean substrate combination of 1.6 and a median of 1 (Table 5), indicating an average array of fine sediments on the gravel shadow. High nutrients are often available in fine sediments that were deposited with organic matter on gravel bars (Merritt & Wohl, 2002). The high number of germinated willow seedlings on the A2 gravel shadow were therefore likely aided by a combination of moisture availability, nutrient availability, and fine sediments. Despite N1 also having fine sediments that could have supported seedling growth, the percent cover of quadrats and vegetation health on N1 were the lowest across all the gravel shadows. The missing variable of sustained moisture and perhaps nutrient availability on N1 coupled with the heat wave in week 3 likely led to poor establishment of vegetation on that gravel shadow.

Out of the log jams chosen for this study, three were engineered log jams and one was a naturally occurring log jam. Overall vegetation establishment and colonization by the native species *S. sitchensis* was the best on the engineered log jam A2, as was percent cover and vegetation health. This was an apex log jam, which was installed in order to redirect river flow and reduce erosion downstream. Engineered log jams are typically installed with the goal of improving channel complexity, erosion control, and/or increasing salmon habitat (Abbe et al., 2003). Increasing salmon habitat in this case is generally defined by an increase in scouring which creates pools, as well as a decrease in river flow, creating safe spaces for salmon to rest or hide from predators (Abbe et al., 2003). This has likely occurred in front of the apex log jams in this study however the scouring occurs underwater and is difficult to confirm visually without performing a stream survey that includes diving (Zimmerman & Winkowski, 2021). The best supported model for the GLMM that was determined using AIC had willow presence as a response variable and substrate and site (random) as independent variables. A higher presence of willow could be achieved with the right substrate and site conditions. In the case of A2, the finer substrate, moist conditions, and nutrient availability of the site likely led to robust establishment of willow after a period of inundation.

Native vegetation establishment on gravel shadows is rarely discussed in the literature as an outcome to installing engineered log jams. However, in addition to large woody debris improving salmon habitat, riparian vegetation lowers stream temperatures by providing shade (Martin et al., 1986) and hosts invertebrate populations which salmon may feed on (Flory & Milner, 1999). As seen in this study, placing an engineered log jam so that river flow may inundate the gravel shadow or provide sustained moisture over the summer months could provide ideal conditions for native species such as willow to colonize the gravel shadow. This has the potential to further improve salmon habitat after vegetation establishment. The nature of willow and cottonwood to deepen their root structures during the dry season (Caponi et al., 2020) will likely stabilize gravel shadows and log jams closer to the structure and improve the longevity of installed log jams.

Future engineered log jam installation projects may consider location of the log jam not just in terms of improving salmon habitat by creating pools and altering river flow but also by anticipating where the river might flow in regard to the gravel shadow behind the log jam (to trap water) and placing the log jam to encourage vegetation establishment on gravel shadows. Substrate was also a factor that improved the establishment of willow on gravel shadows in this study. Finer sediment is ideal for willow recruitment, however engineered log jams already affect substrate size array after installation. McHenry et al. (2007), observed that engineered log jams influenced substrate size from mostly cobble to more gravel fines after installation. Daley & Brooks (2013), also recommended backfilling complex jams with course gravel instead of finer substrate due to the amount of scouring these structures experience once installed. Therefore, substrate size consideration is not as important as location of the log jam for a project wanting to encourage native vegetation growth on gravel shadows.

Overall, additional research needs to be conducted on vegetation recruitment of gravel shadows behind engineered log jams. Vegetation recruitment is not currently measured when looking at the effectiveness of installed engineered log jams, even though the presence of native vegetation could have positive impacts on salmon and help overall log jam structure. However, there are so many different factors that go into river restoration projects that results may vary depending on location. Vegetation recruitment on gravel shadows behind engineered log jams can vary depending on the size of the river or stream system, the location of the log jam in regard to the river flow, seed sources from native plants, seed sources from invasive plants, surrounding infrastructure near the river, flooding, droughts, etc. Recruitment of vegetation on gravel shadows on a site can also vary depending on the year of establishment. Ideal weather conditions such as the absence of droughts could allow for vegetation to strongly establish and be able to survive through the flooding season and droughts in following years. Vegetation could also be hit hard by record weather events that result in low survival rates.

VI. Conclusion

This research project set out to measure vegetation colonization of newly formed gravel shadows behind engineered log jams over the first growing season. Three engineered log jams and one naturally accrued log jam were sampled at a site on the Lower Satsop River in Washington State. The most compelling observation was that the gravel shadow A2 experienced a period of inundation which led to it containing the healthiest vegetation, most of which was the native species Sitka willow (*S. sitchensis*).

Data analysis revealed that there are factors influencing the establishment of *S. sitchensis* which included site location and substrate type. Robust communities established in areas with fine substrate or a mix of fine and gravel substrates, especially on gravel shadow A2. The sustained moisture on A2 and A1 and possible nutrient availability also likely played roles in the successful colonization of Sitka willow on those gravel shadows.

Future restoration projects that plan on utilizing engineered log jams in rivers should consider log jam placement not only to redirect river flow or increase the scouring of pools, but also to optimize native plant recruitment on newly formed gravel shadows. If there is a possibility to place the log jam such that the gravel shadow gets moisture from the current of the river or is partially inundated, there may be increased *Salix* or *Populus* recruitment, provided that those species are native to the area and have established populations upstream. This could save money on the project by avoiding the need to plant native species after project completion, as well as provide stability for the log jam and habitat for terrestrial and aquatic species. The successful establishment of vegetation on gravel shadows would also provide healthy habitats that may be able to withstand the effects of climate change. The uncertainty of the severity of climatic events in the future such as droughts and flooding require restoration projects to support vegetation that is healthy enough to survive environmental changes.

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