Figure 1: Lamprey ammocoetes. photo credit: Justin Alvarez.

Quantifying Pacific lamprey (*Entosphenous tridentus)* ammocoete habitat availability and risk associated with the summer hydrograph recession limb in Coastal Northern California

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February to October 2019
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Table of Contents

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EXECUTIVE SUMMARY

Water levels affect Pacific lamprey (Entosphenous tridentatus) larva (ammocoete) habitat. Ammocoetes live in fine substrate for many years. The goals of the project are to explore the distribution and temporal change of ammocoete habitat. I measured streamflow in Redwood Creek and made three-dimensional models of the habitat to analyzed the loss of habitat through the summer recession limb. I measured geomorphic variables in a variety of stream types across Coastal Northern California to model relationships between geomorphic variables and ammocoete habitat. I created a spatial model of ammocoete habitat using remotely sensed variables such as precipitation, slope, and rock type. I found that although the flow in Redwood Creek dropped 99.99%, in one spot, there was only a 34% drop in habitat. The most predictive geomorphic variable for ammocoete habitat is stream slope. Larger rivers will have more ammocoete habitat than smaller. This project has allowed me to practice the scientific method and has helped with my career goals.

PROJECT OBJECTIVES

A career pathway I identified during my internship is an environmental scientist. My career goals include expanding my professional knowledge and training, improve my communication skills, and eventually work for an institution in the water resources field. This internship will help me achieve my goals. I will be tasked with a research project to implement from design to results communication. I will be working alongside professionals in my field not only learning from them how to be professional in the field but gaining relationships that will help me in the future. Working alongside professionals in a variety of institution types including the federal government (US Forest Service), non-profits, academic, private-consulting, and private land managers will help me understand what the working environment is like in each type of institution to see where I might fit in as well as diversify my interpersonal skills. I will be receiving training to advance my skills in stream ecology specifically with geomorphic measurements and streamflow. I will have the opportunity to use my skills in R and GIS for real life situations. My communications skills will improve with writing reports and giving presentations on the progress and the results of my research. Increased water withdrawals affect stream quality in rural northern California. Summer low flows in this Mediterranean climate are exacerbated by rural water withdrawals for private use. Pacific Lamprey (*Entosphenus tridentatus*) are a jawless anadromous fish whose juvenile life stage occurs in the freshwater environment. Lamprey larva are known as 'ammocoetes,' and live in fine streambed substrate for 3-10 years. The ammocoete life stage of Pacific Lamprey is critically understudied in terms of their ecology and habitat needs. Ammocoetes are rarely observed by humans because they emerge from the fine substrate at night, but can make up the majority of the biomass in the stream and act as bio-engineers performing bioturbation of the river bottom. Pacific Lamprey are important to the Native American tribes in the region because the lamprey adults migrate upstream in winter during a lull in salmon runs and contribute to the tribes' diet during that time (Parker 2018).

The original study goals were to explore the distribution and temporal change of ammocoete habitat through the summer flow recession of 2019. The project included geomorphic measurements in streams along the North Coast of California and a temporal study of how ammocoete habitat area decreases with the summer streamflow recession limb. Geomorphic measurements included stream slope, sinuosity, and entrenchment in a variety of channel types. The temporal study included repeated measurements of riffle crest depth and ammocoete habitat area at multiple sites representative of different drainage areas during the summer streamflow recession of 2019. Together these two studies will evaluate risk to ammocoete habitat associated with water withdrawals in different channel types. Some sites were selected in National Forests with guidance and mentorship from USFS personnel.

The original tasks I set out to accomplish for my internship were: 1. Select study sites in a variety of channel types using both geospatial tools and in-person site reconnaissance visits. 2. Work with personnel from the USFS Pacific Southwest Research Station, including Bret Harvey and others, to acquire landowner access and determine the logistics and safety of visiting sites in the Klamath, Trinity, and Mendocino National Forests. 3. Measure the following factors at each site: slope of the channel, channel sinuosity, sediment type within the active channel, entrenchment, and ammocoete habitat area dimensions. Note the localized site factor associated with habitat area formation. 4. Establish multiple study sites for a temporal study to document stream drying patterns throughout the summer 2019. Install data loggers to record continuous water level and temperature. Record baseline physical measurements (e.g. habitat area, riffle crest depth, slope, entrenchment, radius of curvature) at the beginning of the field season. 5. Monitor the streamflow and percentage of ammocoete habitat loss at established sites through the summer recession limb, from approximately late May to September 2019. Record measurements every two weeks at each site, for a total of 15 site visits.

6. Analyze data to explore relationships among ammocoete habitat availability, channel type, drainage area and other factors measured throughout the summer recession limb. Complete geospatial analysis for risk levels associated with previously mapped channel types. Results will help guide policy to allocate water resources in rural streams. 7. Write reports and give presentations to communicate research results.

A change to the project task above is that instead of measuring the available ammocoete habitat each time I measured streamflow I used a total station to measure the area once near the end of the field season. I used the data from the total station to create a 3D model (Figure 3) of the ammocoete habitat and used the water elevation to calculate the percentage of ammocoete habitat inundated over time (Figure 11).

Instead of meeting specifically with Bret Harvey at the Forest Service Redwood Science Lab I met with Adam Dresser, a hydrologist from the Six Rivers National Forest.

PROJECT APPROACH

Temporal Model

I established 10 sites in the Redwood Creek Watershed for a temporal study to measure the area of fine sediment deposits inundated over time (Figure 2). At each site I established a monument to record water stage. At eight sites I installed water level loggers to record water level and temperature. I measured streamflow every two weeks from May 11th to September 21st 2019 for 11 visits. I used a total station (Leica TCP12013 and RX1220T) to measure the area of fine sediment deposits suitable for ammocoete habitat at nine sites in the Redwood Creek watershed and used ArcGIS to create 3D models of the ammocoete habitat surface (Figure 3). There was one site where I measured streamflow all summer, but there was not suitable habitat in the pool with the water level measurements to conduct a total station survey. The surface was used to estimate the amount of habitat area that was dewatered over the season.

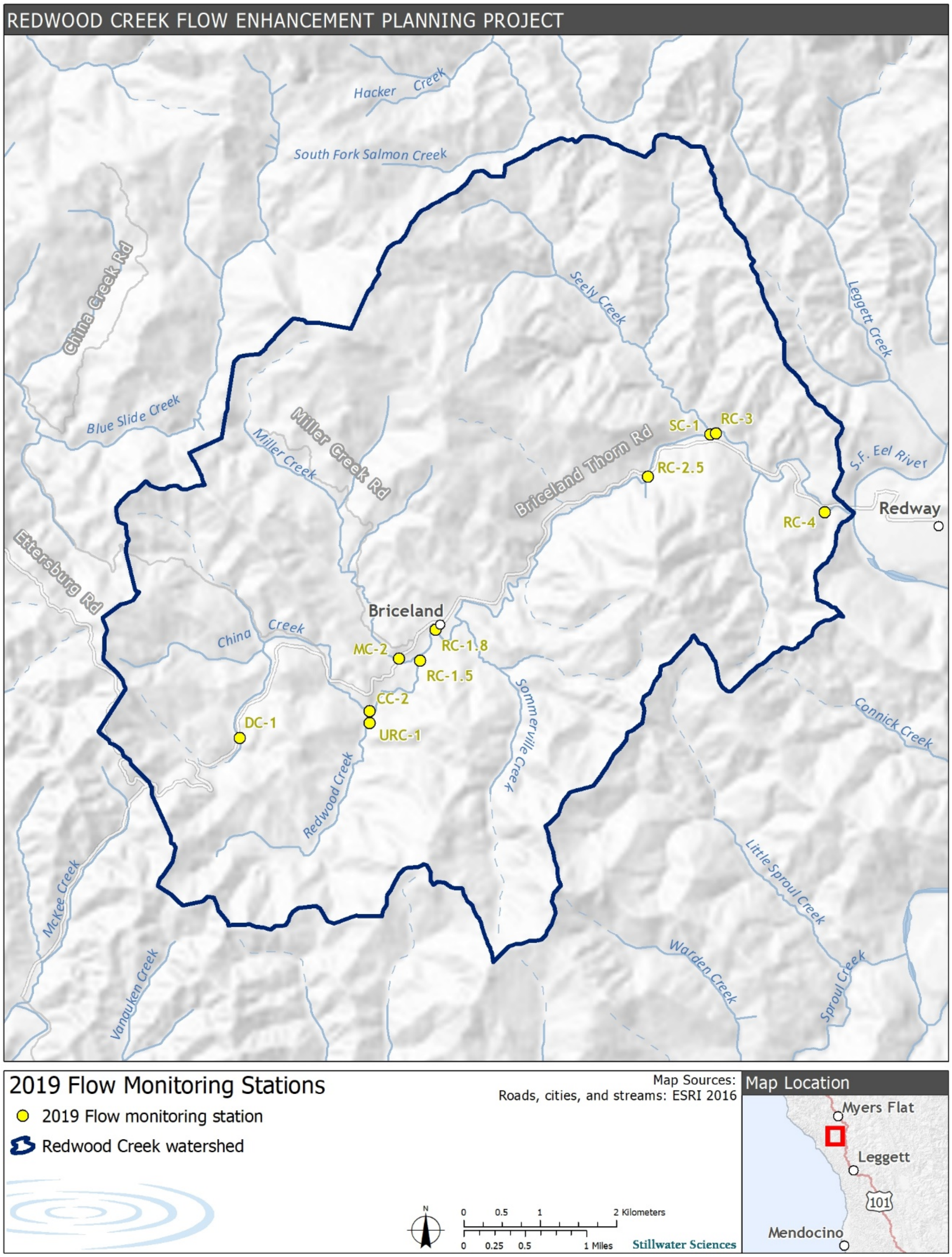

Figure 2: Streamflow monitoring sites in Redwood Creek.

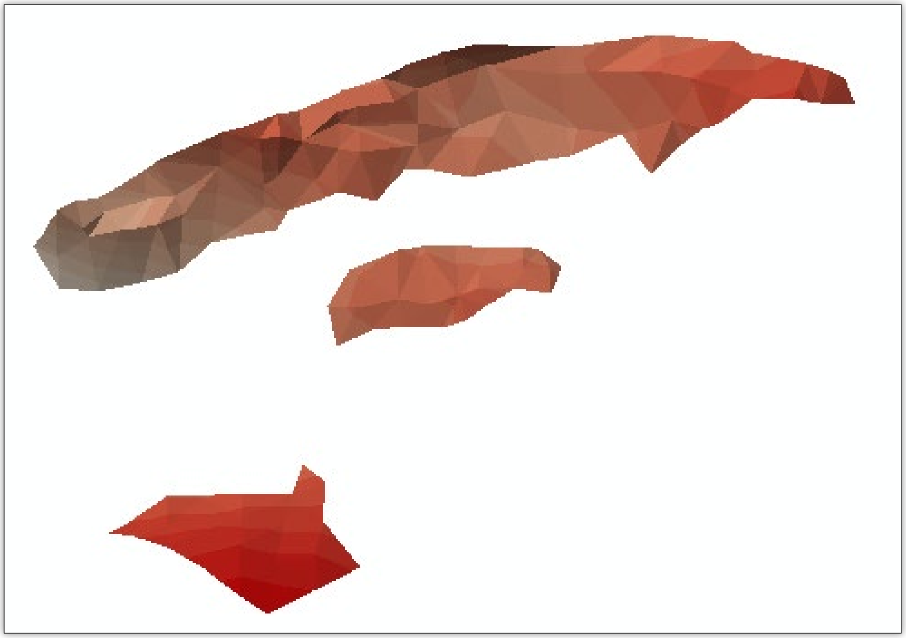

Figure 3: 3D model of ammocoete habitat used to calculate the amount of habitat inundated with water over time. Example from China Creek, CC-2.

Geomorphologic Model

I initially selected survey sites using geospatial tools. I then met with Adam Dresser, a Hydrologist from the Six Rivers National Forest Service who had firsthand experience in the streams and could help with site selection and access. He showed maps and routes to safe locations for surveys. In the field surveys I measured channel slope, sediment composition, terrace levels and ammocoete habitat area on 115 reaches (Figure 4).

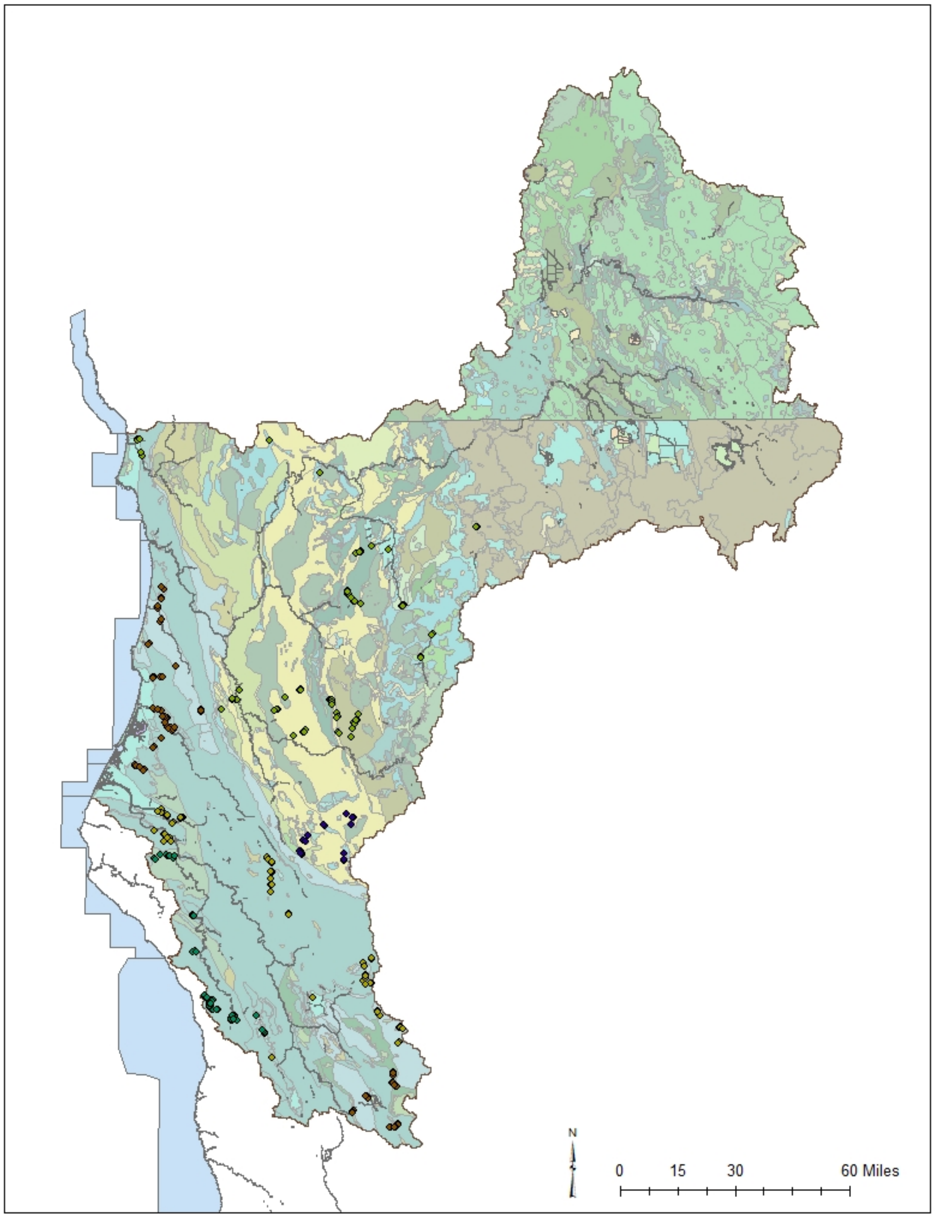

Figure 4: Map of all survey sites on the North Coast of California sampled for the geomorphic model. Background colors indicate the complexity of rock types.

Sampling of Ammocoete habitat was done in coordination with the California hydrogeomorphic classification project. The classification project separated stream reaches into 15 different bin types depending on drainage area and slope; there are three categories of the drainage area and five categories of slope (Lane et al. 2016). The study is designed to sample an equal number of reaches from each bin in each region (Lane et al. 2016). Reaches were not randomly selected because of constraints on access and frequency of bin types in the region (Cooper et al. 2017). Reach lengths were 15 times the mean bankfull width of the channel within the survey area.

Traditional geomorphic diagnostics from Rosgen (1994) were measured in the field including channel slope, bankfull width, bankfull depth, sinuosity, substrate composition, entrenchment ratio, floodplain elevation and undulations (Lane et al. 2016).

In order to measure the availability of ammocoete habitat, areas of fine sediment deposits were measured and recorded in the field. The minimum size of a deposit measured was 5 cm (0.15 ft) deep and 1 m^2 (9 ft^2) in area. Three to five representative widths and at least one length (more if needed to characterize area) were measured for an area estimate. A stadia rod, laser range finder, or marked walking stick was used for width and length measurements. Calculations for the area of silty-sandy deposits were done by multiplying the average width by the length of the deposit. Minimum depth requirement of the silty-sandy deposits was checked with an instrument approximately one centimeter in diameter that can penetrate the substrate, such as a pencil with 5 cm depth marked.

I selected thalweg elevation change, bankfull width, and valley width as the primary variable to analyze. I calculated the slope of each reach by dividing elevation change by reach length (15 x bankfull width). I calculated entrenchment as floodprone width divided by bankfull width. To compare ammocoete habitat over different reach lengths I calculated habitat density by dividing the sum of ammocoete area in the reach (m^2) by the length of the reach (m).

I used multiple linear regression because I had one continuous quantitative variable, habitat density, and two continuous quantitative variables, slope and entrenchment. All of the variables were skewed to the right (Figure 5), so I decided to do a log transformation on all of the variables (Figure 6). When I ran the multiple linear regression including the variables slope, entrenchment, and an interaction between slope and entrenchment the interaction was not significant, so I decided to drop the interaction. I then evaluated with both the variables, and entrenchment was not significant. The model that used only slope was the best. The final model equation is:

$$\text{Log (habitat density)} = -5.8087 - 0.9336 * \log(\text{slope})$$

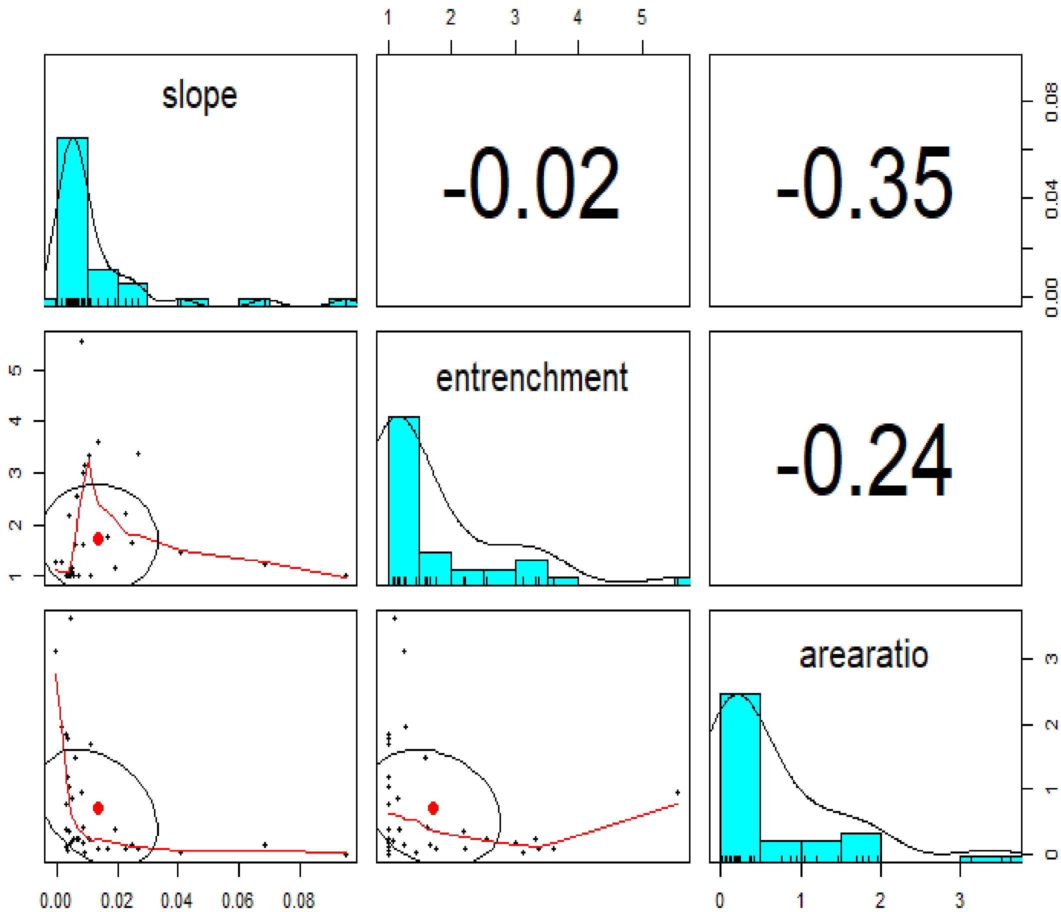

Figure 5: Exploratory graphs showing a histogram of the variables, as wells as scatter plots and correlation between the variables. Variables include slope, entrenchment, and area ratio (habitat density). The x-axis is the variable above, and the y-axis the variable to the right, for example slope versus area ratio is in the bottom left corner. The correlation is between the variables to the left and below, example the correlation between slope and arearatio is -0.35.

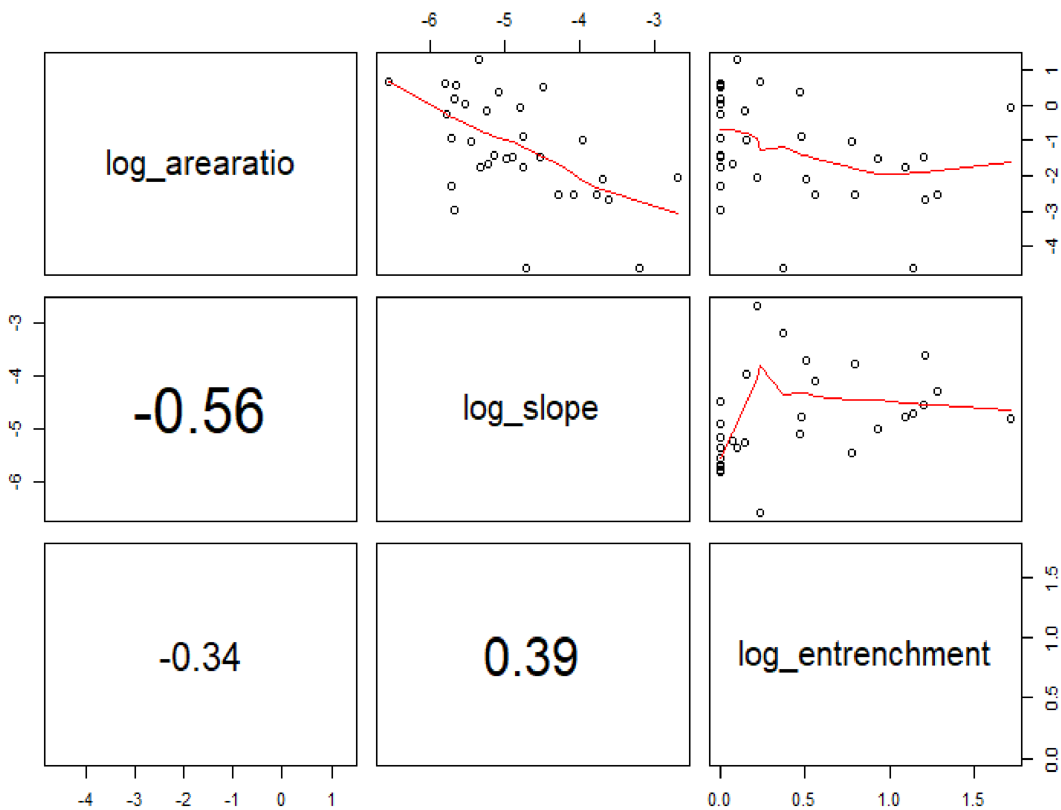

Figure 6: Exploratory graphs showing the variables log transformed in scatter plots and correlation between the variables. Variables include slope, entrenchment, and area ratio (habitat density). The x-axis in the scatterplot is the variable below, and the y-axis the variable to the left, for example log_arearatio versus log_entrenchment is in the top right corner. The correlation is between the variables to the right and above, for example the correlation between log_arearatio and log_entrenchment is -0.34.

Spatial Model

The variables instream slope, water proxy (drainage area * precipitation) and bedrock hardness were used in a spatial model because they are readily available remotely sensed variables and I suspect that they all effect density of ammocoete habitat.

Slope was calculated in the software programs BlueSpray B33, ArcMap 10.5, and Microsoft Excel. A 10-meter resolution Digital Elevation Model (DEM) was collected from the United States Geological Survey (USGS) National Map Data Viewer. A down-sampled 100-meter resolution USGS DEM was used to create a flow accumulation raster using flat processing and hydrologic toolsets in BlueSpray B33 to extract vector stream layers (Figure 7). The stream layers were then divided into 300-meter segments with an upstream and downstream vector point. These points were used to extract the underlying elevation values from the 100-meter DEM so the attribute table could be exported to an Excel Spreadsheet and slope could be calculated. The formula used to calculate slope was:

$$\frac{Upstream\ Elevation - Downstream\ Elevation}{Segement\ Length}$$

The calculated slope value was transformed to an absolute percentage and the table was joined to the stream layer in ArcMap 10.5 using the FID identification number.

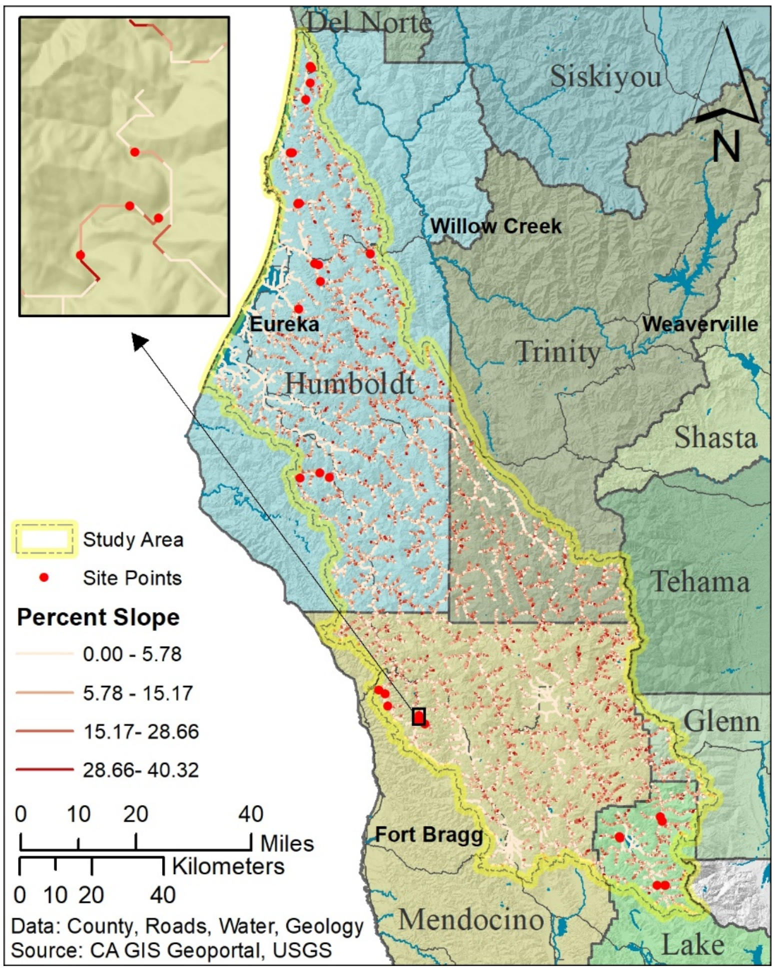

Figure 7: Map showing sites where stream slope was calculated for the spatial model.

A control of water proxy was calculated in ArcMap 10.5 using the flow accumulation raster extracted from the 100-meter USGS DEM and a BioClim precipitation raster gathered from the HSU Geospatial Data Hub (Figure 8). Considering the difference in raster resolution from two different sourced datasets, the precipitation dataset was down-sampled to the resolution of the 100-meter flow accumulation raster. The raster calculator was used to multiply the two raster layers together resulting in a proxy of water abundance per 100-meter squared resolution pixel.

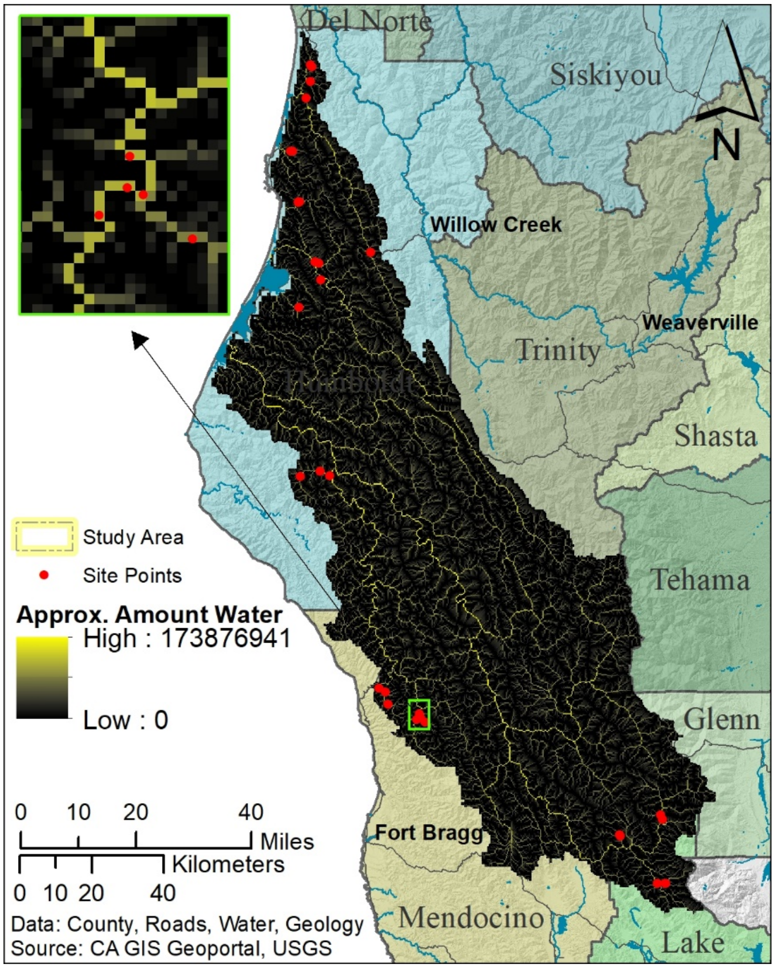

*Figure 8: Map showing a water proxy for the study area in the spatial model. Water proxy=drainage area (m^2)*precipitation(mm).*

Rock hardness is the tensile strength of the bedrock (MPa) (Figure 9). The types of bedrock in the study area are mudstone, sandstone, greenstone, serpentinite, mélange, and alluvium. Mudstone has a tensile strength of 3 and sandstone has a tensile strength of 4 (Sklar et al. 2017). Greenstone has a hardness of 5.5, and serpentinite has a hardness of 5 (Chesterman 1978). Alluvium is weak and mélange is even weaker (Terranova and Raymond 1984).

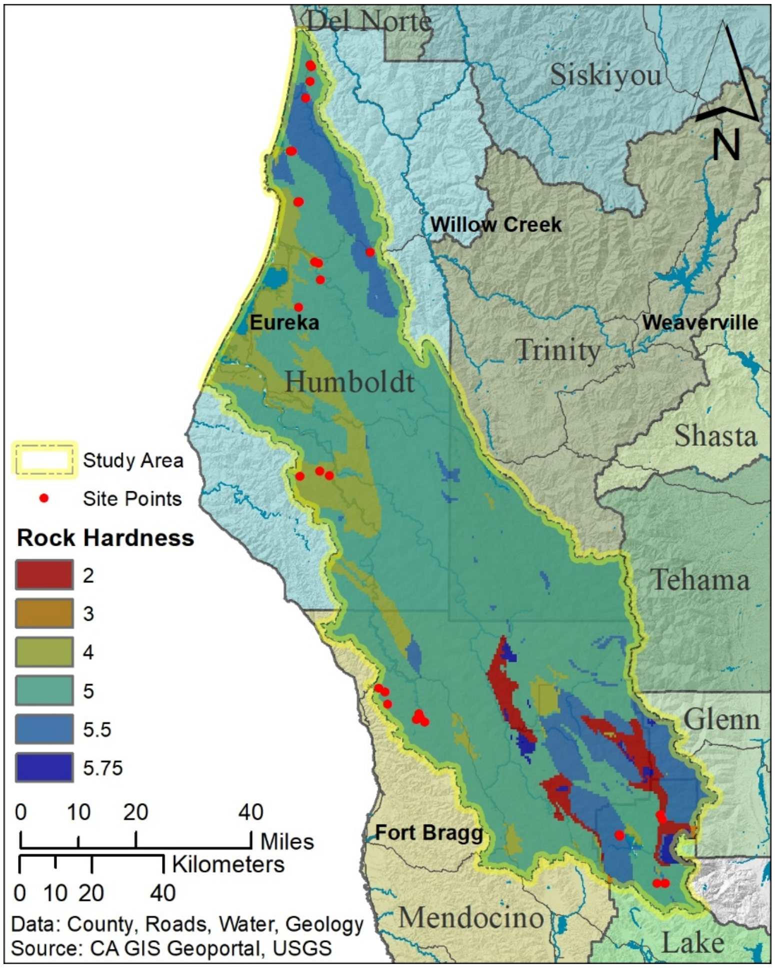

Figure 9: Map of rock hardness (MPa) in the study area used for the spatial model of ammocoete habitat availability. Rock hardness estimated from rock type.

PROJECT OUTCOMES

Temporal Model

2019 was a wet year for the Redwood Creek watershed, as evidenced by a hydrograph of China Creek, tributary to Redwood Creek from May 25-September 22, 2019 (Figure 8).. The highest recorded flow was on May 22 at 0.39 cubic meters per second (cms). The lowest flow was on September 7 with trace amounts of flow over a bedrock lip (<1x10^{-4} cms). On May 25, 92% of the ammocoete habitat was innudated, compared to 58% of habitat innudated on September 7 (Figure 11).

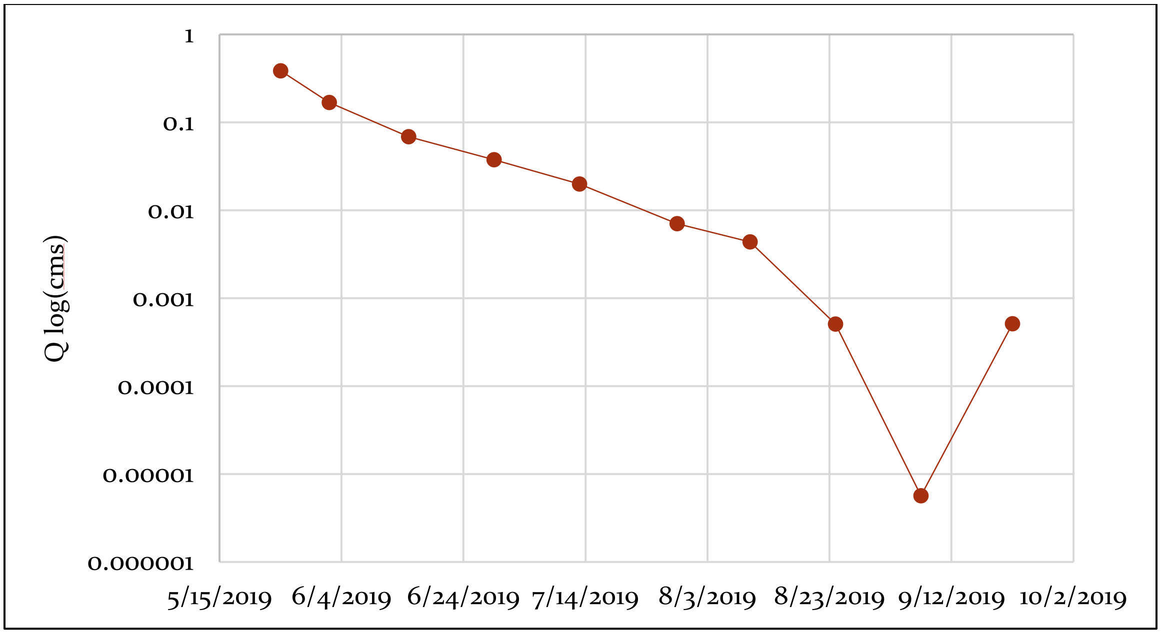

Figure 10: Hydrograph of China Creek, a tributary to Redwood Creek, from May 25 to September 22, 2019.

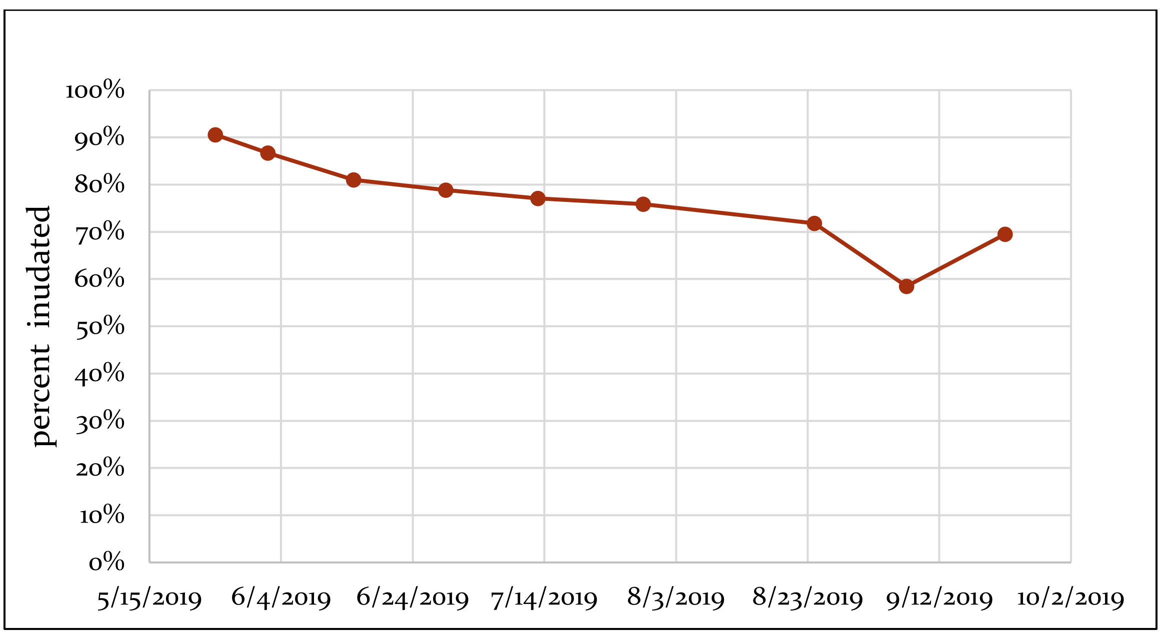

Figure 11: Graph of calculated percent of ammocoete habitat area inundated through the recession limb in China Creek May 25 to September 22, 2019.

Geomorphology Model

A simple linear regression model was used to predict the ammocoete habitat density (area ratio) from channel slope, (Figure 12). The model was significant ($F_{1,30}$=13.4, P=9.616e-4) and explained 30.87% of the variability in the data. This indicates that there is lower ammocoete habitat density at higher slopes. The predictive equation is: log(Area ratio)=-5.8087 -0.9336 *log(slope). (See R script at the end of the report).

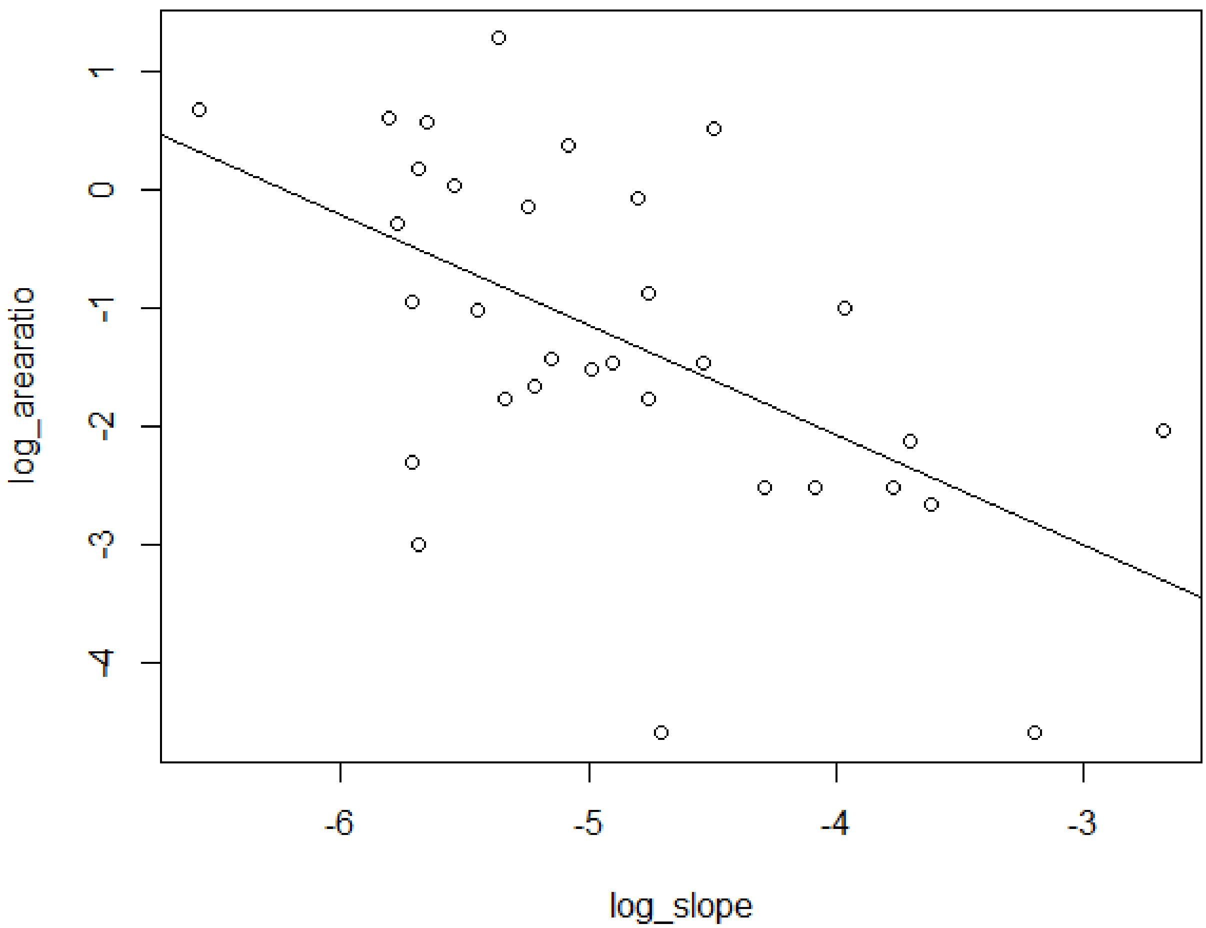

Figure 12: Model of ammocoete habitat density based on instream slope. x y plot of log(arearatio) and log(slope).

Spatial Model

I modeled the effect of rock hardness, slope, and water proxy on habitat density using a generalized additive model (created a map of predicted habitat density in response to the amount of water, stream slope, and bedrock strength. The Model is a realistic view of where ammocoete habitat could be located within a stream channel.

The model is not ready to be a recommendation for conservation, restoration, and reintroduction efforts for Pacific Lamprey in Northern Coastal California because of the variability in our predictor values and prediction. However, this project outlines steps for modeling habitat density of ammocoete which could be beneficial for future work in the area.

There are various limitations for modeling ammocoete habitat which include available data and conducting research over such a large region. I originally planned to use the bin types from the California hydrogeomorphic classification project that was used to pick the sites to measure ammocoete habitat but decided to go with remotely sensed variables that were less esoteric.

The largest challenge was that I had to use a large resolution DEM in order to run the hydrology tools to get flow accumulation. This rough DEM caused the stream to be in the incorrect location in places because it was too generalized. In order to extract values from the DEM we had to move the points in the stream created by the hydrology toolset. When the stream was in the wrong location, for example over a ridge, the slope calculation would be incorrect.

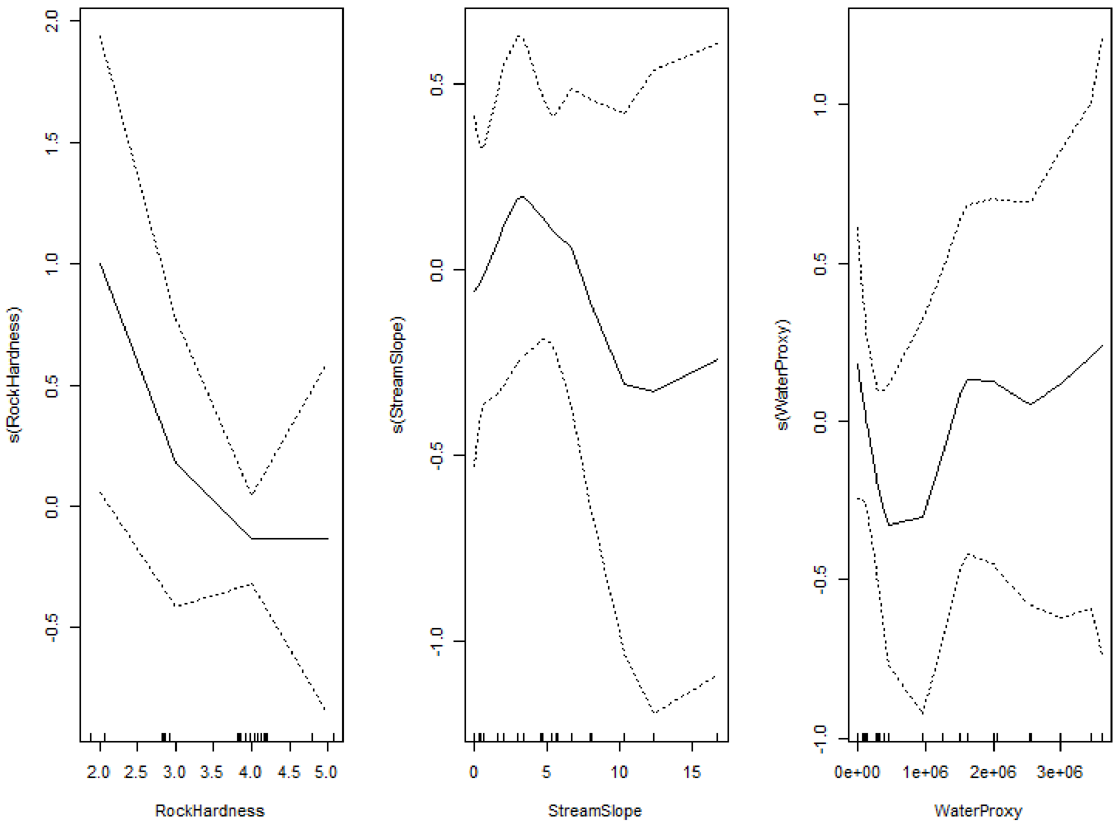

Figure 13: Generalized additive model of ammocoete habitat density using the variables rock hardness, stream slope, and water proxy.

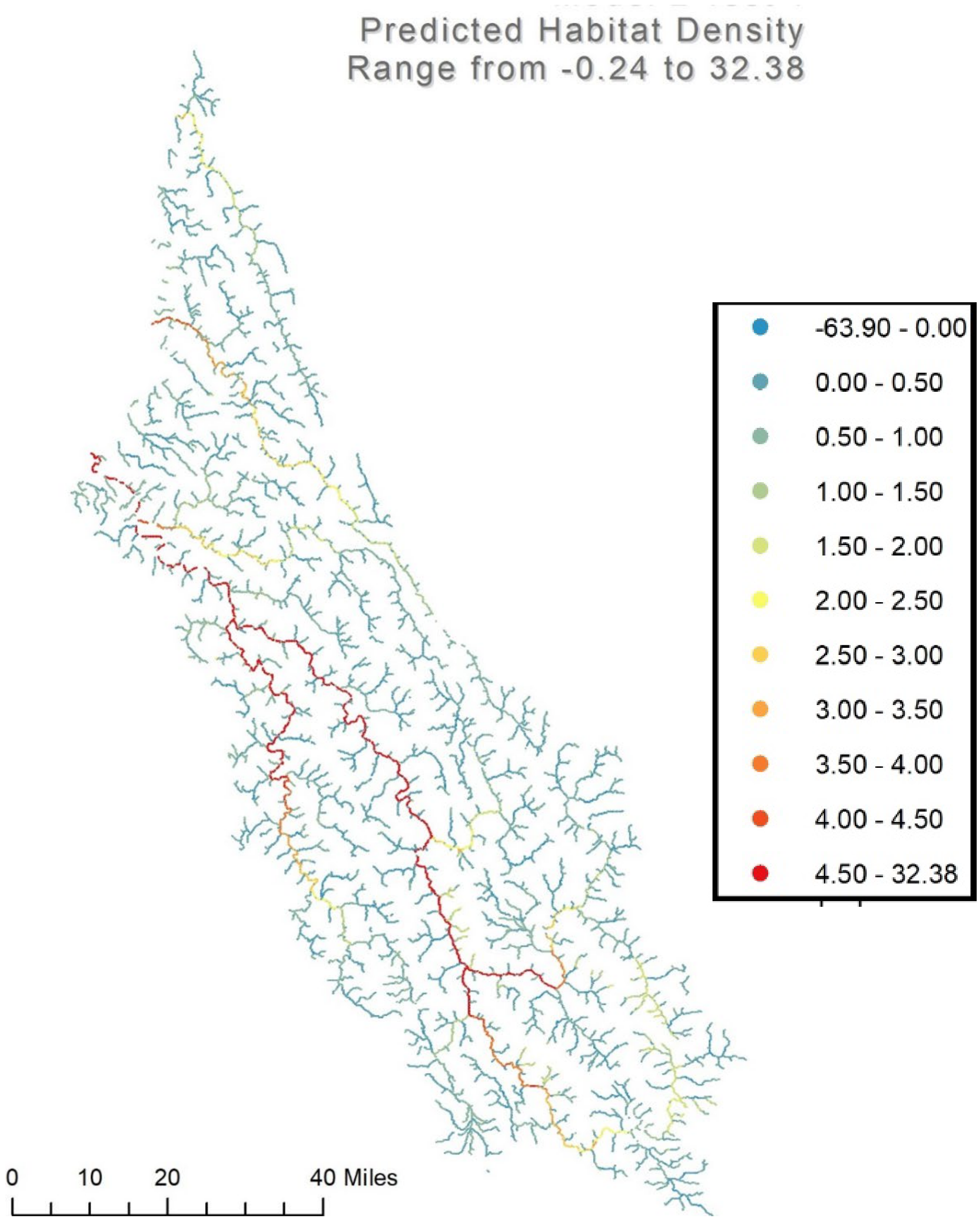

Figure 14: Map of predicted ammocoete habitat density (m^2/m) in study area.

CONCLUSIONS

Temporal Model

Over the season there was a 99.99% (from 0.39 cms to < 1×10^{-4} cms) change in the flow which translated to a 32% change in ammocoete habitat available.

Geomorphology Model

As Hypothesized, ammocoete habitat has a negative relationship with slope and entrenchment, but entrenchment was found to not be a significant variable for predicting the ammocoete habitat area ratio. The more parsimonious model uses only slope to predict the ammocoete habitat area ratio (density). This information can be useful for predicting ammocoete habitat remotely using geospatial analysis and could guide future restoration efforts.

To improve this analysis, I will look at additional variables including sinuosity, average sediment size, and categorical site characteristics.

Spatial Model

This project shows a prediction of ammocoete habitat in Coastal Northern California using a GAM with various limitations. Future research would need to be conducted to improve the model however this project can help identify next steps. In the future, it would be useful to use a higher resolution DEM to increase the accuracy of our predictor variables such as the flow accumulation, streams, and slopes.

Also, I would like to investigate the importance of other predictor variables that may impact habitat density. These include factors collected from the field such as bankfull width, bankfull depth, sinuosity, bed surface sediment composition, and entrenchment ratio. Integration of these factors may increase model performance. Lastly, considering streams being watershed integrators, it is important to model what is happening upslope. For example, we used precipitation and bedrock hardness from the location of our field sites, but in the future the precipitation and bedrock hardness upslope should be accounted for.

Prospective Career with USDA

I am coming to learn that science, like other skills, takes a lifelong practice. This internship has given me the opportunity to practice the skills for every step of the way. For this project I have identified a problem, created a hypothesis, a research plan, implemented the research plan, began analyses and sharing results. I have worked alongside professionals learning their skills and building relationships. I have practiced skills in river research including geomorphology, streamflow, and dissolved oxygen measurements. I have practiced using the computer software R and ArcGIS. I am becoming a stronger scientist that is helping my career goals of working in water resources field as a prospective career with the USDA.

APPENDICES

References

Chesterman, C. W. 1978. The Audubon Society Field Guide to North American Rocks and MineralsA Chanticleer Press. Alfred A. Knopf, Inc., New York.

Cooper, E. J., M. London, A. O'Dowd, and B. Trush. 2017. South Fork Eel river Geomorphic Field Data Collection Report. HSU River Institute.

Lane, B. A., S. Sandoval-Solis, H. E. Dahlke, and G. B. Pasternack. 2016. Geomorphic Classification of Natural Flow Classes for the State of California. Page 25. Univerisity California Davis for State Water Resources Control Board, 2.

Parker, K. A. 2018. Evidence for the genetic basis and inheritance of ocean and river-maturing ecotypes of Pacific lamprey (*Entosphenus tridentatus*) in the Klamath River, California. Humboldt State University.

Sklar, L. S., C. S. Riebe, J. A. Marshall, J. Genetti, S. Leclere, C. L. Lukens, and V. Merces. 2017. The problem of predicting the size distribution of sediment supplied by hillslopes to rivers. Geomorphology 277:31–49.

Terranova, T., and L. A. Raymond. 1984. The melange problem-a review. Page *in* L. A. Raymond, editor. Melanges: Their Nature, Origin, and Significance.

Appendix I

R Code for Spatial Model

```
#Input Model Point

TheData = read.csv("G:/Team Drives/GSP Ammocoete Project/R/1.InputModelPoints/ModelPoint1.csv")

View(TheData)


##visualize the data

#plot scatter, hist, and correlation

library(psych)

pairs.panels(TheData[7:10], smooth=FALSE, density=FALSE, ellipses = FALSE,lm=TRUE, hist.col="grey", breaks = 10 )

detach("package:psych", unload=TRUE)



require(gam)

# We have to use "attach()" because predicting values later on requires it

attach(TheData)
```

```
#Model
TheModel= gam(formula = Density ~ s(StreamSlope) )

print(TheModel)
summary(TheModel)
logLik(TheModel)

par(mfrow=c(1,3)) #to partition the Plotting Window
plot(TheModel,se = TRUE)


################
#The Predicition
################

#InputEnvironmentPoint
NewData = read.csv("G:/Team Drives/GSP Ammocoete
Project/R/2.InputEnvironmentPoint/EnvironmentPoint/1Environment_Complete.csv")


ThePrediction=predict.Gam(TheModel,NewData)

# Create data frame with combined data and prediction
FinalData=data.frame(NewData,ThePrediction)

# Save the prediction to a new file
#OutputTable
write.csv(FinalData, "G:/Team Drives/GSP Ammocoete Project/R/3.OutputTable/Model2_Within.csv")

##visualize the prediction
#plot scatter, hist, and correlation
library(psych)
pairs.panels(FinalData[4:7], smooth=FALSE, density=FALSE, ellipses = FALSE,lm=FALSE, hist.col="grey",
breaks = 10 )
detach("package:psych", unload=TRUE)
```

Appendix II - Site pictures

Figure 15: Katrina Nystrom measuring streamflow on Redwood Creek, site RC4. 5/10/19 (photo by Dan Sheldon)

Figure 16: Back sight location for total station survey on Redwood Creek, site RC4. 9/8/19. (photo by Katrina Nystrom)

Figure 17: Measuring slope of a waterfall during a geomorphic survey on Pink Creek in the Middle Fork Eel River. 6/25/19. (photo by: Kate Stonecypher).