QUANTIFYING CURRENT AND FUTURE FLOODPLAIN HABITAT FOR COHO SALMON (*ONCORHYNCHUS KISUTCH*) IN LAGUNITAS CREEK (MARIN COUNTY, CA)

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By
Adam Fleenor
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CERTIFICATION OF APPROVAL

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Signed Certification of Approval Page is
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Dr. Matthew Cover Associate Professor of Ecology	Date
Dr. Michael Fleming Assistant Professor of Biology	Date
Dr. Peggy Hauselt Associate Professor of Geography	Date

DEDICATION

I dedicate this work to my wife Dr. Jennifer (Jey) Strangfeld who supported me while not allowing me to miss out life. Also, thanks to my children Zoe, Lola, and Forest for giving me time to work and then making sure I played hard afterwards.

ACKNOWLEDGEMENTS

I would like to acknowledge all of my graduate student colleagues and my nearly 200 students who trusted me to teach and guide them for the last two years. Thank you to Kelley Dixon and Denise Garcia for providing me coffee for the last three years.

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ABSTRACT

The coho salmon (*Oncorhynchus kisutch)* Central California Coast evolutionary significant unit (CCCESU) has declined from an estimated 50,000-125,000 adult returns to only 500 spawning adults, and is at high risk for extinction. Lagunitas Creek (Marin County, CA) supports 10% of the remaining population, but much of the watershed has incised stream banks and disconnected floodplains. Previous studies have implicated overwintering habitat for juveniles as a limiting factor and the priority for restoration efforts. Good overwintering habitat is characterized by complex channel form, refugia from predators, connected floodplains, and riparian vegetation. I used data derived from Light Detection and Ranging (LIDAR) to compare the floodplain height above river (HAR), vegetation height, and plant community type attributes in areas of Lagunitas Creek where coho juveniles are successfully overwintering and areas with poor smolt production. I found that 72.2% of the Lagunitas floodplain is five meters or less above base flow, comprised of 24.2% lower (0-2m) and 47.9% upper (2-5m) floodplain. The Tocaloma reach supported the most lower floodplain habitat, while the Point-Reyes-Nicasio reach had the greatest amount of upper floodplain My results, linking the floodplain elevation attributes to the plant height and community type, suggest many sections of the Lagunitas Creek can be restored as overwintering habitat for coho salmon.

INTRODUCTION

Lagunitas Creek (Marin County, CA) supports the most southern stable population of the federally endangered coho salmon (*Oncorhynchus kisutch*) on the Pacific Coast, but the watershed has experienced low returns of adults since 2009, with only 67 adults returning in 2013. Previous studies have identified floodplain habitat that provides flood refugia for coho smolts as the primary limiting factor for the coho salmon population in Lagunitas Creek. In this study, I used remote sensing data to better understand floodplain and riparian forest dynamics in the watershed and to examine the potential for restoration of floodplain habitats that could provide overwintering habitat for coho salmon.

Coho Salmon

Anadromous salmonid populations on the North American Pacific coast have experienced significant declines as a result of human practices such as overfishing (Hilborn et al. 2003), pollution (MacNeale et al. 2010, Sandahl et al. 2005), removal of large wood from streams (Dolloff 1986), and elimination of spawning habitat by dams and barriers (Solazzi et al. 2000). Entire evolutionarily significant units (ESU) have disappeared as a result of spawning and rearing habitat either rendered inhabitable or inaccessible (Gustafson et al. 2007). One-third of the 1,400 historic Pacific wild salmon (*Oncorhynchus*) populations from British Columbia to southern

California, consisting of coho, steelhead trout, Chinook, sockeye, chum, and pink salmon, have been extirpated since European colonization (Gustafson et al. 2007).

The Central California Coast (CCC) coho salmon ESU ranges from Punta Gorda, Humboldt County to the most southern population in the San Lorenzo River, Santa Cruz County (NOAA, 1995) (Figure 1). California commercial coho harvest averaged 163,000 fish annually between 1952-1991, before commercial fishing for coho along the entire California coast was prohibited. Recreational fishing in the ocean for coho salmon averaged 34,000 fish per year from 1962-93 (PFMC 2003b); sport fishing for coho has been prohibited since 1994. Of the 133 streams with historical spawning habitat in this range, only one-half currently support coho salmon (Brown et al. 1994, NMFS 1996b). Citing the Endangered Species Act (ESA), the National Marine Fisheries Service (NMFS) listed the CCCESU coho salmon as threatened in 1996 and endangered in 2005. As of 2010, only 500 adults returned in the entire CCCESU (Miller 2010). As a result of extensive freshwater habitat degradation, none of the remaining coho populations in the CCCESU are sustainable, and are all expected to be extirpated within the next 25 to 50 years, with the possible exception of the Lagunitas Creek population (Moyle et al. 2008).

Figure 1. California Central Coast Evolutionary Significant Unit (CCCESU) (ESRI base map 2015, NOAA.gov 2015).

The coho reproduction phase occurs between November and January in Lagunitas Creek (Figure 2). Spawning female adults construct redds (salmon nest) at transition zones between pools and riffles. Shortly after eggs are deposited by females and fertilized by males, the adult coho die. The eggs incubate for 4-6 weeks, then emerge as alevins (small salmon with attached egg sac) between January and March. In March through May, alevin graduate to the fry stage and gain distinctive dark vertical bands (parr marks) centered on their lateral line. In the warm summer months, after eating and growing, they move to deeper pools. The juvenile coho occupy protected habitat such as complex logjam environments and vegetated banks structures. During the winter high flow season (December – March), the juvenile coho enter their final stage (smolts) as they migrate to the Pacific Ocean through Tomales Bay. Smolt outmigration continues through June. Adults spend approximately two years in the ocean (except for "jacks," males that return after 1 year) before returning to spawn.

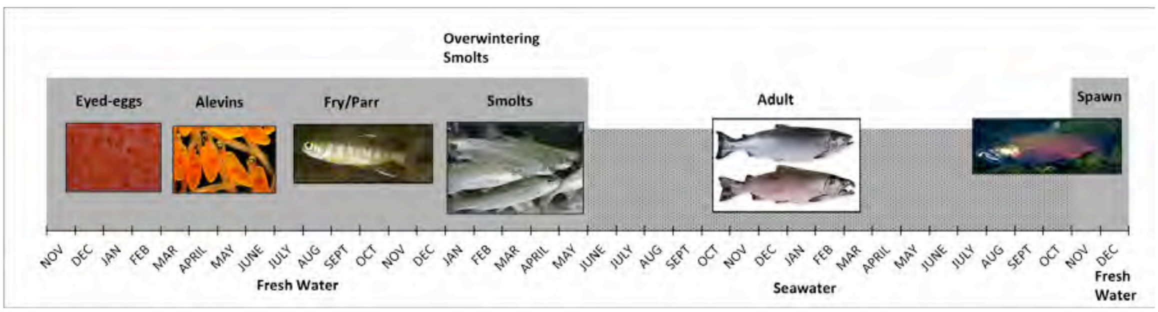

Figure 2. Lagunitas Creek coho life cycle

Coho salmon juveniles require cool water, pool-riffle channel morphology, complex habitat structure provided by abundant woody debris, access to high flow refugia, and extensive riparian vegetation (which provides shade, protection from avian predators, and food sources in the form of terrestrial insects) (Allan et al. 2003, Collins et al. 2011, Giannico 2000, Jeffres et al. 2008, Laeser et al. 2005, Mori 2009, Tomlinson et al. 2011). The availability of protection from predators and abundant food impacts the survival (quantity) and the maturation size (quality) of coho that enter the marine environment, and can only be provided if streams are highly connected to adjacent, complex floodplains with diverse riparian vegetation. While quality summer rearing habitat (i.e., large, deep pools) is associated with large woody debris (LWD), overwintering habitat is related to the availability of floodplain features that can be accessed during high flood flows. A study in two Oregon coastal streams found a correlation between smolt abundance and the availability of overwintering habitat (Solazzi et al. 2000). In California, this habitat is dependent on the coastal riparian forest (Moyle et al. 2008). Stream improvements consistent with increasing access to the secondary watercourses and streamside environment in the floodplain during winter flood events have increased coho smolt survival (Solazzi et al. 2000).

Floodplains and Riparian Vegetation

A floodplain is a relatively flat topographic feature adjacent to a stream that is commonly inundated by flood pulses rising above the streams banks (Leopold 1994). The floodplain is part of the riparian zone ecosystem that includes unique vegetation and landforms such as sand bars, river islands, and palaeochannels, among other topographically complex features. The size and shape of floodplains are dependent on local topography, peak flow regimes, vegetation, and sediment transport from upstream (Hupp et al. 2009).

Local geomorphic process domains have a direct impact on floodplain topography as well as the species composition and successional stage of riparian vegetation communities (Buffington and Montgomery 2013). Vegetation community patches respond to and are shaped by stream flooding; tolerant or rapidly colonizing plant species dominate particular spatial environments (Bendix and Hupp 2000, Comporeale et al. 2012, Latterell et al. 2006). Plant survival is linked to the soil moisture gradient, specifically the ability for a species to withstand prolonged inundation periods without root damage (Hughes 1997). Stream geomorphological processes can construct floodplains that regulate the soil moisture gradient, and therefore influence vegetation composition (Benjankar et al. 2011). Although riparian vegetation patterns are affected by factors other than floodplain geomorphic processes (competition, seed establishment, and other stressors can play important roles), vegetation height and community type can often be used to characterize floodplain inundation cycles (Baker and Walford 1995, Bendix and Hupp 2000)..

Overwintering conditions in California coastal streams are characterized by flashy flood regimes that are exacerbated by human modification of stream systems (McMahon and Hartman 1989, Thomas and Nisbet 2007). Anthropogenic encroachments along riverine systems have simplified floodplain topography, causing a decline in ecosystem functions provide by floodplains (Mori 2009). For example, the removal of large woody debris (LWD) from streams in order to prevent flooding of adjacent homes has resulted in streambed incision (Dolloff 1986). LWD increases hydraulic roughness, resulting in sediment storage, and enhances complex habitat for fish and other aquatic organisms, among other ecosystem functions (Beechie et al. 2006, Corenblit et al. 2007, Forzieri et al. 2012, Quinn et al. 1996, Sparks 1995, Straatsma et al. 2008, Thomas and Nisbet 2007). Other human structures, such as roads, railroad tracks, culverts, agriculture fields, and buildings, limit floodplain services by disconnecting and dividing the expanse required for a full functioning riparian floodplain. Restoring and mitigating riparian floodplains that have been altered by human activities will increase stream complexity (Beechie and Sible, 1997), create pools and slow winter storm flows (Ebersole et al. 2001), and increase aquatic species diversity and richness (Lennox et al. 2011).

Remote Sensing

In seeking potential floodplain restoration sites, scientists are often relegated to reconnaissance missions along stream banks at easily accessible locations. Extracting ecological data to support restoration efforts for floodplains has proven to be expensive and time-consuming (Jones 2006, Sparks 1995). Developing ways to accurately collect floodplain attributes on a reach scale, and increasingly at a watershed scale, has directed researchers to cost-effective remote sensing technology (Forzieri et al. 2012).

Light Detection and Ranging (LIDAR) is a laser pulse directed from a transmitter that is mounted on an airborne platform (plane or helicopter); the light particles (photons) bounce back to the receiver (Johansen 2010). The receiver can recover between 10,000 and 50,000 return pulses per second (Murphy et al. 2008). Data precision is increased using a referenced global positioning system (GPS) located along the flight path of the airborne scanner (Johansen 2010). These referenced point returns (point clouds) capture surface features (height above mean sea level). Additional LiDAR derived data include bare earth (earth surface only) digital elevation model (DEM), first returns (tops of objects), and surface object (e.g., vegetation) height.

LiDAR is used to explore large swaths of territory, develop base maps for field surveys, and locate areas of interest for further review (Buffington and Montgomery 2013). However, terrestrial LiDAR cannot infiltrate water surfaces, thus preventing the differentiation of streambed material and formations below the waterline. Bathymetric LiDAR, which is less available, can produce sub-surface stream data, but has restrictions due to surface wave and water clarity (Faux et al. 2009).

Challenges to using LiDAR data for mapping include misclassification of data points and low-density returns. Jones et al. (2007) found that LiDAR was 80% accurate for mapping geomorphic attributes compared to the results of field surveys. Once the data is interpolated using a mathematical algorithm to define un-sampled ground surface areas based on adjacent sample points, anomalies may emerge in bare earth topographic maps that are products of limited data points (Faux et al. 2009). This phenomenon can be managed with improving the filtering and by using the point cloud viewer to assist in identification of features (Jones et al. 2007).

This Study: Fish and Floodplains in Lagunitas Creek

Lagunitas Creek supports 10% of the total CCCESU population and is the most southern stable population of coho on the Pacific Coast. However, Lagunitas Creek has shown low returns of spawning adult coho since 2009, with 67 adults returning in 2013 (Table 1). Scientists and stakeholders believe Lagunitas Creek is the best opportunity to conserve and protect wild coho in the CCCESU, and are implementing a recovery plan to ensure their survival (Moyle et al. 2008, NMSF

2010). Until recently, the Marin Municipal Water District (MMWD) has implemented restoration projects primarily focused on additions of large wood designed to facilitate the development of pools that provide refugia for juvenile coho from predators. A limiting factors analysis prepared for Lagunitas Creek, however, determined that a lack of overwintering habitat was directly related to increased mortality of juvenile coho salmon (Stillwater Science 2008). During floods, smolts are frequently washed downstream because they are unable to find floodplain refugia from high flows (Stillwater Sciences 2008). Smolt trapping data and reconnaissance surveys suggest that certain limited areas of the Lagunitas Creek watershed support the majority of coho smolts (Stillwater Science 2008). After the limiting factors study was completed, MMWD has been collaborating with the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) and California Department of Parks and Recreation to research and implement projects specifically designed to increase overwintering habitat. However, analyses of the amount of floodplain accessible to overwintering juvenile coho during flood events have not been conducted.

An understanding of the location and extent of floodplain connection in Lagunitas Creek is necessary in order to prioritize restoration efforts. Additionally, the availability of overwintering floodplain habitat should be linked to a process-based understanding of riparian vegetation dynamics and watershed ecogeomorphology. I hypothesize that:

1. There is relatively little available high flow refugia in the Reach 4 State Park (R4 SP) reach (as a result of a narrow bedrock canyon and confined riparian zones) compared to the Reach 2 Tocaloma (R2 TOC) reach (which has a wider, alluvial valley and evidence of recent aggradation).
2. A greater proportion of floodplain habitat is inaccessible (2-5m above the streambed) in the Reach 1 Point Reyes – Nicasio (R1 PRN) reach then in the other study reaches.
3. Throughout the Lagunitas Creek watershed, the lower floodplain (0-2 meter) is dominated by early successional vegetation such as small herbaceous plants and young willow and alder trees (<10m), while the tallest (>20 meter) mature riparian trees (alder, redwood) and non-riparian obligates (California bay) are located on higher elevation floodplains (>2 meter).

To test these hypotheses and further our understanding of the potential for floodplain restoration in the Lagunitas Creek watershed, I: (1) analyze topographic data collected via remote sensing to identify the spatial limits of existing near-channel geomorphic surfaces that provide overwintering coho habitat; (2) analyze remotely sensed vegetation height and community type data relative to geomorphic data to delineate lower and upper floodplains; and (3) specify areas where restoration would increase the amount of coho salmon overwintering habitat. The results of this study will be useful to identify and implement stream restoration projects and will support the ultimate goal of preventing the extinction of the California coho salmon population. This approach to remote sensing and characterization of riparian habitat could be replicated in other stream systems.

Table 1. Life table for coho salmon Lagunitas Creek (SFBRWQCB 2010)

Spawner Years	Adults	Redd	Eggs (2600/ Redd)	Smolts	Juvenile-Smolt Survival (%)	Returning Adults (2x Redds)
81/82 – 84/85	-	-	-	744	49.4	-
82/83 – 85/86	-	139	361,400	713	79.2	-
83/84 – 86/87	-	44	114,400	1,922	76.8	-
95/96 - 98/99	365	86	223,600	-	-	368
96/97 - 99/00	549	254	660,400	-	-	406
97/98 - 00/01	428	253	657,800	-	-	408
98/99 - 01/02	123	184	478,400	-	-	572
99/00 - 02/03	568	203	527,800	-	-	316
00/01 - 03/04	320	204	530,400	-	-	766
01/02 - 04/05	735	286	743,600	-	-	992
02/03 - 05/06	572	158	410,800	-	-	380
03/04 - 06/07	947	383	995,800	-	-	676
04/05 - 07/08	1,342	496	1,289,600	6,261	27.7	296
05/06 - 08/09	679	190	494,000	2,776	102.7	52
06/07 - 09/10	886	338	878,800	6,679	18.2	104
07/08 - 10/11	238	148	384,800	6,373	57.3	-
08/09 - 11/12	43	26	67,600	-	-	-
09/10 - 12/13	67	52	135,200	-	-	-
Average	**524**	**217**	**565,240**	**5,522**	**51.5**	**445**

METERIALS AND METHODS

This study aggregates and processes remote sensing data to model floodplain surface elevation attributes. Vegetation height and plant community type data are collected and evaluated together with floodplain elevation to support the distinction between lower floodplain surfaces and upper floodplain surfaces important to coho salmon overwintering habitat.

Study Area

Lagunitas Creek is located in western Marin County, California, and drains a 270 km^2 watershed (Figure 3). The headwaters originate on the north side of Mount Tamalpais; the coastal stream flows 40 kilometers northwest to its mouth in Tomales Bay, near the town of Point Reyes Station, California. Five dams prevent fish access to the headwater tributaries and confine fish migration to the lower half of Lagunitas Creek below Peters dam and three small tributaries (Devils Gulch, San Geronimo Creek, and Olema Creek). Spawning and overwintering habitat in Lagunitas Creek is limited to the mainstem stream below Peters dam (19.1 river kilometers from the mouth) and three tributaries. This study focuses on the potential overwintering habitat available in the mainstem reaches below the dams and within the anthropogenic boundaries (roads, railroads, and urbanized land parcels) of the Lagunitas Creek's main channel and its riparian floodplain.

Figure 3. Lagunitas watershed Marin County, California (ESRI base map 2015, Marin County 2015)

The downstream end of the Lagunitas creek study area is at 10516591 E, 4209124 N (UTM); the upstream extent is at 10525556 E, 4206370 N. The 19.1-kilometer creek (from Peters Dam to the mouth) has a sinuosity (SI) of 1.7, which reflects a meandering stream type. The creek flows from the southeast to the northwest, emptying into Tomales Bay. The elevation ranges from 0.7 meters at LG1 to 49.5 meters LG191, with a mean slope of 0.29%. The Lagunitas Creek floodplain is bordered on both sides by anthropogenic boundaries: an abandoned railway converted to a trail runs along the west side of the valley, and a rural highway runs on the east side.

Two U.S. Geological Survey (USGS) gage stations provide flow data for Lagunitas Creek. Station 11460600, located at Point Reyes Station, has a 131.5 square kilometer watershed and has 39 years of flow records. The bankfull flow (assuming a recurrence interval of 1.5 years) is 2,020 cubic feet per second (cfs) (Dunne and Leopold 1978). Assuming a bankfull flow average velocity of 1 m/s, the bankfull flow depth is 1.5 meters. A half-bankfull flow event (1,010 cfs) has a recurrence interval of 1.2 years and a bankfull depth of 0.9 meters. The second USGS gage station, USGS 11460400, is located in Samuel P. Taylor State Park and drains 88.8 square kilometers. The bankfull flow is 1,760 cfs and the inferred bankfull depth is 1.6 meters. The one half bankfull recurrence interval is 1.1 years and the depth is 1.2 meters.

For the purposes of this study, I divided Lagunitas Creek into four reaches (Figure 4). The R1 Point Reyes-Nicasio (PRN) reach extends from the mouth of Lagunitas Creek at Point Reyes Station to the confluence with Nicasio Creek. This reach is 6,600 meters in length, with three large meandering bends, and comprises sixty-six 100-meter subsections (LG1-LG66). The lower reach of Lagunitas Creek has the widest riparian zone and transforms into a tidal marsh before entering Tomales Bay. Roads and other permanent boundaries are present but are farther offset from the creek. The riparian plant community in this section is dominated by Red

Alder (*Alnus rubra*), willow (*Salix lasiolepis*) and Coastal Oak (*Quercus agrifolia*). California Bay Laurel (*Umbellularia californica*) and annual grass communities inhabit the terrace and upland regions.

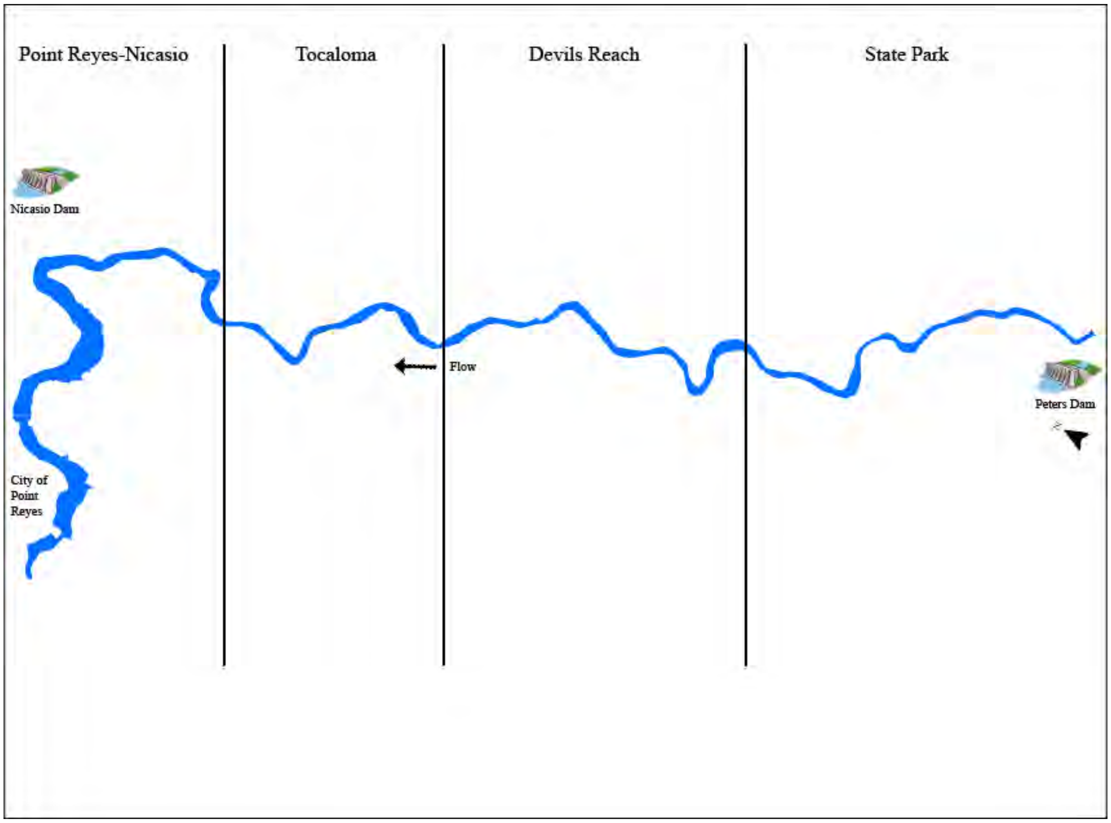

Figure 4. Diagram of the four study reaches in Lagunitas Creek

The next upstream reach is the R2 Tocaloma (TOC) reach, which extends 3,400 meters in length from above the Nicasio Creek confluence to the Tocaloma bridge crossing. This reach has three main meanders, and is comprised of thirty-four 100-meter long subsections (LG67-LG101). The R3 Devil's Reach (DR) starts above the Tocaloma Bridge (LG102) and extends 4000 meters upstream to the confluence with Devil's Gulch at LG142. The most upstream reach is the R4 State Park (SP) reach, which extends 4,800 meters from above the Devils Gulch confluence (LG 143) to Peters Dam (LG 191). The middle and upper reaches of Lagunitas Creek (TOC, DR, SP) have a narrower valley floor, with a natural progression to bedrock canyons common in inland coastal mountain landscapes. Vegetation communities in the middle and upper reaches of the mainstem of Lagunitas Creek alternate between stands of Douglas-fir (*Pseudotsuga menziesii*) and longitudinal strips of coast redwood (*Sequoia sempervirens*) (NPS 2003). Portions of the natural valley floor are further disconnected from the stream because of railroad tracks and roads.

Remote Sensing Acquisition

I downloaded and processed Light Detection and Ranging (LiDAR) data to obtain the raw data used for my analyses. A remote sensing aircraft was flown over sections of San Francisco, San Mateo, and Marin counties in Northern California from April 2010 to July 2010 (Figure 5). LiDAR data was made available to United States Geological Survey (USGS) by San Francisco State University's Golden Gate LiDAR Project; in turn, the USGS made the dataset accessible to the public in 2012. Each dataset consists of one USGS quadrangle tile and an additional Extensible Markup language file (XML) file containing associated metadata. The LiDAR data is distributed in LASer (LAS) file format designed for 3-D data exchange. The horizontal accuracy is 1 meter root mean squared error (RMSE) or better, whereas the vertical accuracy is RMSE(z) ≤ 9.25 cm (Golden Gate LiDAR Final Report 2011). Each data point was pre-classified using American Society of Photogrammetry and Remote Sensing (ASPRS) classification system (Graham 2012).

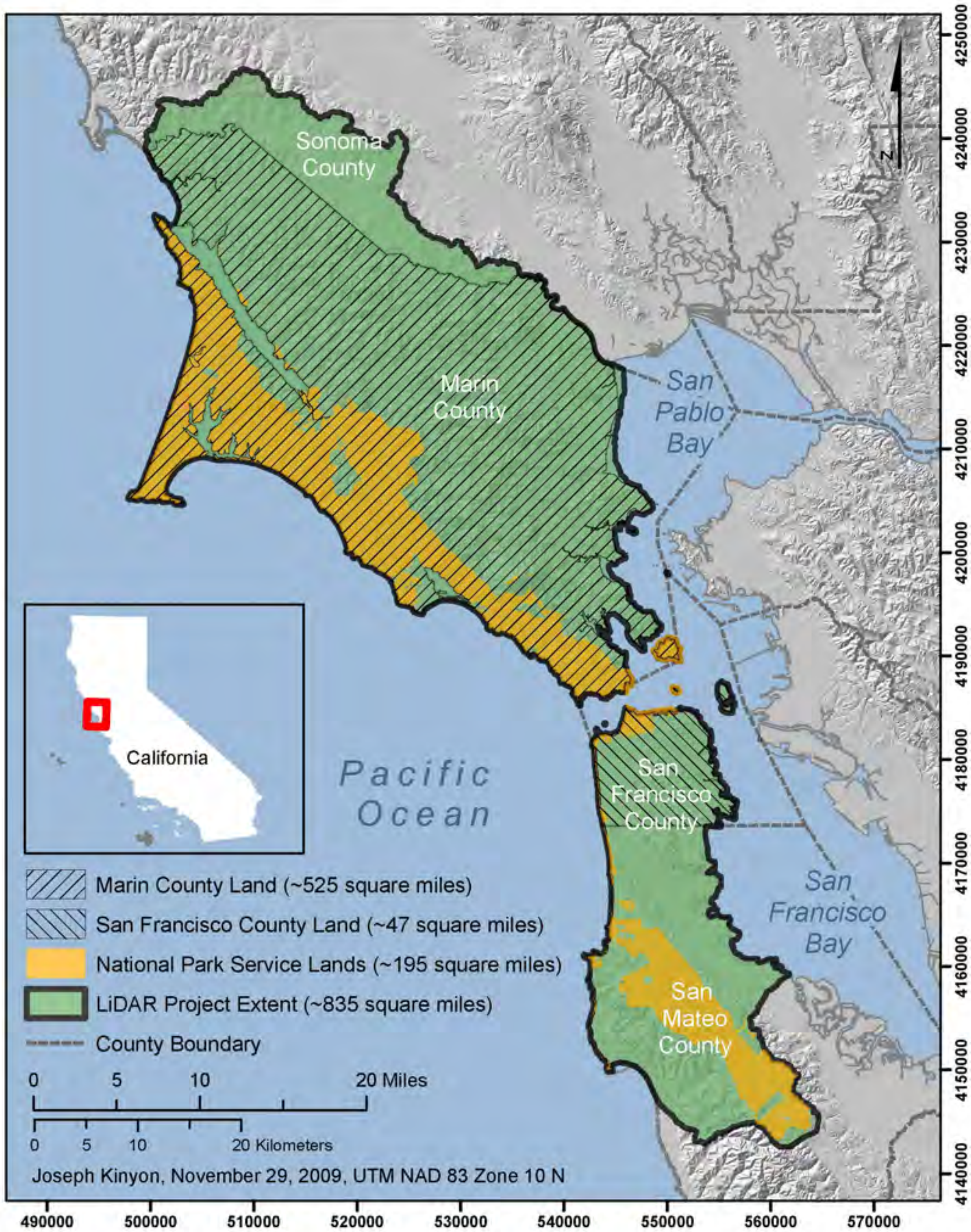

Figure 5. Golden Gate LiDAR Study Area. Map from San Francisco State University

The USGS quadrangle data tiles, containing 262,000,000 geo-referenced data points, were downloaded and decompressed for the Lagunitas Creek study site (USGS, 2014). The LAS files were compiled into a LAS geodatabase using Environmental Systems Research Institute's (ESRI) geographic information system

(GIS) (Esri, Redland, California). The LiDAR data was loaded and displayed in ESRI's ArcMap GIS program using LiDAR Dataset viewing tools, which allow viewing the data in three modes (Figure 6). The overhead mode provides a 2.5-D view of the data. The profile mode displays a ground level side view of a selected cross section composed of a maximum of 150,000 points or point clouds. The third mode displays a 3-D model of the selected area and can be rotated for a 360-degree view.

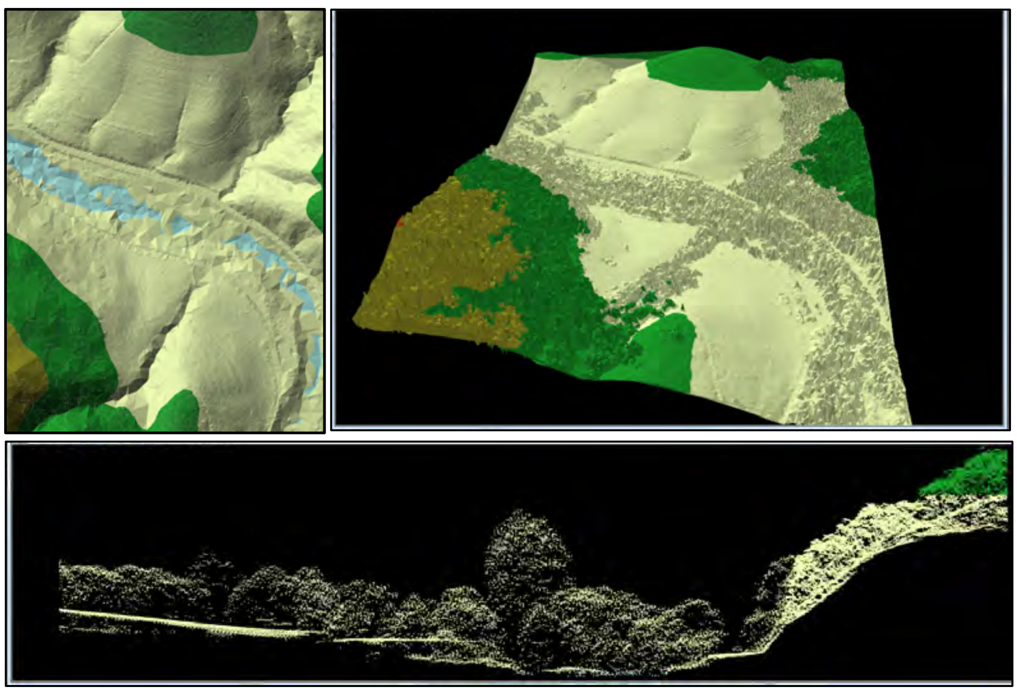

Figure 6. LiDAR data viewing modes: 2.5-D (upper left), 3-D (upper right), and point cloud profile (lower).

I processed the LiDAR data and constructed topographic raster layers to support identification of geomorphic attributes related to coho salmon habitat. To comprehend the floodplain surface underneath the vegetation, I created a bare earth raster layer. This process consists of converting the LAS datasets to a vector multipoint format. In this conversion, only points classified as bare earth were processed. From this format, a 1 meter resolution digital elevation model (DEM) was generated. The DEM layer is the base for building GIS raster layers that display geomorphic features in and adjacent to the Lagunitas Creek main channel. From the bare earth DEM, a hillshade layer was built to visualize elevation variation in the floodplain. This raster layer illuminates the different elevations by replicating solar effects, thus creating a 3-D appearance of hills and valleys. The high resolution of the LiDAR data displays the fine topographic details of depressions and paleochannels. This process used to create the bare earth layer was repeated to produce a vegetation height DEM (Figure 7).

As with many direct remote sensing models, low permeability through dense tree canopy and understory can reduce the LiDAR ground samples. This can in effect generalize the ground micro-topography and thus require interpolation when producing a bare-earth DEM. In this study, interpolation was recognized in dense streamside assemblages at a 1-meter scale. However, the LiDAR sampling density was acceptable and addressed by well-reviewed natural neighbor interpolation techniques (Kowalczyk et al. 2010, Sibson 1981). Improved filtering and interpolation approaches could improve surface definition in areas with substantial canopy. Furthermore, studies have found less of a relationship between vegetation structure, HAR, and vegetation community using ordination (Baker and Walford 1995) in part because of the absence of variability in the reach. Conversely, in this study, the HAR is calculated using newly available high resolution LiDAR and supported by a rigorous vegetation study from the 2003 National Parks Service's Plant Community Classification and Mapping Project. Mapping the spatial variables and visualizing them together provides observable patterns amid the GIS data layers (Figure 7).

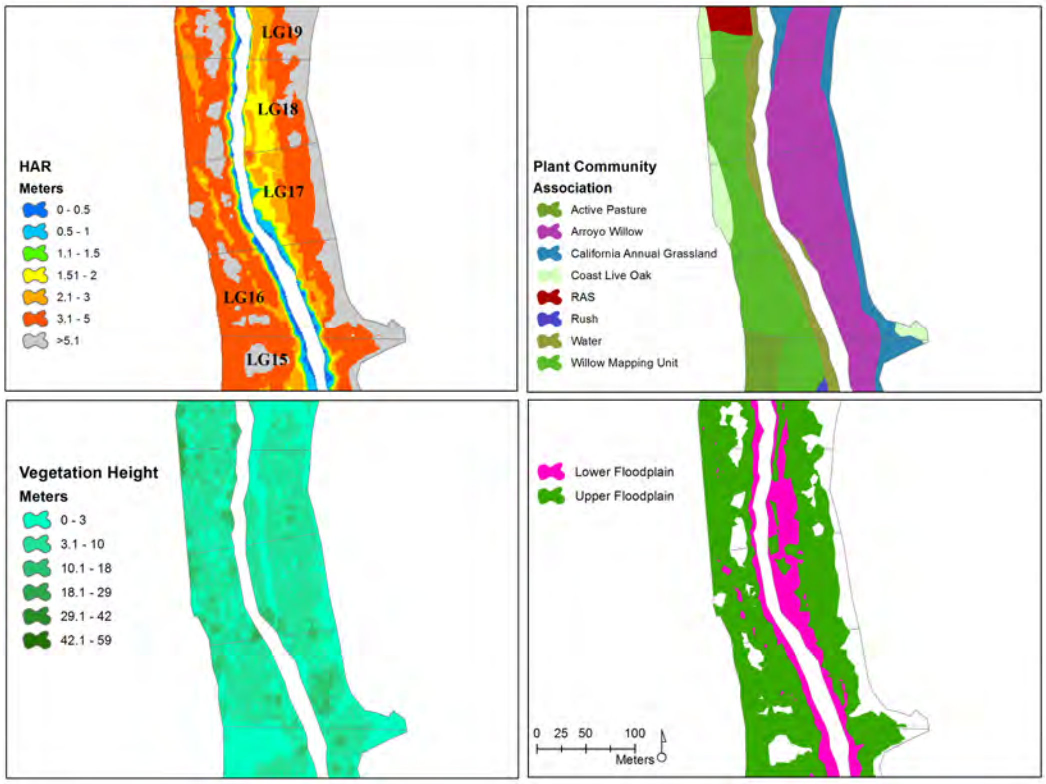

Figure 7. Study variables including Height Above River (HAR) (upper left), Plant community (upper right), vegetation height (lower left), and classified HAR (lower right).

Analysis and Modeling

I used LiDAR derived data layers and aerial photos to visually identify and digitize the primary boundaries of the study area. I produced a boundary polygon to clip the LiDAR and GIS layers from the larger dataset. This reduced the size of the dataset and facilitated further processing as computations were made directly on the area the coho salmon can access (inside anthropogenic boundaries). I created a second GIS polygon masking layer that divided the stream into 100-meter sections for a total of 191 subsections. The section nomenclature starts from the mouth of

Lagunitas Creek (LG1) and continues to Peters Dam (LG191). The section polygon mask was intersected with the LiDAR multipoint dataset to produce a subset of LiDAR data that is within each 100-meter division. From this labeled and classified multipoint dataset, I constructed a DEM. This permits dataset calculations to be spatially identified and compared between individual creek sections.

To assist in understanding the surface area covered during flood events, I digitized the left and right bank edges of the stream channel for the entire mainstem of Lagunitas Creek based on aerial photos and LiDAR bare earth topographic data. Using the surface elevation of the stream base flow (i.e., the lowest elevation represented in each 100m study reach), I prepared a model, based on Jones et al. (2006), to calculate the height above river (HAR) for each 100-meter section of Lagunitas Creek (Figure 7, Figure 8). This model produces a GIS layer displaying 0.5-meter interval elevation data adjacent to the corresponding creek section. To display local elevation, instead of mean sea level, the model recalculates the elevation in reference to local base flow. The subsection HAR spatial data was evaluated to understand distribution of floodplain elevation and the connectivity to the Lagunitas Creek.

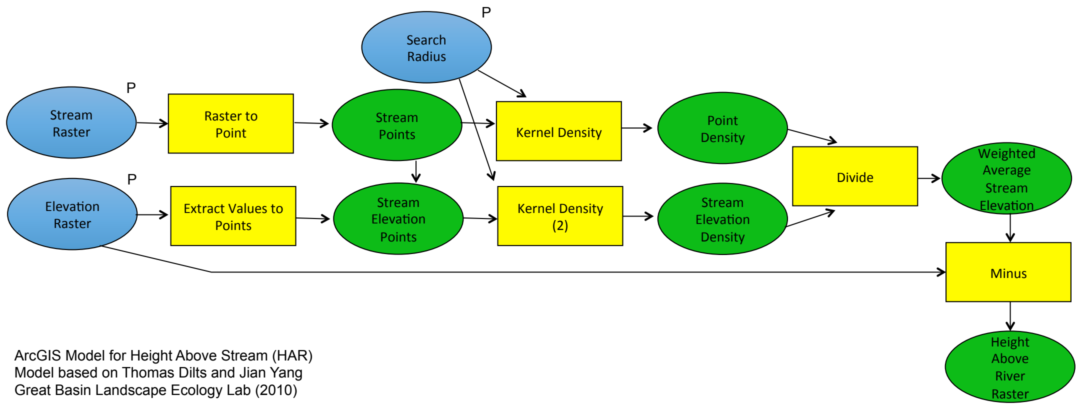

Figure 8. Data processing steps for the Height Above River (HAR) GIS model based on (Dilts and Yang 2010).

Floodplain Delineation and Categorization

To delineate between lower and upper floodplain habitat, I assumed that floodplain features well above the bankfull flow depth would not be regularly inundated, and thus should be classified as inactive floodplain. Bankfull flow is the flood flow that fills the main channel and just begins to spill onto the adjacent floodplain; bankfull flows are also assumed to be the flow level that is most responsible for channel forming process (Dunne and Leopold 1978). Based on data from two USGS stream gages, I calculated average bankfull flow depths of 1.5 m and 1.6 m. Assuming these two gage locations are representative of the mainstem of Lagunitas Creek, I assumed that flood flow depths would rarely exceed 2.0 m along the mainstem of Lagunitas Creek. Flow depths at the time of the LiDAR survey were very low: summer base flows in Lagunitas Creek (~8 cfs) usually just barely cover riffle surfaces. Thus, the Height Above River (HAR) measurements are assumed to represent a base flow depth = 0. I defined the lower floodplain as areas adjacent to the stream channel with HAR <2.0m. Floodplain height (HAR) between 2.0 and 5.0

meters is referred to as upper floodplains. The 0-2 meter (lower floodplain) and 2-5 meter (upper floodplain) were computed and classified on the entire main channel from the HAR dataset.

Lagunitas Creek is hypothesized to have experienced episodes of channel incision over the past ~200 years as a result of land use changes, as well as reduced flood flows over the past ~100 years because of dams. Over millennial timescales, floodplains have likely been abandoned as a result of uplift and/or incision. Thus, the present-day lower floodplain inundation area is hypothesized to be less than historic conditions. To understand the distribution of historic floodplains (i.e., current terraces) I combined floodplain elevation raster HAR with a slope DEM of the study area to form a third raster. This 1-meter resolution GIS layer provides all combinations of slope and HAR in an attribute table. Lower floodplains are typically very flat topographic features; for example, Hall et al. (2007) found that floodplains could be identified as topographic surfaces with slopes less than a 1.04 percent with 86% overall accuracy. To approximate the area of historically lower floodplains in the Lagunitas Creek study area that are now well above the lower channel, I queried landscape features in the study area with slopes <1% and HAR >5m. These locations were aggregated within each of the four study reaches.

Riparian Vegetation Dataset

A vegetation community GIS layer was downloaded from the 2003 Point Reyes National Seashore/Golden Gate National Recreation Area (PRNS GOGA) Plant Community Classification and Mapping Project (Schirokauer et al. 2003). This dataset was originally classified and field evaluated in 2000, with subsequent verification in 2001. The plant community levels were grouped into "superclusters" that exhibit like physiognomy and ecological environment. In classifying by broad categories, the PRNS study surpassed the accuracy threshold of 80% at the 95% confidence level. The mean height of each plant community was extracted from 2010 LiDAR with a 1-meter resolution. Vegetation height and community boundaries expand and contract overtime; however, for this study the broad characterization of vegetation is used as a proxy for distinguishing lower floodplains used by overwintering juvenile coho salmon. Some plant species live for hundreds of years, e.g. Douglas fir. Therefore, I am assuming that the temporal differences between the vegetation type and height datasets (2000 vs. 2010) are acceptable.

The original GIS layer format was a vector layer; using a "Polygon to Raster" script in the conversion toolbox, I transformed the data to a raster layer (Figure 7). I used GIS to calculate the percent of vegetation community type in each of the four major reaches. Subsequently, I computed the vegetation community type in the lower (0-2m HAR) and upper (2-5m HAR) floodplains for the entire riparian corridor (Figure 7). This analysis was used to assist in characterizing vegetation in the lower and upper floodplains available to overwintering juvenile coho salmon.

To examine riparian vegetation communities on different floodplain surfaces, I prepared a one-meter resolution vegetation height GIS layer by subtracting the bare earth DEM from the first return DEM. Raster math processing was preformed using the ArcGIS "raster calculator". The riparian vegetation data was classified into four height classes: 0-1, 1-10, 10-20, 20-55. Next, I evaluated vegetation height classes in lower floodplain surfaces (0-2m HAR) and classified this surface as erosional (bare ground or emerging vegetation) and depositional (mature vegetation) along the riparian zones of the stream. Additionally, I determined vegetation height and community types in the lower floodplains (0-2m HAR) and the upper (2-5m) floodplains in each of the four stream reaches.

Quantitative Analysis

I prepared a GIS raster layer with multiple variables to support spatial examination for the entire study area. I processed three raster datasets with adjoined attribute tables focusing on three variables: floodplain elevation, vegetation height, and vegetation community type. I used ArcGIS "Spatial Analysis Tools" to preform the "Combine" script, merging the three datasets into one new layer. The new layer is further divided into the four reaches (R1-R4) nested within Lagunitas Creek. Using the select by attribute function, I executed queries to collect overlapping spatial data about each of the study reaches.

Field Observations

I made field observations of bankfull width in order to compare field-derived values with values determined from the LiDAR-based topographic data. I prepared maps displaying floodplain topography for eight sites on the Lagunitas Creek floodplains. Some locations were heavily vegetated and without reasonable pathways to enter the lower floodplains. A site adjustment was made in the field if access to the site was judged too dangerous too reach, whereby the next closest available site was selected and GPS points were recorded. To obtain the height above river measurements in the field, I drove a rebar into the creek bed with previously marked 1-meter increments (Figure 9). I used a measuring reel to record the channel width at a 1-meter height. I placed a second 1-meter rebar at the endpoints of the 1-meter height cross-section, and I measured from the 1-meter mark to record the width at the 2-meter height above the streambed surface.

Figure 9. Lagunitas Creek field site 150-1 (Photo by Adam Fleenor 2014)

The location of the cross-section surveys was determined using a Magellan Explorist 210 GPS with 3-7 meters horizontal accuracy at 95% 2D RMS. I uploaded the GPS points to ArcGIS and examined the 1 and 2 meter cross-section field measurements using ArcGIS LAS Dataset profile tools. I reported the variation between remotely sensed LiDAR data and the field survey data, and tested the difference using a student's t-test.

RESULTS

Floodplain Area

Of the ~1.5 million m^2 of total study area (the entire area between the anthropogenic boundaries on either side of the valley) along the Lagunitas Creek mainstem channel, 21.3% was classified as low floodplain (0-2m HAR), 42.5% was classified as high floodplain (2-5m HAR), 13% was classified as terraces (>5m, <1% slope), and the remaining 23% was classified as non-floodplain habitat. Among the four reaches, R1 (PRN), the furthest downstream study reach, had the greatest amount of high floodplain (62.1% of the total for the study area), but a similar amount of low floodplain (0-2m HAR) area as R2 (TOC) and R3 (DR) (Figure 10, Figure 11, Figure 12). In contrast, R4 (SP) had the least total lower (0-2m) floodplain (Figure 10, Figure 11, Figure 12).

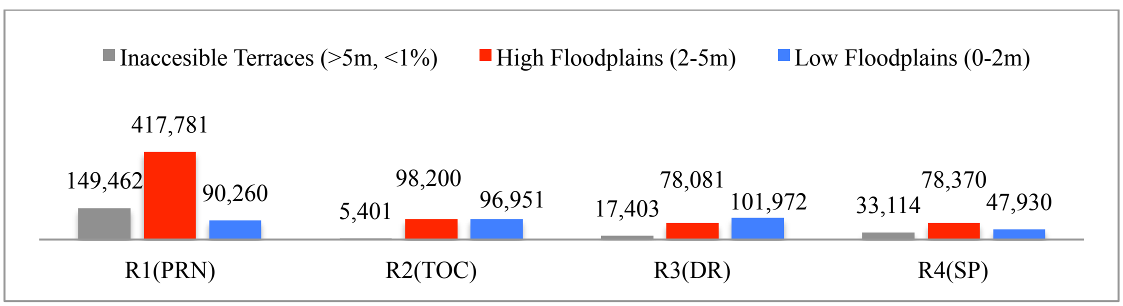

Figure 10. Area of floodplain classifications by reach (m^2)

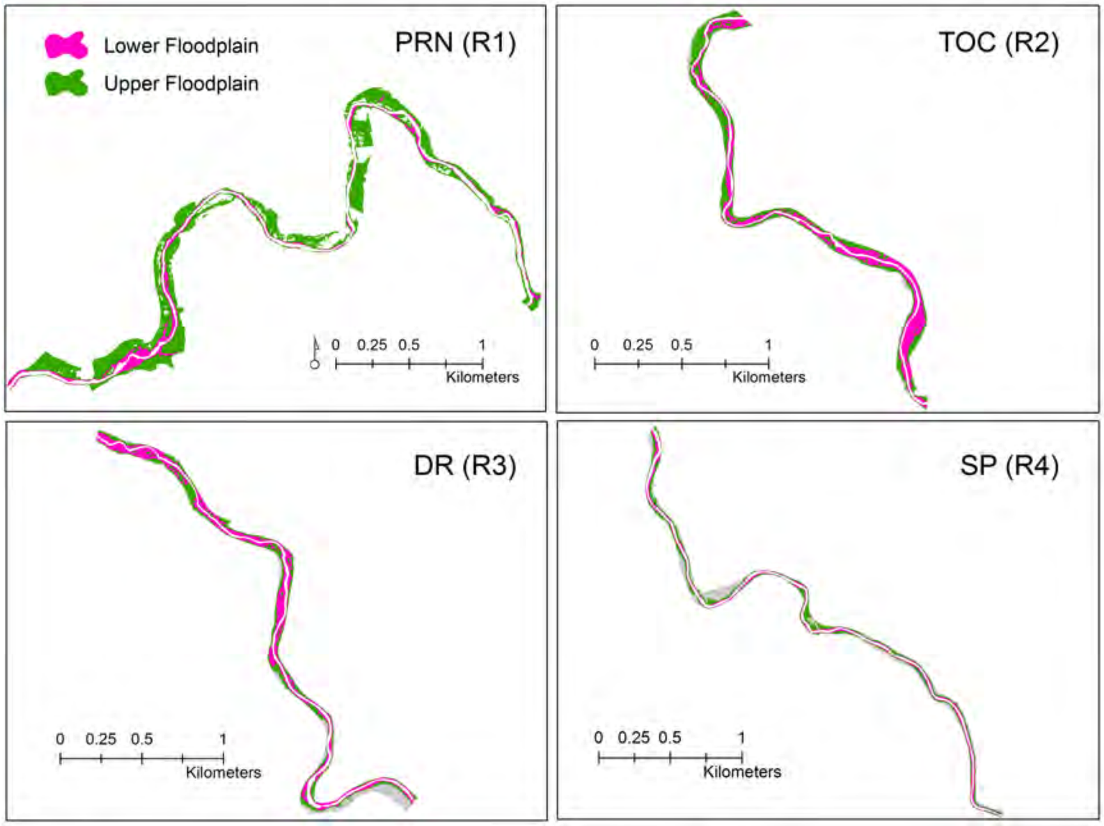

Figure 11. Maps of lower (pink; 0-2 m HAR) and upper (green; 2-5m HAR) floodplains in the R1 (PRN) reach (upper left), R2 (TOC) reach (upper right), R3 (DR) reach (lower left), and R4 (SP) reach (lower right).

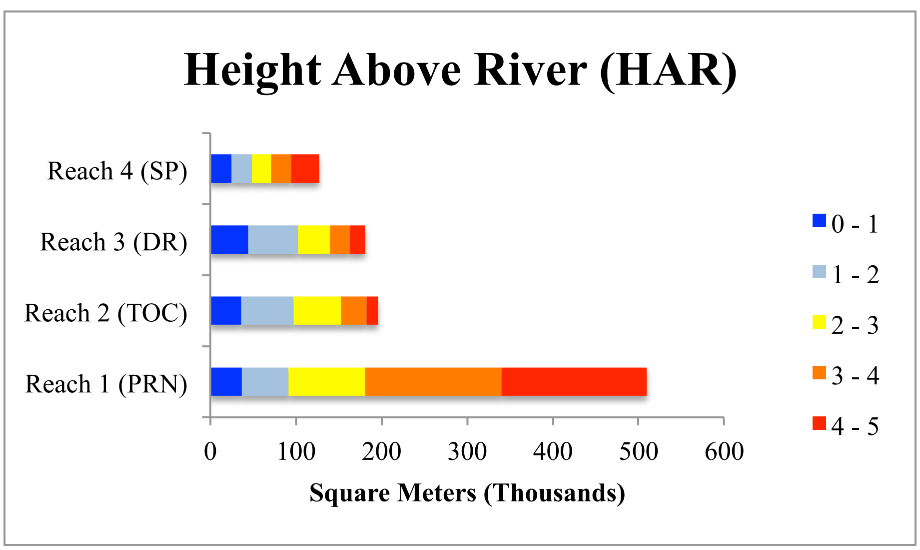

Figure 12. Elevation (height above river) of floodplain areas in the four Lagunitas Creek study reaches

Field Observations

Field-derived cross-section width measurements were smaller than LiDAR-derived measurements in 12 out of 18 comparisons (Table 2). However, there were no statistically significant differences in width between the field- and LiDAR-derived measurements (t-test, P=0.3366 for 1m depth, P=0.2403 for 2m depth).

Table 2. Field measurements for 1 and 2 meter depth cross-section

Site	Field 1m	LiDAR 1m	Percent Difference	Field 2m	LiDAR 2m	Percent Difference
130-1	20.7	18.1	0.1	25.2	29.5	-0.2
130-2	15.2	17.6	-0.2	34.1	71.5	-1.1
150-1	16.7	12.8	0.2	54.4	56.6	0.0
160-1	19.1	20.3	-0.1	35.5	39.3	-0.1
160-2	16.3	18.3	-0.1	40	39.7	0.0
160-3	14.6	22.3	-0.5	25.1	31.7	-0.3
170-1	22.6	19.7	0.1	30.8	28.2	0.1
170-2	6.9	18.7	-1.7	24.6	26.7	-0.1
170-3	19.6	19.7	0.0	33.2	27.6	0.2

Vegetation Community and Height

Alnus-dominated plant communities were the most common vegetation types in every reach in both the lower (0-2m) and upper (2-5m) floodplain regions in all four reaches, with the exception of the Coast Redwood community type in the upper floodplain of the R4 (SP) Reach. Additionally, there were greater amounts of non-riparian species (i.e., oak, bay, redwood) in the upstream reaches and in the upper elevation floodplains. For example, R2 (TOC) and R3 (DR) reaches had the highest proportion of Red Alder forest (>65%) in both the low and high elevation floodplains (Table 3 and Table 4), but California Bay Laurel and Redwood species were more abundant in the upper elevations than in the lower elevations.

Every plant community type had a greater average height in the high floodplains than in the low elevation floodplains. There was also a trend of taller vegetation in the upstream reaches. For example, the average height of the *Alnus rubra/Salix lasioepis* (RAS) community increases in an upstream direction in both the lower and upper elevation floodplains, with the exception of a slightly lower average height in the 0-2m floodplain in the R4 (SP) reach (where *Sequoia* is the dominant overstory species). Furthermore, the RAS community disappears from the upper elevations where large redwood communities exist.

The dominant plant community in the lower floodplain (0-2m) in the R1 (PRN) reach is Red Alder-Arroyo Willow (RAS) community (30.2%) and Red Alder-Salmonberry-Elderberry (RSE) community (21%) with a mean height of 10.1 and 11.8 meters. Arroyo willow and annual grasslands at 12.1% and 10.5% respectively, combine with *Alnus* to represent the majority plant community within 2 meters of the creek base flow. In the high (2-5m) floodplain, the RAS community is less abundant (25.9%) but taller (7.9% greater mean height) than in the low floodplain. Notably, pasture and agriculture land use represent 17.9% or 20.3 acres of upper floodplain.

Table 3. Top four plant communities and mean height in lower floodplains (0-2m) and upper floodplains (2-5m) by reach.

Plant Community Association	Lower Floodplain		Upper Floodplain		
	Cover Percent	Mean Height (m)	Cover Percent	Mean Height (m)	Mean Height Ratio Lower to Upper Floodplain
R1 (PRN)					
Red Alder - (RAS)[1]	30.2%	10.1	25.9%	11.0	1:1.1
Red Alder - (RSE)[2]	21.0%	11.8	11.1%	19.2	1:1.6
Arroyo Willow	12.1%	10.9	-	-	-
Active Pasture or Agriculture	-	-	17.9%	9.7	-
California Annual Grassland	10.5%	6.2	11.3%	12.9	1:2.1
R2 (TOC)					
Red Alder - (RAS)	83.3%	15.2	73.2%	16.6	1:1.1
Built-up Urban disturbance	9.6%	9.4	8.8%	5.5	1:0.6
California Bay – (UQT)[3]	2.4%	15.2	5.1%	14.2	1:0.9
California Bay - Umbellularia/Polystichum	1.9%	8.7	-	-	-
Coast Live Oak - Quercus agrifolia/ Arbutus menziesii/Umbellularia	-	-	4.8%	11.8	-
R3 (DR)					
Red Alder - (RAS)	85.6%	25.9	67.8%	33.8	1:1.3
California Bay - Umbellularia/Polystichum	9.0%	14.4	21.3%	15.4	1:1.1
Coast Redwood - Sequoia – (SPU)[4]	4.8%	27.5	9.5%	32.7	1:1.2
Built-up Urban disturbance	0.6%	13.7	1.2%	14.9	1:1.1
R4 (SP)					
Red Alder – (RAS) spectabilis/Sambucus racemosa (RSE)	46.1%	27.6	32.7%	28.4	1:1.0
Coast Redwood - Sequoia – (SPU)	29.2%	27.8	36.0%	32.7	1:1.2
Coast Redwood	14.0%	26.4	21.9%	29.5	1.1.1
Red Alder - (RAS)	5.7%	13.2	-	-	-
California Bay - Umbellularia/Polystichum	-	-	5.6%	29.8	-

1 (RAS) *Alnus rubra/Salix lasiolepis*
2 (RSE) *Alnus rubra/Rubus spectabilis/Sambucus racemosa*
3 (UQT) *Umbellularia/Quercus agrifolia/Toxicodendron*
4 (SPU) *sempervirens/Pseudotsuga/Umbellularia*

DISCUSSION

One of the main goals of this study was to use LiDAR derived variables to differentiate coho salmon overwintering floodplain habitat for the mainstem of Lagunitas Creek. Based on previous analyses of coho smolt trapping data (Stillwater Sciences 2008), I initially hypothesized that the R2 (TOC) reach would have the greatest abundance of low floodplain habitat (Hypothesis 1). However, my results suggest that the R1 (PRN), R2 (TOC), and R3 (DR) reaches all contained similar amounts of low (0-2m) floodplain habitat. In agreement with my first hypothesis, however, the R4 (SP) reach had the least available floodplain habitat. The R3 (DR) and R2 (TOC) reaches both present opportunities to connect pockets of prime coho habitat with the upper floodplains to increase overwintering capacity. Finally, the R1 (PRN) reach had the greatest amount of upper floodplain due to its wider alluvial valley, larger offsets of road infrastructure, and recent channel incision.

Floodplain restoration actions would likely involve raising the channel bed in order to improve hydrologic connectivity with disconnected floodplains. In order to identify locations where restoration might provide the greatest improvements in coho salmon overwintering habitat, I compared the ratio of lower floodplain area to upper floodplain area in each of the 191 100 meter study sections (Figure 13). Fifteen sections, all in the R1 (PRN) reach, had ratios of lower floodplain to upper floodplain greater than 1:10. (Figure 14). These results support my hypothesis that a greater proportion of floodplain habitat is currently inaccessible (2-5m) in the R1 (PRN) reach (Hypothesis 2). Though many restoration opportunities exist in the study area, areas with the greatest potential for increasing the quantity of floodplain habitat are concentrated in the R1 (PRN) reach.

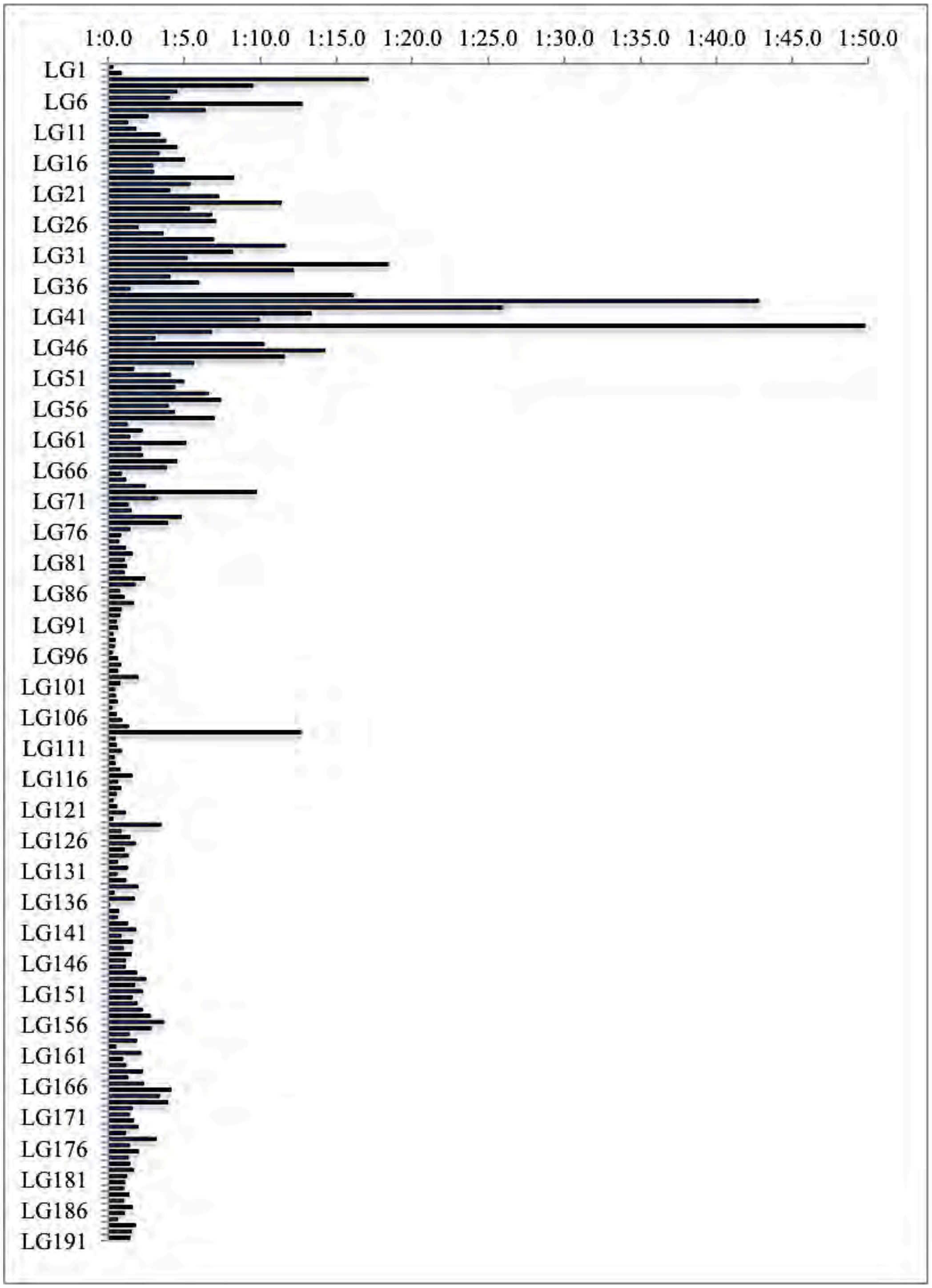

Figure 13. Ratio of lower floodplains to upper floodplains for each 100 meter section in Lagunitas Creek.

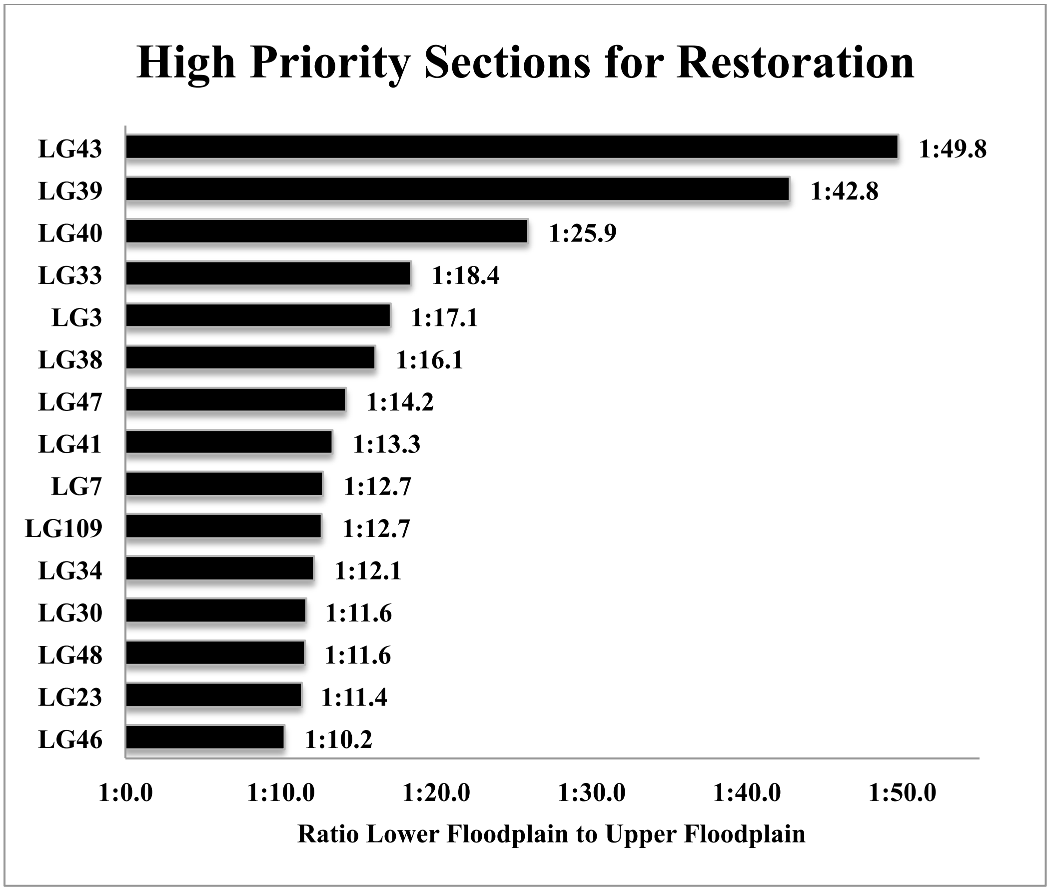

Figure 14. Top 15 100 meter sections based on ratio of lower floodplain to upper floodplain (all sections are located in R1 PRN reach)

The analysis of the vegetation community type and LiDAR derived mean vegetation height data supported my hypothesis that more mature vegetation is found on less connected floodplains (Hypothesis 3). Plant community composition was different between the lower and upper floodplains. For example, the most abundant plant community in the lower floodplain of the R4 SP reach was RAS red alder. Conversely, the Coast Redwood -Sequoia community is more abundant than the *Alnus rubra* community in the upper floodplain. My results, linking the HAR elevation classification to the plant height and community type, suggest many sections of the Lagunitas Creek can be reclaimed for coho overwintering habitat.

Height Above River (HAR)

Using LiDAR remote sensing to successfully define riparian stream topography, in comparison to field-based methods, is well reviewed (Bowen and Waltermire 2002, Jones et al. 2007, Negishi et al. 2010). In some cases, LiDAR based DEMs provided more topographic details when evaluated against traditional photo-interpretation or field mapping (Murphy et al. 2007). In this study, field data-derived 1 and 2 meter cross-section widths were not significantly different from LiDAR profiles. However, cross-section locations were determined with a recreational grade GPS unit with 3 to 7 meter accuracy rating; GPS errors of just a few meters can result in substantially different 1 meter depth measurements because of the meandering character of the Lagunitas Creek.

This height above river (HAR) model application provided 1-meter resolution of floodplain heights that can be useful for site-specific evaluation of restoration potential. To understand broad differences in the availability of floodplain habitat for coho, I classified HAR into lower (0-2m) and upper (2-5m) parcels. Floodplain areas at the scale of 100-meter sections reveal complex, small-scale spatial patterns (Figure 15). For example, section LG109 has 397 m^2 of lower floodplain and 5,105 m^2 of upper floodplain; the sections immediately upstream (LG110) and downstream (LG108) have 4,778 m^2 and 2354 m^2 of lower floodplain habitat, respectively (Figure 16). This could be the result of the model recalculating from an incised section of the creek (LG109). However, the elevation pattern in this reach is consistent with the bare earth DEM. The HAR model highlights the effect of incised stream on local floodplains. If additional low floodplain in LG109 could be restored, such as through strategic wood placement, it would connect patches of adjacent habitat and create a continuous stretch of refugia. Thus, increasing the stream-terrestrial interaction and inundation periods will expand the coho refugia during bankfull flood events.

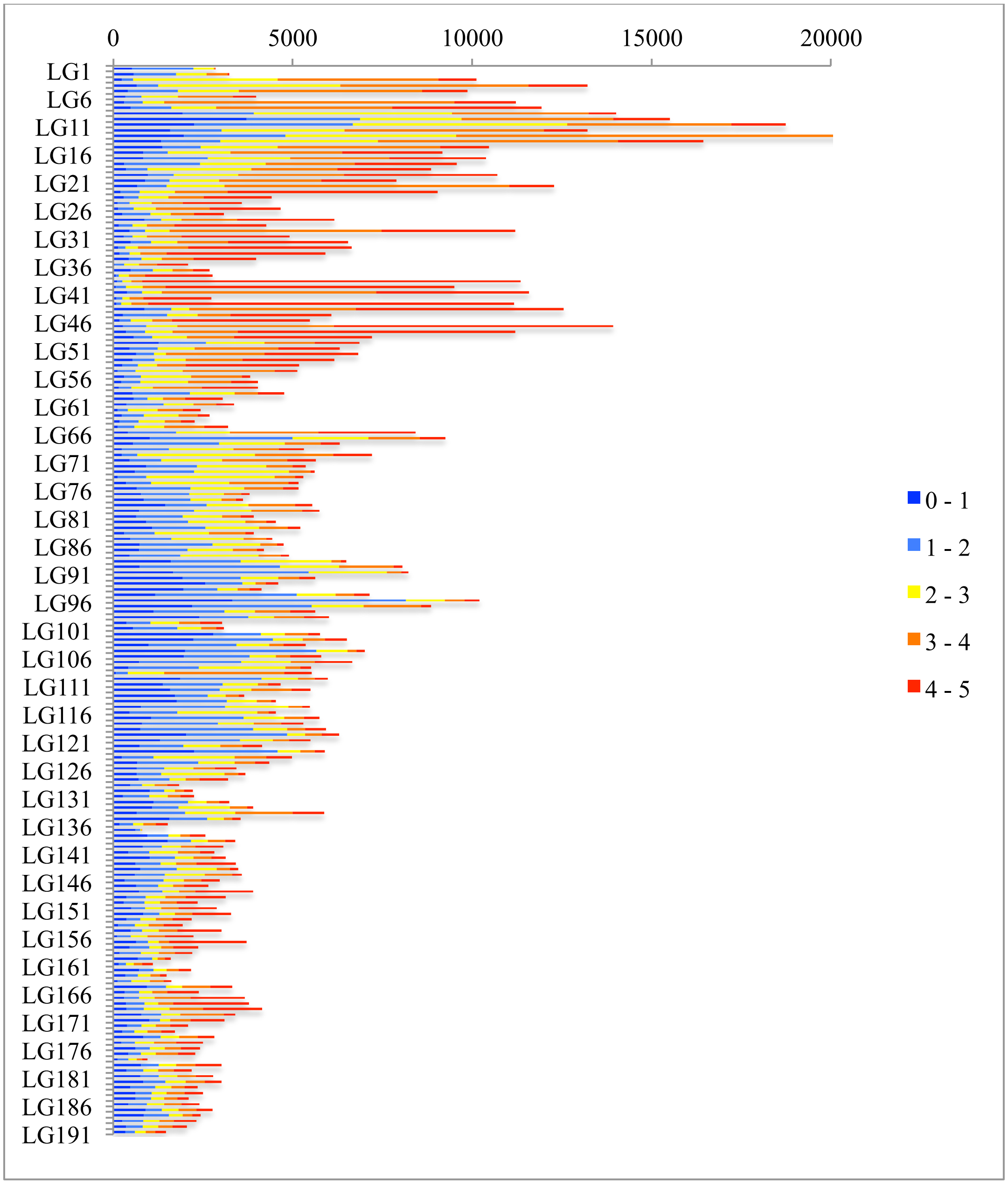

Figure 15. Floodplain Height Above River (HAR) for 191 100 meter sections

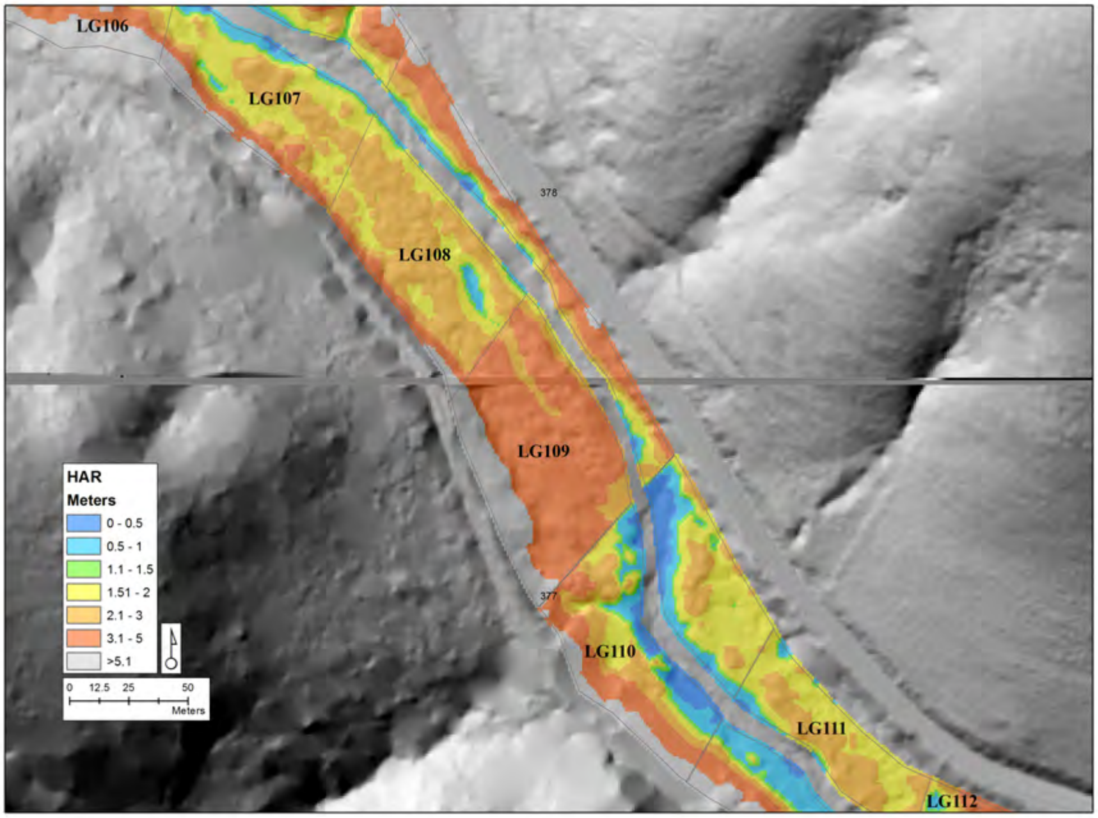

Figure 16. Classified HAR model comparing potential restoration section (LG109) with upstream section (LG110) and downstream section (LG108).

This model does not necessarily indicate hydraulic access or pathways during particular flood levels, but displays the elevation relationship between the stream height and the elevation of terrestrial geomorphic phenomenon. Therefore, as the water level rises in the river the water will spill into floodplains that have less or equal elevation. This "bathtub method" has been shown to overestimate inundation compared to the more laborious hydrodynamic modeling (Neumann, 2013). However, hydraulic roughness and in-stream wood jams displace flows onto the floodplain (Forzieri et al. 2010). This model therefore could underestimate inundation because the hydraulic displacement caused by riparian surface structures. It is not suggested that the inundation errors cancel out one another. Furthermore, hydraulic wave action and hydraulic roughness were not considered in this study.

Vegetation Indicators

The vegetation analysis served two purposes in this study: to identify the growth structure in reference to the flood regime, and to use the plant community type as a proxy. In identifying floodplain attributes, Comporeale et al. (2012) found the flood inundation frequency and magnitude influences plant sucession and species composition in riparian zones. By first calculating bankfull height of the Lagunitas Creek and then mapping the lower and upper riparian floodplain area that corresponded, I was able to document both the plant height and species type differences among the reaches.

Some plant species are tolerant (adapted) to flooding, but have stunted or delayed growth because of repeated disturbance, whereas the same species growing on well drained soils can grow taller as a result of less flood disturbance (Bendix and Hupp 2000). The National Parks Service 2003 Plant Community Classification and Mapping Project report is based on the U.S. National Vegetation Classification (USNVC). The classification scheme weights physiognomic topographies more than floristic structures when assigning plant community assemblages (Grossman et al. 1998). This focus on topography helps explain that plant communities in lower floodplains on the Lagunitas Creek are site-specific (spatial) and correlate with the flood disturbance inherent to accessible floodplains.

The mean vegetation height for all four study reaches is taller in the upper floodplain, than the lower floodplain .In general terms, the vegetation height gradient from lower floodplains to higher elevation is driven by hydrologic regimes, and is controlled by the geomorphic variability (Fantin-Cruz et al. 2011). Therefore, vegetation structure attributes can pose as a proxy, in conjunction with HAR data, to estimate the floodplain available to juvenile coho salmon. This application was less a linear predictor model for vegetation structure or biomass assessment, but a comparison of the vegetation establishment between regularly inundated floodplains and the increasingly abandon floodplains resulting from a depressed flood magnitude (Konrad 2012). Moreover, LiDAR derived landscape analysis has been used for vegetation predictor modeling (Shoutis et al. 2010, Simonson et al. 2012), and riparian restoration mapping (Thomas and Nisbet 2007). These approaches use the flexibility and vastness of LiDAR data to build and organize environmental variables of interest.

Restoration and Connectivity

Stakeholders are exploring multiple restoration sites for floodplain enhancement. One such proposed project is located upstream of the Lagunitas-Nicasio Creek confluence (LG67-LG71) (Figure 17). According to the HAR model, this 500-meter tract has 33,721 m^2 of floodplain (<5m). The lower floodplains consist of 41.2% of the area with 53.8% of the restoration zone between 2-5 meters in elevation. This Red Alder dominated zone is ideal for coho overwintering because of the complex topography and vegetation structure, including a ~800 meter paleochannel. There is an upstream lower floodplain, with addition planning; this could broaden to a 700-1200 river meter corridor of desirable coho habitat.

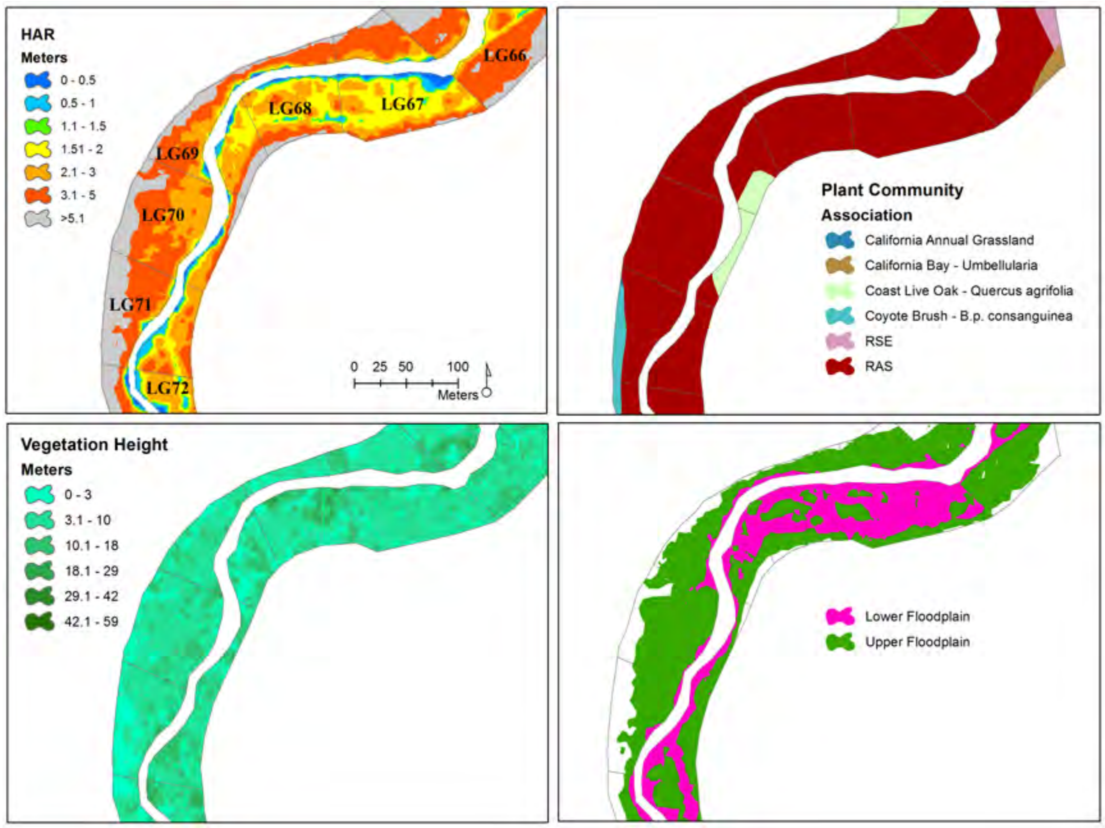

Figure 17. Proposed restoration site variables including 33,721 m2 of floodplain (<5m) HAR (upper left), dominate Red Alder (RAS) plant community (upper right), vegetation height (lower left), and a large extension of upper floodplains visualized in a classified HAR (lower right).

MANAGEMENT RECOMMENDATIONS AND FURTHER STUDY

Further study would be warranted on the loss of floodplain habitat behind each of the five dams. This could show the correlation between habitat loss and salmon population loss. To identify preexisting floodplains before dams were introduced, sediment cores tested in overbank deposits on high terraces thus would help explaining historic flood events.

Applications of my analysis and database for future restoration goals include locating and measuring previously undetected restoration sites. Additionally, an interactive database providing quantified inventory of lower and upper floodplains will support restoration project planning. Currently, a Total Daily Maximum Load (TMDL) for sediment is being prepared in which floodplain data will contribute to supporting the mandate. Integrating sediment studies, limited factor assessments, fish inventory records, and ocean condition data will provide a foundation for efficient project planning. Finally, this aggregated data will provide opportunities for targeted implementation of stream restoration and support the ultimate goal of rebuilding the California coho salmon population.

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