INSTREAM HABITAT USE AND MANAGEMENT OF INVASIVE ARMORED CATFISHES IN THE UPPER SAN MARCOS RIVER

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Dedication

This manuscript is dedicated to my mother, Cheryl A. Warner: the first person to encourage my interest in the natural world, and the one who'd be proudest to see this chapter of my life completed.

I'll carry your memory to the summits and across the sea.

Acknowledgements

I would like to acknowledge the City of San Marcos, the Edwards Aquifer Authority, the Environmental Institute of Houston, and Texas State University for support in performing this research. I'd like to further acknowledge my fellow students and staff at EIH for assistance in field work and data management related to this research. Thank you to University of Houston Clear Lake for the opportunity to seek a graduate degree, and the introduction to lifelong friends. I'd like to thank Justin Hansen for his patience and guidance in teaching me to code. I'd like to thank my family, particularly my father and Dr. Sissy for their unwavering faith and support. I'd like to thank my partner Rebekah for facing this chapter of my life with me. Without you to keep me anchored, I doubt I would have succeeded. Finally, a big thank you to my two furry friends Saoirse and Col. Fuzz Aldrin for being my constant companions. Without all of you, I wouldn't have made it this far. Thank you.

ABSTRACT

INSTREAM HABITAT USE AND MANAGEMENT OF INVASIVE ARMORED CATFISHES IN THE UPPER SAN MARCOS RIVER

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The San Marcos River is a spring-fed aquatic system located in central Texas fed by the San Marcos Springs. This spring system is characterized by high water quality and relatively constant temperatures, pH, discharge and dissolved ion concentrations. The San Marcos River complex provides habitat for eight endemic species that are federally-listed as threatened or endangered. Environmental stability and high concentration, and associated high density, of aquatic macrophytes and macroinvertebrates has made the San Marcos River an easily invaded aquatic system, especially by organisms at lower trophic positions. Two established invasive fish species in the San Marcos River are members of family Loricariidae- the suckermouth catfish (*Hypostomus plecostomus*) and the vermiculated high-fin catfish (*Pterygoplichthys disjunctivus*). In order to better characterize how these invasive species utilize the San Marcos River, a total of 15 snorkel surveys were conducted between December 2016 and May 2017. During these surveys, a total of 115 sightings of Loricariid spp. were recorded. Of these sightings, 26 were identified to species. During these surveys, water quality (surface temperature, dissolved oxygen, specific conductance, pH, flow) and physical (percent vegetation cover, substrate type, and distance from the Spring Lake Dam) were recorded. Negative binomial regression indicated the most influential factor associated with armored catfish occurrence was distance downstream from the Spring Lake Dam ($P<0.0001$). Data collected during this study indicate that armored catfish are more frequently observed in the lower reaches of the upper San Marcos River. These areas are characterized by possessing deeper pools created by dams. These pools contained dense stands of submerged vegetation and slow moving water. Data from armored catfish removal efforts conducted from 2013 to 2016 was also analyzed to assess the effectiveness of contracted removal efforts. Pairwise annual comparisons showed significant reductions in biomass over the removal period. Loricariid burrowing habits may displace sediment which can lead to altered water quality as well as uprooting of aquatic macrophytes during the burrowing and foraging. Furthermore, given the degree in which these invasive species are present in the San Marcos River, nutrient cycling within the river may be altered. It appears that ongoing suppression efforts are effectively reducing the biomass of armored catfish populations in the San Marcos River.

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INTRODUCTION

The San Marcos River

The San Marcos River is a spring fed river system that originates from the Edward's aquifer near Austin, Texas (Figure 1). The river originates from springs within Spring Lake and flows to its confluence with the Blanco River (~6.4 km) and then continues flowing another 121 km before merging with the Guadalupe River. As a spring-fed system, the San Marcos River contains very clear (> 3 meters) water and relatively constant water temperature and associated water chemistry (Abbott and Woodruff 1986). The average annual fluctuation in water temperature is 1.5 ºC and averages 23 ºC (Groeger et al. 1997; Stevens and Olsen 2004). The substrate of the San Marcos River ranges in size from silt to large cobble. The river exhibits an average flow of 6.99 cms (standard deviation 1.17 cms).

The river represents a major socioeconomic asset for the greater San Marcos community as a popular site for year-round recreation (Bradsby 1994). Spring Lake and Sewell Park reside on the campus of Texas State University and then flow through City Park, Rio Vista and Ramon Lucio Parks maintained by the City of San Marcos. Aquatic sports such as swimming, kayaking, paddle boarding, and inner-tubing as well as fishing (spear and hook-and-line) are common activities within the river, with visitors numbering in the thousands annually (Bradsby 1994). The San Marcos is a high-profile body of water in the community because of its economic importance, as well as its ecological importance. The river is home to eight protected aquatic species, including Texas Wild Rice (TWR, *Zizania texana*) (Silveus 1933; Davis et al. 1994) and sixteen different species of aquatic macrophytes, both native and introduced (Tables 1 and 2).

Figure 1. Location of the upper San Marcos River, a spring-fed aquatic system in central Texas. The San Marcos originates at Spring Lake and runs approximately 6.4 km to its confluence with the Blanco River (Poole and Bowles 1999).

Table 1. Endangered species of the Edwards Aquifer (Poole and Bowles 1999).

Scientific Name	Common Name
Zizania texana	Texas Wild Rice
Heterelmis comalensis	Comal Springs Riffle Beetle
Stygoparnus comalensis	Comal Springs Dryopid Beetle
Stygobromus pecki	Peck’s Cave Amphipod
Etheostoma fonticola	Fountain Darter
Typhlomolge rathbuni	Texas Blind Salamander
Gambusia georgei	San Marcos Gambusia
Eurycea nana	San Marcos Salamander

Table 2. Species of aquatic plant observed in the San Marcos River. (N) represents native plants and (E) represents exotic plants (Owens et al. 2001).

Scientific Name	Common Name	Exotic or Native
Cabomba caroliniana	fanwort	N
Ceratopteris thalictroides	water sprite	E
Ceratophyllum demersum	coontail	N
Colocasia esculenta	Elephant eat, wild taro	E
Heteranthera dubia	Water Stargrass	N
Hydrocotyle	pennywort	N
Hydrilla verticillata	Hydrilla	E
Hygrophila polysperma	East Indian Hygrophila	E
Ludwigia repens	water primrose	N
Myriophyllum spicatum	Eurasian watermilfoil	E
Nuphar lutea	yellow cow-lily	N
Pistia stratiotes	water lettuce	E
Potamogeton illinoensis	Illinois pondweed	N
Sagittaria platyphylla	grassy arrowhead	N
Vallisneria americana	water celery	N
Zizania texana	Texas wild rice	N

The Edwards Aquifer Habitat Conservation Plan (EAHCP) contains various measures that were adopted and are being implemented to protect these endangered species (RECON Environmental Inc. et al. 2012). Historically, TWR was reported residing in the upper reaches of the San Marcos River, its associated irrigation canals, and the headwaters of the river (Spring Lake) (Conover et al. 2007). The current distribution of TWR is limited to the upper 4.6 km of the river (Hutchinson and Ostrand 2015; Wilson et al. 2017). In order to aid in recovery of TWR, the San Marcos River is protected from certain anthropogenic influences, such as restricted fishing methodologies, restricted access points to the river and State Scientific Study Areas which preclude recreational access. Ongoing projects in the San Marcos River for non-native plant removal, TWR cultivation and planting of TWR have resulted in substantial increases in areal coverage since 2013. Since 2013, over 50,000 TWR plants have been reintroduced into the upper San Marcos River and has resulted in a 36% increase in areal coverage (EAHCP 2017). The upper San Marcos River is also the primary site of suppression efforts for invasive species that include removal of invasive plants such as *Hydrilla polysperma* and both aquatic and semiaquatic animals including armored catfishes, tilapia, and Nutria, *Myocastor coypus*.

Predisposition to Biological Invasion

The San Marcos River has been subjected to invasion by exotic plants since 1849 when Spring Lake dam was built as a power source for local mills. Since then, the San Marcos River has undergone significant alteration for recreational, agricultural, and industrial purposes (Kollaus et al. 2015). Along with the construction of these dams came the introduction of new aquatic macrophyte species for commercial use in the newly impounded, slower velocity areas of the San Marcos River (Bradsby 1994).

Partially impounded spring-fed freshwater systems are susceptible to invasion by exotic plant species for a variety of reasons including favorable year-round constant temperatures and less variable stream velocity. This is because most temperate rivers undergo seasonal changes in temperature that can often reduce survival of invasive tropical species during the winter (Gido and Franssen 2007), while favorable thermally stable conditions present in spring fed rivers and streams generally lack seasonally extreme conditions. Water temperatures at the San Marcos River headwaters vary between 19.2ºC to 25.2ºC (Groeger et al. 1997), well within the thermal tolerance limits of many exotic species of plants and animals (Davis et al. 2000). Impounded spring fed clear water river systems are also particularly sensitive to invasion by exotic species occupying lower trophic levels (Gido and Franssen 2007). Species that occupy lower trophic levels, such as primary consumers or omnivores, have a higher success rate of invasion during colonization due to plentiful food resources including attached algae and vascular plants that grow in abundance in clear water (Gido and Franssen 2007). The conditions described above that provide ideal conditions for the invasion and establishment of exotic species has been documented during the widespread expansion of invasive armored catfishes (Family Loricariidae) throughout the San Marcos River (Pound et al. 2011).

<u>Armored suckermouth catfish</u>

Two species of armored suckermouth catfishes, the Vermiculated Highfin Catfish (*Pterygoplichthys disjunctivus*) and the Suckermouth Catfish (*Hypostomus Plecostomus*) have established viable populations in the upper reaches of the San Marcos river (Howells 2005; Pound et al. 2011) (Figure 2). The Family Loricariidae is a diverse (> 915 species) group of catfishes that are indigenous to South and Central America (Nelson et al. 2016). These fish, subfamily Hypostominae, are known for their characteristic armor plating, distinct sucker-like mouth, and stiff barbs located on the dorsal and pectoral fins (Reis et al. 2003; Nelson et al. 2016).

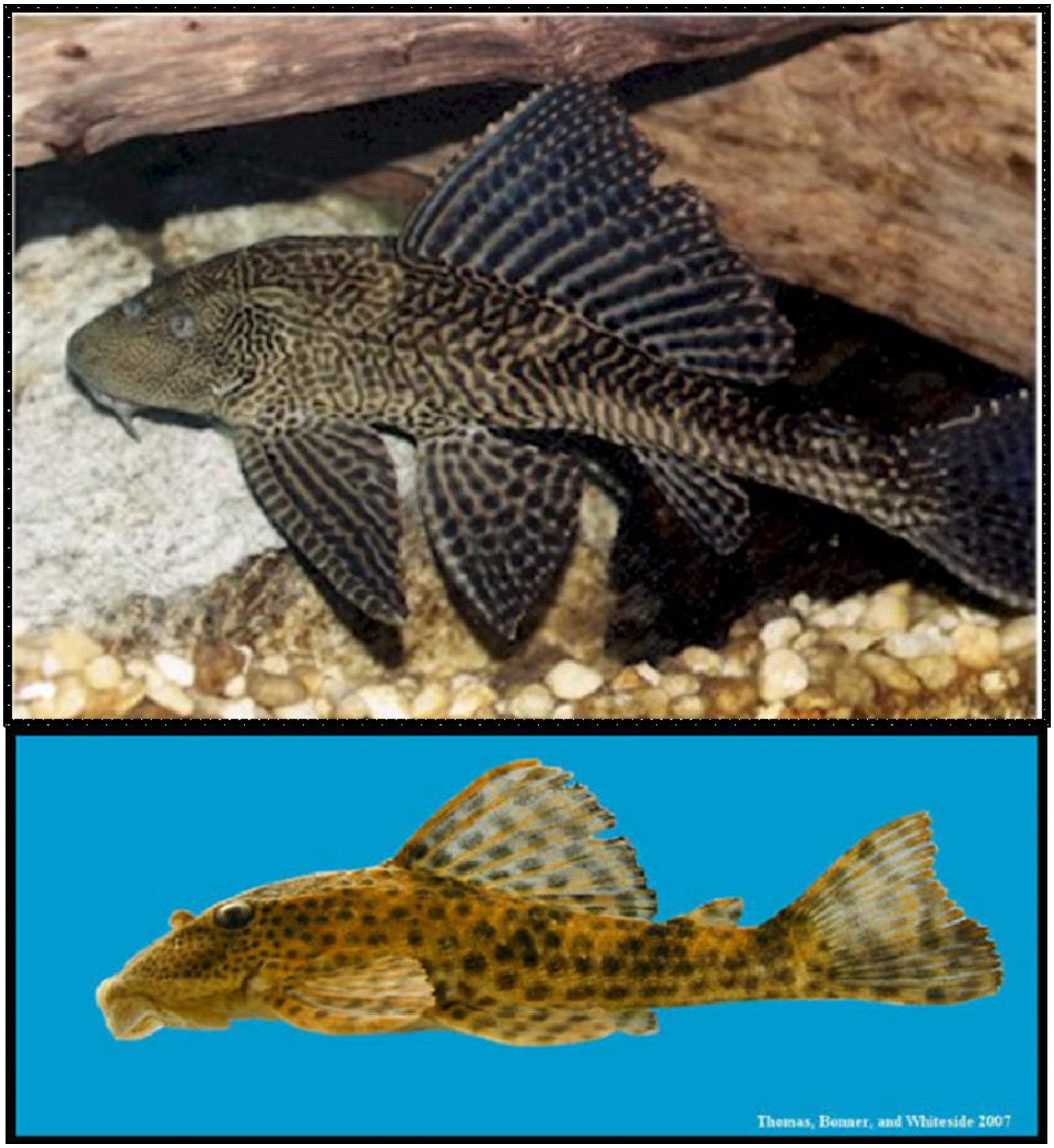

Figure 2. *Pterygoplichthys disjunctivus* (top) and *Hypostomus plecostomus* (bottom). Photo Credit: Bottom-Thomas et al (2007) and top- USGS NAS database.

Suckermouth armored catfishes occupy lower trophic levels in their native ecosystems, with diets consisting primarily of detritus and periphyton (Delariva and Agostinho 2001). Loricariid morphology is closely associated with these dietary patterns with specialized teeth and scraping mouthparts, and cranial musculature that supports strong suction attachment to substrate and bottom feeding (Delariva and Agostinho 2001). This unique mouth morphology also enables suckermouth armored catfish to live in high velocity environments (Hoover et al. 2004)

In native habitats these armored catfishes reach maturity around 21 cm, and grow as large as 28 cm. They have a low trophic position at 2.5. Hypostominae are found most often in water with pH 6.2-8.2, and temperatures 20°C to 28°C (Baensch and Riehl 1985). These conditions are replicated in the San Marcos River's average temperature and pH of 19.2ºC to 25.2ºC and 6.5 to 9 respectively (Groeger et al. 1997).

Many species within the Family Loricariidae are well-known as invasive species, having established populations in several states including Florida, Hawaii, Nevada, Colorado, and Texas with the earliest records of invasion dating back to the late 1950s (Burgess 1958; Fuller et al. 1999; Hoover et al. 2004; Pound et al. 2011). The majority of armored catfishes are batch spawners, that exhibit high recruitment potential based on high fecundity (500-700 eggs), and parental rearing behavior (Cook-Hildreth 2009). Armored catfishes will burrow into softer sediments even in the presence of woody riparian vegetation, albeit to a lesser density than vegetation-poor banks (Lienart et al. 2013). The burrowing behavior of armored catfishes have been associated with bank destabilization and increased sedimentation risks (van den Ende 2014). These nests are guarded by adult armored catfishes which contributes to their high recruitment potential (Suzuki et al. 2000).

In non-native invaded areas where no known predators are present, these life history attributes can lead to explosive growth in armored catfish populations (Bunkley-Williams et al. 1994). Even in the presence of non-native predators such as largemouth bass, which consume juvenile armored catfish in aquaria, wild populations continue to thrive in the environments in which they have been introduced (Bunkley-Williams et al. 1994). Armored catfish are hardy fishes, able to withstand acute and chronic osmotic stresses (salinities up to 16 ppt for brief amounts of time), and possess a modified stomach which facilitates aerial respiration, making them resilient to hypoxia, anoxia, and brief aerial exposure (Cook-Hildreth 2009; Scott et al. 2017). These adaptations enable armored catfishes to withstand potentially lethal events and stressors such as floods, droughts, and polluted water. The movement of many armored catfish species is not impeded by lower and mid-salinity barriers in tidal rivers located in coastal environments such as Florida, Hawaii, Puerto Rico and Texas (Nico et al. 2009). In the San Marcos River, these animals were most likely introduced via aquarium hobbyist releases, based on their commercial importance as aquarium animals (Padilla and Williams 2004).

The severe threats armored catfish pose to the ecosystems they invade have been widely documented (Hoover et al. 2004; Wakida-Kusunoki et al. 2007; Capps et al. 2011; Chaichana et al. 2011). As previously mentioned, their burrowing behavior can lead to bank destabilization, accelerated erosion, and increased turbidity. In some locations burrow frequency can reach ~1.6 burrows per meter (Lienart et al. 2013). The mechanical disturbance of substrate can directly uproot aquatic macrophytes, causing both destruction of plants or contribute indirectly to the spread of undesirable aquatic vegetation (Hussan and Choudhury 2016). Armored catfish invasions have also been associated with decline in native fish and plant species through primary and secondary effects (Mack et al. 2000). Armored catfish are aggressive and can often outcompete native species occupying similar trophic levels (Cohen 2008). Armored catfish have also exerted negative impacts on some potential predators such as the brown pelican in Puerto Rico, where several birds were found dead with *Pterygoplichthys* specimens. lodged in the birds' gullets (Bunkley-Williams et al. 1994). Armored catfishes are also known to alter nutrient cycling in systems with limited access to nutrients such as isolated bodies of water with low nutrient cycling rates (Capps and Flecker 2013). Similar impacts can occur in streams that go through intense seasonal variation in flow, with less nutrients entering the system via runoff during dry seasons (McIntyre et al. 2008). The risk of disruption of nutrient cycling by armored catfish is not as much of a threat in a stable system like the San Marcos in which nutrients remain constant as water exits the springs (Heffernan and Cohen 2010). Based on these observations armored catfish invasions are cause for concern, as outlined thoroughly in the USFWS's ecological risk assessment (Nico 2012). Besides armored catfish, a total of 15 less abundant non-native fish species have been documented in the upper San Marcos River (Kimmel 2006). A total of five non-native species of the Family Cichlidae have been observed in the San Marcos River. Some of these species such as the Rio Grande Cichlid have established viable populations while most species have not.

Research Objectives

The upper reach of the San Marcos River represents an ideal area to examine the ecological habits of invasive armored catfishes in a spring-fed system, and further examine the effectiveness of suppression efforts of these fish. In order to better quantify the effects armored catfishes may be having on the upper San Marcos River ecosystem, I attempted to describe and quantify armored catfish utilization of various instream habitats within the system. Armored catfish suppression efforts have been taking place in the San Marcos River since 2013 as an implementation measure of the Edwards Aquifer Habitat Conservation Plan (RECON Environmental Inc. et al. 2012). However, no systematic evaluation of the effectiveness of these efforts on suppression of armored catfish has been undertaken. This research attempts to describe what types of habitats armored catfish utilize, as well as provide recommendation on improvements to current management strategies associated with armored catfish control in the upper San Marcos River in order to preserve both the endangered species present there, as well as the river system as a whole.

METHODOLOGY

Study Area

The study area extended from the base of Spring Lake dam to a point downstream of IH-35, approximately 2.29 river kilometers (Figure 3). The study area was subdivided into three study reaches (Figure 3). The reaches were created based on dividing the number of transects by three, and allocating equal number of transects per reach. This area represents the region of the San Marcos River where Texas Wild Rice is distributed (Hardy and Raphelt 2015).

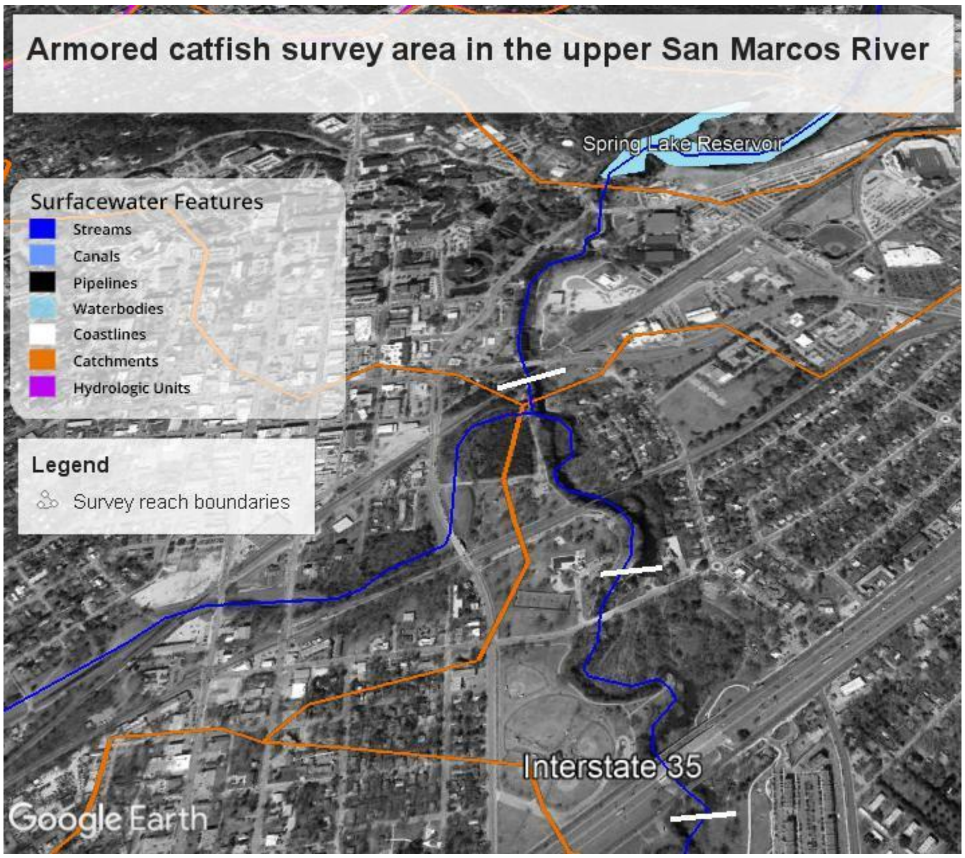

Figure 3. Upper reaches of the San Marcos River where transect surveys were conducted. Bold white lines show boundaries between the three survey reaches, based upon random allocation of transects. Layer features credit: United States Environmental Protection Agency

Snorkel Surveys

A total of 15 snorkel survey events were conducted from December 14, 2016 through May 25, 2017. Snorkel surveys have long been used as a method of monitoring fishes in clear streams (Schill et al. 1986; Scanes 2016). During this project, estimates of numbers of individuals per armored catfish species and habitat classification were performed through a series of snorkeling surveys. Reconnaissance surveys were performed prior to actual data collection in October 2015 in order to define the upper and lower limit of the survey area. Ten control points were established during this reconnaissance period. These ten sites represented areas where armored catfish had been observed historically during annual monitoring sponsored by the Edwards Aquifer Authority, as well as confirmed sightings during the reconnaissance period. The control point locations were visited on an alternating schedule based on even versus odd station numbering. In addition to these fixed survey locations, additional survey sites were selected based on selection of a random starting point within the first 500 meters of the San Marcos River headwaters below Spring Lake at the start of each survey trip. From these starting points a systematic random sampling effort was implemented at fixed intervals of 300m from the randomly selected starting point. The Interstate 35 overpass was established as the lower limit of the survey for several reasons. Below Interstate 35 the river is dominated by a backwater from Capes Dam and consequently depth increases substantially, rendering visual snorkel survey methods unreliable for primarily substrate-dwelling fishes such as armored suckermouth catfishes. This section of the San Marcos River was mapped for TWR stands in 2015 and only 126 TWR (total area of 237 m^2)

were found within the 0.5 kilometer stretch of the San Marcos River upstream of Cape's Dam. Approximately 80 percent of TWR stands were located more than 250 meters upstream of Cape's Dam while only 16 TWR stands were located within the 100-meter section just upstream of Cape's Dam (Hardy and Raphelt 2015). While traveling between selected transect points, if an armored catfish was observed from the bank or while snorkeling to the next transect location, an opportunistic transect was also surveyed (Figure 4).

Wetted width measurements were taken using digital laser rangefinders. At each survey location, the river bed was surveyed within the wetted width and over a five-meter longitudinal distance. The wetted width and longitudinal distance were used to estimate survey area (m^2). Two research swimmers would position themselves five meters apart, and swim simultaneously to cross-stream (Figure 5). During each survey biotic (percent vegetation cover, plant species present, armored catfishes present) and abiotic (water quality, sediment type) variables were measured at each survey transect. At the midpoint of each transect, total depth was measured, and at a surface depth of 0.3m water quality variables were measured in-situ using a model YSI Pro-DSS meter and multi-probe sonde. Water quality variables included temperature, specific conductance at 25 °C, pH, dissolved oxygen, and water clarity (using a Secchi disk transparency tube. Analysis of water clarity data was not conducted since all measurements were greater than 1.2 m. River discharge (m^3/s) were obtained from the USGS flow gauge located on the San Marcos River immediately downstream of Spring Lake (Station ID USGS 08170500 San Marcos River at San Marcos, TX).

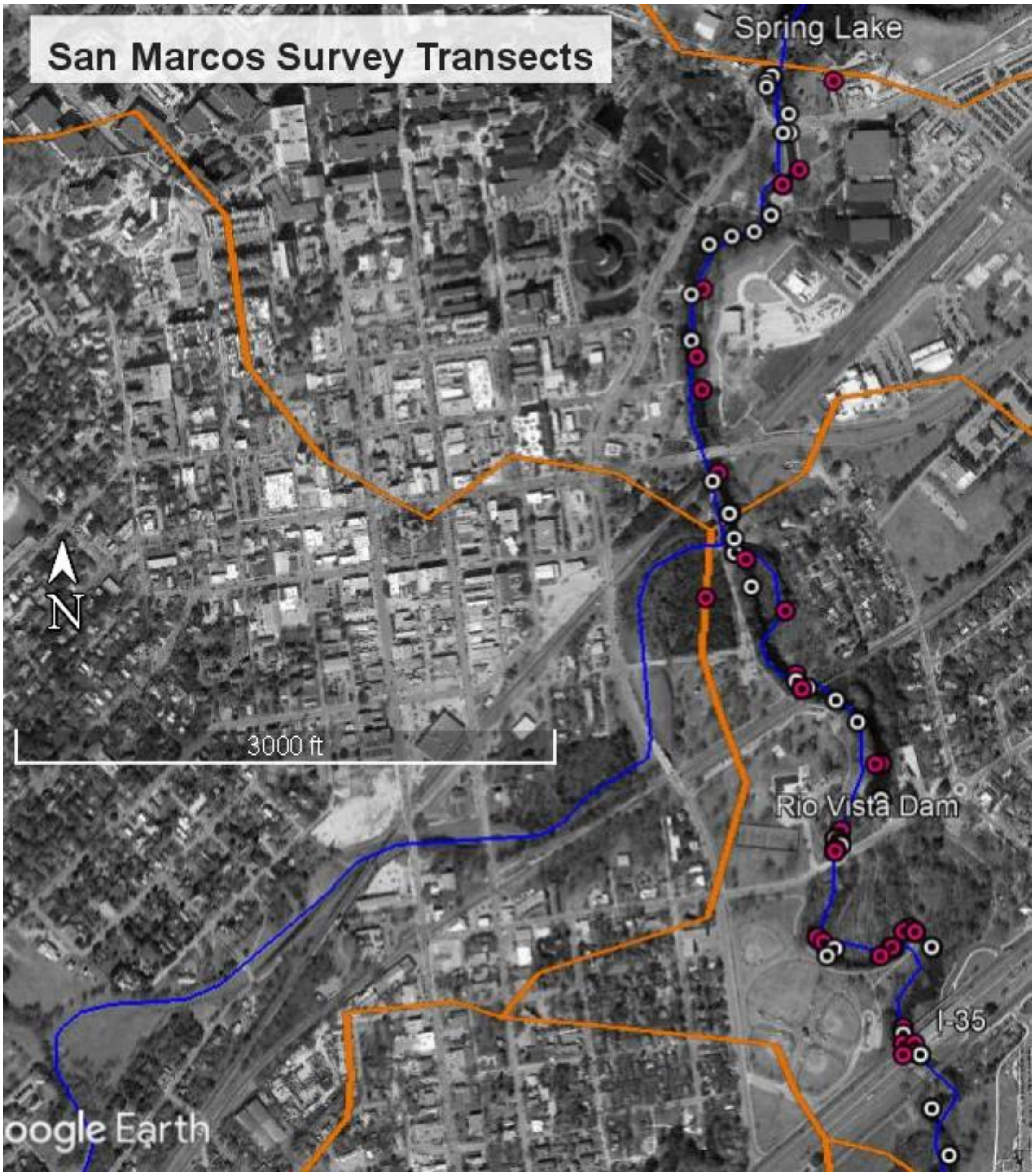

Figure 4. Map of the San Marcos River surveys. Each point is a single random or opportunistic transect. Points marked in pink are transects in which armored catfish were observed.

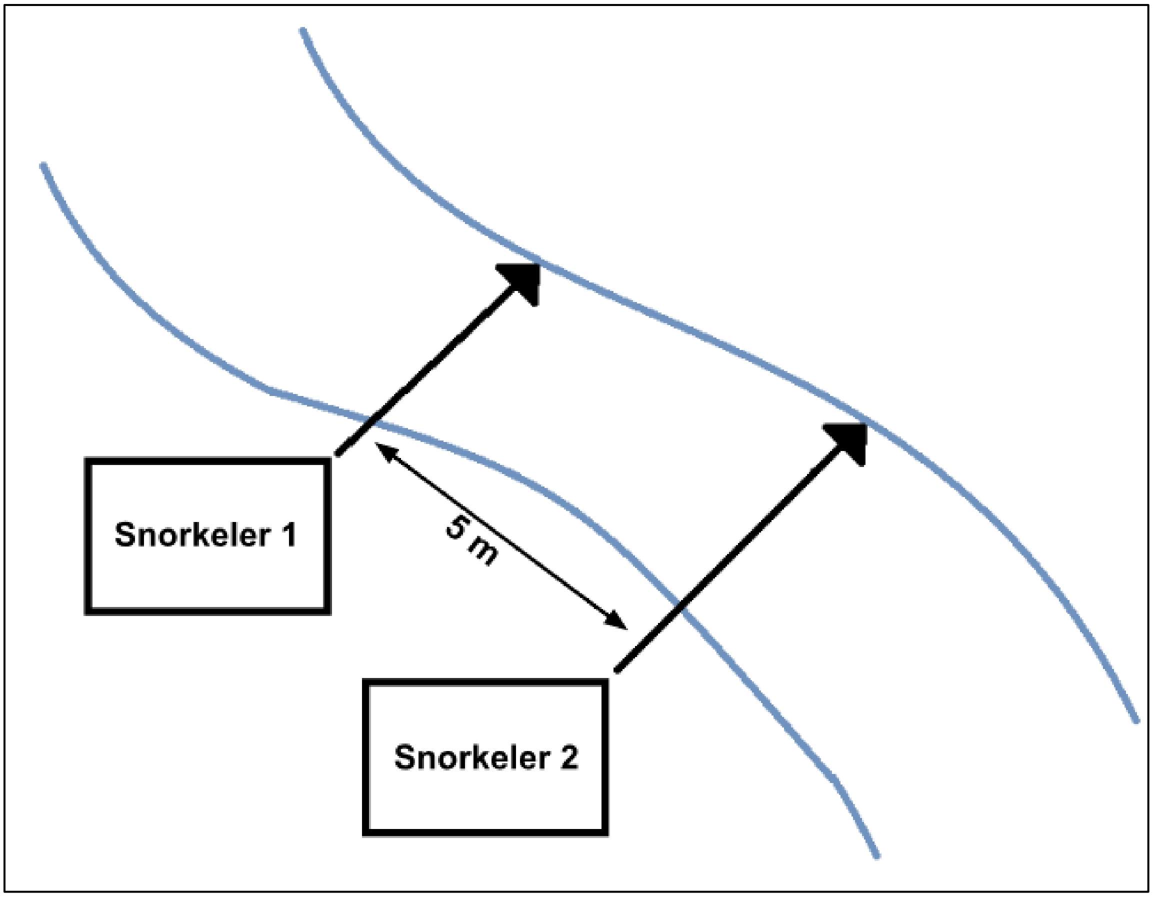

Figure 5. Snorkel surveys were performed with a two-person survey team. Snorkelers stood five meters apart and swam cross-stream together at all random and opportunistic transects. Water quality and physical variables were recorded within every transect.

Fish Identification

During the snorkel surveys, any observed armored suckermouth catfish was identified to its lowest possible taxa. Fish observed during survey efforts were identified as either *Pterygoplichthys disjunctivus*, *Hypostomus plecostomus*, or Loricariidae spp. The two species have similar morphology, but can be identified by their number of dorsal fin rays (*P. disjunctivus* has 10 to 14, *H. Plecostomus* has less than 9) (Burgess 1989). When attached to the substrate or swimming, individuals often erect the dorsal fin allowing for better identification. Any individuals that were either startled or kept their dorsal fin pressed against their bodies were recorded as Loricariid spp. to avoid misidentification. When an armored catfish was sighted, a (1 x 1m) quadrat was established at the point of observation and used as the measurement site for the previously mentioned water quality variables, as well as type of substrate the fish was observed attached to. These data were later analyzed to determine what types of substrates armored catfish were most commonly observed utilizing. In transects where catfish were not observed, substrate was collected from the midpoint.

Habitat Assessment

At each snorkeling transect, visual estimates were taken of the bed area covered by aquatic macrophytes including both filamentous algae and large vascular plants, and all observed plants were identified to species. Average sediment sizes were calculated after identifying dominant substrate type (>50% total area). If the substrate was gravel or cobble, average grain size was calculated by taking blind grabs, and randomly choosing three grains. The stones/grains were measured at their maximum lengths using a caliper and an average was calculated. Averages greater than 64mm were classified as cobble, while grains less than 64 mm were classified as gravel. Substrates too fine to measure (unable to be measured with a calipers) were recorded as 'too fine to measure' and qualitatively categorized based on sediment type- silt, shell hash, sand, etc. At each survey transect, the total percent plant coverage as well as the percent by species was computed. If no aquatic plants were observed within the survey transect, a value of zero was assigned to percent vegetation cover.

Suppression Efforts

Invasive species removal funded by the Edward's Aquifer Authority Habitat Conservation Plan has been ongoing in the San Marcos River since 2013 (Blanton & Associates Inc. 2018). Armored catfish were removed from the river by various means, but most often with the use of a Hawaiian sling spear system. Most commonly, fish are removed by contracted resource managers working for the Edward's Aquifer Authority and the City of San Marcos. Biannually, public events are hosted in the form of competitive spear fishing rodeos. During these rodeos the public was recruited to assist in this management effort while enjoying the recreational sport of spear fishing. Data collected from these suppression efforts have primarily been used for annual reporting as required by the EAHCP, with little examination of these data in terms of trends and effectiveness of these efforts over time (Blanton & Associates Inc. 2018). Invasive catfish removal data was obtained from Atlas Environmental for the period of 2013 to 2016.

Statistical Analysis – Survey Data

Data management and analysis were performed using a variety of software packages including "R", PAST, and Microsoft Excel. Prior to analysis, data were tested for normality using a Quantile-Quantile normality plot to visualize distribution of abundance data. Abundance data was then tested for normality using a Shapiro-Wilk's w-test. Data fitting a normal distribution were analyzed using parametric methods including t-tests and ANOVA. Prior to statistical analysis DOY was adjusted as a time series by reassigning the first day of sampling (December 14, 2016) as day 1 (sampling day). Environmental variables were examined for temporal trends using linear regression (variable versus day of sampling day) and polynomial regression to account for potentially non-linear cyclical trends. To address variable effort (area of survey transects), catch of armored catfish per unit (CPUE) effort (# catfish/m^2) was calculated (Ramsey and Schafer 2012). To reduce variability CPUE was $\log_e$ transformed. The relationship of Log_e CPUE of armored catfish and various environmental variables was tested using two types of models that account for over-dispersed (high variance) data. Zero-inflated Poisson (ZIP) and negative binomial (NB) regression models were chosen as the best two candidates for handling high-variance data fitting a Poisson distribution, and were conducted with the MASS R package (Ramsey and Schafer 2012). A Vuong test was used to select between candidate models (Vuong 1989; Hilbe 2011). This test essentially compares the predicted fit values of the NB and ZIP to the observed data, assessing if there is a significant difference between the two. Depending on the value of the test statistic "V or z" one model is identified as fitting the data best. For this study several test statistics were used including the original raw Vuong, and the AIC and BIC corrected test statistic z (Desmarais and Harden 2013). It is also possible that in some cases no model may be identified as superior over the other (Hilbe 2011). The resulting negative binomial model was reduced from a saturated (including all variables) state using the stepAIC function, which selects the most parsimonious model that yields the lowest AICc score. This model selection approach (Figure 6) was undertaken due to the large amount of zero-inflated data: of the 115 armored catfish sightings over the course of 99 transects, 60 transects failed to detect any catfish (Yau et al. 2003).

Principal components analyses (PCA) of environmental (water quality and physical variables) data collected during the snorkel surveys was conducted based on non-redundant, centered-and-rescaled variables including discharge, water temperature, specific conductance, dissolved oxygen, and river distance (meters) from Spring Lake Dam. PCA was conducted and associated graphical output was produced using the PAST 3.21 software package in order to assess patterns of variation in environmental data both spatially and temporally (Ryan et al. 2001).

Statistical Analysis – Suppression Efforts

Trends in catch per unit effort over time, as well as correlations between biomass and number of removed individuals were analyzed as part of this study. Due to a lack of resolution in the data set (individuals were measured to the nearest half-inch) and missing data (average and total fish weights recorded, but individual weights are missing for some years, fish not sexed), only total biomass removed and total number of individuals caught during each event could be statistically examined for time trends. Linear regression models were run comparing total biomass removed (kg) to number of armored catfish captured using reported daily sums of these variables. ANOVA testing followed by Tukey's pairwise t-test to detect significant changes in biomass and individual daily catch totals from year to year, and 95% confidence interval plots were produced using PAST 3.21 software to visually illustrate differences.

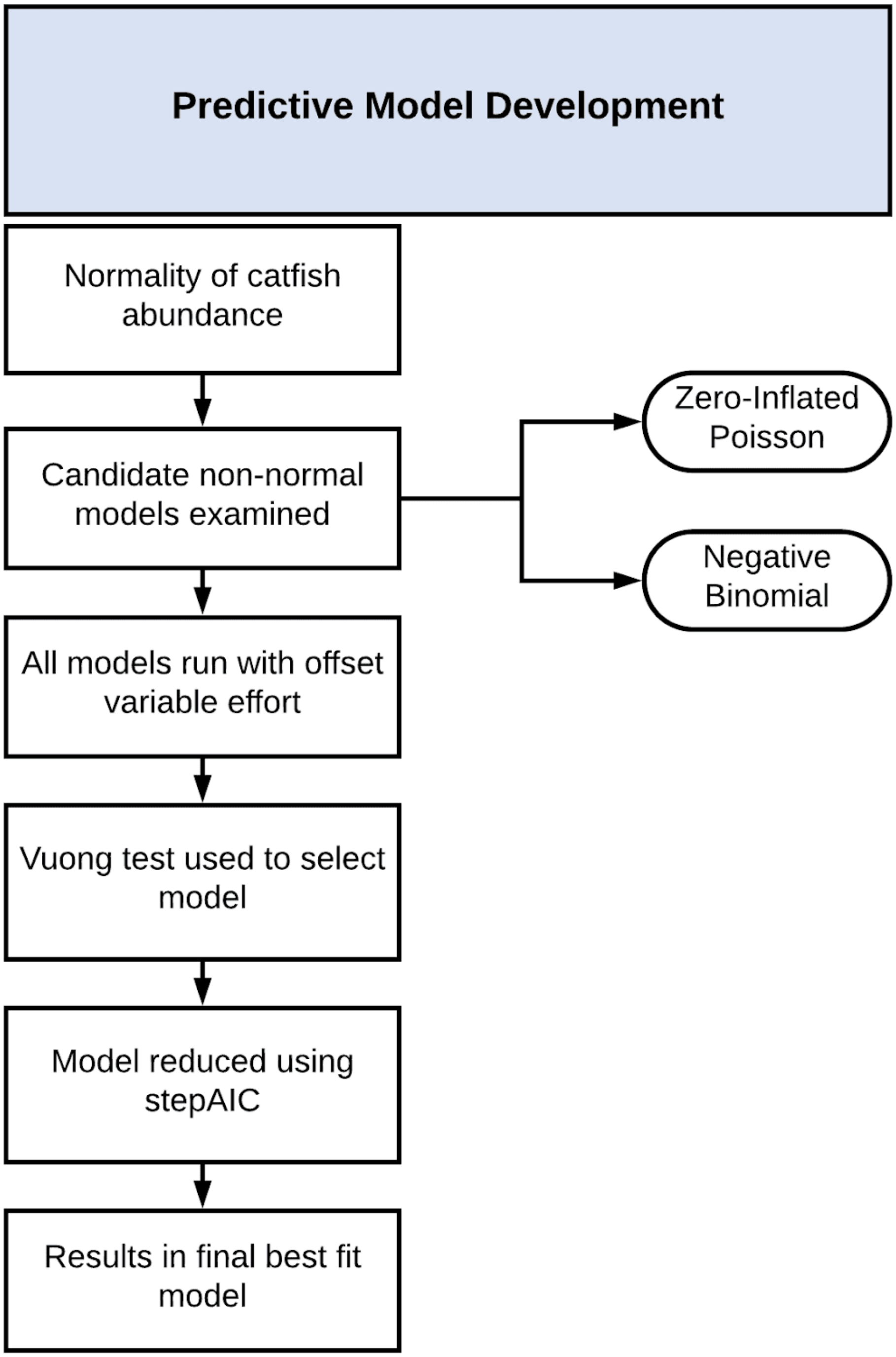

Figure 6. Model selection workflow used to determine best-fit model of variables associated with observed armored catfish abundance and catch per unit effort (CPUE).

RESULTS

Snorkel Surveys and Water Quality Assessment

A total of 99 observation transects were snorkeled over the course of six months from December 14, 2016 through May 25, 2017. This effort resulted in 115 total sightings of catfish (Figure 7). Of the total sightings only 26 were identified to species (17 *Hypostomus plecostomus,* 9 *Pterygoplichthys disjunctivus).* Therefore, all statistical analyses were performed assessing loricariids at the family level in order to increase statistical power. Quadrat data was used to identify type of substrate catfish (n=115) were observed attached to, with the largest number of armored catfish observed attached to gravel (n=30) (Figure 8). Categories of observed surfaces were gravel, cobble, solid objects (such as pilings and boulders), hardpack, free-swimming, vegetation, and burrowed.

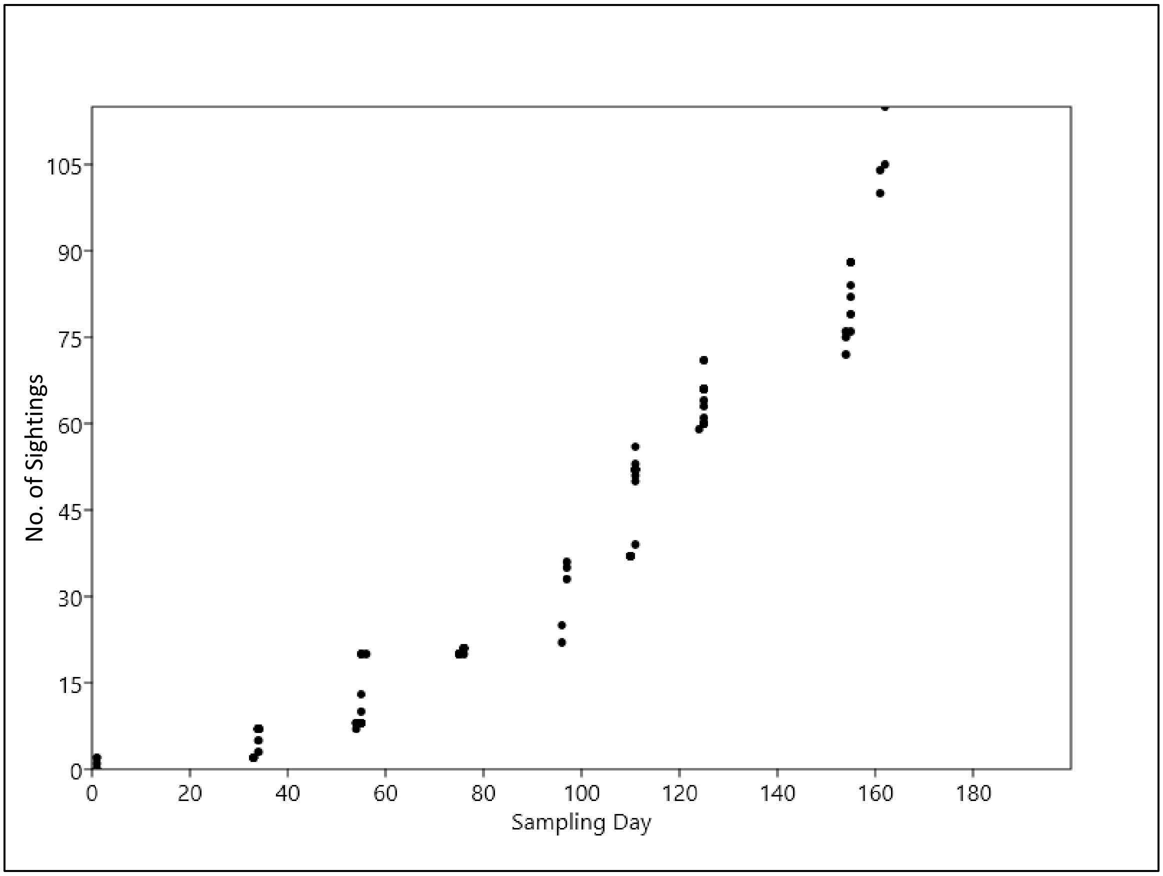

Figure 7. Cumulative armored catfish sightings (n=115) from December 14, 2016 to May 25, 2017.

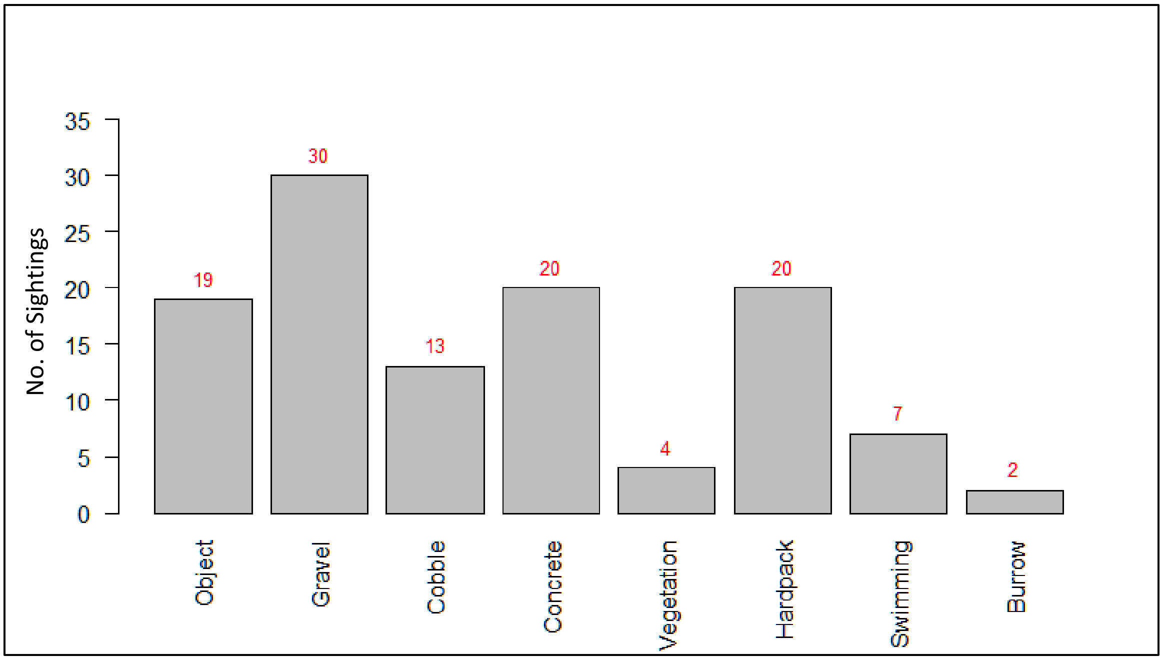

Figure 8. Frequency plot of all (n=115) armored catfish sightings by associated attachment substrates. Object refers to any non-substrate surface attachment sight such as boulders, pilings and tree stumps.

Water quality variables from each transect were plotted on scatter plots generated in PAST 3.21 versus sampling day and spatial distribution (distance from the Spring Lake Dam in meters) (Appendix A). Regression models were constructed to examine relationships between all environmental variables, sampling day and downstream distance. A second-order polynomial regression was also utilized to account for potentially parabolic trends. Linear and polynomial regression models detected significant, but weak relationships between sampling day and pH ($p = 0.004$, r^2: 0.081), temperature °C ($p = <0.001$, r^2: 0.595), specific conductance (µS) ($p = <0.001$, r^2: 0.393), and dissolved oxygen (mg/L) ($p = 0.02$, r^2: 0.05) (Appendix A). Of these models, temperature and specific conductance show the best fit considering the respective r-squared values. Linear regression models of variables detected significant but weak relationships between temperature ($p = 0.002$, r^2: 0.090), pH ($p = <0.001$, r^2: 0.275), and depth (m) ($p = 0.04$, r^2: 0.044) versus longitudinal distance from Spring Lake Dam (Appendix A). The declining trend in pH is attributed to downstream off gassing of carbon dioxide leached from the Edwards aquifer's limestone bed (Groeger et al. 1997).

During the study period surface water temperature averaged 21.83 °C and varied less than 2.01 °C (Table 3). Specific conductance averaged 616.4 μS/m and varied less than 75 μS/m (Table 3). Dissolved oxygen averaged 8.30 mg/L, and varied 5.41 mg/L (Table 3). The pH averaged 7.40 and varied less than 0.98 units (Table 3). Water clarity was always greater than 1.2 m as measured with a Secchi tube with the exception on one occasion following heavy rainfall when visibility dropped to 0.0 m. Therefore, further statistical analysis of Secchi tube transparency was not conducted.

Table 3. Summary of water quality data collected in the San Marcos River surveys. Secchi measurements were not analyzed since every Secchi measurement surpassed 1.2m.

	Temperature (°C)	Sp. Conductance (μS/m)	Dissolved Oxygen (mg/L)	pH
Min	20.69	580.0	6.370	6.96
1st Q.	21.68	610.0	7.835	7.27
Median	21.88	613.0	8.250	7.39
Mean	21.83	616.4	8.302	7.40
3rd Q.	22.17	17.0	8.520	7.51
Max	22.70	655.0	11.78	7.94

Principal components analysis

Percent dissolved oxygen was not included in the principal components analysis (PCA) since it is highly correlated and redundant with dissolved oxygen concentration. A PCA was run in order to reduce the number of environmental variables into a smaller set of explanatory factors as potential sources of variance in the data set. The second objective for conducting PCA was to identify any potential multivariate physiochemical gradients in transect surveys. Based on the Scree Plot eigenvalues and loading table, PC 1 and 2 account for over 50 percent of variance in the data (Tables 4 and 5, Figure 9). Examination of the PCA biplot with overlying 95% confidence ellipses of each monthly group (sample month denoted by point color) documents distinct seasonal progression in ordination scores (Figure 10). This suggests that the assemblage of water quality variables appeared to vary more over time than spatially.

Table 4. Results of principal components analysis of environmental variables in surveys of the upper San Marcos River.

Principal Component	Eigenvalue	% variance
1	2.622	37.457
2	1.285	18.358
3	0.975	13.925
4	0.881	12.590
5	0.607	8.667
6	0.358	5.114
7	0.272	3.889

Table 5. Loadings of individual variables considered in principal components analysis.

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7
Flow (m^3/s)	0.402	0.410	0.170	0.182	0.637	-0.086	-0.441
Temp. (°C)	0.543	0.017	0.199	0.032	0.141	0.011	0.803
Spec. Con. (µS)	0.387	0.428	0.196	0.027	-0.674	0.362	-0.207
DO (mg/L)	0.083	-0.639	0.637	-0.003	0.084	0.351	-0.221
pH	-0.437	0.389	0.116	-0.283	0.307	0.654	0.207
Depth (m)	-0.282	0.059	0.077	0.934	-0.033	0.139	0.137
Dist. From Spring Lake Dam (m)	-0.341	0.292	0.684	-0.115	-0.133	-0.540	0.090

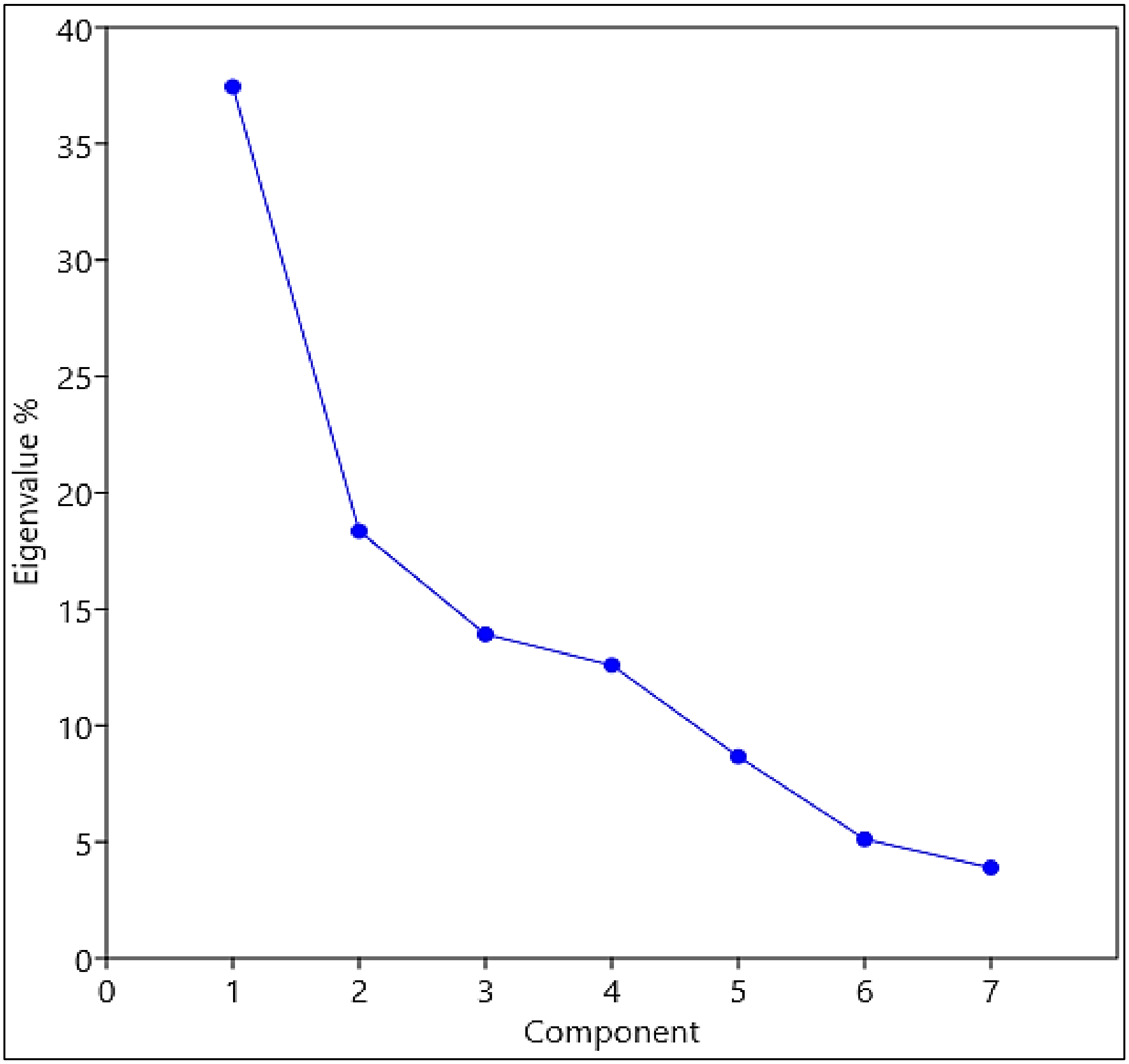

Figure 9. Scree plot of principal components analysis of environmental variables in the San Marcos River surveys. PC1 accounted for 37% of variance.

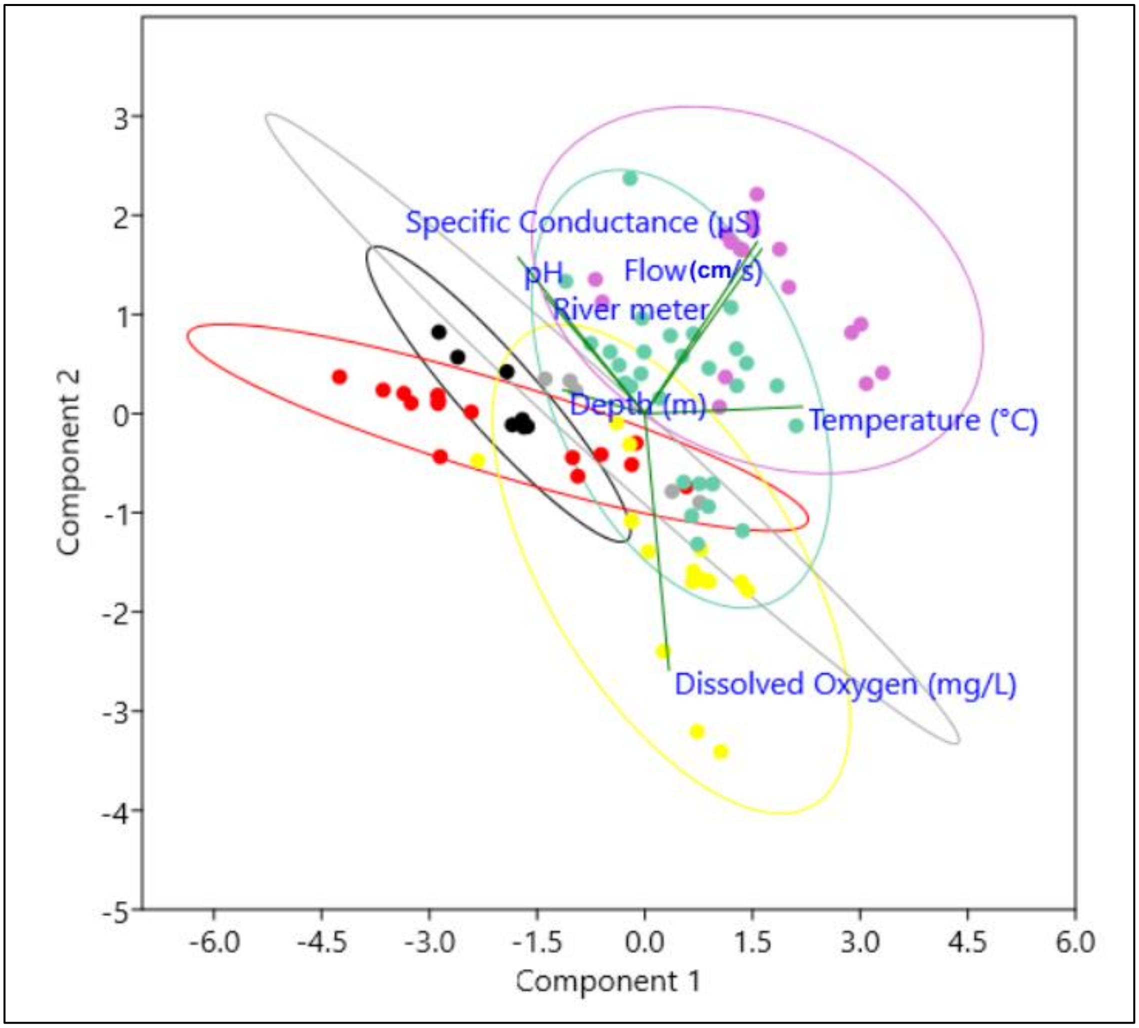

Figure 10. Principal components analysis of environmental variables measured during San Marcos River transect surveys. Color denotes month of survey (Black-Dec, Red-Jan, Yellow-Feb, Grey-Mar, Teal-Apr, Pink-May). Confidence ellipses of ordination scores associated with month of sampling effort.

Modeling variables that potentially influence armored catfish occurrence

Traditional parametric linear regressions were deemed unsuitable due to lack of normality in the distribution of CPUE of catfish data. CPUE was tested for normality using a Quantile-Quantile normality plot (Figure 11) which depicted heavily zero-weighted data. This data was further tested for normality using a Shapiro-Wilk's normality test which rejected ($p=7.53e-15$) the assumption of normality in abundance data. As such, candidate ZIP (Table 6) and NB (Table 7) models that account for overdispersion in data were tested for goodness of fit. The Vuong goodness of fit test identified the NB model as the best-fitting model based on the BIC-corrected criteria (Table 8). As such, negative binomial regression was chosen because of the model's capability of handling over dispersed data (standard error of abundance data was five times the mean) (Yau et al. 2003). Based on the AIC-corrected (AICc) statistic, the best-fit model for catfish abundance with the fewest independent variables was a negative binomial regression including pH, specific conductance, depth (m), day of sample, and distance downstream from Spring Lake Dam (Table 9). The resulting model displayed statistical significance ($p < 0.05$) (Table 10) among the variables pH, depth (m), day of sample, and distance downstream from Spring Lake Dam. However, the reduced model exhibited a poor fit (Figure 12) displaying an extremely high amount of error (Standard error = 14.35 * mean (abundance of armored catfishes).

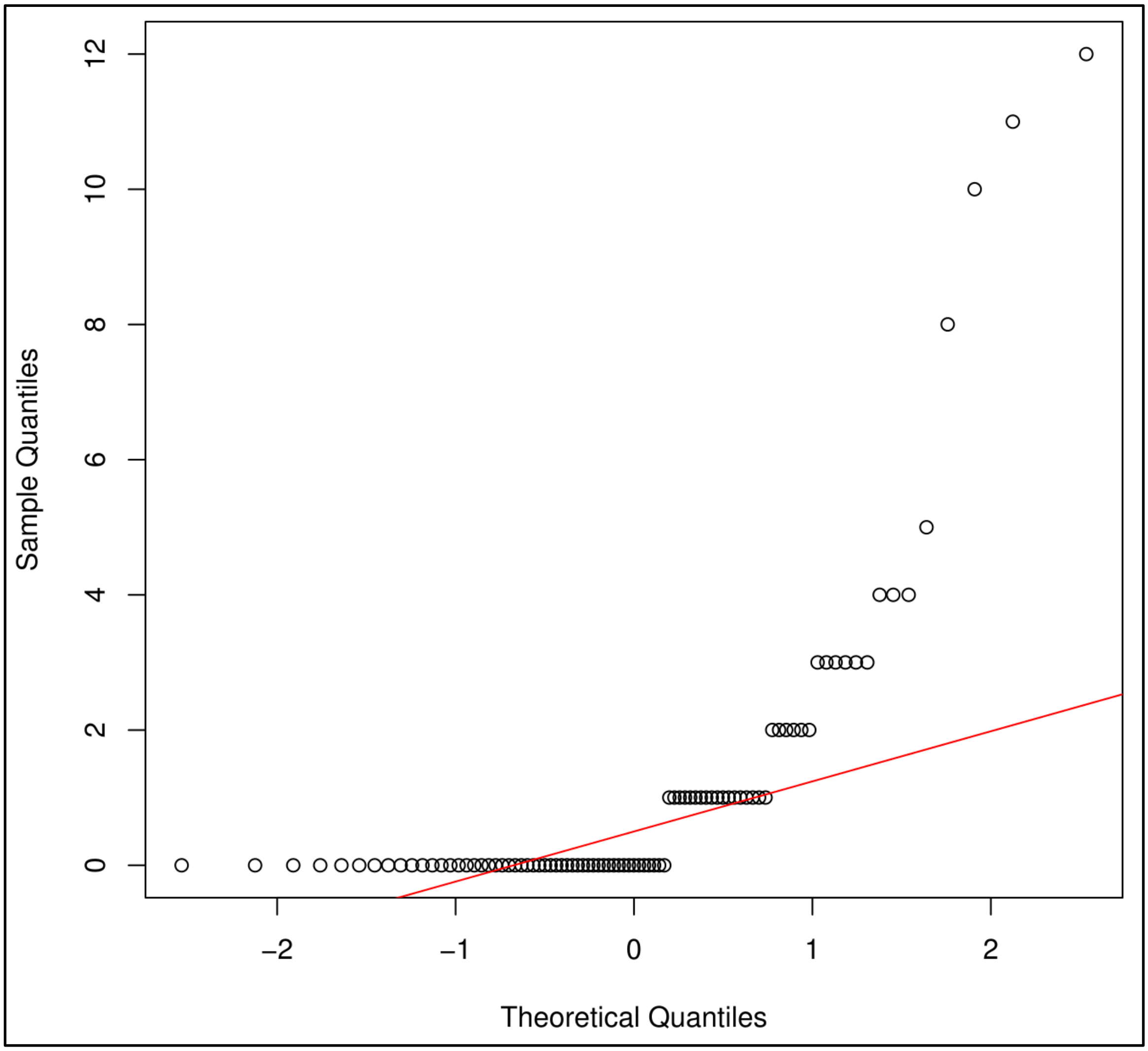

Figure 11. Quantile-Quantile normality plot showing observed catfish abundance data as distinctly non-normal.

Table 6. Coefficients of ZIP regression model. * denotes significance.

Coefficient	Estimate	Std. Error	Z value	Pr (>|z|)
(Intercept)	-4.49E+01	4.41E+01	-1.018	0.309
Flow (m^3/s)	-2.40E-01	7.67E-01	-0.312	0.755
Temperature °C	2.33	1.35	1.725	0.085
Specific Conductance	4.27E-02	2.92E-02	1.461	0.144
DOmg	-2.60E-0	4.68E-01	-0.555	0.579
pH	-4.170	2.66	-1.571	0.116
Depth (m)	1.618	8.45E-01	1.91	0.056
Percent.Cover	-2.52E-02	1.04E-02	-2.404	0.016 *
Sampling Day	-3.30E-02	2.00E-02	-1.642	0.101
Distance Downstream	-8.29E-04	5.97E-04	-1.388	0.165

Table 7. Coefficients of variables in saturated NB regression model. *denotes significance.

Coefficient	Estimate	Std. Error	Z value	Pr (>|z|)
(Intercept)	43.968	23.302	1.887	0.059
Flow (m^3/s)	-0.556	0.459	-1.211	0.226
Temperature °C	-0.517	0.733	-0.705	0.481
Specific Conductance	-0.029	0.015	-1.946	0.052
DOmg	0.401	0.273	1.470	0.142
pH	-2.848	1.370	-2.079	0.038*
Depth (m)	-0.930	0.452	-2.058	0.04*
Percent.Cover	-0.001	0.007	-0.140	0.888
Sampling Day	0.023	0.010	2.392	0.017*
Distance Downstream	0.001	3.33E-04	3.481	4.90E-04*

Table 8. Vuong Non-Nested Hypothesis Test-Statistic: (test-statistic is asymptotically distributed N (0,1) under the null that the models are indistinguishable)

Vuong Test	Vuong z-statistic	Hypothesis (model A fit data better than model B) Model A > Model B	p-value
Raw (uncorrected)	1.501123	ZIP > NB	0.066662
AIC-corrected	-0.062028	NB > ZIP	0.475270
BIC-corrected	-2.090310	NB > ZIP	0.018295*

Table 9. AIC corrected variables retaining significance. These variables were considered in the reduced NB model of CPUE.

Variable	Df	Deviance	AIC
Constant		81.213	282.36
Depth (m)	1	84.189	283.33
pH	1	85.033	284.18
Specific Conductance (µS)	1	85.178	284.32
Sampling Day	1	87.571	286.72
Distance Downstream (m)	1	92.877	292.02

Table 10. Coefficients of STEP-reduced NB model of variables associated with observed CPUE of armored catfish.

Coefficient	Estimate	Std. Error	Z value	Pr (>|z|)
(Intercept)	32.936	14.353	2.295	0.022*
Depth (m)	-2.865	1.273	-2.252	0.024*
pH	-0.029	0.015	-1.941	0.052
Specific Conductance (µS)	-0.0870	0.428	-2.034	0.042*
Sampling Day	0.012	0.005	2.290	0.022*
Distance Downstream (m)	0.001	3.28E-04	3.781	1.56E-04*

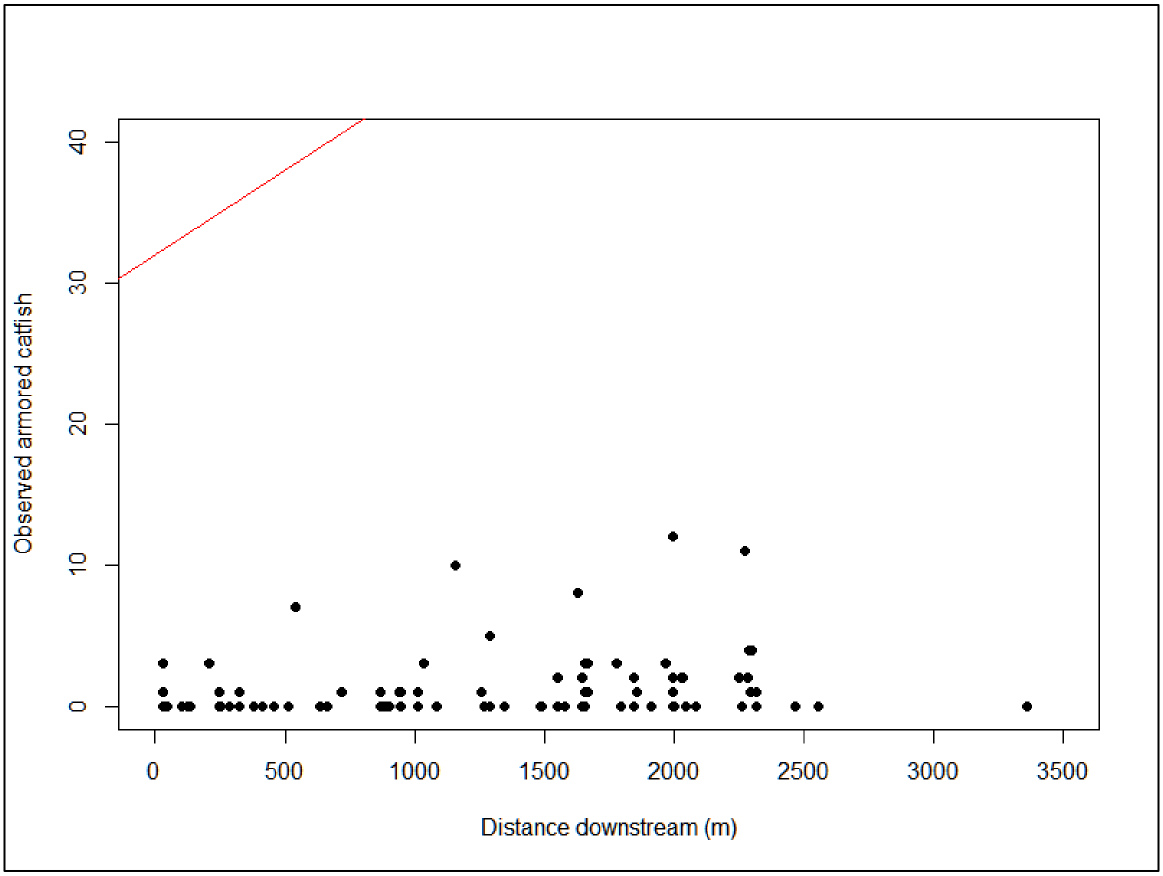

Figure 12. Reduced negative binomial regression model of observed armored catfish versus distance downstream, while accounting for variable effort. All significant variables held constant. The model shows statistical significance, but a poor predictive fit. The model is represented by the equation: $\log_e$(CPUE) of catfish = 32.936+ 0.001(Distance downstream (m).

Analysis of Suppression Data

Linear regression models detected significant relationships between biomass and number of individuals caught from year to year (Appendix B). Analysis of variance (ANOVA) failed to detect any significant difference in number of catfish removed/day between years (Figure 13; Table 11). ANOVA did detect significant differences in total catfish biomass removed/day between years (Figure 14). Tukey's pairwise tests further detected significant differences in armored catfish biomass harvested between specific years (Table 12). The total biomass harvested per daily event had significantly declined in 2015 and 2016 compared to 2013 and 2014 (Figure 14). Contracted removal efforts by professionals as well as public removal efforts (spearfishing rodeos) yielded similar daily catch rates (Figure 15 and 16). However, the amount of spearfishing effort (e.g. number of participants, number of hours of spearfishing) was not recorded by the harvest organizers.

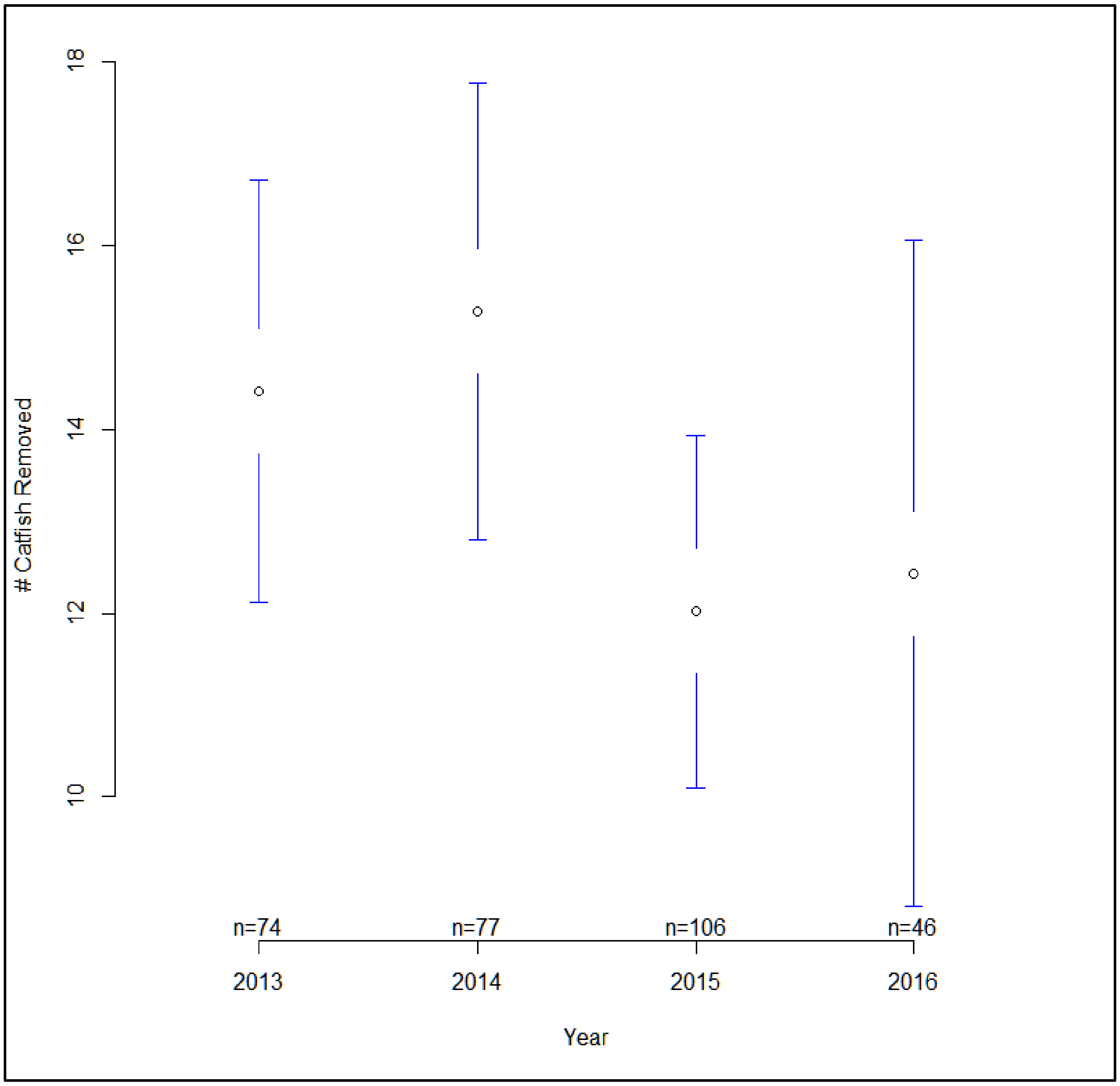

Figure 13. The 95% confidence interval plot depicting differences in daily armored catfish removal rates by year. The one-way ANOVA failed to detect significant (p< 0.05) differences between years overall.

Table 11. Tukey's pairwise test of daily armored catfish removal rates by year. Tukey's Q below diagonal, p(same) above diagonal. * denotes p-Value < 0.05. The one-way ANOVA test also failed to detect significant ($p<0.05$) differences in daily catch rates by year overall.

	2013	2014	2015	2016
2013		0.958	0.440	0.750
2014	0.712		0.168	0.472
2015	2.118	2.917		0.996
2016	1.413	2.045	0.315	

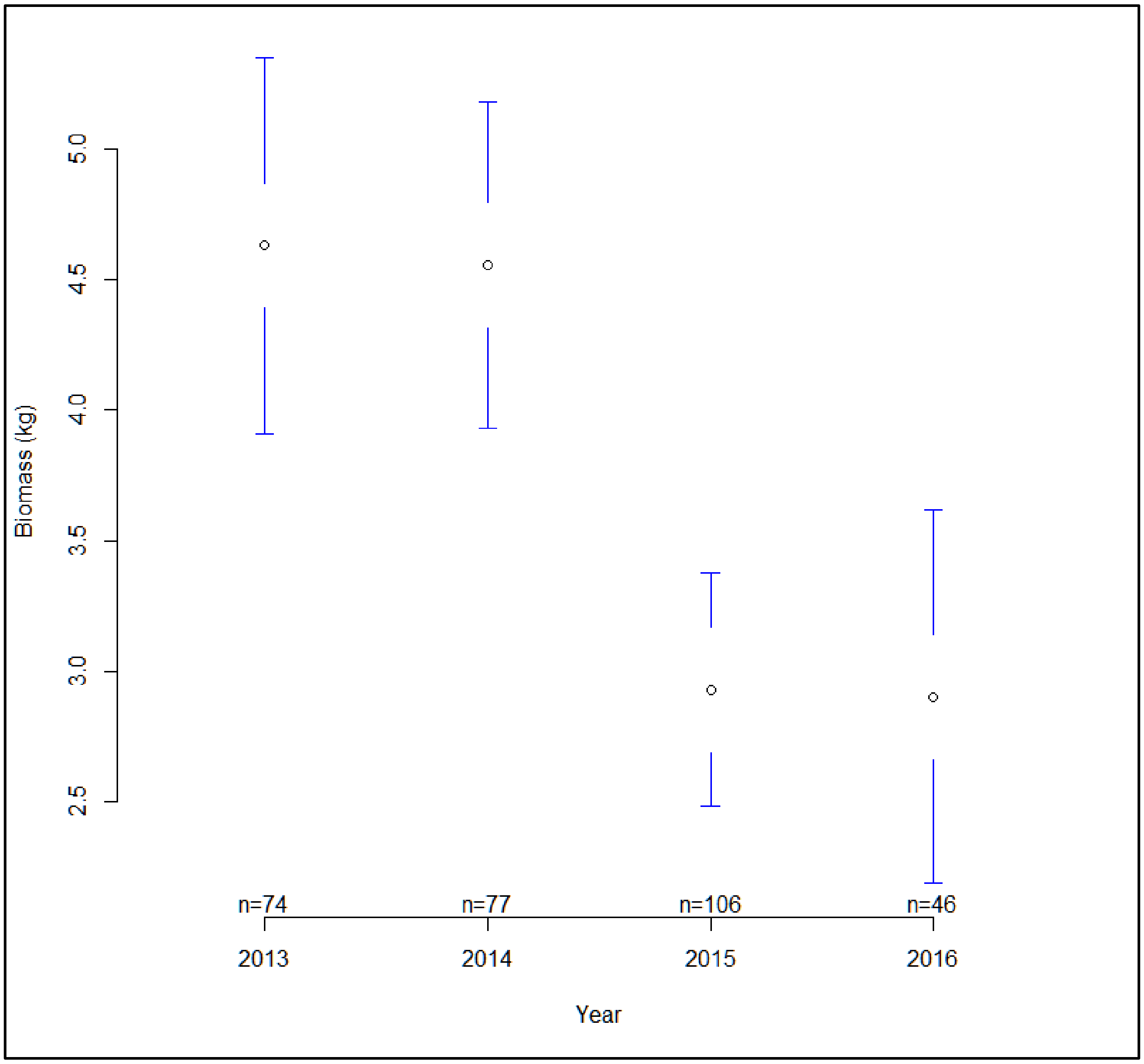

Figure 14. The 95% confidence interval plot depicting differences in daily armored catfish biomass removal rates by year. The one-way ANOVA detected significant ($p < 0.05$) differences between years overall.

Table 12. Tukey's pairwise test showing significant differences in daily armored catfish biomass removal rates annually. Tukey's Q below diagonal, p(same) above diagonal. * denotes p-Value < 0.05. The one-way ANOVA test detected a significant ($p<0.05$) differences in daily biomass removal rates by year overall.

	2013	2014	2015	2016
2013		0.998	1.82E-04*	0.003*
2014	0.240		3.17E-04*	0.005*
2015	5.982	5.790		1.000
2016	4.905	4.732	0.084*	

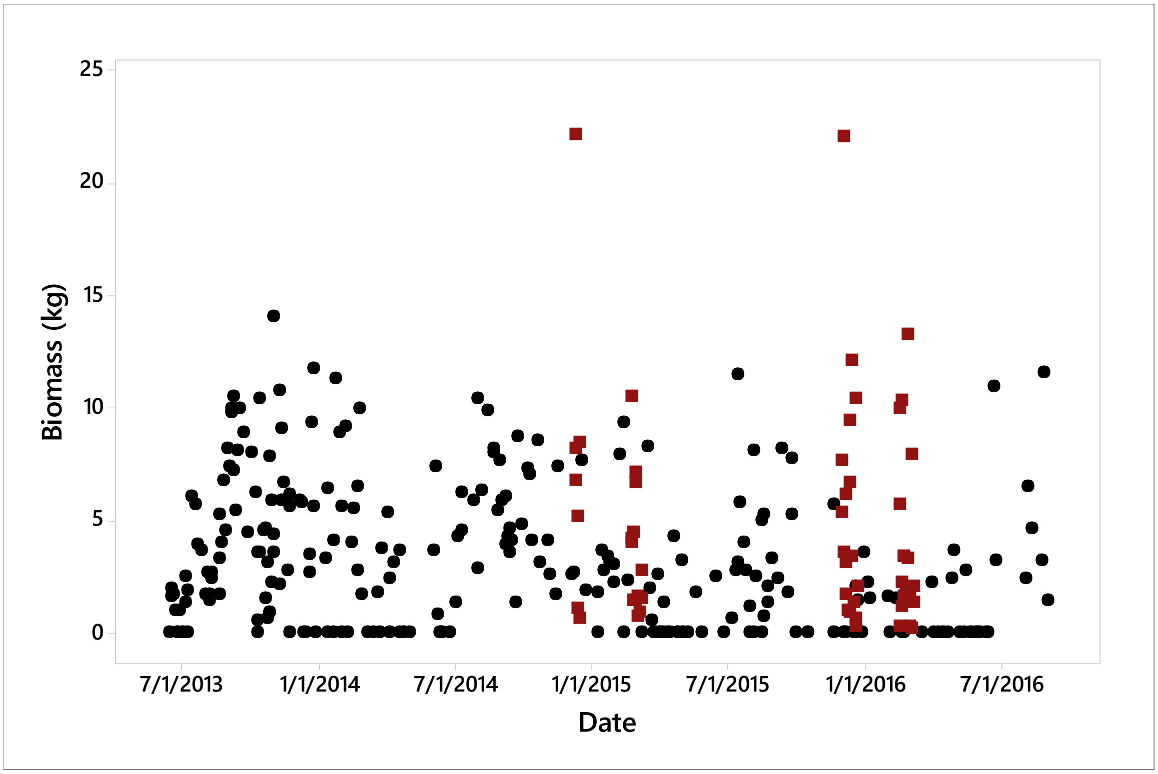

Figure 15. Invasive armored catfish biomass removed per day by contracted officials (black) and volunteer tournament harvesters (red) from 6/12/2013 to 8/31/2016.

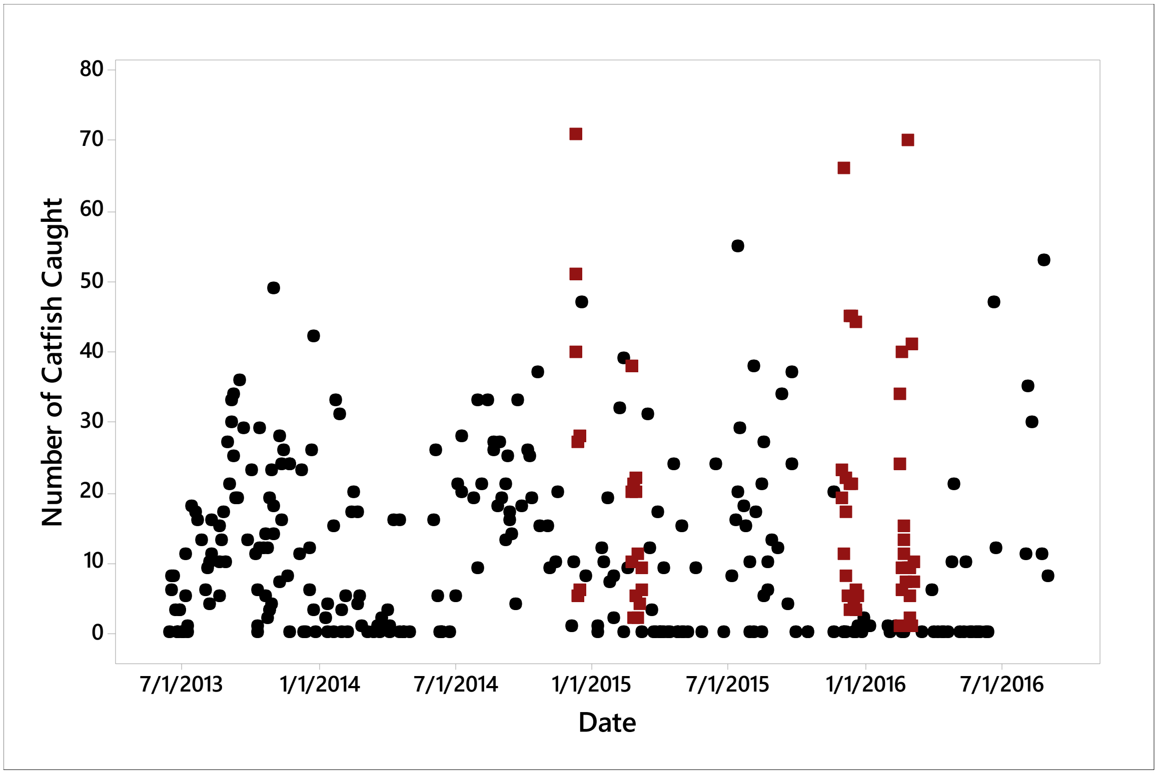

Figure 16. Invasive armored catfish totals removed per day by contracted officials (black) and volunteer tournament harvesters (red) from 6/12/2013 to 8/31/2016.

DISCUSSION

Snorkel Surveys and Water Quality Assessment

Variation in water quality between survey transects was statistically significant, but this variation was not considered biologically relevant. The variation in specific conductance, pH, surface temperature, and river discharge although statistically significant were well within the ranges of armored catfish documented tolerance and adaptation when considering the upper and lower limits of each of these variables (Baensch and Riehl 1985).

Armored catfish habitat selection

During this study, 115 sightings of armored catfishes occurred, of which only 27 were positively identified to species. As such, all conclusions drawn from this research regarding habitat selection apply to the family Loricariidae as represented by the two species known to occur in the river, rather than species-specific trends. The variables showing the highest association with catfish distribution appeared to be pH, specific conductance, water depth, day of year, and distance downstream from the Spring Lake Dam in meters. However, aside from specific conductance, these environmental variables are all heavily associated with hydrological impacts of dams that are located further downstream from the headwaters at Spring Lake (Stevens and Olsen 2004). Backwater areas upstream of and influenced by dams supported higher densities of vegetation, contained deeper pools, had slower water velocities, are were located further downstream. These areas typically higher pH values since considerable time and distance downstream had resulted in CO_2 off gassing. Armored catfishes may have been present in higher numbers in areas with aquatic vegetation but where difficult to detect. However, the highest frequency of sightings of armored catfish occurred in hard bottom habitat gravel (gravel, cobble, concrete etc.), which probably reflects their preference for grazing on epiphytes.

Linear Modeling of Suppression Data

Ongoing armored catfish suppression (active removal) activities in the San Marcos River showed significant changes ($P<0.05$) annually in biomass removed. The trend is generally declining in biomass, while the number of individuals removed seems to be remaining similar. This indicates that over time these populations may be able to be significantly suppressed, but previous research has shown that suppression of these animals will not likely result in complete removal (Chaichana et al. 2011). Similar suppression efforts have had significant effects on invasive predators, but there's little documented success of removal of lower-trophic invaders (De León et al. 2013). Due to the high recruitment potential of armored catfish, suppression efforts may have to be adopted as a permanent management tool deployed periodically. Also, it is unlikely that the population of armored catfish could be totally eradicated since it is very difficult to locate all smaller individuals in deeper or heavily vegetated parts of the river. Without competitors at the same trophic level and non-human predators, this may be the only solution. However, contracted management efforts may be able to focus entirely on sections of the river below the Rio Vista falls, considering strong associations between armored catfish and lower sections of the San Marcos River.

Unfortunately, more detailed analyses incorporating catch per unit effort, age and length data could not be conducted at this time due to lack of this information. Variable effort and lack of effort records prevented examining changes in catch per unit effort over time. Furthermore, changes in population, mortality, and size class data could also not be examined due to lack of this information.

Implications and future suggested research

In order to further understand how these animals are using the system, a more focused effort could be done utilizing higher resolution detection methods. For example, this research was performed without removal of these animals, and as such sightings of armored catfish likely contain multiple detections of the some individual animals. As such, habitat use analysis performed using acoustic and or radio tagging of specific individuals could help determine the affinity of individual specimens for specific locations and habitat and by extension generate more accurate information for management officials in regards to habitat associations of this species and their potential impact. Nonlethal marking through dermal tags would also allow surveyors to identify previously detected animals.

The distribution of invasive armored catfishes in the upper San Marcos River did appear to be correlated with multiple environmental variables. Higher density catfish populations were most often located in areas farther downstream from the San Marcos

River headwaters. As such, considering that management efforts are having a significant impact on biomass reduction of these armored catfish populations, increased focus should be given to this region to maximize efficiency of management efforts. In order to better understand the impact these suppression efforts are having on invasive armored catfish; data collection should be expanded in both scope and accuracy. Individuals removed, or at least a subsample thereof, should be accurately measured in length, weight, and sexed. Gonads could be collected for the construction of a gonadosomatic index in order to examine the impact removal efforts are having on maturity rates and recruitment potential. These research projects could help inform the management, and by extension the conservation of sensitive natural resources within the San Marcos River.

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APPENDIX A: GRAPHICAL REPRESENTATIONS OF DATA

Ordinary Least Squares Regression: Sampling Day versus Temperature (°C)

Slope a:	0.0077793	**Std. error a:**	0.00072216
t:	10.772	**p (slope):**	2.9083E-18*
Intercept b:	21.143	**Std. error b:**	0.07243

95% bootstrapped confidence intervals (N=1999):

Slope a: (0.0064604, 0.0091897)
Intercept b: (20.987, 21.279)

Correlation:

r: 0.73803
r^2: 0.54469
t: 10.772
p (uncorr.): 2.9083E-18*
Permutation p: 0.0001*

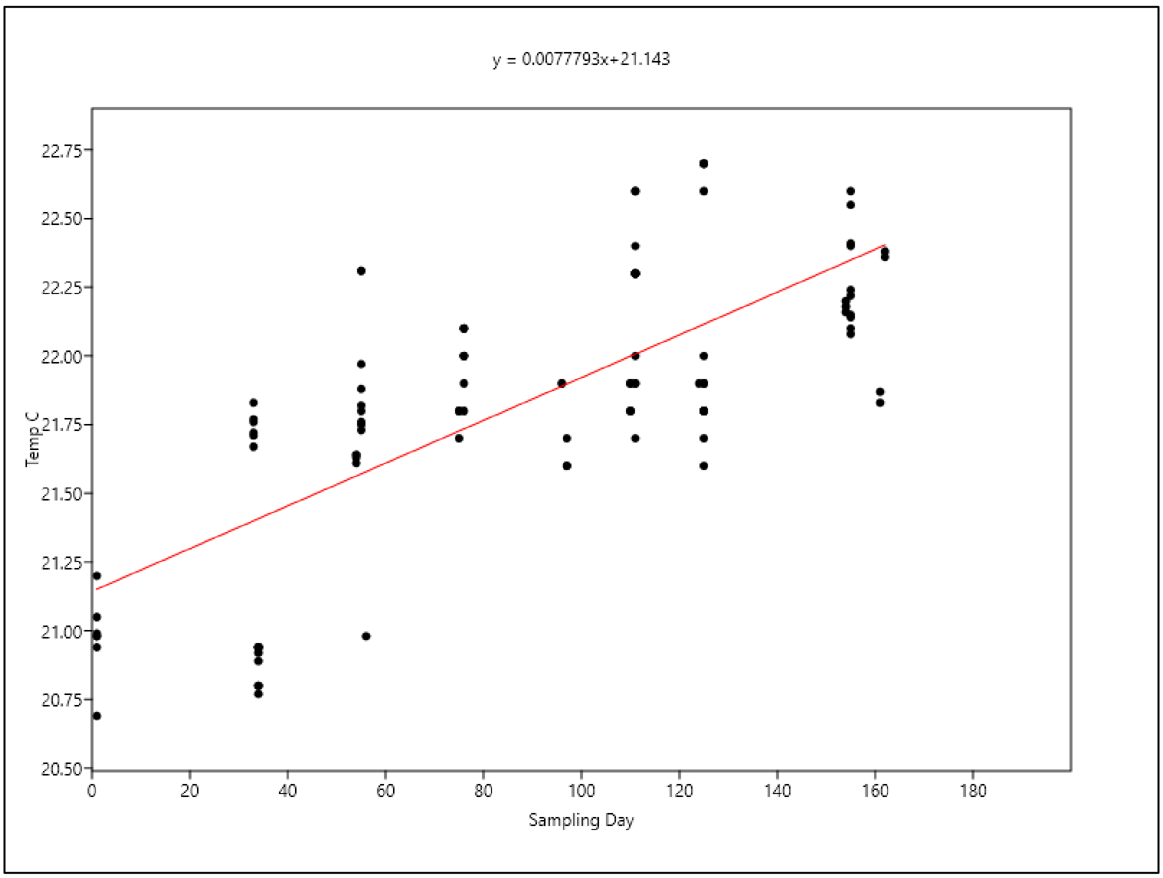


Figure A-1. General linear model of water temperature °C versus sampling day of year.

Polynomial regression, order 2: Sampling Day versus Temperature (°C)

chi²: 9.9296
Akaike ICc: 16.182
Akaike IC: 15.93
R^2: 0.59549
F: 70.662
p: 1.3574E-19*

a0: 20.8823
a1: 0.0166995
a2: -5.25014E-05

Equation: $-5.25E\text{-}05x^2 + 0.0167x + 20.88$

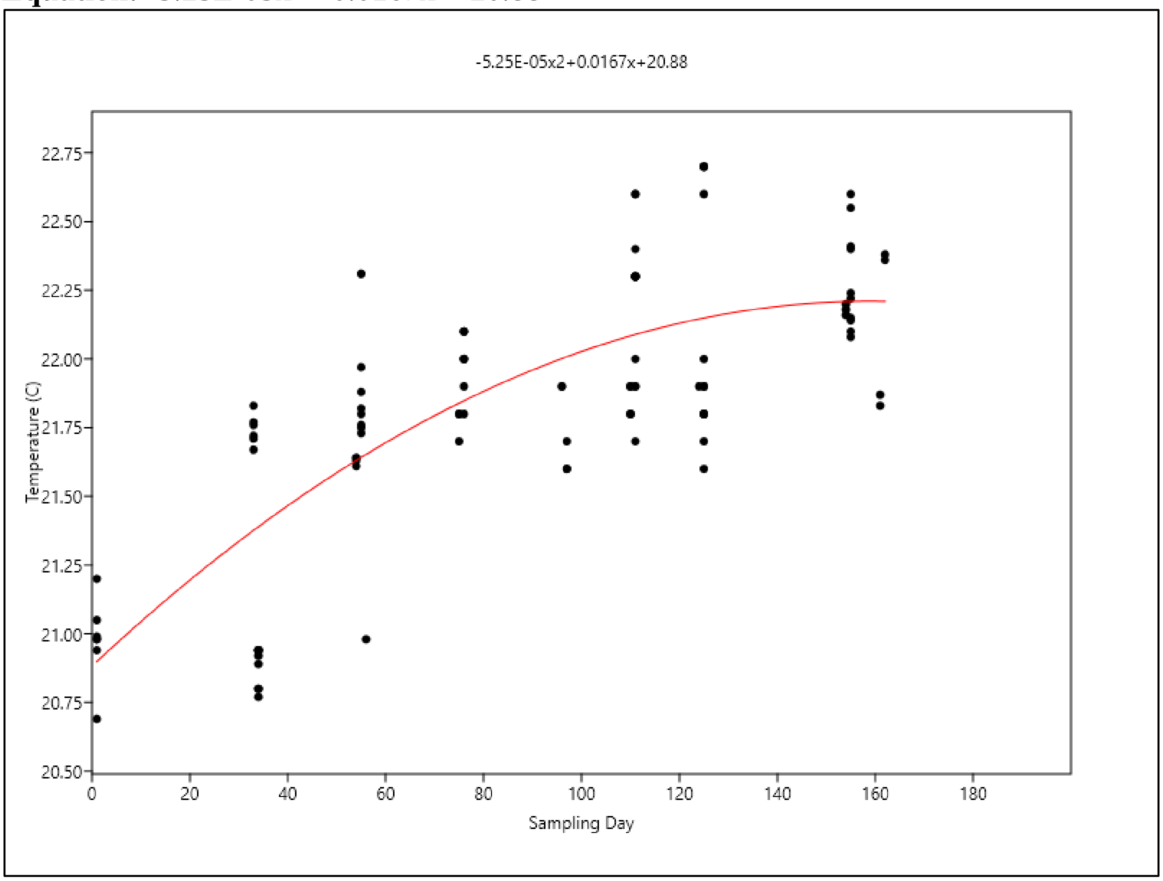


Figure A-2. Quadratic model of water temperature °C versus sampling day of year.

Ordinary Least Squares Regression: Sampling Day versus pH

Slope a:	-0.0012053	**Std. error a:**	0.00041269
t:	2.9206	**p (slope):**	0.0043449*
Intercept b:	7.5034	**Std. error b:**	0.041392

95% bootstrapped confidence intervals (N=1999):
Slope a: (-0.00204, -0.00047569)
Intercept b: (7.4219, 7.6055)

Correlation:
r: -0.2843
r^2: 0.080829
t: -2.9206
p (uncorr.): 0.0043449*
Permutation p: 0.0043*

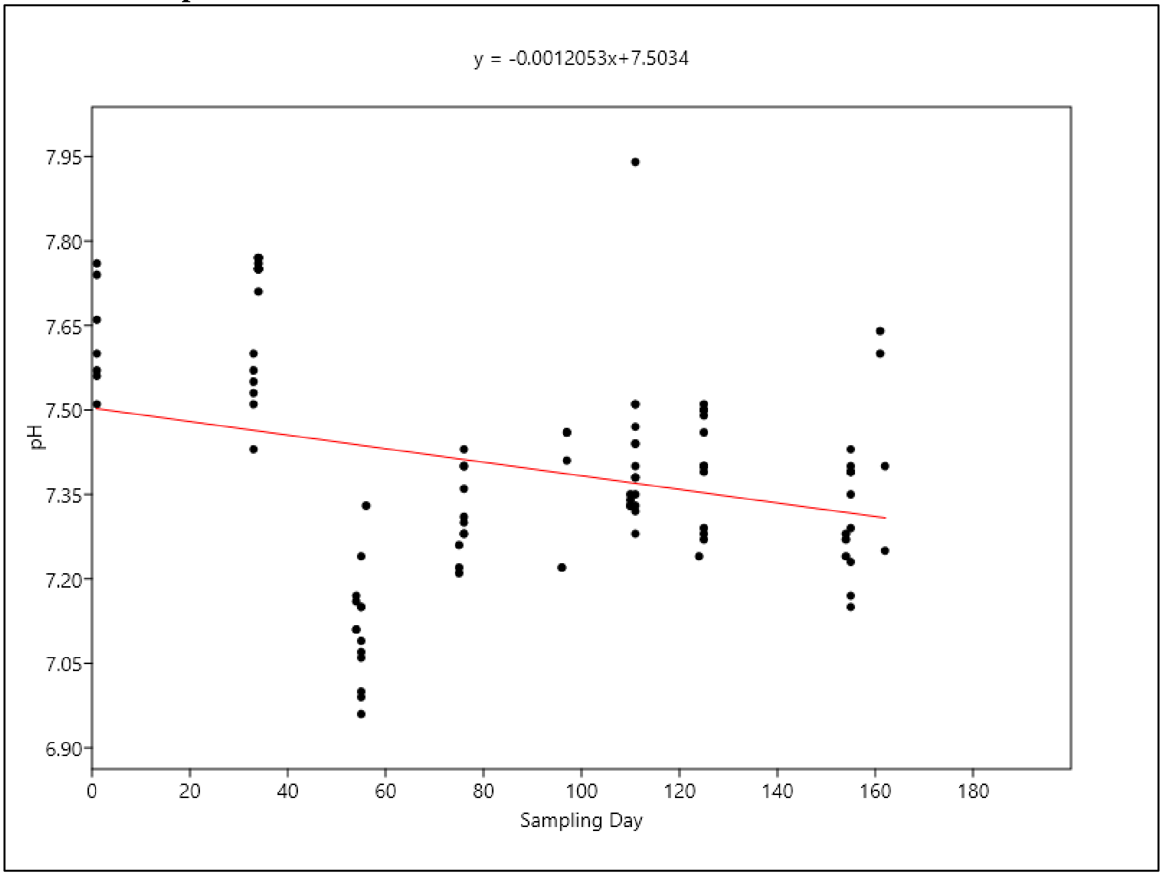


Figure A-3. General linear model of water pH versus sampling day of year.

Ordinary Least Squares Regression: Sampling Day versus Specific Conductance (μS)

Slope a:	0.20629	**Std. error a:**	0.026034
t:	7.9239	**p (slope):**	3.8935E-12*
Intercept b:	598.17	**Std. error b:**	2.6112

95% bootstrapped confidence intervals (N=1999):
Slope a: (0.14619, 0.26796)
Intercept b: (594.73, 602.17)

Correlation:
r: 0.62685
r^2: 0.39294
t: 7.9239
p (uncorr.): 3.8935E-12*
Permutation p: 0.0001*

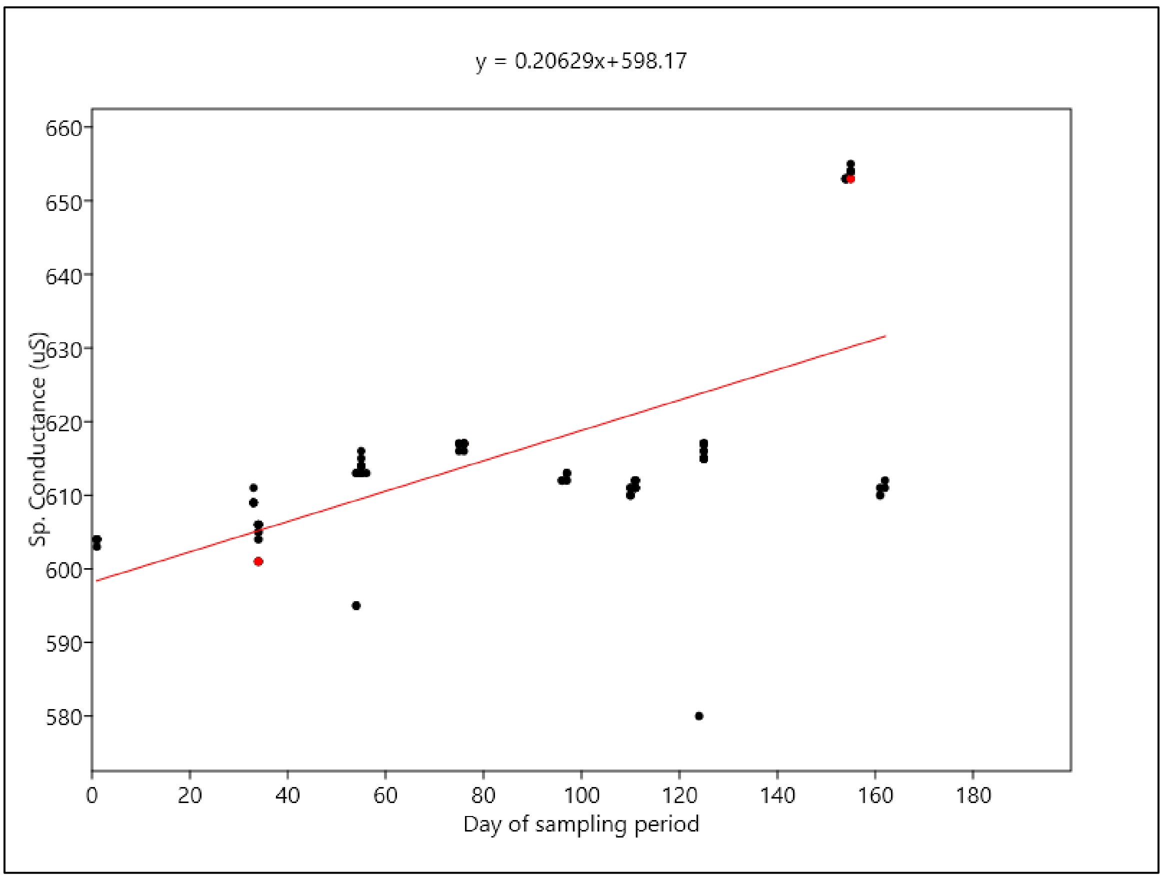


Figure A-4. General linear model of specific conductance versus sampling day of year.

Ordinary Least Squares Regression: Sampling Day versus Dissolved Oxygen (mg/L)

Slope a:	-0.0038344	**Std. error a:**	0.0016882
t:	2.2713	**p (slope):**	0.025336*
Intercept b:	8.6412	**Std. error b:**	0.16932

95% bootstrapped confidence intervals (N=1999):
Slope a: (-0.0062129, -0.0010698)
Intercept b: (8.3097, 8.8957)

Correlation:
r: -0.22472
r^2: 0.0505
t: -2.2713
p (uncorr.): 0.025336*
Permutation p: 0.0252*

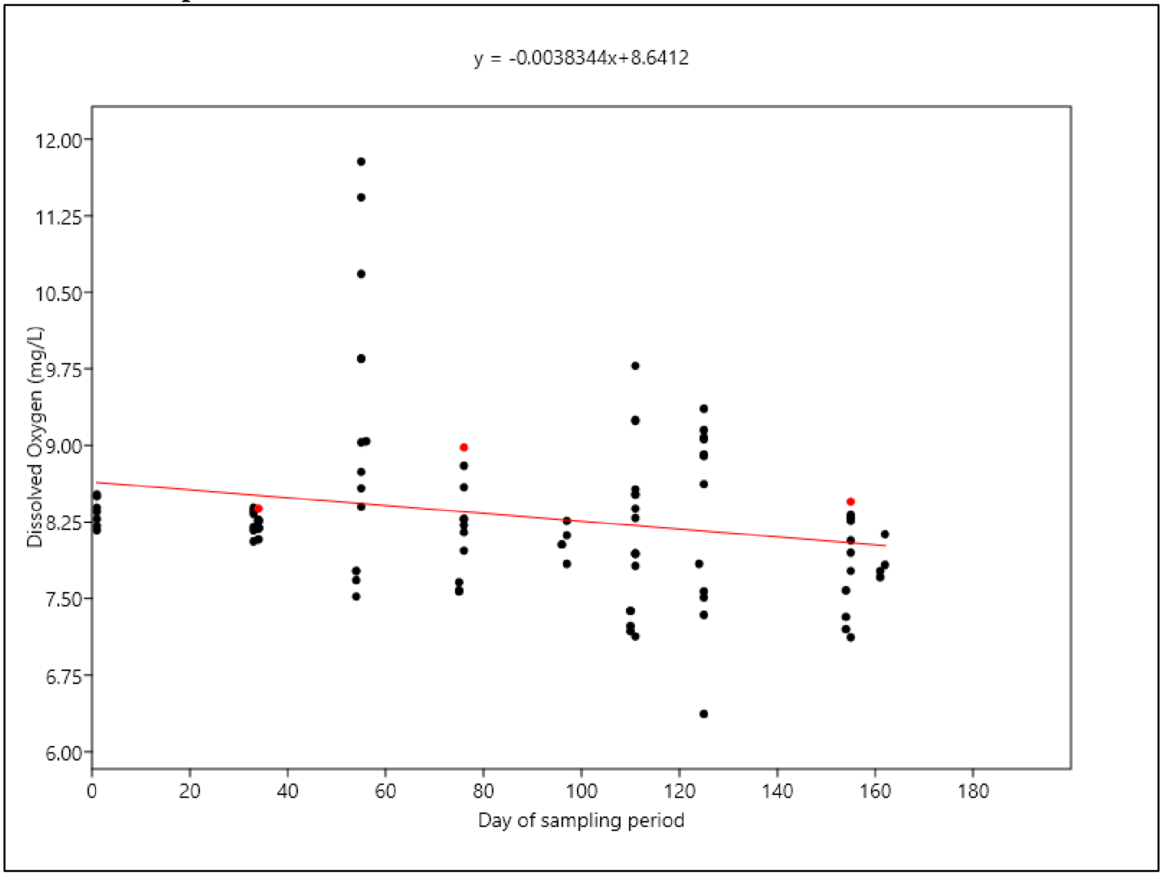


Figure A-5. General linear model of dissolved oxygen (mg/L) versus sampling day of year.

Ordinary Least Squares Regression: Distance Downstream of Spring Lake Dam versus Depth (m)

Slope a:	0.00013784	**Std. error a:**	6.5394E-05
t:	2.1078	**p (slope):**	0.037624*
Intercept b:	1.0164	**Std. error b:**	0.097093

95% bootstrapped confidence intervals (N=1999):

Slope a:	(-1.5617E-06, 0.00028)
Intercept b:	(0.82077, 1.2111)

Correlation:

r:	0.20928
r^2:	0.043798
t:	2.1078
p (uncorr.):	0.037624*
Permutation p:	0.0355*

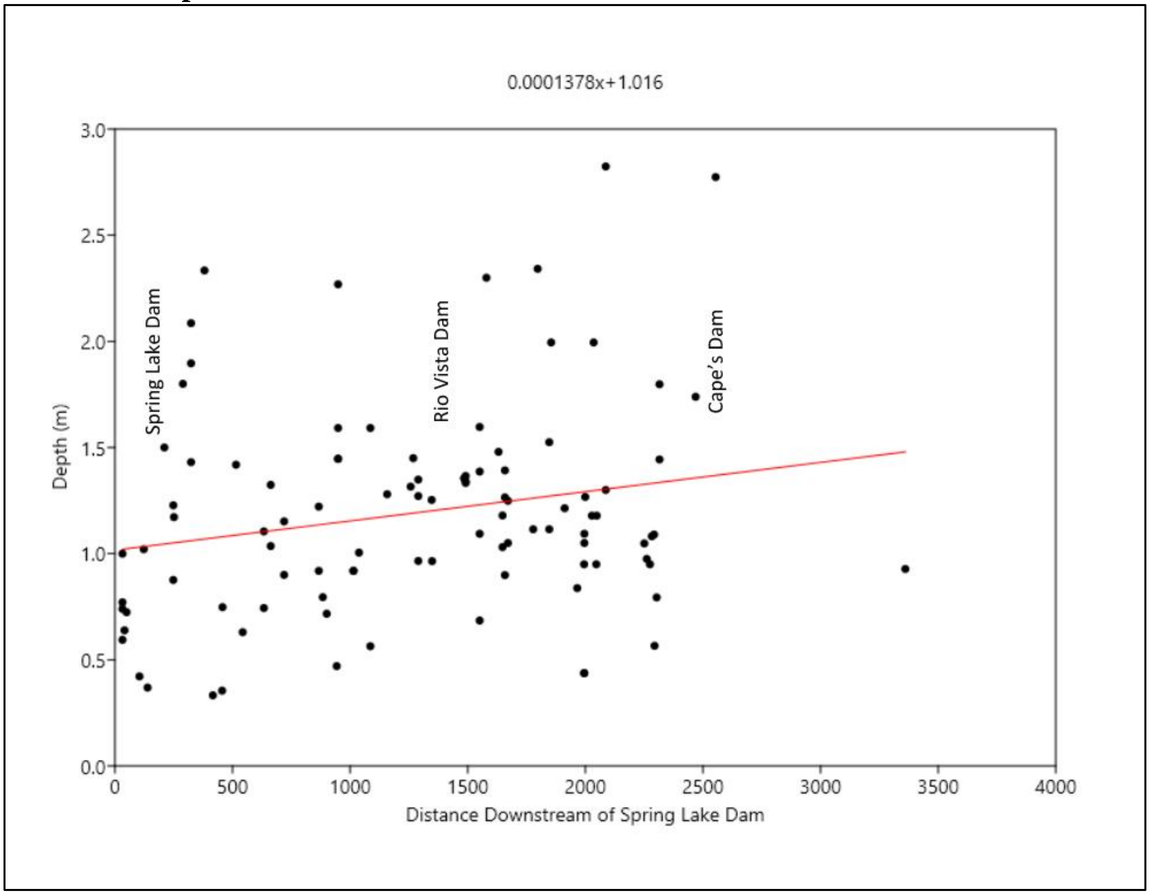


Figure A-6. General linear model of site depth (m) versus distance downstream of Spring Lake. Approximate longitudinal proximity of dams noted on figure.

Ordinary Least Squares Regression: Distance Downstream of Spring Lake Dam (m) versus pH

Slope a:	0.0001392	**Std. error a:**	2.2949E-05
t:	6.0659	**p (slope):**	2.5293E-08*
Intercept b:	7.2188	**Std. error b:**	0.034073

95% bootstrapped confidence intervals (N=1999):

Slope a:	(9.6613E-05, 0.00018393)
Intercept b:	(7.1587, 7.2805)

Correlation:

r:	0.52441
r^2:	0.27501
t:	6.0659
p (uncorr.):	2.5293E-08*
Permutation p:	0.0001*

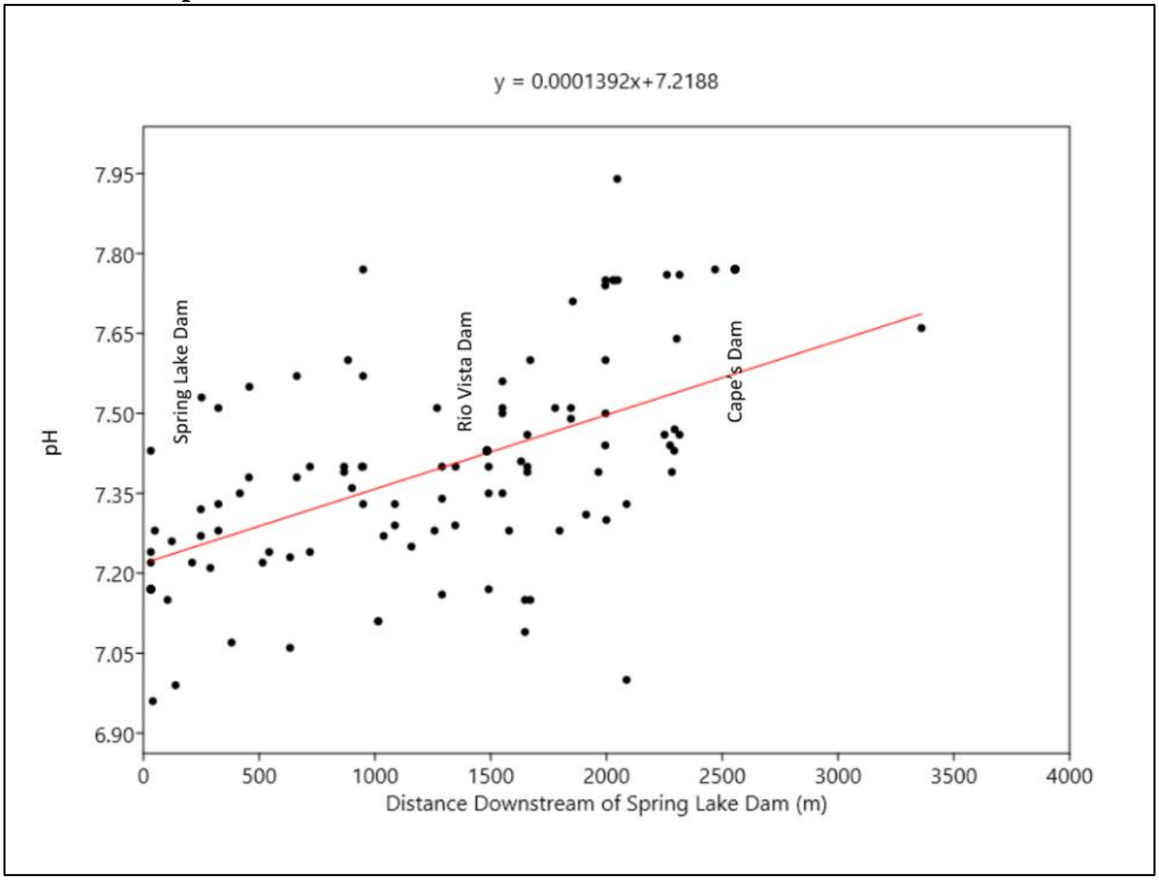


Figure A-7. General linear model of site pH versus distance downstream of Spring Lake. Approximate longitudinal proximity of dams noted on figure.

Ordinary Least Squares Regression: Distance Downstream of Spring Lake Dam (m) versus Temperature (°C)

Slope a:	-0.00019745	**Std. error a:**	6.3941E-05
t:	3.0879	**p (slope):**	0.0026287*
Intercept b:	22.084	**Std. error b:**	0.094937

95% bootstrapped confidence intervals (N=1999):

Slope a: (-0.0003324, -7.6051E-05)

Intercept b: (21.936, 22.235)

Correlation:

r: -0.29917

r^2: 0.089503

t: -3.0879

p (uncorr.): 0.0026287*

Permutation p: 0.0038*

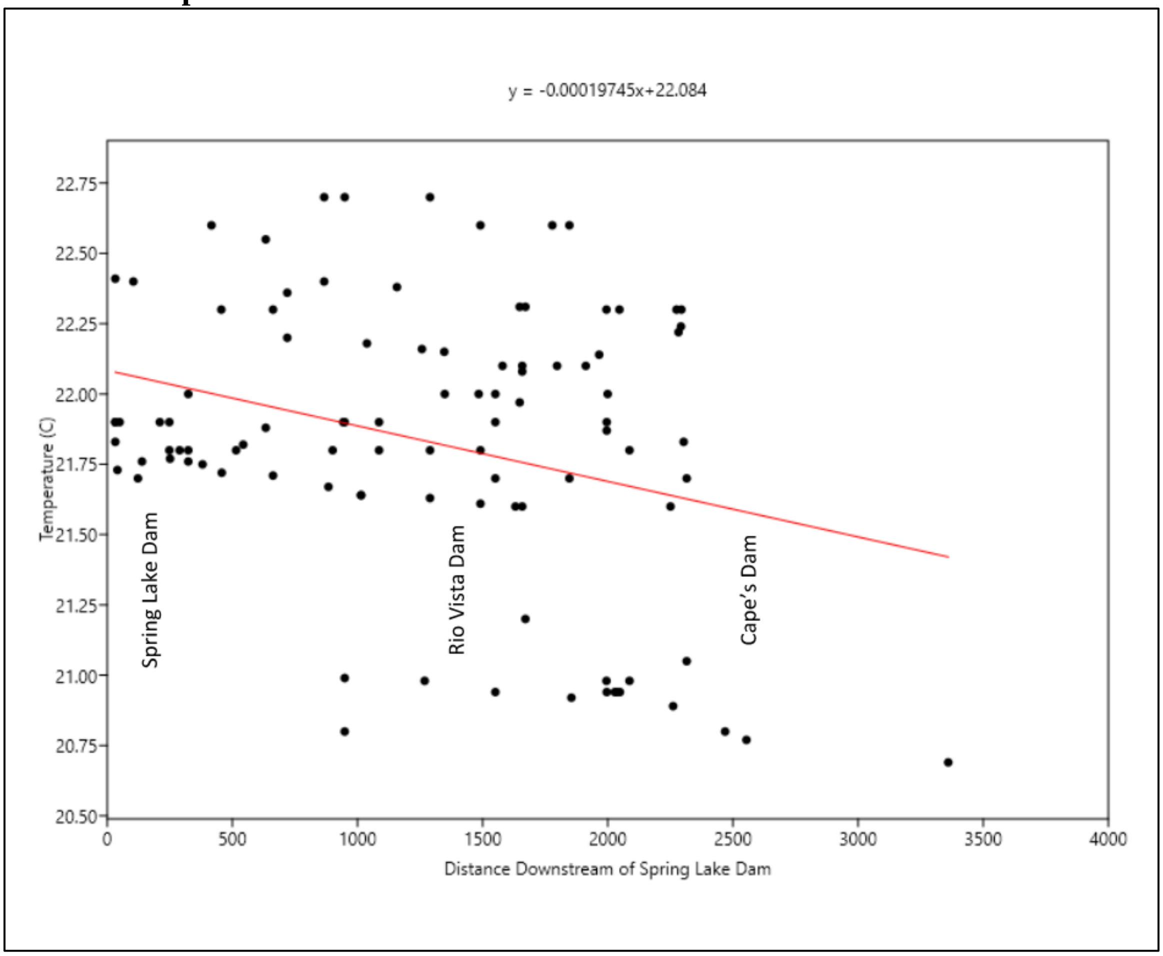


Figure A-8. General linear model of temperature °C versus distance downstream of Spring Lake. Approximate longitudinal proximity of dams noted on figure.

__**Ordinary Least Squares Regression: Distance Downstream of Spring Lake Dam (m) versus Specific Conductance (µS)**__

Slope a:	-0.0015574	**Std. error a:**	0.0020862
t:	0.74654	**p (slope):**	0.45714
Intercept b:	618.42	**Std. error b:**	3.0975

95% bootstrapped confidence intervals (N=1999):
Slope a: (-0.0060973, 0.0025475)
Intercept b: (611.49, 625.07)
Correlation:
r: -0.075583
r^2: 0.0057128
t: -0.74654
p (uncorr.): 0.45714
Permutation p: 0.4589

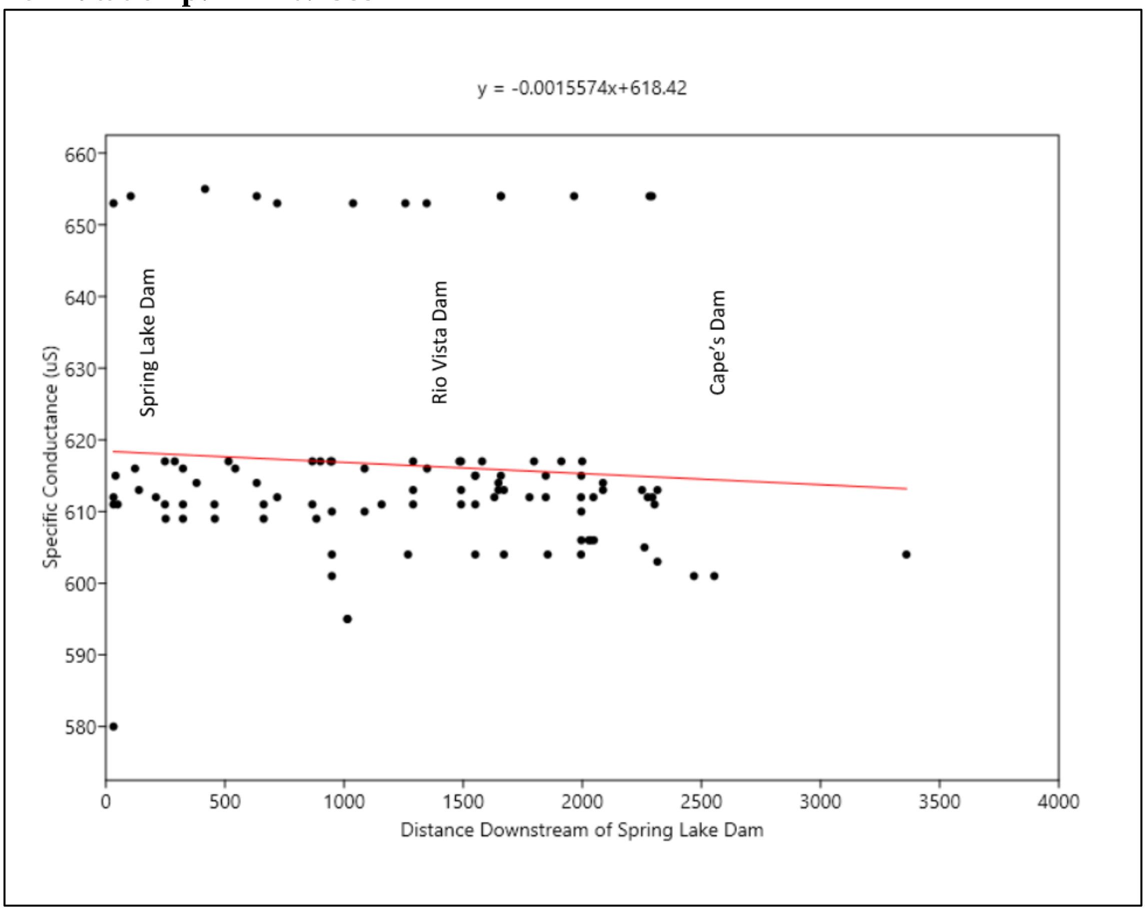


Figure A-9. General linear model of specific conductance (µS) versus distance downstream of Spring Lake. Approximate longitudinal proximity of dams noted on figure.

<u>Ordinary Least Squares Regression: Distance Downstream of Spring Lake Dam (m) versus Dissolved Oxygen (mg/L)</u>

Slope a:	2.2114E-05	**Std. error a:**	0.00010845
t:	0.20391	**p (slope):**	0.83885
Intercept b:	8.2736	**Std. error b:**	0.16102

95% bootstrapped confidence intervals (N=1999):

Slope a:	(-0.00013199, 0.00018286)
Intercept b:	(8.0084, 8.5033)

Correlation:

r:	0.020699
r^2:	0.00042845
t:	0.20391
p (uncorr.):	0.83885
Permutation p:	0.836

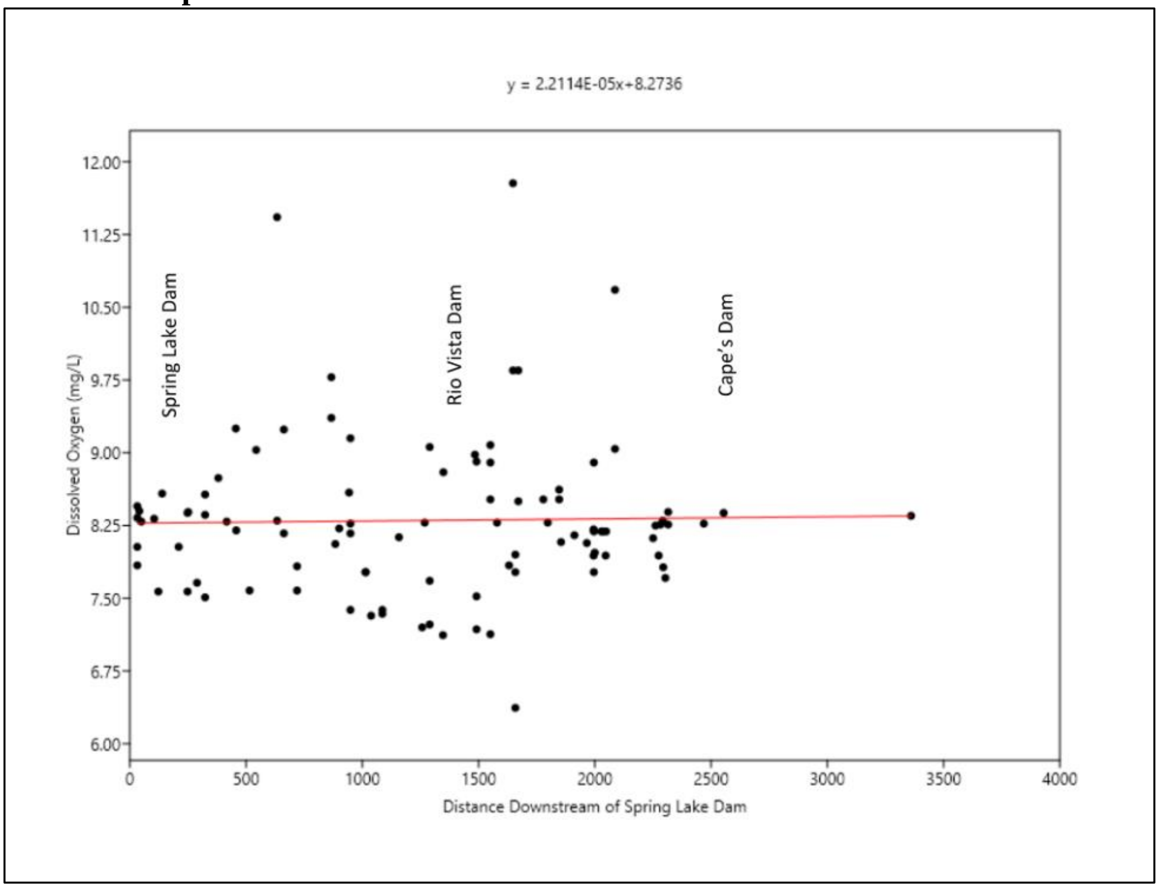


Figure A-10. General linear model of dissolved oxygen (mg/L) versus distance downstream of Spring Lake. Approximate longitudinal proximity of dams noted on figure.

Ordinary Least Squares Regression: Distance Downstream of Spring Lake Dam (m) versus Vegetation Cover (%)

Slope a:	-0.0037996	**Std. error a:**	0.0039123
t:	0.9712	**p (slope):**	0.33386
Intercept b:	19.404	**Std. error b:**	5.8088

95% bootstrapped confidence intervals (N=1999):

Slope a: (-0.0090673, 0.0017471)
Intercept b: (9.2364, 27.949)

Correlation:

r: -0.098135
r^2: 0.0096304
t: -0.9712
p (uncorr.): 0.33386
Permutation p: 0.3339

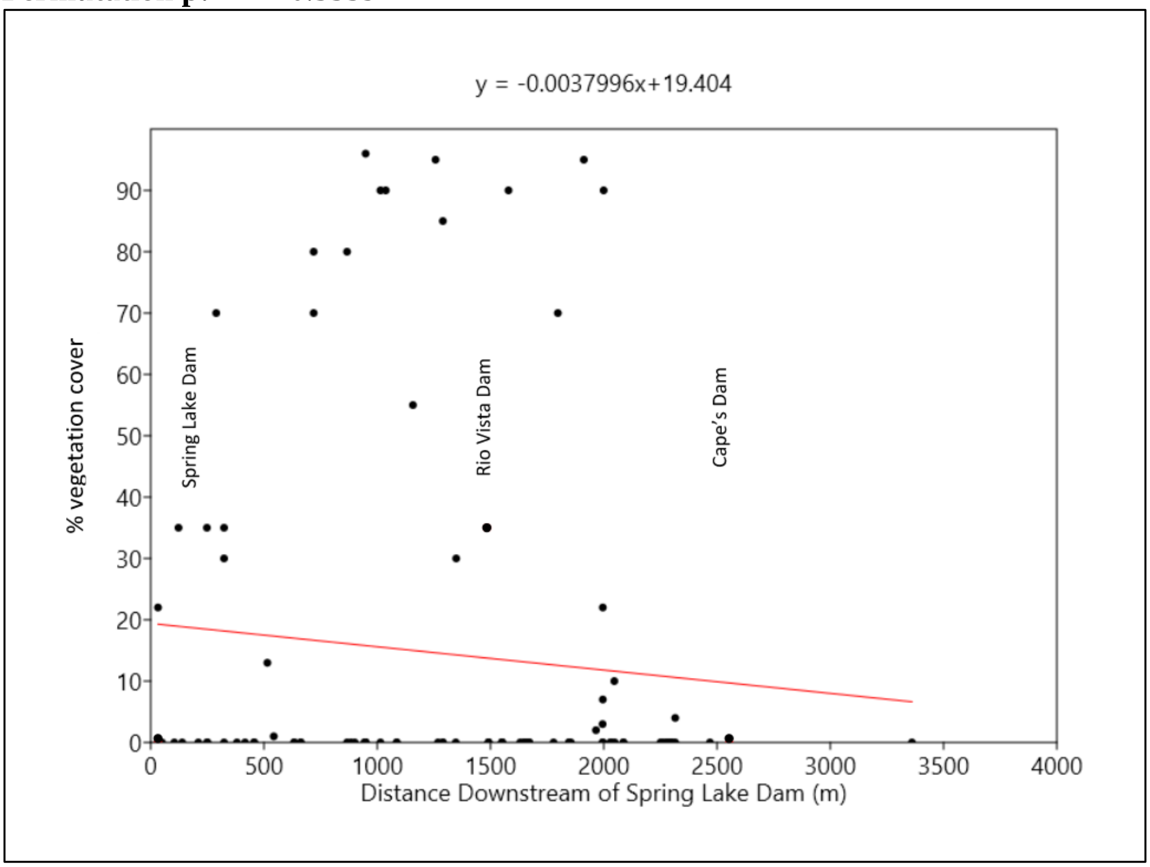
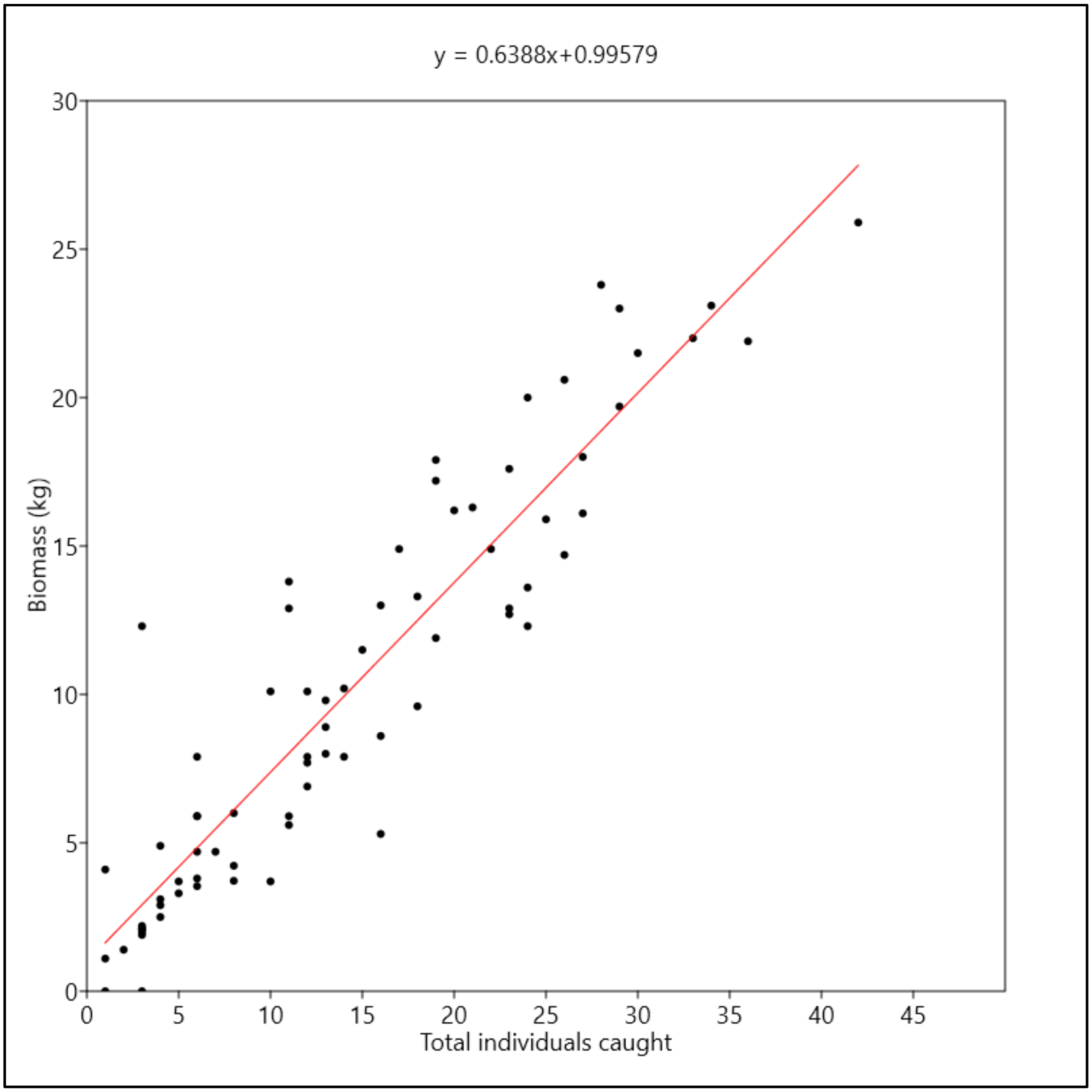


Figure A-11. General linear model of vegetation cover (%) versus distance downstream of Spring Lake. Approximate longitudinal proximity of dams noted on figure.

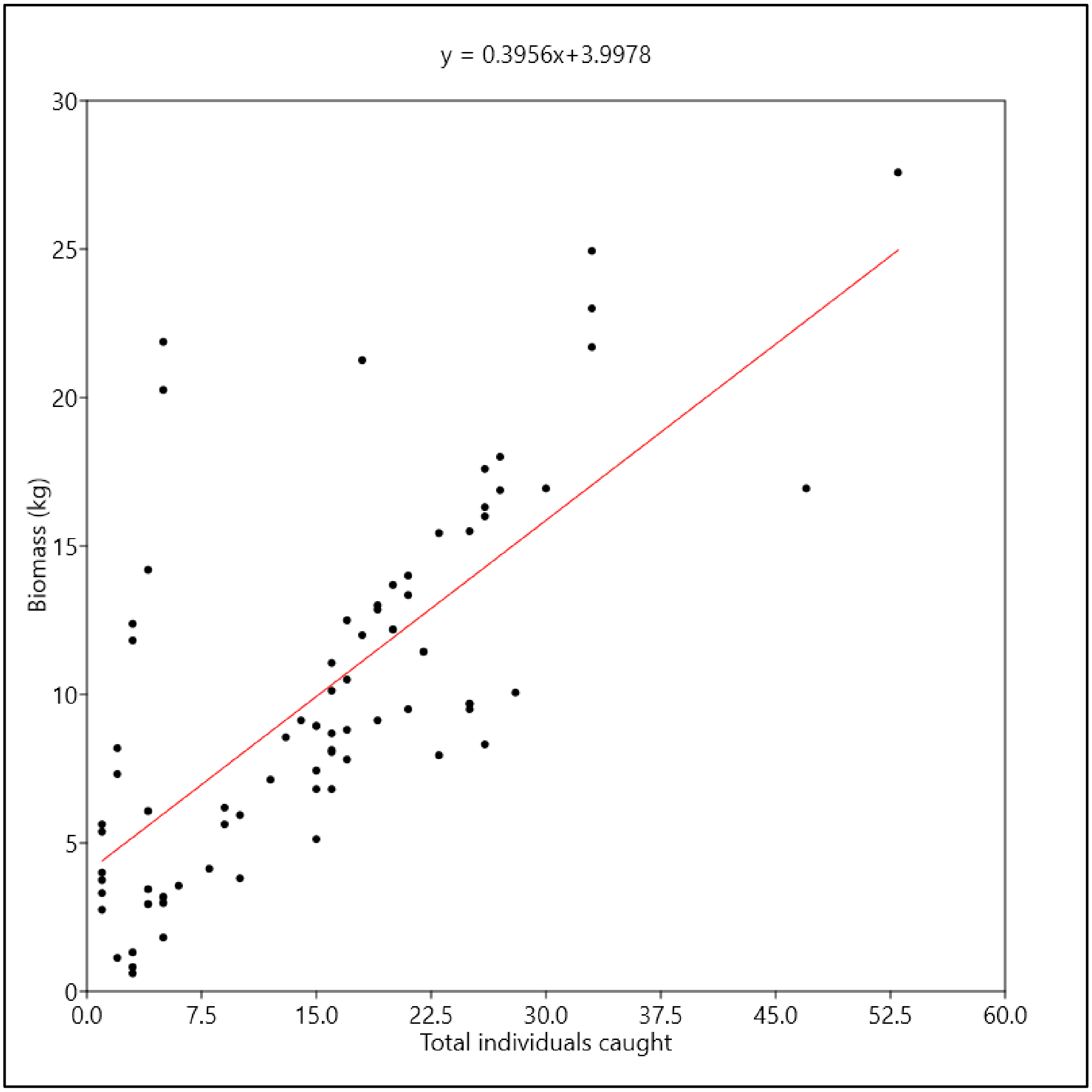
APPENDIX B:

LINEAR MODELING OF ARMORED CATFISH REMOVAL DATA



Generalized linear model
Normal distribution, identity link
Dispersion phi: 6.6939 (estimated)
Slope a: 0.6388 **Std. err. a:** 0.030546
Intercept b: 0.99579 **Std. err. b:** 0.53334
Log likelihood: -36
G: 437.34 **p(slope=0):** 4.1071E-97*

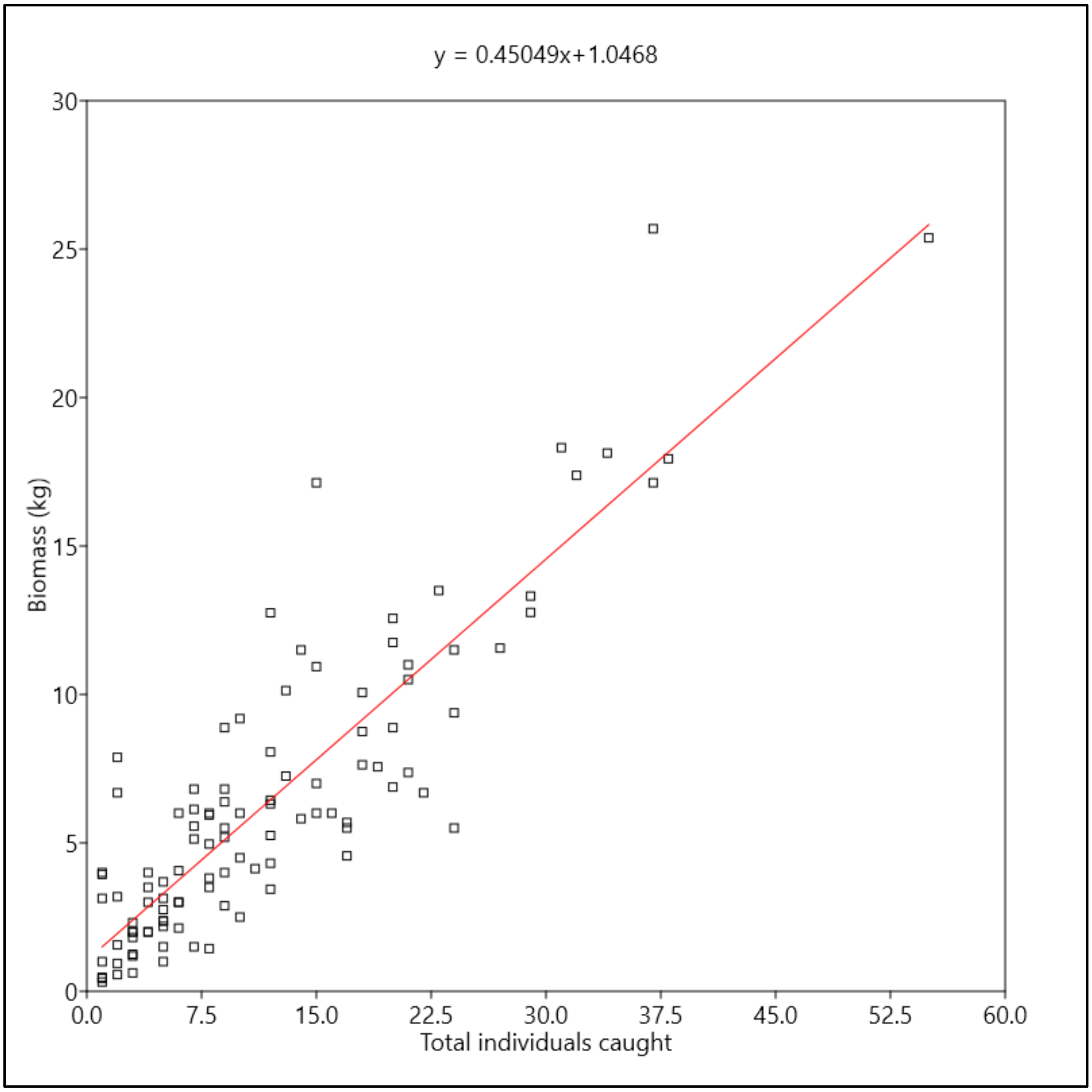
Figure B-1. Linear modeling of total individual catfish caught versus biomass (kg) removed in 2013.



Generalized linear model
Normal distribution, identity link

Dispersion phi:	18.241 (estimated)		
Slope a:	0.3956	**Std. err. a:**	0.044832
Intercept b:	3.9978	**Std. err. b:**	0.84055
Log likelihood:	-37.5		
G:	77.866	**p(slope=0):**	1.1027E-18*

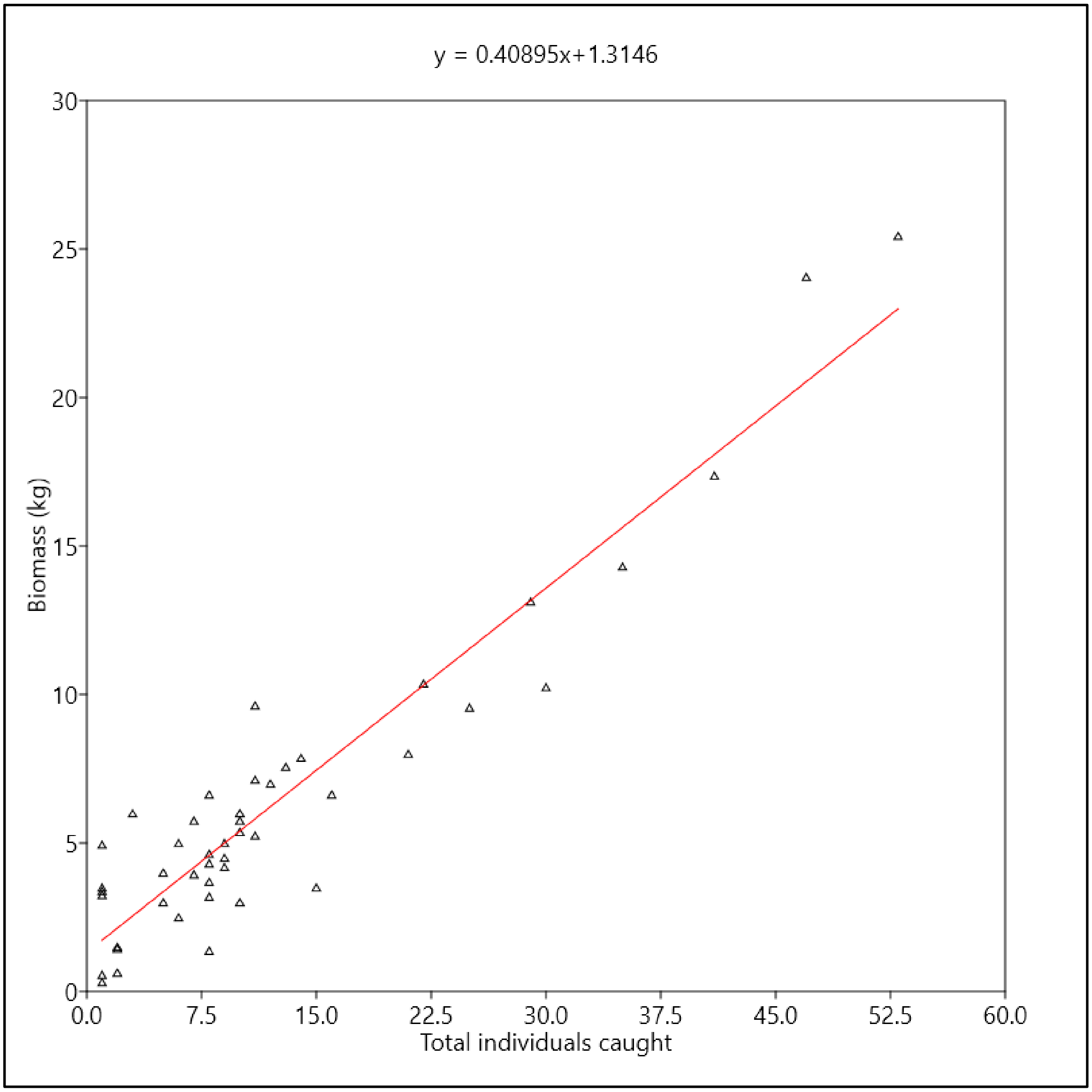
Figure B-2. Linear regression of total individual catfish removed vs total biomass (kg) removed from the San Marcos River in 2014.



Generalized linear model
Normal distribution, identity link

Dispersion phi:	6.0102 (estimated)		
Slope a:	0.45049	**Std. err. a:**	0.023952
Intercept b:	1.0468	**Std. err. b:**	0.3736
Log likelihood:	-52		
G:	353.74	**p(slope=0):**	6.5112E-79*

Figure B-3. Linear regression of total individual catfish removed vs total biomass (kg) removed from the San Marcos River in 2015.



Generalized linear model
Normal distribution, identity link

Dispersion phi:	3.2483 (estimated)		
Slope a:	0.40895	**Std. err. a:**	0.021971
Intercept b:	1.3146	**Std. err. b:**	0.38112
Log likelihood:	-22		
G:	346.46	**p(slope=0):**	2.5025E-77

Figure B-4. Linear regression of total individual catfish removed vs total biomass (kg) removed from the San Marcos River in 2016.