SKAGIT RIVER LARGE WOODY DEBRIS ASSESSMENT

Connecting LWD to the 2005 Skagit Chinook Recovery Plan

SKAGIT WATERSHED COUNCIL
A Community Partnership for Salmon

Skagit Watershed Council
815 Cleveland Ave, Suite 201
Mount Vernon, WA 98273
360-419-9326

Natural Systems Design

1900 N. Northlake Way, Suite 211
Seattle, WA 98103

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In 2005, the National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) listed Puget Sound Chinook salmon as threatened under the Endangered Species Act of 1973. The 2005 Skagit Chinook Recovery Plan (Plan) was published in the same year to provide "a detailed pathway by which Skagit Chinook populations can recover to sustained numbers." The Plan describes recovery goals, limiting factors, and recovery actions for Skagit Chinook salmon. The specific listed restoration strategies are based on an understanding of limiting factors for Chinook recovery, and some of these limiting factors are directly connected to the presence and function of large woody debris (LWD). LWD should be recognized as a tool in the path toward regional Chinook recovery. An understanding of large wood in the context of geomorphic and riverine processes in the Skagit River Basin is critical to prioritization of salmon recovery actions, assessment of baseline conditions and restoration actions, and adaptive management of restoration strategies.

Large woody debris resources have been significantly depleted in the Skagit River Basin and across the Pacific Northwest since European colonization, and this loss is directly connected to extensive salmonid habitat degradation throughout the Basin and the region (Collins 1998). This report synthesizes information on the function of large wood in the Skagit River and similar river systems to aid in the potential development of an effective large woody debris assessment. Our goals are to create a set of descriptive, conceptual models that explain how large wood in the Skagit River Basin functions to achieve the implicit and explicit goals of the 2005 Skagit Chinook Recovery Plan, and to investigate and present potential methods for comprehensive assessment of large wood resources across Tier 1 and Tier 2 Chinook habitat in the Skagit Basin (Figure 1).

FUNCTION OF LARGE WOOD IN THE SKAGIT RIVER BASIN

Connecting LWD to Limiting Factors for Skagit Chinook

The 2005 Skagit Chinook Recovery Plan (Beamer et al. 2005) identifies six distinct Chinook populations that currently exist in the Skagit River Basin (Lower Skagit Falls, Upper Skagit Summers, Lower Sauk Summers, Upper Sauk Springs, Suiattle Springs, and Upper Cascade Springs) and lists 16 specific factors that are significantly limiting these populations:

1. Seeding Levels*
2. Degraded Riparian Zones *
3. Poaching
4. Dam Operations*
5. Sedimentation and Mass Wasting*
6. Flooding*
7. High Water Temperatures*
8. Hydromodification*
9. Water Withdrawals
10. Loss of Delta Habitat
11. Loss of Delta Habitat Connectivity
12. Loss of Pocket Estuary Habitat
13. Loss of Pocket Estuary Habitat Connectivity

14. Availability of Prey Fish Species
15. Illegal Habitat Destruction and Degradation
16. High Seas Survival

*indicates a limiting factor directly connected to LWD functions.

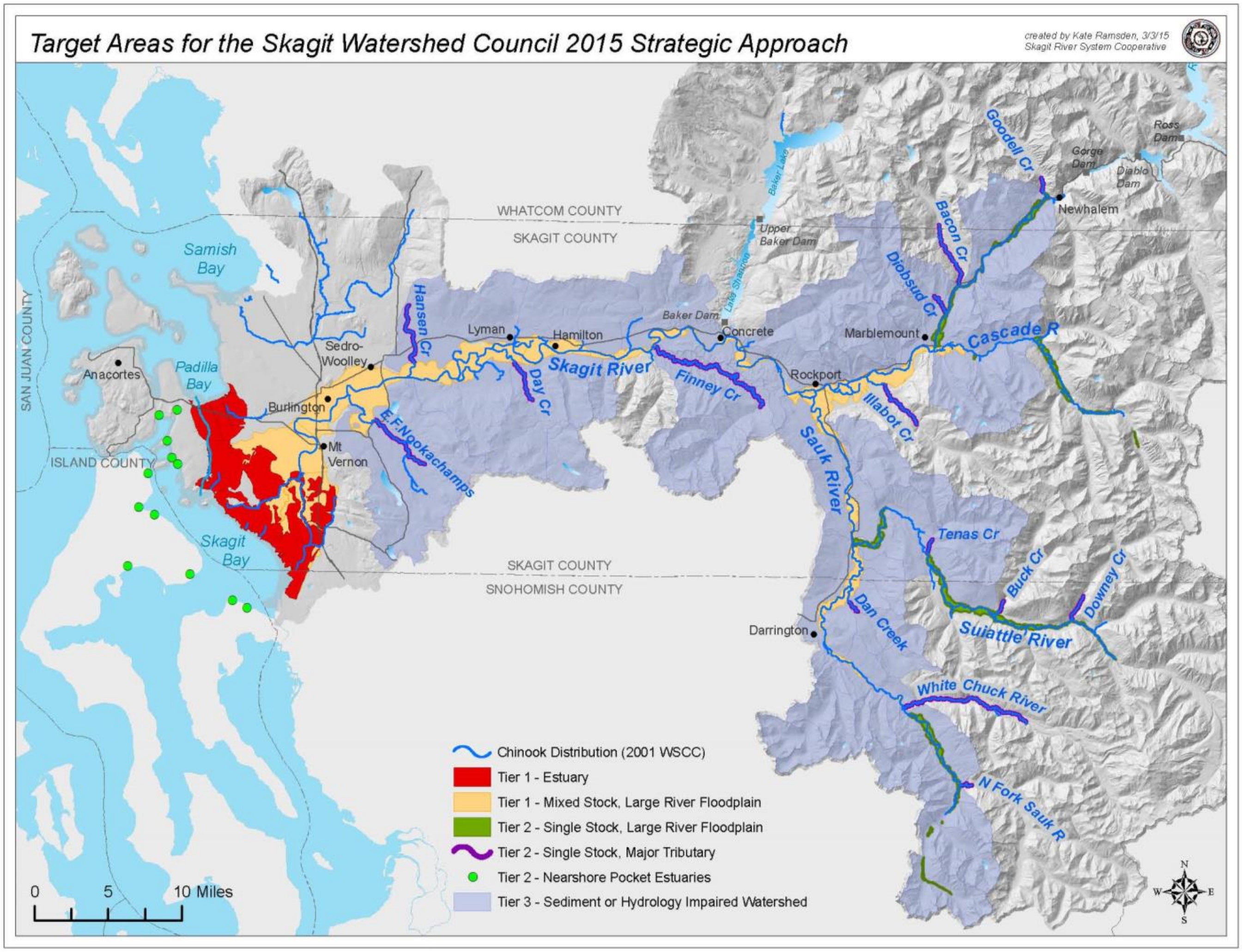

Figure 1. **Extent of Tier 1 and Tier 2 habitat in the Skagit River Basin**

For the purposes of this investigation, we have identified limiting factors that are influenced by the presence of large woody debris (marked above with an asterisk). Though a lack of large woody debris (LWD) is not specifically mentioned in the 2005 report as a limiting factor for Chinook salmon in the Skagit River Basin, presence and function of LWD is directly connected to many of the listed factors. Additionally, the role played by a given piece of large wood is highly dependent on local geomorphology and stream size. For example, a log that is both channel-spanning and pool-forming in a headwater tributary might have no more than a trivial impact on a large lower Skagit River reach, unless it becomes a part of an LWD aggregate, or jam. Lack of LWD would have a particularly significant impact on stream-type or yearling Chinook, which have a freshwater residence time of at least one year and are highly dependent on freshwater habitat (Lowery et al. in press). All six Skagit River Chinook populations exhibit both ocean-type and stream-type life histories (Lowery et al. in press).

There are also several areas in the 2005 Plan where placement of LWD is identified as a specific part of recommended restoration actions, especially in the context of floodplain restoration and reconnection. The Plan states that “floodplain areas are especially important for freshwater rearing because the availability of complex mainstem edge habitat, backwaters, and off-channel habitat is essential for the foraging and refugia of all freshwater life history phases [of Chinook salmon].” The Plan’s General Freshwater Habitat Restoration Strategy emphasizes “reconnecting isolated floodplain areas and restoring mainstem edge habitat by removing, relocating, or improving hydromodification and floodplain structures.” In prioritizing the improvement of floodplain connection and mainstem habitat complexity, the Plan highlights the importance of large wood as a tool to ameliorate the impacts of hydromodification, induce reconnection of disconnected floodplain areas, and improve mainstem habitat where presence of unmovable infrastructure precludes floodplain reconnection actions.

It is clear that riverine LWD resources have declined significantly throughout the Skagit River since European colonization, and that this change has affected the character of riverine habitats in the Basin (Collins 1998). This report investigates the connection between the goals of the 2005 recovery plan and the function of large wood, using the limiting factors and restoration strategies outlined in the 2005 Skagit Chinook Recovery Plan as a framework for these connections.

Seeding Levels (and Habitat Availability)

The 2005 Skagit Chinook Recovery Plan states that “without spawners, unlimited restoration actions won’t restore [Chinook] runs; thus, a fundamental action in Chinook recovery is to provide sufficient spawners.” However, the Plan also reports that, though it is possible that certain Chinook populations lack sufficient spawning returns, the Skagit system as a whole is not underseeded. At the time of the 2005 Plan, the Skagit system appeared to be at capacity for at least three age-0+ life history strategies: freshwater parr, estuary/delta-rearing smolts, and pocket estuary-rearing smolts. In other words, the addition of more adult spawners in the system would not lead to more Chinook in subsequent generations unless there is an increase in habitat to support more fish in multiple life stages. Thus, availability of freshwater spawning and rearing habitat is one of the key limiting factors for Chinook recovery in the Skagit Basin. According to the 2005 Plan, “increasing the availability of freshwater rearing habitat should increase the number of parr migrants.”

The addition of large wood to the Skagit River has the potential to immediately increase availability of salmonid rearing and spawning habitat and improve the river’s natural ability to create quality habitat in the short- and long-term, thereby increasing the production capacity of the river system and increasing seeding levels in future generations. Large woody debris is a key component of salmonid habitats across the Pacific Northwest, and the presence of riverine LWD fosters the development and enhancement of rearing habitats in many ways. In both small and large channels, LWD formations (ranging from single key pieces to massive jams) trap sediment, diversify flow characteristics, create changes in bed profile, promote side channel and off-channel development, stabilize bars, and form islands which provide edge habitat for juvenile Chinook and other species (Abbe and Montgomery 1996, Beschta and Platts 1986, George Robison and Beschta 1990, Heede 1972, Lisle 1986a, b, Marston 1982, Nakamura and Swanson 1993). Montgomery et al. (1995) and Beechie and Sibley (1997) found that pool frequency increases with increasing LWD loading in various forested channel types of southeast Alaska and Washington State, while Torgersen et al. (1999) reported that Chinook salmon have an affinity to pool habitat. Numerous other studies have shown the importance of diverse habitats (including pools, instream structures, off-channel habitat, and large wood) to salmonid population health. Roni and Quinn (2001) sampled thirty streams in western Oregon and Washington and found that LWD placement can lead to higher densities of juvenile coho salmon in summer and winter and higher densities of steelhead (*O. mykiss*) and cutthroat trout (*O. clarki*) in winter. Cederholm et al. (1997)

reported significantly increased coho salmon smolt yields in a Chehalis River tributary following LWD addition. Bisson et al. (1987) found that riverine large wood improves fish habitat quality in all sizes of streams. Shirvell (1990) observed that 99% of juvenile coho and 83% of juvenile steelhead occupied areas immediately downstream of placed instream root wads across drought, normal, and flood flows. Johnson et al. (2005) used a multiple before-after control-impact study to examine the biological effect of LWD loading in a western Oregon stream, and found that the abundance of juvenile salmonids surviving to smolt increased significantly after LWD placement. Lowery et al. (in press) found that across the Skagit River Basin stream-type Chinook juveniles were very frequently associated with large log jams (Figure 3). All of this information together reveals that a loss of LWD can lead to simplification of stream habitats, decreased pool frequency, reduction in productivity of juvenile salmonids, and decreased abundance and diversity of fish communities.

In general, across the Skagit River Basin, we expect that the addition of LWD in simplified reaches of the river system would spur an increase in habitat complexity, natural formation of new habitats, and survival rates for juvenile and spawning Chinook salmon. Nichols and Ketcheson (2013) observed that addition of 181 artificially-placed log jams in Finney Creek, a tributary of the Skagit River, increased natural recruitment of LWD. In the Elwha River, Pess et al. (2012) found that juvenile Chinook densities were significantly higher in reaches with placed log jams compared to untreated control reaches. Additionally, Zimmerman et al. (2015) found that juvenile Chinook of at least one freshwater rearing strategy, subyearling parr, "should benefit from continued restoration of freshwater habitats in the Skagit River system." There is also evidence that the targeted addition of LWD to relieve pressure on key Chinook life stages may offer the best return on investment. For example, the 2005 Skagit Chinook Recovery Plan reported that the Suiattle Spring Chinook population, which only spawns in low-gradient reaches above the mouths of Suiattle tributaries, is likely adequately seeded and is probably limited by available spawning habitat. The Plan specifies that 81% of the 7.4 stream kilometers that have a potentially suitable gradient for Chinook spawning in these Suiattle tributaries would only function as appropriate spawning habitat if channel obstructions (e.g. large woody debris) create forced Pool-Riffle (fPR) habitat. Merz (2001) studied associations between Chinook spawning and LWD in northern California and found that LWD can make less optimal habitats more suitable for Chinook spawning, and may allow for higher concentrations of redds in already suitable reaches. Also, MacInnis et al. (2008) found that redd counts of Atlantic salmon (*Salmo salar*) increased dramatically after LWD placement on a stream in Nova Scotia, Canada. This evidence provides a compelling case for the addition of LWD in these Suiattle tributaries. Aside from Suiattle Spring Chinook, other Skagit populations are not believed to be spawning habitat limited (Beamer et al. 2005). However, other stages of Skagit Chinook life histories may face habitat-related bottlenecks that could be remedied through artificial addition or natural recruitment of large wood. A large-scale inventory of large wood recruitment and resources across the Basin could help identify areas where LWD addition is critical to removing these bottlenecks and identify areas of functional wood in the systems as analogs or reference areas.

Degraded Riparian Zones

The 2005 Skagit Chinook Recovery Plan (2005) states that "riparian wood is necessary to create pool-riffle (PR) habitat, which is the preferred spawning and early rearing habitat of Chinook salmon." Mature riparian forests provide fish cover, prevent waters from overheating, and contribute large wood to rivers, the latter of which is a primary driver in the formation of pool-riffle habitats and other complex habitat features (Bilby and Ward 1991, Collins et al. 2012, Fetherston et al. 1995, Meehan et al. 1977, Montgomery et al. 2003). Unfortunately, human activities have significantly degraded riparian zones throughout the Skagit River Basin and beyond, which has limited natural recruitment of LWD (Beamer et al. 2005, Bisson et al. 1987, Collins 1998).

It is commonly understood that mature forests with healthy riparian areas contribute to riverine LWD resources (Bilby and Ward 1991, Naiman et al. 2002), but, less intuitively, it appears that riverine LWD resources can contribute to the development of healthy riparian areas and mature forests (Montgomery and Abbe 2006). Abbe and Montgomery (1996) conducted field surveys on the Queets River on the Olympic Peninsula and found that LWD jams can control local channel hydraulics to provide refugia for riparian forest development over many years. According to Naiman et al. (2000), "LWD becomes uniquely important in creating suitable sites for colonization by riparian plants in alluvial rivers." In a managed setting, LWD placement can be strategically utilized to prevent excessive bank erosion while planted vegetation grows up on formerly denuded banks. According to Collins and Montgomery (2002), "reforested floodplains can develop naturally recruited wood jams within 50 to 100 years," at which point natural processes should maintain sufficient riverine LWD abundance to support increased salmonid production.

This data suggests that the addition of riverine LWD in the Skagit River Basin will aid in the recovery of degraded riparian areas that limit populations of Chinook salmon. However, LWD additions for the benefit of riparian communities should be considered only within the context of existing geomorphic conditions and other riparian restoration actions. The 2005 Plan states that "LWD projects should be limited to sites where pool-riffle habitat once existed and where the LWD won't be washed away." Additionally, of course, many other actions can be taken to restore riparian habitat and function, including managed livestock grazing or exclusion, replanting of native vegetation, and protection of existing riparian buffers. These actions will help ensure long-term sources for wood recruitment. Understanding the current condition of wood resources in the Skagit can help us target the riparian restoration efforts for the longer term as well as short-term installation of wood where needed to improve spawning and rearing habitat and to achieve the goals of the 2005 Skagit Chinook Recovery Plan.

Dam Operations

Between 1920 and 1959 three hydroelectric dams were constructed upstream of Newhalem on the Skagit River as a part of the Skagit River Hydroelectric Project and two dams were constructed on the Baker River near Concrete as a part of the Baker River Hydroelectric Project. According to the 2005 Skagit Chinook Recovery Plan, these dams have introduced numerous problems to Skagit salmonid communities, including dewatering of redds, loss of habitat, and loss of channel diversity. The dams have transformed the entirety of the mainstem Skagit into a regulated or semi-regulated hydrosystem. Additionally, these structures almost entirely cut off the LWD supply from the upper Skagit and Baker Rivers, as dams trap wood coming from upstream (Gurnell et al. 2002). Some wood trapped behind Gorge Dam and Diablo Dam is moved downstream into the flowing Skagit, but all the large wood trapped behind Ross Dam is isolated from the lower river (Lowery 2017).

The Skagit and Baker River dams also significantly change downstream hydrologic regimes, which limits LWD recruitment downstream of the dams. Before the dams were constructed, major flood events were unregulated and had more potential to inundate the floodplain, create new off-channel features, and recruit large wood from riparian areas and floodplain forests (Beamer et al. 2005). Though the Skagit River still receives LWD inputs from the mainstem downstream of Newhalem, the entire Sauk-Suiattle tributary watershed, the Cascade River, and numerous smaller tributaries, LWD supply is likely highly limited compared to historic levels due in large part to the multiple impacts of hydroelectric infrastructure (Beamer et al. 2005, Collins 1998).

Sedimentation and Mass Wasting

Sedimentation issues identified in the 2005 Skagit Chinook Recovery Plan mainly are a result of extensive timber harvest activities across the Basin and glacial melt from Glacier Peak. Sedimentation primarily affects

Chinook spawning, egg incubation, and egg survival. The 2005 Plan states 1) that increased bed mobility leads to redd scour from higher sediment supply, 2) that the deposition of fines over redds leads to egg suffocation and increased difficultly of emergence, and 3) that excess fine sediment deposition causes a reduction of macroinvertebrate production and degradation of edge habitat.

LWD affects streambed and sediment mobility, and the removal of LWD exacerbates the impacts of sedimentation. The ability for sediment to be transported in a stream is a function of water velocity, where sediment transport potential increases with velocity. Removal of instream wood reduces flow resistance resulting in increased energy for erosion (Abbe et al. 2016, Manga and Kirchner 2000). LWD acts to obstruct flow in the channel, dissipating energy and reducing water velocity (Abbe and Brooks 2011, Linstead 2001). The effect of LWD on flow can be quite dramatic. Manga and Kirchner (2000) studied a spring-fed river in which LWD covered less than 2% of the streambed and found that it provided roughly half of the total flow resistance. Nakamura and Swanson (1993) found LWD played an important role in storing sediment in an Oregon coastal watershed, particularly in first through fourth order streams. Additional studies have also demonstrated the ability of LWD to help retain sediment (Abbe 2000, Abbe et al. 2016, Abbe and Montgomery 1996, Montgomery and Abbe 2006, Montgomery et al. 2003). The loss of LWD supply and removal of LWD from streams ultimately promotes sediment mobility, exacerbating the issue of redd scour.

Sediment mobility and erosion also contribute to fine sediment issues. Increased erosional power in streams from the removal of LWD leads to channel incision (Lane 1955, Montgomery et al. 2003). As streams incise they become disconnected from their floodplains. When flow from a stream spills out onto the floodplain, it greatly decreases in velocity due to the drastic increase in stream width and increased resistance. The slower moving water over the floodplain is less able to hold sediment in suspension, resulting in deposition of fine sediments on the floodplain. Reducing transport of fine sediments in Skagit tributaries will help to improve salmonid egg survival further down in the watershed.

Flooding

Flooding during egg incubation has the greatest impact on egg to migrant fry survival. Reduced egg survival during flooding is assumed to be due to bed mobility leading to redd scour and fill (Beamer et al. 2005). Additionally, flood frequency and magnitude is anticipated to increase over the next century due to climate change (Tohver et al. 2014). Flooding is already the largest contributor to salmonid egg mortality, and, with floods expected to worsen over the next century, mitigating the effects of flooding is a key to Chinook recovery in the Skagit River system.

The 2005 Skagit Chinook Recovery Plan highlights restoration of floodplain function as a key mechanism for mitigating the impacts of flooding on Chinook salmon. The Plan describes how functioning floodplains allow floods to dissipate energy and store sediment that would otherwise destabilize streambeds, and that hydraulically sheltered floodplain habitat can protect eggs and provide juvenile salmonid with flow refugia. LWD plays an essential role in the connection of rivers to their floodplains and the formation of floodplain channels and off-channel habitat in the Pacific Northwest (Collins and Montgomery 2002). Brummer et al. (2006) investigated wood accumulations in eleven unconfined forested rivers in Washington State, and found that log jams contributed to lower channel gradients, reduced bank heights, increased channel roughness, and the initiation of side channels and channel avulsions. Wood removal reduces the frequency of overbank inundation and floodplain connectivity (Abbe et al. 2016). Collins and Montgomery (2002) observed that large wood jams are "integral to maintaining a multiple-channel pattern and in causing and mediating avulsions" in the Nisqually River, which also flows into the Puget Sound. In the opposite situation, the removal of LWD from streams can lead to incision and the disconnection of streams from their floodplains (Abbe et al. 2016, Collins 1998, Lane 1955, Montgomery et al. 2003). Additionally, Abbe and Montgomery (1996) found that apex LWD jams in the Queets River promoted forested island development.

Forested islands create stable features in the floodplain that split flow and form floodplain channels, as well as provide edge habitat. Rivers with high amounts of wood can also have lower sediment transport rates (Manga and Kirchner 2000, Montgomery et al. 2003).

The combination of the role of LWD in maintaining floodplain water storage, forming floodplain habitats and refugia, storing sediment, and slowing floodwaters make large wood integral to the mitigation of flooding impacts on Chinook survival.

High Water Temperatures

High water temperatures harm Chinook populations by stressing individuals, decreasing salmonid survival rates, promoting the growth of competitor species, and blocking access to upstream habitats. In the Skagit River Basin, the removal of riparian vegetation and reduction of stream flows have resulted in higher water temperatures (Beamer et al. 2005).

The presence of large woody debris can aid Chinook and other salmonid populations in streams with high water temperatures. LWD promotes pool formation, and deep pools can provide thermal refugia (Thompson 2012, Torgersen et al. 1999). LWD also increases floodplain connectivity, anabranching channel formation, and hyporheic exchange, which can provide a consistent influx of cool water even in the hottest seasons (Abbe and Brooks 2011, Bilby 1984, Bisson et al. 1987, Collins and Montgomery 2002, Sawyer et al. 2011). Bilby (1984) found that cool water pockets in a fifth-order western Washington stream were on average 4.7°C cooler than ambient streamwater on warm afternoons, and LWD has the potential to form such pocket habitats. Torgersen et al. (1999) quantified distribution and behavior of adult spring Chinook salmon in the John Day River Basin, and found that Chinook adults in multiple sub-basins preferred pools and areas of relatively cool water. Their study stresses the potential for thermal refugia to provide key habitat for species existing at the margin of their environmental tolerances (Torgersen et al. 1999). Loheide and Gorelick (2006) combined stream temperature measurements with coupled ground/surface water modeling to demonstrate elevated groundwater inflow through a restored reach in a Sierra Nevada meadow. In the restored reach, which was returned to a pool-riffle morphology after having been incised, they also observed streamflow that persisted several weeks after adjoining reaches were dry, and stream temperatures that were more than 3 °C lower than in adjoining reaches. Presence of riverine LWD can help decrease channel widths and improve riparian plant communities (Abbe and Brooks 2011, Abbe and Montgomery 1996, Montgomery and Abbe 2006), and both Justice et al. (2017) and White et al. (2017) predicted significant decreases in temperature with narrowing of channel widths and riparian restoration in the Grande Ronde River system in Oregon. Nichols and Ketcheson (2013) studied changes in Finney Creek, a tributary of the Skagit River, for over a decade as 181 LWD jams were installed along 12km of the stream. They found that extensive placement of LWD structures was connected to an increase in pool area and depth, additional recruitment of natural LWD, and a significant decrease in water temperatures even as air temperatures increased (Nichols and Ketcheson 2013).

These studies reveal that sufficient riverine LWD loading could be especially important as climate change continues to place additional thermal stresses on salmonid populations of the Skagit River Basin and the Pacific Northwest. According to Beechie et al. (2013), many restorative actions that are connected to LWD functions, including re-establishing floodplain connectivity, restoring streamflow regimes, and re-aggrading incised channels, are most likely to ameliorate streamflow and temperature changes and increase salmonid population resilience in the face of climate change.

Hydromodification

Riverine floodplains are some of the most biologically productive ecosystems on the planet, but have been widely degraded and destroyed for conversion to agriculture, industry, and development worldwide (Opperman et al. 2010). Prior to European occupation of the area, the Skagit River system was highly dynamic. Local creeks and rivers frequently shifted channels, created new side channels, forged connections to off-channel areas, and inundated floodplain habitats. According to 19th century accounts, a massive log jam present near Mount Vernon until the 1870s would cause the river to overflow its banks annually, "flooding 150 square miles" (Collins 1998). In the mid-1800s, people started armoring riverbanks with riprap, building roads that constricted channel migration, removing large wood from the river, and constructing levee systems to prevent flooding in certain areas of the Skagit's natural floodplain (Collins 1998). Unfortunately, these actions have seriously limited the Skagit River's biological productivity and intrinsic potential to create complex natural habitats (Beamer et al. 2005). Beechie et al. (1994) investigated losses in coho salmon (*Oncorhynchus kisutch*) habitat and smolt production in the Skagit River Basin, finding that the production capacity of summer and winter habitats had decreased by ~24% and ~34% respectively since European settlement. The study cited hydromodification—including diking, ditching, dredging, and the associated destruction of off-channel habitats (including side channels, sloughs, alcoves, and tributaries)—as the driving force in overall habitat degradation. Lowery et al. (in press) found that generally Chinook use the same habitats as coho in the Skagit River, so we can only assume that such habitat degradations have significantly affected Chinook populations as well.

Large wood can be a primary driver in channel avulsion, floodplain formation, and the creation and engagement of side- and off-channel habitats, both in undisturbed systems and in rivers where complex habitat features have been lost as a result of hydromodification (Collins and Montgomery 2002, Davidson 2011, Gurnell et al. 2002). LWD jams are influential in the creation of delta distributary channels in estuaries (Abbe 2000, Abbe and Montgomery 2003). Wood accumulations contribute to lower bank erosion rates (Abbe et al. 2016). By naturally reducing bank erosion rates and splitting flow, logjams result in narrower channels, increase flow depths and pool frequency, as well as increasing wood retention (narrower, more complex channels reduce wood transport capacity). According to Bisson et al. (1987), large woody debris creates and maintains diverse physical habitats by "(1) anchoring the position of pools along the thalweg, (2) creating backwaters along the stream margin, (3) casing lateral migration of the channel and the formation of secondary channel systems in alluvial valley floors, and (4) increasing depth variability." Though it may be impossible today to foster wildly dynamic, habitat-forming riverine events in the Skagit Valley in the context of modern development, agriculture, and infrastructure, LWD can still be used on a smaller scale to improve Chinook salmon habitat, restore natural riverine processes, and undo some of the damages of hydromodification. For example, Hafs et al. (2014) used coupled hydrodynamic and bioenergetic models to investigate the impact of complexity-generating LWD on the growth potential of Chinook salmon. They found that the addition of LWD to simplified reaches asymptotically improved Chinook growth potential on a reach scale, and that growth potential was quadrupled under ideal LWD loading. With an understanding of normal river dynamics, as well as physical and structural constraints, LWD can be strategically placed to influence large scale floodplain reconnection and expansive habitat formation at and beyond the reach scale (Figure 2).

Figure 2. Large wood jams dominate channel morphology on the lower Quinault River, another large river in western Washington. This natural jam, which formed in 2009, completely blocked the former main channel and forced the creation of the complex, anabranching channel features shown in the photo. The photo shows a portion of the log jam in 2017 located about 3 miles upstream of Taholah, WA (source: Quinault Indian Nation, 2017). Flow is from bottom to top of photo. A 2017 field survey found the logjam raised water elevations approximately two feet during low flows.

Conceptual Model for LWD in the Skagit Basin

Drawing on our investigations into the relationship between LWD and the above limiting factors, our research on large wood dynamics in diverse river systems, and an understanding of the unique ecology and geography of the Skagit River Basin, we have created a brief conceptual model describing the varying functions of LWD from the headwaters to the mouth of the river:

The Skagit River begins high in the North Cascades of Washington and British Columbia. These forested headwaters historically contributed plentiful large wood resources to the Skagit River. However, the construction of three dams on the Skagit River upstream of Newhalem and the two dams on the Baker River near Concrete effectively removed the LWD supply from the upper Skagit and Baker Rivers and transformed the entirety of the mainstem Skagit into a regulated or semi-regulated hydrosystem. Though the Skagit River still receives LWD inputs from the mainstem downstream of Newhalem, the entire Sauk-Suiattle tributary watershed, the Cascade River, and numerous smaller tributaries, LWD supply is likely highly limited compared to historic levels. Additionally, intensive logging throughout much of the Basin, disconnection of floodplain habitats, changes in riparian land use, hydromodification, and intentional removal of LWD jams have also led to a dramatic decrease in Skagit riverine LWD resources over the past 150 years.

Throughout the Skagit River Basin, large woody debris forms key riverine habitat features that have a significant impact on hydraulic processes, geomorphology, and salmonid habitat quality (Abbe and Montgomery 1996, Naiman et al. 2002, Opperman et al. 2006, Shields and Alonso 2012). LWD structures (also known as jams) are integral to forested stream ecosystems (Turcotte et al. 2016), and the presence of LWD throughout the Skagit watershed promotes the development of complex habitat features (Abbe et al. 2016, Montgomery et al. 1995), diversifies water flow characteristics while decreasing average magnitude of flow velocity (Hafs et al. 2014, Linstead 2001, Shields and Gippel 1995), controls sediment transport (Abbe and Montgomery 1996, Manga and Kirchner 2000, Montgomery et al. 2003, Nakamura and Swanson 1993), and improves habitat for fish and macroinvertebrates (Bisson et al. 1987, Lester and Boulton 2008, Roni and Quinn 2001, Shirvell 1990).

Large woody debris also has unique impacts on distinct geomorphic sections of the Skagit River:

- In narrow, high-gradient, headwater reaches of the Skagit River system, individual large wood pieces can easily span the channel and dominate stream bedform and hydraulics. There may be some clumping of LWD into jams, or LWD may remain as scattered pieces. LWD creates a stepped longitudinal profile that controls the storage and release of sediment and detritus, which enables effective processing of organic inputs from the surrounding forest (Bisson et al. 1987).
- In somewhat wider, intermediate-gradient reaches in the middle of the Skagit River system, single pieces of large wood no longer span the channel, and LWD becomes lodged on the banks, on bars, or in the channel bed. These lodged pieces and ensuing LWD accumulations often form the most productive fish habitat in the mainstem of the river (Bisson et al. 1987), and can easily form established jams that control local bedform and hydraulics (Montgomery and Abbe 2006). In intermediate-gradient reaches that would be slightly too steep for Chinook spawning, presence of LWD can create a forced pool-riffle morphology that allows for redd creation (Beamer et al. 2005). Lowery et al. (in press)found that in hydrologically mixed rain and snow dominated reaches, which are generally in the middle of the Skagit River system, juvenile stream-type Chinook were frequently associated with LWD jams and jam-related river features across multiple seasons (Figure 3).
- In low-gradient tributaries of the Skagit River, single pieces of wood generally do not span the entire channel, but can form snags in the channel that precipitate large LWD jams that obstruct large portions of the channel and dominate local hydraulics. LWD jams can induce the creation of off-channel habitats, thermal refugia, and unique floodplain features. Lowery et al. (in press) observed that stream-type Skagit Chinook use non-natal habitats on a seasonal basis, including the lower reaches of many non-natal Skagit tributaries.
- In wide, low-gradient Skagit River reaches surrounded by historic floodplain, even single pieces of large wood can lead to the formation of massive LWD accumulations, or jams, that can change the course of the river, completely block river channels, induce massive floods, and last for centuries (Abbe and Brooks 2011, Abbe and Montgomery 1996, Montgomery and Abbe 2006). For example, a 4,000-foot-long LWD jam on the Skagit River near Mount Vernon was present for at least a century until its removal in the late 1870s (Collins 1998). This jam hosted living trees up to 3 feet in diameter and is estimated to have frequently caused flooding of over 150 square miles. The size and spacing of riverine LWD accumulations generally increase as stream order increases (Bisson et al. 1987). LWD plays a key role in activating floodplain features and side channels (Abbe and Brooks 2011), and the

loss of side channels along the mainstem Skagit River has been shown to be a major limiting factor for coho salmon (O. kisutch) smolt production and to have an impact on Chinook salmon (Beechie et al. 1994). According to Zimmerman et al. (2015), "off-channel habitat in the middle and lower portions of the Skagit River are of particular importance for Chinook salmon rearing and survival given that the majority of spawning occurs in the main stem and all out-migrants pass through the region." In wide-valley reaches, LWD helps to stabilize channel migration while increasing floodplain connectivity (Beechie et al. 2010, Booth et al. 1996). Additionally, LWD is a major source of flow refugia and habitat complexity in mainstem reaches of the lower Skagit River (Beamer et al. 2005). Lowery et al. (in press) found that in hydrologically rain-dominated lower reaches of the Skagit River system, LWD jams and jam-related river features hosted the highest densities of juvenile Chinook across multiple seasons (Figure 3).

The depletion of LWD supplies and resources has led to extensive degradation of fish habitats throughout the Skagit River Basin and the region (Collins 1998, Gippel et al. 1996, Montgomery and Abbe 2006). Now large wood is commonly placed in the Skagit River and across the Pacific Northwest as a part of habitat restoration actions (Beechie et al. 2010, Hilderbrand et al. 1998, Manners et al. 2007, Nichols and Ketcheson 2013). In considering the application of large woody debris for salmon recovery, it is important to remember that the Skagit River has the innate potential to provide superior habitat for Chinook salmon and other key species if it were allowed to recover from excessive human impacts and function naturally. The river provided those ecological benefits for many millennia before the arrival of European settlers. However, to provide many of the benefits documented in this report large wood pieces need to be inherently stable (i.e. supported by key pieces that the river channel is incapable of transporting at most flows over a long period of time) or engineered for such stability (Embertson 2017). The artificial installation of large woody debris should be recognized as an interim technique to aid in the eventual restoration of large- and small-scale natural riverine processes (Beechie et al. 2010, Nagayama and Nakamura 2010). Further assessment to gain a spatially explicit understanding of LWD supply and loading across the Skagit River Basin would help in the prioritization of Chinook recovery actions and the restoration of degraded habitats.

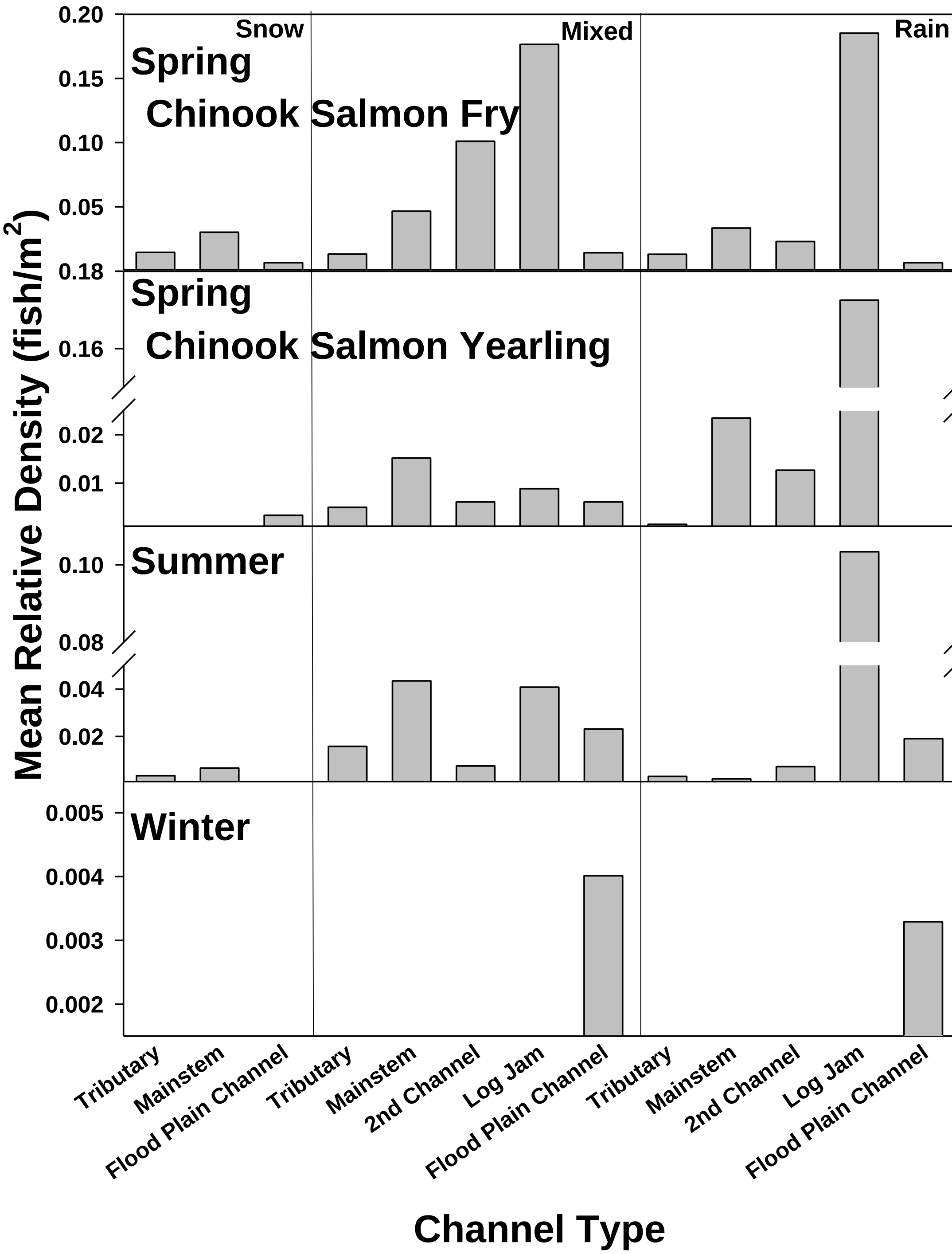

Figure 3. Mean relative density of Chinook salmon, fry and stream-type, by season and channel type from snorkel surveys in the Skagit River (Lowery et al. in press). Snow-dominated survey sites were located on the Suiattle River upstream of the Snohomish County line and on the Sauk River near Bedal Campground. Hydrologically mixed sites were located on the Sauk River, Suiattle River, Cascade River, Day Creek, the mainstem Skagit River above Birdsview, and area tributaries. Rain-dominated survey sites were located on the mainstem Skagit River and lower tributaries downstream of Birdsview (see Figure 4).

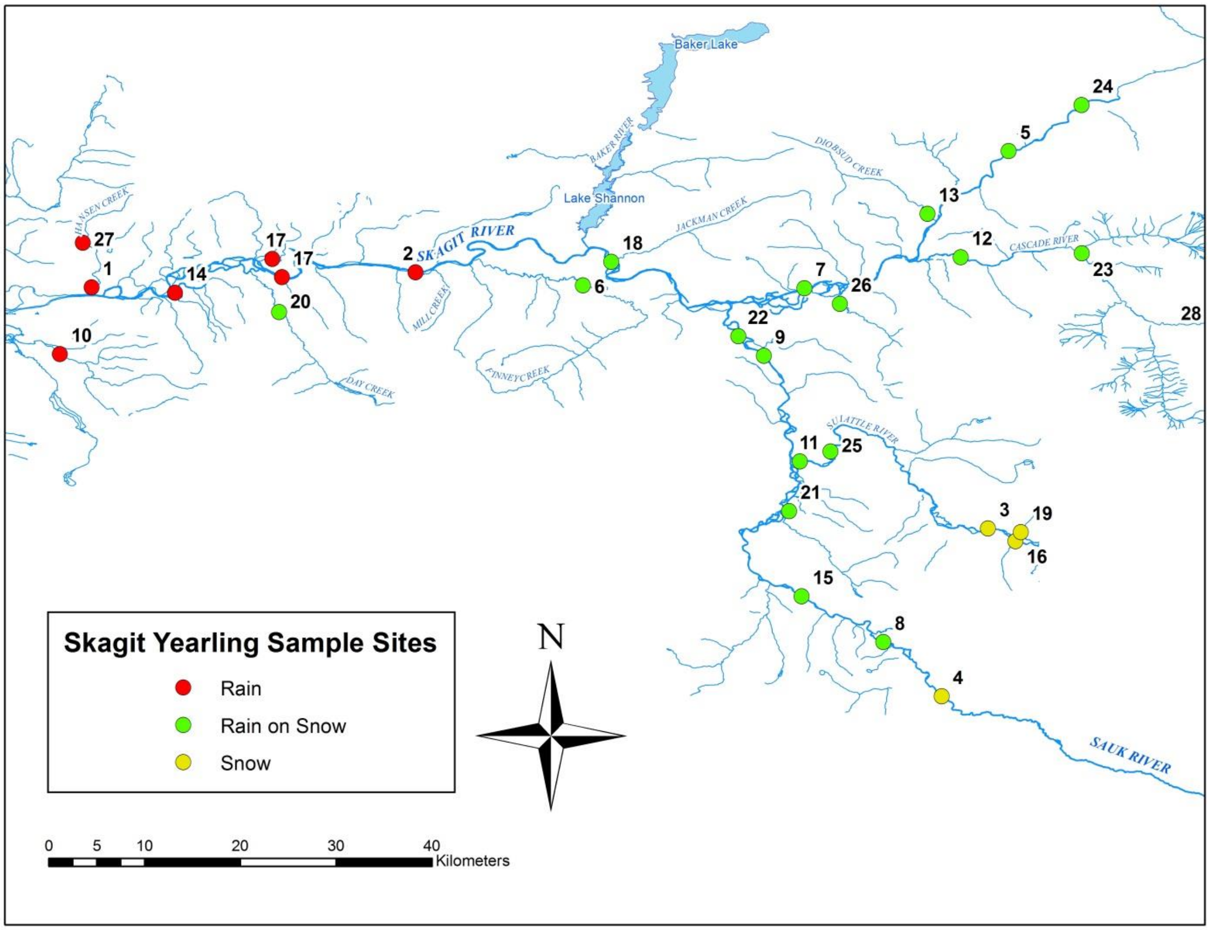

Figure 4. Location of snow-dominated, mixed, and rain-dominated study sites within the Skagit River basin in Lowery et al. (in press).

Further assessment to gain a spatially explicit understanding of LWD supply and loading across the Skagit River Basin would help in the prioritization of Chinook recovery actions and the restoration of degraded habitats.

Integration of Limiting Factors and Conceptual Model into Metrics Matrix

Starting with the background identified in the discussion on limiting factors from the 2005 Skagit Chinook Recovery Plan, and applying the context of the conceptual model allows a visualization of processes that are most affected by wood and relate to the limiting factors. Using the categories of factors identified above, we developed a matrix to show the processes that are tied to those limiting factors and also related to the amount of function of wood in the Skagit River watershed. From these processes, we then identified the measurements and metrics that could be used to monitor changes in those processes, and in turn, changes in the limiting factors. The matrix is presented in Table 1 and the metrics will be used as one of the selection criteria for recommended methods described in the next section.

Table 1. Metrics Matrix for Limiting Factors

LIMITING FACTOR (2005 PLAN)	PROCESSES AFFECTED	MEASURES	METRICS
Seeding Levels	Sediment storage	# and frequency of stable wood structures, volume of jams, types of jams (cover, meander jam, apex jam)	number of jams, jams/km, m^3, jam type
	Pool and pool tail out formation	# and frequency of stable wood structures, riparian input modeling/wood recruitment	number of jams, jams/km, m^3 and m^3 per km in smaller streams (modeled)
	Wood loading	# and frequency of stable wood structures/ location, volume of wood, area of jams, types of jams (cover, meander jam, apex jam)	jam type, map layer, number of jams, jams/km, m^3, m^2
Dam Operations	Wood transport	wood abundance, frequency, distribution in regulated vs. non-regulated reaches, persistence as compared to 2006 data	total number or pieces in a reach, jams/km, number of functional jams in regulated vs. non-regulated systems, number of jams > than 100ft in contact with landform in 2017 vs. number of jams > 100 ft in contact with landform in 2006
	Flow regime	wood volume and distribution of jams - reduced flood flows are less likely to cause channel migration and bank erosion which would lead to wood recruitment, transport and loading. Also, formation of off-channel habitat which may be a depositional sink for floating wood in the Skagit.	map layer, number of jams, jams/km, m^3
	Wood loading	wood frequency in Sauk and Suiattle vs. in Upper Skagit (using historic changes in size of trees vs. present day riparian conditions*)	total number or pieces in a reach, jams/km, number of functional jams in regulated vs. non-regulated systems, number of jams > than 100ft in contact with landform in 2017 vs. number of jams > 100 ft in contact with landform in 2006
Sedimentation and Mass Wasting	Pool tail-out formation	# and frequency of stable wood structures, riparian input modeling/wood recruitment	number of jams, jams/km, m3 and m3 per km in smaller streams (modeled)
	Sediment transport	# and frequency of stable wood structures/ location, volume of wood, area of jams, types of jams (cover, meander jam, apex jam)	jam type, map layer, number of jams, jams/km, m^3, m^2
	Landscape - mass wasting	volume of wood downstream from slide areas, key members downstream from slide areas or tributaries	m^3, number of key members
	Wood loading	# and frequency of stable wood accumulations, riparian input modeling/wood recruitment	number of jams, jams/km, m3 and m3 per km in smaller streams (modeled)
Flooding	Hydraulics/Hydrology	number of nodes/split flow associated with wood (Beechie 2017)	number of nodes (Beechie 2017), River Complexity Index (Brown 2002)
	Sediment transport	# and frequency of stable wood structures/ location, volume of wood, area of jams, types of jams (cover, meander jam, apex jam)	jam type, map layer, number of jams, jams/km, m^3, m^2

LIMITING FACTOR (2005 PLAN)	PROCESSES AFFECTED	MEASURES	METRICS
	Wood transport/recruitment	wood frequency, abundance, volume of wood in confined reaches vs. connected floodplain reaches, riparian input modeling/wood recruitment	jam type, map layer, number of jams, jams/km, m^3, $m^{2,}$ m^3 and m^3 per km in smaller streams (modeled)
	Floodplain Interactions	# of functional jams / map jams with > 100 ft in contact with landform	# of functional jams / map jams with > 100 ft in contact with landform
	Floodplain Interactions	riparian input modeling/wood recruitment	m3 and m3 per km in smaller streams (modeled)
High Water Temperatures	Hydrology	# and frequency of stable wood structures, riparian input modeling/wood recruitment, number of nodes/split flow associated with wood (Beechie 2017)	number of nodes (Beechie 2017), River Complexity Index (Brown 2002), jam type, map layer, number of jams, jams/km, m3, m2, m3 and m3 per km in smaller streams (modeled)
	Residence Time of water - temporal effect on temperature	# of pools (> 1m depth) - where feasible from green LiDAR	# of pools >1m by reach
	Hydraulics	see wood loading metrics above	number of nodes (Beechie 2017), River Complexity Index (Brown 2002), jam type, map layer, number of jams, jams/km, m3, m2, m3 and m3 per km in smaller streams (modeled)
	Riparian health/shading	riparian structure modeling/seral class	m^3 and m^3 per km in smaller streams (modeled)
	Riparian health/shading	channel width, anabranching (multiple channels) vs single thread	number of nodes (Beechie 2017), River Complexity Index (Brown 2002), jam type, map layer, number of jams, jams/km, m3, m2, m3 and m3 per km in smaller streams (modeled)
Hydromodifications	Floodplain Interactions/function	# and frequency of stable wood structures/ location, volume of wood, area of jams, types of jams (cover, meander jam, apex jam), number of nodes/split flow associated with wood (Beechie 2017)	number of nodes (Beechie 2017), River Complexity Index (Brown 2002), jam type, map layer, number of jams, jams/km, m3, m2, m3 and m3 per km in smaller streams (modeled)
	Lateral migration	Wood loading along bank	jam type, map layer, number of jams, jams/km, m^3, m^2 in contact with bank
	Lateral migration	Riparian conditions - SWC data, riparian modeling (diameter of trees - see Abbe et al. 2003)	SWC data metrics
	Lateral migration	# of functional jams / map jams with > 100 ft in contact with landform	number of jams, number of jams in contact with >100 ft of landform

METHODS IDENTIFIED FOR WOOD INVENTORY AND ASSESSMENT

The development of a watershed scale assessment of LWD dynamics across the Skagit River Basin will be essential for guiding future Chinook recovery efforts given the importance of LWD on processes that limit viable Chinook habitat (Table 1). An inventory of the location, form, and function of existing LWD can help identify discrete river locations that are lacking LWD in which to target habitat actions, and those locations that currently have adequate LWD supplies. Furthermore, an assessment of the LWD dynamics (loading, recruitment, stability over time) within the system can help to categorize reaches where it is necessary to re-engage river processes (such as channel migration) to improve habitat instead of solely adding more LWD because it is unlikely that the system will repair itself in terms of natural recruitment of wood. In order for these assessments to be effective, large wood needs to be spatially catalogued and analyzed which can be challenging in a watershed the size of the Skagit. These measurement challenges however, can be overcome with the employment of modern geospatial techniques as well as statistical modeling for reaches where remote sensing methods do not work (Atha and Dietrich 2015, Kasprak et al. 2012, Marcus et al. 2002, Vondrasek 2017, pers. comm).

The advancement of geospatial technology and data availability over the past decade has greatly increased the feasibility of conducting large-scale watershed assessments of LWD dynamics for basins the size of the Skagit (Abalharth et al. 2015, Atha and Dietrich 2015, Dietrich 2016, Fonstad et al. 2013, Kasprak et al. 2012, Richardson and Moskal 2016). Prior to the improvement in geospatial techniques, LWD assessments consisted of field surveys where technicians would walk entire stream networks and map LWD by hand (Fausch and Northcote 1992, Faustini and Jones 2003, Hyatt 2001, Montgomery et al. 1995). Although effective, these types of assessments can be very time-consuming (and expensive) for larger systems such as the Skagit. Modern geospatial techniques such as the analysis of aerial photography, LiDAR, and hyperspectral imagery allow practitioners to perform desktop evaluations of LWD which can greatly reduce costs and increase repeatability. These techniques however, are only effective in wider reaches where the stream is unabated by canopy cover and can be viewed from aerial photography. In smaller systems with dense canopy cover, field methods still represent the most effective LWD assessment technique, although efficiencies can be gained for larger watershed by sub-sampling reaches and developing statistical models to extrapolate the findings. The next two sections review the most current methodologies for assessing LWD dynamics in both larger rivers using imaging (such as the mainstem Skagit) and smaller streams (i.e. Bacon Creek) and off-channel habitat areas where geospatial methods are infeasible.

Large Rivers

The majority of streams within Tier 1 and Tier 2 Chinook habitat within the Skagit basin have open canopies and are able to be assessed by remote sensing techniques (Figure 1). These rivers include the main-stem Skagit, Sauk, Suiattle, Cascade, and White Chuck Rivers. In these systems, the active channel can be readily observed from aerial photography and/or LiDAR and LWD can be analyzed. This allows practitioners to dramatically reduce the time and effort for LWD assessments compared to field methods. The following section reviews specific techniques for potential LWD assessments within these larger systems.

Aerial Photography

Aerial Imagery (e.g. National Agriculture Imagery Program (NAIP))

Traditional aerial photographs have been used to accurately map and measure LWD jams when the active channel can be visualized (Marcus et al. 2002, Tonkin et al. 2016, Ulloa et al. 2015). This method involves manually reviewing geo-referenced aerial images of the study reach and using a geographic information system (GIS) tool to measure and catalogue the desired metrics in planform. The size of LWD that can be measured using this method is dependent on the pixel size of the photograph, and inaccuracies have been reported when pieces of LWD smaller than an individual pixel was attempted to be measured (Marcus et al. 2002). Thus, this method is more suitable for large accumulations of LWD instead of individual pieces. Furthermore, because no elevation data is associated with each photograph, LWD volumes cannot be measured using this technique. Given the wide availability of aerial photograph time-series however, this method allows for the addition of a time component to LWD analyses. This method is commonly incorporated into other analysis protocols such as LiDAR to improve accuracy (Richardson and Moskal 2016).

Pros:

- Inexpensive
- Widely available public data
- Time series can be analyzed due to availability of several years of photographs

Cons:

- LWD measurement size dependent on resolution of photographs
- Only surface area of jams can be measured (and not volume)
- Submerged wood cannot be assessed
- Cannot assess areas of the stream covered by the forest canopy (i.e. along banks)

Photogrammetry (SfM)

Photogrammetry (also known as Structure from Motion or SfM) is a recently revitalized technique that uses a multi-view photogrammetric process to develop a digital elevation model (DEM) from thousands of continuous aerial photos (Dietrich 2016, Fonstad et al. 2013). Although photogrammetry has been around for decades, SfM has become more ubiquitous in environmental research and engineering due to dramatic improvements in computing power that allow for processing the high quantity of data rich images. Thus, SfM produces both a DEM and a mosaic of high resolution images, instead of one or the other, which allows for the measurement of LWD volumes. As the method is still in development, it is not as accurate as traditional LiDAR, although it is significantly less expensive. Cameras can be mounted to traditional aircraft, helicopters, or even drones which increases the availability of this technique to smaller organizations.

The methods to assess LWD would be similar to traditional aerial photography (manually reviewing images and delineating LWD), however volume calculations could also be made because top and water surface elevations could be derived from the DEM.

Pros:

- Lower cost than LiDAR
- Intermediate between large scale commercial aerial technology and small scale drone technology
- Both high resolution aerial images and DEM are created using method
- Volume calculations can be made from DEM

Cons:

- Method still in development
- DEM can have distortion
- Covering large areas unfeasible with a drone
- DEM cannot typically measure below the water surface
- Manual mapping needed

Photogrammetry (Multiresolution Seamless Image Database (MrSID))

Multiresolution Seamless Image Databases can be used as an approach to photogrammetry which can allow for automated calculation of wood counts and volumes with additional processing of the database and quantity calculations using Computer Assisted Drafting (CAD). Work in the White River, a tributary to Lake Wenatchee, was performed over a 4 kilometer reach to assess the quantities of wood placed and captured as the result of a restoration project implemented by the US Fish and Wildlife Service. Using the high resolution images of the reach, calculations of the length and diameter, and volume of wood accumulations were performed as a method of effectiveness monitoring for a restored reach and a comparable control reach. Automation of estimates was accomplished using a specifically developed software to process the MrSID files. Estimates were evaluated for quality assurance and quality control using manual measurements of the images and CAD calculations. Source images were collected using an aircraft to specifically fly the reach. Some evaluation of wood volumes below the water surface were made where water clarity allowed.

Pros:

- Could get economies of scale for large areas
- High resolution aerial images, MrSID, and CAD files are created using method
- Volume calculations can be made from CAD

Cons:

- Method still in development- few contractors provide
- Requires manual QA/QC
- Cost for image collection and processing
- Cannot typically measure below the water surface, application is limited

LiDAR

LiDAR (Light detection and Ranging) is a commonly used method for measuring the topography over large areas (i.e. Atha and Dietrich 2015, Vondrasek 2017 pers. comm.). LiDAR involves using lasers to measure topography of both the ground surface and any physical object (such as a tree or boulder) on top of the ground surface. Although the method has been around for over a decade, it has just recently been employed to assess LWD with most studies occurring in the Pacific Northwest and elsewhere(Abalharth et al. 2015, Atha and Dietrich 2015, Kasprak et al. 2012, Richardson and Moskal 2016, Vondrasek 2017, pers. comm.). This method involves using the entire array (point cloud) of LiDAR return data to create a filtered DEM to identify LWD. Vegetation is filtered out using the LiDAR classification scheme and all elevations above a certain threshold relative to the ground surface (i.e. the height of LWD) are highlighted. Because there are few features in river systems besides vegetation that are within this height class other than LWD, it can be easily spatially identified in both 3D (i.e. Atha and Dietrich 2015) or 2D (i.e. Abalharth et al. 2015, Richardson and Moskal 2016) space. Cross-checks with aerial imagery could be conducted in GIS and have been shown to increase accuracy which has been reported as high as 95% (Abalharth et al. 2015). Wood volumes can then be easily calculated using the LiDAR DEM. There is current work to automate these methods using object-based identification methods which could greatly speed up analyses (Richardson and Moskal 2016).

Pros:

- Quick once LiDAR is processed
- High accuracy (~95%) of volume and surface area calculations
- Semi-automated processing
- Time-series can be developed if multiple years of LiDAR are available
- LiDAR data can be used to measure other pertinent parameters such as reach geomorphology

Cons:

- Expensive due to both data collection and expertise needed to process data
- Aerial photography needed for contextualization of LWD (i.e. jam type) and confirmation

Hyperspectral Imagery

Hyperspectral imagery is a tool that measures many narrow bandwidths (>64) of the electromagnetic spectrum (for comparison, typical aerial imagery such as NAIP images consist of 4 bands – red, green, blue, and infrared). The spectral signature of river features (such as LWD) can be identified in each image by comparing against a typical aerial image and then used to filter the images across wider geographic areas (Marcus et al. 2003). The resulting image is similar to the filtered LiDAR dataset described above, where LWD can be quickly identified, measured, and compared to aerial photography if necessary. This method has been shown to be highly accurate (~86%) although has not been utilized extensively to identify LWD due to the significant cost of acquiring hyperspectral images. Furthermore, wood volumes cannot be calculated because there is no elevation data within the image.

Pros

- High accuracy (~86%)
- Semi-automated processing

Cons:

- Expensive
- Accuracy dependent on clear water and limited vegetation
- No wood volumes or elevation data are calculated

Small Streams

There are several small, forested, tributary streams within the Tier 1 and 2 Chinook habitat area of the Skagit river system including Hansen Creek, Finley Creek, Diobsub Creek, Bacon Creek, Goodell Creek, Illabot Creek, Tenas Creek, Buck Creek, and Downey Creek (Figure 1). This is in addition to off-channel habitat areas such as oxbows and side channels. These streams have densely forested riparian areas and the active channel is covered by the vegetation canopy for most of their extents. Because of this, aerial photography based remote sensing methodologies cannot be employed because the stream bed cannot be seen in the images. Thus, field based methods must be utilized to measure and assess LWD within these systems. Efficiencies can be gained however, by categorizing reaches based on geomorphic and riparian characteristics and developing a model to extrapolate sub-sampled field data rather than walk the entire reach. The following sections review common field sampling protocols and present an overview of different modeling techniques.

Field Based Methods

The general method for field based LWD surveys involves walking/floating along a study reach and measuring and cataloging each piece and/or jam of LWD (e.g. Fausch and Northcote 1992, Faustini and Jones 2003, Hyatt 2001, Montgomery et al. 1995, Segura and Booth 2010, Swanson et al. 1976, Wallerstein and Thorne 2004). The variance between published methods involves both what is classified as LWD (diameter and length) and how the wood is measured (i.e. hand tape, total station, or visual estimation). The majority of methods reviewed for this report utilized a LWD size classification from Swanson et al. 1976 which defined a piece of LWD as being greater than 0.1 m in diameter and 1 m in length. Most studies also measured wood using hand tapes (or digital range finders), although visual estimation has been employed elsewhere with decreased the accuracy (and increased the subjectivity) of the measurements (Beechie and Sibley 1997). LWD jam locations can be marked on a GPS device in the field and processed using a GIS to develop a spatial distribution.

Pros:

- High degree of accuracy if hand measurements are conducted
- Submerged wood can potentially be estimated
- The entire stream can be assessed, rather than just what is open to the canopy

Cons:

- Expensive and time consuming if large areas are desired
- Low accuracy and repeatability if visual estimation is used to save time

Modeling

Developing a predictive model of in-channel LWD within smaller streams based on the fundamental processes driving LWD recruitment and stability can be an advantageous approach to reduce field time and increase reproducibility. A general modeling approach involves categorizing reaches of the stream network based on remotely measurable variables that are thought to drive LWD dynamics within the system such as geomorphic setting, channel gradient, bank slope and vegetation composition and seral class. Reaches from each category would then be surveyed and the data would be used to develop a statistical model to extrapolate the results to the un-sampled reaches. The model could then be tested and refined based on additional field data as necessary. Models of LWD have been developed for other systems within the Pacific Northwest and elsewhere (i.e. Atha and Dietrich 2015, Beechie et al. 2000, Kasprak et al. 2012) with good results, however to date, we are not aware of an off the shelf model that incorporates both recruitment potential and delivery mechanisms into a comprehensive package, although some are currently in development (Wheaton 2017).

Utilizing a model to predict LWD dynamics within a system instead of surveying the entirety can dramatically reduce field and processing time (and thus cost). Furthermore, it allows for a better understanding of the fundamental processes driving LWD dynamics to be identified which would help large scale restoration efforts seeking to improve those processes. Those findings could then be potentially applied to similar basins elsewhere. This methodology however, does not produce a spatially explicit distribution of LWD in un-sampled reaches and introduces additional sources of error and uncertainty to the results.

Pros:

- Decreases field and processing time (and thus cost)
- Identifies fundamental processes driving LWD dynamics
- Can potentially be applied to similar systems within (and outside) the Skagit watershed

Cons:

- Does not produce a spatially explicit distribution of LWD in un-sampled reaches
- Introduces additional sources of uncertainty into data (estimates)
- Past modeling efforts have not been able to estimate depletion rate (Hyatt and Naiman 2001, Beechie et al. 2000) so estimates of wood in specific reaches would be very difficult

The next two sections review common metrics that could be used to categorize reaches based on LWD recruitment potential and a discussion on two potential statistical methods that could be used to develop a predictive model.

Reach Classification using Fundamental Processes

The three general characteristics of a reach that drive LWD recruitment are 1) the source of the large wood within the riparian forest - the *recruitment potential*, 2) the mechanism by which that material gets recruited into the stream – the *recruitment mechanism*, and 3) the properties of the stream that either store or transport the material within the system - the *storage and transport mechanisms* (Abbe and Montgomery 2003, Beechie et al. 2000, Benda and Sias 2003, Kasprak et al. 2012, Swanson et al. 1976). Each of these characteristics can be described by environmental/geographic variables that can be measured using remote sensing methods which further decreases field time (Table 2). However, the storage and transport mechanisms have been shown to be difficult to accurately model (Hyatt and Naiman 2001, Beechie et al. 2000).

The recruitment potential of a reach is determined by whether there is large wood within the riparian zone that *can* be recruited by the stream and is large enough to remain stable. Thus, it is driven both by the size of trees and their proximity to the channel network (Beechie et al. 2000, Benda et al. 2003, Kasprak et al. 2012, Vondrasek 2017 pers. comm.). Recent advances in LiDAR processing methodology allow for rapid measurement of tree heights and canopy diameters by differencing the first-return and bare-earth LiDAR DEMs (Akay et al. 2012, Kasprak et al. 2012, Vondrasek 2017 pers. comm.). The trees can then be categorized as whether they will remain stable in a channel based on the ratio between tree height and diameter and the bankfull geometry of a channel (Abbe and Montgomery 2003). The potential LWD can then be sorted based on its proximity to the channel network and other bank slope characteristics to determine whether it can be easily recruited by the stream. The riparian zone can be further classified based on characteristics of the forest such as successional pathway, age, fire rotation, and management methods which have been shown to influence LWD recruitment, although further research would be needed to discretize each additional variable (Beechie et al. 2000, Benda and Sias 2003).

Table 2. Variables used to describe the processes driving LWD dynamics.

DRIVING PROCESS	VARIABLES	REFERENCES
Recruitment Potential	Tree Height	(Beechie et al. 2000, Benda and Sias 2003, Kasprak et al. 2012, Vondrasek 2017 pers. comm.)
	Tree diameter	(Beechie et al. 2000, Benda and Sias 2003, Kasprak et al. 2012, Vondrasek 2017 pers. comm.)
	Proximity to Channel	(Beechie et al. 2000, Benda and Sias 2003, Kasprak et al. 2012, Vondrasek 2017 pers. comm.)
	Geomorphic setting of riparian zone	(Kasprak et al. 2012)
	Stand management	(Beechie et al. 2000)
	Forest successional pathway	(Beechie et al. 2000)
	Forest age	(Benda and Sias 2003)
	Fire rotation	(Benda and Sias 2003)
Recruitment Mechanisms	Stream size	(Atha and Dietrich 2015, Benda and Sias 2003, Kasprak et al. 2012)
	Stream power	(Atha and Dietrich 2015, Benda and Sias 2003, Kasprak et al. 2012)
	Sinuosity (i.e. channel migration)	(Kasprak et al. 2012, Vondrasek 2017 pers. comm.)
	Slope	(Atha and Dietrich 2015, Benda and Sias 2003, Kasprak et al. 2012)
	Channel confinement	(Kasprak et al. 2012, Vondrasek 2017 pers. comm.)
	Mass-wasting (i.e. landslides and debris flows) potential	(Benda and Sias 2003, Kasprak et al. 2012)
	Valley width	(Benda and Sias 2003, Kasprak et al. 2012)
Storage and Transport Mechanisms	Stream power	(Atha and Dietrich 2015)
	Slope	(Atha and Dietrich 2015)
	Morphology	(Atha and Dietrich 2015)

The recruitment mechanisms that input LWD within a given reach are determined both by the frequency and magnitude of both colluvial (i.e. landslides and debris flows) and alluvial (i.e. stream power and channel migration) processes (Atha and Dietrich 2015, Benda and Sias 2003, Kasprak et al. 2012). Colluvial processes such as debris flows and landslides have been shown to be important drivers of LWD recruitment and can be estimated based on simple geographic derived variables such as valley wall slope (Kasprak et al. 2012) although more sophisticated metrics such as the landslide potential index are available (Gritzner et al. 2001, Sarkar and Kanungo 2004). Alluvial processes driving LWD recruitment can also be categorized by geographic variables such as stream power (a derivative of hydrology and channel slope) (Atha and Dietrich 2015), channel sinuosity (as a surrogate for channel migration) and channel confinement (Kasprak et al. 2012), and channel morphology (Montgomery and Buffington 1997). These metrics are common measurements in geomorphic studies and are readily calculated using available topographic information. They also can be used as indicators to classify the storage and transport mechanisms within a reach (Atha and Dietrich 2015). Once the study reaches are characterized based on the different drivers of LWD dynamics, a predictive modeling scheme can be developed that will inform the experimental design and modeling outcomes.

Predictive Model Development

The manner in which reaches are classified will determine the type of statistical methods used to derive a predictive model of LWD potential. Variables can be either binned into discrete categories (binned/binary) to describe reaches or they can be combined with other variables and treated as a continuous dataset (multi-variate). The basics behind each method are outlined below:

Binned/binary method

For the binned/binary method, a few variables would be chosen that are thought to be the most important in driving LWD dynamics (such as confinement, recruitment potential score, etc.). The study area would then be discretized into bins representing each variable (i.e. low vs high recruitment) and a field survey would be conducted within a % of each population. Half of the resulting data would then be used to calibrate the model and the other half used to validate it. Once the model has been validated in the field, reach averages of the desired LWD metrics (i.e. jams/100m) could be extrapolated to the remainder of the population. Field validation would involve checking model estimates against field data to identify the accuracy of the extrapolation procedure. If estimates were not to the desired level of accuracy, the model would be modified until results were satisfactory.

Pros:

- Likely lower effort than multi-variate method
- Easier to understand outcomes

Cons:

- Challenging to evaluate strength of model
- May over-simplify processes
- Likely will not provide an accurate estimate of depletion rates

Multi-variate method

The multi-variate method does not classify reaches into certain categories. Instead, the characteristics of each reach are treated equally against the remainder of the watershed along a continuum. Once variables have been defined for each reach, a subsample of the overall reaches within the watershed can be surveyed for LWD. The data would then be input into a multi-variate regression model using different combinations of driving variables (e.g. channel slope and recruitment potential *or* channel slope, valley slope, and tree height within riparian zone). The strength of the model can be directly evaluated using common statistical methods (e.g. R^2) and once the model is finalized, it can be used to extrapolate to un-sampled reaches across the basin.

Pros:

- More statistical strength than binned/binary method
- Many variables can be included
- Can be used to predict changes in future years/other parts of the basin

Cons:

- Likely higher effort both in terms of sampling and data analysis/statistics than binned/binary method
- May be more difficult to interpret results
- Likely will not provide an accurate estimate of depletion rates

EVALUATION OF METHODS IDENTIFIED

Using the information about each of the methods described above, and additional knowledge about each method, an evaluation matrix was applied to provide a rating and basis for recommendations for approaches to assessing LWD in the Skagit Basin (Tier 1 and 2 habitat). The process of evaluation of methods involved assignment of ratings for each method in an evaluation matrix (large rivers separated from small streams) to determine which of the methods or combination of methods was most effective for meeting the widest range of objectives at the lowest cost. Table 3 shows a range of criteria that can be used to evaluate and recommend methods. Other elements could be included in the evaluation, but these are provided as a starting point in the decision process for the Skagit Watershed Council. Criteria below were selected based on achieving objectives (metrics), scientific validity, and financial and time considerations. Ratings used in evaluation were not numerical, but more reflective of the general effectiveness of the approach [++ = very positive, + = somewhat positive, 0 = neutral, - = somewhat negative, -- = very negative, ND = no data.]

Table 3. Criteria used to evaluate methods for LWD assessment in the Skagit Basin

EVALUATION MATRIX FOR METHODS	
Accuracy	Volume by Reach
Precision	Percent of Metrics Addressed
Repeatability	Feasibility
Time to Implement	Costs for Intern/Technician Labor
Time to Process	Costs for High Tech
Scale Best Suited (watershed, river, reach)	Overall Costs
Location Specificity (small streams)	

Recommended Methods and Metrics

Based on the evaluation matrix data, the methods recommended for the assessment of large wood in the Skagit Watershed are a combination of LiDAR and aerial imagery (NAIP or equivalent) for larger rivers and a similar approach with field verification for small streams. The metrics identified across all limiting factors are summarized in Table 4 and can be collected for the most part by both approaches (metrics with an asterisk may not be able to be collected with a high level of accuracy).

Table 4. Summary of Recommended Metrics for LWD Assessment in the Skagit Basin

SUMMARY OF RECOMMENDED METRICS	
Number of jams	Number of jams >100ft in contact with landform (2006, 2017)
Jams/km	Number of key members
Jam type	Number of nodes (Beechie 2017)
Map of jams	River Complexity Index (Brown 2002)
Total number of pieces in reach	Volume of wood*
Number of functional jams in regulated vs. non-regulated systems/reaches	Number of pools > 1m depth by reach*

*May not be able to be collected with a high level of accuracy

The following rationale were identified for these recommendations:

Large Rivers

- High resolution LiDAR is an effective and cost-effective method for measurement of wood across large areas
- Green LiDAR has the potential to record data under the water surface if conditions are appropriate
- Imagery can be used to assess jam type and function and to validate LiDAR
- LiDAR for the basin was collected in 2017 and would be available for analysis
- Comparison with 2006 data layer could be made for change through time

Small Streams

- High resolution LiDAR is an effective and cost-effective method for measurement of wood across large areas
- Green LiDAR has the potential to record data under the water surface if conditions are appropriate
- Imagery can be used to assess jam type and function and to validate LiDAR if stream is visible through the canopy
- LiDAR for the basin was collected in 2017 and would be available for analysis
- Field verification of remote estimates will help to improve accuracy through an iterative process.
- Modeling could be used to provide additional lines of evidence to support or better understand observed wood loading.
- The level and intensity of modeling can be scaled to optimize objectives and meet cost constraints.

After a review of existing literature on modeling LWD dynamics in streams and consultation with members of the Adaptive Management Committee, we recommend that the approach to small streams include the LiDAR and aerial photo analysis used in the large rivers, supplemented by field work to calibrate the remote sensing process. The issues identified by members of the committee with past modeling efforts indicated that efforts to actually measure wood in small streams using a combination of LiDAR, aerial photography and field verification would provide more accurate information on the recommended metrics and would also provide spatial data on wood in small streams, which could be used by others in the watershed for restoration planning and habitat evaluation. We worked collaboratively with the Monitoring and Adaptive Management Committee to further refine the desired/required metrics and the levels of specificity needed for the effort, and feel this approach can better address the needs for small stream wood assessment in the

Skagit Basin. We look forward to additional interactions with the Skagit Watershed Council and the Monitoring and Adaptive Management Committee to implement the recommendations made in this report.

REFERENCES

Abalharth, M., Hassan, M.A., Klinkenberg, B., Leung, V. and McCleary, R. (2015) Using LiDAR to characterize logjams in lowland rivers. Geomorphology 246, 531-541.

Abbe, T. (2000) Patterns, mechanics, and geomorphic effects of wood debris accumulation in a forest river system, University of Washington, Seattle, WA.

Abbe, T., Belby, B. and Shields Jr, F.D. (2016) National Large Wood Manual - Assessment, Planning, and Design of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure., p. 628, Bureau of Reclamation and U.S. Army Corps Research and Development Center.

Abbe, T. and Brooks, A. (2011) Geomorphic, engineering, and ecological considerations when using wood in river restoration. Geophysical Monograph Series 194, 419-451.

Abbe, T. and Montgomery, D.R. (2003) Patterns and processes of wood debris accumulation in the Queets River basin, Washington. Geomorphology 51, 81-107.

Abbe, T.B. and Montgomery, D.R. (1996) Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research & Management 12, 201-221.

Akay, A.E., Wing, M.G. and Sessions, J. (2012) Estimating structural properties of riparian forests with airborne lidar data. International Journal of Remote Sensing 33(22), 7010-7023.

Atha, J.B. and Dietrich, J.T. (2015) Detecting fluvial wood in forested watersheds using LiDAR Data: a methodological assessment. River Research and Applications.

Beamer, E., Bernard, R., Hayman, B., Hebner, B., Hinton, S., Hood, G., Kraemer, C., McBride, A., Musslewhite, J., Smith, D., Wasserman, L. and Wyman, K. (2005) Skagit Chinook Recovery Plan. Skagit River System Cooperative and Washington Department of Fish and Wildlife, 327p.

Beechie, T., Imaki, H., Greene, J., Wade, A., Wu, H., Pess, G., Roni, P., Kimball, J., Stanford, J. and Kiffney, P. (2013) Restoring salmon habitat for a changing climate. River Research and Applications 29(8), 939-960.

Beechie, T.J., Beamer, E. and Wasserman, L. (1994) Estimating Coho salmon rearing habitat and smolt production losses in a large river basin, and implications for habitat restoration. North American Journal of Fisheries Management 14, 797-811.

Beechie, T.J., Pess, G., Kennard, P., Bilby, R.E. and Bolton, S. (2000) Modeling recovery rates and pathways for woody debris recruitment in northwestern Washington streams. North American Journal of Fisheries Management 20(2), 436-452.

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P. and Pollock, M.M. (2010) Process-based Principles for Restoring River Ecosystems. BioScience 60(3), 209-222.

Beechie, T.J. and Sibley, T.H. (1997) Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. Transactions of the American Fisheries Society 126(2), 217-229.

Benda, L., Miller, D., Sias, J., Martin, D., Bilby, R., Veldhuisen, C. and Dunne, T. (2003) Wood recruitment processes and wood budgeting, pp. 49-74, American Fisheries Society.

Benda, L.E. and Sias, J.C. (2003) A quantitative framework for evaluating the mass balance of in-stream organic debris. Forest Ecology and Management 172(1), 1-16.

Beschta, R.L. and Platts, W.S. (1986) Morphological features of small streams: significance and function. JAWRA Journal of the American Water Resources Association 22(3), 369-379.

Bilby, R.E. (1984) Characteristics and frequency of cool-water areas in a western Washington stream. Journal of Freshwater Ecology 2(6), 593-602.

Bilby, R.E. and Ward, J.W. (1991) Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48(12), 2499-2508.

Bisson, P.A., Bilby, R.E., Bryant, M.D., Dolloff, C.A., Grette, G.B., House, R.A., Murphy, M.L., Koski, K.V. and Sedell, J.R. (1987) Large woody debris in forested streams in the Pacific Northwest: past, present, and future. In E. O. Salo and T. Cundy [ed.] Proceedings of an interdisciplinary symposium on streamside management: forestry and fisheries interactions. University of Washington Press, Seattle, WA.

Booth, D.B., Montgomery, D.R. and Bethel, J. (1996) Large woody debris in urban streams of the Pacific Northwest. Effects of Watershed Development and Management on Aquatic Ecosystems: Engineering Foundation Conference Proceedings, Snowbird, Utah, 178-197.

Brummer, C.J., Abbe, T.B., Sampson, J.R. and Montgomery, D.R. (2006) Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. Geomorphology 80(3), 295-309.

Cederholm, C., Bilby, R., Bisson, P., Bumstead, T., Fransen, B., Scarlett, W. and Ward, J. (1997) Response of juvenile coho salmon and steelhead to placement of large woody debris in a coastal Washington stream. North American Journal of Fisheries Management 17(4), 947-963.

Collins, B.D. (1998) Preliminary assessment of historic conditions of the Skagit River in the Fir Island area: implications for salmonid habitat restoration. Report to Skagit River System Cooperative, La Conner, WA, 72p.

Collins, B.D. and Montgomery, D.R. (2002) Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington. Restoration Ecology 10(2), 237-247.

Collins, B.D., Montgomery, D.R., Fetherston, K.L. and Abbe, T. (2012) The floodplain large wood cycle hypothesis: a mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the north Pacific coastal ecoregion. Geomorphology 139/140, 460-470.

Davidson, S. (2011) Modeling channel morphodynamics associated with large wood in an intermedieate-sized stream (masters thesis). The University of British Columbia, Vancouver, BC, 124p.

Dietrich, J.T. (2016) Riverscape mapping with helicopter-based Structure-from-Motion photogrammetry. Geomorphology 252, 144-157.

Embertson, L. (2017) Personal communication.

Fausch, K.D. and Northcote, T.G. (1992) Large Woody Debris and Salmonid Habitat in a Small Coastal British Columbia Stream. Canadian Journal of Fisheries and Aquatic Sciences 49(4), 682-693.

Faustini, J.M. and Jones, J.A. (2003) Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. Geomorphology 51(1), 187-205.

Fetherston, K.L., Naiman, R.J. and Bilby, R.E. (1995) Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. Geomorphology 13(1-4), 133-144.

Fonstad, M.A., Dietrich, J.T., Courville, B.C., Jensen, J.L. and Carbonneau, P.E. (2013) Topographic structure from motion: a new development in photogrammetric measurement. Earth Surface Processes and Landforms 38(4), 421-430.

George Robison, E. and Beschta, R.L. (1990) Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, USA. Earth Surface Processes and Landforms 15(2), 149-156.

Gippel, C.J., O'Neill, I.C., Finlayson, B.L. and Schnatz, I. (1996) Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers. River Research and Applications 12(2), 223-236.

Gregory K, J., Gurnell, A.M. and Hill, C.T. (1985) The permanence of debris jams related to river channel processes. Hydrological Sciences Journal 30(3), 371-381.

Gritzner, M.L., Marcus, W.A., Aspinall, R. and Custer, S.G. (2001) Assessing landslide potential using GIS, soil wetness modeling and topographic attributes, Payette River, Idaho. Geomorphology 37(1), 149-165.

Gurnell, A., Piegay, H., Swanson, F. and Gregory, S. (2002) Large wood and fluvial processes. Freshwater Biology 47(4), 601-619.

Gurnell, A.M. and Sweet, R. (1998) The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. Earth Surface Processes and Landforms 23, 1101-1121.

Hafs, A.W., Harrison, L.R., Utz, R.M. and Dunne, T. (2014) Quantifying the role of woody debris in providing bioenergetically favorable habitat for juvenile salmon. Ecological Modelling 285, 30-38.

Heede, B.H. (1972) Influences of a forest on the hydraulic geometry of two mountain streams. Journal of the American Water Resources Association 8(3), 523-530.

Hilderbrand, R.H., Lemly, A.D., Dolloff, C.A. and Harpster, K.L. (1998) Design considerations for large woody debris placement in stream enhancement projects. North American Journal of Fisheries Management 18, 161-167.

Hyatt, T.L. (2001) Inventory Methods for Wadable Streams in King County.

Hyatt, T.L. and Naiman, R.J. (2001) The residence time of large woody debris in the Queets River, Washington, USA. Ecological Applications 11(1), 191-202.

Hygelund, B. and Manga, M. (2003) Field measurements of drag coefficients for model large woody debris. Geomorphology 51, 175-185.

Johnson, S.L., Rodgers, J.D., Solazzi, M.F. and Nickelson, T.E. (2005) Effects of an increase in large wood on abundance and survival of juvenile salmonids (Oncorhynchus spp.) in an Oregon coastal stream. Canadian Journal of Fisheries and Aquatic Sciences 62(2), 412-424.

Justice, C., White, S.M., McCullough, D.A., Graves, D.S. and Blanchard, M.R. (2017) Can stream and riparian restoration offset climate change impacts to salmon populations? Journal of Environmental Management 188, 212-227.

Kasprak, A., Magilligan, F.J., Nislow, K.H. and Snyder, N.P. (2012) A Lidar-derived evaluation of watershed-scale large woody debris sources and recruitment mechanisms: Coastal Maine, USA. River Research and Applications 28(9), 1462-1476.

Lacey, R.W.J. and Millar, R.G. (2001) Application of a 2-dimensional hydrodynamic model for the assessment and design of instream channel restoration works. Province of British Columbia, Ministry of Water, Land and Air Protection, and Ministry of Forests Watershed Restoration Management Report No. 9, 70p.

Lane, E.W. (1955) Design of stable alluvial channels. American Society of Civil Engineers Transactions 120(2776), 1234-1260.

Lester, R.E. and Boulton, A.J. (2008) Rehabilitating agricultural streams in Australia with wood: a review. Environmental Management 42(2), 310-326.

Linstead, C. (2001) The effects of large woody debris accumulations on river hydraulics and implications for physical habitat. Hydro-ecology: Linking Hydrology and Aquatic Ecology (Proceedings of Workshop held in Birmingham, UK, July 1999), 91-99.

Lisle, T.E. (1986a) Effects of woody debris on anadromous salmonid habitat, Prince of Wales Island, southeast Alaska. North American Journal of Fisheries Management 6(4), 538-550.

Lisle, T.E. (1986b) Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. Geological Society of America Bulletin 97(8), 999-1011.

LizardTech. 2004. https://web.archive.org/web/20110522210303/http://www.lizardtech.com/files/geo/techinfo/MrSID_Tech_Primer.pdf. Accessed June 26, 2017.

Loheide, S.P. and Gorelick, S.M. (2006) Quantifying stream-aquifer interactions through the analysis of remotely sensed thermographic profiles and in situ temperature histories. Environmental Science and Technology 40(10).

Lowery, E.D. (2017) Personal communication at meeting with Skagit Watershed Council.

Lowery, E.D., Thompson, J.N., Shannahan, J.-P., Connor, E.J., Pflug, D.E., Donahue, B., Torgersen, C.E. and Beauchamp, D.A. (in press) Seasonal distribution and habitat associations of salmonids with extended juvenile freshwater rearing in different precipitation zones of the Skagit River, WA. Unpublished research.

MacInnis, C., Floyd, T.A. and Taylor, B.R. (2008) Large woody debris structures and their influence on Atlantic salmon spawning in a stream in Nova Scotia, Canada. North American Journal of Fisheries Management 28(3), 781-791.

Manga, M. and Kirchner, J.W. (2000) Stress partitioning in streams by large woody debris. Water Resources Research 36(8), 2373-2379.

Manners, R.B., Doyle, M.W. and Small, M.J. (2007) Structure and hydraulics of natural woody debris jams. Water Resources Research 43(6).

Marcus, W.A., Legleiter, C.J., Aspinall, R.J., Boardman, J.W. and Crabtree, R.L. (2003) High spatial resolution hyperspectral mapping of in-stream habitats, depths, and woody debris in mountain streams. Geomorphology 55(1), 363-380.

Marcus, W.A., Marston, R.A., Colvard, C.R. and Gray, R.D. (2002) Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA. Geomorphology 44(3), 323-335.

Marston, R.A. (1982) The Geomorphic Significance of Log Steps in Forest Streams. Annals of the Association of American Geographers 72(1), 99-108.

Matheson, A., Thoms, M., Southwell, M. and Reid, M. (2017) Does reintroducing large wood influence the hydraulic landscape of a lowland river at multiple discharges? Ecohydrology.

Meehan, W.R., Swanson, F.J. and Sedell, J.R. (1977) General Technical Report RM-43, pp. 137-145, U.S. Forest Service, Washington D.C.

Merz, J.E. (2001) Association of fall-run chinook salmon redds with woody debris in the lower Mokelumne River, California. California Fish and Game 87(2), 51-60.

Montgomery, D.R. and Abbe, T.B. (2006) Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA. Quaternary Research 65(1), 147-155.

Montgomery, D.R. and Buffington, J.M. (1997) Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109, 596-611.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M. and Pess, G.R. (1995) Pool spacing in forest channels. Water Resources Research 31(4), 1097-1105.

Montgomery, D.R., Collins, B.D., Buffington, J.M. and Abbe, T.B. (2003) Geomorphic effects of wood in rivers. American Fisheries Society Symposium.

Moulin, B., Schenk, E.R. and Hupp, C.R. (2011) Distribution and characterization of in-channel large wood in relation to geomorphic patterns on a low-gradient river. Earth Surface Processes and Landforms 36(9), 1137-1151.

Nagayama, S. and Nakamura, F. (2010) Fish habitat rehabilitation using wood in the world. Landscape and Ecological Engineering 6(2), 289-305.

Naiman, R.J., Balian, E.V., Bartz, K.K., Bilby, R.E. and Latterell, J.J. (2002) Dead wood dynamics in stream ecosystems. USDA Forest Service General Technical Report PSW-GTR-181, 23-48.

Naiman, R.J., Bilby, R.E. and Bisson, P.A. (2000) Riparian ecology and management in the Pacific coastal rain forest. BioScience 50(11), 996-1011.

Nakamura, F. and Swanson, F.J. (1993) Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. Earth Surface Processes and Landforms 18(1), 43-61.

Nichols, R.A. and Ketcheson, G.L. (2013) A Two-Decade Watershed Approach to Stream Restoration Log Jam Design and Stream Recovery Monitoring: Finney Creek, Washington. Journal of the American Water Resources Association 49(6), 1367-1384.

Opperman, J., Luster, R., McKenney, B.A., Roberts, M. and Meadows, A.W. (2010) Ecologically functional floodplains: connectivity, flow regime, and scale. Journal of the American Water Resources Association 1-16.

Opperman, J., Merenlender, A. and Lewis, D. (2006) Maintaining wood in streams: A vital action for fish conservation. University of California ANR Publications, 11p.

Pess, G., Liermann, M., McHenry, M., Peters, R. and Bennett, T. (2012) Juvenile salmon response to the placement of engineered log jams (ELJs) in the Elwha River, Washington State, USA. River Research and Applications 28(7), 872-881.

Richardson, J.J. and Moskal, L.M. (2016) An Integrated Approach for Monitoring Contemporary and Recruitable Large Woody Debris. Remote Sensing 8(9), 778.

Roni, P. and Quinn, T. (2001) Density and size of juvenile salmonids in response to placement of large woody debris in western Oregon and Washington streams. Canadian Journal of Fisheries and Aquatic Sciences 58(2), 282-292.

Sarkar, S. and Kanungo, D.P. (2004) An integrated approach for landslide susceptibility mapping using remote sensing and GIS. Photogrammetric Engineering & Remote Sensing 70(5), 617-625.

Sawyer, A.H., Bayani Cardenas, M. and Buttles, J. (2011) Hyporheic exchange due to channel-spanning logs. Water Resources Research 47(8).

Segura, C. and Booth, D.B. (2010) Effects of Geomorphic Setting and Urbanization on Wood, Pools, Sediment Storage, and Bank Erosion in Puget Sound Streams1. JAWRA Journal of the American Water Resources Association 46(5), 972-986.

Shields, F.D. and Alonso, C.V. (2012) Assessment of flow forces on large wood in rivers. Water Resources Research 48(4), n/a-n/a.

Shields, F.D. and Gippel, C.J. (1995) Prediction of Effects of Woody Debris Removal on Flow Resistance. Journal of Hydraulic Engineering 121(4), 341.

Shirvell, C.S. (1990) Role of instream rootwads as juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead (*O. mykiss*) cover habitat under varying streamflows. Canadian Journal of Fisheries and Aquatic Sciences 47, 852-861.

Swanson, F.J., Lienkaemper, G.W., Sedell, J.R., Pacific Northwest, F., Range Experiment, S. and United States. Forest, S. (1976) History, physical effects, and management implications of large organic debris in western Oregon streams, Pacific Northwest Forest and Range Experimnt Station, U.S. Dept. of Agriculture, Forest Service, Portland Or.

Thompson, D.M. (2012) The challenge of modeling pool–riffle morphologies in channels with different densities of large woody debris and boulders. Earth Surface Processes and Landforms 37(2), 223-239.

Tohver, I.M., Hamlet, A.F. and Lee, S.Y. (2014) Impacts of 21st-Century Climate Change on Hydrologic Extremes in the Pacific Northwest Region of North America. Journal of the American Water Resources Association 50(6), 1461-1476.

Tonkin, Z., Kitchingman, A., Ayres, R.M., Lyon, J., Rutherfurd, I.D., Stout, J.C. and Wilson, P. (2016) Assessing the Distribution and Changes of Instream Woody Habitat in South-Eastern Australian Rivers. River Research and Applications 32(7), 1576-1586.

Torgersen, C.E., Price, D.M., Li, H.W. and McIntosh, B.A. (1999) Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. Ecological Applications 9(1), 301-319.

Turcotte, B., Millar, R.G. and Hassan, M.A. (2016) Drag forces on large cylinders. River Research and Applications 32(3), 411-417.

Ulloa, H., Iroumé, A., Mao, L., Andreoli, A., Diez, S. and Lara, L.E. (2015) Use of Remote Imagery to Analyse Changes in Morphology and Longitudinal Large Wood Distribution in the Blanco River After the 2008 Chaitén Volcanic Eruption, Southern Chile. Geografiska Annaler: Series A, Physical Geography 97(3), 523-541.

Vondrasek, C. (2017) Personal Communication, Skagit Watershed Council staff.

Wallerstein, N.P. and Thorne, C.R. (2004) Influence of large woody debris on morphological evolution of incised, sand-bed channels. Geomorphology 57(1-2), 53-73.

Wheaton, J. (2017) Personal Communication with Jennifer O'Neal.

White, S.M., Justice, C., Kelsey, D.A., McCullough, D.A. and Smith, T. (2017) Legacies of stream channel modification revealed using General Land Office surveys, with implications for water temperature and aquatic life. Elementa Science of the Anthropocene 5(3).

Zimmerman, M.S., Kinsel, C., Beamer, E., Connor, E.J. and Pflug, D.E. (2015) Abundance, survival, and life history strategies of juvenile Chinook Salmon in the Skagit River, Washington. Transactions of the American Fisheries Society 144(3), 627-641.