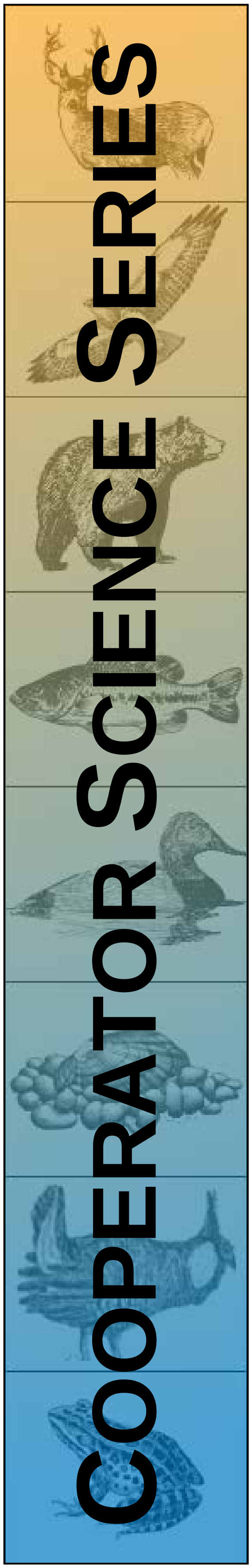

Variation and plasticity and their interaction with urbanization in Guadalupe Bass populations on and off the Edwards Plateau

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Final Project report to Texas Parks and Wildlife Department and the U.S. Fish and Wildlife Service

August 2017

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Executive Summary:

The Colorado River Basin in Texas has experienced major alterations to its hydrologic regime due to changing land and water use patterns. These anthropogenic influences on hydrologic variability have had major implications for riparian and aquatic ecosystems and the species dependent upon them. However, impacts are often assessed at a limited temporal and spatial scale, tending to focus on relatively short and discrete periods or portions of a river basin. It is not clear how basin-wide alterations occurring over decades affect species. Guadalupe Bass *Micropterus treculii* are endemic to central Texas and are typically associated with shallow runs and riffles in small streams. However, Guadalupe Bass are found throughout the Colorado River Basin, including the mainstem portion of the lower river downstream of the city of Austin where they support a popular fishery. Because Guadalupe Bass exist across a wide range of stream orders within the basin, it is unclear whether populations respond similarly to anthropogenic disturbances or to conservation and restoration activities. Therefore, our objectives were to:

1. Assess the effects of urbanization and hydrology on the population structure and dynamics of Guadalupe Bass.
2. Evaluate the effects of environmental gradients on ecomorphological variation in Guadalupe Bass populations across multiple spatial scales.
3. Describe the life history, habitat use, and behavior of the Guadalupe Bass population in the lower Colorado River and compare it to populations in more "typical" habitats.

Results contribute to an understanding of the response of Guadalupe Bass to anthropogenic disturbances, including increased urbanization in central Texas and further assist in the conservation of the species. The ability of the population to not only persist, but flourish downstream of a heavily populated urban area presented a unique opportunity to investigate a native species response to anthropogenic disturbance. This research revealed differences in Guadalupe Bass habitat associations and movements, contrasts in age and growth, and morphological variation across a gradient of disturbance throughout the Colorado River Basin. Results of this work provide information on the potential effects of human population growth and increased water withdrawals on Guadalupe Bass populations. Additionally, this work adds to an understanding of the unique Guadalupe Bass population found in the lower Colorado River and how it differs from upstream tributary populations. Gathering additional population-level information facilitates conservation actions critical to preserving preferred habitat and promoting growth rates for Guadalupe Bass in streams of different sizes and flow conditions while highlighting interpopulation differences that may warrant consideration for stocking programs and other management strategies. Key findings of this study were:

- The similarity in response of growth rates to streamflow throughout the Colorado Basin suggests phenotypic plasticity in this trait rather than population-specific adaptations.

- Reductions in streamflows in the Colorado River Basin, whether due to increased frequency of drought or increased anthropogenic water withdrawal, will likely result in lower Guadalupe Bass growth rates with the potential to impact the structure of populations.
- Growth and recruitment showed a positive correlation with increased baseflows and mean monthly flows; however, continued assessment is necessary to determine a true relationship.
- We documented morphological divergence among Guadalupe Bass populations in response to spatial and temporal environmental variation. These ecomorphological differences among populations provide insight into the ability of Guadalupe Bass to respond to the differing in-stream habitat and flow conditions between small 'typical' tributary systems and the mainstem Colorado River.
- Morphological variation may be a population-level adaptation that potentially needs to be taken into consideration when choosing broodstock to maximize stocking success within a system. Understanding the morphological differences between Guadalupe Bass populations in response to local conditions could improve the success of restoration and supplemental stocking programs, especially in the ever-changing landscape of central Texas.
- We established a baseline for understanding the morphological response of Guadalupe Bass to increased population growth and the threats posed by increased water withdrawals and impervious surface.
- The mainstem population of Guadalupe Bass was generally more mobile, and more responsive to changes in streamflow, than tributary populations. The observed differences could influence the response of Guadalupe Bass populations to conservation and management actions, such as habitat restoration efforts.
- Continued monitoring of recruitment and angler exploitation may be beneficial to identify any changes that could negatively impact the population. Conservation initiatives solely focused on physical instream or riparian habitat are unlikely to be as beneficial to Guadalupe Bass as those focused on restoring or maintaining adequate streamflow

Introduction

Guadalupe Bass *Micropterus treculii* is a native black bass species endemic to central Texas. It is found primarily in the Edwards Plateau ecoregion, but its range also extends downstream into the Blackland Prairie and Coastal Plains ecoregions in the lower Colorado River Basin (Curtis et al. 2015). Guadalupe Bass populations have declined across much of this range due to introgressive hybridization with introduced Smallmouth Bass *Micropterus dolomieu*. As a result, Guadalupe Bass has been identified as a species of greatest conservation need by Texas Parks and Wildlife Department and of special concern by Hubbs et al. (2008). Hybridization rates have exceeded 45% in some rivers (Garrett 1991; Littrell et al. 2007) with non-introgressed Guadalupe Bass being extirpated from the South Concho and the Blanco river until 2011 (Littrell et al. 2007). However, recent efforts to remove Smallmouth Bass and Guadalupe Bass X Smallmouth Bass hybrids or to stock large numbers of Guadalupe Bass fingerlings genetic swamping restoration are proving to be effective at reducing this acute threat . A more chronic threat facing Guadalupe Bass populations is habitat degradation and alteration resulting from changing land and water use patterns in central Texas (Bean et al. 2013; Curtis et al. 2015).

Streams throughout the Colorado River Basin, especially urbanized streams in Austin, have experienced changes in geomorphology and hydrology, including changes in slope and increases in peak flood magnitudes (Swezey 1991; Glick 2009; Passarello et al. 2012). The impacts of these changes and other urbanization effects, such as eutrophication, on Guadalupe Bass are not known and represent a significant information gap in the understanding of the threats to the species. Guadalupe Bass in the Colorado River Basin presents a unique model species with specimens in museum collections spanning a long-term temporal scale (Hendrickson and Cohen 2013), as well as extending spatially throughout the entire basin (Koppelman and Garrett 2002). In the smaller tributaries of the Colorado River Basin, Guadalupe Bass occupy a wide range of habitat types (Heilman et al. 2009). In these streams, Guadalupe Bass are most commonly associated with eddy mesohabitats and finer substrate where the depth is approximately 1.0 m and the current velocity of 0.05 m/s (Perkin et al. 2010), though there seem to be ontogenetic shifts in habitat use (Groeschel 2013). The population in the lower Colorado River occurs in a habitat that is greatly different from what is considered “typical” Guadalupe Bass habitat in Hill Country streams on the Edwards Plateau. It is unknown how this population differs in its age and length structure, habitat requirements, and recruitment dynamics from upstream populations that occur in habitat of a smaller Hill Country stream on the Edwards Plateau.

The mainstem Colorado River, flowing through the Edwards Plateau in central Texas (Figure 1), is one of the major rivers within the Guadalupe Bass range. Human populations are expected to increase drastically in the basin by 2050, with some areas expected to more than double in size, increasing demands on water resources (Hoque et al. 2014; Colby and Ortman 2015). In the reach from Lady Bird Lake in Austin, Texas to the most downstream occurrence of Guadalupe Bass, there is a pronounced gradient in watershed urbanization. The mainstem Colorado River and its tributaries experience increasing urbanization as they flow into Austin, and the extent of urbanization declines as the river progresses downstream. Altered land and water use patterns along the gradient of urbanization are accompanied by flow-regime alteration, including agricultural and municipal water supply diversions, irrigation and treated sewage effluent return flows, changes in run-off dynamics associated with impervious surfaces, and low-water dams. These impacts lead to fragmentation and homogenization of instream habitat in the mainstem and tributaries of the Colorado River. The compounding effects of urbanization place stressors on downstream aquatic populations that can be either acute, resulting in the rapid extirpation of local populations (Onorato et al. 1998), or chronic and cumulative, changing population dynamics and increasing the vulnerability of local populations to environmental stressors or stochasticity (McDonnell and Hahs 2008). Because many species are sensitive to stressors associated with landscape alteration, fish are considered reliable indicators of urbanization impacts (Wang et al. 1997; Helms et al. 2005; Poff and Zimmerman 2010). Variation in urbanization impacts throughout the Colorado River Basin provides an opportunity for determining the degree to which Guadalupe Bass and other stream fishes exhibit plasticity in their behavior and biology in response to anthropogenic disturbance.

Understanding intraspecific variation, whether through genetic diversity or phenotypic plasticity, is critical in determining the resiliency of populations in rapidly changing environments (Lande 2009; Chevin et al. 2010; Seebacher et al. 2014). Documenting inter-population trait variation in response to environmental change, as well as the consequences of these responses, is essential to the understanding of population resiliency and the success of management regimes for a single species across systems (Storz et al. 2010; Wennersten and Forsman 2012). For example, two *Cyprinella* species, *C. lutrensis* and *C. venusta*, exhibit intraspecific trait divergence between reservoir and stream-residing populations (Haas et al. 2010; Franssen 2011). *Cyprinella lutrensis* individuals in reservoirs tended to have smaller heads and deeper bodies, which are associated with habitats under low flow conditions and high predator densities. Increased predator evasion, swimming performance and maneuverability for feeding are all associated with increasing body depth and caudal fin area suggesting morphological shifts favor greater fitness for individuals residing in reservoirs (Franssen 2011; Franssen et al. 2013). In addition to understanding of morphological divergence between reservoir and stream populations, there is a need to understand variation that may exist between populations upstream and downstream separated by barriers to movement. This is especially important in central Texas, where increasing urbanization and demand for water resources has established a gradient of disturbance from upstream tributary systems to downstream mainstem populations.

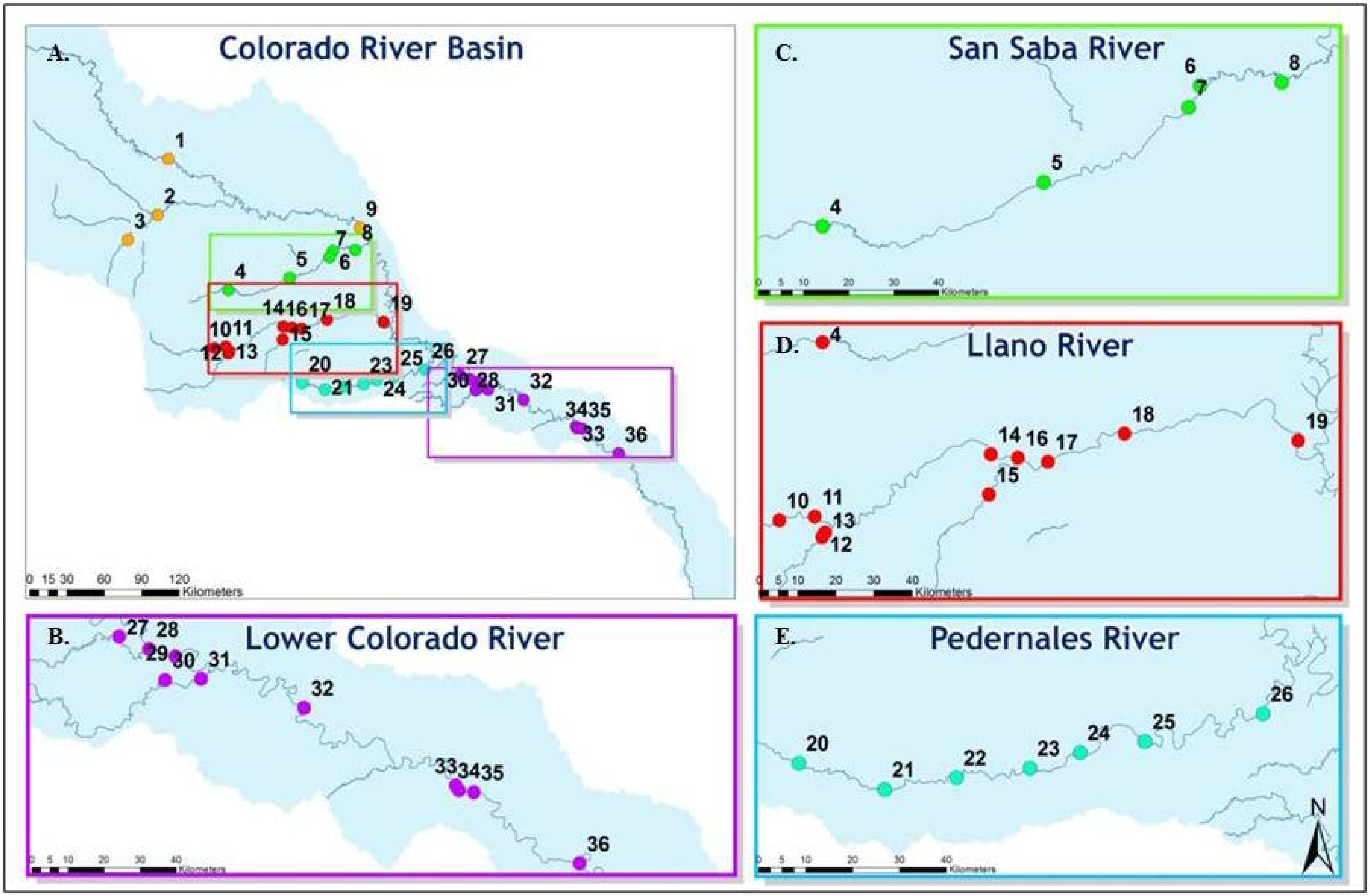

Figure 1. Map indicating the distribution of study sites in the Colorado River Basin. Inset C-E indicate major tributary sites and B shows sites located on the lower Colorado River below Longhorn Dam in Austin, Texas.

Guadalupe Bass are found across a wide range of habitats throughout the Edwards Plateau; a population also occurs in the lower Colorado River and has been documented as far downstream as Altair, Texas (Hendrickson and Cohen 2013; Curtis et al. 2015). Despite the extensive range of Guadalupe Bass in Texas, they are considered fluvial habitat specialists, exhibiting both ontogenetic and seasonal shifts in habitat utilization (Perkin et al. 2010; Groeschel 2013). Dependence on instream structure and variable habitats for different life history stages heightens the vulnerability of the population to habitat alteration (Garrett et al. 2015; Birdsong et al. 2015). Seasonal shifts in habitat utilization range from deeper pools with some current for overwintering and shallow sheltered areas near flowing water for nest construction and spawning (Edwards 1980; Perkin et al. 2010; Enriquez et al. 2016). Ontogenetic habitat shifts occur throughout early life stages with movement toward increased current and depth following the juvenile stage (Edwards 1980). Guadalupe Bass are listed as a 'intolerant' species in the regionalized Index of Biotic Integrity due to their dependence on an undisturbed heterogeneous habitat mosaic for the completion of their life history (Linam et al. 2002). Intolerant species are the first to disappear due to factors ranging from siltation to altered hydrology associated with human disturbance (Karr 1981; Fausch et al. 1984; Karr et al. 1986).

While the sensitivity of the species has been documented in tributary systems on Edwards Plateau, the persistence of populations in the lower Colorado and the Highland reservoirs are relatively understudied. The ability of Guadalupe Bass to respond and tolerate a range of conditions is evident based on the capacity of these populations to thrive across a variety of habitats, as well as persistence in novel environments under altered conditions. Further study of trait variation within Guadalupe Bass in response to changing environmental conditions would facilitate improved management and conservation of intraspecific variation within the population. Previous research has found that intra-population niche variation across nine Guadalupe Bass populations was mostly influenced by morphological variation. Individual specialization in wild Guadalupe Bass populations can occur at low levels of genetic diversity due to plasticity . Trophic diversity in Guadalupe Bass wild populations has been shown to be largely driven by plasticity in morphological characters in response to the differences in flows and productivity across systems (Bean 2012). The inclusion of strategies for monitoring intraspecific variation is emerging as an important consideration for successful management of populations (Mimura et al. 2017). Understanding and monitoring intraspecific variation of Guadalupe Bass requires comprehensive knowledge on both genetic and phenotypic variation within the population. The Texas Parks and Wildlife Department (TPWD) has committed a great deal of resources to monitoring and eliminating genetic threats to the population (Whitmore 1983; Koppelman and Garrett 2002; Fleming et al. 2015). A next step for the successful management of the population is to gain an understanding of the plasticity within the population and the ability to respond to environmental stressors permitting population persistence under variable conditions.

The overall objectives of this study were to 1) assess the effects of anthropogenic disturbance on Guadalupe Bass population structure and dynamics in the Colorado River Basin, 2) evaluate spatial variation in ecomorphology, 3) compare the life history, habitat use, and behavior of Guadalupe Bass populations in the lower Colorado River to smaller Hill Country stream populations on the Edwards Plateau. Results of this work will assist in gaining an understanding of the response of Guadalupe Bass to anthropogenic disturbances, including increased urbanization in central Texas, and further assist in the conservation of the species.

Methods

Study Areas

The Colorado River begins in Dawson County, Texas and flows approximately 965 km before flowing into Matagorda Bay. The river and its tributaries run through multiple ecoregions including the Central Great Plains, Edwards Plateau, Cross Timbers, Texas Blackland Prairie, and the East Central Texas Plains. The watershed drains an area of 103, 341 km^2, and the majority (93,000 km^2) lies within the karst ecoregion of the Edwards Plateau in central Texas. It is within the Edwards Plateau that spring systems feed the Colorado's major tributaries: the Llano, Pedernales, San Saba, and Concho Rivers (Clay and Kleiner 2010). The study reach on the lower Colorado River extended approximately 285 km from Longhorn Dam in Austin to the Garwood Dam (29.51490°N, 96.40828°W) downstream of Altair, Texas (Figure 1).

Sites on the three upper watershed tributaries, the Llano, San Saba, and Pedernales Rivers, were sampled (Figure 2, Appendix A). The San Saba River is formed at the confluence of the North Valley Prong and the Middle Valley Prong in Schleicher County. The mainstem of the San Saba runs approximately 225 km through Menard, Mason, and McCulloch counties draining an area of 8,158 km^2 before reaching the Colorado River in San Saba County. The Llano River is a larger tributary that drains approximately 11,559 km^2 area. The mainstem of the Llano River runs 161 km from the confluence of the North and South Llano Rivers into Lake Lyndon B. Johnson. Sites on the North and South Llano River and James Rivers were sampled in addition to the mainstem. The North Llano River begins in Sutton County and runs approximately 64 km to its confluence with the South Llano River. The South Llano River begins in Edwards County and runs 89 km, before joining the North Llano River in Kimble County. The James River runs approximately 55 km and drains into the Llano River in Mason County. Finally, the headwaters of the Pedernales River are in Kimble County and flow 208 km to Lake Travis on the Colorado River. The Pedernales River watershed encompasses 3,314 km^2 in Gillespie, Blanco, Hays, and Travis counties. All sampling sites were selected based on public access to the stream and the availability of historical collection materials of (Appendix B) Guadalupe Bass (Edwards 1980).

Characterizing instream habitat availability

Instream substrate in the lower Colorado River between TX- 130 highway crossing and the agricultural dam in Garwood, Texas was identified from side-scan sonar video of the river bottom recorded using a Humminbird 998cSI sonar unit (Humminbird™, Eufaula, Alabama) with a starboard rail mounted transducer. The position and heading of the boat was tracked at 3-s intervals throughout the survey using a Garmin 78c handheld GPS unit (Garmin™ International, Olathe, KS) connected directly to the control head of the sonar unit. SonarTRX™ (Leerand Engineering Inc., Honolulu, Hawaii) was used to process all recorded video in preparation for substrate classification. Videos were converted into georeferenced images, the water column was removed, and corrections were made for altitude of the transducer and beam angle. Once corrected images were imported into ArcGIS 10.2.2 (ESRI™, Redland, California) and classified using digitized polygons to distinguish substrate classes. Dominant substrate classifications were: bedrock, cobble, gravel, sand, mud and silt, submerged aquatic vegetation (SAV), and unidentifiable substrates. In addition, mesohabitats (riffles, runs, and pools) were also classified (Barnhardt et al. 1998; Kaeser et al. 2013). Mesohabitats were delineated using high resolution aerial imagery available on Google Earth and provided by the United States Department of Agriculture (USDA). Shallow areas where the side-scan sonar could not be deployed were characterized as riffle habitats. Runs were characterized as the areas upstream or downstream of riffles where the water's surface is not broken at baseflow conditions. Finally, pools were deeper areas with slower current. All potential riffles were identified and then ground-truthed to confirm presence and accurate delineation. Mesohabitat was confirmed on-site (Appendix E).

Land Cover and Flow Data

Land use and land cover (LULC) changes were determined for 30 hydrologic unit code (HUC) 10 watersheds (Figure 2) encompassing all study sites chosen based on previous collections by Edwards (1980) during 1975-1978. Historical and present geospatial data were used to determine land use alteration and total watershed area. Land use and land cover data from the 1970s and 1980s were obtained from the U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA) Program, which classified Landsat images (30 m resolution) collected from 1972 to 1976 using the Anderson II classification system for LULC. Once images were collected they were classified into 45 different classes from 1975 to 1981 (McMahan et al. 1984). Current LULC data were obtained from the Texas Parks and Wildlife (TPWD) Ecological Systems of Texas (Diamond and Elliott 2015). TPWD used remote sensing to classify the current landscape at 10 m resolution and into over 100 different classes. Additionally, USGS National Land Cover Datasets (NLCD) for 1992 and 2001 were obtained for further comparison (Fry et al. 2009). Historical and present LULC data were reclassified into broad landscape classes of agriculture, barren, forested, herbaceous, urban high, and urban low consistent between data sets in order to focus comparison on primary land conversion rather than vegetation types. Reclassification of each LULC dataset is defined in Appendix F. Land use and

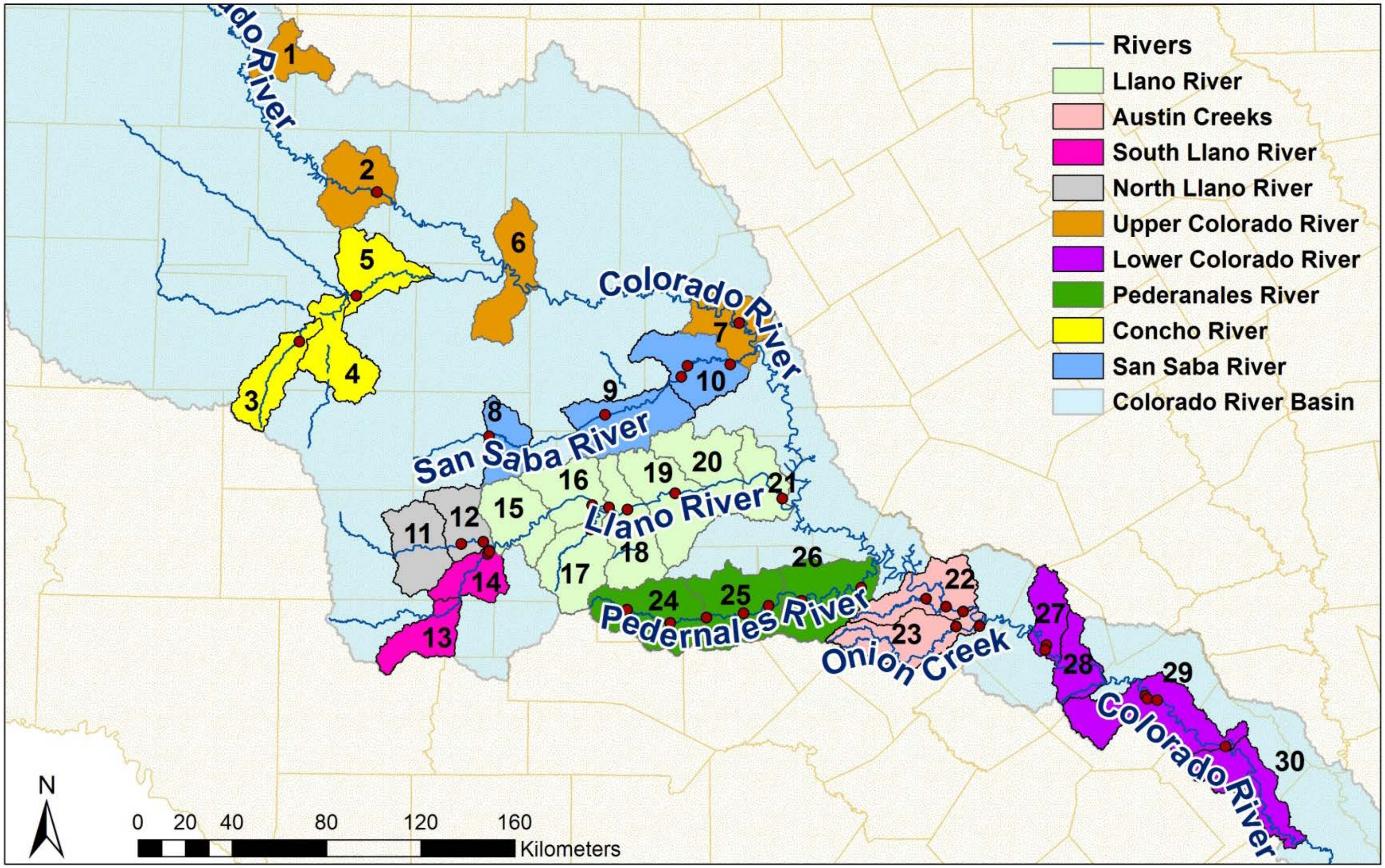

Figure 2. HUC10 watersheds used to evaluate land use alterations for study sites from 1980 to 2012 (Appendix C). The red dots also represent the USGS stream gages used for Indicators of Hydrologic Alteration (IHA) statistics (Appendix D).

land cover (LULC) data were evaluated for percent difference between two time periods in order to visualize the gradient in of disturbance in the Colorado River Basin. Percent changes in LULC within each HUC 10 watershed (Figure 2; Appendix G-H) were used as environmental variables for further analysis.

We evaluated changes in the variability of flow conditions across tributaries of interest and the mainstem Colorado River between the 1970s and 1980s and present collection periods. Hydrological alteration was determined from the historic and present discharge records using USGS streamgages closest to each sampling location (Appendix D). Distance between each stream gage and sample location was also calculated using the Network Analyst tool in ArcGIS. Discharge records were divided into pre-1980 and 1995 to 2016. Using Indicators of Hydrologic Alteration (IHA) (TNC (The Nature Conservancy) 2012) analysis, we assessed the amount of variability between the two periods using the range of variability approach (RVA) proposed by Richter et al. (1997). This approach scales hydrologic alteration between the two periods on a scale of variability ranging from -1 to 1 for 34 parameters from monthly flows to maximum and minimum flows at varying time periods. Variability is assessed as the years during the current period where a given parameter is above or below the historic 25^{th} and 75^{th} percentiles for the same hydrologic parameter established using the historical period. When there is a positive value there is a decrease in the variability and when there is a negative value then there is an increase in the variability. Range of Variability scores allow for the comparison of those streams influenced by anthropogenic disturbance and those that reflect more undisturbed streams (Richter et al. 1997; Principato and Viggiani 2007).

Range of variability scores were used to compare flows between two time periods, across multiple years and establish a gradient in comparison of all sub-watersheds of interest. In addition, inter-annual hydrologic variability within the periods was assessed using the coefficient of variation (CV) for each of the hydrologic parameters. The CV measures the variability of individual hydrologic parameters as the average standard deviation across years for the mean of the parameter within the time period. Morphological analyses were conducted with the most informative flow and LULC variables determined by stepwise discriminant function analysis.

Annual flow variables for a single year were also evaluated in IHA. Annual flow parameters were associated with standardized residual growth and shape variables to evaluate the influence of flow between single years. The numbers of variables associated with the IHA parameters were reduced to the two principal component axes explaining the most variation in hydrological parameters determined using principal component analysis (PCA). Principal component scores for hydrological alteration were then associated with each individual Guadalupe Bass collected based on proximity to collection site. When the closest gage data was not available for the time of collection, the next closest upstream or downstream gage was used. Discharge data for the South Llano River did not become available until 01 October 2012, therefore prior to 2012 discharge data for the South Llano River was estimated as the difference between the North

Llano River gage and the downstream Llano River gage. The Llano River gage is located 5.33 km downstream of the confluence of the North Llano River and the South Llano River, which are the only contributing tributaries to the discharge rates recorded at the Llano River gage. The James River did not have a stream gage and estimates from comparing upstream and downstream Llano River gages was not feasible due their distances from the James River confluence.

Data Analysis

Land cover and hydrologic alteration variables were reduced to linear components representing the variation across sites within the Colorado River Basin using a principal component analysis (PCA). Hydrologic variability between sites was assessed using Indicators of Hydrologic Alteration (IHA) software (TNC (The Nature Conservancy) 2012) to compare tributary to mainstem Colorado River sites. Variables were put into four groups for further analysis: 1) monthly average, 2) annual extremes in water minimum and maximums flow, 3) high and low pulse duration and frequency, and 4) overall change rate and frequency in water conditions. Principal components analysis was then used to differentiate between historical and present flow conditions, as well as between river systems.

Electrofishing Surveys

Surveys were conducted at thirty 100-m long sites (Figure 1) throughout the Colorado River Basin from March 2014 to May 2016 using backpack electroshocking and seining. Boat electroshocking was used when applicable on the mainstem Colorado River in the study reach starting at the 130-highway crossing just east of Austin downstream to the agricultural dam in Garwood, Texas. Each site was sampled twice each year with all black bass being identified and measured. Water temperature, current velocity, conductivity, turbidity, canopy cover, stream width, riparian vegetation present and substrate were recorded for each sampling transect. A Marsh McBirney Flow-Mate 2000 flow meter (Hach Company, Loveland, Colorado) was used to record the flow velocity profile. All other water quality parameters were recorded using an YSI Model 95 handheld water quality meter (YSI, Yellow Springs, Ohio) and an Oakton TN-100 portable turbidimeter (Oakton, Vernon Hills, Illinois).

All Guadalupe Bass individuals were measured to the nearest mm total length (mm TL). Three to five scales were then removed from the lateral line posterior to the pectoral fin (White and Chittenden 1977). A subsample of captured Guadalupe Bass and potential prey species was euthanized through immersion in a > 400-mg/L aqueous solution of clove oil (eugenol) as per American Veterinary Medical Association Guidelines on Euthanasia (Leary et al. 2013). These samples were preserved on ice for transfer to the lab where a photograph was taken and scales, and otoliths were removed. Scales and otoliths were cleaned of any adhering tissue and stored dry in a standard scale envelope.

Age and Growth

Dried scales were laid flat between two glass slides and then submerged in a petri dish of water to capture digital images using an Olympus brand model SZX16, Infinity 1, compound microscope. Image J v. 1.48 (Abramoff et al. 2004) software was used to measure the annuli. Fish length at each annulus was back calculated using (methods decribed by Devries and Frie 1996. January 1 of each year was the assumed birthdate for all scale readings (Jones and Wells 1998). Age estimates were made by two readers and a concert read made by a third reader if there were discrepancies. Sagittal otoliths from a subsample of Guadalupe Bass were removed and set in small weigh boats (Scientific Equipment of Houston, Navasota, Texas) with epoxy (EasyCast™, Environmental Technology Inc., Fields Landing, California). Otoliths were sectioned using a low-speed isometric saw (Model 650 Low Speed Diamond Wheel Saw, South Bay Technology, San Clemente, California), through the nucleus of the otolith. Sections were then set on microscope slides using super glue (Loctite™ Brand, Westlake, Ohio). All otolith sections were measured for radius of section from the edge of the nucleus to the outer edge of the otolith and the width of each annulus.

Data Analysis

Age and growth analysis of Guadalupe Bass was performed using 310 scales and 271 otoliths. The influence of structure type on age estimates of Guadalupe Bass was examined for individuals (n=71) where both scales and otoliths were used. Scale data included scales from historical specimens collected between 1975 and 1978 by Edwards (1980) and stored at the Texas Natural Historical Museum collection. Von Bertalanffy growth curves were fit to the back calculated length at age data for both scales and otoliths throughout the Colorado River Basin. Age and growth in the lower Colorado River was assessed separately in order to determine relative recruitment and mortality of this population. An age-length key was created with 25 mm total length (TL) intervals (Table 1). The age-length key was then used to determine the probability that an individual in a length interval is a given age (Ricker 1975; Coggins et al. 2013). Relative recruitment was calculated as the residual of a cohort from the regression model of the descending leg of the catch curve for a sample of 336 Guadalupe Bass captured in 2015 following Ricker (1975) and Maceina (1997).

An age-length key was generated from a sub-sample of fish that were aged (Coggins et al. 2013). The key was then used to assign ages to all individuals collected whose ages were not determined using otoliths or scales. Individuals were probabilistically assigned to an age given the length. Length and ages were then used to estimate growth and mortality throughout the Colorado River Basin. Growth rate and the relationship of residuals from the growth curve to environmental variables were determined from Guadalupe Bass back-calculated length-at-age data. The coefficient of variation (%CV) was calculated for scales and otoliths in order to determine the precision of age determination between both structures (Chang 1982; Campana 2001).

Total length at age was calculated and back-fitted to a Von Bertalanffy growth curve, (Von Bertalanffy 1938). Back-calculated length-at-age data fitted to a Von Bertalanffy growth curve were used to determine the growth rate and differences related to environmental variables. Additionally, mortality and recruitment for the Guadalupe Bass population in the lower Colorado River were evaluated. The slope of the catch curve on the descending leg was used to estimate instantaneous mortality (Z) as described by Ricker (1975). There was a significant difference between age estimates from otoliths versus scales ($F_{1,72}$= 45.84, P<0.01). Scales reported older ages for individuals collected in the spring and winter compared to otoliths, while otoliths tended to give older ages for individuals collected in the fall.

Flow metrics, individual age, time and river were then tested for influence on standardized growth using a mixed-model repeated measures analysis of covariance (ANCOVA) (Rutherford 2011). ANCOVA results for scale ages were limited to the larger tributary systems (Llano, San Saba, and Pedernales Rivers), as well as the mainstem Colorado due to inadequate sample size. Discharge rates were represented as covariates, site and back-calculated age as independent variables and individual as the effect in the models. All analyses were performed using SAS 9.4 (SAS Institute, Inc., Cary, North Carolina).

Geometric Morphometrics

Methods modified from Zelditch et al. (2004) were used for taking geometric morphometric measurements. A digital camera (Nikon D3200, Melville, New York) was used to take a lateral left-side photo of each individual Guadalupe Bass collected, along with historical specimens (n=457) from the Colorado River basin stored at the Texas Natural History Collection (Appendix B). Photos were taken with a reference scale. Morphological landmarks (Table 2) were digitized and a scale set using tpsDig v. 2 software (Rohlf 2004a). Specific landmarks were chosen (Table 2, Figure 3) based on previous fish morphological studies (Svanbäck and Eklöv 2006; Langerhans 2008; Arbour et al. 2011; Franssen et al. 2013a). All photographs were marked by a single observer for consistency and TPSUtil v. 1.46 software (Rohlf 2004b) was used to randomize images after a landmark had been marked on each photograph in order to any prevent sequence effects.

Table 1. Age-length key for Guadalupe Bass in the lower Colorado River, Texas based on otolith age at capture and total length (TL) at age of collection between 2014-2015. Rows indicate the percent probability that with the given 25mm length interval a Guadalupe Bass individual is a certain age.

	Age						
TL(mm)	1	2	3	4	5	6	
75-99	100	0	0	0	0	0	
100-124	33.33	66.67	0	0	0	0	
124-149	25	75	0	0	0	0	
150-174	12.5	62.5	25	0	0	0	
175-199	0	62.5	12.5	25	0	0	
200-224	0	40	40	20	0	0	
225-249	0	40	0	60	0	0	
250-274	0	0	42.86	28.57	14.29	14.29	
275-299	0	0	57.14	28.57	14.29	0	
300-324	0	0	0	66.67	33.33	0	
325-349	0	0	0	44.44	44.44	11.11	
350-374	0	0	0	0	100	0	
375-399	0	0	0	0	0	100	
400+	0	0	0	0	0	100	
Total	9	19	12	18	11	4	73

Once morphometric images were landmarked, General Procrustes Analysis (GPA) (Rohlf 2004c; Mitteroecker and Gunz 2009; Webster and Sheets 2010; Zelditch et al. 2012) was used to take into account the effects of translation, scale, and rotation on the spatial covariation of the landmarks using TPSRelw software (Rohlf 2004c). Variation in multivariate body shape was represented as the deviation of the individual from the consensus or the mean configuration. Deviations were quantified as non-affine (partial warps) components. Principal components analysis was performed using partial warps in TPSRelw to derive principal components, also known as relative warps. Relative warps were used in all further analyses as dependent variables representing shape changes. TPSRelw was also used to calculate the square root of the sum of the squared distances from each landmark to the centroid for all 15 landmarks to determine centroid size, a metric for body size (Bookstein 1984; Zelditch et al. 2012). While superimposition is useful for removing size differences in shape variables (relative warps) produced, we used centroid size as a covariate in further statistical analyses to account for allometric relationships between body size and shape differences (Mitteroecker and Gunz 2009; Krabbenhoft et al. 2009; Webster and Sheets 2010; Elmer et al. 2010). Thin-plate spline transformation grids were then used to visualize the individual variation in shape.

Due to concerns about preservation effects influencing the results of comparisons made between historical collections and this study, we conducted an experiment to assess the effects of preservation on morphology. Guadalupe Bass collected by Edwards (1980) were stored for 20+ years in formalin before being transferred to ethanol at the Texas Historical Museum Collections for long-term storage. We photographed a sample (n=21) of Guadalupe Bass following the procedure described previously, before fixing and storing them in a 10% buffered formalin solution for 18 months. The fish were removed at six-month intervals, rinsed, and photographed and returned to the formalin solution After 18 months, the fish were rinsed in running tap water for 48-hours and transferred to 70% ethanol. The ethanol was changed after five days, and after 30 days the fish were removed and photographed a final time. The same 15 landmarks as described above were used for measurements. Overall morphological change was determined using principal components analysis also known as relative warp analysis (Rohlf 1993; Milliron et al. 2002; Querino et al. 2002; Zelditch et al. 2012). We examined morphological variation at each time period from the mean relative warp (RW) scores at initial capture.

Data Analysis

Spatial and temporal morphological variation across all rivers was detected using mixed model multivariate analysis of covariance (MANCOVA) (Marcus et al. 1996) with 26 relative warps and two uniform components as dependent shape variables. Each individual was assigned to either the historical or present time period, river, and time category nested within river were independent variables in the model with centroid size as a covariate. Centroid size is the square root of the sum of squared distances from the centroid to each landmark in the configuration.

Centroid size was included in the analysis in order to determine if there was any ontogenetic variation in shape variables. The analysis was conducted with and without centroid size to see if there was a significant effect of allometry.

The partial variance explained by each factor in the model was estimated using an F-test based on Wilks's n^2 (Langerhans and Makowicz 2009). Discriminant function analysis (DFA) (McGarigal et al. 2000a)was used for cross-validation and to determine assignment of individuals for river and time category based on shape variables (relative warps) and centroid size. Classification into stream order classes was determined using DFA, with the four classes low order upper watershed tributaries (Dove Creek, North Llano River, South Llano River, James River), higher order upper watershed tributaries (San Saba River, Pedernales River, Llano River), lower order Austin area creeks (Barton Creek, Walnut Creek, Onion Creek), and finally the mainstem Colorado River. Canonical correlation analysis (CCA) (McGarigal et al. 2000b) was used to determine variation in body shape distinguishing between historical and present individuals in relation to environmental variables. All statistical analyses were performed using SAS 9.4 (SAS Institute, Inc., Cary, North Carolina).

Movement

Guadalupe Bass (≥ 200 mm TL) were collected from the lower Colorado River using a boat-mounted electrofisher during December 2014 (*n*=26) and December 2015 (*n*=5; Figure 4). Radio transmitter tags were surgically implanted into the abdominal cavity following the methods described by Grabowski and Isley (2006). All fish used were large enough so the tag in air was ≤ 2% of the body weight (Winter 1983) to minimize impacts of the tag on movement. Immediately after capture, fish were anesthetized by being immersed in a 40 mg/L solution of clove oil (eugenol; Peake 1998). Once a loss of equilibrium was observed they were placed in a surgical cradle and the incision site was wiped with gauze soaked in betadine solution. A 2-cm incision was made into the peritoneal cavity and a Lotek MCFT2-3BM (11 x 43mm, 8.0 g in air) radio transmitter tag (Lotek Wireless Inc., Newmarket, Ontario) with a trailing wire antenna was inserted into the body cavity. Radio transmitter standard battery life was between 444 and 723 days when signaling with 5.0 seconds between bursts. The wire antenna was then threaded through a stainless steel 304 gage syringe needle poked through the body wall approximately 3-4 cm posterior of the incision (Ross and Kleiner 1982). The incision was then sutured using 1-2 non-absorbable, polypropylene sutures (Walsh et al. 2000; Grabowski and Isely 2006; Grabowski and Jennings 2009). Following surgery all fish where held in a holding tank until fully recovered and released within a 100 m of their capture site.

Table 2. Location of the 15 landmarks used for morphological comparisons of Guadalupe Bass throughout the Colorado River Basin, Texas.

Landmark	Location
1	Anterior edge of premaxillary
2	Caudal peduncle
3	Fork the caudal fin
4	Center of the eye
5	Insertion of the last ventral ray on the pectoral fin
6	Anterior end of the dentary
7	Posterior most point of maxillary
8	Origin of first dorsal fin
9	Origin of second dorsal fin
10	Origin of anal fin
11	Insertion of last anal fin ray
12	Dorsal origin of caudal fin
13	Ventral origin of caudal fin
14	Insertion of last ray of second dorsal fin
15	Insertion of pelvic fin

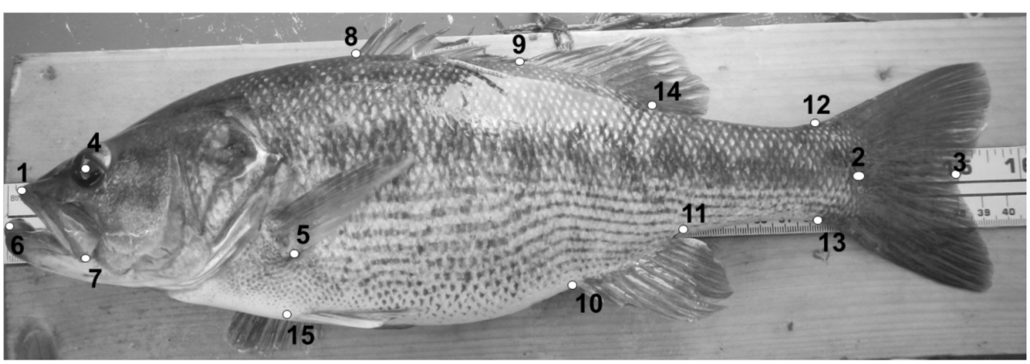

Figure 3. Location of the 15 landmarks used for morphological comparison of Guadalupe Bass throughout the Colorado River Basin, Texas. A description of the landmarks used is presented in Table 2.

Table 3. Tagging location and date, total length (TL), tag identification number, and number of relocation events for thirty Guadalupe Bass implanted with MCFT2-3BM radio transmitter tags (Lotek Wireless Inc., Newmarket, Ontario, Canada) during December 2014 and December 2015 in the lower Colorado River, downstream of Austin, Texas. Locations of tagging sites are listed from the most upstream site to the most downstream site. Exact locations are shown in Figure 4.

Tagging site	Date	TL (mm)	Tag identification	Number of relocations
Utley	16-Dec-15	368	90	7
(*n* = 5)		371	95	5
		372	92	7
		399	94	7
		436	93	6
Bastrop	17-Dec-14	279	31	9
(*n* = 6)		331	39	17
		336	40	11
		357	32	6
		401	47	17
		415	43	20
Smithville	15-Dec-14	264	33	9
(*n* = 8)		266	35	10
		277	12	11
		281	18	17
		285	38	18
		290	14	18
		385	11	17
		400	20	13
La Grange	15-Dec-14	266	27	11
(*n* = 3)		279	26	18
		323	25	13
Altair	16-Dec-14	249	15	16
(*n* = 7)		262	28	11
		317	19	16
		319	30	7
		324	24	7
		343	17	3
		351	23	8

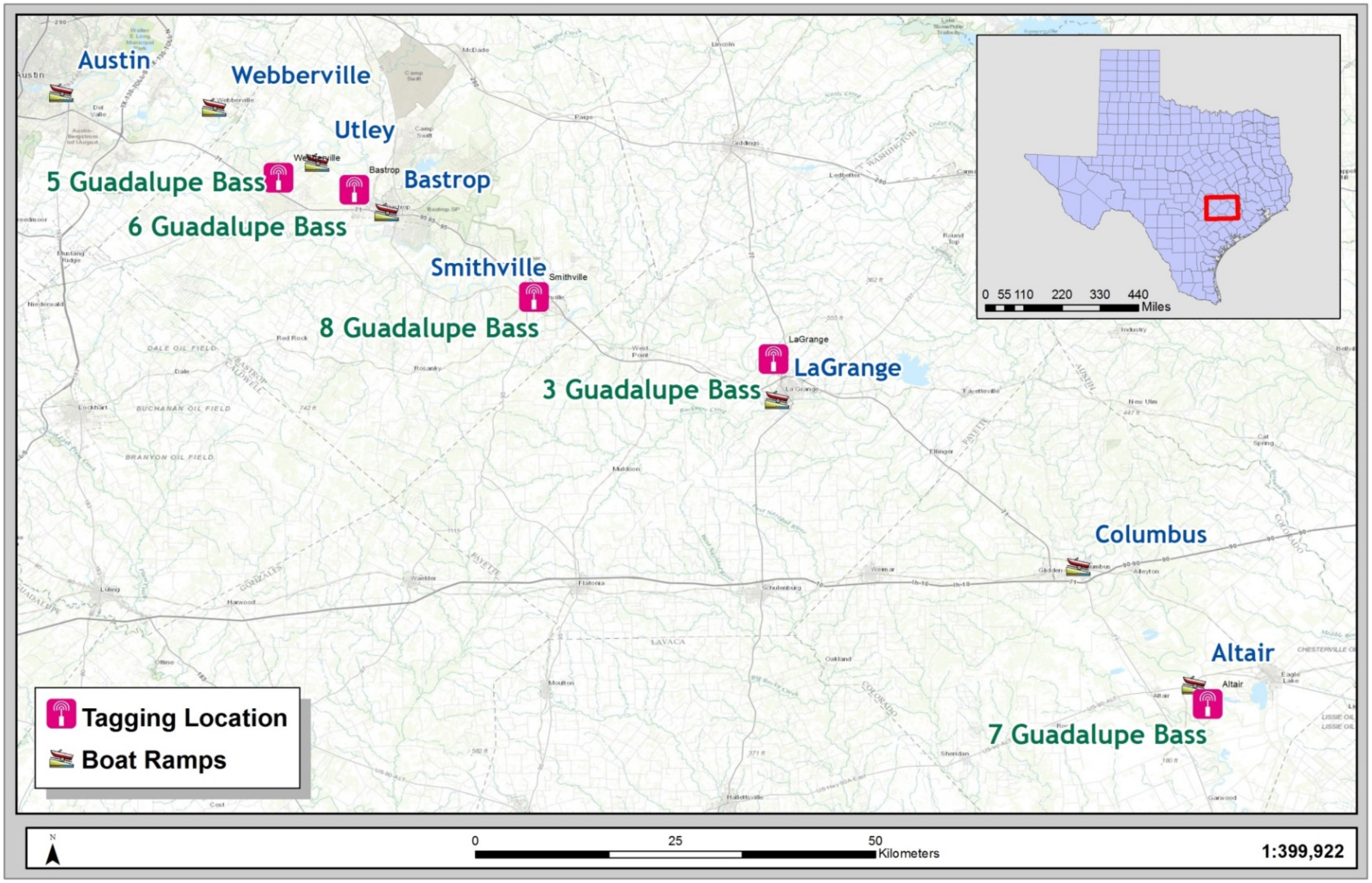

Figure 4. Locations of the original capture locations of Guadalupe Bass implanted with radio transmitters (*n* = 29) during December 2014 and December 2015 in the lower Colorado River downstream of Austin, Texas. Twenty-four Guadalupe Bass were tagged in December 2014 at the Bastrop, Smithville, LaGrange and Altair sites. An additional five Guadalupe Bass received radio transmitters in Utley during December 2015.

Data Analysis

Individuals were considered as primary sampling units and statistical inference was based on the individual as replicates. Repeated measures analysis of variance (ANOVA) with individual fish as the repeated measure was used to determine if mean movement varied across site or season. Movement was quantified as displacement and absolute movement. Displacement is defined as the minimum movement from the previous location, where net upstream movement is indicated by positive displacement values and negative values indicate downstream movement. Mean absolute movement was determined as total movement from tagging location with no associated upstream or downstream value. ANOVA was also used to determine mesohabitat and substrate availability differences seasonally and between sites. Home range analysis was done in ArcGIS 10.2.2 (ESRI, Redland, California), following the methods of Laffan and Taylor (2013). We calculated the 90% isopleth, where the fish is located 90 percent of the time and then the subset 50% isopleth range. The 50% isopleth range indicates the area where the fish was located 50% of the time. The core home range area of high use is indicated by the 50% estimate of home range (Laffan and Taylor 2013).

Fish were tracked over 260 river km between Webberville and Altair, TX. Approximately seven tracking surveys were performed in the spring (March, April, May) of each year, followed by surveys every other month. Fish were relocated for the entire battery life of the transmitter. Water temperature, conductivity, turbidity, time, GPS coordinates, mesohabitat and substrate type were recorded at each relocation. Water quality parameters were measured using a YSI Model 95 handheld water quality meter (YSI, Yellow Springs, Ohio) and an Oakton TN-100 portable turbidimeter (Oakton, Vernon Hills, Illinois). Global Positioning System data was visualized in ArcGIS using network analysis in order to determine distance moved by each individual. The movement rates, home range size, site fidelity and the influence of discharge and habitat on the activity levels of Guadalupe Bass in the lower Colorado River Basin, Texas through weekly and bi-monthly tracking were evaluated.

Results

Land Cover and Flow Data

Retention of the first two principal components from the PCA explained the majority of cumulative variance for both landscape variables and range of variability (RVA) scores for flow variables (Figures 5-7; Appendix G- J). The first three principal component scores explained 64.6% of the variance among the sites for RVA-scored hydrologic alteration and 81.2% of the variance among the sites for the percentage difference across the landscape variables. The first two principal components for the LULC comparison between historical (1970s and 1980s) and present (2012) explained 82.8 % of the variation. The first principal component (PC1) accounted for changes in urbanization, as decreasing low urban area and increasing high urban area, as well as decreasing forested area (eigenvector: 2.83; proportion of variation: 0.47). Decreasing herbaceous land cover, increasing agricultural and forested land were the primary sources of variation accounted for by the second principal component (eigenvector: 2.14; proportion of variation: 0.36). The first two principal components for the LULC comparison between historical (1992) and present (2012) explained 67.8 % of the variation. The first PC largely explained changes in agricultural and forested land (eigenvector: 2.93; proportion of variation: 0.49). The second PC differentiated between barren and urbanized LULC variables (eigenvector: 1.13; proportion of variation: 0.18).

Overall, there were decreases in herbaceous land cover reflected in increases in forested land cover in all sub-watersheds. The consistent trends across all sub-watersheds are likely due to differences in classification schemes between the two LULC datasets. The San Saba River and Llano River sub-watersheds showed the least amount of change out of all sub-watersheds of interest. Two HUC 10 watersheds encompass the city of Austin, Texas (Figure 2) and over the thirty-year period HUC 10: 1209020504 showed little change in LULC, while HUC 10: 1209020503 showed a decrease (-3.6%) in high urban area and an increase (7.8%) in low urban area. Urbanization increases or shifts from low urban to high urbanized areas were greatest in two Pedernales River watersheds (HUC 10: 1209020601; HUC 10: 1209020602), two Colorado River watersheds (HUC 10: 1209030102; HUC 10: 1209030107) and one San Saba River watershed (HUC 10: 1209010905). The Pedernales River basin, followed by the lower Colorado River basin showed the most change in LULC across all sub-watersheds. The Pedernales River watershed (HUC 10: 1209020601) showed the greatest change over the thirty plus year period with a large shift from agricultural, low urban and herbaceous land cover to forested land cover (Appendix G).

The PCA for the range of flow variability between the two periods resulted in three primary principal components that explained 64.6% of the variance among the sites. The first principal component (eigenvector: 7.83; proportion of variation: 0.24) for the RVA explained increased minimum and 30- and 90-day maximum flows with a decrease in the fall rate between the two periods. The second principal component (PC2; eigenvector: 4.70; proportion of variation: 0.14) discriminated between sites with decreased 3- and 7-day minimum flows and base flow, as well as increased maximum flows. The majority of stream systems displayed a positive shift between the two periods (pre-1985, post-2005) along the first principal component. Therefore, between the two periods of interest there was an increase in the variability of monthly flows for Barton Creek, Colorado River, Onion Creek, Pedernales River, and the South Llano River. Decreases in the variability of monthly flows between the two periods were associated with Dove Creek, and to a lesser extent with the Llano River, San Saba River, and Walnut Creek. Barton Creek, Colorado River, and the South Llano River all showed positive shifts along PC1 and PC2, suggesting that between the two periods there were differences in variability of monthly flows, minimum flows, and baseflows. While the Pedernales River showed a positive relationship with PC1, there was little to no range in scores for PC2, suggesting that minimum flow and baseflow variability remained rather steady or similar between the two periods. Decreases in variability of minimum flows or baseflows, or negative associations with PC2, were found for the North Llano River, Onion Creek, San Saba River, and Walnut Creek.

Stream Flow Metrics

In addition to examining how variability in flows changed across time periods (1970-1985; 2005-2016), we examined stream flow metrics within each time period using the coefficient of variation and annual stream flow metrics for individual years. The stepwise discriminant function procedure determined the most informative hydrologic variables based on their coefficient of variation and land cover variables for distinguishing morphological variation. Hydrologic variables retained from the stepwise discriminant function procedure were 90-day maximum flows, low pulse count, high pulse count, reversals, monthly August flows, seven-day maximum flows, one-day maximum flows, high pulse duration, baseflow, three-day minimum flows, 30-day maximum flows, monthly July flows, date of maximum flow and monthly November flows. The LULC variables selected for further analysis were herbaceous, barren, urban high and wetland.

Annual stream flow metrics were used to associate IHA flow variables that an individual Guadalupe Bass experienced during their lifetime. The first two principal components were retained for further analysis based on the proportion of variance explained by each component (Appendix I). The first principal component was largely defined by increasing mean monthly flows and duration of one-day minimum flow period (eigenvector: 7.27; proportion of variation: 0.23). The second principal component separated years by overall increased minimum flows, base flow, and a decrease in zero-flow days (eigenvector: 2.64; proportion of variation: 0.08). The remaining seven principal components combined to explain the remaining variation; however, these principal components each explained less than 2% of the variance.

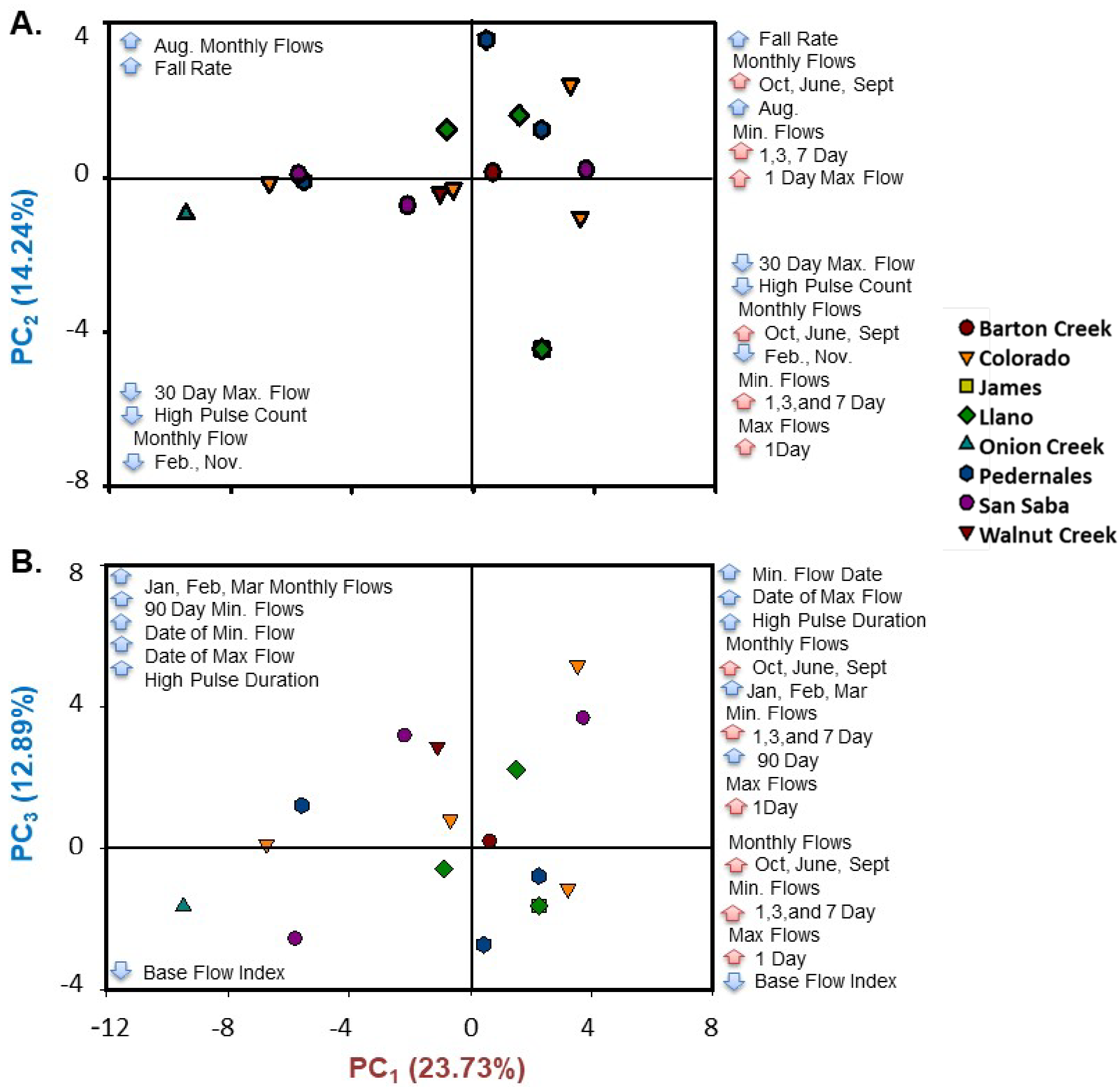

Figure 5. Scatterplots representing hydrologic alteration between pre-1980 and 1995-2014 for U.S. Geological Survey (USGS) gaging stations closest to the sampling locations with historic and current discharge records. Hydrologic alteration was assessed using the range of variability approach (RVA) as described by Richter et al. (1997). The first three PCs explained 64.64% of the variance among the sites for RVA scored hydrologic alteration. RVA scores range from -1 to 1 with an RVA score of zero for the years in the current time period (1980 – 2013) that are within the 25th and 75th percentile of the historic values. Positive values indicate a decrease in the variability; negative values indicate an increase in variability between the two periods of comparison

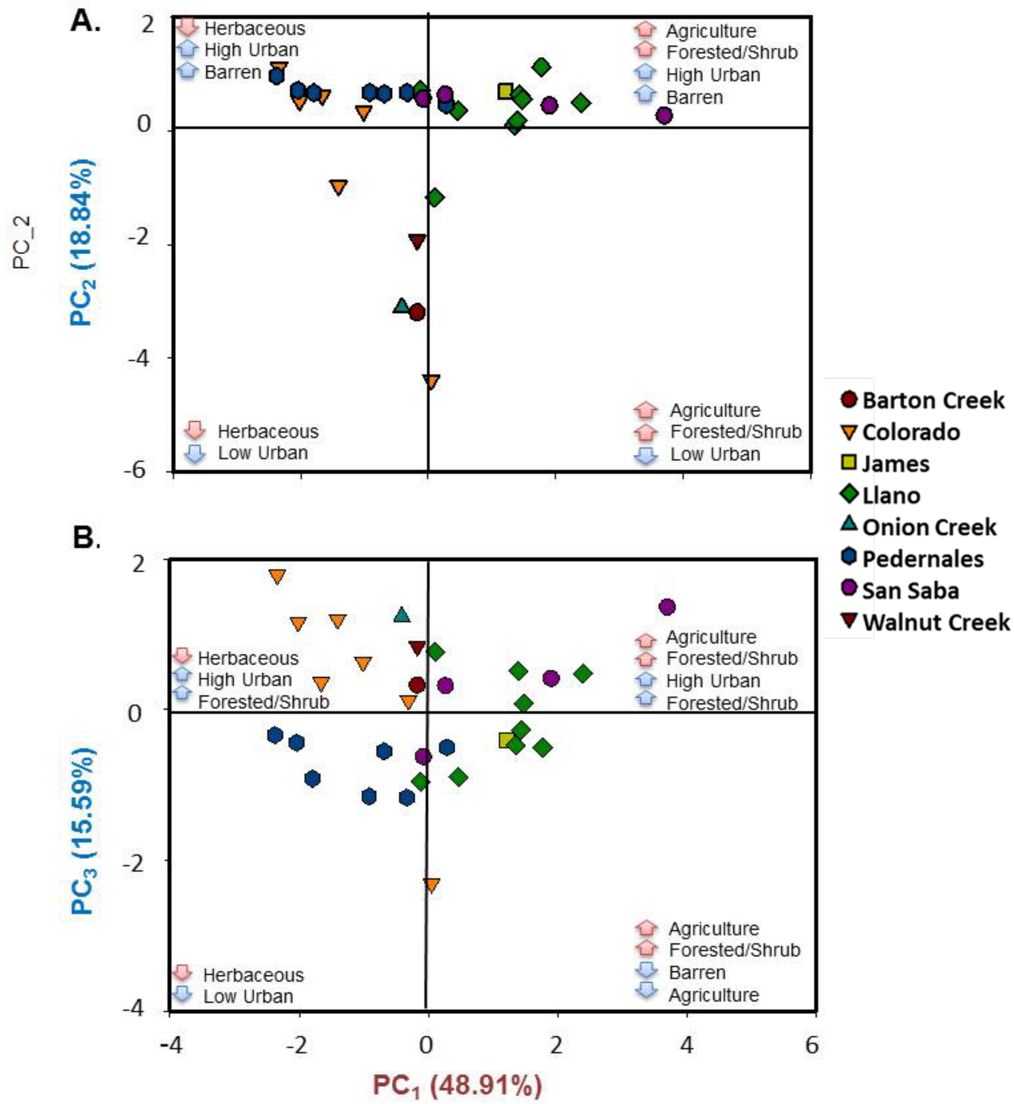

Figure 6. Scatterplots representing land-use alteration for 30 HUC 10 watersheds (Figure 2) within the Colorado River Basin encompassing all study reaches. Alteration was assessed between 1975-1978 classification by the U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA) Program to the 2012 classification of land cover and land use by Texas Parks and Wildlife (TPWD) Ecological Systems of Texas. Historical and present LULC data were reclassified into six broad classes consistent between data sets in order to focus comparison on primary land conversion rather than vegetation types. The first three PCs explained 81.17% of the variance among sites for the percentage difference in landscape variables.

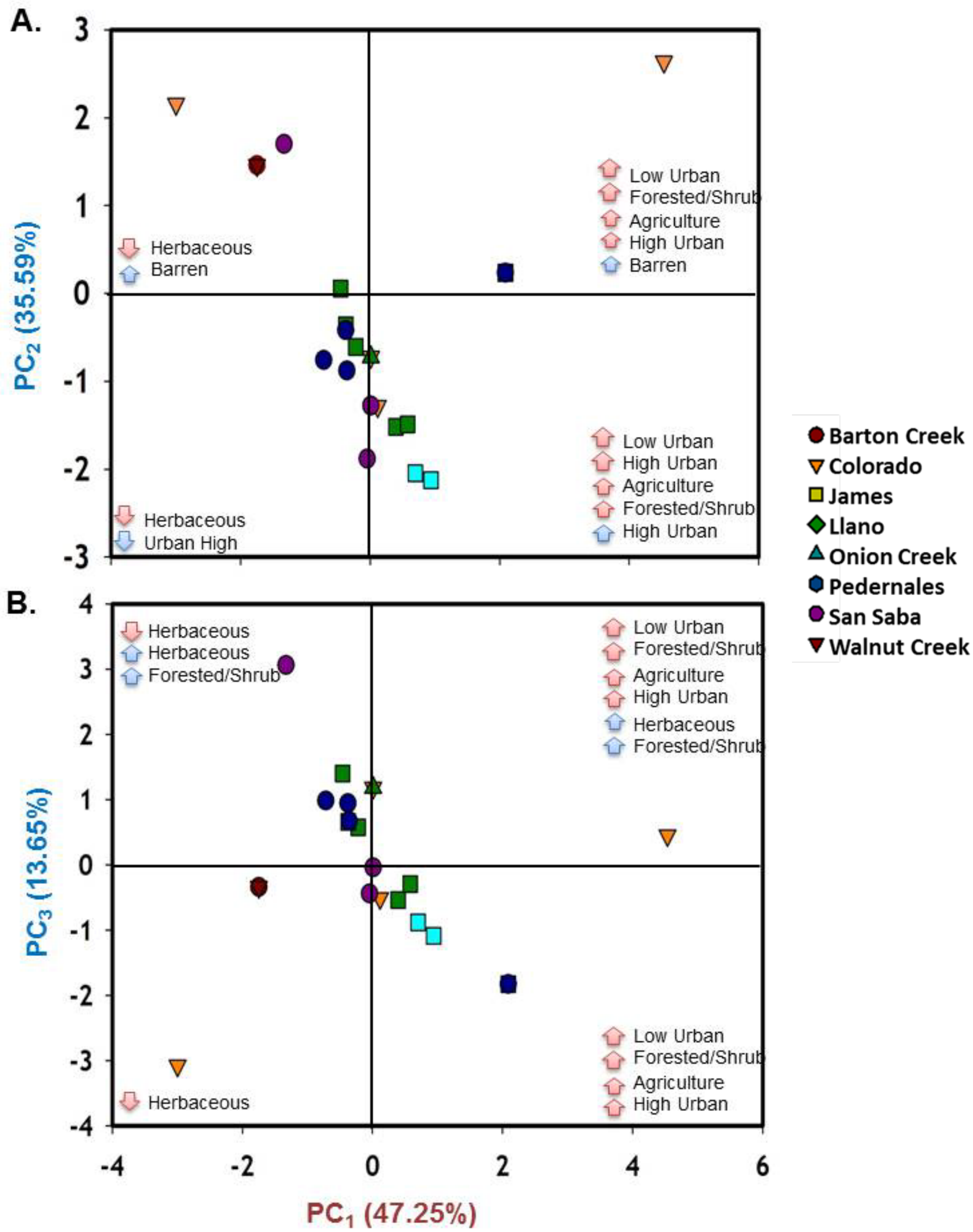

Figure 7. Scatterplots representing land-use alteration for 30 HUC 10 watersheds (Figure 2) within the Colorado River Basin encompassing all study reaches. Alteration was assessed between 1992 land cover data obtained from the U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD) to the 2012 classification of land cover and land use by Texas Parks and Wildlife (TPWD) Ecological Systems of Texas. Historical and present LULC data were reclassified into six broad classes consistent between data sets in order to focus comparison on primary land conversion rather than vegetation types. The first three PCs explained 91.45% of the variance among the sites for the percentage difference in landscape variables.

Age and Growth

Guadalupe Bass ranged from 1-6 years in age and lengths ranged from 60 to 419 mm TL (Figure 9). Historical specimens were generally smaller and younger than present-day specimens, likely because they were collected by seining, which is biased towards the collection of smaller individuals when compared to the electrofishing methods used for our study (Jackson and Noble 1995; Fischer and Quist 2014). Von Bertalanffy growth curve back-calculated parameter estimates (±SE) for combined historical and present scale data were L_∞= 537.4±81.8, k = 0.185±0.050 and t_0 = -0.262±0.130 (Figure 10). Parameter estimates (±SE) for back calculated length at age otolith data were L_∞= 621.2±132.4, k = 0.118±0.03 and t_0 = -0.456±0.140 (Figure 11). Additional Von Bertlanffy growth curve was fit to the length-at-age data for only the lower Colorado River scale data resulting in the following parameters L_∞= 540.6±130.9, k = 0.153 ± 0.06 and t_0 = -1.234 ± 0.40. The instantaneous mortality estimate, Z, for Guadalupe Bass in the lower Colorado River was -0.156 after age-2, based on the descending leg of the catch curve (Figure 12). Present-day Guadalupe Bass in the mainstem lower Colorado River had higher mean growth for age-1 individuals (128.75 mm TL ± 32.8 SD) in comparison to the mean growth of tributary populations in the first year (94.8 mm TL ± 27.96 SD, t_{437} = 4.69, P = 0.01).

Flow conditions represented by PC1 and PC2 were related to the first year of standardized growth determined from aged scales of Guadalupe Bass in the Llano and Pedernales Rivers for both historical and present time periods. Standardized growth in the Llano River was negatively correlated with PC1 and positively correlated with PC2. In the Pedernales River standardized growth related to flow metrics was opposite the Llano River results for age-1 individuals. PC 1 was positively correlated to standardized growth, while PC2 was negatively correlated to standardized growth in the Pedernales River. Correlations for the first year of growth over both time periods represented by the scale aged data were not significant for the Colorado River and the San Saba River (Table 4). Standardized residual growth for all aged Guadalupe Bass scales across river systems was primarily influenced by PC 2. In the Llano River PC1 and PC2 influenced standardized growth independent of age, while in the Colorado River and the Pedernales River the influence of PC1 and PC2 was not independent of age. In contrast to the Pedernales River and the Llano River, standardized growth in the Colorado River was not influenced by PC 1 (Table 5). There were no significant correlations between PC1 or PC 2 and standardized growth for all aged individuals in the San Saba River. Similar trends in standardized growth showing differences in rivers and strong overall influences of PC2 were shown in all aged Guadalupe Bass otoliths ($F_{1,208}$ = 5.22, P=0.02; Table 6, Figure 13, Figure 14).

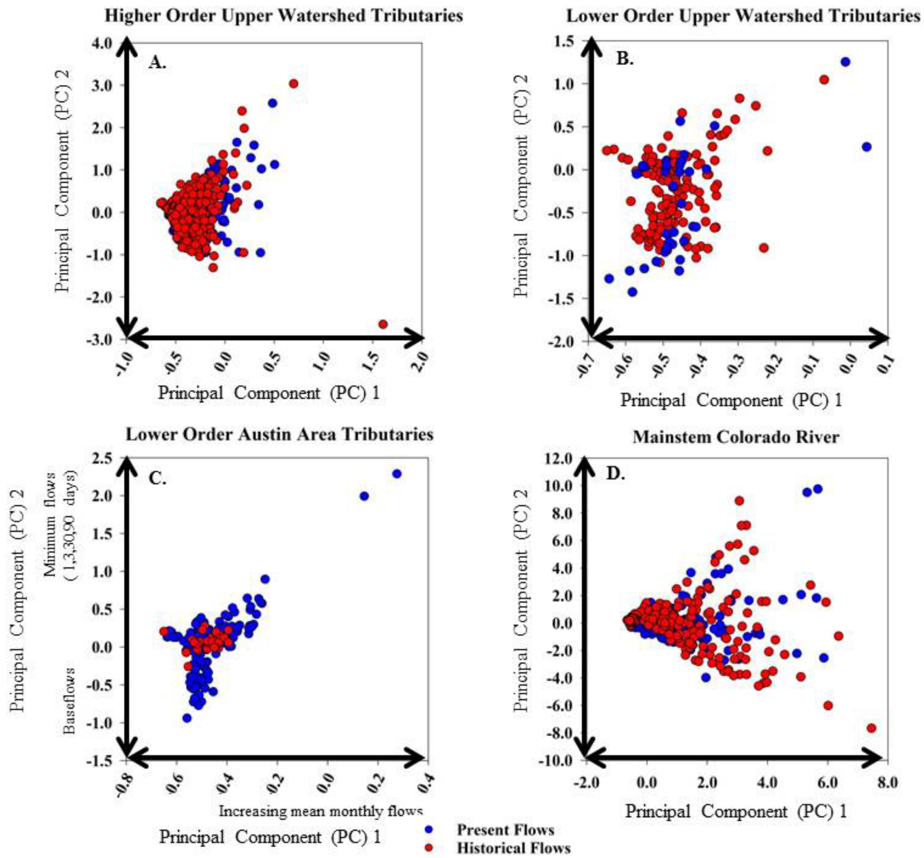

Figure 8. Scatterplot of the two primary PC scores (Appendix I) for flow between historical (prior to 1999; red circles) and present (2000-2016; blue circles) flows. Upper watershed tributaries are represented by scatterplot A and B. Scatterplot A shows higher order upper watershed tributaries (San Saba River, Llano River, and Pedernales River) and scatterplot B shows flows in lower order upper watershed tributaries (North Llano River, South Llano River, Dove Creek, and James River). Flows in Barton, Walnut, and Onion Creeks are represented in scatterplot C. Scatterplot D shows flows in the mainstem Colorado River. All scatterplots are scaled to the flows conditions within the system. Principal component (PC) 1was largely defined by increasing mean monthly flows and duration of minimum 1 day flow periods (eigenvector: 13.26; proportion of variation: 0.43). PC 2 was defined by increasing 3, 7, 30, and 90 day minimum flows and overall baseflow, and a decrease in zero-flow days (eigenvector: 4.32; proportion of variation: 0.14).

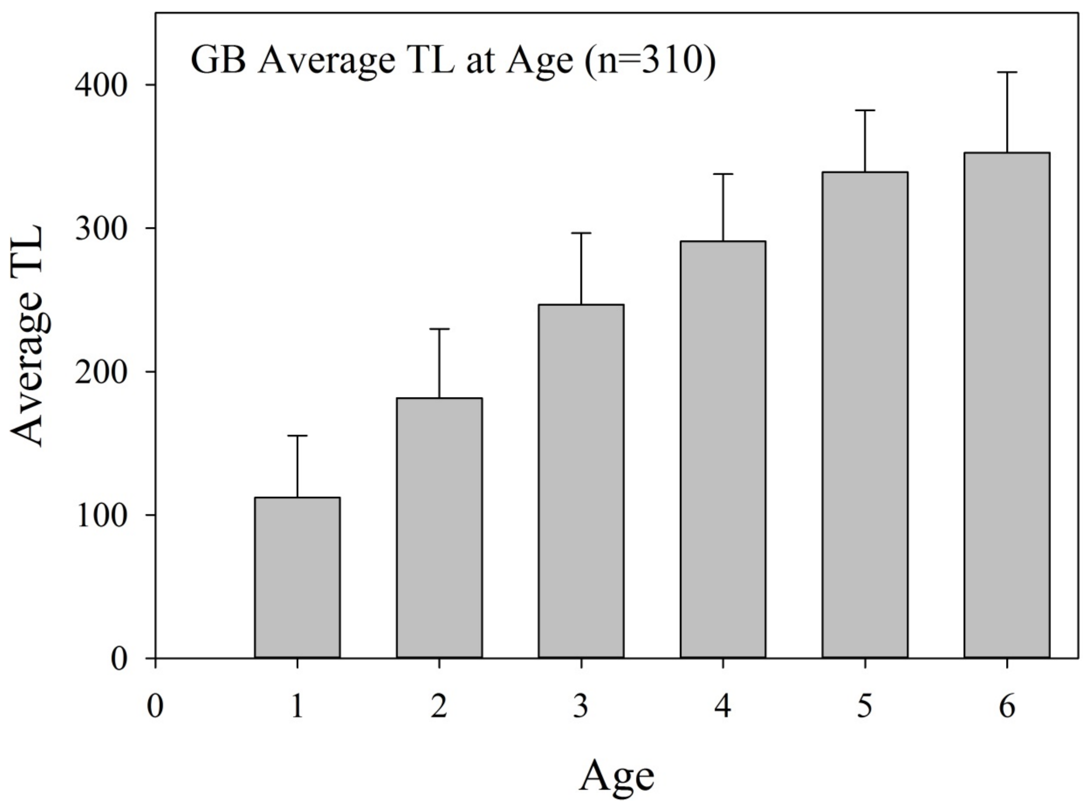

Figure 9. Average total length at age based on scale-aged Guadalupe Bass in the Colorado River Basin collected from March 2014 to September 2016.

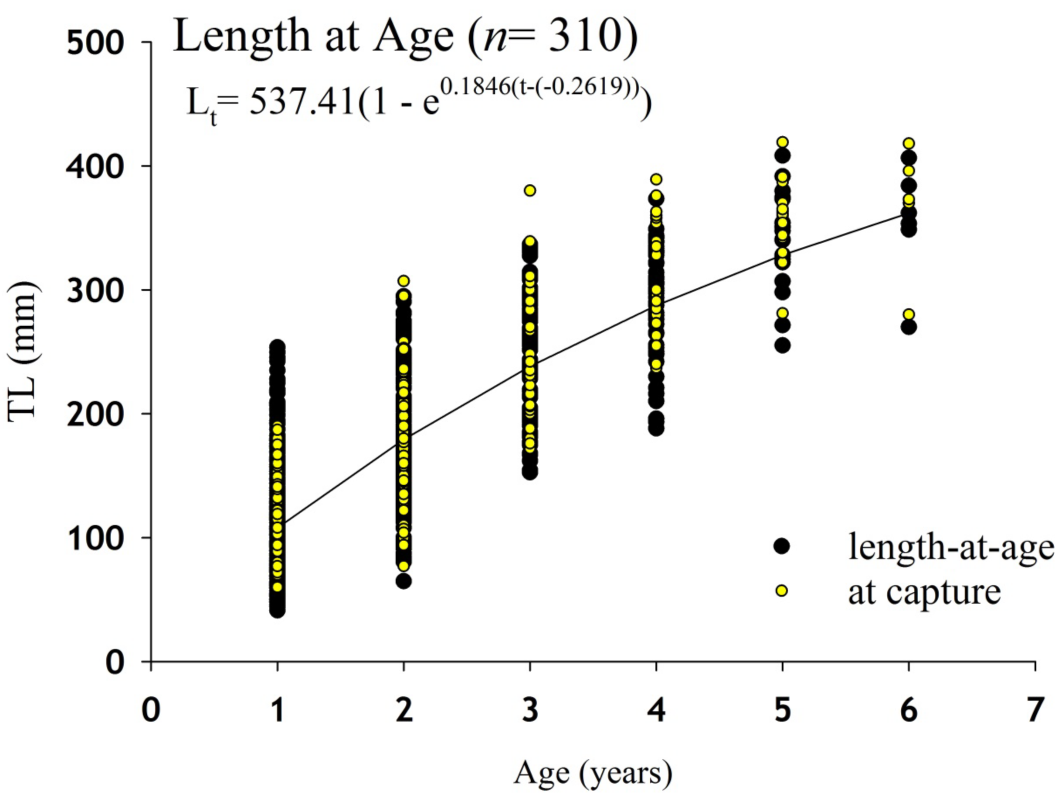

Figure 10. Von Bertalanffy growth curve based on back-calculated total length at age of Guadalupe Bass (n=310) scales and historical scales (n=115) were collected from specimens at the Texas Natural History Collection collected throughout the Colorado River Basin, Texas from March 2013 to September 2016. Accession numbers for individuals used in the analysis can be found in Appendix B. Back-calculated total lengths (TL) at age are represented by black circles and the total length at initial capture is represented by yellow circles.

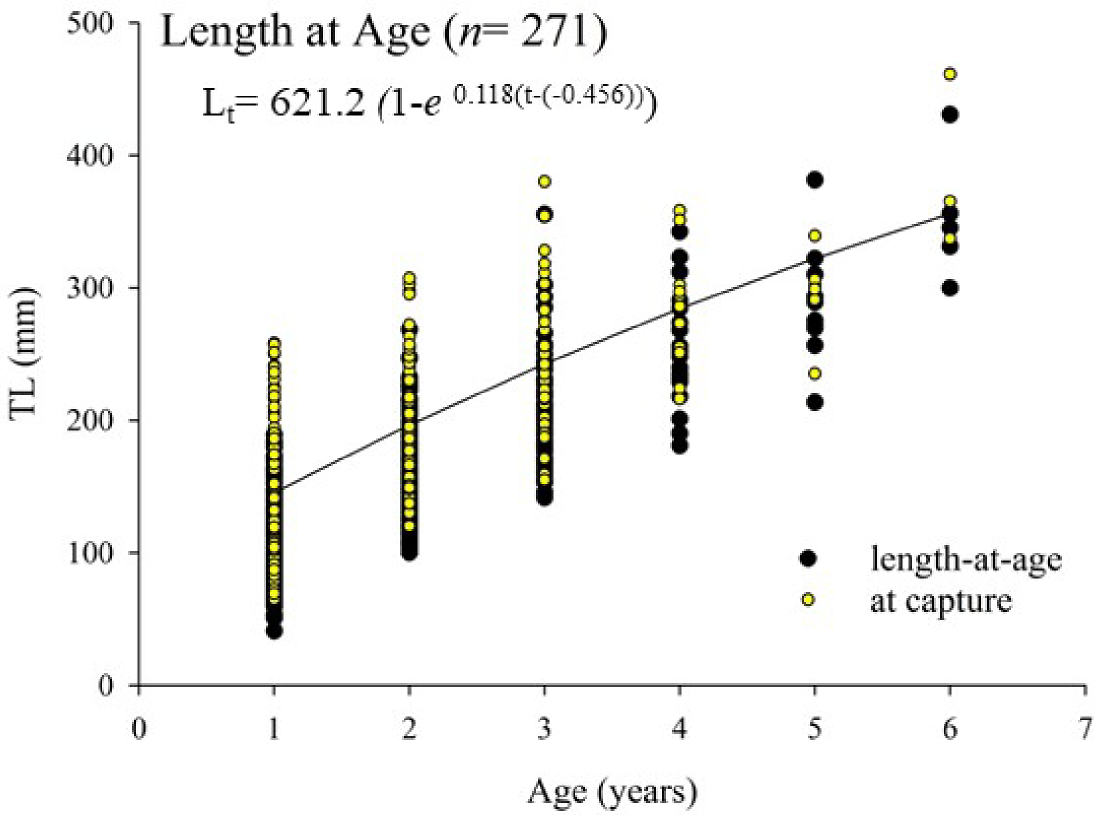

Figure 11. Von Bertalanffy growth curve based on back-calculated total length at age of Guadalupe Bass (n=271) otoliths collected throughout the Colorado River Basin, Texas from March 2014 to August 2015. Back-calculated total lengths (TL) at age are represented by black circles and the total length at initial capture is represented by yellow circles.

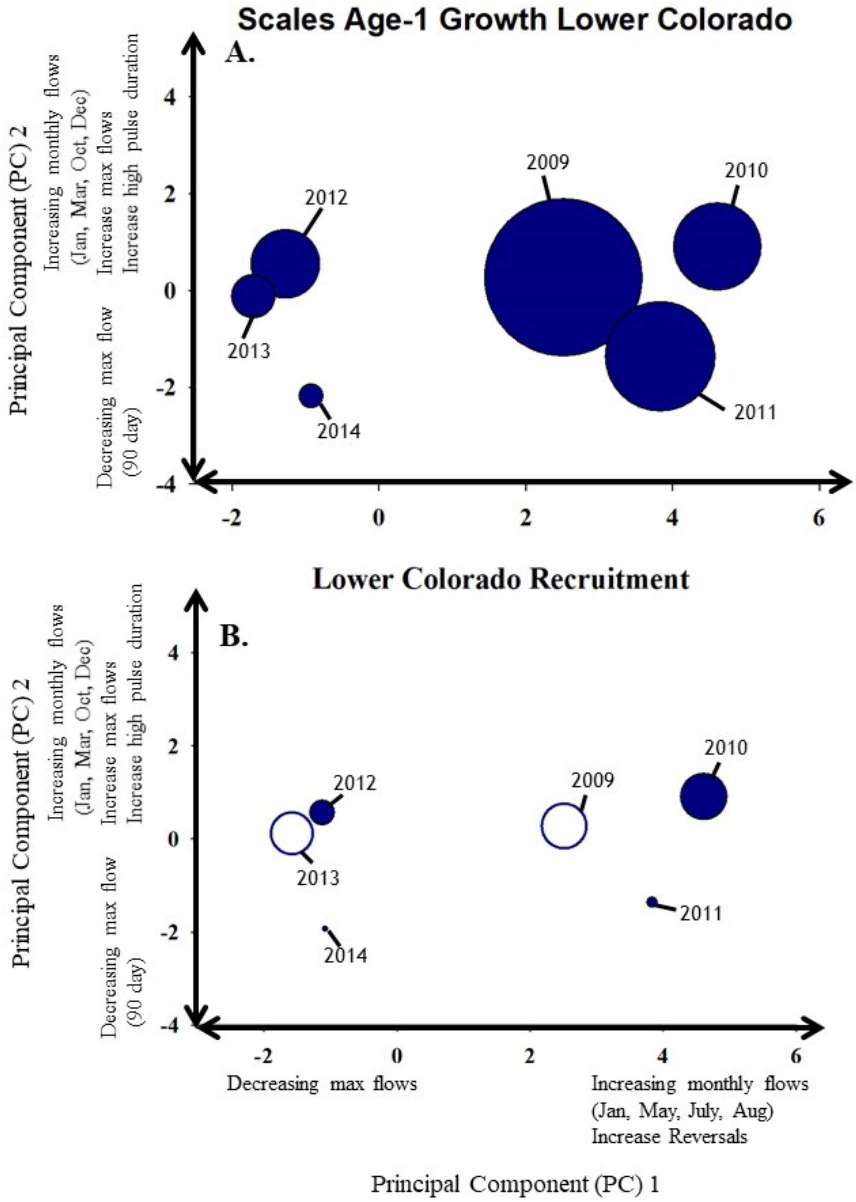

Figure 12. Relationship between annual Indicators of Hydrological Alteration metrics (Richter et al. 1996) as described by their first two principle components and Guadalupe Bass YOY growth (A) and recruitment (B) in the lower Colorado River downstream of Austin, Texas during 2009-2015. Relative recruitment was calculated as the residual of a cohort from the regression model of the descending leg of the catch curve for a sample of 336 Guadalupe Bass captured in 2016. The magnitude of relative recruitment is represented by the size of the bubbles. Filled blue bubbles indicate a positive residual or higher than predicted relative recruitment while empty bubbles indicate negative residuals or lower relative recruitment.

Table 4. Mixed-model repeated-measures ANCOVA results for Guadalupe Bass growth rate residuals during the first year based on scales. Annual stream flow metrics influences on growth rate residuals were evaluated by river for Guadalupe Bass collected between 2014 and 2016. **Model effects with a *P*-value ≤ 0.05** were considered significant and terms with no associated value are indicated by "/".

River	Effect	Value (±SE)	*F*	DF_1	DF_2	*P*
Colorado	Intercept	-0.01 ± 0.03	/	/	86	-
River	PC1	0.22 ± 0.24	0.8	1	86	0.44
	PC2	0.00 ± 0.02	0.01	1	86	0.15
Llano River	Intercept	-0.20 ± 0.04	/	/	86	/
	PC1	-0.52± 0.11	22.27	1	80	**< 0.01**
	PC2	0.19 ± 0.05	17.1	1	80	**< 0.01**
Pedernales	Intercept	0.42 ± 0.19	/	/	23	/
River	PC1	1.15± 0.45	6.34	1	23	**0.02**
	PC2	-0.41 ± 0.05	59.69	1	23	**< 0.01**
San Saba	Intercept	-0.96 ±1.68	/	/	15	/
River	PC1	-3.60± 5.21	0.48	1	15	0.5
	PC2	0.50 ± 0.47	1.14	1	15	0.3

Table 5. Mixed-model repeated-measures ANCOVA results for Guadalupe Bass scales growth rate residuals for all ages. Annual stream flow metrics influences on growth rate residuals were evaluated by river for Guadalupe Bass collected between 2014 and 2016. Model effects with a ***P*-value ≤ 0.05** were considered significant and terms with no associated value are indicated by "/".

River	**Effect**	**Value (±SE)**	***F***	**DF_1**	**DF_2**	***P***
Colorado River	Intercept	0.05 ± 0.03	/	/	87	/
	BC age	-0.05 ± 0.01	25.16	1	213	**<0.01**
	PC1	0.01 ± 0.05	0.02	1	213	0.9
	PC2	0.10 ± 0.03	15.72	1	213	**<0.01**
Llano River	Intercept	-0.16 ± 0.06	/	/	82	/
	BC age	-0.02 ± 0.03	0.5	1	30	0.49
	PC1	-0.47± 0.09	24.47	1	30	**<0.01**
	PC2	0.15 ± 0.04	14.63	1	30	**0.01**
Pedernales River	Intercept	0.35 ± 0.12	/	/	25	/
	BC age	-0.09 ± 0.04	6.38	1	16	**0.02**
	PC1	0.69 ± 0.23	8.83	1	16	**0.02**
	PC2	-0.24 ± 0.04	37.16	1	16	**<0.01**
San Saba River	Intercept	0.70 ±0.35			17	
	BC age	-0.03 ± 0.04	0.74	1	6	0.42
	PC1	1.50 ± 0.95	2.51	1	6	0.16
	PC2	0.02 ± 0.04	0.28	1	6	0.62

Table 6. Mixed-model repeated-measures ANCOVA results for Guadalupe Bass otoliths growth rate residuals for all ages. Annual stream flow metrics influences on growth rate residuals were evaluated for Guadalupe Bass collected between 2014 and 2016. Model effects with a *P*-value ≤ 0.05 were considered significant and terms with no associated value are indicated by "/".

Effect		**Value (±SE)**	***F***	**DF_1**	**DF_2**	***P***
Intercept		0.38 ± 0.15	/	/	224	/
River			18.4	7	224	<0.01
	BART	-0.34 ± 0.16	/	/	/	/
	COLO	-0.14 ± 0.15	/	/	/	/
	LLAN	-0.30± 0.15	/	/	/	/
	NLR	-0.53 ± 0.15	/	/	/	/
	PEDE	-0.14 ± 0.15	/	/	/	/
	SABA	-0.20± 0.15	/	/	/	/
	SLR	-0.60± 0.16	/	/	/	/
BC Age		0.03± 0.01	10.39	1	208	0.01
PC 1		0.03 ± 0.02	1.19	1	208	0.28
PC 2		0.04 ± 0.02	5.46	1	208	0.02

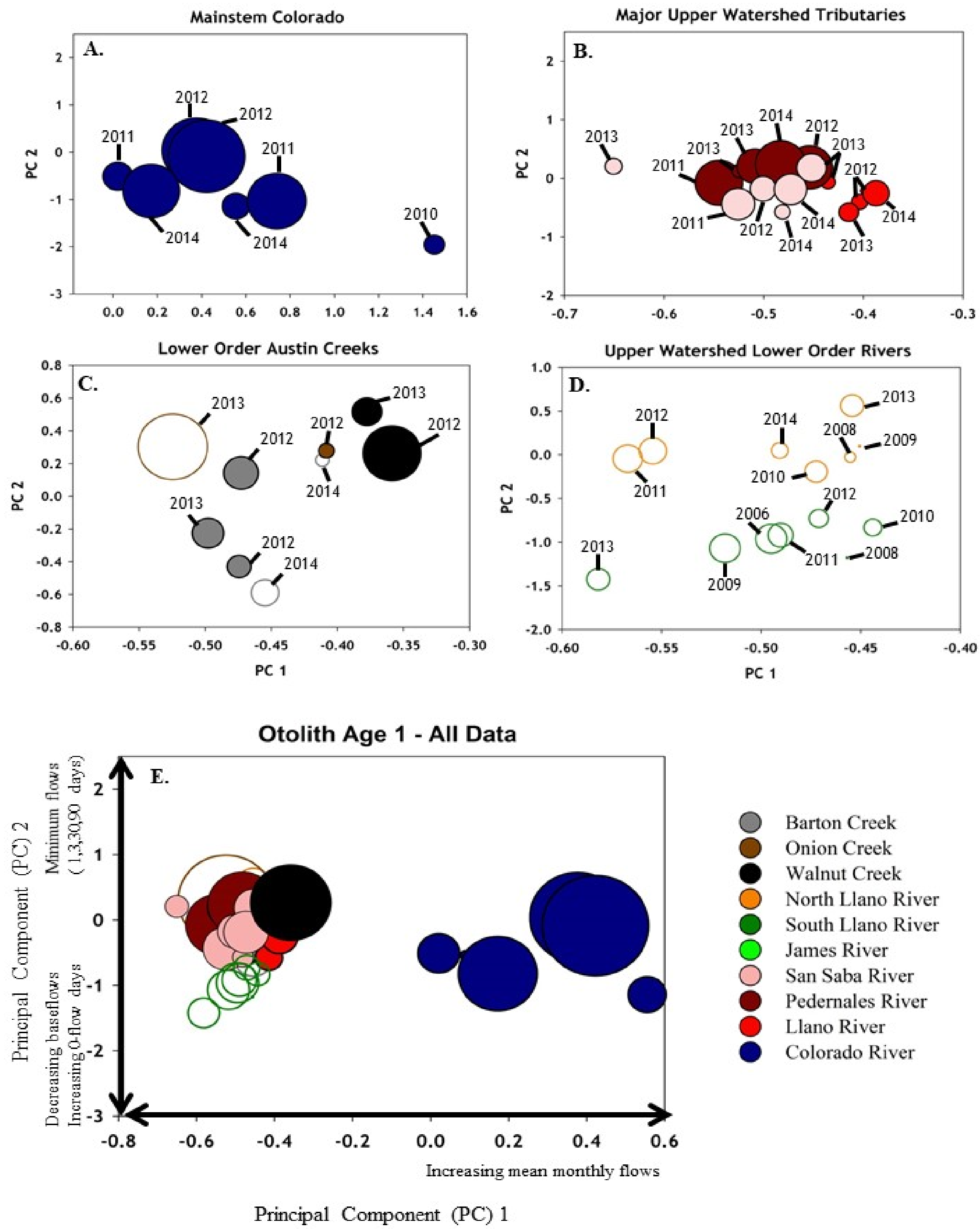

Figure 13. Standardized otolith growth for age-1 Guadalupe Bass captured throughout the Colorado River Basin, Texas from 2014-2015. The sizes of individual bubbles represent the magnitude of response in standardized growth to annual stream discharge metrics. Filled bubbles represent increased growth response, while unfilled bubbles represent a decreased growth response. A-D represent the influence of annual stream discharge metrics for individual systems throughout the Upper Colorado River Basin.

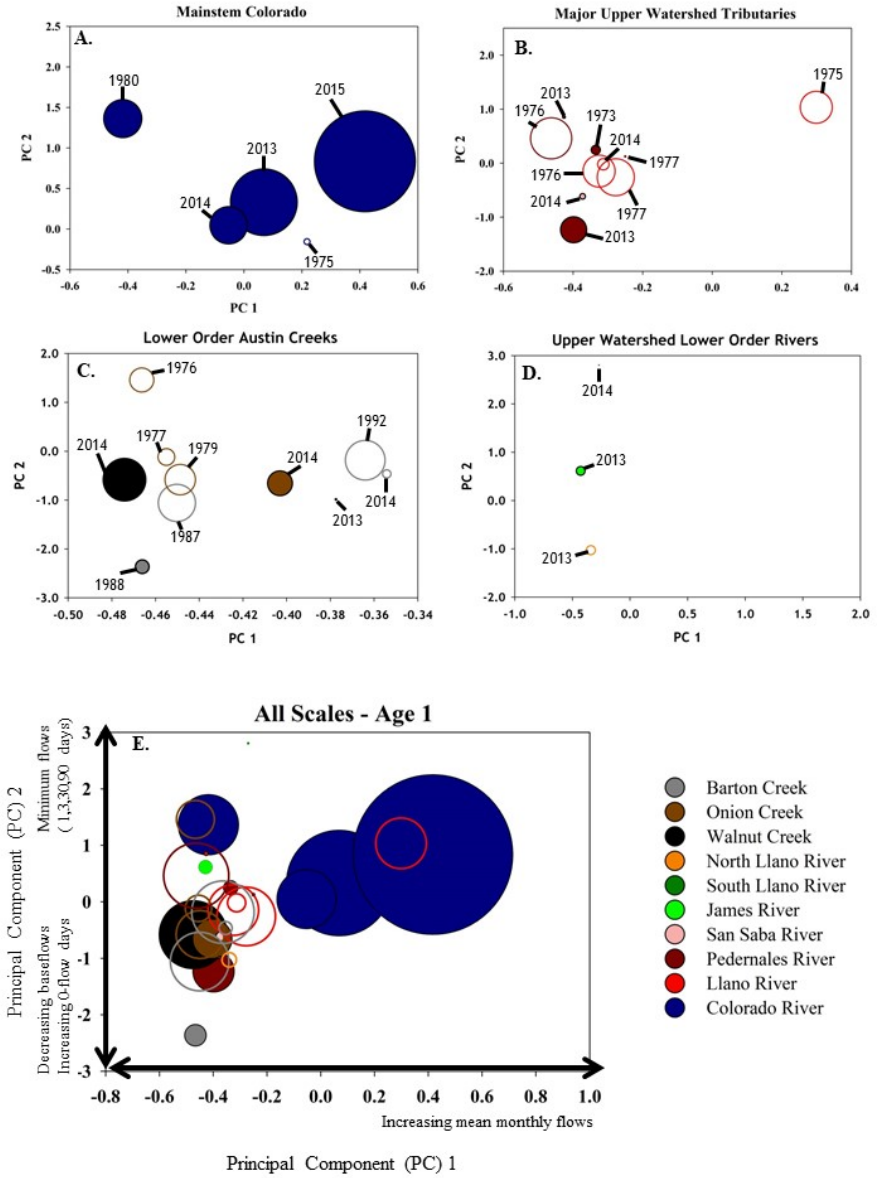

Figure 14. Standardized scale growth for age 1 Guadalupe Bass captured throughout the Colorado River Basin, Texas. Historical scales (n=115) were collected from specimens at the Texas Natural History Collection. Accession numbers for individuals used in the analysis can be found in Appendix B. Present day scales were collected between March 2014 and September 2016. The sizes of individual bubbles represent the magnitude of response in standardized growth to annual stream discharge metrics. Filled bubbles represent increased growth response, while unfilled bubbles represent a decreased growth response. A-D represent the influence of annual stream discharge metrics for individual systems throughout the Upper Colorado River Basin. A-D are scaled separately to better illustrate the growth between lower order creeks in the Austin, Texas area, upper watershed lower order rivers, major upper watershed tributaries, and the mainstem Colorado river.

Morphology

The first three relative warps cumulatively explained 63.33% of the variation in shape across rivers. The first relative warp explained 30.0% of the variation. The second relative warp explained 21.16% of the variation in the data and was related to the distance between the pre-maxillary and maxillary. RW3 explained 7.45% of the variation in the data and was related to longer maxillary region with a greater distance between the caudal fin and anal fin region. Results from the mixed-model MANCOVA showed that time period, i.e., "historical" or "present," and allometry (centroid size) had significant effects on the morphological scores, where significant effects were determined as P-value 0.05 (Table 7). The interaction between period and river did not significantly affect morphological scores. Both river (Wilk's $\lambda = 0.98$, $P = 0.04$) and period (Wilk's $\lambda = 0.98$, $P < 0.01$) had a significant effect on the morphological scores. Allometry (centroid size) also had a significant effect on morphological scores (Wilk's $\lambda = 0.81$, $P < 0.01$) indicating that RW scores and body size are correlated. An additional mixed model MANOVA was ran to determine if there were any stream order effects on morphology. When stream order was accounted for there was a significant stream order effect (Wilk's $\lambda = 0.98$, $P = 0.03$), where significant effects were determined as P-value 0.05 (Table 8). Additionally, time period (Wilk's $\lambda = 0.95$, $P < 0.01$) and centroid size (Wilk's $\lambda = 0.81$, $P < 0.01$), still had an effect on morphological scores. The interaction between period and stream order did not significantly affect morphological scores (Wilk's $\lambda = 0.99$, $P = 0.16$).

Morphological and environment variables were related along a single canonical function for both historical (Wilk's $\lambda = 0.40$, $P < 0.001$) and present-day (Wilk's $\lambda = 0.36$, $P < 0.001$) Guadalupe Bass with the morphological variables explaining 31.0% of the variance in the environmental gradient defined by the canonical functions (Table 9). The first environmental canonical dimension separated the sites by decreasing rise rate and overall fall monthly flows from sites with increased baseflow, 7-day maximum flows and summer monthly flows (Table 10). The second morphological canonical axes represented morphological variation amongst and within sites throughout the Colorado River Basin (Figure 15). The first morphological canonical axis was largely associated with differences in the placement of the pectoral fin, indicating body depth, discriminated Guadalupe Bass with slender and shallower bodies (Table 11).

The second morphological canonical axis differentiated Guadalupe Bass individuals with shorter maxillary and mouth regions (Figure 15). Head shape changes were largely correlated with hydrologic variables related to the second canonical environmental axis. Slimmer and condensed head shapes were associated with increasing summer monthly flows, increased baseflow and increased ninety day maximum flows. These hydrological relationships indicate that sustained flows, especially in the summer months were related to more streamlined head shape. Broader head shape was associated with decreased time of high pulses, lower fall monthly flows and more sporadic flows conditions. In both historical and present-day specimens, the morphological predictors were largely correlated with hydrologic variables, though land-cover variables slightly contributed to the second environmental canonical axis.

Movement

A total of 28 Guadalupe Bass, ranging 249-436 mm TL, were tagged at five separate locations on the lower Colorado River (Table 2, Figure 4). Of the 23 total Guadalupe Bass tagged in December of 2014, one individual tagged in Altair was never relocated. An additional five Guadalupe Bass were tagged in Utley in December of 2015. A total of 21 tracking events were conducted between January of 2015 and May 2016. There were 21 possible relocations for each individual tagged in 2014 (483) and individuals tagged in 2015 had a total of 8 possible relocations (40). Tagged fish were relocated 378 of the 523 possible relocations (72% relocation rate) (Table 2).

Guadalupe Bass tagged at Altair and Bastrop showed the largest movement in March and June of 2015 (Figure 16, Figure 17). These movements coincided with a large flood pulse that occurred in the spring of 2015. Movements were both upstream and downstream, and two individuals moved into tributaries likely in response to the flooding. In late October 2015, there was another substantial flood pulse. Following the October flood, relocation success decreased especially in the lower part of the Colorado River in Altair. Four individuals previously tracked were never relocated again following the 2015 October flood pulse. Seasonal movement patterns observed were relatively small movements in the fall and upstream movements in the spring followed by trends in downstream movement in the summer (Figure 18, Figure 19). Total length of tagged individuals did not affect overall displacement; where displacement is quantified as the minimum movement from the previous location. Net upstream movement is indicated by positive displacement values, while negative values indicate downstream movement. Mean absolute movement, defined as total movement from tagging location with no associated upstream or downstream value, was highest in individuals greater than 300 mm (Figure 18, Figure 20).

Overall linear home range across all sites was 10.71 km (range of 0.68-46.73 km). Mean linear home ranges were not significantly different ($F_{4,23}$=1.87, P=0.15) across sites. The mean overall 50% core area was 0.44 ha (0.05-0.90 ha) and increased to an average 95% core area of 93.42 ha (39.10 -178.66 ha). Both 95% home range and 50% mean core area were smallest at the upstream sites of Bastrop and Utley and increased moving downstream from Bastrop (Figure 21). Individuals in Altair had the largest core areas. However, mean core areas were not significantly different across sites for 50% core areas ($F_{4,23}$=0.75, P=0.57) or for 95% home ranges ($F_{4,23}$=0.59, P=0.68).

Table 7. Mixed-model nested multivariate analysis of covariance (MANCOVA) of Guadalupe Bass body shape variation across all rivers represented by relative warps.

Factor	d.f.	F	P
HorP	3,791	4.23	<0.01
River	9,1750	2.00	0.04
HorP*River	9,1750	0.67	0.73
Centroid size	3,791	55.78	<0.01

Table 8. Mixed-model nested multivariate analysis of covariance (MANCOVA) of Guadalupe Bass body shape variation across streams grouped by similar order represented by relative warps.

Factor	d.f.	F	P
HorP	3,727	11.33	<0.001
Order	6,1454	2.31	0.03
HorP*Order	6,1454	1.53	0.16
Centroid size	3,727	55.37	<0.0001

Table 9. Standardized canonical function coefficients for relative warps used in canonical correspondence analysis of the morphology of Guadalupe Bass collected throughout the Colorado River basin, Texas. Historical individuals were collected by Edwards (1980) and stored at the Texas Natural Historical Museum collection where morphological photos were taken for analysis. Present-day individuals were collected between March 2014 and September 2016.

Variable	**Can1**	**Can2**	**Can3**
RW1	**0.92909**	0.03394	0.2065
RW2	-0.3375	-0.1999	**0.73509**
RW3	-0.1057	**0.94713**	-0.0272
RW4	-0.0857	-0.2561	**-0.6542**

Table 10. Canonical structure coefficients for the first three canonical variates for environmental variables (land use and landcover (LULC) changes and principal component scores for indicators of hydrologic alteration (IHA) with loadings in Appendix J used in the canonical correlation analysis of Guadalupe Bass morphology related to altered flow and LULC throughout the Colorado River basin, Texas. Historical individuals were collected by Edwards (1980) and stored at the Texas Natural Historical Museum collection where morphological photos were taken for analysis (Appendix B) Present-day individuals were collected between March 2014 and September 2016. Location of landmarks comprising relative warps are described in Table 2 and illustrated in Figure 3. Bolded values indicate the most correlated variables for the particular morphological variable.

Variable	Environment 1	Environment 2	Environment 3
Herbaceous	0.1075	-0.7246	**-1.172**
Barren	-0.0507	0.638	-0.4856
90-day max flows	0.2484	**3.101**	**2.9708**
Low pulse count	-0.2932	-0.6033	-0.8193
High pulse count	-0.0442	0.9325	0.0818
High urban area	0.1966	-0.4542	0.1822
Reversals	0.133	0.1205	0.8949
Monthly August Flows	-0.3479	-1.3167	-0.75
7-day max flows	**0.9746**	-0.186	0.5037
1-day max flows	-0.4268	0.4504	**1.1268**
High pulse duration	-0.3946	**-1.5423**	**-1.2493**
Baseflow	**1.6902**	1.3891	0.1972
3-day minimum flows	-0.1233	1.0147	-0.2197
30-day max flows	**0.5489**	**-2.7789**	**-2.7596**
Rise rate	**-1.2251**	-0.4403	**3.3365**
Monthly September flows	**-1.9817**	-0.8375	-0.5274
Monthly July flows	**2.6005**	**8.0512**	**1.5222**
Date of Maximum flow	-0.3238	0.1816	-0.335
Wetland	0.2239	0.1923	-0.8801
Monthly November flow	**-0.7118**	**-6.1513**	**-3.1308**

Table 11. Canonical structure coefficients for the first three canonical variates for relative warp scores used in the canonical correlation analysis of Guadalupe Bass morphology related to altered flow and land cover throughout the Colorado River basin, Texas. Historical individuals were collected by Edwards (1980) and stored at the Texas Natural Historical Museum collection where morphological photos were taken for analysis (Appendix B). Present-day individuals were collected between March 2014 and September 2016. Location of landmarks comprising relative warps are described in Table 2 and illustrated in Figure 3. Bolded values indicate the most correlated variables for the particular morphological variable.

Variable	Morphology1	Morphology2	Morphology3
RW1	**-0.9422**	-0.0169	-0.0539
RW2	**0.3341**	0.1029	-0.3377
RW3	0.0758	**-0.9912**	0.0626
RW4	0.0791	0.0771	**0.9237**

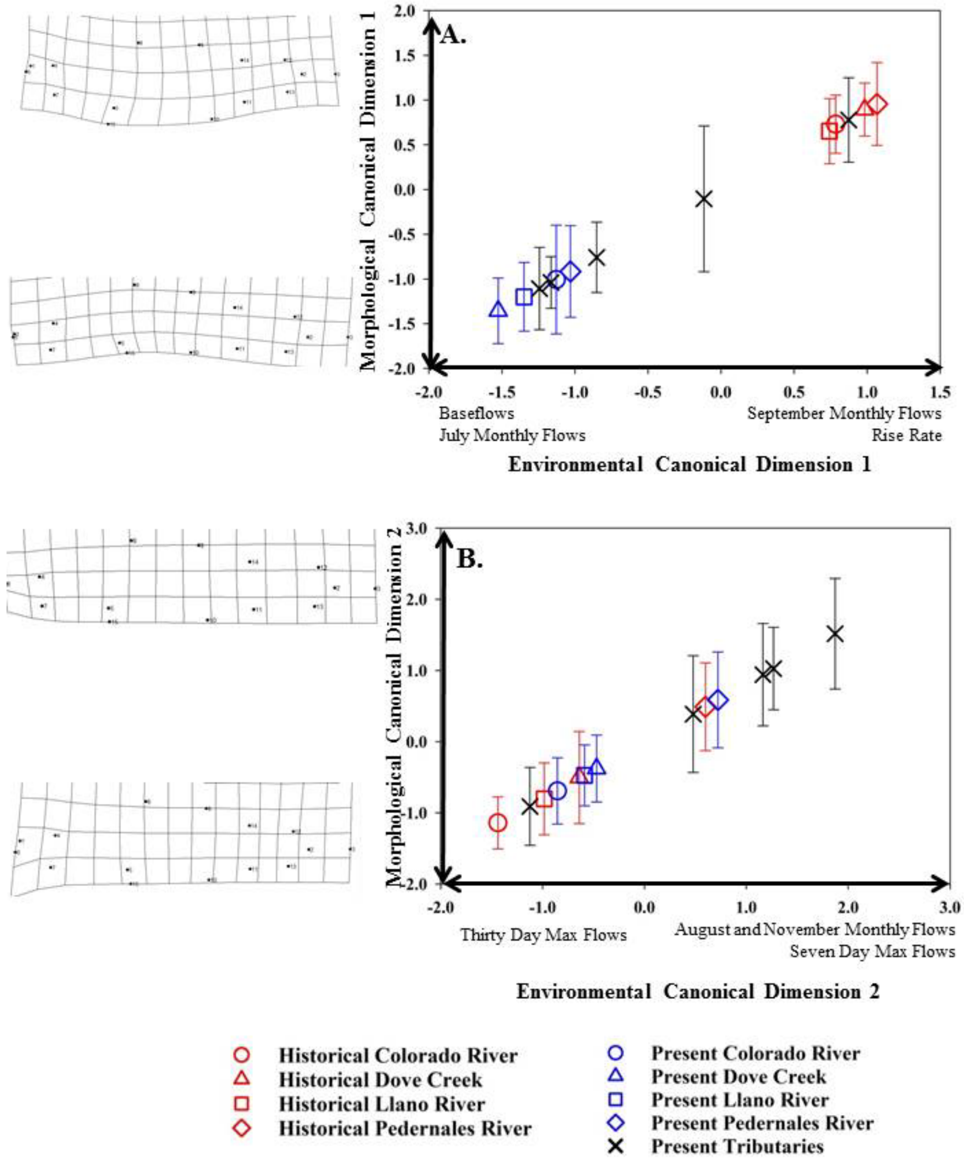

Figure 15. Mean morphological scores for historical and present-day collected Guadalupe Bass where red symbols represent historical morphological canonical scores and blue symbols represent present morphological canonical scores for the mainstem Colorado River and tributaries of the Colorado River. Historical specimens were obtained from Texas Natural Historical Museum for morphological analysis. Tributaries where historical specimens were not archived or available are indicated by black X's. Thin-plate spline transformation grids on the y-axis illustrate variation of body shape along the axis. The mainstem Colorado River and the three tributaries for which there were museum specimens are indicated by similar symbols with historical means represented in red and present means represented in blue. Environmental canonical scores representing hydrological and percentage difference in landscape are shown on the X axis.

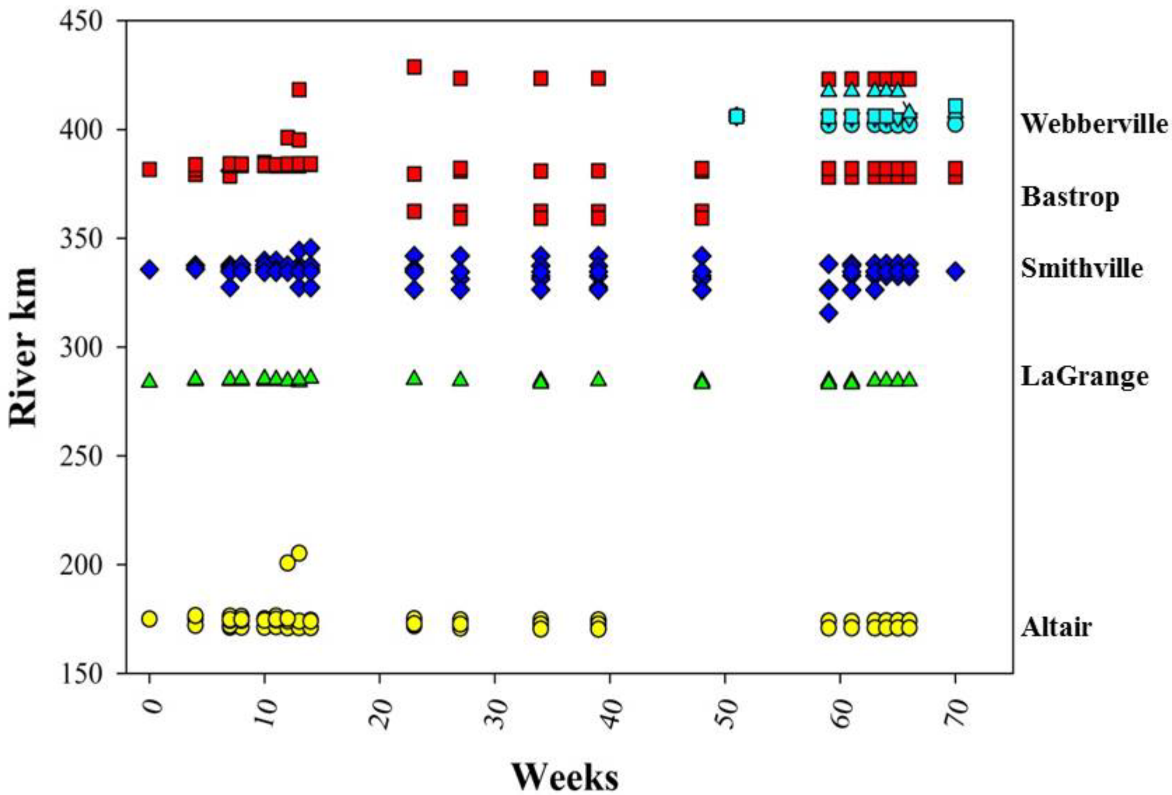

Figure 16. Locations of Guadalupe Bass implanted with radio transmitters from the lower Colorado River downstream of Austin, Texas during December 2014- May 2016. River kilometers are measured from the mouth of the Colorado River at Matagorda Bay. Symbol color denotes individuals captured and tagged at the same location.

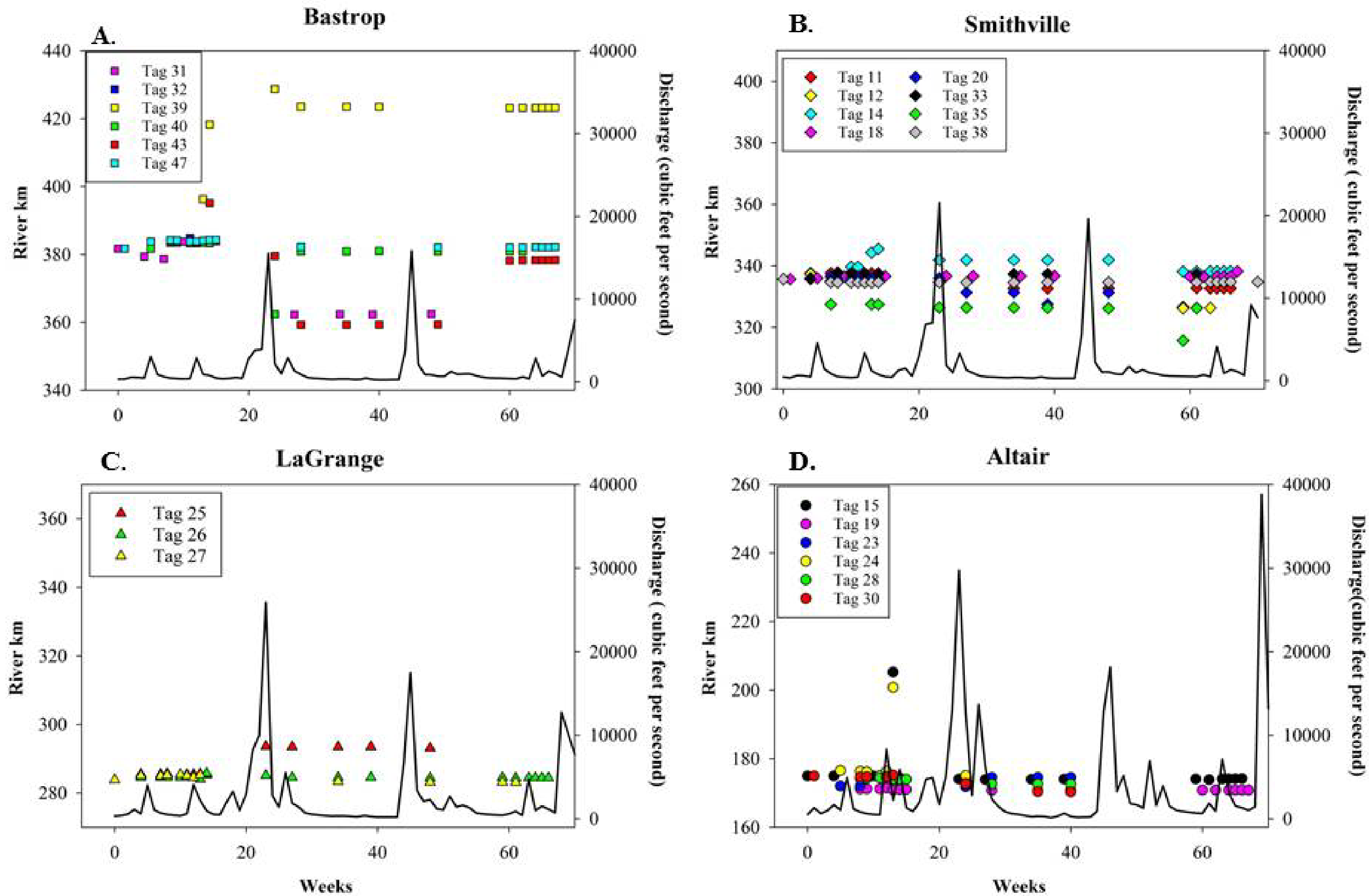

Figure 17. Scatter plots (A-D) of individual Guadalupe Bass movements at each complete tagging location for twenty-one tracking events conducted between January 2015 and May 2016. The first Y-axis is the distance (km) moved in river kilometers from the mouth of the Colorado River with Matagorda Bay. The second Y-axis on the left of the figures shows the discharge in cubic feet per second. The X-axis shows the number of weeks from initial tagging.

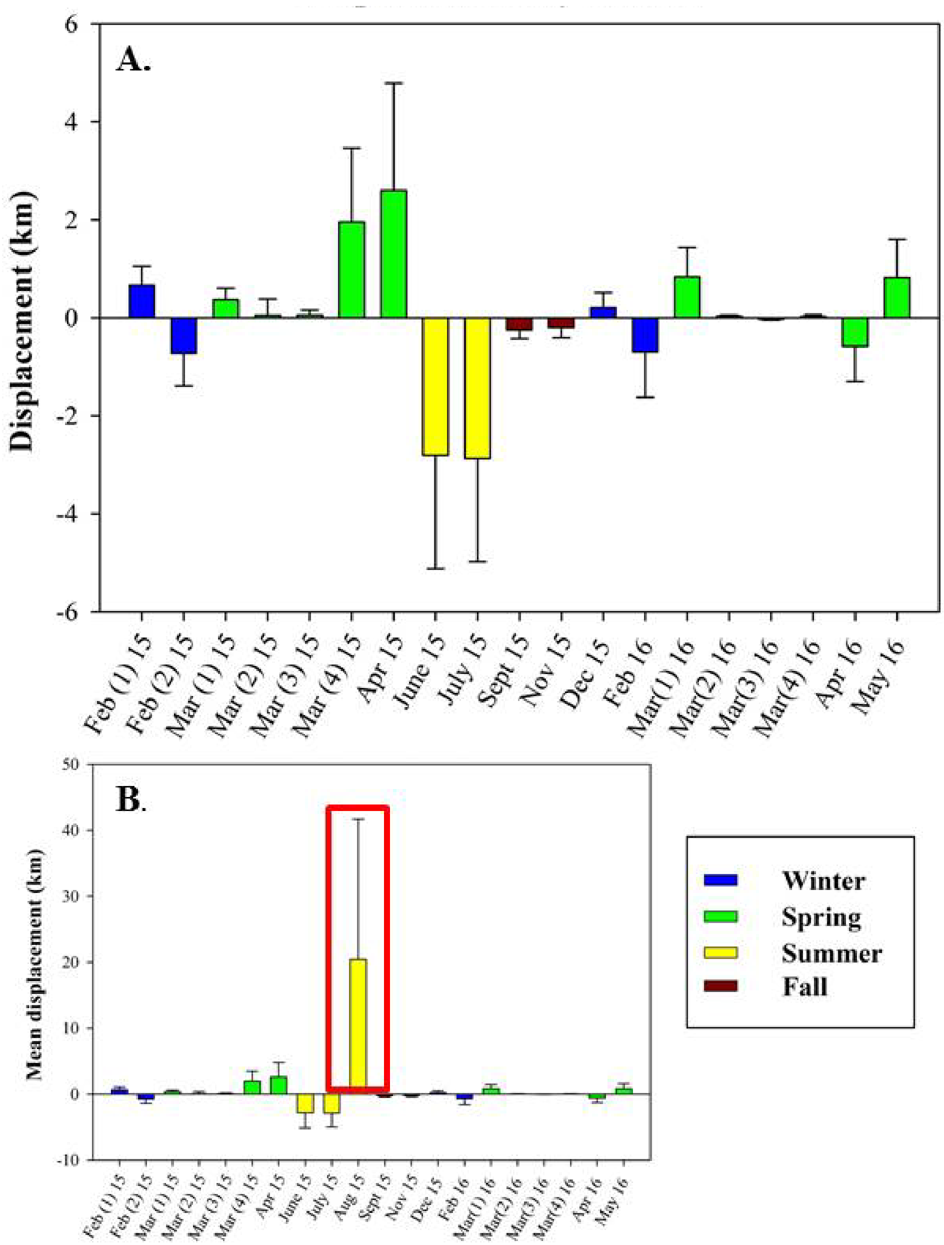

Figure 18. Mean monthly displacement of Guadalupe Bass (*n* = 27) implanted with radio transmitters in the lower Colorado River between Utley, Texas and Altair, Texas over 21 tracking events conducted between December 2014 and May 2016. Net upstream movement is indicated by positive displacement values, while negative values indicate downstream movement. Upstream movements are seen in the spring followed by downstream summer movements and upstream late summer movements. A) Smaller-scale movements where mean displacement was less than ten kilometers. B) August 2015 displacement in comparison to all other tracking events. August 2015 is removed in A in order to illustrate movement patterns in all other tracking events. Error bars represent ± 1 standard error.

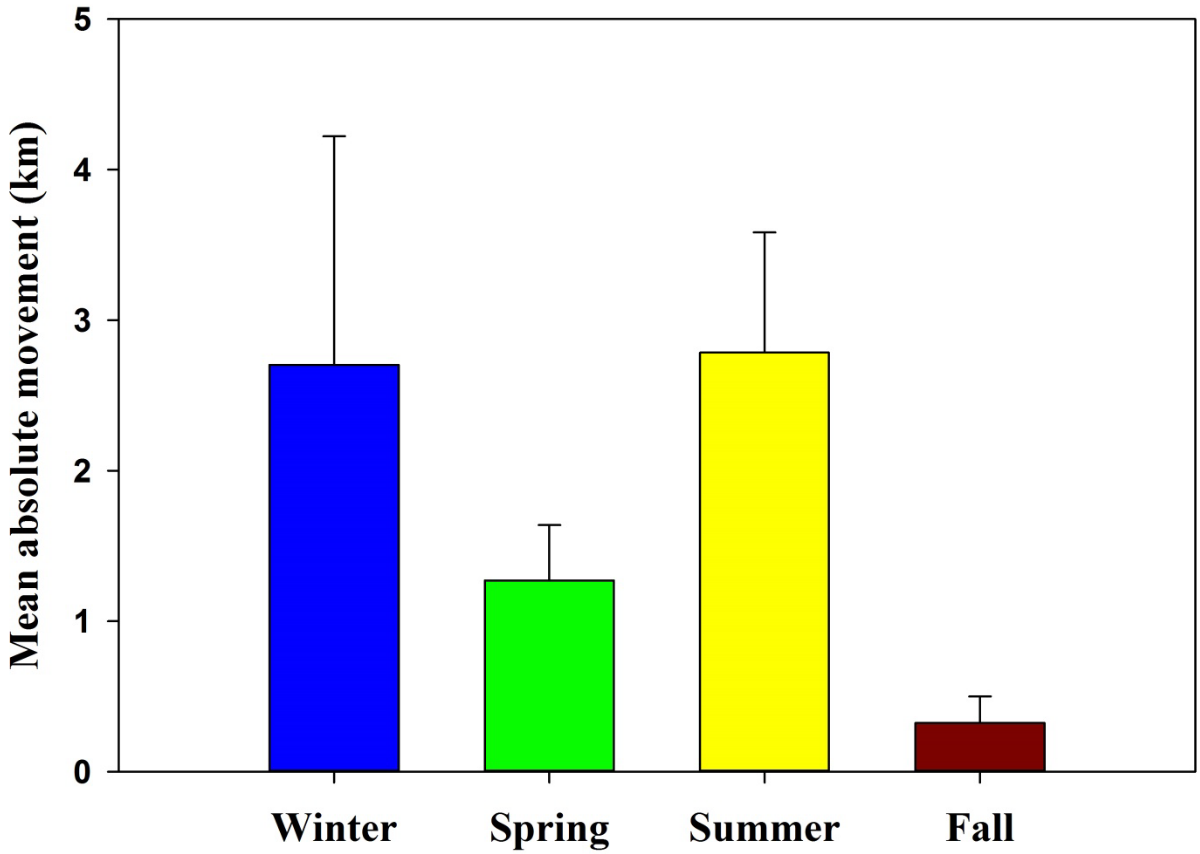

Figure 19. Mean seasonal absolute movement of Guadalupe Bass (n =27) implanted with radio transmitters in the lower Colorado River, Texas downstream of Austin, Texas during December 2014-May 2016. Twenty-one tracking events were conducted from Webberville to Altair, Texas starting in January 2015 and going through May 2016. Approximately seven tracking surveys were performed in the spring each year, followed by bi-monthly surveys in all other seasons. Error bars represent ± 1 standard error.

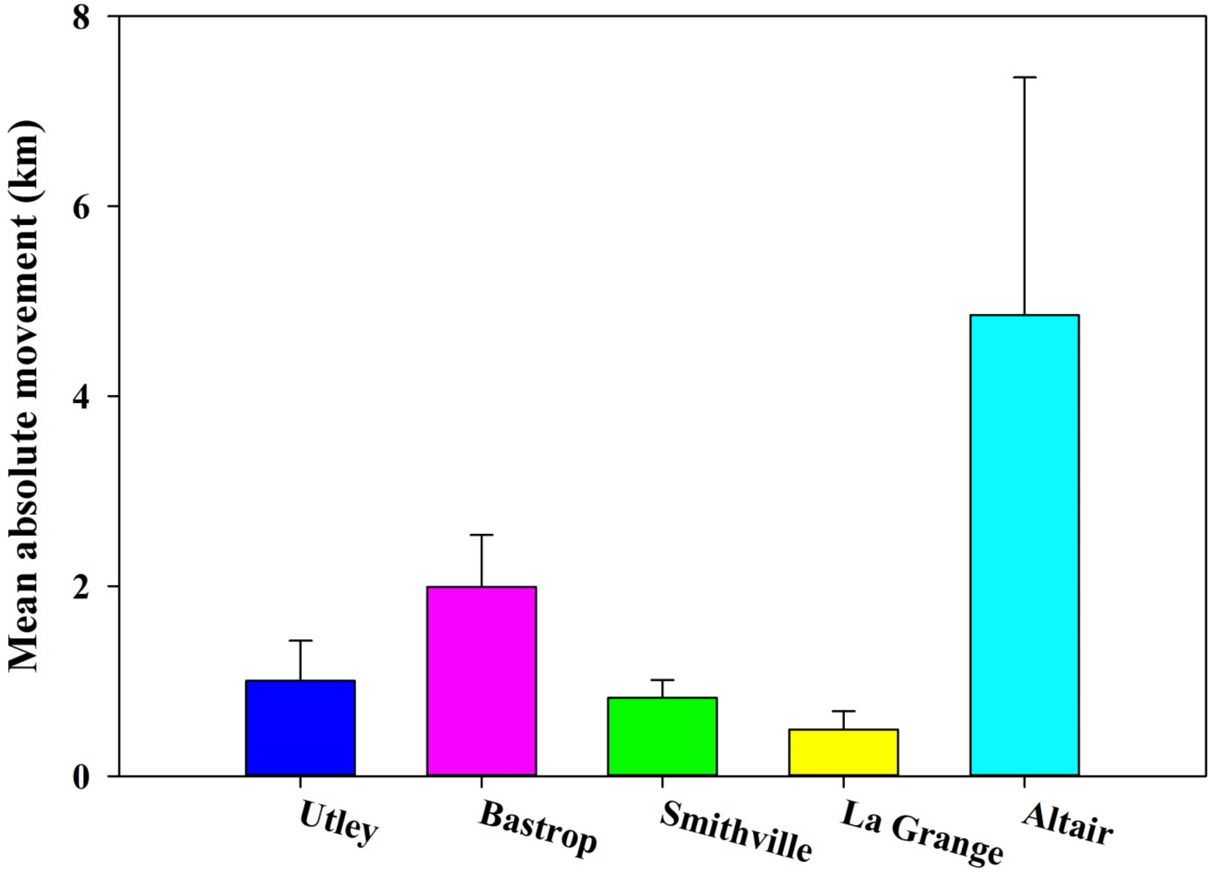

Figure 20. Mean absolute movement of Guadalupe Bass implanted with radio transmitters from five locations, Utley, Bastrop, Smithville, LaGrange, and Altair, in the lower Colorado River downstream of Austin, Texas during December 2014-May 2016. Error bars represent ± 1 standard error.

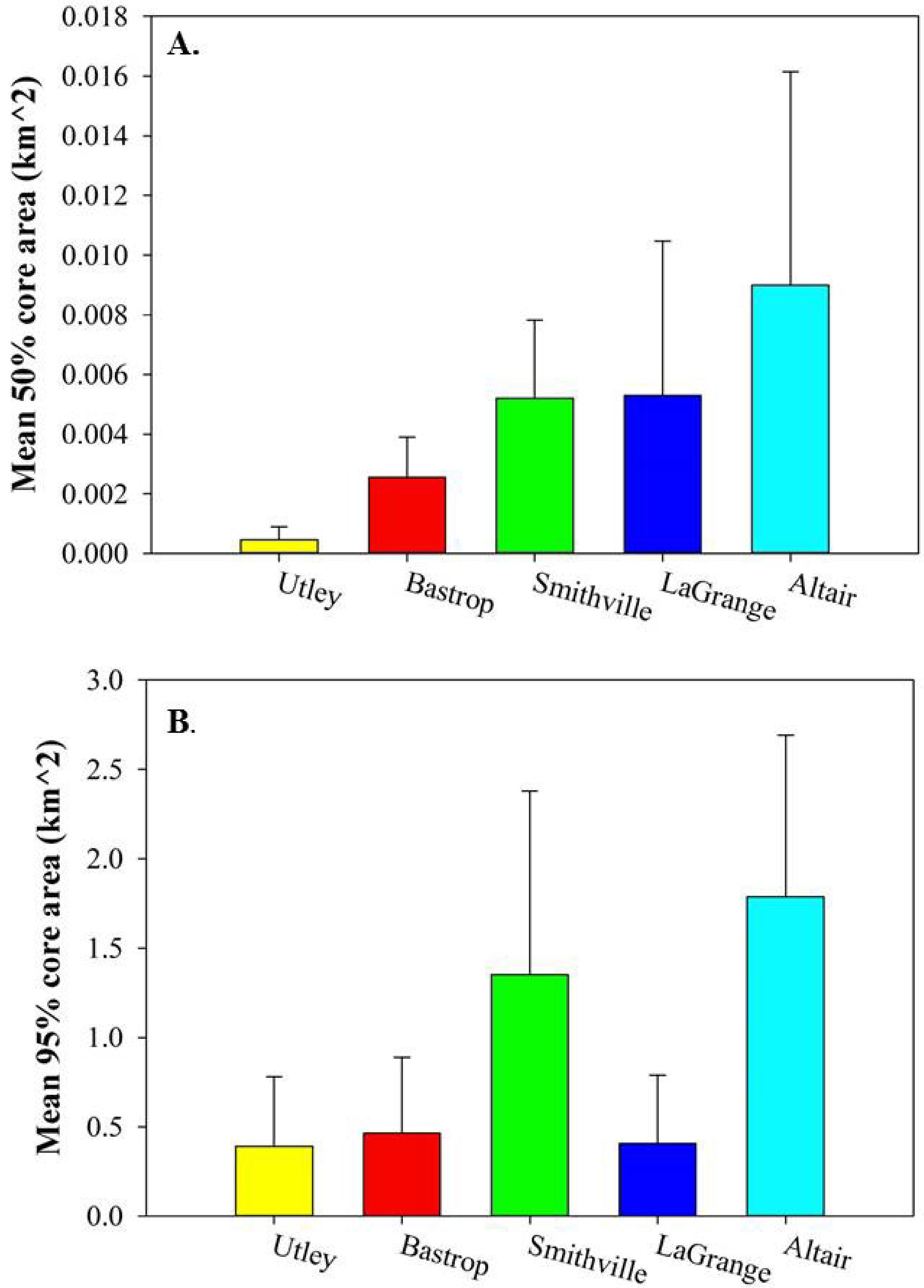

Figure 21. Mean 50% core area (A) and 95% kernel density estimation of home range (B) by tagging location of Guadalupe Bass implanted with radio transmitters in the lower Colorado River downstream of Austin, Texas during December 2014 to May 2016. Sites are listed in order from the most upstream tagging location Utley down to the furthest downstream location Altair. The three other tagging locations are Bastrop, Smithville and LaGrange. Error bars represent ± 1 standard error.

Guadalupe Bass mesohabitat associations were largely dominated by pool classed mesohabitat downstream ($F_{3,12}$=6.74, P=0.01) of Bastrop (Figure 22), while mesohabitat associations in Bastrop were dominated by riffle ($F_{3,12}$=4.28, P=0.02). Substrate association was largely dominated by sand and boulder with cobble being significantly selected ($F_{3,12}$=10.86, P=0.001) for in downstream sites at LaGrange and Altair (Figure 23). Gravel was selected in equal proportion across all sites and there was no significant difference in selection of any other dominated by sand and boulder with cobble being significantly selected ($F_{3,12}$=10.86, P=0.001) for in downstream sites at LaGrange and Altair (Figure 23).substrate type across sites. There was also no significant difference in selection across seasons: fine sediment ($F_{3,12}$=0.52, P=0.67), sand ($F_{3,12}$=0.49, P=0.69), gravel ($F_{3,12}$=0.16, P=0.92), cobble ($F_{3,12}$=0.12, P=0.95), boulder ($F_{3,12}$=0.03, P=0.99) and bedrock ($F_{3,12}$=0.96, P=0.45) (Figure 23).

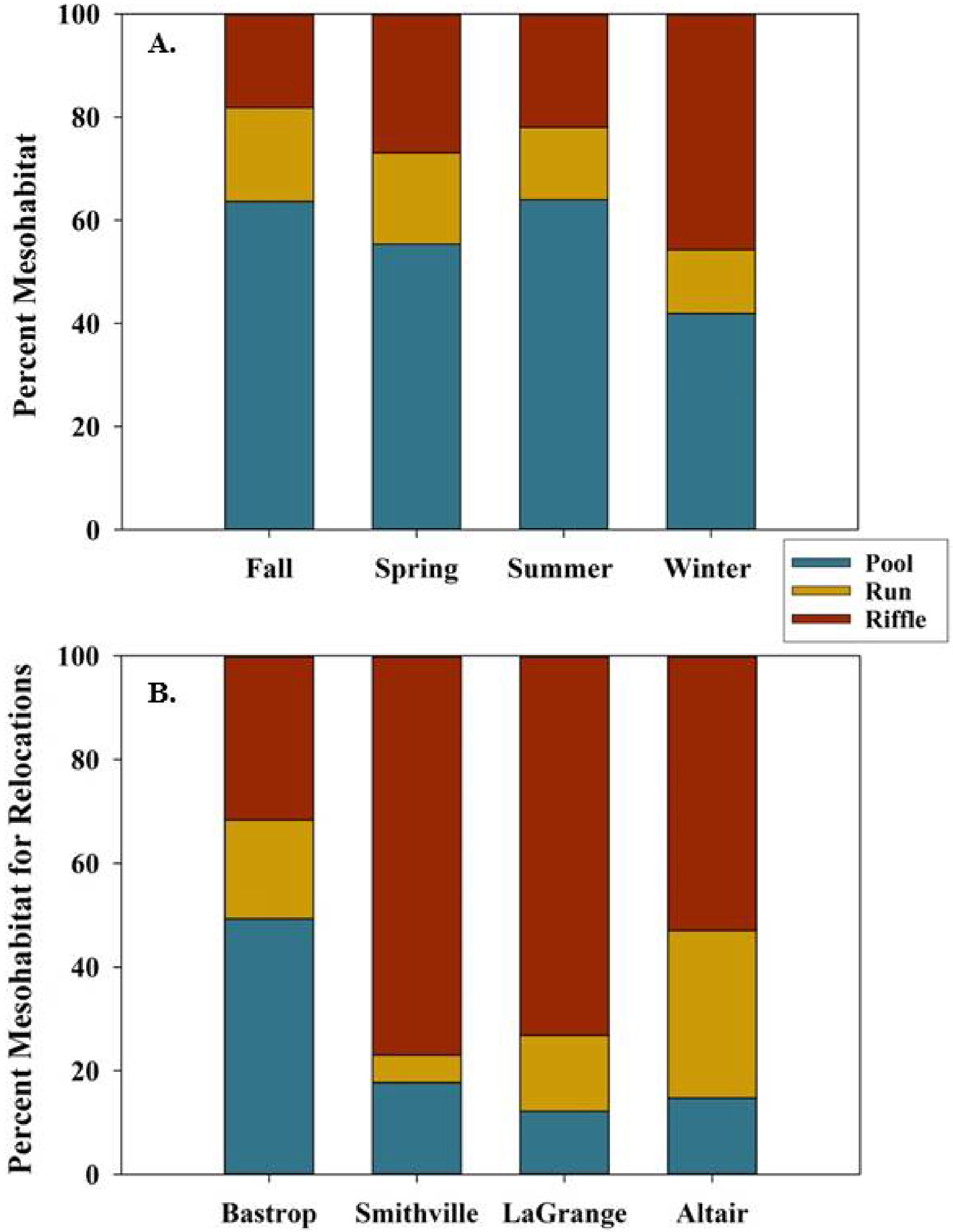

Figure 22. Percentage of mesohabitat composition used seasonally (A) at relocation points by Guadalupe Bass implanted with radio transmitters at four different sites: Bastrop, Smithville, LaGrange, and Altair in the lower Colorado River downstream of Austin, Texas during January 2015 to May 2016. The percent of mesohabitat selected (B) by individuals at each site. Locations of the tagging sites are presented in Figure 4.

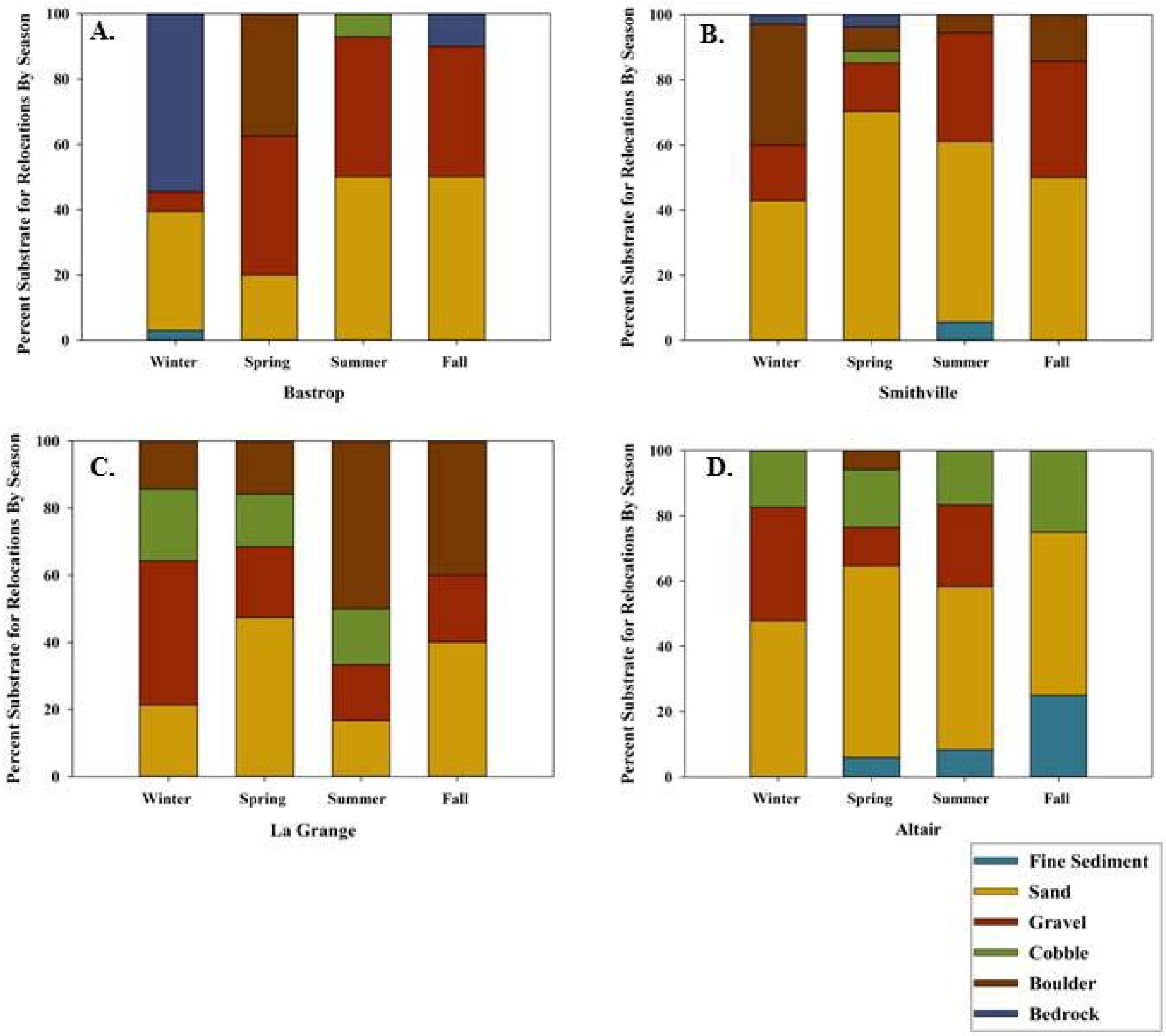

Figure 23. Percentage of substrate composition used seasonally at relocation points by Guadalupe Bass implanted with radio transmitters at four different sites: Bastrop (A), Smithville (B), LaGrange (C), and Altair (D) in the lower Colorado River downstream of Austin, Texas during January 2015 to May 2016. Locations of the tagging sites are presented in Figure 4.

Discussion

Our results suggest that the Guadalupe Bass population in the lower Colorado River downstream of Austin differs in many respects compared to populations inhabiting streams on the Edwards Plateau. Specifically, individuals in the population in the lower Colorado River are more mobile and occupy larger home ranges, have higher growth rates that are less sensitive to flow conditions, and have are morphologically different from conspecifics in the upper portions of the Colorado River Basin. Furthermore, the lower Colorado River seems to support a much higher population density of Guadalupe Bass relative to what has been documented in streams on the Edwards Plateau (Bean and Grabowski 2014). Our results indicate that Guadalupe Bass collected today have different morphology from individuals collected from the same sites 30 years ago and that these changes are correlated with changes in hydrology and land use throughout the Colorado River Basin. However, while our results show that the persistence and viability of the Guadalupe Bass population in the lower Colorado River is not of immediate concern, continuing trends related to the altered hydrology and changing land use within the Colorado River Basin may threaten the ability of this population to support a trophy sport fishery given the observed influence of stream discharge on growth and recruitment.

Changes in Land Cover and Flow

The Colorado River Basin has experienced a wide range of changes over the past 30 years associated with increasing human populations, particularly changing land-use patterns and hydrologic alteration. Reservoirs forming the Highland Lakes along the Colorado River have altered quantity and timing of water to the lower river channel in comparison to what would be considered a natural flow regime (Montagna et al. 2011). Our analyses revealed changes in both land cover and flow regime that reflect a gradient in disturbance influencing Guadalupe Bass at the landscape level. We determined that morphological differentiation, movement patterns, and variation in growth and recruitment of Guadalupe Bass throughout the watershed may be driven by environmental factors associated with LULC and flow conditions. Understanding these factors is critical for successful population management and conservation as anthropogenic alteration and human population growth are likely to continue.

Growth and Recruitment

The growth of Guadalupe Bass inhabiting tributary systems showed a more pronounced response to interannual variation in minimum, maximum, and mean monthly flows compared to individuals in the mainstem Colorado downstream of Austin. Mainstem Colorado River Guadalupe Bass were less sensitive to interannual variation in flow, and they generally grew faster than counterparts in tributary systems regardless of flow conditions. Our data, along with those of Groeschel (2013) and Massure (2016) indicate that there has been no appreciable change in the standardized growth rates of Guadalupe Bass in smaller tributary systems since the late 1970s (Edwards 1980). However, there is increased growth in larger tributary systems, such as the San Saba, Llano, and Pedernales, in comparison to the late 1970s. Furthermore, growth rates of Guadalupe Bass inhabiting the mainstem Colorado River were more similar to those of Guadalupe Bass in Lake L.B.J in the 1970s. Increased growth rates in higher-order systems may reflect populations' response to decreased variability and extreme flow events under anthropogenically altered flow regimes. Extreme high and low flows can be detrimental to growth and recruitment, and increased growth in *Micropterus* spp. has been shown to occur under moderate flow conditions with less flow variability. Managing populations with variable recruitment requires an understanding of the factors driving variability, as well as an understanding of the predictability of recruitment based on abiotic factors, such as stream discharge.

Weaker year classes may be linked to high flow conditions wiping out nests or causing nest failure, as well as increased mortality due to juvenile displacement (Harvey 1987; Simonson and Swenson 1990; Lukas and Orth 1995; Orth and Newcomb 2002). In addition to juvenile displacement, decreased dissolved oxygen has been linked to high juvenile mortality under high flow conditions in Wisconsin streams (Mason et al. 1991). Strong year classes have been linked to low flows in Santa Fe River for both Largemouth Bass and Suwannee Bass (Bonvechio and Allen 2005). Similarly, Smallmouth Bass in three Virginia Rivers also had strong year classes when flows were low during the spring (Smith et al. 2005). However, the timing of low flows is critical and can also have negative effects on growth and recruitment due to increases in competition and predation when there is reduced habitat availability (Harvey 1987; Smith et al. 2005; Dutterer et al. 2013). Our data showed that prolonged periods of low flows caused by disturbance such as the channel fragmentation and zero-flow days caused by water withdrawals in the North Llano River, negatively influences Guadalupe Bass growth rates.

Low-flow conditions are associated with reduced invertebrate production, which can slow growth and influence survival of juvenile individuals dependent upon drift feeding in riffles (Paragamian and Wiley 1987; Dewson et al. 2007). Recruitment may also potentially be lower due to size-dependent mortality from increased predation, elevated by the lack of refuge habitat under low flow conditions (Garvey et al. 2004; DeVries et al. 2009). Annual variation in Guadalupe Bass growth has been linked to mean monthly flows in the North and South Llano Rivers with lower growth rates in both systems during drought years. Our data suggest that the relationship between Guadalupe Bass growth and flow conditions in the smaller tributary systems holds true for present-day growth and recruitment in the lower Colorado River, with lower growth rates and weaker year classes during decreased maximum flow conditions. Similar results have been found for Largemouth Bass in the Apalachicola River, Florida, where increased discharge in the spring and summer caused significant growth increases due to sustained floodplain inundation providing nesting habitat, refuge for juveniles, and increased productivity of the system (Dutterer et al. 2013).

Higher recruitment and YOY growth for Guadalupe Bass were most strongly associated with increased minimum flows, especially higher mean monthly flows in the late summer months (July, August), in the early winter (January), as well as in the spring (May) within the time span of known spawning period for Guadalupe Bass. However, YOY growth rates were intermediate in years with the highest recruitment. Our data suggests Guadalupe Bass are growing at a faster rate in the lower Colorado River and recruitment is variable with potential density-dependent effects playing a role in years that are also associated with higher rates of growth. However, in years with decreased maximum flows there are potentially density-independent effects impacting recruitment. Assessment of recruitment and growth using aging structures facilitates additional understanding of the relative population dynamics. However, the brief duration of this study limited the predicted recruitment to the life of the fish, which is six or seven years. While collected individuals were exposed to drought and flooding conditions, data reflect single years of contrasting conditions. Long-term monitoring of Guadalupe Bass recruitment would permit more precise quantification of recruitment over periods of environmental fluctuation, potentially revealing the impacts of extreme drought or flooding.

Morphology

Our results showed distinct morphological differentiation both temporally and spatially, supporting the continued consideration of local adaptation as well as genetic population structure for conservation stocking efforts. Morphological diversity of present day Guadalupe Bass formed a geographic separation between five tributary sites (Onion Creek, Walnut Creek, North Llano River, Pedernales River, and San Saba River) and the mainstem Colorado River with three additional tributaries (Llano River, Dove Creek, and South Llano River). Patterns of morphological differentiation were somewhat similar to patterns of population genetic structure revealed by Bean (2012) based on microsatellite data. The Pedernales population was morphologically distinct from the mainstem Colorado River and the Llano River, and Bean (2012) found similar genetic separation of these populations. However, the San Saba River population was morphologically similar to the Pedernales River, but genetically it clustered with the Colorado River and the Llano River (Bean 2012). Our data suggest that determining the relationship between phenotypic and genotypic response of individuals may need consideration in future conservation and restoration management, specifically when selecting locations for stocking or for broodstock collection. This practice would ensure the success of progeny and avoid detrimental impacts on target populations (Rhymer and Simberloff 1996) ensuring successful outcomes like those seen in the Guadalupe River (Fleming et al. 2015).

In addition to exhibiting morphological variation throughout the Colorado River Basin, our data indicates that Guadalupe Bass populations have undergone substantial morphological changes through time. Whether these shifts in morphology are the result of genetic or phenotypic processes is undetermined; however, changes in flow regime and land use in the Colorado River Basin since the 1970s are the underlying factors associated with these morphological shifts.

Similar morphological shifts have been observed in species occupying reservoirs (Franssen et al. 2013a, 2013b), and likely provide a fitness benefit to Guadalupe Bass living in altered streams. Therefore, it is important to understand how Guadalupe Bass are changing in response to anthropogenic habitat disturbances as it provides an indication of the resiliency of this species and reveals issues that may impede conservation and management in the future. For example, rapid restoration of stream habitats has the potential to be detrimental to Guadalupe Bass, particularly in small populations, if the pace of restoration is not paired with phenotypic response time. When implementing restoration, consideration for the morphological response of species will allow managers to modify timing and efforts for populations that have adjusted under altered environments increasing the success of management efforts. These morphological differences may possibly influence interactions with conspecifics, such as Largemouth Bass. If the current trajectory of LULC and flow regime alteration results in the loss of habitat upon which Guadalupe Bass currently depend, their morphological response may be more similar to other *Micropterus* species, potentially increasing competition for resources. Consideration of differences between populations presents further challenges for current planning; however, it may be a proactive response to continued trends in climatic change, increased water withdrawal, and LULC changes that differ throughout Guadalupe Bass range.

Movement

Individuals in the mainstem Guadalupe Bass population were more mobile, and more responsive to changes in streamflow, than those observed in tributaries. Observed habitat associations and movement patterns of Guadalupe Bass in the lower Colorado River are, in a general sense, similar to those described for Guadalupe Bass in upper watershed tributaries. However, there are some important differences in the movements and habitat uses of Guadalupe Bass in the lower Colorado River relative to those occupying smaller rivers and streams that may influence the outcome of conservation or management actions. The dominant mesohabitat used in tributaries is typically runs, commonly associated with eddies (Edwards 1980; Perkin et al. 2010). In contrast, Guadalupe Bass mesohabitat associations in the mainstem lower Colorado River were largely dominated by pool-classed mesohabitat downstream of Bastrop, while upstream of Bastrop, riffle was the dominant mesohabitat.

Our results indicate that Guadalupe Bass exhibit differences in habitat associations based on the order of the stream they inhabit, but whether this is due to differences in habitat availability or population-level differences in habitat preferences in not clear. The habitat associations of Spotted Bass vary regionally with populations favoring pool mesohabitats in Kansas streams, while Alabama populations showed preference for riffles and shoal habitats (Sammons and Maceina 2009). In addition to regional difference in mesohabitat use, Spotted Bass have been found to show high variation in habitat use in association with proportion of available habitat (Goclowski et al. 2013). Perkin et al. (2010) found that in the South Llano River and the Pedernales River, habitat availability played a role in Guadalupe Bass distribution, abundance and habitat associations. In the late summer Guadalupe Bass in the South Llano River were associated with run mesohabitats due to higher and more consistent flows. In comparison, Guadalupe Bass in the Pedernales River were associated with pool mesohabitat under conditions of low flow and limited habitat availability in the late summer. The Colorado River becomes deeper and wider downstream of Longhorn Dam with progressively higher proportions of finer substrates as the gradient of the stream bed decreases, resulting in a decrease in the frequency of riffle habitat further downstream. Greater availability of riffle habitat upstream of Bastrop compared to downstream locations may drive the differences in mesohabitat associations that we observed.

Differences in habitat preferences possibly contribute to movement differences between Guadalupe Bass main stem and tributary populations. Guadalupe Bass routinely moved much greater distances in the lower Colorado River than the previously reported maximum of 3.4 km for individuals in smaller streams (Perkin et al. 2010). The largest individual movements made by Guadalupe Bass in the lower Colorado River regardless of directionality occurred in the months of March and June. Given that Guadalupe Bass spawning has been observed from March to June (Edwards 1980; Warren 2009), these larger movements observed during this time in the lower Colorado River were likely associated with individuals moving to suitable nesting habitat and returning to their feeding areas. Guadalupe Bass in the smaller tributary systems of the Pedernales River and the South Llano River have also shown similar seasonal differences in movement associated with the spawning season (Perkin et al. 2010; Groeschel 2013), but the magnitude of the movements tended to be considerably smaller. Additional seasonal differences in movement are likely driven at least in part by variability in flow conditions. Especially in higher-order streams, centrarchids have been observed moving out of the river channel or retreating downstream in association with flood events. For example, in Arizona streams Smallmouth Bass and Green Sunfish *Lepomis cyanellu*s were displaced following high flood pulses, but typically returned within a two-week period to pre-flood locations (Minckley and Meffe 1987). Guadalupe Bass in the Pedernales River moved downstream during a flash flood event, shifting from woody debris instream cover to boulders and bedrock ledges (Perkin et al. 2010). In the lower Colorado River large downstream movements, as well as occasional movements into tributaries were associated with Guadalupe Bass being displaced or seeking refuge during large flood events.

Larger movements by the population in the lower Colorado River suggest that individuals complete their life history in a longer stretch of river and move greater distances between essential habitat in comparison to individuals in smaller tributary populations. Their extensive home range is comparable in size to those used by other black bass species in reservoirs and higher-order streams. Increasing movement and home range size with increasing stream order has also been seen in Smallmouth Bass in Kentucky between mainstem and tributary populations (Bare 2005). Unlike tributary systems where zero flow days may limit or isolate individuals, zero flow days occur in the lower Colorado River only rarely, if ever. However, extended low flow periods and altered flow regime modify the location and quantity of mesohabitat, potentially leading to extended movements by individuals to find optimal spawning or overwintering habitat. Requiring access to longer stretches of river increases the vulnerability of big-river populations to habitat fragmentation and further disruption of flows that result in restrictions to movement (Lande 2009; Hugueny et al. 2011).

Overall, the mainstem population was generally more mobile, and more responsive to changes in streamflow, than tributary populations. The movements we documented suggest that Guadalupe Bass in the lower Colorado River represent a heterogeneous population with both stationary and mobile individuals having different seasonal movements and habitat associations based on availability of riffle habitat. Maintaining access to both overwintering and nesting areas ensures the population is not negatively impacted by the loss of necessary habitat for the completion of life history stages. While different movement patterns within a single population of stream-dwelling black bass have been observed, information on the mechanistic drivers and the spatiotemporal scales at which these movements differ is relatively sparse. Observed differences between mainstem and tributary populations could influence the response of Guadalupe Bass to conservation and management actions, such as habitat restoration efforts. Management may be most effective if broader-scale restoration is considered that takes into account the mobile and stationary individuals comprising a population, as well as access and availability of habitat for seasonal movements.

Conclusions

Our results indicate that the lower Colorado River population is adapted to this higher order system and not a population comprising transient individuals from tributary systems. Consideration of the differences between the mainstem and tributary populations may be necessary to adapt management strategies currently used for tributary populations to the lower Colorado River. Individuals in the mainstem population showed movement patterns that were not associated with tributaries for any particular life-history stage; any observed use of tributaries seems to be refuge for escaping high flows. The lower Colorado River population does not seem to be habitat limited, recruitment and growth suggest a very robust population, and there are no signs of overfishing.

Mainstem population individuals are capable of thriving under present-day development within the watershed and regulated flow conditions of the Highland Lakes, but effects of continued environmental change are unknown. Basin-wide variation in the population dynamics of Guadalupe Bass support further watershed scale approaches to management and conservation planning to maintain the ecological processes and natural habitat that support distinct populations. When planning for the conservation of the unique mainstem population under current projected population growth and further urbanization within the watershed, managers could consider increasing releases prior to and immediately following spawning in the lower

Colorado River. Watershed-scale restoration and management of the population would not only be beneficial to Guadalupe Bass, but has the potential to also benefit other focal or endemic species, such as the Guadalupe Roundnose Minnow *Dionda nigrotaeniata*, Texas Logperch *Percina carbonaria*, as well as the state threatened Blue Sucker *Cycleptus elongatus* (Garrett 1991; Birdsong et al. 2010). Our results suggest that additional regulation or management of the lower Colorado population Guadalupe Bass population is not warranted at the present time. However, the potential for continued alteration of the hydrology of the lower Colorado River that might occur with future growth of Austin and the surrounding urban areas and increasing fishing pressure suggests that continued monitoring of recruitment and population status is warranted to ensure the productivity of this trophy fishery.

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APPENDICES

Appendix A. Summary table of site locations and the associated ten-digit hydrologic unit code (HUC) and United States Geological Survey stream gage number.

Site	River	River	Latitude	Longitude	HUC 10	USGS Gage	Watershed
Barton Creek Greenbelt S Capital of Texas Hwy 360	1	BART	30.244703	-97.8022	1209020503	8155240	22
Lost Creek Access to Barton Creek Greenbelt off Lost Creek Blvd.	1	BART	30.2743	-97.8444	1209020503	8155240	22
South of US 90 Alt Boat Ramp in Eagle Lake	2	COLO	29.5532	-96.4008	1209030201	8161000	30
South of Fisherman's Park Boat Launch in Bastrop	2	COLO	30.0994	-97.3211	1209030102	8159200	27
South of Webberville Park	2	COLO	30.2019	-97.4868	1209030102	8159200	27
North of Fisherman's Park Boat Launch in Bastrop	2	COLO	30.1333	-97.3614	1209030102	8159200	27
South of the Fannin St. TX 71 Business Boat Ramp	2	COLO	29.7158	-96.5416	1209030107	8160400	29
State Highway 71	2	COLO	29.9012	-96.8870	1209030107	8160400	29
South of State Highway 71 Boat Ramp	2	COLO	29.8957	-96.8843	1209030107	8160400	29
South of the State Hwy 71 crossing in Smithville	2	COLO	30.0145	-97.0942	1209030104	8159200	28

FM 2335 outside Knickerbocker	3	DOVE	31.2738	-100.6308	1209010203	8130500	3
James River Rd. crossing north of Eckert James River Bat Cave Preserve	4	JAME	30.5725	-99.3233	1209020404	8150700	17
RR 1871	5	LLAN	30.6579	-99.3246	1209020402	8150000	16
RR 2389 James River and Llano River confluence.	5	LLAN	30.6502	-99.2507	1209020405	8150700	17
South Llano and North Llano confluence off Camino Rio St.	5	LLAN	30.4926	-99.7567	1209020202	8148500	15
FM 3404 in Kingland, Texas	5	LLAN	30.6824	-98.4835	1209020408	8151500	21
Simonsville Rd.	5	LLAN	30.64002	-99.168097	1209020405	8150700	18
Bear Creek at Interstate 10	6	NLR	30.5210	-99.8293	1209020203	8148500	12
CR260	6	NLR	30.4986	-100.0927	1209020203	8148500	11
CR271	6	NLR	30.5181	-99.8102	1209020203	8148500	12
CR274	6	NLR	30.4981	-99.9448	1209020203	8148500	12
CR275	6	NLR	30.4909	-99.9864	1209020203	8148500	11

CR260 at River Rd in Roosevelt	6	NLR	30.4796	-100.1195	1209020203	8148500	11
CR310 to River Rd. in Sonora	6	NLR	30.4826	-100.1474	1209020203	8148500	11
McKinney Falls State Park	7	ONION	30.1885	-97.7205	1209020504	8159000	23
RR 1320	8	PEDE	30.2726	-98.5455	1209020602	8153500	25
Texas Hwy 16	8	PEDE	30.2070	-98.9790	1209020601	8153500	24
Hamilton Pool Rd. (FM 3238) Crossing	8	PEDE	30.3399	-98.1392	1209020504	8152900	26
U.S. Route 290	8	PEDE	30.2276	-98.8188	1209020602	8153500	25
Fiedler Rd.	8	PEDE	30.2277	-99.2001	1209020601	8152900	24
RR 1623	8	PEDE	30.2433	-98.6572	1209020602	8153500	25
Decker St. off TX Hwy 83 in Menard	9	SABA	30.9190	-99.7840	1209010905	8144500	8
FM 340 / S. Cotton Belt Rd.	9	SABA	31.1910	-98.9026	1209010908	8146000	10
Texas Hwy 16 at the intersection with FM 1480	9	SABA	31.2133	-98.7199	1209010908	8146000	10

US Hwy 377/87 outside Brady	9	SABA	31.0040	-99.2695	1209010907	8146000	9
Flatrock Ln. off US 377	10	SLR	30.4790	-99.7779	1209020302	1111111	14
CR150	10	SLR	30.3936	-99.8820	1209020302	1111111	14
CR408	10	SLR	30.2419	-99.9628	1209020302	1111111	13
US Hwy 377 at the first crossing south of Junction	10	SLR	30.3504	-99.9017	1209020302	1111111	14
South Llano State Park (State Park Rd. 73)	10	SLR	30.4502	-99.8128	1209020302	1111111	14
Stevenson RR in Telegraph	10	SLR	30.3199	-99.9109	1209020302	1111111	14
Springdale Rd.	11	WC	30.3375	-97.6502	1209020503	8158600	22
Walnut Creek Bike Trail off FM 969	11	WC	30.2906	-97.6567	1209020503	8158600	22

Appendix B. Catalog identification numbers for all Guadalupe Bass used in the morphometric analysis. These specimens were accessed at the Texas Natural History Collection in the Biodiversity Collections of the Department of Integrative Biology at The University of Texas at Austin.

Hendrickson, Dean A. and Adam E. Cohen. 2015. Fishes of Texas Project and Online Database (version 2.0) (http://fishesoftexas.org). Published by the Ichthyology Collection of The University of Texas at Austin. Accessed (3 September 2015).

Catalog ID	*Specimens*	*River*	*County*	*Location*	*Collecting Date*	*Collector*	*Coordinates*
TNHC10349	6	Llano	Llano	Llano River 1 km NE Kingsland off Highway 1431	18-Jul-77	Edwards	30.65119252, -98.48866364
TNHC10110	6	Onion Creek	Travis	Onion Creek, 12 km. SE Austin, State Hwy 183	19-Mar-78	Edwards	30.17791123, -97.68897812
TNHC10114	4	Barton Creek	Travis	Barton Creek, 21 km. SW Austin at State Hwy 71	9-Oct-77	Edwards	30.296277, -97.925624
TNHC10117	34	Onion Creek	Travis	Onion Creek, 12 km. SE Austin, State Hwy 183	18-Jun-77	Edwards	30.17791123, -97.68897812
TNHC10192	42	Llano	Llano	Llano River, 19 km. W Llano off Hwy 152	16-Jul-78	Edwards	30.71027191, -98.86003926
TNHC10194	1	Llano	Llano	Llano River, Kingsland near Kingsland Estates	24-Apr-77	Edwards	30.64016489, -98.47570928
TNHC10198	4	Pedernales	Gillespie	Pedernales River, 6.4 km. S Fredericksburg, State Hwy 16	16-Dec-78	Edwards	30.20919787, -98.94879018
TNHC10200	15	Llano	Llano	Llano River, Llano near Hwy 16	11-Jun-78	Edwards	30.75243093, -98.67581467
TNHC10205	2	Llano	Llano	Llano River, Llano near Hwy 16	18-Nov-78	Edwards	30.75243093, -98.67581467
TNHC10206	4	Llano	Llano	Llano River, Llano near Hwy 17	18-Nov-78	Edwards	30.75243093, -98.67581467

TNHC10207	39	Onion Creek	Travis	Onion Creek, 12 km. SE Austin, State Hwy 183	4-Jul-77	Edwards	30.17791123, -97.68897812
TNHC10213	43	Pedernales	Travis	Pedernales River, 40 km. E Johnson City, State Hwy 962	21-Jun-77	Edwards	30.33990517, -98.13912996
TNHC10218	52	Pedernales	Gillespie	Pedernales River, 6.5 km. SE Fredericksburg, US Hwy 290	6-Aug-77	Edwards	30.22709728, -98.94879023
TNHC10225	3	Pedernales	Blanco	Pedernales River, 12 km. W Johnson City, State Hwy 1320	3-Dec-77	Edwards	30.2722066, -98.54552012
TNHC10229	13	Colorado	Colorado	Colorado River, Columbus, State Hwy 90	10-Jul-77	Edwards	29.70625864, -96.53656784
TNHC10232	1	Pedernales	Gillespie	Pedernales River, 6.5 km. SE Fredericksburg, US Hwy 290	5-Mar-78	Edwards	30.22709728, -98.94879023
TNHC10233	1	Pedernales	Gillespie	Pedernales River, State Hwy 1 Immediately Downstream from Lbj Ranch	3-Dec-77	Edwards	30.2445474, -98.59765137
TNHC10239	18	Llano	Llano	Llano River, .2 km. N Castell, State Hwy 2768	28-Aug-76	Edwards	30.70380192, -98.95863175
TNHC10241	13	Llano	Llano	Llano River, Llano near Hwy 16	15-Oct-77	Edwards	30.75243093, -98.67581467
TNHC10247	5	Colorado	Colorado	Colorado River, 7.2 km. NE Altair, US Hwy 90A	10-Jul-77	Edwards	29.58034302, -96.41714457
TNHC10327	4	Colorado	Travis	Colorado River, 14.5 km. E Austin, Hwy 973	31-Oct-76	Edwards	30.20818034, -97.6380769
TNHC10330	2	Llano	Kimble	Llano River, 32 km. NE Junction, State Hwy 385	20-Feb-77	Edwards	30.6587426, -99.32412093
TNHC10113	46	Llano	Mason	14.5 km. SE Mason, State Hwy 87	17-Jun-77	Edwards	30.66117297, -99.10949548
TNHC17318	1	Dove Creek	Irion	Dove Creek at first crossing	22-Feb-86	Hubbs, Marsh-	31.15589373, -100.7527988

						Matthews, and Scott	
TNHC17355	3	Llano	Kimble	Llano River at Junction	25-Jun-86	Hubbs and Morales	30.49784685, -99.75186133
TNHC17356	1	Llano	Kimble	Llano River at Junction	25-Jun-86	Hubbs and Morales	30.49784685, -99.75186133
TNHC2072	2	San Saba	Menard	San Saba River, 1 mi. N Ft. McKavitt	10-Feb-52	Hubbs and Strawn	30.83592528, -100.1050113
TNHC2525	1	San Saba	Menard	San Saba River, 1 mi. E Ft. McKavitt	10-Feb-52	Hubbs and Strawn	30.83461535, -100.093721
TNHC2599	1	North Concho	Tom Green	N Fork Concho River, near dam, San Angelo	9-Feb-52	Hubbs, Strawn, Henderson, and Pyburn	31.46714483, -100.450052
TNHC3068	1	South Llano	Kimble	S Fork Llano River, 14.5 mi. SW Junction	27-Dec-52	Hubbs and Strawn	30.38543019, -99.88780445
TNHC3102	3	Dove Creek	Irion	Dove Creek, headsprings, 7 mi. SW Knickerbocker	21-Feb-53	Hubbs and Strawn	31.20565229, -100.7065677
TNHC3276	1	Colorado	Bastrop	Colorado River at SH969 Southeast of Utley	13-Mar-53	Hubbs	30.16746206, -97.40291082
TNHC5419	1	San Saba	Menard	San Saba River north of Fort McKavett	16-Jul-56	Hubbs and Strawn	30.83592528, -100.1050113
TNHC8008	1	San Saba	Menard	San Saba River at SH 864 (first crossing north-northeast of Fort McKavett)	16-Jul-56	Hubbs and Strawn	30.83461535, -100.093721
TNHC5419	1	San Saba	Menard	N Valley Prong San Saba River, 1 mi. N Ft. McKavitt	17-Jul-56	Hubbs and Strawn	30.83592528, -100.1050113

TCWC235.01	3	Colorado River	Colordao	Colorado River drainage; 6.0 mi NE Columbus on Cummings Creek	24-Oct-59	Jones	29.73585769, -96.5089472
TCWC6670.03	2	Llano	Llano	Llano River; Llano River: 4 mi W Llano.	30-May-86	WFS 300 Class	30.74395108, -98.73857625
TCWC7826.06	5	Dove Creek	Tom Green	Dove Creek.; Dove Creek, 0.5 mi NW Knickerbocker at FR 2335.	21-May-91	Brown and Smith	31.27377036, -100.630536
TCWC8925.08	3	Colorado River	Concho	Colorado River; Colorado River, FM 1929 downstream from Freese Dam	14-Oct-96	Brown and Smith	31.49830568, -99.66221199
TNHC10536	6	Onion Creek	Travis	State Hwy 183 crossing, 5 km. SE Austin	6-Aug-80	Pezold	30.17791123, -97.68897812
TNHC11233	1	Colorado River	Travis	Colorado River near SH 71 in vicinity of Del Valle	4-Oct-81	Winemiller	30.21226018, -97.64852718
TNHC21719	2	Barton Creek	Travis	Barton Creek at Lost Creek Blvd.	18-May-93	Warren and Freeman	30.27412783, -97.8444023
TNHC10536	6	Onion Creek	Travis	Onion Creek, State Hwy 183 crossing, 5 km. SE Austin	6-Aug-80	Pezold	30.17791123, -97.68897812
TNHC1428	1	Pedernales River	Travis	Pedernales River at Cypress Creek	11-May-51	Jameson and Phillips	30.35100481, -98.13701993
TNHC21746	1	Barton Creek	Travis	Barton Creek at SH 71	15-Feb-93	Warren and Wright	30.29627697, -97.92562442
TNHC21806	5	Barton Creek	Travis	Barton Creek at Barton West subdivision off Bee Cave drive	7-Jul-88	Kleinsasser and Linam	30.29889697, -97.87623317
TNHC22059	1	South Llano	Kimble	South Llano River at first FM 377 crossing SW of Junction	21-Jun-89	Kleinsasser and Sager	30.36201094, -99.88930442
TNHC22323	1	Little Barton Creek	Travis	Little Barton Creek at private raod off SH 71 W of Austin near confluence with Barton Creek	15-Mar-89	Linam and Sauders	30.29586698, -97.92731446

TNHC22797	3	Barton Creek	Travis	Barton Creek, 13.8 mi SW of Austin on St. Hwy. 71	7-Jun-93	Warren and Freeman	30.29627697, -97.92562442
TNHC22817	79	Barton Creek	Travis	Barton Creek, Austin, 0.8 mi E of Lost Creek Blvd. on Plumbrook Road	11-Jul-93	Warren and Freeman	30.269878, -97.82928191
TNHC22819	5	Barton Creek	Travis	Barton Creek, Austin, below Barton Springs Pool at Zilker Park	29-Jul-93	Warren and Freeman	30.26495827, -97.76569028
TNHC22841	4	Barton Creek	Travis	Barton Creek, Austin, 1.7 mi S of Loop 360 on Lost Creek Blvd.	24-Aug-93	Warren and Freeman	30.27412783, -97.8444023
TNHC22848	1	Barton Creek	Travis	Barton Creek, Austin, below Barton Springs Pool at Zilker Park	20-Nov-93	Warren and Freeman	30.26495827, -97.76569028
TNHC22866	1	Barton Creek	Travis	Barton Creek, Austin, 1.7 mi S of Loop 360 on Lost Creek Blvd.	19-Dec-93	Warren and Freeman	30.27412783, -97.8444023
TNHC22915	9	Barton Creek	Travis	Barton Creek. 1.4 mi S of Bee Cave Road on Crystal Creek Drive	17-Jun-94	Warren and Freeman	30.30145691, -97.86433287
TNHC22928	30	Barton Creek	Travis	Barton Creek, 1.4 mi SW of Loop 360 on Plumbrook road below Lost Creek subdivision	28-Aug-93	Warren, Freeman, and Hiers	30.269878, -97.82928191
TNHC22973	1	Little Barton Creek	Travis	Little Barton Creek at private road off SH 71 W of Austin at Fandango Way	7-Jul-88	Kleinsasser and Linam	30.29586698, -97.92731446
TNHC22989	1	Barton Creek	Travis	Barton Creek, 1.4 mi SW of Loop 360 on Plumbrook road below Lost Creek subdivision	25-Aug-93	Warren and Freeman	30.269878, -97.82928191
TNHC230	5	Onion Creek	Travis	10 mi. SE on Onion Creek, near del Valle	17-Sep-47	Blair	30.18925098, -97.6201864
TNHC23004	7	Barton Creek	Travis	Barton Creek, 13.8 mi SW of Austin on St. Hwy. 71	23-Aug-93	Warren and Freeman	30.29627697, -97.92562442

TNHC23015	2	Barton Creek	Travis	Barton Creek, 7.0 mi NE of Dripping Springs on Co. Rd. 185 (or Trautwein Road)	24-Aug-93	Warren and Freeman	30.23644873, -98.0248168
TNHC23116	7	Colorado River	Bastrop	Colorado River in town of Bastrop at loop 150 river crossing	Jul-87	Morales	30.10989408, -97.32286866
TNHC23120	1	Colorado River	Bastrop	Colorado River in town of Bastrop at loop 150 river crossing	Oct-86	Morales	30.10989408, -97.32286866
TNHC23122	8	Colorado River	Bastrop	Colorado River in town of Bastrop at loop 150 river crossing	Jun-87	Morales	30.10989408, -97.32286866
TNHC23146	1	Colorado River	Bastrop	Colorado River in town of Bastrop at loop 150 river crossing	Nov-86	Morales	30.10989408, -97.32286866
TNHC23155	7	Colorado River	Bastrop	Colorado River at Pope Bend off of FM 969 approx 7 mi E of its jct with SH71	May-86	Morales	30.18786136, -97.42345139
TNHC23163	3	Colorado River	Bastrop	Colorado River at Pope Bend off of FM 969 approx 7 mi E of its jct with SH71	Jul-87	Morales	30.18786136, -97.42345139
TNHC23173	3	Colorado River	Bastrop	Colorado River at Pope Bend off of FM 969 approx 7 mi E of its jct with SH71	Sep-86	Morales	30.18786136, -97.42345139
TNHC23181	1	Colorado River	Bastrop	Colorado River at Pope Bend off of FM 969 approx 7 mi E of its jct with SH71	August - September 1986	Morales	30.18786136, -97.42345139
TNHC23196	15	Colorado River	Bastrop	Colorado River at Pope Bend off of FM 969 approx 7 mi E of its jct with SH71	Jun-87	Morales	30.18786136, -97.42345139
TNHC23203	1	Colorado River	Travis	Colorado River at FM 973 highway crossing	Sep-86	Morales	30.20816034, -97.6379969

TNHC23233	2	Colorado River	Travis	Colorado River at Longhorn Dam	May-86	Morales	30.25036883, -97.71344891
TNHC23244	3	Colorado River	Travis	Colorado River at Longhorn Dam	Jun-87	Morales	30.25036883, -97.71344891
TNHC23605	5	Colorado River	Colorado	Colorado River at Smithville from about 50m below St. Hwy. 95 to 400m below St. Hwy. 71	29-Jun-96	Hendrickson, Mosier, and Southwest Texas State University Class	30.02294702, -97.26388697
TNHC23645	4	Colorado River	Travis	Colorado River at FM 973 highway crossing	Jul-87	Morales	30.20816034, -97.6379969
TNHC23648	2	Colorado River	Travis	Colorado River at FM 973 highway crossing	Jul-87	Morales	30.20816034, -97.6379969
TNHC23651	2	Colorado River	Travis	Colorado River at Longhorn Dam	Jun-87	Morales	30.25036883, -97.71344891
TNHC23658	3	Colorado River	Bastrop	Colorado River at Pope Bend off of FM 969 approx 7 mi E of its jct with SH71	August - September 1986	Morales	30.18786136, -97.42345139
TNHC2525	1	San Saba	Menard	San Saba River at SH 864 (first crossing north-northeast of Fort McKavett)	10-Feb-52	Hubbs and Strawn	30.83461535, -100.093721
TNHC2599	1	N Fork Concho River	Tom Green	North Concho River downstream of O. C. Fisher Dam	9-Feb-52	Hubbs, Strawn, Henderson, and Pyburn	31.46714483, -100.450052

TNHC29916	3	Walnut Creek	Travis	Walnut Creek, reach from Springdale Road upstream to Sprinkle Cutoff Road	20-Mar-03	Hendrickson, Hendrickson, and Hicks	30.35145566, -97.65306761
TNHC29926	3	Walnut Creek	Travis	Walnut Creek, reach from Springdale Road upstream to Sprinkle Cutoff Road	30-Mar-03	Hendrickson, Hendrickson, and Hicks	30.35145566, -97.65306761
TNHC29947	3	Walnut Creek	Travis	Walnut Creek, reach from Springdale Road upstream to Sprinkle Cutoff Road	30-Mar-03	Hendrickson, Hendrickson, and Hicks	30.35145566, -97.65306761
TNHC5076	1	Pedernales River	Travis	Pedernales River at confluence of Cypress Creek and Hamilton Creek	6-May-55	McCoy	30.34975485, -98.13725993
TNHC538	2	Colorado River	Travis	Colorado River at Waller Street	3-Oct-47	Blair and Class	30.25068878, -97.73535947
TNHC7313	1	Llano	Llano	Llano River, near Submerged bridge Past Kingsland to The Left of Fr 1431	8-Mar-68	Rogers and Leach	30.68206354, -98.4841796
TNHC8200	1	Llano	Kimble	Llano River at Junction	28-Apr-68	Eddleman	30.49784685, -99.75186133

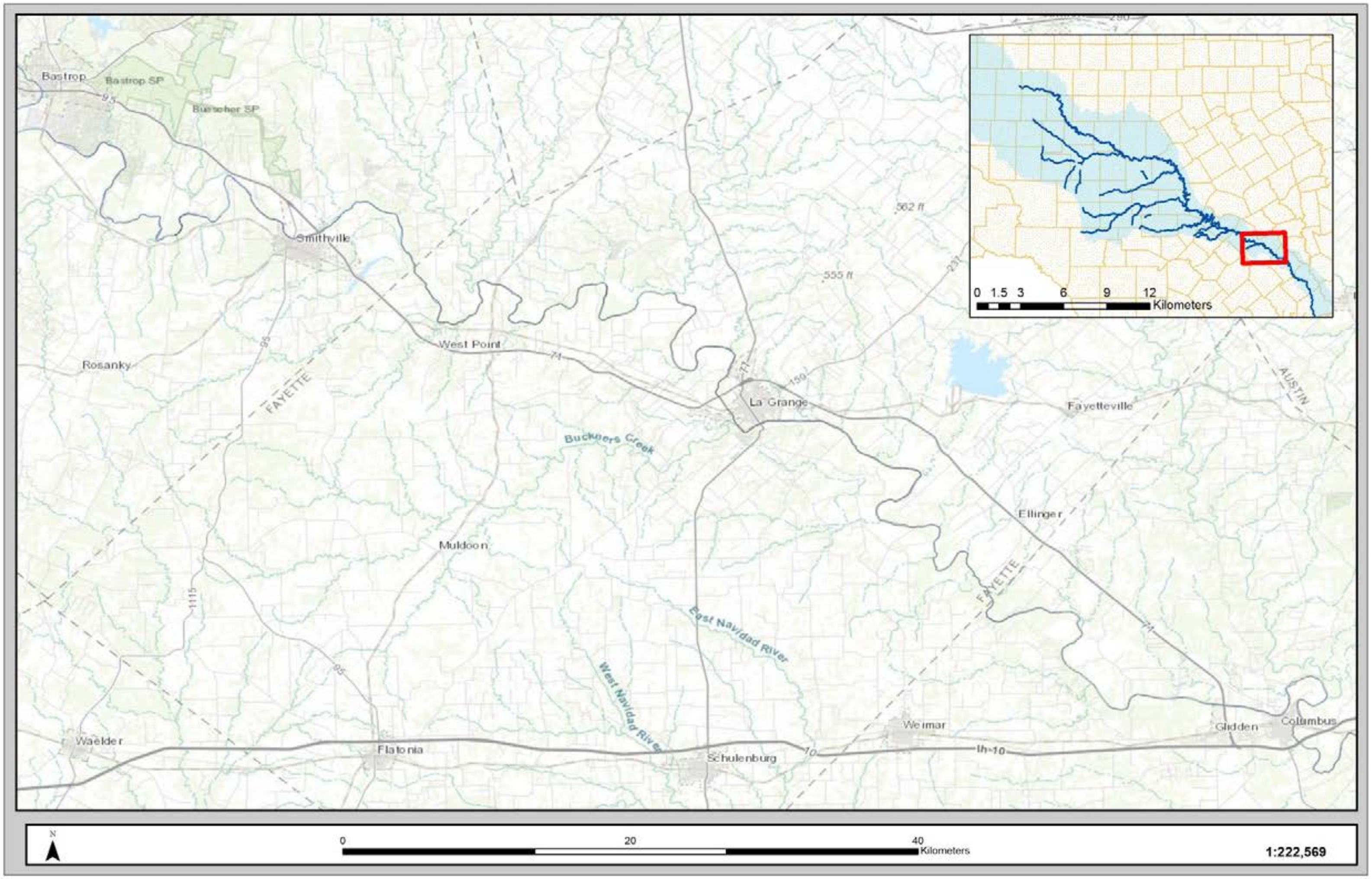
Appendix C. Summary table of Hydrologic Unit Codes for Sub-watersheds (Figure 2) encompassing study sites of interest. HUC 10 watersheds were accessed through USGS.

SUBBASIN	HUC_10	HU_10_NAME	Area_km
Austin-Travis Lakes			
	1209020503	City of Austin-Colorado River	848.77
	1209020504	Onion Creek-Colorado River	944.14
Colorado Headwaters			
	1208000209	Champion Creek	459.68
Concho			
	1209010502	Willow Creek-Concho River	800.32
Llano			
	1209020402	Big Saline Creek-Llano River	787.56
	1209020403	Honey Creek-Llano River	731.25
	1209020404	Little Devils River-James River	879.60
	1209020405	Comanche Creek-Llano River	958.23
	1209020406	Hickory Creek-Llano River	1092.77
	1209020407	San Fernando Creek-Llano River	870.56
	1209020408	Little Llano River-Llano River	616.74
Lower Colorado			
	1209030201	Skull Creek-Colorado River	890.35
Lower Colorado-Cummins			
	1209030102	Piney Creek-Colorado River	497.75
	1209030104	Alum Creek-Colorado River	482.73
	1209030107	Buckners Creek-Colorado River	1316.76
Middle Colorado			
	1209010601	Mustang Creek-Colorado River	857.72
	1209010606	San Saba River-Colorado River	758.23
North Llano			
	1209020202	Middle North Llano River	803.70
	1209020203	Lower North Llano River	560.22
Pedernales			
	1209020601	Headwaters Pedernales River	1095.37
	1209020602	North Grape Creek-Pedernales River	1094.16
	1209020603	Pedernales River-Lake Travis	1127.10

San Saba			
	1209010905	Elm Creek-San Saba River	534.72
	1209010907	Tiger Creek-San Saba River	1043.93
	1209010908	Richland Springs Creek-San Saba River	923.85
South Concho			
	1209010203	Dove Creek	689.75
	1209010205	Pecan Creek-South Concho River	835.94
South Llano			
	1209020302	Middle South Llano River	564.39
	1209020304	Lower South Llano River	494.04
Upper Colorado			
	1208000804	Kickapoo Creek-Colorado River	856.84

Appendix D. Summary table of USGS gage numbers for study sites of interest. USGS gage data was accessed through USGS.

USGS Gage Number	Gage Name
08123600	Champion Ck Res nr Colorado City, TX
08124000	Colorado Rv at Robert Lee, TX
08128000	Concho Rv at Christoval, TX
08130500	Dove Ck at Knickerbocker, TX
08136000	Concho Rv at San Angelo, TX
08136700	Colorado Rv nr Stacy, TX
08144500	San Saba Rv at Menard, TX
08144600	San Saba Rv nr Brady, TX
08146000	San Saba Rv at San Saba, TX
08148500	N Llano Rv nr Junction, TX
08149900	S Llano Rv at Flat Rock Ln at Junction, TX
08150000	Llano Rv nr Junction, TX
08150700	Llano Rv nr Mason, TX
08151500	Llano Rv at Llano, TX
08152900	Pedernales Rv nr Fredericksburg, TX
08153500	Pedernales Rv nr Johnson City, TX
08155240	Barton Ck at Lost Ck Blvd nr Austin, TX
08155300	Barton Ck at Loop 360, Austin, TX
08158000	Colorado Rv at Austin, TX
08158700	Onion Ck nr Driftwood, TX
08158827	Onion Ck at Twin Creeks Rd nr Manchaca, TX
08159000	Onion Ck at US Hwy 183, Austin, TX
08159200	Colorado Rv at Bastrop, TX
08159500	Colorado Rv at Smithville, TX
08160400	Colorado Rv abv La Grange, TX
08161000	Colorado Rv at Columbus, TX



Appendix E. The 158 km study area in the lower Colorado River between Fisherman's Park in Bastrop, Texas (30°6'40.47" N, 97° 19'29.13" W) and Columbus, Texas (29°42'47.8" N, 96° 32'51.4" W). Instream habitat was classified from video of the river bottom recorded using a Humminbird 998cSI side scan sonar unit throughout this reach into seven broad classes: bedrock, cobble, gravel, sand, mud and silt, submerged aquatic vegetation (SAV), and unidentifiable substrates.

Appendix F. Broad land cover classes used to reclassify historical and current land use and land cover (LULC) dataset within HUC 10 watersheds (Figure 2) within the Colorado River Basin, Texas. Historical LULC data was re-classified from the Anderson II classification system used to classify Landsat images from the 1970's ad 1980's. Current LULC was reclassified from remote sensing data collected in 2011 and classified by Texas Parks and Wildlife Ecological Systems of Texas.

Broad Reclassed Classes	Historical	Current
Agriculture	Cropland, pasture, orchards, groves, vineyards, nurseries, ornamental horticultural, confined feeding operations, other agricultural land	Agriculture
Barren	Dry salt flats, Beaches, Sandy areas not beaches, bare exposed rock, strip mines, quarries, gravel pits, transitional areas, mixed barren land, bare ground	Barren, Cliff
Deciduous	Deciduous forest land	Deciduous Forest, Deciduous Shrubland, Floodplain CD Forest, Floodplain Deciduous Shrubland, Floodplain Live Oak Forest, Live Oak Forest, Mesquite Shrubland, Post Oak Forest, Riparian CD Forest, Riparian Deciduous Shrubland, Riparian Live Oak Forest, Sandy Oak Forest, Slope Cold Deciduous Forest, Slope Deciduous Shrubland, Slope Live Oak Forest
Evergreen	Evergreen forest land	Evergreen Shrubland, Floodplain Juniper Forest, Floodplain Juniper Shrubland, Juniper Forest, Juniper Shrubland, Pine Forest, Riparian Juniper Forest, Riparian Juniper Shrubland, Slope Evergreen Shrubland, Slope Juniper Forest
Herbaceous	Herbaceous rangeland, Shrub and Brush rangeland, Mixed rangeland, Shrub and brush tundra, Herbaceous tundra	Floodplain Herbaceous, Grassland, Marsh, Riparian Herbaceous
Mixed	Mixed forest land	Floodplain Mixed Forest, Mixed Forest, Riparian Mixed Forest, Slope Mixed Forest
Water	Streams and Canals, Lakes, Reservoirs	Open Water
Urban High	Commercial and Services, Industrial, Transportation, communication, utilities, Industrial	Urban High

	and commercial complexes, Mixed urban or built-up land, other urban or built-up land	
Urban Low	Residential	Urban Low
Wetland	Forested wetland, Non-forested wetland	Swamp

Appendix G. Eigenvectors for broad land cover classes resulting from a principle component analysis of the historical and current land use and land cover (LULC) percentage difference in twenty-three HUC 10 watersheds (Figure 2) within the Colorado River Basin, Texas. The twenty-three HUC10 watersheds are listed in Appendix C. Historical LULC data was re-classified from the Anderson II classification system used to classify Landsat images from the 1970's ad 1980's. Current LULC was reclassified from remote sensing data collected in 2011 and classified by Texas Parks and Wildlife Ecological Systems of Texas. Duplicate watershed values indicate that multiple stream gages were located within a HUC10 watershed area.

Percent difference between 1970-1980 land use and land cover (LULC) data and 2012 LULC										
Stream Gage	River	Watershed Id	HUC 10 Watershed	Agriculture	Barren	Herbaceous	Forested	Open Water	High Urban	Low Urban
8144500	San Saba	8	1209010905	2.70	0.00	48.94	0.06	-0.05	-0.11	0.00
8146000	San Saba	9	1209010907	-1.70	-0.29	-38.93	-0.28	0.01	0.11	-0.02
8146000	San Saba	10	1209010908	-8.50	0.23	-46.02	-0.10	-0.09	0.60	-0.03
8150000	Llano	15	1209020402	-0.90	0.10	-51.67	-0.16	0.14	0.39	-0.02
8153500	Pedernales	24	1209020601	-5.06	-0.04	-19.03	-0.05	-0.01	0.35	-0.01
8153500	Pedernales	25	1209020602	-7.49	-0.06	-8.68	-0.15	0.02	0.13	-0.01
8153500	Pedernales	26	1209020603	-0.65	-0.24	-12.30	-0.35	0.15	0.89	-0.01
8158000	Colorado	23	1209020504	-2.94	-0.18	-14.25	-0.31	-0.55	7.35	-0.02
8158600	Walnut Creek	22	1209020503	0.17	0.68	-0.49	1.35	8.69	-9.53	-0.05
8159200	Colorado	27	1209030102	-0.24	0.30	-24.26	0.81	21.21	-2.33	-0.21
8161000	Colorado	29	1209030107	26.31	1.01	-57.64	10.59	4.91	9.81	0.07
8151500	Llano	20	1209020407	-0.38	-0.05	-20.57	-0.23	0.01	0.03	-0.02

8151500	Llano	21	1209020408	0.00	0.37	-13.67	-0.51	0.09	-0.36	-0.02
8159000	Onion Creek	23	1209020504	-2.94	-0.18	-14.25	-0.31	-0.55	7.35	-0.02
8158000	Colorado	22	1209020503	0.17	0.68	-0.49	1.35	8.69	-9.53	-0.05
8155300	Barton Creek	22	1209020503	0.17	0.68	-0.49	1.35	8.69	-9.53	-0.05
8152900	Pedernales	3	1209010203	11.51	5.78	-54.49	1.10	0.64	1.03	-0.01
8152900	Pedernales	24	1209020601	-5.06	-0.04	-19.03	-0.05	-0.01	0.35	-0.01
8130500	Dove Creek	3	1209010203	11.51	5.78	-54.49	1.10	0.64	1.03	-0.01
8159500	Colorado	16	1209020403	-0.05	0.04	-45.74	-0.19	0.00	0.00	-0.04
8150700	Llano	18	1209020405	0.00	0.00	-0.05	0.00	0.00	0.00	0.00
8150700	Llano	17	1209020404	-0.33	0.00	-50.83	-0.10	0.04	0.32	0.00
8155400	Barton Creek	22	1209020503	0.17	0.68	-0.49	1.35	8.69	-9.53	-0.05
8155240	Barton Creek	22	1209020503	0.17	0.68	-0.49	1.35	8.69	-9.53	-0.05
8160400	Colorado	29	1209030107	26.31	1.01	-57.64	10.59	4.91	9.81	0.07
8148500	North Llano	11	1209020202	-1.15	0.22	-71.30	-0.12	0.04	0.45	-0.01
8148500	North Llano	12	1209020203	-2.43	-0.06	-65.67	-0.10	0.26	0.73	-0.01

Appendix H. Eigenvectors for broad land cover classes resulting from a principle component analysis of the historical and current land use and land cover (LULC) percentage difference in twenty-three HUC 10 watersheds within the Colorado River Basin, Texas. The twenty-three HUC10 watersheds are listed in Appendix C. Historical LULC data was obtained from the USGS National Land Cover Datasets (NLCD) for 1992. Current LULC was reclassified from remote sensing data collected in 2011 and classified by Texas Parks and Wildlife Ecological Systems of Texas. Duplicate watershed values indicate that multiple stream gages were located within a HUC10 watershed area.

Percent difference between 1992 land use and land cover (LULC) data and 2012 LULC										
Stream Gage	River	Watershed Id	HUC 10 Watershed	Agriculture	Barren	Herbaceous	Forested	Open Water	High Urban	Low Urban
8144500	San Saba	8	1209010905	-0.41	0.50	-19.95	-1.35	1.17	-11.07	31.12
8146000	San Saba	9	1209010907	0.21	0.48	-45.42	42.97	0.18	0.16	1.40
8146000	San Saba	10	1209010908	0.21	0.48	-45.42	42.97	0.18	0.16	1.40
8150000	Llano	15	1209020402	1.19	0.43	-34.57	30.95	0.04	0.28	1.65
8153500	Pedernales	24	1209020601	-18.68	0.23	-19.77	55.57	1.56	0.63	-19.59
8153500	Pedernales	25	1209020602	-0.41	0.50	-19.95	-1.35	1.17	-11.07	31.12
8153500	Pedernales	26	1209020603	0.45	0.32	-26.79	25.36	0.10	0.06	0.50
8158000	Colorado	23	1209020504	0.31	0.37	-29.44	28.25	0.30	0.00	0.18
8158600	Walnut Creek	22	1209020503	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83
8159200	Colorado	27	1209030102	-25.63	-4.12	-11.87	23.98	1.44	20.05	-3.86
8161000	Colorado	29	1209030107	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83
8151500	Llano	20	1209020407	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83

8151500	Llano	21	1209020408	-35.48	0.53	2.08	31.56	0.40	0.70	0.24
8159000	Onion Creek	23	1209020504	2.89	1.49	-32.05	29.08	-1.88	0.15	0.31
8158000	Colorado	22	1209020503	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83
8155300	Barton Creek	22	1209020503	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83
8152900	Pedernales	3	1209010203	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83
8152900	Pedernales	24	1209020601	0.19	0.16	-54.35	53.00	0.22	0.11	0.66
8130500	Dove Creek	3	1209010203	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83
8159500	Colorado	16	1209020403	0.21	0.48	-45.42	42.97	0.18	0.16	1.40
8150700	Llano	18	1209020405	0.21	0.48	-45.42	42.97	0.18	0.16	1.40
8150700	Llano	17	1209020404	0.21	0.48	-45.42	42.97	0.18	0.16	1.40
8155400	Barton Creek	22	1209020503	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83
8155240	Barton Creek	22	1209020503	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83
8160400	Colorado	29	1209030107	-0.41	0.50	-19.95	-1.35	1.17	-11.07	31.12
8148500	North Llano	11	1209020202	1.19	0.43	-34.57	30.95	0.04	0.28	1.65
8148500	North Llano	12	1209020203	-4.87	0.64	-27.80	27.40	0.46	-3.66	7.83

Appendix I. Eigenvectors for discharge metrics of the Index of Hydrologic Alteration (Richter et al. 1996) resulting from a principle component analysis of the amount of variability between the two periods, pre-1980 and 1995 to 2016, using the range of variability approach (RVA) proposed by Richter et al. (1997). The variability of hydrologic alteration between the two periods is assessed on a scale ranging from 1 to -1 for the 34 IHA parameters. Variability is assessed as the years during the current period where a given parameter is above or below the historic 25th and 75th percentiles for the same hydrologic parameter established using the historical period.

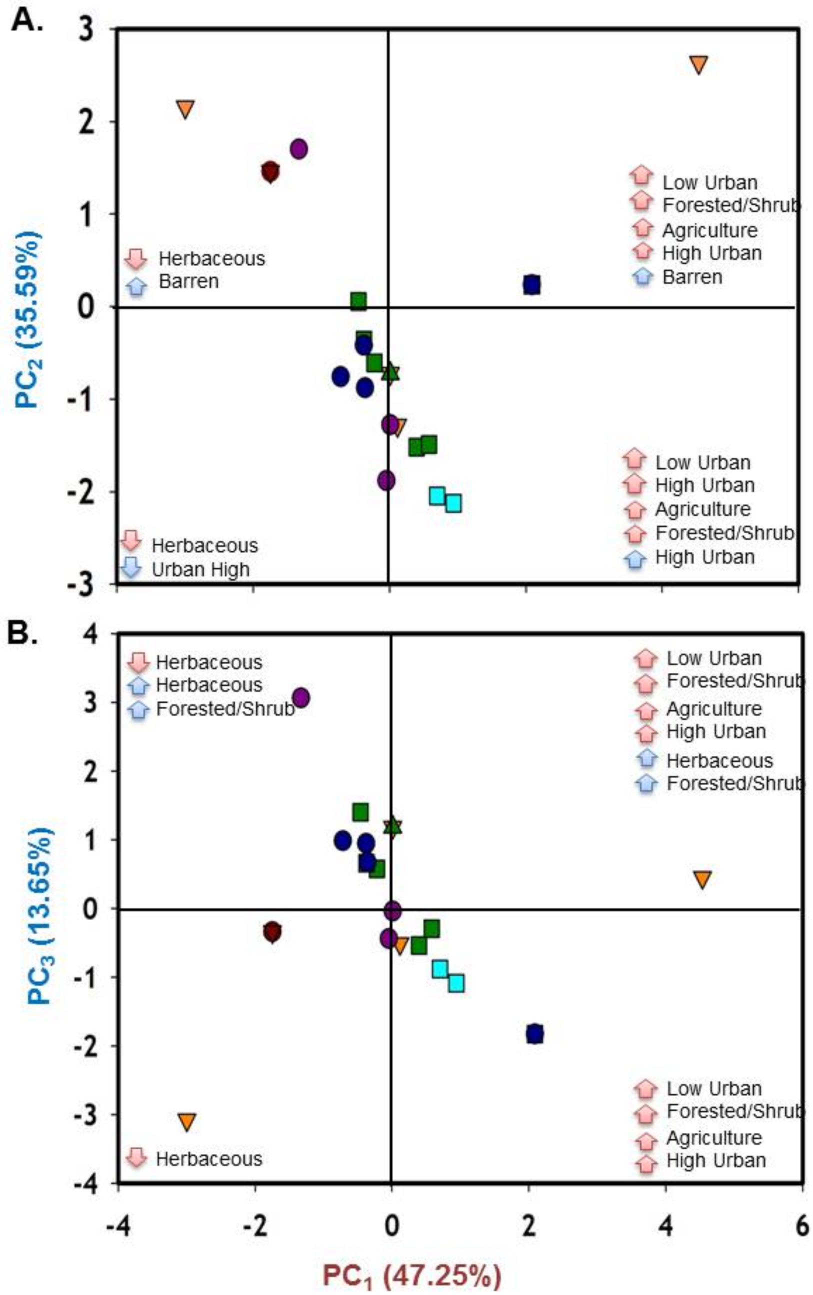
IHA Type	IHA Attribute	PC1 Eigenvector	PC2 Eigenvector
Magnitude of monthly flow conditions (mean for each month)	October	0.1859	-0.2051
	November	0.1977	-0.2148
	December	0.2033	-0.1962
	January	0.2028	-0.1140
	February	0.1567	-0.0490
	March	0.2061	-0.1029
	April	0.2047	-0.0260
	May	0.1925	0.1293
	June	0.1974	0.1625
	July	0.1646	0.1737
	August	0.1658	0.1641
	September	0.1660	0.2184
Magnitude and duration of annual extremes	1-day minimum	0.2175	-0.2196
	3-day minimum	**0.2239**	**-0.2213**
	7-day minimum	**0.2251**	**-0.2274**
	30-day minimum	**0.2323**	-0.2024
	90-day minimum	**0.2442**	-0.1429
	1-day maximum	0.1630	**0.3080**
	3-day maximum	0.1862	**0.3023**
	7-day maximum	0.1989	**0.2912**
	30-day maximum	**0.2259**	**0.2682**
	90-day maximum	**0.2383**	**0.2315**
Frequency and duration of high- and low-flow pulses	Zero flow days	-0.0466	0.0463
	Base flow	0.0100	**-0.2422**
	Date of minimum	0.0041	0.0822
	Date of maximum	0.0121	0.0288
	Number of low pulses	0.0099	0.0864
	Number of high pulses	0.0829	-0.0375
Rate and frequency of changes in water conditions	Rise rate	0.1744	0.0506
	Fall rate	**-0.2370**	0.0596
	Reversals	0.1026	-0.0922

Appendix J. Eigenvectors for discharge metrics of the Index of Hydrologic Alteration (Richter et al. 1996) resulting from a principle component analysis of the annual flow regime for the twenty U.S. Geological Survey (USGS) streamgages listed in Appendix D with years of analysis for both historical and present flows at each individual gage based on availability. IHA metrics with eigenvector values ≥± 0.23 were used to interpret principal component axis.

IHA Type	IHA Attribute	PC1 Eigenvector	PC2 Eigenvector
Magnitude of monthly flow conditions (mean for each month)	October	**0.2971**	-0.0135
	November	0.13531	0.14235
	December	**0.3395**	-0.0074
	January	**0.3373**	-0.0239
	February	0.1348	0.08151
	March	**0.32502**	-0.0133
	April	0.11192	0.09869
	May	**0.29775**	-0.029
	June	0.1633	0.1266
	July	**0.29835**	-0.0088
	August	**0.30858**	-0.0029
	September	0.15211	0.15781
Magnitude and duration of annual extremes	1-day minimum	**0.30578**	-0.0148
	3-day minimum	-0.0169	**0.3428**
	7-day minimum	-0.0402	**0.39042**
	30-day minimum	-0.0249	**0.47147**
	90-day minimum	-0.0545	**0.3327**
	1-day maximum	0.15182	0.12581
	3-day maximum	0.08266	-0.0818
	7-day maximum	0.06755	-0.1626
	30-day maximum	0.02062	-0.0939
	90-day maximum	-0.0206	-0.1602
Frequency and duration of high- and low-flow pulses	Zero flow days	-0.0435	**-0.3088**
	Base flow	0.01266	**0.31394**
	Date of minimum	-0.0223	-0.1459
	Date of maximum	0.03204	0.00535
	Number of low pulses	-0.0359	-0.082
	Number of high pulses	0.11514	-0.0816
Rate and frequency of changes in water conditions	Rise rate	-0.0933	0.04492
	Fall rate	0.06745	-0.0125
	Reversals	0.19928	-0.0558

Appendix K. Eigenvectors for discharge metrics of the Index of Hydrologic Alteration (Richter et al. 1996) resulting from a principle component analysis of the annual flow regime for the five U.S. Geological Survey (USGS) streamgages on the lower Colorado River listed in Appendix D with years of analysis for both historical and present flows at each individual gage based on availability. IHA metrics with eigenvector values ≥± 0.20 were used to interpret principal component axis.

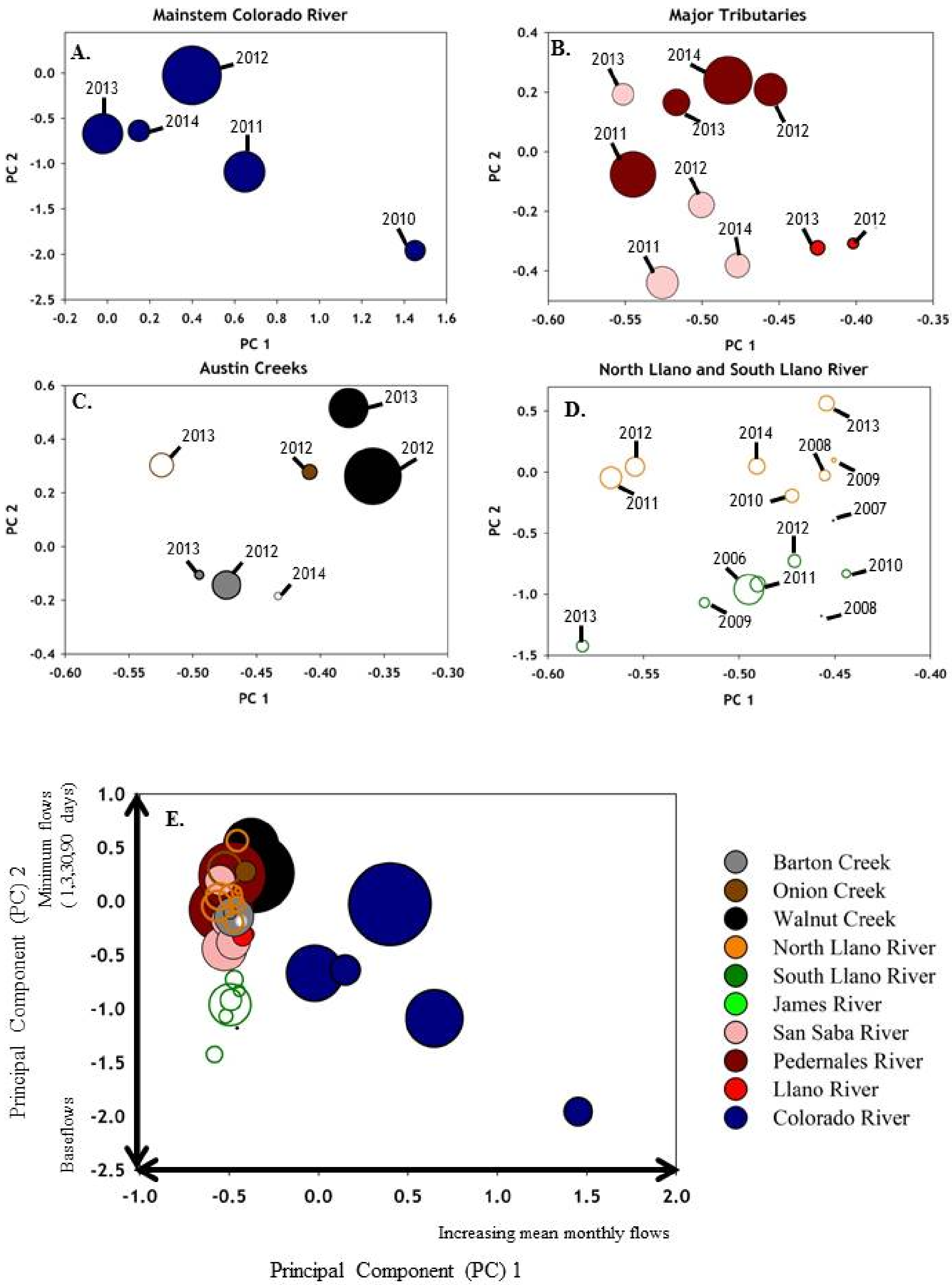
IHA Type	IHA Attribute	PC1 Eigenvector	PC2 Eigenvector
Magnitude of monthly flow conditions (mean for each month)	January	**0.24535**	**0.21649**
	February	-0.05749	0.07196
	March	0.19292	**0.20339**
	April	-0.17301	0.18282
	May	**0.22627**	**0.20617**
	June	-0.05654	-0.01601
	July	**0.30871**	0.12787
	August	**0.31558**	0.02212
	September	-0.09832	-0.12656
	October	0.16703	**0.29629**
	November	0.16051	-0.15901
	December	0.17937	**0.3026**
Magnitude and duration of annual extremes	1-day minimum	**0.23814**	-0.0503
	3-day minimum	0.16673	-0.05262
	7-day minimum	**0.21592**	0.01164
	30-day minimum	0.13784	0.10173
	90-day minimum	**0.20543**	-0.18331
	1-day maximum	**-0.21513**	**0.30258**
	3-day maximum	**-0.20267**	**0.32456**
	7-day maximum	-0.17596	**0.35426**
	30-day maximum	-0.01504	-0.02462
	90-day maximum	-0.02082	**-0.25753**
Frequency and duration of high- and low-flow pulses	Base flow	0.17426	-0.04457
	Date of minimum	-0.04356	-0.0222
	Date of maximum	-0.07793	0.01002
	Number of low pulses	-0.16544	0.03733
	Low pulse duration	-0.16289	0.12102
	Number of high pulses	-0.01153	0.17627
	High pulse duration	0.13805	**0.26305**
Rate and frequency of changes in water conditions	Rise rate	-0.00829	-0.06314
	Fall rate	0.14236	-0.1725
	Reversals	**0.28546**	0.03952



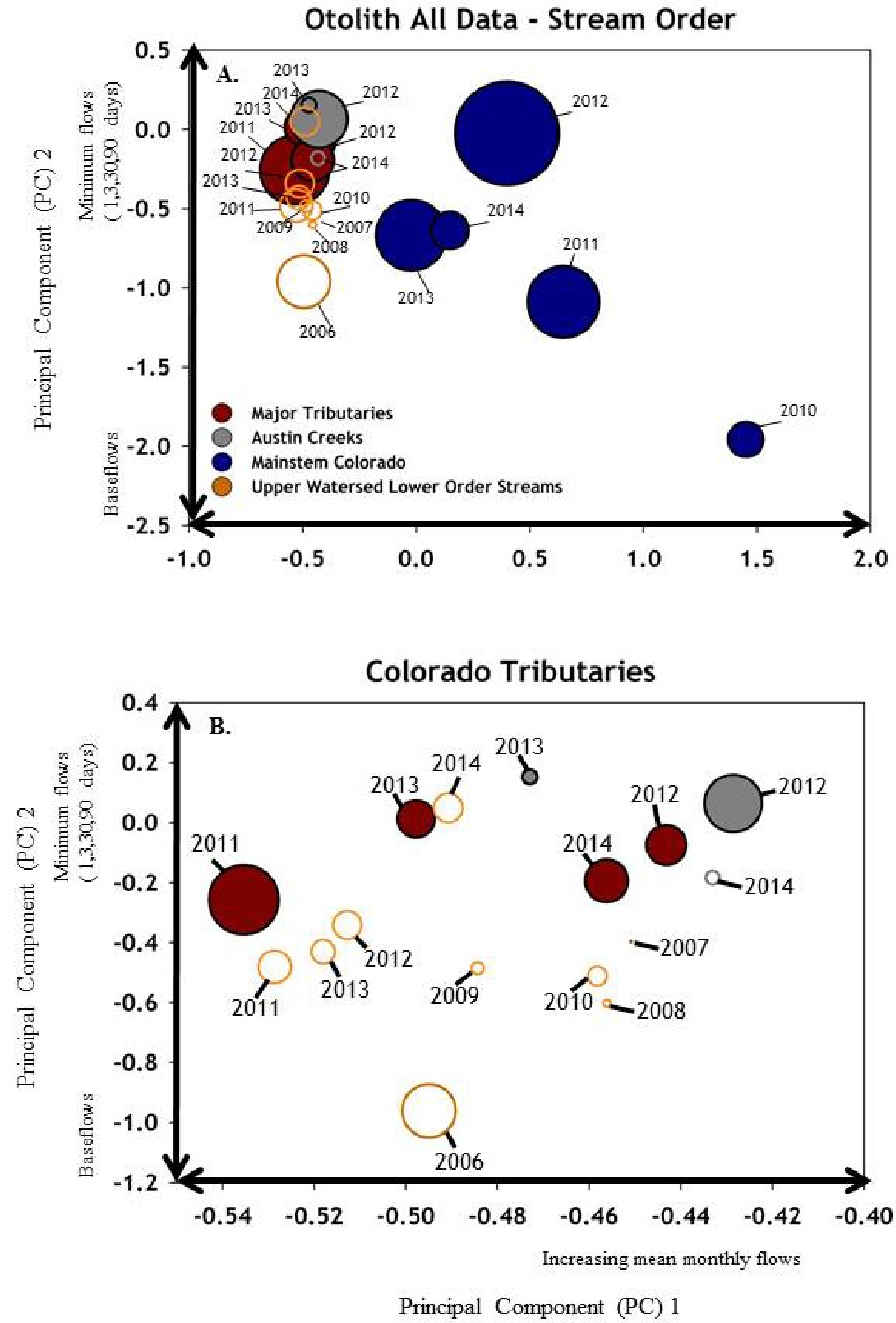
Appendix L. Scatterplots representing land use alteration for 30 HUC 10 watersheds (Figure 2) within the Colorado River Basin encompassing all study reaches. Alteration was assessed between 1992 land cover data obtained from the U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD) to the 2012 classification of land cover and land use by Texas Parks and Wildlife (TPWD) Ecological Systems of Texas. Historical and present LULC data was reclassified into six broad classes consistent between data sets in order to focus comparison on primary land conversion rather than vegetation types. The first three PCs explained 91.45% of the variance among the sites for the percentage difference across the landscape variable.

Appendix M. Class means on the canonical variables for the first three canonical variates for relative warp scores used in the canonical correlation analysis of Guadalupe Bass morphology related to altered flow and land cover throughout the Colorado River basin, Texas. Historical individuals were collected by Edwards (1980) and stored at the Texas Natural Historical Museum collection where morphological photos were taken for analysis (Appendix B). Present individuals were collected between March 2014 and September 2016. Location of landmarks comprising relative warps are described in Table 2 and illustrated in Figure 3.

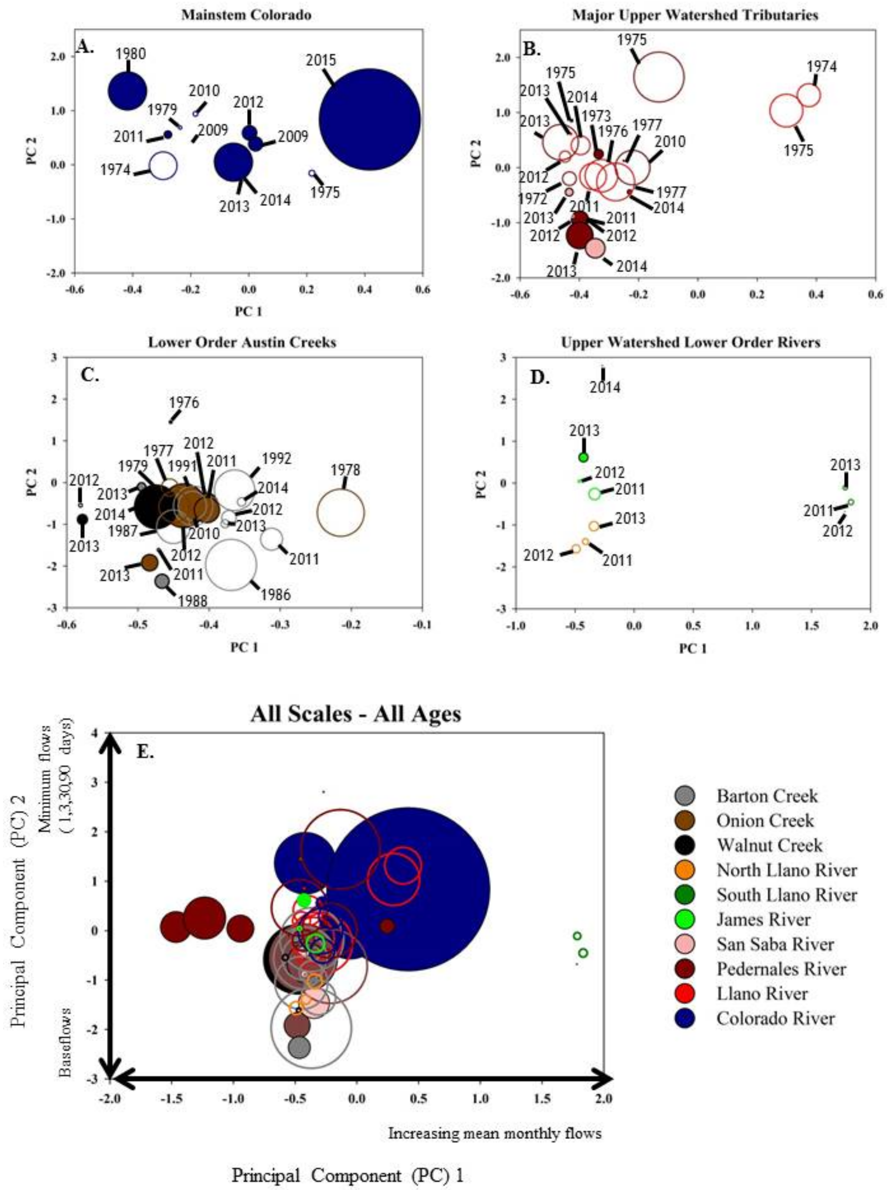
Variable	Morphology 1	Morphology 2	Morphology 3
Historical Colorado	1.40	-0.14	0.11
Historical Dove Creek	1.80	-1.31	-0.02
Historical Llano	1.35	0.37	-0.12
Historical Pedernales	1.50	-0.33	0.26
Present Colorado	-1.57	0.13	0.32
Present Barton Creek	0.30	0.02	0.00
Present Dove Creek	-1.85	-1.07	-0.09
Present James	-2.80	0.17	-0.33
Present Llano	-1.85	0.33	-0.11
Present North Llano	-1.22	-0.54	-0.24
Present Onion Creek	1.28	0.12	-0.16
Present Pedernales	-1.46	0.25	0.88
Present San Saba	-1.61	0.31	0.09
Present South Llano	-1.31	0.01	0.07
Present Walnut Creek	-0.89	0.35	0.27



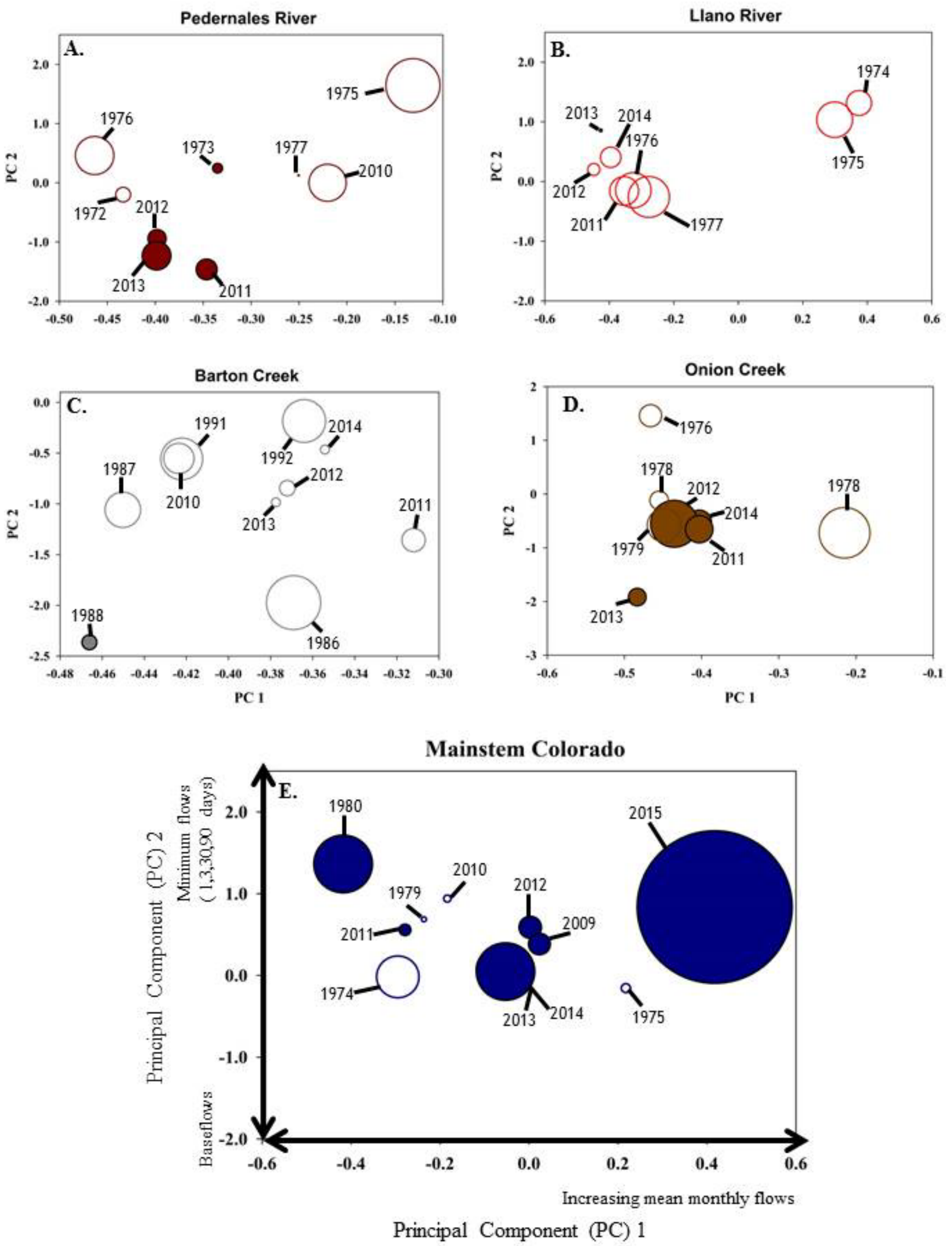
Appendix N. Standardized otolith growth for Guadalupe Bass captured throughout the Colorado River Basin, Texas from 2014-2015. The sizes of individual bubbles represent the magnitude of response in standardized growth to annual stream discharge metrics. Filled bubbles represent increased growth response, while unfilled bubbles represent a decreased growth response. A-D represent the influence of annual stream discharge metrics on parsed out individual systems throughout the Upper Colorado River Basin.



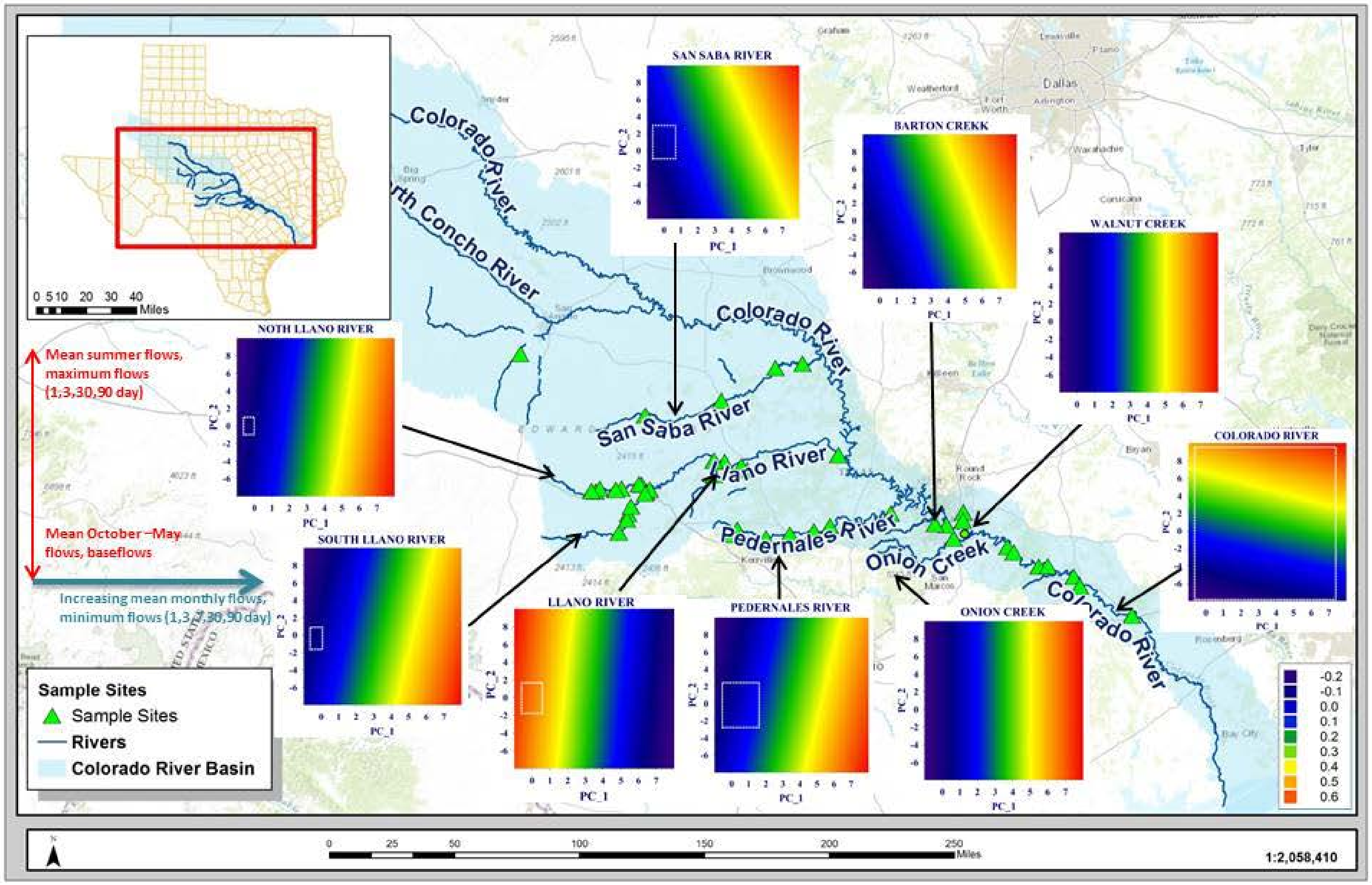
Appendix O. Standardized otolith growth for Guadalupe Bass captured throughout the Colorado River Basin, Texas from 2014-2015. The sizes of individual bubbles represent the magnitude of response in standardized growth to annual stream discharge metrics. Filled bubbles represent increased growth response, while unfilled bubbles represent a decreased growth response. Graph A represents the mainstem Colorado River and tributaries combined. Graph B is an inset of Graph A representing the influence of annual stream discharge metrics on the tributaries of the Colorado River Basin.



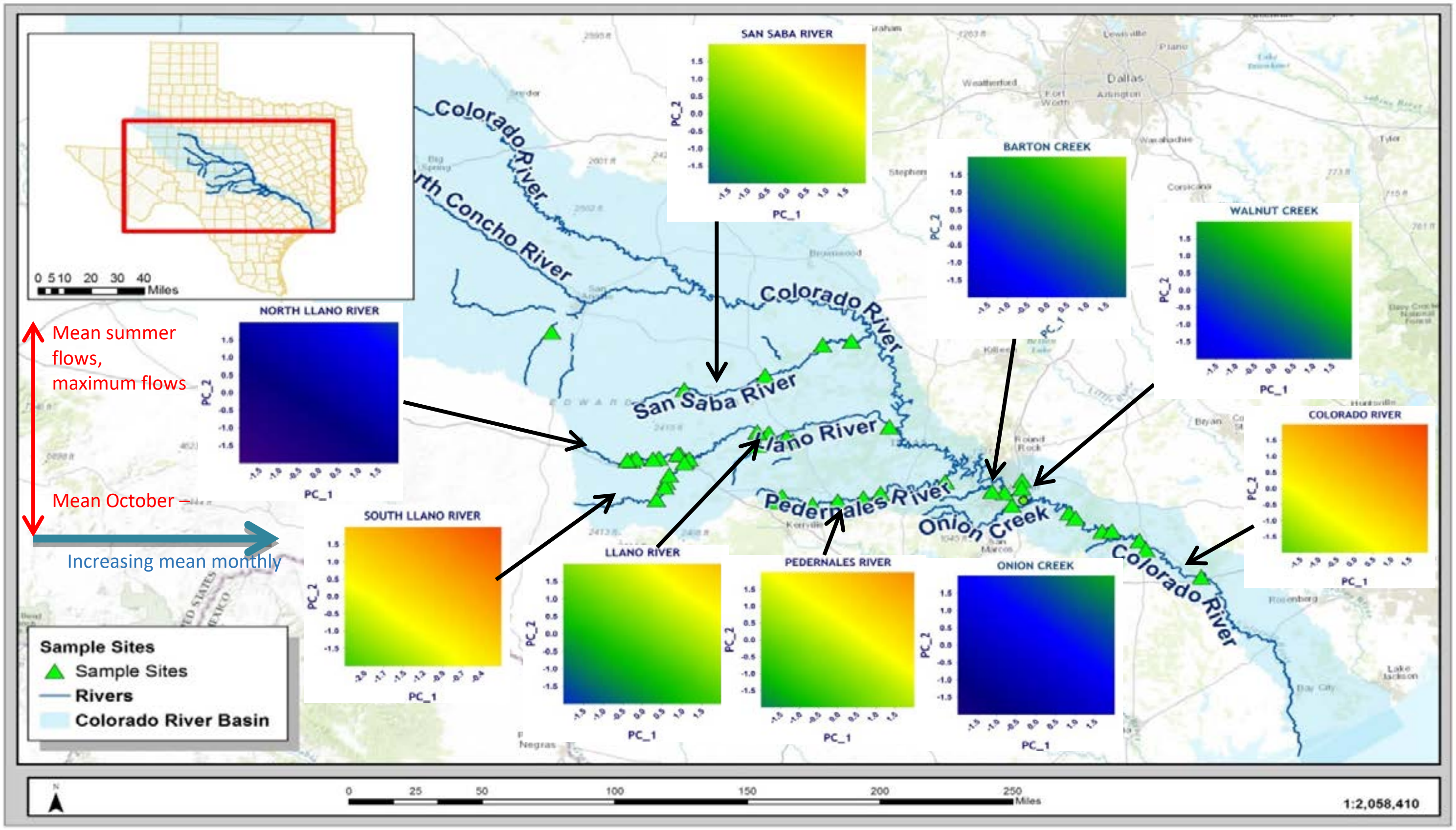
Appendix P. Standardized scale growth for all age Guadalupe Bass captured throughout the Colorado River Basin, Texas. Historical scales (n=115) were collected from specimens at the Texas Natural History Collection. Accession numbers for individuals used in the analysis can be found in Appendix B. Present day scales were collected between March 2014 and September 2016. The sizes of individual bubbles represent the magnitude of response in standardized growth to annual stream discharge metrics. Filled bubbles represent increased growth response, while unfilled bubbles represent a decreased growth response. A-D represent the influence of annual stream discharge metrics on parsed out individual systems throughout the Upper Colorado River Basin. Figures A-D are scales separately to better illustrate the growth between lower order creeks in the Austin, Texas area, upper watershed lower order rivers, major upper watershed tributaries, and the mainstem Colorado river.



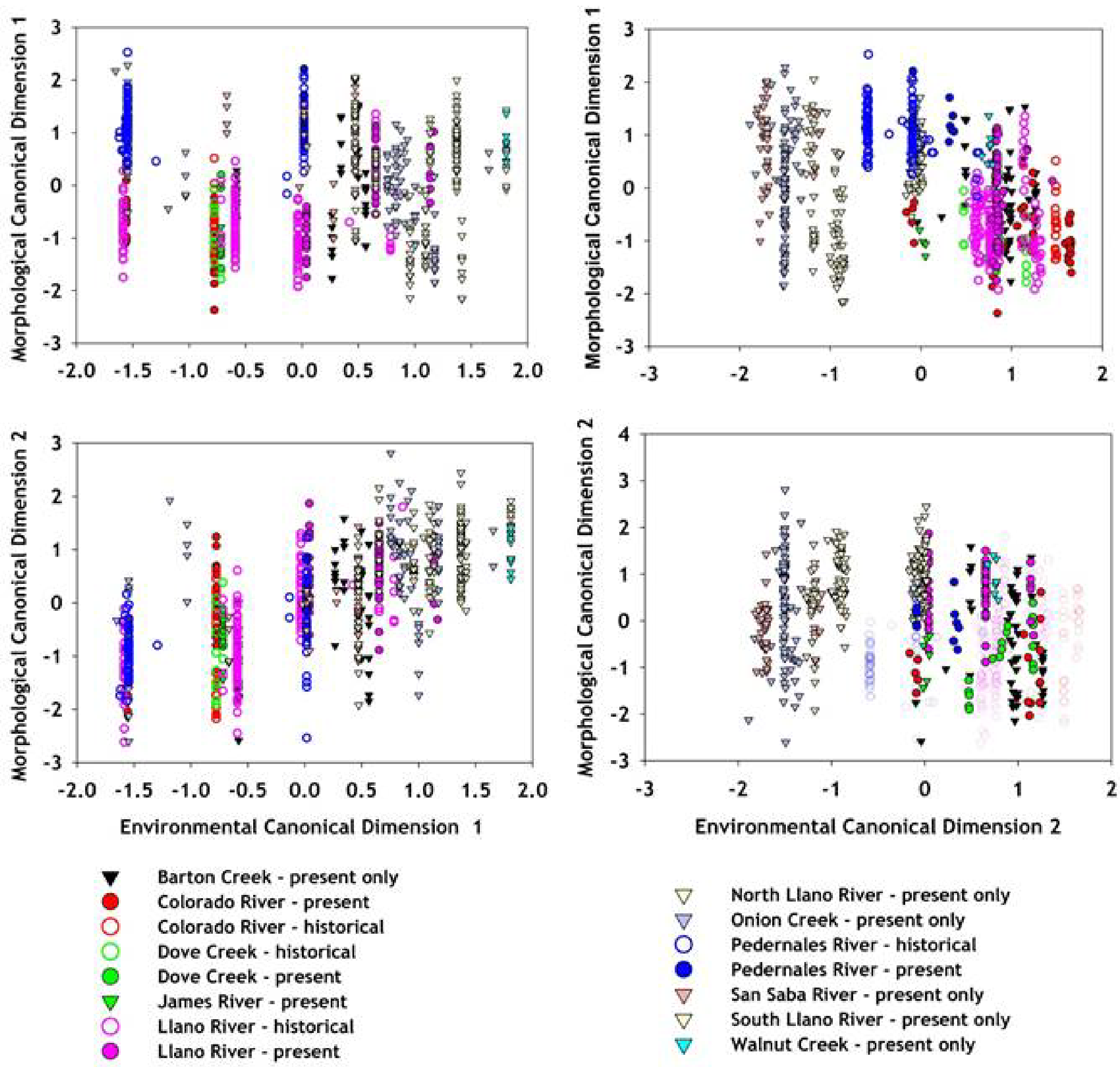
Appendix Q. Standardized scale growth for all age Guadalupe Bass captured throughout the Colorado River Basin, Texas. Historical scales (n=115) were collected from specimens at the Texas Natural History Collection. Accession numbers for individuals used in the analysis can be found in Appendix B. Present day scales were collected between March 2014 and September 2016. The sizes of individual bubbles represent the magnitude of response in standardized growth to annual stream discharge metrics. Filled bubbles represent increased growth response, while unfilled bubbles represent a decreased growth response. Individual graphs represent the mainstem Colorado River and select tributaries where scales were aged for historical and present Guadalupe Bass collected.



Appendix R. Contour plots illustrating the predicted values for standardized growth for Guadalupe Bass throughout the Colorado River Basin based on otolith data collected from March 2014- August 2015. Predicted values for standardized growth were estimated from the model evaluating the effect of river system and flow metric principal component scores. Flow metrics were considered throughout the Colorado River basin and were not standardized based on the mean flows within each river system. In each contour plot the color represents the magnitude and the direction of standardized growth indicated in the legend. Principal component 1 (PC1) axis is primarily driven by increasing mean monthly flows and 1 day minimum flows. PC2 separates out increasing 3,7,30,90 day minimum and baseflow, and decrease in zero flow days. The loadings for all variables can be found in Appendix G.



Appendix S: Contour plots illustrating the predicted values for standardized growth for Guadalupe Bass throughout the Colorado River Basin based on otolith data collected from March 2014- August 2015. Predicted values for standardized growth were estimated from the model evaluating the effect of river system and flow metric principal component scores. In each contour plot the green represents a Von Bertlanffy growth curve prediction of 0, red is positive and blue is negative standardized growth. Annual flow metrics were reduced to two principal components using a principal component analysis. Principal component 1 (PC1) axis is primarily driven by increasing mean monthly flows and 1 day minimum flows. PC2 separates out increasing 3,7,30,90 day minimum and baseflow, and decrease in zero flow days. The loadings for all variables can be found in Appendix G.



Appendix T: Morphological scores for historical and present collected Guadalupe Bass where open circles represent historical morphological canonical scores and closed circles represent present morphological canonical scores for the Pedernales River, Dove Creek, Colorado River and Llano River, all of which had historical and present individuals. Tributaries where historical specimens were not archived or available are indicated by triangles. Historical specimens were obtained from Texas Natural Historical Museum for morphological analysis. Environmental canonical scores representing hydrological and percentage difference in landscape are shown on the X.