Delineating forested river habitats and riparian floodplain hydrology with LiDAR.

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Abstract

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Rivers and the riparian forest corridor comprise a valuable freshwater ecosystem that has been altered by human activities including timber management, road building, and other land conversions. The habitats of river dependent species in the Pacific Northwest, in particular salmon have often been degraded by these activities. Many salmon runs have become threatened with extinction and have been Endangered Species Act listed. New conservation planning and policies have developed around protecting freshwater habitats and restoring more natural river processes. In WA State, timber landowners, officials from State and Federal agencies, Native tribes, and other stakeholders developed Forest Practice rules and codified a Habitat Conservation Plan with dual goals of providing regulatory surety for timber land owners and helping to recover the threatened salmon runs in forested watersheds. Conserving critical stream

ecological functions and potential fish habitats throughout watersheds while managing and regulating timber harvest across the State requires accurate and up-to-date delineation and mapping of channels, tributaries, and off-channel wetlands. Monitoring the effectiveness of protection efforts is necessary but can also be difficult. Agency staff and resources are limited for both day-to-day implementation of Forest Practice rules and adaptive management. The goal of this research has been to develop efficient and accessible methods to delineate wetlands, side-channels, tributaries, and pools and backwaters created by large log jams in forested watersheds. It was also essential to use publicly available LiDAR data and to model these waters at ecologically meaningful flows. I tested a hydraulic model at a 2-year and 50-year flows, and a relative height above river surface model and compared them. I completed two additional remote sensing investigations to correlate channel movement and the locations of off-channel wetlands: an analysis of historical aerial imagery and models of the riparian forest tree establishment using the first-return lidar data. The research includes two fieldwork components: an appraisal of the delineated off-channel and active channel water features, and an assessment of the accuracy of the lidar under the forest canopy. Both the hydraulic and the relative elevation models accurately delineated the key off-channel and active channel waters. The historical imagery analysis confirmed past channel movement left many of the side channels and wetlands near to the contemporary active channel. The sequence of tree establishment tracked where channel migration had exposed new banks, colonized first by deciduous trees, then followed by cohorts of conifers, some maturing and achieving great heights. Often the

lack of a closed canopy corresponded to the locations of persistent wetlands or mid-channel logjams

Key Words: Floodplain hydrology, channel movement, wetlands, off-channel habitats, habitat conservation plans, hydraulic models, lidar, historical imagery, riparian forest establishment

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1. Introduction

Accurate delineation and mapping of riparian forest wetlands, side channels, and other connected waters in the active channel and in the adjacent floodplain, and at ecologically significant flows, is needed to achieve conservation goals for river dependent species, especially fish. The listing of numerous salmon runs under the Endangered Species Act and potentially conflicting resource management goals make the need for improved mapping of fish habitats especially critical in forested watersheds. In WA State, the Forest Practices Habitat Conservation Plan codified land use practices and habitat protection goals for salmon and other species in non-federal forest lands. New publicly available remote sensing data and innovative analysis approaches offer the potential to significantly improve the delineation of key hydrological features in forested watersheds and to aid in conservation and restoration planning.

This research uses aerial LiDAR data to model the extents of environmentally important flows in the active channel, and also where and how they flow into the adjacent floodplains. LiDAR stands for Light Detection And Ranging, and is an active remote sensing technology. LiDAR data is generated by flying over an area of interest with a GPS, a gyroscope, an infrared laser firing pulses of light toward the ground with a finely calibrated sensor capturing the time and the intensity of the return of the laser light. The time of the return measures the distance from the sensor and describes the elevation of the object the light has returned from. Remote sensing data such as LiDAR offer a high spatial resolution essential to capture hydrological details and also a large coverage allowing watershed scale analysis and context. I developed 2 models, a hydraulic model and a relative elevation model using the bare earth lidar DEM. The hydraulic model delineated the extents of over bank discharges for 2-year flows and a 50-year flow event. Accuracy assessments in the field verified how well the models captured the locations and qualities of wetlands, side channels, and connected waters. The field assessments also tested the accuracy of the lidar to capture the elevation of critical water features and their connection to the active channel. The elevation assessment compared the lidar elevations to both a survey grade GPS and also a point-to-point elevation change measurements taken on transects both across the floodplain and along the longitudinal profile of the river channel.

The research also tested two other remote sensing approaches to validate the flow models in Goodman Creek. I used three dates of historical aerial photography to map evidence of past channel location and movement, and timber harvest history over 65 years. I also used the first return lidar data to develop canopy height and change models to map near channel patterns of tree type and relative tree establishment dates. I compared these patterns of tree establishment intervals with the modeled and field verified locations of past channel movement and wetlands.

This research integrates and exceeds facets of other approaches attempted in different watershed settings to answer river and floodplain ecological questions. Yang et. al. (2006) used iterations of hydraulic simulations derived from HEC-RAS to generate water surface profiles in order to describe the possible floods of 6 different design storm events in agricultural and urban areas in the Canadian Great Lakes. Bummer et. al. (2006) used hydraulic modeling to evaluate connection between large woody debris (LWD) accumulations in NW rivers and their influence on channel bed and water surface elevations. They did not specifically consider the riparian floodplain ecology including wetlands and off-channel habitats for salmon. Holmes and Goebel (2011) developed a geospatial approach to riparian area delineation based on ecological function using aerial photography, a medium-coarse resolution 30m DEM, and infrastructure data layers. Stream network tools and "Intrinsic Potential" models of stream habitats have also used coarse DEMs and GIS to model metrics such as river gradient, valley width, erosion risk, and obstacles to fish passages (Benda et. al, 2007, Bennett and Wecker, 2013). These approaches capture the broader geomorphic settings where general ecological functions should exist. Notebaert et. al. (2009) tested the accuracy of lidar by comparing it to kinematic GPS surveys in agricultural areas of the Belgian lowlands. This study using high spatial resolution LiDAR data developed detailed and specific delineations of in-channel and off-channel riparian floodplain hydrology and habitats under dense forest canopy, while also corroborating the GPS survey with measurements of the point to point elevation changes over long cross section and longitudinal channel profile survey transects.

1.1 Organization of the Thesis

This thesis has 5 components.

A summary of the key river and fluvial geomorphological processes, the freshwater needs of salmon especially for juvenile rearing habitats, and the regulatory imperatives surrounding riparian forest practices and the protection of possible salmon habitats.

A description of the development of a hydraulic model that simulates ecologically significant flows, and then delineates inundated riparian forest wetlands, side channels, and other connected waters in the active channel and in the adjacent floodplain. These ecologically significant flows will be a 2 year flow (one with a 50% probability of yearly occurrence) and a 50 year flow (one with a 2% probability of yearly occurrence).

A description of the development of a relative elevation model that captures the locations of the same hydrological features in the floodplain. The goal of this model is to offer a simpler but informed GIS method to land managers, and the thesis includes a comparison of the two models.

A description of additional two investigations to detect corroborating evidence of channel movement using historical imagery and lidar based forest succession models.

A discussion of policy implications of increased lidar availability and its inclusion into the FPHCP riparian protection protocols. A discussion of the use of lidar based stream models toward improving habitat protections and guiding restoration decisions in the future.

1.2 Research Questions

With airborne LiDAR as the elevation data source, can a hydraulic model accurately delineate riparian wetlands, side channels, and other connected waters in the active channel and in the adjacent floodplain, and at ecologically significant flows under a dense forest?

Can an additional simpler but informed topographic model be developed which generates similar results, and can be used by agency managers of forested watersheds with GIS capability and comprehensive regulatory responsibilities, but without hydraulic modeling expertise?

Can other remote sensing approaches (historic aerial image analysis, canopy height modeling with first return lidar data) corroborate changes in channel location and connected riparian hydrological features?

2. Background

2.1 Descriptive history of the remote sensing of rivers

This section provides a brief overview of remote sensing of rivers and a context for the remote sensing focus in my research on active channel and forested floodplain conditions.

River scientists and water resource managers have mapped and assessed rivers remotely since the beginnings of aerial photography. With the addition of new technologies, sensing platforms, and skillful users, the remote sensing of rivers has rapidly evolved. Researchers can access data sources with a range of spatial, spectral, and temporal resolutions. Remote sensing analysis of riverine environments now includes channel morphology changes, stream temperatures, water chemistry, river bathymetry, habitat conditions and species use, and riparian vegetation conditions (Marcus and Fonstad, 2010, Charbonneau and Piegay, 2012). Remote sensing research into river structure and function includes new scales of analysis of rivers, extending from continental assessments of fish habitat (Luck et. al., 2010) or flooding regimes in the world's largest rivers (Jung et. al., 2010) to measurements of sub-meter changes in channel morphology (Hauet et al., 2008).

From the 1930s through the 1970s aerial photographs offered the main source of remote sensing data for river analysis. Aerial photographs continue to be used today. Archival photographs form a primary data source for the analysis of historical change in rivers and watersheds (Jones and Grant 1996, Stover and Montgomery, 2001, Lunt and Bridge, 2004, Latterell et. al., 2006, Hood, 2010). Aerial photographs comprise a key remote sensing data source for river studies at a wide range of scales. In a region-wide study of PNW rivers, Beechie et al. (2006) used aerial photographs along with digital elevation models (DEM) and precipitation records to quantify channel patterns and predict their corresponding floodplain change dynamics. At a reach scale of less than 1km, Hauet et al. (2008) utilized photogrammetry and digital image processing of photo sequences of flood events to assess surface velocities and the rates of changes to banks and floodplain vegetation.

Satellite spectral imagery from the Landsat satellite platforms became available to river scientists beginning in 1974. The contemporary Landsat satellite sensors collect imagery in the visible (R,G,B) spectrum (.44 - .69 μm), as well as in the near-infrared (.77 - .89μm), and into the short wave and thermal infrared (> 1.5 μm) ranges. The spatial resolution of Landsat sensor data in the visible and near infrared is 30m per pixel, and described as “medium resolution”. Landsat offers high temporal resolution. The satellites collect imagery continually, and depending on weather and cloud cover, and whether the satellite scene occurred in daylight, a location can captured in many good images per year. (USGSa, 2013). Although the 30m resolution limits the usefulness of Landsat for analysis of some smaller scale riverine studies (where the channel width, river sinuosity, or openings through the surrounding tree canopy are smaller than the pixel size) the frequency of image acquisition, the low cost, and large coverage of Landsat scenes benefit many researchers in studies of larger rivers. Often research combines satellite imagery with other methods to achieve good results. Baker et. al. (2006) mapped riparian wetlands with multiple season Landsat scenes together with topographic maps and soils data. Wang et. al. (2002) combined multiple dates of Landsat imagery and DEMs to improve mapping after an extreme flooding event. The thermal infrared bands gathered by Landsat (as well as airborne sensors in smaller pixel sizes) offer researchers critical data for remote sensing of water temperatures in riverine landscapes (Torgersen et. al., 2001, Handcock et. al., 2010, Handcock et. al., 2012).

Radar (using electromagnetic spectrum in the microwave region, 1mm-1m) also offers a source of remote sensing data for analysis of larger scale rivers, and became more widely available after 1990. Radar offers elevation models developed from the measured returns of radio wave energy. Radar has been collected in international efforts such as the Shuttle Radar Topography Mission (SRTM). The SRTM was flown on the space shuttle Endeavor in 2000, and it provided coverage across the globe except from the Polar Regions. SRTM has 90m pixel resolution outside of the United States. Other countries have also independently flown synthetic aperture radar (SAR) satellite missions to gather elevation data. Radar is more often used outside the US.

Radar has been used on some of the world's larger river systems, especially large scale flood inundation studies (Schmann et. al., 2012). To describe and analyze the season flooding regime in the large Paraguay River basin (>1,000,000km^2), Paz et al. (2010) combined a 90m DEM derived from radar and analyzed with a hydrological model, with Landsat imagery. Radar has also been used to analyze watershed scale variations in water levels and flows in the Amazon, Congo, and Brahmaputra rivers (Jung et. al., 2010)

LiDAR has been used in river studies since the mid-1990s (Bailly et al. 2012). Due to its fine spatial resolution, especially vertically, lidar has been used in studies of rivers and wetlands particularly where limited height differences challenge topographic maps to show key water and landforms, such as floodplains in Belgium (Notebaert et. al., 2008), or the flat boreal plains of eastern Alberta, Canada (White et. al., 2013). LiDAR has been critical for study of active channel environments and riparian vegetation on the terrestrial surfaces surrounding the river. Jones (2006) used a LiDAR DEM with imagery to map suitable fish habitat in side channels. Johansen et. al. (2010) and Akay et. al. (2012) used LiDAR to develop metrics to measure riparian forest and understory plant coverage, bank stability, and stream width. To quantify floodplain roughness and derive a Manning's n coefficients from the near channel vegetation, Antonarakis et. al. (2008) used aerial LiDAR and resistance metrics developed by Jarvela (2004). LiDAR has also been used to derive information for river bathymetry studies (McKean et. al., 2008, Millar, 2008).

LiDAR is an active sensing technology, specifically acquired for a location (limiting its potential for temporal change analysis). It also is data rich and requires substantial computer memory for computations and data storage. Research on LiDARuse in rivers has compared it to digital elevation models with lower resolutions, lower data memory requirements, or that are publicly available (Charrier and Li, 2012). Although multiple LiDAR acquisitions of the same location are uncommon, the US EPA acquired LiDAR 5 times (every two years in a ten-year period) to both characterize changes in riparian areas and channel morphology changes in an urban river watershed and to test LiDAR accuracy as change analysis tool (Jarnagin, 2010).

2.2 Description of channel migration, movement

Both study reaches (see Figure 1) flow through forested alluvial floodplains. Both have meandering channel patterns constrained by banks blanketed by dense forest. In a few places along Goodman Creek steep valley walls confine the left bank side of the floodplain. This section describes general influences on channel movement related to the two research stream locations.

The form and shape of a river channel is determined by flowing water, the materials it moves as well as the features it flows through. The resistance of the underlying geology or channel substrate materials, the flow regime and its variance (especially the intensity of channel changing high flows), and human disturbance combine to impact channel movement (Knighton, 1998, Montgomery and Buffington, 1998).

In addition to moving water and sediment, large trees and large woody debris in the channel often have a large effect of channel movement in the forested riparian corridors of the rivers in the Pacific Northwest, (Fetherson et. al. 1995, Abbe and Montgomery, 1996, Montgomery et. al., 2003, Montgomery and Piegay, 2003). In these watersheds the abundant trees both help to stabilize channel banks with their roots and also become large woody debris when the trees topple and die (Collins et. al., 2012). Large woody debris can force changes in channel form, both by reshaping the channel dimensions on a local reach scale, and also by effecting flows, pool scour, and sediment transport for distances downstream (Montgomery et. al., 1995, Abbe and Montgomery, 1996, Montgomery et. al., 2003).

Channel movement occurs more readily in rivers flowing in alluvial channels on unconfined valleys. These channels are formed of unconsolidated particles deposited onto the valley floor by the river, ranging from large boulders, cobbles, gravels, and sands to fine sediments. Rivers rework their surrounding channels, eroding and re-depositing sediments from the channel bed and banks. Where a wide enough valley floor exists, the alluvial materials along with finer silts deposited by flood events will over time form a floodplain beside the river channel (Knighton, 1998, Montgomery and Buffington, 1998, Charlton, 2008). The river flows carve into the side walls and bed of the channel removing bank and substrate material in some areas. In other places it aggrades and deposits materials. The meandering or braided channel forms created by the degradation or deposition also moderate the energy and velocity of the river at high flows (Gordon et. al., 2004).

Meandering channels develop in alluvial channel materials as river bends gradually migrate across a floodplain, eroding the outside of the bends and depositing on the inside of the bend, while the channel maintains its width. In rivers with a mixed load of alluvial sediments, the meandering channel pattern will vary with the stream's power, the sediment size and total sediment amount or load. (Knighton, 1998, Charlton, 2008). The meandering pattern of the river combined with the stream width track with the rates that the channel will migrate across floodplain (Beechie et. al., 2006). Both of this research's study rivers have a bank full width approximately at a threshold where previous investigations on channel pattern predict the channels will be deep enough to erode the banks and undermine the roots of the large trees on the river edge (Beechie et. al., 2006). This channel movement assures the continued recruitment of large trees into the channel (Collins et. al., 2012).

2.3 Description of riparian corridor and ecology

The channel setting where the flowing river courses through the surrounding alluvial floodplain or carves through bedrock, and the vegetation along it comprise the riparian corridor. Riparian corridors provide critical habitats for endangered salmon (Richardson et. al., 2010). This section describes the key aspects of the riparian corridor and river processes in the two study watersheds.

In both Goodman and Snahapish Creek, Quaternary alluvium geology underlays large parts of the riparian corridors of the study areas. Upstream of the study areas both rivers flow through colluvial and bedrock reaches that provide sediment sources to downstream reaches. Both upper Goodman Creek and its main tributary Minter Creek cut their channels through colluvial Pleistocene glacial drift and exposed bedrock of Miocene marine sandstone. The headwaters of Snahapish Creek flow through similar Miocene marine sandstones and shales. (WADNR, 2014)

The riparian corridor of the two study rivers is densely forested, and trees, especially large trees, reign as the key riparian vegetation. The floodplain is mantled by both deciduous and conifer tree species. Red alder (*Aldus rubus*) and big leaf maple (*Acer macrophyllum*) are the key deciduous trees. Sitka Spruce (*Picea sitchea*), Western hemlock (*Tsuga heterophylla*), Western Red Cedar (*Thuja plicata*) are the dominant conifer species.

In both rivers the large trees act to stabilize the channel banks (Simon et al, 2004). Also in both rivers, large trees have fallen into the river and the channel. Large woody debris

(LWD) diverts flows, causes substrate scouring and pool development, slows water speed and encourages sediment deposition, and causes channel widening. (Montgomery et. al., 1995, Abbe and Montgomery, 1996, Fetherson et. al., 1995, Montgomery and Piegay, 2003, Montgomery et. al., 2003)

Both river channels have been moved in the past by large trees falling into the channel and initiating even larger log jams. The active channel widens to flow around a log jam and channel carves into the banks and migrates into the floodplain (Montgomery et. al., 2003, Collins et. al., 2012). The LWD not only acts as a disturbance in the channel flow. The sediment deposition from LWD and the sites formed from and behind large fallen trees act as sites for new riparian forests (Fonda, 1974, Collins et. al., 2012). The riparian forest succession after a disturbance such as channel movement begins with colonization by alders, cottonwood, and woody shrubs such as salmonberry. These deciduous trees help add organic materials and especially nitrogen to the bare mineral alluvial soils. Conifers gradually replace these colonizers, and eventually the conifers shade the deciduous trees out (Fonda, 1974, Featherson et al, 1995).

The riparian vegetation has both direct and indirect effects on the local hydrologic cycle and floodplain soil moisture. Adjacent to the main channels of both study rivers, wetlands and small tributaries held moisture into the late summer. In fall site visits, side channel wetland ponds had quickly refilled, possibly due to a rising water table and increasing flows in the nearby river. The riparian forest appears to act to modulate both peak flows and their impacts to the channel (Jones and Grant, 1996, Grant et. al., 2008). The vegetation and its roots help the landscape resist overland and concentrated flows in the river channel and on the floodplains. The tree canopy intercepts rainfall that would otherwise fall directly onto the stream bank soils (Simon et. al., 2004).

In addition to the geological setting and the forest, the precipitation and hydrological regime shape the rivers and their associated riparian corridors here. Both watersheds enjoy abundant rain, in excess of 270cm (> 100”). Precipitation varies greatly throughout the year with most of the rain falling in the fall, winter, and spring followed by a dry summer. November, December, and January see >45cm (18”) per month on average. June, July, and August see 5 – 8 cm (2 – 3”) per month on average. Flows in the area rivers follow a similar pattern (USGS(c), 2014). The highest flows occur in winter, lowest in summer. The hydro-periods of the riparian corridor wetlands also follow this pattern (Mitsch and Gosselink, 2007). The wetlands recharge as the ground becomes saturated and the water table rises. Over bank full flows and seasonal reconnection to the river also replenish the riparian wetland ponds in the study watershed.

2.4 Description of salmon life cycle and river uses

In the two study watersheds, Goodman Creek supports documented spawning and juvenile rearing presences of Coho salmon (*Oncorhynchus. kisutch)* and winter steelhead (*O. mykiss)*. Fall Chinook salmon (*O. tshawytscha)* and anadromous bull trout

(Salvelinus confluentus) have been documented in the lower river, approximately within the lower 4 kilometers where Goodman Creek flows through Olympic National Park. In Snahapish Creek, Coho salmon, winter steelhead, and summer steelhead have documented spawning and juvenile rearing presences (WDFW, 2014). These runs, as "evolutionary significant units" of their populations have not been listed under the ESA, with the exception of the bull trout (*S. confluentus*) which is listed as threatened in WA State coastal rivers including Goodman Creek (RCO, 2009).

Five species of anadromous salmon and steelhead trout use rivers and lakes in the Pacific Northwest for the spawning, and the juvenile rearing life stage. Each species utilizes the rivers, tributaries, and various off-channel waters for different periods and durations of time, and selects different parts of the watershed for its use (Bisson et. al, 1982, Quinn, 2005). All salmonids spawn in the gravel substrate of the rivers, and sockeye salmon (*O. nerka*) also will utilize the nearshore substrate of lakes. Although the different species generally prefer different sized spawning gravels and utilize different locations in the river channel and tributaries, all require gravels small enough to be moved by the females into egg nests or redds, and also large enough to allow oxygenated water to flow through the gravel to the buried, incubating eggs. All spawn in the fall, except steelhead. All demonstrate semelparity, meaning they die after reproduction, again except for steelhead which often survive spawning and may spawn multiple times over a lifetime.

O. kisutch, or Coho or silver salmon spawn in gravels of smaller, moderate gradient streams (Quinn, 2005). *O. kisutch* fry commonly reside and grow in streams for one or two years before going to salt water. In forested western WA rivers, like the study streams, off-channel ponds, wetlands, and LWD and the deep pools formed by LWD have been shown to improve the survival of juvenile coho salmon (Sharma and Hillborn, 2001, Pess et. al., 2002, Anlauf-Dunn et. al., 2014). Coho juveniles seek slow moving waters in off-channel areas and small tributaries to rear (Bisson et. al., 1982), and the quality and complexity of these habitats impact the abundance of coho adults (Anlauf-Dunn et. al., 2014). Forested rivers also support greater coho abundance (Pess et. al., 2002).

O. mykiss, or steelhead trout are an anadromous form of the species whose freshwater form are the rainbow trout. *O. mykiss* steelhead vary in their phenotype, commonly divided into a winter and summer types based on when they re-enter freshwater and how long they reside in the river before spawning. Steelhead are widely distributed, and can be iterparous (meaning they can reproduce more than once and do not die after reproduction). Unlike the other anadromous salmon, steelhead spawn in the spring. Steelhead juveniles typically rear 1-3 years in freshwater before going to sea (Quinn, 2005). Steelhead appear to move upstream more readily than the coho in fall and winter, and then to use downstream pools near to the main channel as refugee in times of summer low flows (Bramblett et. al., 2002) making quality habitats with summer connectivity to the main channel critical for steelhead in the study rivers.

Lastly, *O. tshawytscha*, Chinook or king salmon spawn in larger gravels (>80mm) in medium to large rivers. *O. tshawytscha* fry have two patterns of freshwater use. One is an "ocean-type" that migrates downstream toward the ocean soon after emergence, and spends up to a few months in the river, commonly in the estuary. As the chinook in Goodman Creek spawn within 2km of the ocean it seems likely they are "ocean-type". A "stream-type" chinook spends a full year in the river before migrating downstream and directly into salt water. The "stream-type" chinook tend to spawn and rear either river farther inland or at higher elevations (Waples et al. 2008, Beechie et al. 2006).

The three other Pacific Northwest salmon: pink, chum and sockeye have not been documented in these rivers. *O. gorbusha,* or pink salmon spawn in the lower reaches of rivers and the fry migrate to the salt water directly after emerging from their natal gravels. Pink salmon make little or no use of freshwater for juvenile rearing. *O. keta,* or chum salmon also spawn in the lower reaches of rivers but stay in their natal streams including using the estuaries up to several weeks to grow before migrating out to the ocean. *O. nerka,* or sockeye salmon fry nearly always travel into a lake immediately after their emergence from their natal gravel. *O. nerka* require the presence of lakes and an access to lacustrine habitats within a watershed, and are only seen in rivers with these habitats. (Quinn, 2005).

2.5 Description of how channel movement, formation affects salmon habitats

For the fresh water parts of their life cycles salmon and steelhead trout use different parts of Northwest rivers for spawning and rearing. The channel forming interactions of the moving water, sediments, and large wood together create a shifting habitat mosaic that salmonids have evolved with over geologic time (Waples et al. 2008). As the life history of the three documented species in Goodman and Snahapish Creek (coho, *O. kitsuch*, steelhead, *O. mykiss*, and chinook, *O. tshawytscha*) include from months to multiple years rearing in freshwater before entering the ocean, a variety of juvenile rearing habitats throughout the year are critical (Bustard and Narver, 1975, Peterson, 1982, Quinn, 2005).

The hydraulic forces of the flowing water form and move the channel, and transport and sort the gravels critical to spawning salmon. Spawning salmon seek places in the river system with sediments small enough to move and shape into redds. The gravels must be both small enough for the female salmon to mobilize when digging her redds, but also coarse enough to allow water through with adequate flow to keep the eggs oxygenated (You said this already). The flowing water rearranges and sorts these gravels and sediments of the channel bed (Quinn, 2005, Harrison et. al., 2011).

The flowing water forms the channel and shapes it, both continually and gradually in small increments and also at a larger scale during times of higher flows. At times or locations of high flows, larger materials (>80mm) can be easily moved and smaller sediments can be flushed from the channel. In lower flows, or in places where the channel sinuosity or large woody debris slow the water, smaller sediments and particles tend to stay in place in the substrate or settle from the water column. The flow regime of both peak flows and times of more modest flows will impact the availability of spawning gravel or favorable rearing habitats in a river system (Harrison et. al., 2011). Within a variable flow regime, the contemporary channel forms and large wood structures in different reaches also help determine the gravels available for spawning or offering quality rearing habitats (Quinn, 2005, Harrison et. al., 2011).

In Pacific Northwest rivers (including the study watersheds) channel movement initiates the recruitment of trees from the banks into the channel. Large wood in rivers develops heterogeneous salmon habitats. LWD diverts flows, causes substrate scouring and pool development, slows water speed and encourages sediment deposition, and causes channel widening (Montgomery et. al., 1995, Abbe and Montgomery, 1996, Fetherson et. al., 1995, Montgomery and Piegay, 2003, Montgomery et. al., 2003). When water flows around large wood it scours pools into the substrate and pushes flows into and over the banks. The pools of deeper, low velocity water offer young fish both concealment from predators in addition to a place from which to venture out to forage (Bustard and Narver, 1975, Quinn, 2005).

Both high flows capable of moving the channel, and more frequent over bank full flows that intermittently flood into the floodplain create and fill rearing habitats for juvenile salmon. The movement of the channel can leave behind areas with off-channel wetland ponds and remnant side-channels. In rivers on the west side of the Olympic Peninsula, riverine wetland ponds offer critical refuge to juvenile coho from the extremes of high winter flows (Peterson, 1982). The over bank full flows that occur every 1.5 to 2 years help sustain existing wetlands and off-channel ponds. These slower moving sheltered waters allow small fish to conserve precious energy they would use just to stay in place in the river (Bustard and Narver, 1975). Both off-channel wetland ponds and deeper pools also offer juvenile fish seasonal refuges at lower flows when other parts of the channel may dry out. Lastly, these ponds slowly release their water providing year-round flows into the active channel.

2.6 Description of the riparian protections in the WA FPHCP

This section outlines the Forest Practice rules and the Habitat Conservation Plan related to forested rivers, and how the approaches to delineating and documenting off-channel waters and potential habitats in the HCP relate to the goals of this research.

The Washington State Forest Practices Habitat Conservation Plan (FPHCP) came into being in 2005 in response to a growing number of salmon species listed under Endangered Species Act. It represents a significant addition to the State's Forest

Practice Rules and to the agency structures available for implementing conservation of fish habitats. The FPHCP enables WA State and the forest practices regulated by the Department of Natural Resources to comply with the Federal Endangered Species Act (ESA) and conserve ESA listed species in non-federal forests in WA State. The FPHCP codified habitat protections and an adaptive management process for 50 years. The FPHCP evolved from several earlier efforts to improve the management of forests in Washington and protect fish habitat and ecological values in rivers and the surrounding riparian forest. These included the Timber Fish and Wildlife agreement in 1987, the Forest and Fish Report in 1999, and the adoption of the Forest and Fish Rules in 2001 (FFR, 1999, FPHCP, 2005). The FPHCP expands the Forest Practice Rules to include protection of riverine, wetlands, and off-channel habitats.

In Washington State, the Department of Natural Resources (DNR) oversees forest practices including protections of forested riparian corridor habitats and wetlands on non-federal lands through the Forest Practices Rules (WADNR(c), 2014). The Forest Practices Board is an independent State agency which adopts these Forest Practices Rules and sets the standards for forest practices such as timber harvest, pre-commercial thinning, and road construction. The Forest Practices Board developed a “Board Manual” which serves as an advisory technical supplement to the forest practices rules (WADNR(b), 2010). The Board Manual defines methods for defining riparian forest features critical for implementing the FPHCP, including bankfull channel features, channel migrations zones, wetlands, riparian management zones, and “typed” waters based on fish use (WADNR(b), 2010).

As described in the FPHCP Executive Summary (2005), “Protection measures in the FPHCP include state forest practices laws, rules and guidance designed to minimize and mitigate forestry-related impacts and conserve habitat for species covered by the plan. The protection measures determine the level of on-the-ground habitat protection for covered species.” The FPHCP has two spatially separate and related conservation strategies, one for the riparian corridor, and one aimed at upland management.

The Riparian Conservation Strategy relates most closely to the questions and analysis in this thesis. It includes protection measures implemented in and adjacent to surface waters and wetlands. The delineation of riparian wetlands, channel migration zones, wetland and riparian management zones and equipment limitation zones are important parts of the riparian strategy. These conservation measures are designed to provide adequate levels of large wood recruitment and shade, and to limit excess fine sediment delivery to flowing waters and wetlands (FPHCP, 2005).

The Upland Conservation Strategy compliments the Riparian. It seeks to protect the habitats of covered species by minimizing and mitigating upslope forest practices impacts. The upland strategy limits activities on unstable slopes including road construction, seeks to improve fish passage at road crossings, and develops protection measures against the impacts of rain-on-snow hydrology. These measures seek to limit excess coarse and fine sediment delivery to surface waters and wetlands, and to maintain hydrological regimes in watersheds (FPHCP, 2005).

Under Forest Practice Rules and the FPHCP, landowners wanting to harvest timber or conduct other activities on their forest land must submit a Forest Practice Application/Notification (FPA/N). The FPA/N requires mapping and documentation of all flowing waters including a determination whether they are fish bearing, of all wetlands, as well as a detailed description of possible channel migration zones and the riparian management zones in the area of the proposed activity. The FPA/N requires of the landowner specific calculations to determine the riparian management prescriptions for the site. The riparian management zone (RMZ) prescriptions include a stepped approach of a "core zone", "inner zone", and "outer zones", with diminishing protections and harvest limitations as activity moves away from the river bank full edge. The prescriptions are based on the channel width, the water type (whether the stream segment is fish bearing), and the site class (how well the trees grow there). Harvest is permitted in the "inner zone" (nearest to the river, outside of the "core zone") if the number of trees per acre, the basal area, and the number of conifers exceeds "stand requirements". The "stand requirements" should place the stand on a trajectory toward a "desired future condition" of a riparian forest that will ensure sustainable fish habitat in the stream (WADNR(b), 2010). In practice, a prescribed 150' stream buffer can have basal area goals that can be met and still allow harvest of all trees to the outer edge of the 50' core zone stream buffer.

Timber harvest goals and generalized site measurements from the edge of the channel bank full width, as opposed to ecological specifications or the physical characteristics of potential habitats define current RMZ regulations. The FPHCP protections are defined in a way that provides timber land owners regulatory surety, but which results in a ‘one size fits all’ enforcement and implementation regime. In addition, enforcement appears inconsistent across regions, staff, and agencies from WA DNR, DFW, and Department of Ecology (WADNR(d), 2012, Silver, 2014, WFLC,2014).

As part of regulating harvest in the RMZ, the FPA/N requires the forest landowner with flowing water to define bank full channel features and to document the presence of a possible channel migration zone (CMZ). The FPA/N tasks the landowner and the WA DNR application reviewer to consult historical and current aerial photographs and topographic maps. Then the Forest Practices Board Manual outlines a WA DNR “office review” to determine channel boundaries, channel movement and a possible CMZ, followed by a field evaluation if needed. The office review form describes channel migration as “likely occurring” if “secondary channels, large gravel bars, young disturbance vegetation, high sinuosity, or wood jams” can be seen in the aerial imagery.

The Manual advises landowners and the WA DNR reviewer to conduct reconnaissance in “the entire floodplain within or adjacent to the project and, as necessary, some distance beyond the area of the forest practice” (WADNR(b) (2010). The field evaluation review form lists valley confinement, lateral activity, vegetation changes, and secondary channels with bed elevations at or below the bankfull elevation of the main channel as additional criteria to establish evidence channel movement. The evidence of possible channel movement then informs adjustments to the edge of the bank full channel and the inner boundary of the RMZ. Then the stepped “core zone”, inner zone”, and “outer zone” areas expand out from that line.

The approaches in this research should address many difficulties in the current approach. The dense forest canopy that obscures the two study rivers limits the value of aerial photographs for observing channel movement, as it does in many forested watersheds across WA State. The Forest Practices Board Manual recommends landowners and WA DNR reviewers pay special attention to areas where the valley becomes unconfined, where lateral movement has occurred, where tree succession documents changes, and places where the floodplain elevations lie below the bankfull elevations of the active channel. The lidar data and the models seek to map the critical wetlands, side-channels, tributaries, and pools and backwaters created by large log jams precisely in those floodplain areas in forested watersheds.

3. Methods

3.1 Study Rivers

This research focuses on Goodman Creek and Snahapish Creek, two rivers in forested watersheds on the west side of the Olympic Peninsula of WA State. The study areas of both rivers focus on unconfined floodplain reaches, unconfined meaning the floodplains extend greater than 4 times the active channel widths. Goodman Creek flows into the Pacific Ocean approximately 11km north of the mouth of the Hoh River. It flows ~25rkm in the main stem, with an additional ~14rkm flow in its main tributary Minter Creek. The total drainage area is 80.55 km^2 (31.1 sq.miles). The mean annual precipitation is 274cm (108"). The USGS StreamStats tool calculates a 2-year peak flow (50% probability of occurrence in any one year) in Goodman Creek at 2770 cfs (78.4 cms) (USGS(b), 2014). The study reach length runs 7.4 kilometers from the input of Minter Creek to Olympic National Park.

Snahapish Creek flows into the Clearwater River, a major tributary of the Queets River. The total drainage area of Snahapish Creek to its input to the Clearwater is 51.1 km^2 (20 sq. miles). The mean annual precipitation is 317.5cm (125"). The USGS StreamStats calculates a 2-year peak flow (50% probability of occurrence in any one year) in Snahapish Creek at 2210 cfs (62.6 cms) (USGS(b), 2014). The study reach runs 18.6 kilometers from the Hoh Mainline Road to confluence of the Clearwater River.

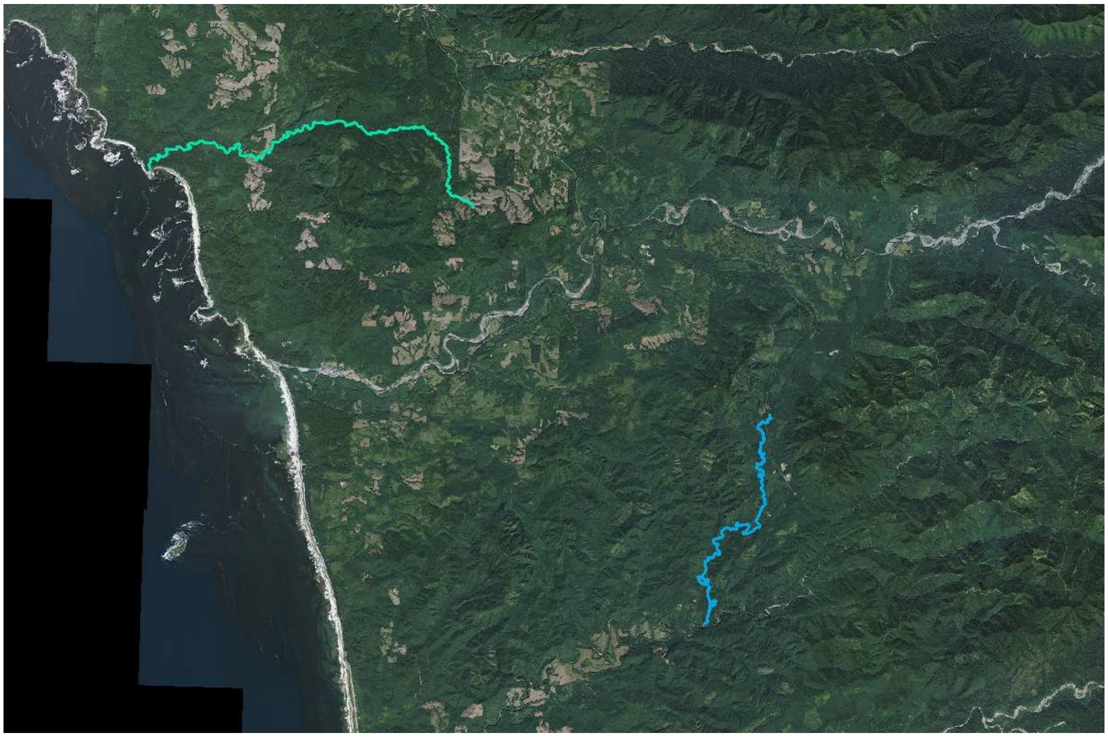


Figure 1. Goodman Creek indicated by the light green line, flows right to left, east to west draining into the Pacific Ocean (along the left edge of the image). Snahapish Creek indicated by the light blue line, flows downward, north to south entering the Clearwater River. The Clearwater flows into the Queets before it flows to the Pacific.

These two rivers share key similarities in scale and setting including watershed size, channel size, precipitation, elevation, geological substrates, and characteristics of their surrounding riparian forests. Annual precipitation ranges from 4m to 5m and falls primarily as rain between September and June (Heusser, 1974). Both rivers begin in the foothills off of the western flank of the Olympic Mountains, and mountain snow melts feed neither stream.

The watersheds and their riparian corridors also have a range of ownerships and have seen a spectrum of historical and contemporary land uses. In Goodman Creek, the WA

State DNR owns and manages the headwaters and the upper river. The Rayonier timber company owns the lands surrounding the mid-river and Minter Creek the main tributary. The lower 3 river miles flow through Olympic National Park. The WA State DNR lands include both areas of past timber harvest and areas with never logged Native forest including old growth. The Rayonier lands were harvested first in the 1950s and 1960s, and have been logged again recently, some in 2012 and 2013. The lower river flows through Olympic National Park and a riparian corridor of protected old growth forests of sitka spruce (*Picea sitchnesis*) western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), big leaf maple (*Acer macrophyllum*), and red alder (*Alnus rubus*).

Snahapish Creek flows entirely through WA State DNR lands with the near stream corridor included within the Clearwater Corridor Natural Resource Conservation Area (NRCA). Most of the surrounding riparian plain was harvested in the 1980s and 1990s. The NRCA protects riparian forest similarly aged as the Olympic National Park sections of Goodman Creek, with younger second-growth forests away from the river. Goodman Creek flows in WA State Water Resource Inventory Area, (WRIA) 20. Snahapish Creek flows in WRIA 21. Both rivers are Type F waters (fish bearing, perennial) under the WA State water typing system (FFR, 1999, WADNR(c), 2014).

3.2 Data: Lidar and aerial photographs

Both rivers have modest channel widths. Goodman Creek begins <4m bankfull width below its headwaters to >40m where it flows into the Pacific Ocean. Snahapish Creek similarly begins <4m bankfull width and grows to >25m downstream where flows into the Clearwater River, a major tributary of the Queets River. They both flow through dense tree cover, such that much of their main channels as well as a great majority of their off-channel riparian side channels, backwaters, ponds, and wetlands are obscured or invisible in aerial photographs.

For the purposes of visualizing the watersheds or investigating historical and landscape scale changes in the channel and surrounding land uses, I used both contemporary and historical aerial photographs. For the purpose of investigating the conditions and locations of off-channel riparian side channels, backwaters, ponds, and wetlands, the lidar data was the primary remote sensing data source. All the source data, both the lidar and the imagery were in the publicly available without cost. The Puget Sound Lidar Consortium archives and provides lidar data from a suite of regional acquisitions to the public, and the University of Washington libraries hosts the WA State Geospatial Data Archive and make available both the NAIP and historical aerial imagery.

3.2.1 LiDAR

LiDAR data acquisitions typically yield two vendor supplied products, the last return or bare earth model and the first or highest return model. The raw LiDAR point cloud data set can also be obtained, as can a data set of the intensity returns (how strongly the laser returns). In this analysis I restricted my analysis to using the vendor supplied products. Particularly, for publicly available LiDAR data (including the LiDAR for this research) these are the commonly available products.

The LiDAR data used in the Goodman Creek analysis was acquired in April 2012 by Watershed Science Inc, for the Hoh Indian Tribe and the Puget Sound Lidar Consortium. The April flight dates sought to both avoid snow on the ground and acquire the lidar during leaf-off or early bud out conditions in lower elevations. The average first return point density for the lidar dataset was 8.40 points/m^2 (0.78 points/ft^2). The average ground classified point density was 0.75 points/m^2 (0.07points/ft^2). Low ground densities are a direct result of the dense rainforest vegetation in the drainage (PSLC, 2013).

The LiDAR data used in the Snahapish Creek analysis was acquired in November and December 2011 by Watershed Science Inc, for the Quinault Indian Tribe and the Puget Sound Lidar Consortium. The late autumn flight dates similarly sought to acquire the lidar during leaf-off conditions in lower elevations and to avoid snow on the ground. The average first return point density for the lidar dataset was 9.60 points/m^2 (0.89 points/ft^2). The average ground classified point density was 0.69 points/m^2 (0.065 points/ft^2). (PSLC, 2012)

Both lidar data sets have a pixel resolution of 1 meter and the coordinate system is defined as NAD 1983, Washington State Plane South. For both acquisitions, Watershed Science documented a vertical accuracy of RMSE ≤ 15cm. For both acquisitions, Watershed Sciences used extensive monumentation combined with stationary and real-time kinematic ground survey GPS data both to support the airborne acquisition process and also to perform quality assurance checks on final LiDAR data (PSLC, 2013). I used primarily the vendor supplied bare earth, or last return, data set in my model building and analysis. I also used the first return data to test my additional hypothesis of a connection between channel movement and tree establishment and succession.

3.2.2 Imagery

For contemporary aerial imagery, I used georeferenced, aerial photography for 2009 supplied by the U.S. Department of Agriculture's National Agriculture Imagery Program (NAIP). NAIP imagery is flown primarily to support Farm Services Agency programs and is often available to public users for no or low cost. The aerial photography was flown in early fall 2009 and was used in a compressed "MrSID" format. The 2009 NAIP imagery has a pixel resolution of 1 meter and the coordinate system is defined as NAD 1983, UTM Zone10.

I used two sets of historical aerial photographs, from 1949 and 1973, to investigate early channel locations and forest conditions in Goodman Creek. The1949 photographs document the watershed before the advent of either roads or extensive timber harvests.

These photographs were taken by Carl Berry for an early forest inventory in Jefferson County. The 1973 set captures the watershed when much of the first logging of the native forests had occurred. These photographs were taken by WA DNR as part of the "OL-H-73" aerial survey. Both sets were digitally scanned from the originals in the University of Washington library collection.

Both dates of historical imagery were manually georeferenced and mosaicked using ArcMap (ESRI, 2013). Due to the paucity of ground control points in a wide forested landscape, especially in 1949 before any road building or logging, I used the coastal rock outcropping and islands near the mouth of Goodman Creek to georeference the photos. Due to a complete lack of ground control points further inland in the Snahapish Creek watershed, I did not attempt an historical analysis there.

The remaining imagery I used came from 2014 via GoogleEarth. Since the 2012 Hoh lidar acquisition, an area of ~.87km^2 (.34 miles^2, ~1.1miles by .3miles) had been logged in 2013 along the north, right bank of Goodman Creek in the floodplain study area. This high resolution satellite imagery was used to locate and visualize the new timber harvest areas relative to the main channel and off-channel water locations, as well as the riparian forest conditions before the logging that I derived from the 2012 lidar and from the field surveys. The original imagery came from a DigiGlobe satellite imagery collection provided to GoogleEarth. A screen capture from GoogleEarth was georeferenced using ArcMap (ESRI, 2014)

3.3 Model Summaries

I tested two different modeling methods, a hydraulic model and a relative elevation model, to map channel movement, wetlands, side channels, and tributaries in a forested riparian corridor using the high resolution lidar data. The hydraulic model computed the locations of off-channel waters and channel movement based how different iterations of over-bank full flows “filled” these places in the floodplain. The hydraulic model allowed me to capture the dynamic quality of the range of discharges, especially the flows with the potential to reshape the channel or seasonally inundate wetlands.

The relative elevation model delineated these fluvial features through their topography relative to the downstream elevation trending of the river water surface captured in the lidar. I had an expectation that although a hydraulic model would be robust and allow an analysis of the floodplain at ecologically meaningful flows, that a relative elevation model potentially offered an informed but easier to use method for improving mapping of channel movement and off-channel waters that offer critical habitats for juvenile salmon. The relative elevation methodology could be learned by anyone with access to GIS software.

3.3.1 The hydraulic model

I used the US Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) software to develop my hydraulic model. HEC-RAS software has been developed for river analysis tasks including steady flow water surface profiles computations, unsteady flow simulations, sediment transport computations, and water quality analysis. HEC-RAS software allows users to create a geometric data representation of a river and its setting, and add hydraulic computations to develop basic water surface profiles for the river reaches of interest (USACOE, 2010). The steady flow analysis tools in HEC-RAS have been designed for use in "flood plain management and flood insurance studies", such as to evaluate floodway encroachments (USACOE, 2010). Although designed for studies of the possible flood risks to dwellings and infrastructure (Yang et. al. 2005), the tool also has the capability to create a geometric or digital representation of a river channel absent questions of impacts to human infrastructure.

I tested steady flow water surface profiles for several different flows and chose 2 as ecologically and morphologically representative. I modeled a 2-year peak flow (50% probability in any one year) seeking to create an over bank full flood that mimics the 1.5 to 2 year interval of over bank full events that has been widely observed (Knighton, 1998, Gordon et. al., 2004). I also modeled a 50-year peak flow (2% probability in any one year). I chose a 50-year peak flow event to model a flow and flood with the potential to move the channel laterally or to dramatically change the channel planform.

For both rivers I used the USGS Streamstats tool for ungaged rivers to derive the 2-year (50% probability in any one year) and 50-year (2% probability in any one year) peak flow discharges that I input into the HEC-RAS models. Streamstats uses regression equations based on large hydrological datasets combining specific watershed basin parameters, , regional flow characteristics and local precipitation data to develop peak flow statistics under natural conditions ((USGS(b), 2014). The USGS does not provide confidence intervals describing the accuracy of the flow estimates, as specific basin characteristics may fall outside the ranges for the site. In Goodman Creek the 2-year peak flow was 2770 cfs (78.4cms), and the 50-year peak flow was 5850 cfs (165.65cms). In Snahapish Creek the 2-year peak flow was 2210 cfs (62.6cms), and the 50-year peak flow was 4600 cfs (130.25cms).

HEC-RAS includes a GIS toolkit called HEC-GeoRAS to enable users to develop the geometric data for the HEC-RAS modeling aspects of the system. To prepare the lidar to use as geometric data in HEC-RAS required transforming it from a raster DEM into a triangulated irregular network (TIN) data structure. A TIN is a vector-based representation of a three dimensional surface made up of points and lines with *x*, *y*, and *z* (3-dimensional) coordinates. The lines form the edges of a network of non-overlapping triangles. The TIN has a computational advantage over the raster. It is simpler. The points of a TIN are distributed based on an algorithm to simplifies the model to those points are most necessary to an accurate representation of the terrain. Data input is therefore flexible and far fewer points need to be stored than in a raster DEM.

Using data-rich lidar challenges the necessity of a creating a simplified TIN data structure to use in HEC-RAS. A TIN data set in ArcGIS allows a maximum of ~20 million data points. This number can be quickly overcome with 1m per pixel resolution raster data sets. The clash of high resolution raster data and a simple TIN vector structure requires the analyst either limit the size of the analysis or to aggregate the lidar source data. I tried both approaches to create useful TINs. In Goodman Creek I limited the extent of the analysis to the channel and riparian corridor from river km 1 upstream to river km 8 (7.4rkm total). At the upstream end of this analysis area the river exits a confined reach with stretches of exposed bedrock into a large, relatively unconfined alluvial floodplain with increased channel sinuosity, more channel movement due to LWD, and more off-channel wetlands and side-channels. In Snahapish Creek, the channel and riparian floodplain study area extended beyond the footprint of limit of a 20 million pixel raster. The river flows 18.6rkm in the study area. In this case I aggregated the lidar raster data, grouping 9 pixels into one (3 X 3) pixel sharing the mean elevation value of the 9. I created the TIN for the Snahapish Creek HEC-RAS analysis from this aggregated raster. To complete the creation of the geometric data of the river channel and surrounding floodplain, I then connected the river centerline and its flow pathways to the two TIN's elevations. This brought together the downward trending slope of water surface elevation inside the active channel and the floodplain. The geometric data is then exported from GIS to the HEC-RAS software.

In HEC-RAS the analyst specifies perimeters for hydraulic computations depending on the infrastructure and characteristics of the river and the analysis. In addition to the Streamstats derived flows outlined above the tool incorporates a Manning's n roughness coefficient for the channel and the floodplain. I used a Manning's n of .08 in the existing sinuous coarse gravel bottomed channel and banks and 0.12 for the forested floodplain. The HEC-RAS software returns profiles, rasters extents with water depths, and vectors of the water coverage that each can be exported back into a GIS to be mapped.

3.3.2 The relative elevation model

The relative elevation model uses topography and GIS to relate the river water surface to the surrounding terrain. It does not model flows. Versions of relative elevation, “height above water”, “depth to water index” models have been developed to inform possible restoration planning (Jones, 2006), boreal forest and wetland management (White et. al. 2013) and as a part of testimony in a channel migration zone legal dispute between the Quinault Tribe and WA DNR (WFLC, 2010). In contrast to HEC-RAS, where a key step in the analysis requires the conversion of the data-rich and computationally demanding raster DEM into a simpler vector TIN, a relative elevation model retains the original (lidar) rasters and their 1m per pixel resolution.

A key part of any model of the relationship of a river to its floodplain must account for the downward elevation trend of the river. With GIS tools I created a river centerline and intersecting cross section lines across the floodplain perpendicular to it. I attached the elevations from the lidar to the points where the river channel centerline intersected the cross sections. Then I created a polygon of a virtual plane from these points, one that captured the elevation of the downward trending elevation of the river surface and extended it outward and corresponding to the area of the floodplain. Within the dimensions of the virtual plane polygon I then subtracted virtual elevations from the actual digital elevations of the topography of the floodplains. The resulting raster captures floodplain elevations relative to the river elevation.

In both of the study watersheds I compared the spatial extents and the elevation returns of the hydrological features delineated by the hydraulic model and the relative elevation model. With the hydraulic model, I modeled two discharges, a 2-year over bank full flow and a 50-year flow. These discharges were determined using the USGS Streamstats tool for ungaged streams. For the relative elevation model I delineated extents with elevations <8' and <7' above the water surface elevation of the river. I also delineated an extent that described the active channel, where the vegetated banks transitioned to exposed gravel bars or flowing water. Both models returned a results raster with elevations. HEC-RAS also returned an extent polygon.

In Goodman Creek, the two models focused on the floodplain in the alluvial areas below the lowest bridge and into Olympic National Park. This focus resulted from the decision to test HEC-RAS with a TIN created with an unaggregated lidar raster data set (see the hydraulic model section above). In Snahapish Creek, the modeled area included the riparian corridor surrounding 18.6 rkm. This longer extent used a TIN derived from an aggregated lidar raster in its HEC-RAS model.

3.3.3 Analysis of the historical imagery

I also used historical aerial imagery to track changes in channel location and morphology, and to do so at a human time scale (Buffington, 2012, Simon and Castro, 2003). I compared how the locations of past channel migration relate to the floodplain geomorphology and riparian vegetation. Bellmore and Baxter (2014) described a strong relationship between the geomorphic setting and the ecosystem structure and functions within montane riverine ecosystems. I hypothesized an observable relationship between the geomorphic setting including the structure provided by large woody debris and a habitat heterogeneity along the Goodman Creek riparian corridor. I looked for evidence of the ways that changes in the channel location functioned to shape wetlands and potential off-channel fish habitats. An analysis of historical imagery provides a additional way of corroborate the causes and effects of channel movement (Latterell et. al., 2006).

In addition, the FPHCP defines its goal to improve “desired future conditions” for in-stream fish habitats based on a trajectory toward establishing mature riparian forest stands out 140-years into the future (FPHCP, 2005). Looking backward 65 years at the changes in the riparian corridor will possibly illuminate the rates of changes in the Goodman Creek floodplain and the interplay of the maturing forest and the river.

I digitized the stream centerlines for the three dates of imagery (the georeferenced and mosaicked 1949 and 1973 historical aerial photographs, and the 2009 NAIP imagery) and compared locations of channel movement over 65 years. I placed the 3 stream centerlines over the lidar derived relative elevation model channel planform and pattern in the Goodman Creek floodplain. I evaluated how the locations of the greatest channel migration related to cross sectional characteristics, especially changes in channel width due to log jams and large woody debris, I also evaluated locations where the valley shape confines channel movement. I assessed channel migration related planform characteristics such as sinuosity. Lastly, I looked to correlate past channel location with the wetlands remaining in places abandoned by the channel when it moved in the floodplain.

A stream centerline approach to analyzing channel migration might be open to criticism due to possible errors. Errors can occur in georeferencing the imagery, in the process of hand delineation of the stream under the canopy, and the likelihood that the digitized center line may not represent the center of the river because high flows will skew the centerline location. I judged the approach satisfactory for this analysis. My goals for reviewing the historical imagery were to highlight locations of past channel movement over decades and to try to explain the causes. I limited errors in georeferencing by using visible, immobile ground control points. Hand delineation allowed me to draw the stream center line based on my photo interpretation experience and knowledge of the site. Placing the center line precisely over the thalweg or perfectly on the center of the river was not as critical as capturing the movement of the river and the character of the long term change.

3.3.4 Canopy and tree establishment models

I developed models to explore a hypothesis that I could detect a record of channel movement through its influence on the tree establishment and succession in the riparian corridor using the “first returns” from the lidar data and a canopy height model. Within the active channel, in the reaches where the river flows during all or part of the year, trees will not be able to establish. On newly exposed banks, a chronosequence beginning with shrubs and deciduous trees such as alder (*Alnus rubus*), preceeds the establishment of conifers. Where the river has not flowed in many decades, the trees will come to achieve their greatest heights and the species composition of the mature riparian forest . Within this range of succession, a timeline of recent channel movement and then emergent tree establishment might be discoverable in the first return lidar data.

In these rivers, the channel movement causes an undercutting of the stream banks at the edge of the riparian forest and recruits trees into the river. As the channel moves it also exposes new land to colonization by vegetation, especially trees. In the coastal riparian forests of the Pacific Northwest, the stand development follows a successional chronosequence, beginning from recently exposed alluvial deposits being colonized by willows (*Salix sitchensis*) and alders (*Alnus rubra*), followed by seedlings of sitka spruce (*Picea sitchensis*). If the surface remains outside the active channel, later colonizers such as big leaf maple (*Acer macrophyllum*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*) take root. Ultimately, over centuries a complex, old-growth forest develops (Fetherston et. al., 1995, Collins et. al. 2012). New channel movement or the return of the channel to earlier paths can disrupt or reset the sequence. Remnant side channels will also retard initial colonization (Van Pelt et. al., 2006, Latrell et. al., 2006).

Based on the forest stand characteristics of these species, I theorized that younger stands of the hardwoods *Salix sp.* and *Alnus rubra* would have lower canopy heights and less variation in heights, and older conifer stands would have higher canopy heights and more variation in height. As the lidar data has a 1m per pixel resolution, the analysis required aggregating the data into “stands”. These stands had to be large enough to capture several trees, and not so large as to obscure their physical connection to the river and past channel movement. I iteratively tested 15m^2, 20m^2, and 30m^2 aggregation sizes for the analysis pixels. I chose 15m^2 pixels, as the active channel ranged from ~30m to >100m across, and few of even the largest *Picea sitchensis* crowns exceed 15m.

I tested three forest canopy metrics to capture a signature of forest establishment and the time of a transition in species composition from the pioneering willows and alders to the conifer dominated stands: amount of canopy cover, the maximum canopy height, and a coefficient of variation between the highest and lowest values within a 15m^2 "stand". I selected these metrics from a range of possibilities that have been developed for studying forest stand and canopy structure (Lefsky et. al., 2005). I used metrics most related to stand succession and channel movement, and I also restricted myself to the vendor supplied, more publicly available products. I created a canopy height model by subtracting the terrain heights of the bare earth model from the first returns model for all of the extents I analyzed. I compared several indexes pairing the effects of the maximum height, the canopy cover, and the standard deviation of the variation in 15m^2 pixels across the landscape extents.

Initially I attempted to develop a canopy and tree establishment model on a spatial extent encompassing the whole of the Goodman Creek floodplain, similar to the extent covered by the relative elevation floodplain model. This extent included both downstream areas of native forest within Olympic National Park and industrial forest lands upstream owned by Rayonier Timber. The Rayonier lands were harvested in the 1960s and 1970s, and several units have been cut again recently. The newest logging occurred just prior to the 2012 lidar acquisition. This land use history confounded the timeline of tree establishment and my ability to clearly model forest succession due to channel movement across the spatial extent of my original floodplain water features models. These initial model attempts captured native riparian forest formed of natural processes including channel movement, previously harvested areas where the forest succession had been reset at different times 40+ years ago, and recent clearcuts.

To eliminate the effect of the land use history I attempted a smaller extent limited to the river and riparian forests within Olympic National Park plus a few hundred meters upstream where the intact riparian forest corridor remained. This extent included large areas of channel movement recorded in the historical aerial photographs. The reshaped channel pattern left by the past channel movements could also be seen in the hydraulic and relative elevation models. Lastly, during the field work assessments, I mapped the locations large wetland complexes and near channel alder stands on inside bends this lower extent. These attempts captured a signature in the canopy that followed the locations of channel change and wetlands.

3.4 Field Surveys

With assistance in the field, I surveyed both the Goodman Creek and Snahapish Creek floodplains to assess and confirm key features in the lidar derived hydraulic flow model and relative elevation model. I surveyed 12 transects, 4 in Snahapish Creek and 8 in Goodman Creek from June to September 2014. The transect lengths ranged from 500m to 2,800m, with one longitudinal profile transect of Goodman Creek over 4,500m. Dense understory vegetation, especially large LWD and log jams, and access to the river, all influenced the survey routes in the field. Most transects required a whole day to complete.

There were three goals. I sought to judge the accuracy of my categorization of different hydrological and potential habitat features in the riparian floodplain. I wanted to evaluate the accuracy of the lidar below the tree canopy. I hoped to review land use history captured in the canopy and tree establishment model. The survey transects included both cross sectional transects and longitudinal transects, capturing mapped locations and elevation changes both across the floodplain and the off-channel hydrological features and also up and downstream within the active channel.

In both Goodman Creek and Snahapish Creek we completed transects both in the longitudinal direction of the river and focused on hydrological features close to the active channel and also in cross sectional directions working more across the floodplain. The shorter transects were often more cross sectional in direction. Dense understory vegetation, especially large LWD and log jams, complex floodplain topography, access to the river, and river sinuosity all influenced the survey routes in the field. The locations chosen for transects corresponded to places where past field experience and the models predicted the existence of key floodplain and river hydrological features. The past field experience including taking GPS points at examples of floodplain wetlands and side channels acted similarly to the image analysis "training sites" described in Halabisky et. al. (2011). After the results from the models had been developed, a polyline GIS shapefile of expected hydrological features was created with attributes to be assessed in the field. This shapefile was used in a handhand GPS to locate the modeled features. In Goodman Creek 36 polylines with discrete and potentially linked attributes were field assessed. Table 2 illustrates the attribute table for the GPS field assessment polylines.

First, I surveyed to verify the accuracy of the modeled hydrological features, and affirm geomorphological factors that helped to create various categories of waters or features along the main channel and in the surrounding floodplain. In my models I had categorized and mapped these features as tributaries, year round or seasonally connected wetlands and wetland ponds, side channels, and areas where the channel shape had been changed and overflow areas had been created by log jams and LWD. We recorded evidence of channels and side channels (such as defined banks and the location of bankfull flows), drivers of channel movement or over bank flows (such as LWD and log jams), riparian wetlands and off-channel ponds (including their connections to the main river, wetland vegetation), tributaries (including fish presence or difficulty of fish access at any flows), and off-channel waters and wetlands without clear surface connections to the main rivers.

Secondly, I surveyed with survey grade GPS (JAVAD , 2008, Trimble 2014) and a hand-held Garmin GPS (Garmin, 2014), together with stadia rod and laser rangefinder to corroborate both the locations and elevations of main channel features and connections to off-channel waters that I had modeled in the lidar. With the survey grade GPS I used a post-processed kinematic (PPK) methodology. I set up a reference base station and receiver in the open (in an elevated, logged location) together to collect precise satellite information concurrent with collecting GPS points with the roving receiver in the forest and channel. In the post-processing the position data and satellite path information captured by the reference base station is used to improving the accuracy of the roving receiver. Still, dense canopy cover has been known to greatly challenge GPS accuracy, especially vertical accuracy (Wing, 2008, Wang and Nihan, 2005). I encountered bad satellite multi-pathing whenever I surveyed beneath the forest canopy. The figure below (Figure 2) show clusters of multiple satellite returns around the roving GPS receptor (the swarm of points surrounding each blue or orange location).

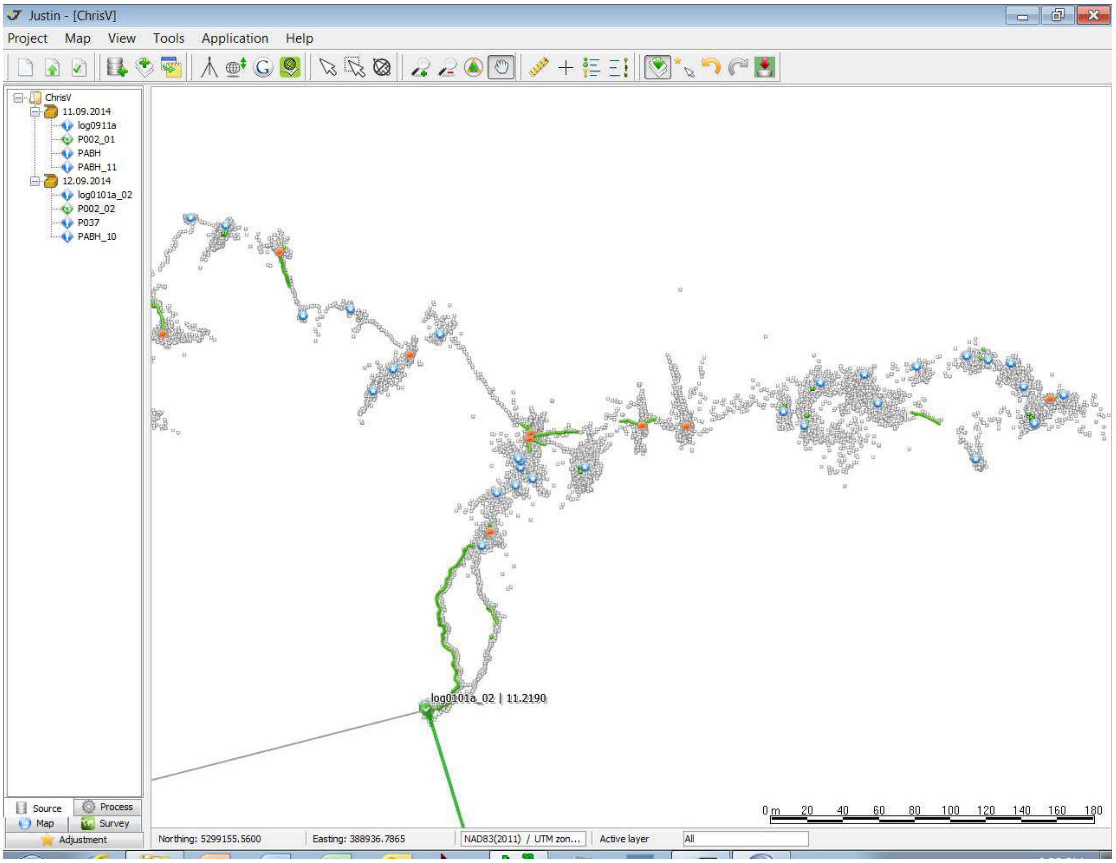


Figure 2. Survey grade GPS base station and rover satellite transmission map of part of one Goodman Creek survey. The numerous satellite points record “multi-pathing” as transmissions to and from the GPS receiver reflect on the trees and in the canopy, and illustrate the high number of errors whenever the rover has entered the canopy.

I also measured the lidar elevation changes empirically under the forest canopy. Using a laser ranger finder and a stadia rod I measured the distance and angle of elevation change from each GPS point to point, and empirically confirmed the relative elevations of off-channel features there. At approximately 5m to 50m intervals (depending in complexity of the elevation changes and the off-channel waters, as well as the density of the understory vegetation) I recorded elevations and locations in the active channel and beside it in the floodplain.

Lastly, I surveyed in the recently logged Goodman Creek floodplain in an attempt to map the locations of the stumps of longer established trees, especially conifers, and to connect them with places where the lidar “first returns” canopy model indicated them. The recent logging offered a relatively easy way to measure the stand establishment dates, and the lidar acquisition the year before offered a pair of “before” pictures, one of the canopy and the other of the ground below it. I looked to see if these conifer locations might correspond with places in the floodplain with a slightly higher elevation and at the limit of off-channel waters in the 2 models from the lidar bare earth DEM. Persistent off-channel waters or wetlands would limit the establishment of conifers, and their long-term absence might confirm a long-term hydrological pattern of periodic inundation or saturation. Due to the absence of the dense forest canopy and a view to the open sky we mapped these transects of the tree and wetland locations across the plain with a survey grade GPS alone and without empirically confirming the point-to-point elevation changes.

4. Results

4.1 Model summaries and a comparison of the extents and the elevations delineated

In both watersheds, the extent modeled for the 2-year flow in HEC-RAS corresponded closely to the 7' extent defined in the relative elevation model. In Goodman Creek, the 2-year peak flow inundated an area 87.8% of the extent of the 7' relative elevation model. Similarly, in Snahapish Creek, the 2-year peak flow inundated an area 92.3% of the 7' relative elevation model. See Figure 3.

In Goodman Creek, the 50-year event covered 114.7% of the area <8' above the river water surface. In Snahapish Creek the 50-year flood event covered just 88.1%, less than the extent of the area below 8' above the river surface elevation. This difference is due simply to the greater variety of confined and unconfined valley sections in the two watersheds and to the longer length of Snahapish Creek that was modeled there. Several river km of Snahapish Creek flowed through relatively confined reaches. This meant that even at the higher flows the greater volumes of water stayed in the confined valley and did not travel far outside the active channel. Table 1 shows the different modeled extents in km^2.

Comparing the two modeled extents includes a review of possible errors of commission or omission. This logically requires viewing one of the models as true or original, and the other as over-predictive or over-classifying in some areas, and under-predictive or under-classifying in other areas. In Snahapish Creek the extent modeled by the 2-year hydraulic model covered 1.466 km^2, and the relative elevation model covered 1.589 km^2, a .123 km^2 difference (or 7.7%). Nearly all of the difference (.095 km^2) appeared as over-prediction of the relative elevation model (areas it said would be inundated beyond the 2-year hydraulic model extent). The remaining (.028 km^2) appeared downstream of the main floodplain in more confined reaches, and the hydraulic model predicted areas of over bankfull flows where the relative elevation model did not. See Table 2.

In Goodman Creek, the extent of the active channel, across any midstream gravel bars to the toe of each bank, corresponded to approximately 1.5' above the water surface elevation. In Snahapish Creek, the extent of the active channel more closely corresponded to 2' above the water surface elevation. These slightly differing extents derive from the differences in the water surface elevations on the dates to the lidar acquisition and small, local differences in the topography of the active channel.

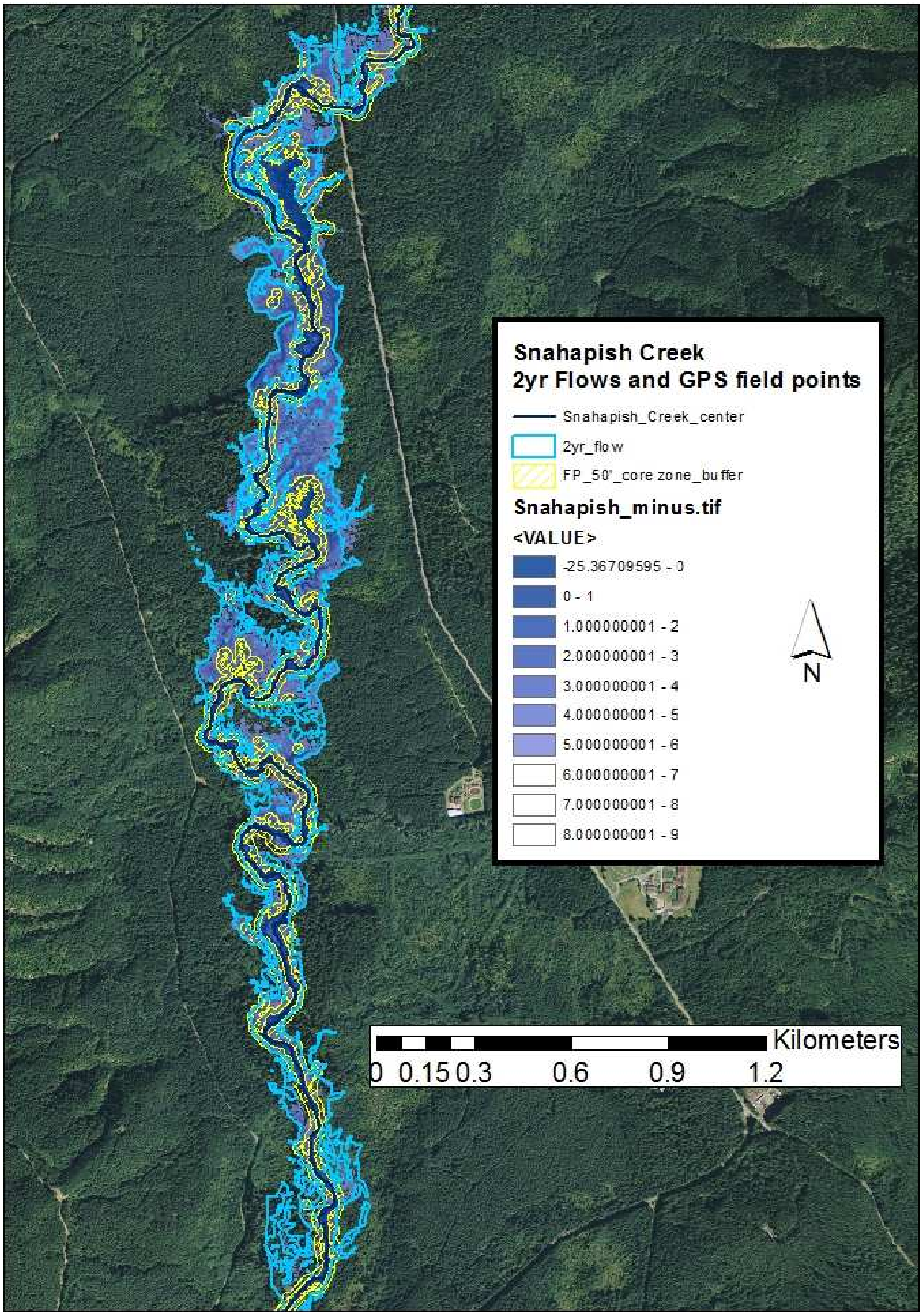


Figure 3. Snahapish Creek. Comparison of hydraulically modeled 2-year flows with a relative elevation model of <6' above the water surface elevation. Snahapish Creek flows north to south.

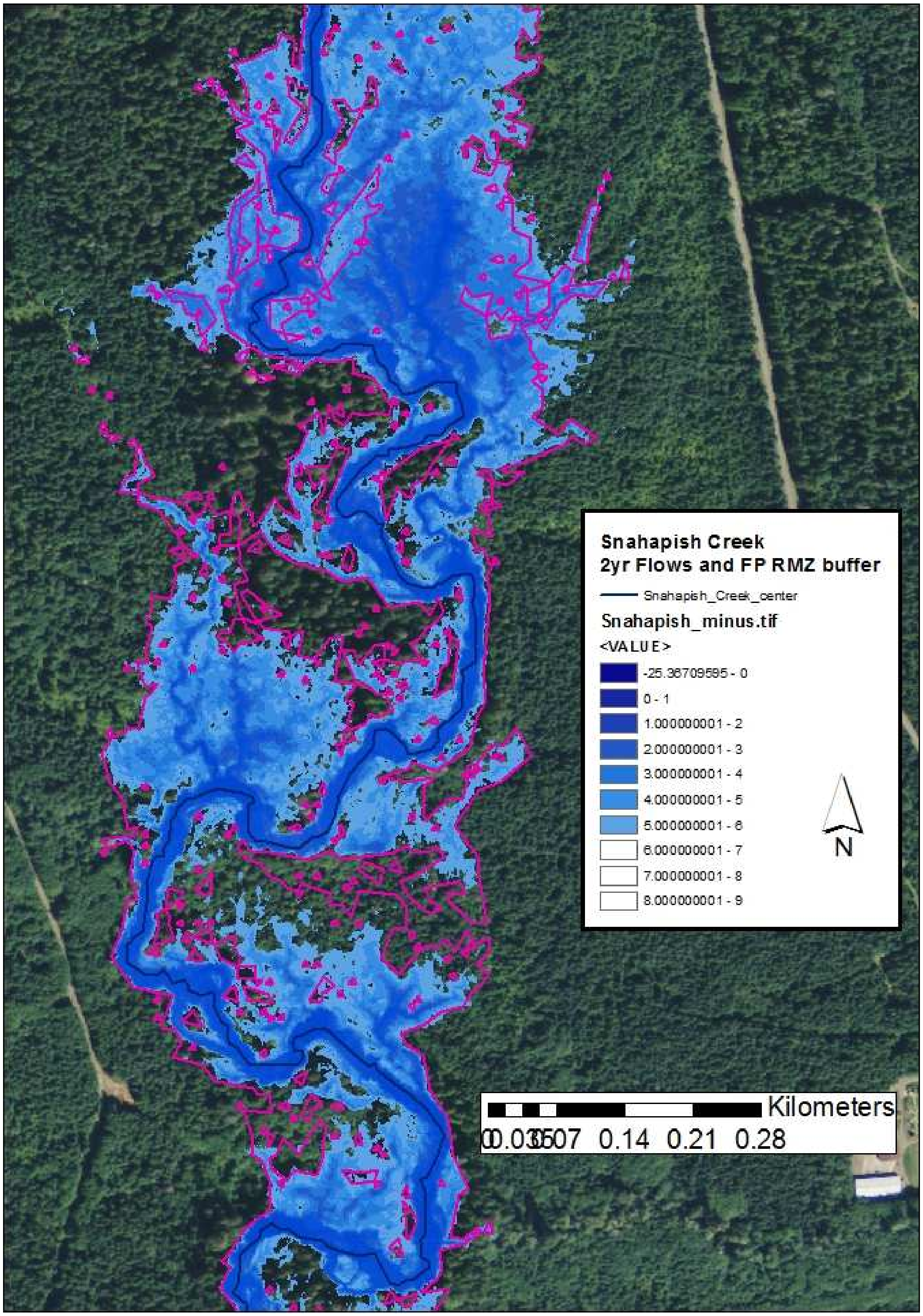


Figure 4. Snahapish Creek Detail. Comparison of hydraulically modeled 2-year flows with a relative elevation model of <6' above the water surface elevation. Purple outline marks the 2-year flow extent.

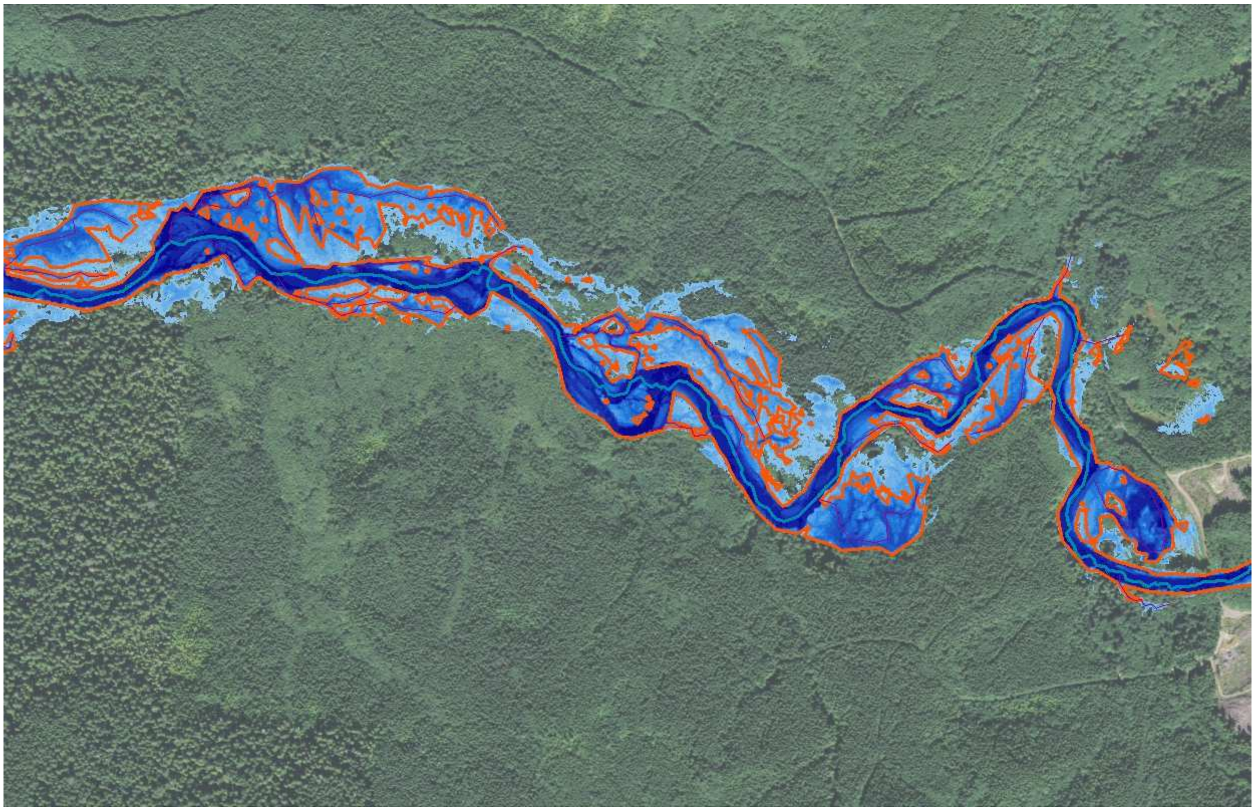


Figure 5. Goodman Creek. Comparison of hydraulically modeled 2-year flows with a relative elevation model of <7' above the water surface elevation. Orange outline marks the 2-year flow extent. Overlaid onto 2009 NAIP imagery. Goodman Creek flows right to left, east to west.

4.2 Field Assessments

4.2.1 Accuracy in qualitative assessment of potential habitats

Both the hydraulic model and relative elevation model methods achieved the goal and delineated potential habitat locations within the floodplains. In both Snahapish Creek and Goodman Creek I compared the mapped locations of the different categorized waters (wetlands and wetland ponds, side channels, tributaries, changes in channel shape and form and formation of back waters adjoining the main channel due to LWD) with the actual conditions in the field. Figure 6 illustrates GPS assessment points for the Snahapish Creek surveys. Initial, pre-modeling field assessments had provided examples of the floodplain and river channel hydrological features and GPS locations that informed the modeling. The post-model field assessment sought to verify how well the models predicted the hydrological features, and each transect included the assessment of several modeled locations of the different categorized waters. Table 2 illustrates, for Goodman Creek, the 36 polylines of hydrological features and their attributes as they were assessed. Accuracy was largely excellent, 94.4% (34 of 36) locations corresponding with the anticipated hydrological river or floodplain features. Both of the 2 exceptions were locations where a mapped possible side channels did not see frequent enough flows and lacked truly defined banks. These locations (not side channel, not wetland pond) appeared to be wetted in the 2-year flows delineated by the hydraulic model (muddy depressions ringed with wetland plants) but were not clearly connected to the channel upstream. They might be refuges for juvenile fish at the highest flows but did not conform to the criteria of the categorized waters. The models accurately mapped the deeper wetlands, ponds, small tributaries, and LWD scoured pools as well as their connections to the channel.

I assessed each mapped potential habitat in the field and conducted a visual assessment to judge whether it correctly corresponded with anticipated category. Wetlands were assessed for hydrophilic plants, standing water, hydric soils, and connections to the active channel. The connections were assessed as currently wet and actively connected or as connected at below bankfull flows, based on bankfull indicators at the outflow of the wetland. Side channels were assessed for connections to the active channel both up and downstream, and for defined banks. Tributaries exhibited defined banks and evidence of active or recent flows. Features in the active channel attributable to the impacts of large woody debris exhibited both changes in the channel planform shape and waters directed into the floodplain by the LWD. Flows around large wood also often scoured deep pools, increased the depositing of sediments and the creation of bars in the channel, and created wetlands adjoined to the active channel.

4.2.2 Accuracy of lidar elevations and GPS under forest canopy

Across 7 transects in Goodman Creek and 2 transects in Snahapish Creek I compared the elevation changes recorded in the lidar with two types of field measurements. I compared the lidar elevations to measurements taken with a survey grade GPS. I also surveyed point to point elevation changes using a stadia rod and a laser rangefinder.

The survey transects included both cross sectional transects and longitudinal transects, capturing elevation changes both across the floodplain and the off-channel hydrological features and also up and downstream within the active channel.

While the forest canopy greatly reduces the number of lidar returns per m^2 getting to the forest floor and back to the sensors, and requires some interpolation between locations lacking sufficient returns in the post-processing, I found the LiDAR derived bare earth DEM had the resolution and precision needed to delineate both the in-channel and off-channel hydrological features. Our point to point measurements corroborated the elevation changes between locations captured with the lidar. The lidar captured the elevation changes both down the longitudinal profile of the stream channel and across the floodplain transects down into and out of both the active channel and off-channel wetlands. Our methodology, with a hand-held laser rangerfinder and GPS, allowed us to survey long transects efficiently. Using this method on several out and back, looping transects that returned back to the base station after surveying >1.2km lineally, we recorded <2m measurement error. Although the thick forest understory limited greater precision, this method sufficed for our purpose. A more precise assessment of lidar DEM accuracy under the canopy, although on a more limited range, could be done with stationary surveying tools, such as a Total Station.

The thick forest canopy greatly limited the accuracy of the survey-grade GPS. The canopy deflected the satellite signals and created a large multi-pathing problem. The X and Y information sufficed for location, but the elevation accuracy could not be replied on. The difference between lidar elevations and GPS elevations varied everywhere under the canopy sometimes by >30m. Even keeping the receiver in one location for 5 minutes did not allow enough consistent contact with the satellite to generate an accurate location elevation. The lidar was much more accurate than the survey-grade GPS for elevations in part due to the overall coverage aspect of the lidar. The GPS and gyroscope in the lidar sensors fly in the open sky accessible to satellite reception all through the acquisition activities. Collecting data points across the landscape allows connecting and interpolating elevations more accurately than individual elevation points hindered by the forest canopy can be.

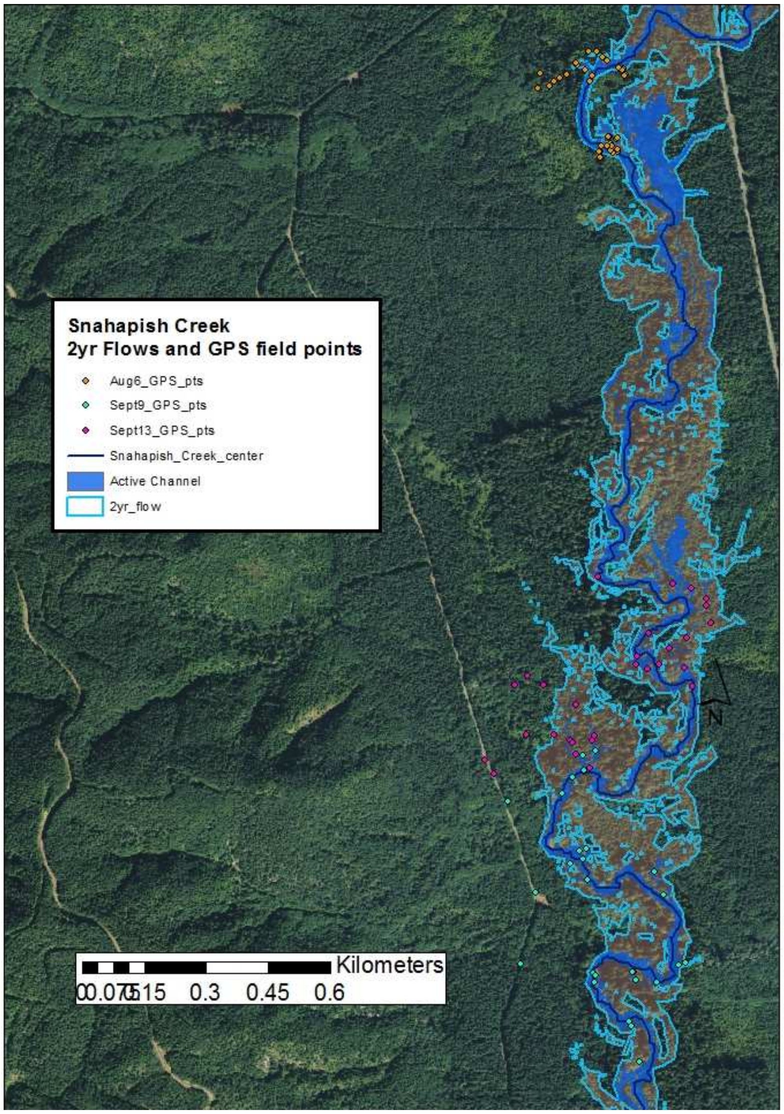


Figure 6. Snahapish Creek. Detail of GPS points for field survey transects. Snahapish Creek flows north to south, top to bottom of map.

4.3 The channel change seen in the historical photographs and its relation to the modeled fluvial geomorphology and LWD

In Goodman Creek I overlaid the evidence of the channel movement captured in 65 years of aerial photographs onto the fluvial geomorphic setting of the floodplain and the inundation extents I modeled with the relative elevation model (Figure 7). The pairing highlights both the points where the valley walls confine and direct the flows and the power of large wood and log jams to dramatically reshape and move the channel. Goodman Creek alternates between reaches where the river has consistently remained through the decades and places where the channel has migrated as much as 175m in 65 years. The channel migration has occurred where the floodplain opens up and becomes unconfined, and either at the outside of meander bends or where LWD and log jams force the flows toward the banks on the floodplain side of the channel. The pattern of active channel cross sectional width also varies widely. In many reaches, the bank full channel does not exceed 35m. But in several reaches the bank full channel cross section has widened to over 150m. These locations correspond to log jams and the effects of LWD.

Goodman Creek flows through an alluvial floodplain to the Pacific Ocean for ~8 rkm in the study area. A low plain stretches along the right, northern bank for the most part. But moderate slopes rise up from the channel and line much of the left, southern bank. These hillsides restrict channel movement to this direction. Within this larger geomorphic setting, most all of the channel movement recorded in 65 years has occurred toward the right bank. Figure 7 (below), illustrates the impact of the left bank hills and the majority of channel movement toward the right bank.

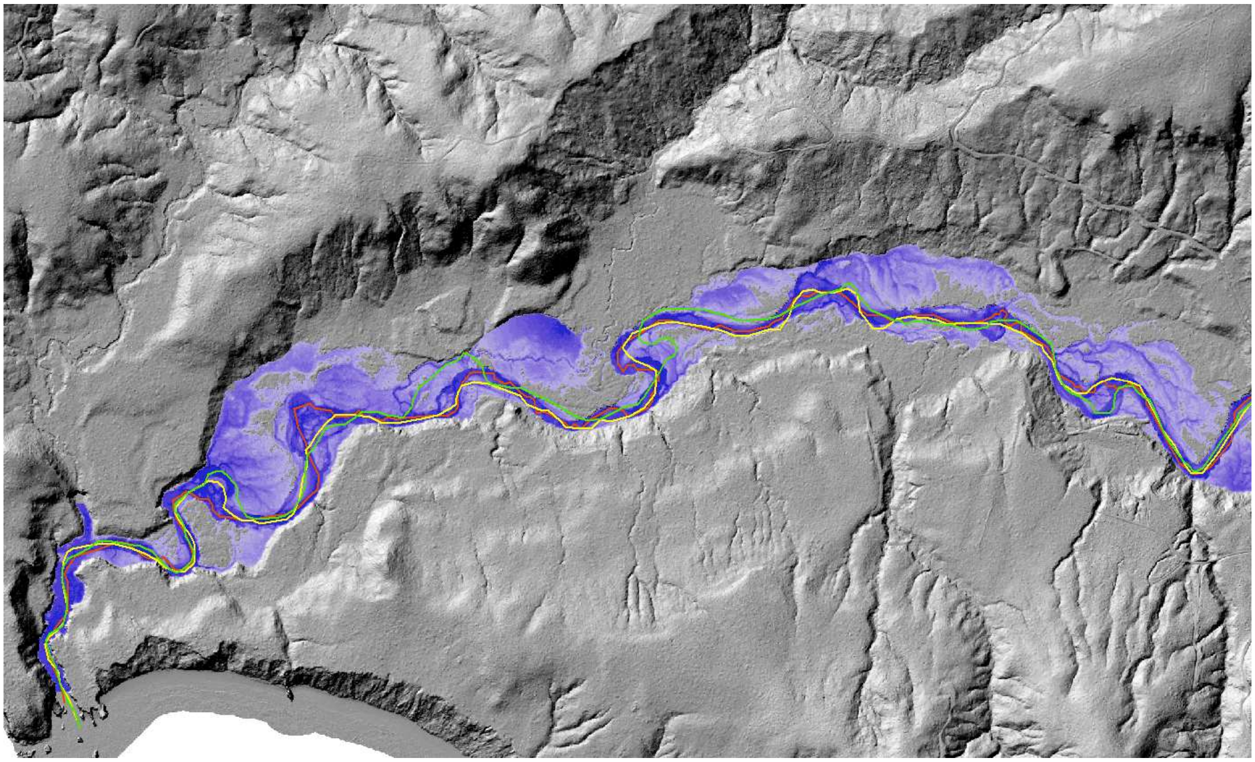


Figure 7. Over a lidar derived hillshade DEM, the 3 historical stream centerlines and the relative elevation model. Geomorphology of the floodplain modeled to <8' above the relative river surface elevation. The historical stream centerlines converge where the valley wall confines the channel, and diverge across the floodplain, and mostly toward the right bank, where the valley opens and where LWD/log jams divert and widen the flows. The green line shows the 1949 centerline, the yellow line shows the 1973 cnterline, and red line the centerline of 2009. Goodman Creek flows right to left, and into the Pacific Ocean.

Figures 7, 8, and 9 illustrate the interplay of large woody debris and log jams together with the confinement of the geomorphic setting. All show the same extent, same river reaches, and the same dates of the 3 stream center lines. In the 1949 image, large log jam structures can be seen along the river path of that date. Similarly, in 2009 large log jam structures can be seen. Where the channel opens up in the center of the 2009 image the log jam covers over 3 hectares. The third figure shows the relative elevation model over the bare earth hillshade. Over the decades, the path of the river varies least when it flows up against the hillslopes. The channel moves widely where the setting allows and where forced by the large wood.

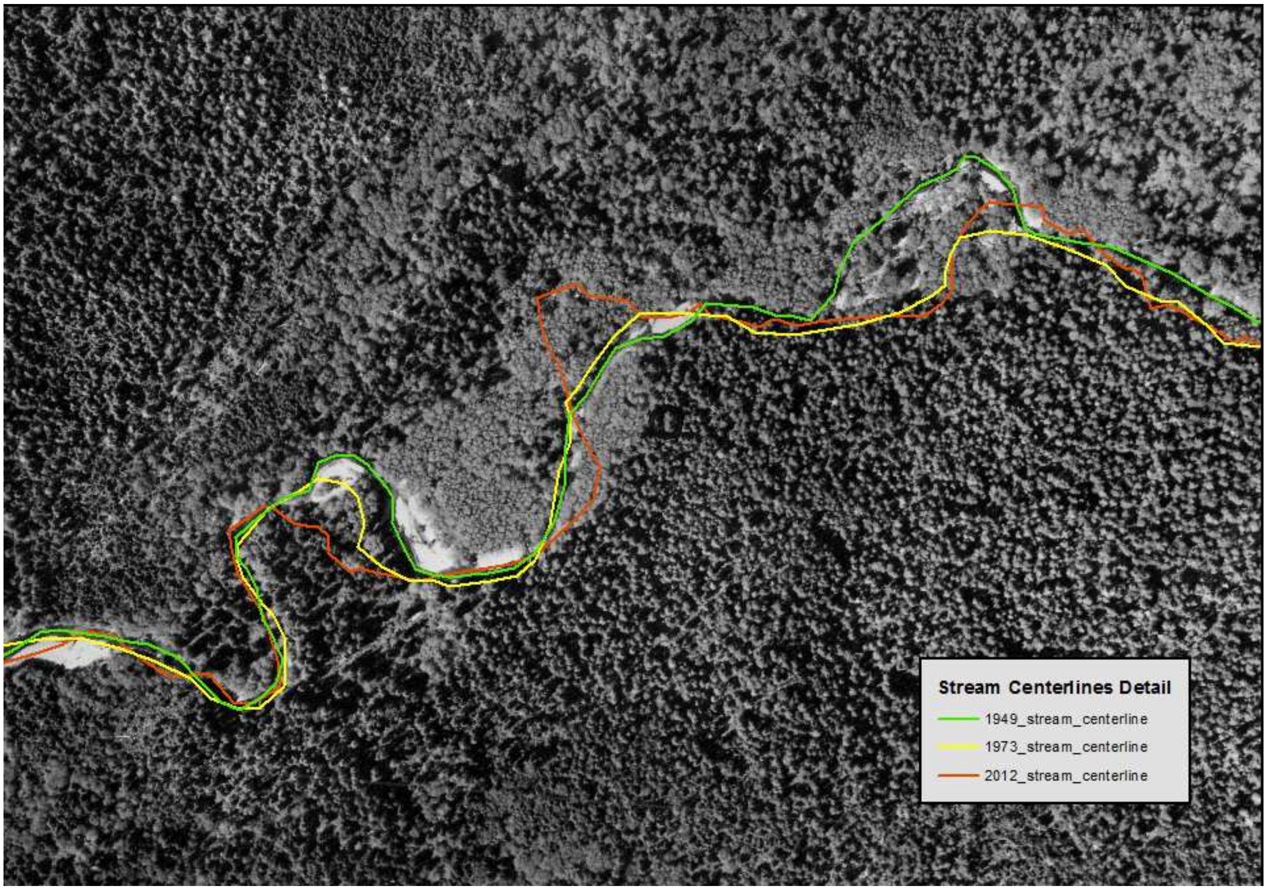


Figure 8. 1949 aerial photograph with 3 dates of stream center lines. Log jams and large woody debris visible in the active channel. Goodman Creek flows right to left.

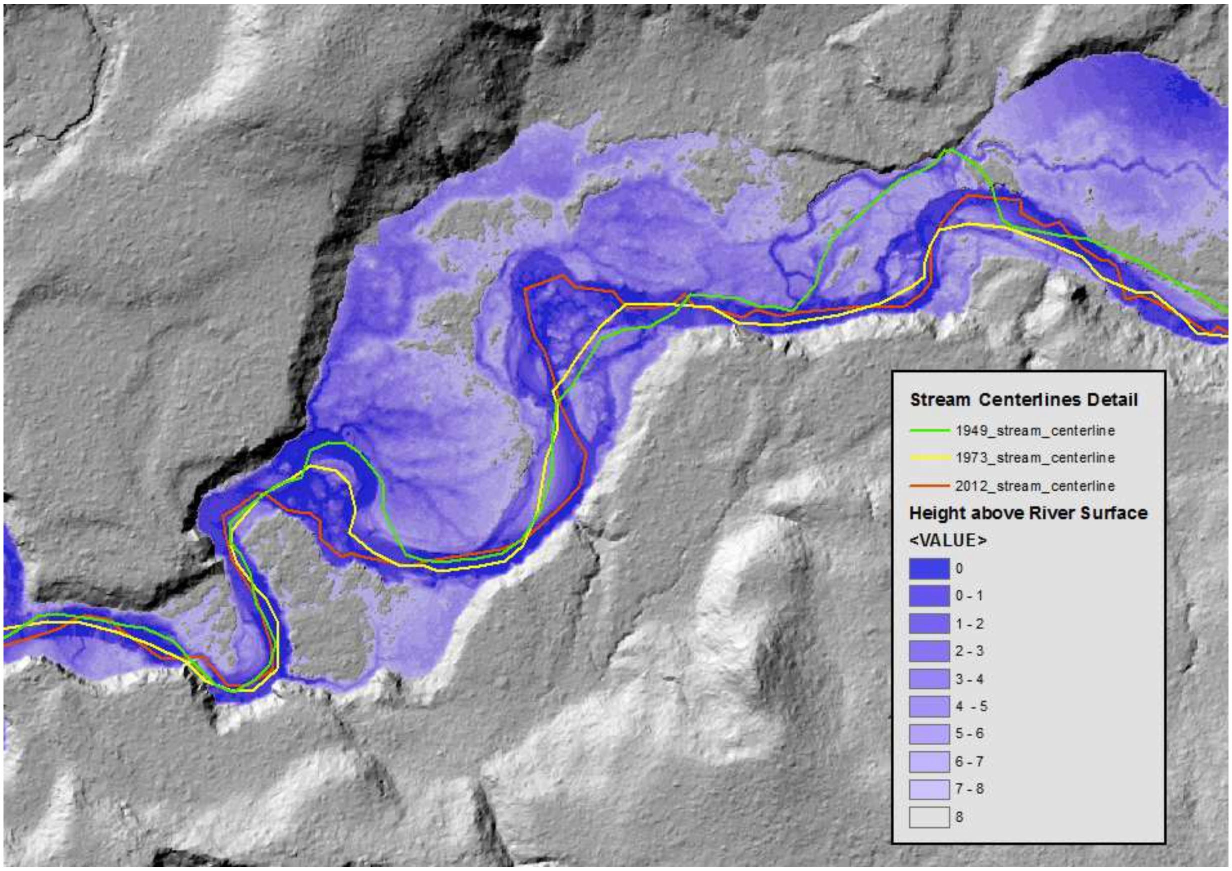
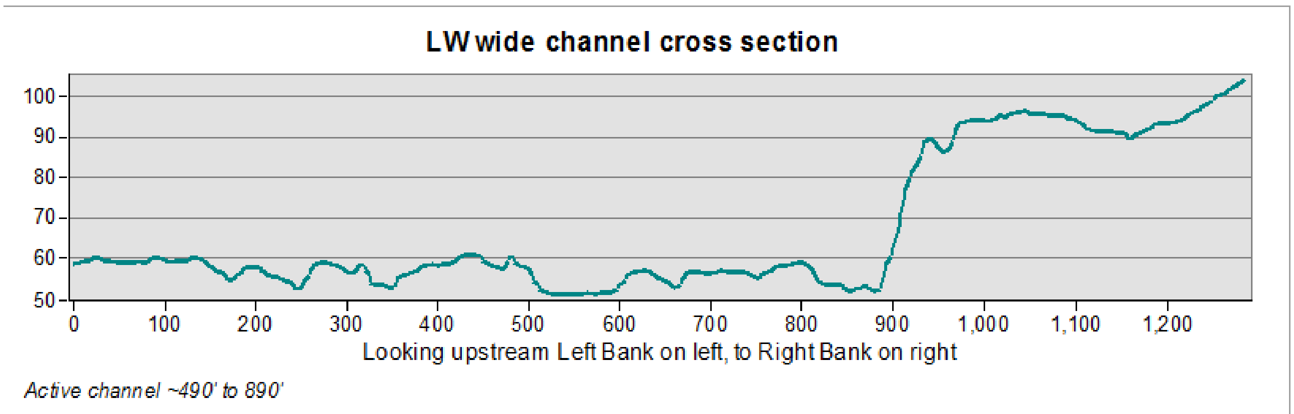
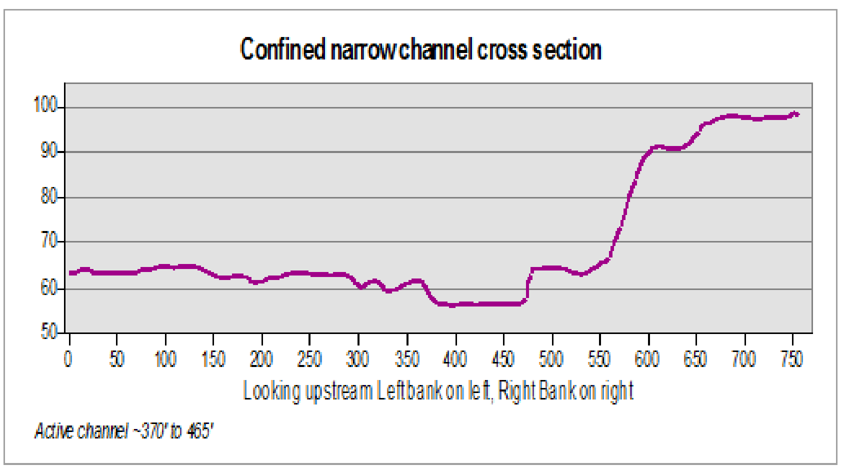


Figure 9. The same detail reach of the above figure with the bare earth lidar hillshade and 3 dates of stream center lines. Geomorphology of the floodplain modeled to <8' above the relative river surface elevation. The historical stream centerlines converge where the valley wall confines the channel, and diverge across the floodplain where the valley opens and where LWD/log jams divert and widen the flows. Goodman Creek flows right to left.

At 12 cross section locations in the study area, the stream centerline of Goodman Creek has moved laterally >50m in the 65 years of the photographic record. In 11 of the cross sections (91.6%) large woody debris or a log jam can be detected in the photographs, together with a widening in the active channel in the relative elevation model. The LWD/log jam has clearly reshaped the active channel, widening it.

In a comparison of 6 pairs of cross sectional lines, one cross section in the narrow or confined reach upstream of the LWD/log jam and one drawn across the width of the log jam, the active channel widens an average of 3.25 times. (38.6m to 123.6m mean changes, with a maximum change of 5.26 times, 34m to 179m). Two cross section graphs are shown below, as examples of the difference between a confined upstream reach and an LW expanded reach. They have been adjusted so that the distance from 0' to 700' appears similar. The active channel in the LWD widened reach is ~400' (122m) and in the narrow reach it is ~95' (29m).





4.4 Using the lidar first returns and canopy height models to correlate tree establishment and forest characteristics with channel movement

Detecting a signature of channel movement through its impacts on the tree establishment and succession in the riparian corridor proved difficult, but ultimately I could link tree establishment and characteristics of the forest canopy to past channel movement and surface hydrology in the Goodman Creek floodplain using the lidar first return data.

My initial efforts used the same spatial extent of the Goodman Creek floodplain that I used for the hydraulic and relative elevation models. This initial extent included native riparian forest formed of natural processes, previously harvested areas where the forest succession had been reset with the first logging of the native forest 40+ years ago, and recently areas clearcut a second time. This land use history confounded the results. Timber harvest reset the dates of tree establishment several times across this spatial extent and challenged my ability to clearly model forest succession in a way that related to the past behavior of channel or the near stream hydrology. To eliminate the effect of the land use history, I limited the extent to the river and the riparian corridor within Olympic National Park plus a few hundred meters upstream where the intact riparian forest corridor remained. Restricting the extent to an unlogged riparian forest and floodplain helped define the results and clarified the most useful canopy metrics. The figures (Figure 10, 11, and 12) illustrate the aggregated 15m^2 per pixel rasters for 3 metrics: canopy cover, maximum height, and coefficient of variation (for the lower native forest extent). Canopy cover ranged from 0 to 225 (the number of 1m pixels within a

15m^2 pixel). Maximum height ranged from 0m to 74m (from open ground or channel to the tallest tree per pixel). The coefficient of variation ranged from 0 to 7694.

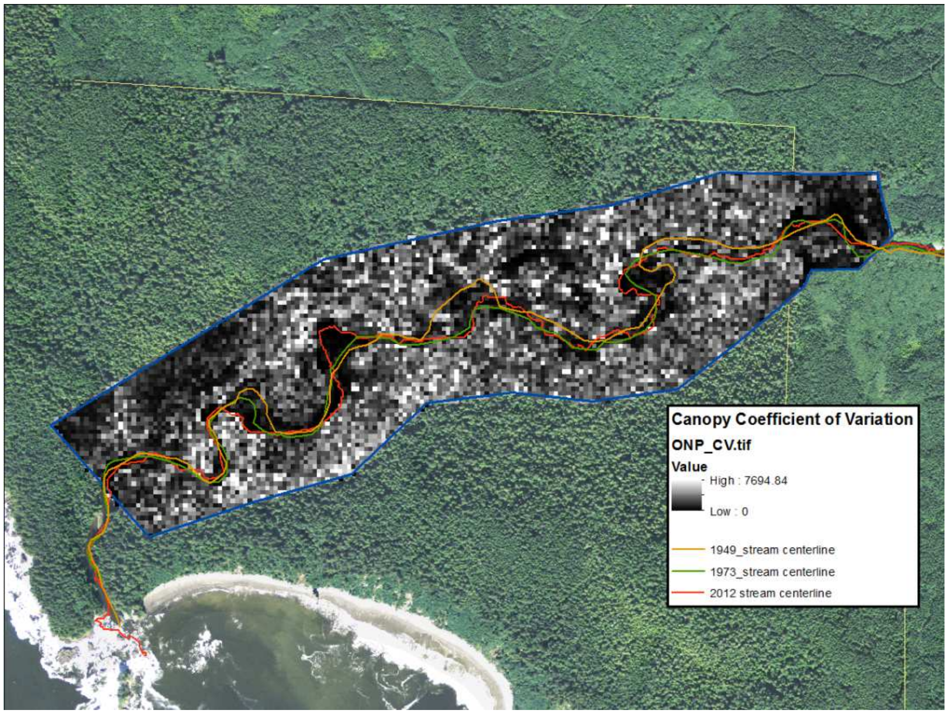


Figure 10. Coefficient of Variation in lower native forest extent.

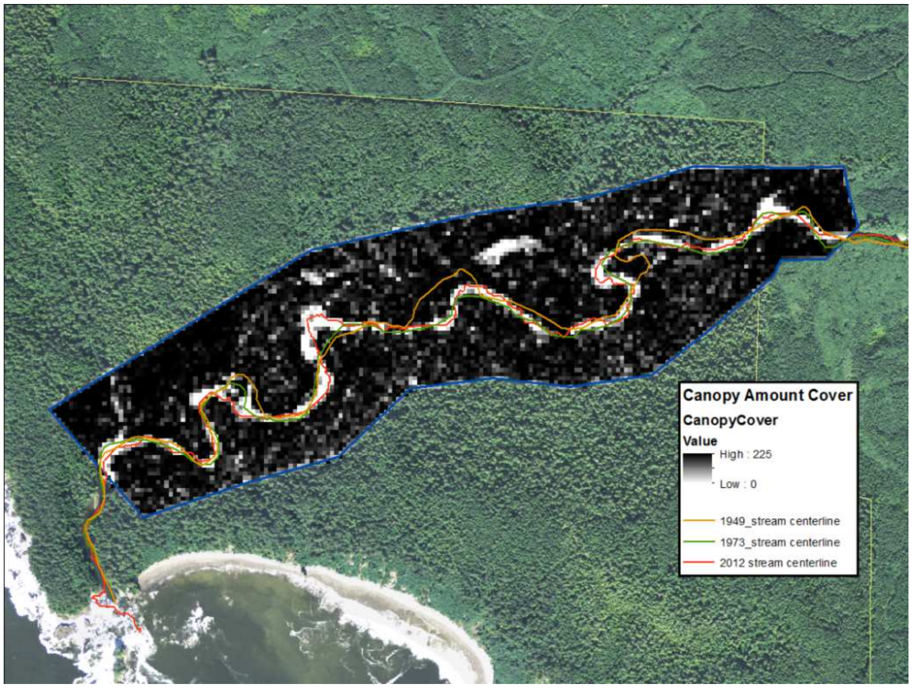


Figure 11. Canopy cover in lower native forest extent

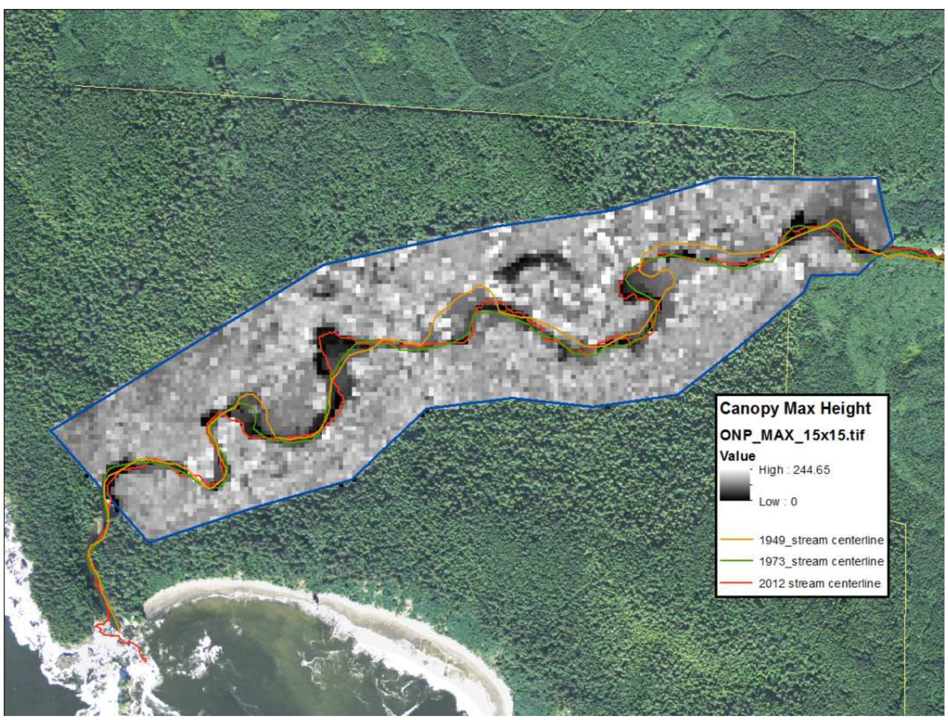


Figure 12. Canopy Maximum height (in feet) in lower native forest extent (244' due to the LiDAR data being supplied in feet)

I found the combination of the maximum height and the coefficient of variation captured the locations where the channel had moved, and upon the alluvial soils that the migrating river had left in its wake either a stand of alders or a wetland now existed. An index that paired a maximum height limited to 85' and the coefficient of variation to 245 produced a map (Figure 13 below) capturing the locations of the large alder stands and the wetlands. The plot (Figures 14) with height on the x-axis and standard deviation on the y-axis also illustrates these trends within the data.

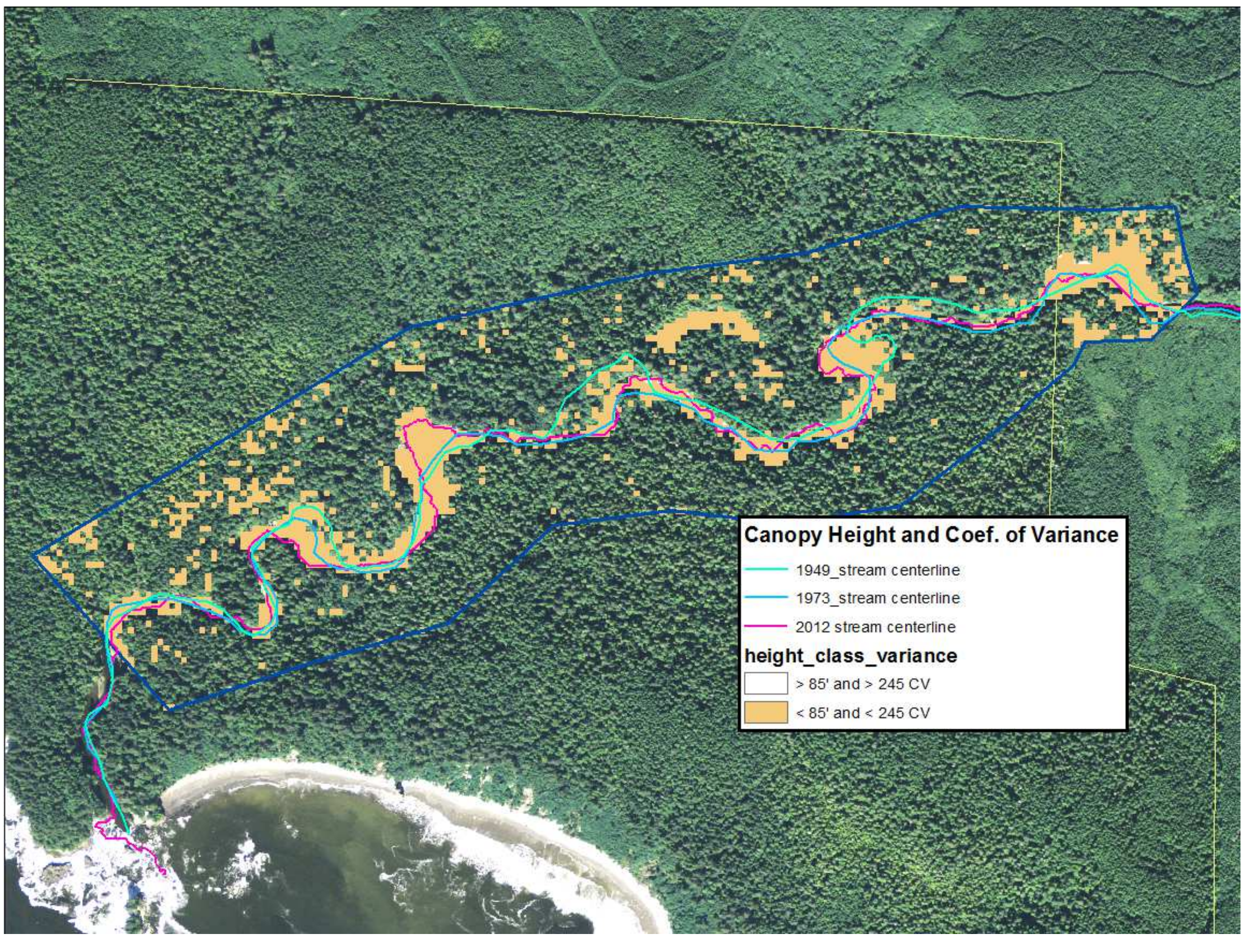


Figure 13. The result of an indexed combination of maximum height and a coefficient of variation (in light brown), correlating past channel movement (overlaying the 2009 NAIP imagery and the historic stream centerlines). Goodman Creek flows upper right to lower left, into the Pacific Ocean.

The amount of total canopy cover metric proved not to help the classification. In the active river channel and in the large wetland area few trees survive and establish to create a canopy. Otherwise dense forest cover blankets the rest of the floodplain. The April lidar acquisition date means a partial or wholly “leaf on” condition. The deciduous alder stands register as much a complete closed canopy as the conifer stand (>180m^2 within the aggregated 225m^2 pixel).

An additional comparison (visible in the two plots, Figures 14 and 15below) between the larger whole floodplain extent (with the timber harvest history) and the lower reach restricted to the native forest riparian corridor highlights some of the difference in the rates of change in the natural processes within the unlogged floodplain. The graph charts a regression of mean height against the standard deviation of the height variation calculated in R statistical software (R Project, 2015). The plot of larger floodplain extent (with the two cycles of past harvest) shows a large number of 80' to 120' tall trees (second growth conifers), a large area comprised of pixels of very low heights (the recently logged areas), and a large range of variation in all heights over approximately 50'. The native forest riparian corridor lacks large areas of very low height (only the active channel), large numbers of pixels of 50' to 80' tall trees, together with a significantly greater proportion of pixels with both trees over 85' and with a large variation in canopy heights.

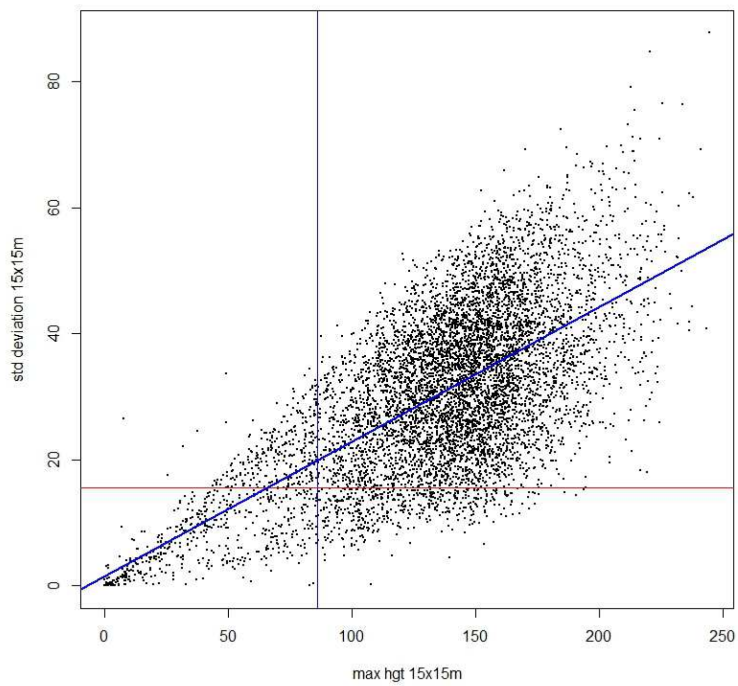


Figure 14. Maximum height (ft) plotted against standard deviation, in the native riparian forest in Olympic NP.

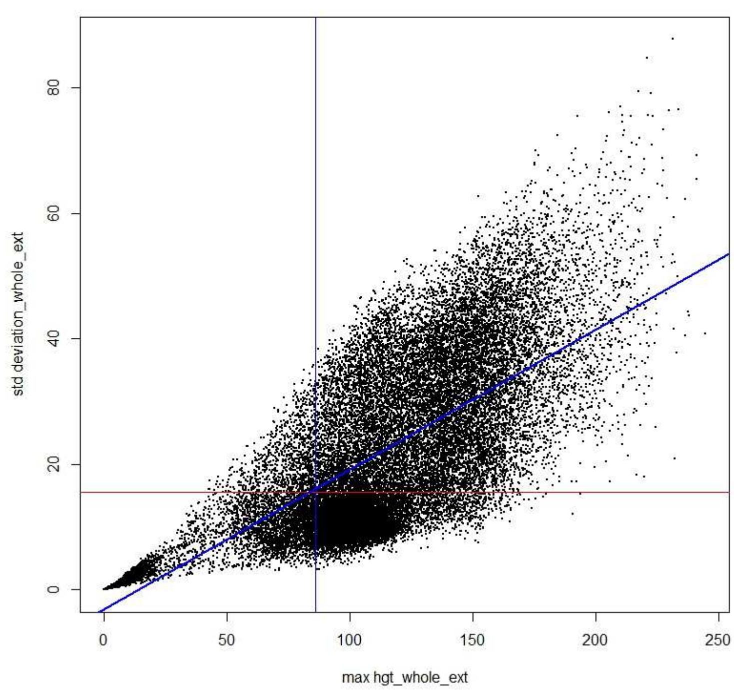


Figure 15. Maximum. height (ft) plotted against standard deviation, for the complete Goodman floodplain study area

4.5 Sources of Error

The dense forest cover affects the potential accuracy of the lidar, and ultimately is the source of possible error in the lidar data. Processing the raw lidar acquisition and developing a bare earth model requires interpolating between last return or ground classified points when a paucity of points have been returned through the canopy. Often one tenth or less points per m^2 reach the ground and return to create the bare earth DEM as return per m^2 from the canopy to make the first returns models. For example, in the Hoh watershed acquisition that included Goodman Creek, the average first return point density for the lidar dataset was 8.40 points/m^2 (0.78 points/ft^2). The average ground classified point density was 0.75 points/m^2 (0.07points/ft^2). The bare earth DEM was constructed from 1/11 of the points per m^2 as the canopy model. Low ground densities are a direct result of the dense rain forest vegetation in the drainage (PSLC, 2013).

Sources of error in field data collection may appear due human fallibility including poor fieldwork design, lack of focus or diligence, and data transfer errors. In addition, in this location errors can arise due to the difficulties of collecting data in the dense understory of the riparian forest, and the short comings of using GPS equipment under forest canopy. I reduced the human factors as much as possible by participating in all the fieldwork, and by designing a simple but complete field protocol that I could communicate readily to my assistants. I reduced data collection and data transcription errors by using pre-printed data sheets, a data logger, and recording point details directly into the GPS. Because the goal of the fieldwork was to confirm hydrological features and relative elevation changes, I limited the impact of the reduced sight lines in the understory by choosing relatively accessible transect paths and temporarily moving vegetation where necessary. We were also able to shoot elevations just above much of the salmonberry and other understory plants.

The errors in the GPS equipment due to the tree obstructing the satellite reception and the resulting satellite multipathing were so great that the elevation data from the survey-grade GPS could not be used. Survey grade GPS equipment requires either a clear line of sight to the sky and the satellites, or a lengthy, stationary acquisition time. We had both at the base station location, a multi-hour acquisition at an elevated position in a clearcut. With the roving GPS receiver we often had neither a clear line of sight to the sky nor the luxury of a long occupancy at each survey point.

5. Discussion

This research demonstrates the usefulness of LiDAR for delineating riparian active channel and off-channel waters in densely forested watersheds, especially those places potentially useful as spawning and rearing habitats to salmon. The high spatial resolution of the LiDAR data allows detailed remote sensing analysis on a watershed scale even where the forest cover limits the usefulness of aerial imagery. The data-rich LiDAR raster DEM can serve as excellent source data for use in hydraulic models such as HEC-RAS that have been extensive tested on coarser raster and TIN vector data. HEC-RAS requires a data conversion from raster to a TIN vector, which has a 20 million pixel data size limit. This research demonstrated both an approach of aggregating the lidar raster and also an approach of limiting the spatial extent of the analysis can be successful. Modeling a range of possible flows allows ecological analysis of rivers and riparian corridors which can include consideration of hydro-periods, peak flow events, and temporal changes.

This work improves on past work using hydraulic modeling to evaluate wood-forced changes in channel form, such as Bummer et. al. (2006) In Goodman and Snahapish Creeks, I also modeled large wood as it influenced channel movement and changes in channel form, but using a high resolution LiDAR DEM as my elevation source data allowed me to widen the scope of, and to scale, my analysis in important ways. I compared and considered two watersheds using similar modeling and field survey protocols. My analysis followed the hydrological influences of the large wood and the flows out into the floodplain to improve the delineation of riparian wetlands, side channels, and seasonally connected off-channel habitats important for juvenile salmonids. Whereas Yang et. al. (2006) modeled a range of flows to access the vulnerability of infrastructure, I created ecologically meaningful flows to delineate critical small scale riparian habitats.

This work also improves on past work by incorporating data with high spatial resolution. Both the LiDAR and the historical aerial imagery have 1m per pixel resolution, and the lidar better than .5m vertical accuracy. In many locations the delineation of the riparian area that can be achieved with a 30m DEM and aerial imagery will be an adequate improvement over a fixed-width riparian buffer (Holmes and Goebel, 2011). Or a 30m DEM based, “Intrinsic Potential” model can adequately describe where a landscape feature such as a waterfall will stop fish passage (Bennett and Wecker, 2013). In these watersheds where the active channel is often less than 30m and a dense forest canopy obscures critical hydrological and habitat features, the LiDAR data provides a unique hydraulic modeling input that allows the researcher to not just locate the riparian area but to delineate discrete off-channel wetlands, tributaries, and side channels. It also allows the researcher to capture the effects of the changes in flow on these places, such as hydrological connections in the channel or seasonal inundation.

Both models accurately captured the locations and extents of the key wetlands and wetland ponds, side channels, tributaries, the formation of pools, sediment deposition, and back waters adjoining the main channel due to LWD. But I recognize possible limitations in the models. The hydraulic tool modeled the over bankfull effects on the floodplains at different ecologically and geomorphologically important flows. It may not always be possible to determine flows adequately. In its description of the Streamstats tool, the USGS acknowledges changes in the natural flows in individual rivers may produce possible errors (USGS(b), 2014). Or in a river corridor where the river lacks sediment or when the river has incised (due to land use history like timber harvest, or the removal of beavers, for examples), no realistic flow will ever inundate the floodplain. The similarity of the two rivers in this study points to a possible limitation in the research. Both of these rivers share characteristics (precipitation, forested floodplains, varied land management) that made a realistic comparison possible. But perhaps the inclusion of another river, or rivers, with different precipitation, different basin topography, different underlying geology, or different land use history could have made this study more complete. More diverse watersheds might have yielded very different extents, or different ratios of errors of commission or omission between the models. The relative elevation approach illustrated a simpler method that could possibly be used efficiently and economically by land managers with modest GIS training and experience. But perhaps the hydraulic model, despite the training and experience needed would offer the most reliable results when tested over a number of varied watersheds.

6. Conclusions

6.1 The implications for including lidar use in Forest Practice Rules implementation and improving FPHCP habitat protection.

These ecologically relevant results allow for a rethinking of the current simplistic, cookie cutter approach to defining the riparian management zone (RMZ) and to protecting in-stream habitats based on the simple approach of mechanically measuring the distance from the stream and calculating a basal area timber harvest target as currently codified in the WA State Forest Practices Board Manual and Forest Practice Rules. An approach that protects the hydrologically and ecologically important habitats may be slightly more difficult implement, but it will improve the chance that the salmon recovery goals of the

FPHCP might be achieved. A critical component of the adaptive management process of the FPHCP will be to improve the description and accurate mapping of the hydrological processes and how they provide off-channel refuges for fish (Goldman, 2015). The results of this research point to two different potential improvements to the conservation of areas that offer spawning and juvenile rearing habitats to salmon in the forested riparian corridor.

The analysis points to a need to change the RMZ core and inner zone designations for Type 2 waters in unconfined floodplains. A new designation could expand beyond the bankfull width of the active channel into the regulatory RMZ core and inner zones where the hydraulic models demonstrate flows travel there more often than a 2 or 5 year flood interval. If the 2 or 5 year flood interval exceeds the 50' width of the core zone, then the core zone would be excluded from the "stand requirement" timber harvest calculations. The "stand requirements" for the amount of riparian forest left toward achieving the FPHCP "desired future conditions" could be counted only outside of the 2 or 5 year flow extent. If the 2 or 5 year interval flood extent also exceeds the 50' width of the inner zone, then the inner zone would also be excluded from timber harvest and "stand requirement" calculations. This kind of a regulatory change will require an updated WA DNR Watershed Analysis for forested watersheds with lidar.

The figures (16, 17, 18, and 19) below illustrate the concept in both the Goodman Creek and Snahapish Creek floodplains, and the amount of the 2-year over bank full flood extent that flows beyond the current Forest Practices regulatory RMZ 50' "core zone" buffer. In many places, and in these example reaches, the 2-year over bank full flood extent would be beyond the RMZ “inner zone” line.

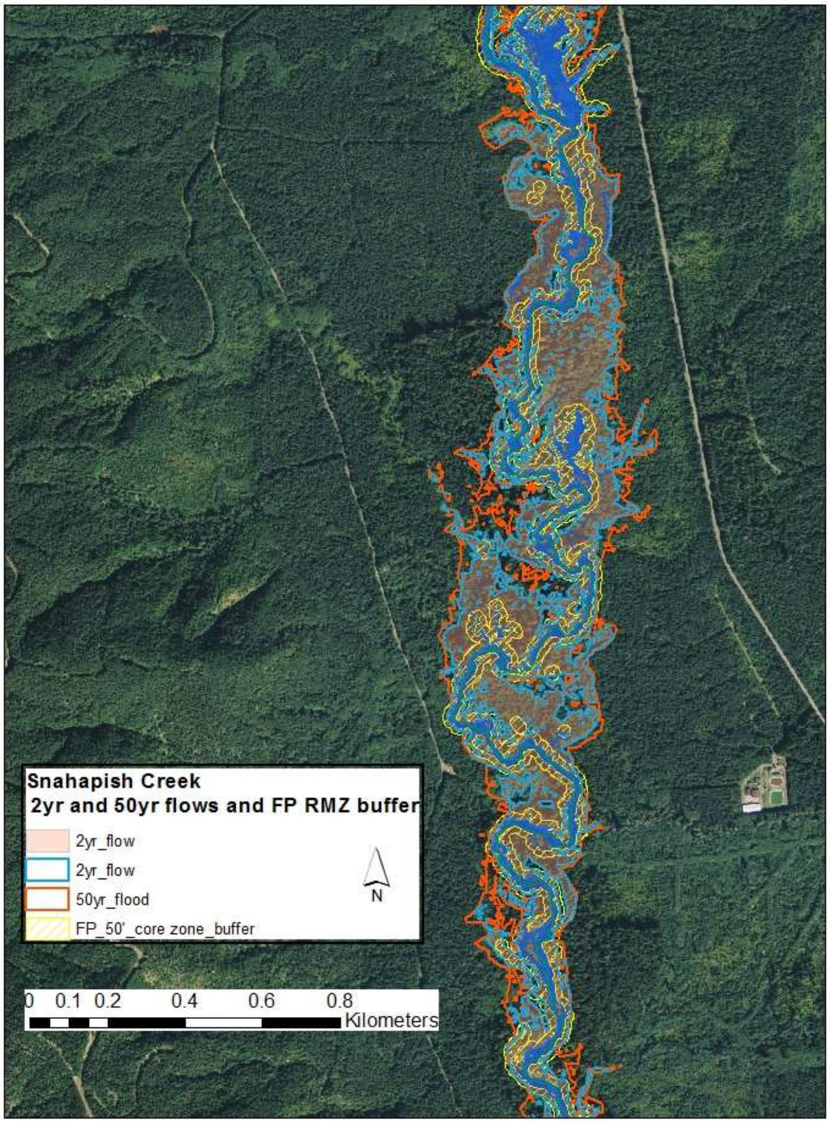


Figure 16. Snahapish Creek showing the 50’ “core zone” of the Forest Practices rules RMZ and the extents of the 2-year (and the 50-yr) over bankfull flows. The river flows top to bottom, north to south.

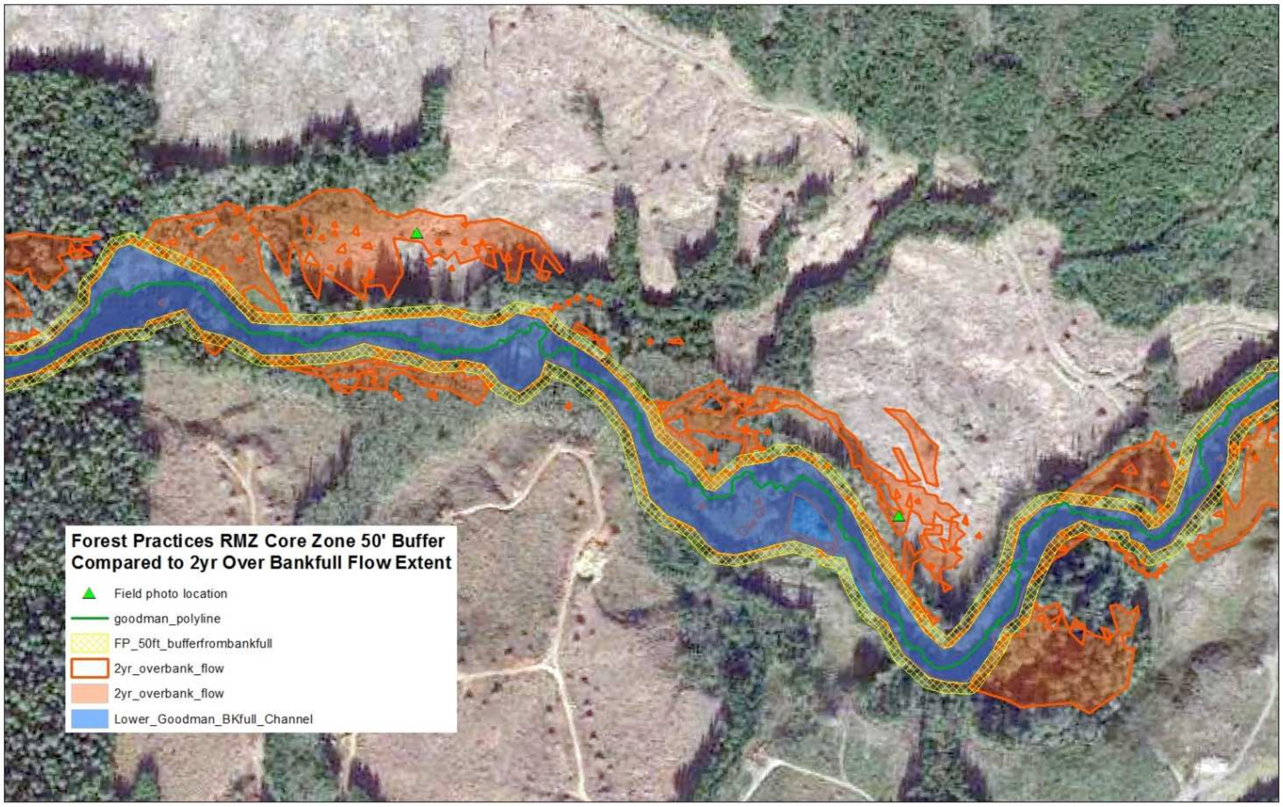


Figure17. Goodman Creek showing the 50’ “core zone” of the Forest Practices rules RMZ and the extents of the 2-year over bankfull flows. The areas were harvested between 2012 and 2013. The river flows right to left. The boundary of Olympic National Park follows the tree line on the left edge of the map.

Figures 18 and 19. Goodman Creek floodplain at location of the 2 green triangles in the Figure 17 map on the previous page, showing standing water and sedge lined swales in the 2-year modeled flow areas, and within 2012, 2013 harvest areas in Rayonier timber lands.

The other potential improvement to current practices would be a mandated change in the FPA review implementation protocol. The FPA/N application currently asks the land owner/applicant to provide WA DNR with “activity area maps” to review. GPS coordinates should also be required of applicants. Precise GPS locations will enable WA DNR staff to efficiently place their review into the digital GIS realm, and facilitate easily determining if a harvest activity falls within existing lidar coverage and whether it might be near to any water course. A simple relative elevation model could be developed for review of any FPA/N application near to any potentially fish-bearing stream and its riparian corridor. These steps would improve the quality of the “office review” part of the FPA/N application, and aid in making a potential “field review” more efficient, as agency staff would now have accurate maps of wetlands and other potential in-channel and off-channel habitats.

The continuing acquisition and publicly availability of lidar datasets, together with informed but simple to use models also offers tribal co-managers, environmental groups, and other stakeholders new tools to oversee implementation of the FPHCP in particular, and to assess forested riparian conditions in general.

6.2 The implications for lidar use in salmon recovery and river restoration planning

Riparian wetland and other hydrological features obtained from these models can be used with other remotely sensed data to help prioritize salmon recovery projects and to guide river restoration planning. Currently, the public processes for developing and funding salmon recovery projects include coordinating the best available science and data on fish use with strategies for evaluating cost effectiveness and viability. Many watershed and fisheries enhancement groups have developed coarse screening tools such as “intrinsic potential” habitat models. Using remotely sensed data with high spatial resolution, such as using lidar with these kinds of models promises more accurate delineations of potential habitats in the riparian corridor within the larger watershed context.

Many river restoration projects focus on increasing channel complexity and restoring the river processes associated with LWD. Resources for restoration must be used well, whether the work involved setting back levees, adding engineered log structures into rivers, or augmenting available large wood into the river. Lidar data together with these kinds of models offer tools to improve restoration planning both by accurately describing the river channel and floodplain and also by allowing planners to consider their designs in a larger watershed context..

Figure 20 below illustrates an example, a simple method of mapping large wood recruitment potential built on the relative elevation or hydraulic models. The relative elevation model can describe the channel, valley confinement, and key floodplain features. These channel locations can then be related to the canopy height model of the available trees within a 100' river buffer. These maps could help to locate reaches where adding structures might capture and hold LWD, and where the redirected flows could act to shape the active channel or connect to off-channel wetlands. These maps would help focus field assessments necessary to verify local conditions.

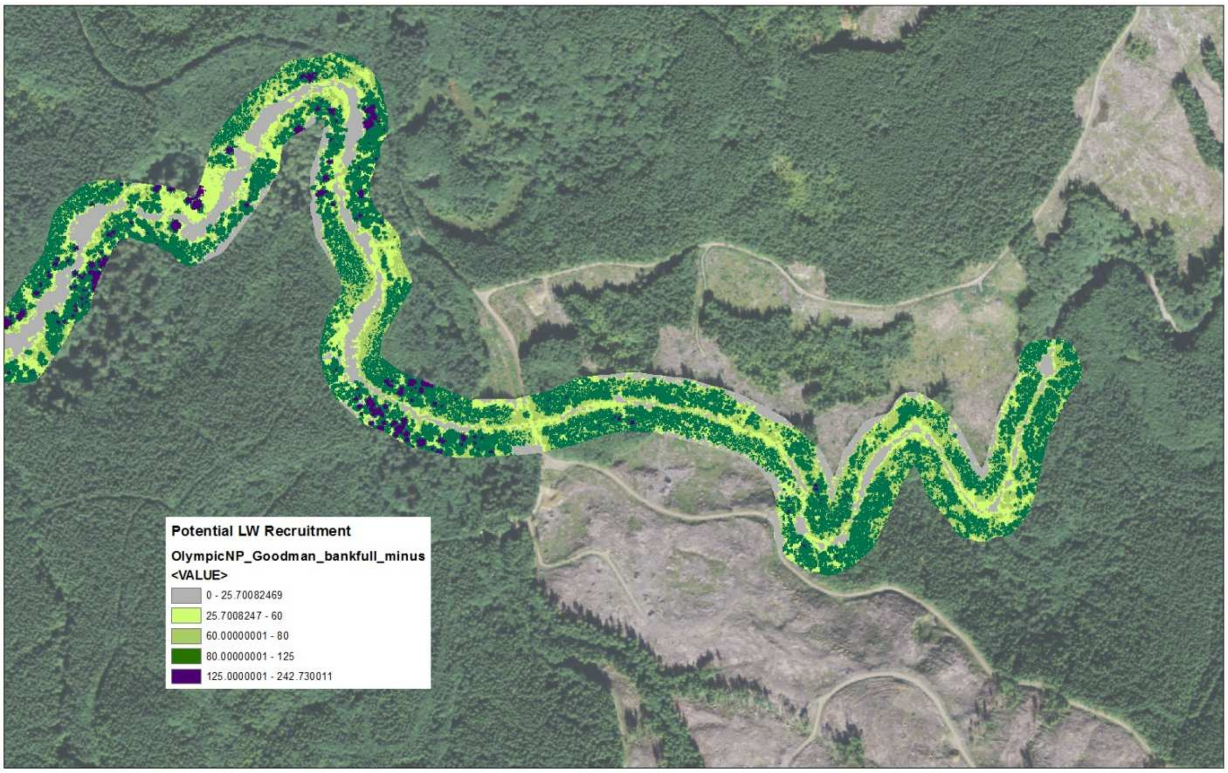


Figure 20. A canopy height classification map. Within a 100’ buffer to the stream banks, the five classes in the canopy height map are grey (channel to shrubs), yellow green (“alders”<60’), pale green (“alders and conifers” < 80’), deep green (“conifers” <125’), and violet (“conifers”> 125’). This simple classification can be combined with a relative elevation model map to locate stream reaches where LW recruitment might be lacking or structures to restore river processes might encourage the formation of log jams and pool formation. Goodman Creek flows right to left.

6.3 Future research: Using the lidar first returns and other lidar data toward better delineation of other forested wetlands away from the active channel

Although the tree establishment models using maximum canopy height and the coefficient of variation in the canopy may have limited widespread usefulness in corroborating movement of the channel and the riparian corridor given the history and extent of timber harvest in the Pacific Northwest, the approach points to ways that lidar data might improve the delineation of forested wetlands away from the rivers. A combination of the features modeled in this research, such as relative elevation, changes in gradient, flow paths, and valley forms from the bare earth DEM and an absence of trees or a complex canopy offer promising research directions to model a probability of wetlands occurrence in the upland forest.

Other aspects of the lidar acquisition (although these are not part of the common publicly accessible data sets) include an intensity measure. The intensity value can indicate absorption of the lidar beam in water and wetland pond areas, or high reflectance in clearcut areas and roads for example. A combination of the features modeled in this research, again such as relative elevation, changes in gradient, valley form, or an absence of trees might all be supplemented with the lidar intensity data to improve forested wetlands further from the active channel but hydrologically important such as those connected to upland tributaries.

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Table 1.

Goodman Creek		**7.4 rkm length**	
HEC-RAS	**Extents (km^2)**	**2yr extent/<7' extent**	**50yr extent/<8' extent**
2yr	0.5537	0.878032922	1.147364803
10yr	0.7393		
50yr	0.8680		
Relative Elevation			
< 8' above water surface	0.7565	50yr (+) .111 km^2	
< 7' above water surface	0.6306	2yr (-) .077 km^2	
active channel ~ 2' above surface	0.2406		
active channel ~ 1.5' above surface	0.2144		
Snahapish Creek		**18.6 rkm length**	
HEC-RAS	**Extents (km^2)**	**2yr extent/<7' extent**	**50yr extent/<8' extent**
2yr	1.4660	0.922592826	0.881252719
10yr			
50yr	2.0260		
Relative Elevation			
< 8' above water surface	2.2990	50yr (+) .274 km^2	
< 7' above water surface	1.5890	2yr (-) .123 km^2	

Commission/ommission

2 year HEC-RAS extent beyond 7’ relative elevation extent .028 km^2

7’ relative elevation extent beyond 2 year HEC-RAS extent .095 km^2

Table 2.

Polyline GPS files to take into field for Goodman Creek accuracy assessments

FID	**Possible_Category_Expected**	**Notes_checklist**
0	connected wetland w pond complex	any filling if there's rain
1	side channel, former channel	
2	continuation of 2, side channel	defined banks
3	connected wetland w pond complex	can you tell where's the water come from?
4	side channel up and downstream connected	
5	small side channel connected up and downstream	
6	wetland plants present, hillslope runoff?	can you tell where's the water come from?
7	side channel	log jamb created, shaped?
8	side channel ? intermittmently connected	part of 7
9	side channel connected up and downstream ?	connected up and downstream
10	side channel ? intermittmently connected upstream	
11	side channel up and downstream connected	
12	creeklet, hillslope runoff ?	
13	long connected wetland w ponds complex	
14	side channel ? intermittmently connected upstream	
15	hillslope or backwater wetland	
16	pond wetland	
17	connected wetland w pond complex	
18	overflow from LWD	connection upstream
19	side channel	connections?
20	side channel up and downstream connected	
21	off channel wetland	downstream connection walked
22	UNKNOWN former channel bend	connected to 21 and upstream?
23	tributary or flowthrough	trib? side channel w connections?
24	flowing input tributary fish accessible	
25	outflow from wetlands pond complex w culvert	
26	small creeklet, perched	
27	between Minter creek and 3000rd trib	upstream of bridge
28	aldered intermittmently connected	

29	side channel	left bank side channel? w connections?
30	LWD flow	connect to 23
31	side channel up and downstream connected ?	
32	large wetland	hydric plants? inputs, ouflows
33	possible overflow channel	connection to main channel
34	large jam	side ch, pools, flows to off-channel floodplain
35	large jam	side channels, pools
36	large jam	side channels, pools