MUSSEL COMMUNITY AND CHANGES IN WATER QUALITY WITHIN A SOUTHCENTRAL RIVER BASIN OF NORTH AMERICA WITH EMPHASIS ON TWO FEDERAL CANDIDATE SPECIES

by

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ABSTRACT

Louisiana Pigtoe *Pleurobema riddellii* and Texas Heelsplitter *Potamilus amphichaenus* are candidates for listing by the USFWS under the Endangered Species Act and recognized as functionally extirpated within the Sabine River basin of Texas and Louisiana. Threats to range-wide population viability include changes in water quality. Purposes of this study were to update current knowledge of Louisiana Pigtoe and Texas Heelsplitter occurrences, catch-per-unit effort (CPUE), and habitat associations and to assess changes in Sabine River basin water quality over a 50-year period. A total of 9,244 individuals, representing 28 species, were identified and enumerated among five reaches (two mainstem reaches, three tributary reaches) and 46 samples. Mean CPUE (± 1 SD) per species among all reaches ranged from 0.01 (0.04) mussels/person hour (p-hr) to 10.4 (21.1) mussels/p-hr. Louisiana Pigtoe (N = 57) and Texas Heelsplitter (N = 7) were only observed in the upper Sabine River with a mean CPUE of 0.51 (± 1.68) mussels/p-hr for Louisiana Pigtoe and 0.06 (± 0.20) mussels/p-hr for Texas Heelsplitter. Louisiana Pigtoe was associated with mid-channel, riffle and run habitats with swift current velocities, shallow depths, and gravel substrates. Texas Heelsplitter, based on a small sample size, was associated with mid-channel, riffle habitats with swift current velocities and shallow depths and sand and gravel substrates. Between 1960/1970s and 2020s, water quality variables generally improved when referencing water quality standards deemed suitable for aquatic life use within the Sabine River basin. One exception was noted in two reaches with recent elevation in sulfates. Between

1960/1970s and 2020s, information on mussel occurrences and CPUE are lacking to assess trends in mussel communities. Nevertheless, mussel community and water quality data provided herein will provide baselines for future monitoring of the mussel community.

I. MUSSEL COMMUNITY AND WATER QUALITY IN A SOUTHEASTERN RIVER BASIN WITH EMPHASIS ON TWO FEDERAL CANDIDATE SPECIES

Introduction

Spatial and temporal patterns of aquatic communities are regulated by historical and contemporary processes (Velland 2010). Among contemporary processes, biotic and abiotic factors at local and regional scales interact to create patterns in community structure. However, the contribution of factors and their exact mechanisms in structuring communities are often elusive and unknown, especially among communities that lack suitable quantification of their spatial and temporal patterns. Thus, quantification of community patterns (e.g., species abundances, habitat associations) is a step towards understanding the influence of contemporary processes on community structure (Moniruzzaman et al. 2021).

North American freshwater mussel community consists of about 300 species ranging as far north as Alaska (USA) to Mexico (Tiemann et al. 2020; Graf and Cummings 2021). Collectively, mussels inhabit a diversity of aquatic habitats, including lentic (e.g., wetlands, ponds, lakes) and lotic (e.g., streams, rivers) environments, slow to swift current velocities, shallow to deep waters, and variety of substrate types (Hagg 2012; Ford et al. 2014; Bossenbroek et al. 2018). Among a limited number of studies, mussels are reported to survive for periods of time under low dissolved oxygen (Chen et al. 2001), elevated levels of ammonia (Haney et al. 2020), elevated levels of salinity (Johnson et al. 2018), and water temperature extremes (Pandolfo et al. 2010), although mussels are generally thought to be somewhat sensitive to changes in water quality, especially during reproduction (Augspurger et al. 2003; Wang et al. 2010). Many species are reported long-lived (e.g., up to 100 years of age) (Haag and Rypel 2011), consume suspended phytoplankton (Vaughn et al. 2008) and likely microbial biofilms associated with benthic coarse particulate organic matter (Fogelman 2022), and require a fish host to complete their life cycle (Anthony et al. 2001; Hagg 2012).

In recent years, population viabilities of many freshwater mussel species have become an emerging concern (Lydeard et al. 2004). Two species, found in southcentral USA, are under review for listing by U.S. Fish and Wildlife Service (USFWS): Louisiana Pigtoe *Pleurobema riddellii* and Texas Heelsplitter *Potamilus amphichaenus.* Presumed range of Louisiana Pigtoe extends from Pearl River of Mississippi in the east to Trinity River of Texas in the west with discontinuous populations in the Red River drainages of Oklahoma, Arkansas, and Louisiana (USFWS 2020). Presumed range of Texas Heelsplitter extends from Sabine River drainage of Texas and Louisiana in the east to the Trinity River drainage of Texas in the west. According to USFWS (2020), current conditions of population viabilities range from functionally extirpated/extirpated in the upper Sabine River to high condition in the upper Neches River (TX) and Cossatot River (AR) for Louisiana Pigtoe among 13 known populations. Current conditions range from Functionally Extirpated/Extirpated in the upper Sabine River to Low Condition in the Neches River and Trinity River for Texas Heelsplitter among five known populations. Descriptions of habitat associations include stable environments, positive association with gravel substrates, and negative associations with organic matter for Louisiana Pigtoe (Howells et al. 1996; Vaughan et al. 2020; Kiser et al. 2021) and large rivers, sandy substrates, and positive association with organic matter for Texas Heelsplitter (Walters et al. 2017; Dickson 2018). Description of water quality associations is lacking for either species and inferred from general knowledge of water quality thresholds reported for other mussel species (USFWS 2020). However, changes in water quality are considered a primary threat to both mussel species, including changes in water temperature, dissolved oxygen, salinity, and ammonium levels.

Purpose of this study was to update current knowledge of Louisiana Pigtoe and Texas Heelsplitter and water quality conditions within the Sabine River drainage of Texas and Louisiana, which supports both species but currently recognized as functionally extirpated/extirpated (USFWS 2020). Study objectives were to quantify occurrences, relative abundances, catch per unit effort (CPUE), and habitat associations of Louisiana Pigtoe and Texas Heelsplitter in priority reaches of the Sabine River drainage. Priority reaches were defined as reaches where Louisiana Pigtoe and Texas Heelsplitter were historically reported, currently reported, or expected to occur. Since information on mussel communities are generally lacking in the Sabine River basin, a secondary objective was to quantify occurrences, relative abundances, catch per unit effort, and habitat associations for all mussel species in the priority reaches, which potentially includes state listed Texas Pigtoe *Fusconaia askewi* and Sandbank Pocketbook *Lampsilis satura*. An additional study objective was to summarize water quality measurements of the five reaches using long-term datasets (1960/1970s – 2020s). Predictions for Louisiana Pigtoe and Texas Heelsplitter abundances and CPUE follow those of USFWS (2020). Specifically, Louisiana Pigtoe and Texas Heelsplitter will have low abundances (<0.5 CPUE or <3 per population survey). Predictions for water quality changes between 1960/1970s and 2020 follow those of others (Parker et al. 2016, Perkin and Bonner 2016, Smith et al. 2018), where water quality should improve since the passage of the Clean Water Act in 1972.

Methods

Field Surveys

Field surveys were conducted from June 2020 through September 2021 and among five reaches within the Sabine River basin for a total 46 samples: Lake Fork Creek (*N* of samples = 4), upper Sabine River (upstream from Toledo Bend Reservoir; *N* = 28), lower Sabine River (downstream from Toledo Bend Reservoir; *N* = 11), Toro Bayou (*N* = 1) and Anacoco Bayou (*N* = 2) (Figure 1). At each sample, a 150-m^2 plot was established and two consecutive one person-hour (p-hr) searches were conducted, using surface supplied air or SCUBA for deep water habitats. If no mussels were found, the sample was considered complete. If mussels were located, then two additional consecutive p-hr searches were conducted for a total of four p-hr per sample. Mussels were collected by visual and tactile methods, placed in mesh bags separated by p-hr, and submerged in the river until the sample was complete. All mussels were then sorted by species and enumerated before returned to the capture area. Common and scientific names follow the mussels of Texas checklist developed by Texas A&M Natural Resources Institute (Randklev et al. 2020). Louisiana Pigtoe can be challenging to identify given the taxonomic uncertainty of the species complex and morphological similarities with other species. As such, specimens identified as Louisiana Pigtoe were genetically confirmed (Harrison 2022). For each sample, the following instream habitat variables were quantified: mesohabitat type (i.e., riffle, run, pool, backwater), water depth (m), benthic current velocity (m/s), percent substrate (i.e., clay, silt, sand, gravel, cobble, boulder, bedrock, detritus), mesohabitat morphology (i.e., straightway, outside bend, behind point bar, point bar), and mesohabitat position (i.e., edge, mid-channel).

Assessment of water quality changes through time

Water quality data were obtained from Texas Commission of Environmental Quality (TCEQ) Surface Water Quality Monitoring database (www.tceq.texas.gov) for Texas reaches (i.e., Lake Fork Creek, upper Sabine River, lower Sabine River) and from National Water Quality Monitoring Council database (www.waterqualitydata.us/provider/NWIS) for Louisiana reaches (i.e., Toro Bayou, Anacoco Bayou). Toro Bayou contained only 19 years of data sporadically between the 1950s and 2020 and, therefore, excluded from subsequent analyses. The three Texas reaches consisted of one or two TCEQ water quality segments. The first year of water quality variable recording differed among segments (Table 1), but generally corresponded with the passage of the Clean Water Act (1972) and collected continuously or near continuously through 2020, the ending year for this assessment. The following 13 water quality variables were extracted, when available: ammonia (NH_3-N; mg/l), chloride (Cl^-; mg/l), dissolved oxygen (DO; mg/l), hardness (mg/l), nitrate (NO_3-N; mg/l), pH, sulfate (SO_4^{2-}; mg/l), alkalinity (mg/l), total dissolved solids (TDS; mg/l), total organic carbon (TOC; mg/l), total phosphorus (P; mg/l), turbidity (NTU), and water temperature (°C).

Data Analysis

Relative abundance (%) and average catch-per-unit-effort (CPUE; individuals/p-hr) were calculated for each species within each reach and overall. Principal component analysis (PCA; Canoco 4.5, Microcomputer Power 2002) was used to quantify instream habitats among reaches. Mesohabitat type, position, and morphology were coded as dummy variables (0,1). Continuous variables (i.e., depth and benthic current velocity) and percentage data (i.e., substrates) were z-transformed (Krebs, 1999) before analysis. Resulting PC scores for axes I and II were grouped by reach to assess instream habitat similarities and differences among reaches.

For mussel-habitat association analyses, species with low sample sizes ($N < 100$) were omitted except for the two federal candidate species (Louisiana Pigtoe and Texas Heelsplitter) and one state-listed species (Sandbank Pocketbook) since insights into species of concern are valuable despite estimates derived from small sample sizes. Canonical correspondence analysis (CCA; Canoco 4.5) was used to quantify mussel-habitat associations among reaches. Habitat matrix was similar to the dataset used in PCA but with reaches identified with dummy variables. Species matrix consisted of species and counts per sample. Total variation explained in species were partitioned by pure effects of habitat and reach (Borcard et al. 1992). Monte Carlo test (10,000 permutations) was used to assess significance ($\alpha = 0.05$) of the relationships between mussel-habitat associations. Univariate assessments were used to visualize central tendencies and variabilities of distributions for habitat variables with continuous data (i.e., benthic current velocity and depth). For mesohabitat type, position, morphology and for percentage data (i.e., substrates), mussel associations were described using a modified version of the ACFOR scale (Abundance, Common, Frequent, Occasional, Rare; Stiers et al. 2011, Faucheux et al. 2019), where each variable level was quantified as having abundant (>75% of total N), common (50 to 74.9%), frequent (25 to 49.9%), occasional (5 to 24.9%), or rare (> 0 to 4.9%) number of a mussel species.

Two datasets were constructed from extracted water quality variables. The first dataset consisted of water quality variables (columns) averaged by year (rows), separated by the six water quality segments among the four reaches. Since segments lacked continuously record data for some water quality variables among the years, water quality variables were deleted if >30% of years lacked data for a particular variable. Therefore, water quality variables assessed in these analyses were not consistent among the six segments. If water quality variables were missing ≤ 30% of the years, missing data points were replaced with the mean of the water quality variable. Water quality variables were z-transformed, thereby missing data points equal zero, having no effect on subsequent analysis, and analyzed with principal component analyses for each segment. Principal component loadings for each row (year) were averaged by decade (i.e., earliest decade to 2010 with Year 2020 added to 2010 decade) for PC axes I and II. Differences among decades with years as replicates were assessed ANOVA ($\alpha = 0.05$) followed by Fisher's LSD tests to detect differences in linear combinations of water quality variables for PC axes I and II for each segment.

The second dataset consisted of water quality variables in their original form. For each segment, nine water quality variables were plotted through time and compared to TCEQ screening levels (Table 2). The remaining four water quality variables (i.e., hardness, total alkalinity, TOC, turbidity, and water temperature) lack a screen level.

Screening levels were developed as measures to assess water quality concerns and can vary by segment. Developed primarily for macroinvertebrates and fishes, current TCEQ screening levels appear to be inclusive for assessing water concerns for freshwater mussels, although robust water quality information for mussels is generally lacking. The percentage of times a variable exceeded a screening level was calculated for each segment. For consistency across segments, TCEQ screening levels were used for Anacoco Bayou, although Anacoco Bayou outside of TCEQ jurisdiction.

Results

Twenty-eight species and 9,244 individuals were collected among five reaches and 46 samples. State-threatened Texas Pigtoe *Fusconaia askewi* was the most abundant species (21%), followed by Pistolgrip *Tritogonia verrucosa* (18%) and Pimpleback *Cyclonaias pustulosa* (12%) (Table 3). Among reaches, mussel communities were most similar (Renkonen Similarity Index = 73%) between upper Sabine River and Toro Bayou and most dissimilar (7.6%) between Anacoco Bayou and the other four reaches (Figure 2). Within reaches, Texas Pigtoe, Pistolgrip, and Pimpleback (individually ≥13% in relative abundances) were the most abundant species in upper Sabine River and Toro Bayou, Pistolgrip (47%) and Bankclimber *Plectomerus dombeyanus* (18%) were the most abundant species in Lake Fork Creek, Round Pearlshell *Glebula rotundata* (22%) and Pimpleback (17%) were most abundant in lower Sabine River, and Pimpleback (57%) and Louisiana Fatmucket *Lampsilis hydiana* (14%) were the most abundant in Anacoco Bayou. Relative abundance of state-threatened Sandbank Pocketbook was 0.8% overall, 1.0% in upper Sabine River, 0.85% in lower Sabine River, and 7.1% in Anacoco Bayou.

Relative abundance of federal candidate Louisiana Pigtoe was 0.6% overall and 1.1% in upper Sabine River. Relative abundance of federal candidate Texas Heelsplitter was 0.08% and 0.14% in upper Sabine River.

Mean CPUE (± 1 SD) ranged from 0.01 mussels/p-hr (± 1 SD range: 0.04 – 0.05) for four species to 10.4 mussels/p-hr (± 21.1) for Texas Pigtoe among five reaches (Table 4). Within reaches, greatest mean CPUE per reach was Pistolgrip (33.1 mussels/p-hr, ± 38.3) in Lake Fork Creek, Texas Pigtoe (15.4 mussels/p-hr, ± 25.6) in the upper Sabine River, Round Pearlshell (14.0 mussels/p-hr, ± 33.5) in the lower Sabine River, Texas Pigtoe (6.0 mussels/p-hr) in Toro Bayou, and Pimpleback (1.0 mussels/p-hr, ± 1.41) in Anacoco Bayou. Mean CPUE of state-threatened Sandbank Pocketbook was 0.41 mussels/p-hr (± 0.58) overall, 0.45 mussels/p-hr (± 0.63) in upper Sabine River, 0.55 mussels/p-hr (± 0.55) in lower Sabine River, and 0.13 mussels/p-hr (± 0.18) in Anacoco Bayou. Mean CPUE of federal candidate Louisiana Pigtoe was 0.31 mussels/p-hr (± 1.32) overall, 0.51 mussels/p-hr (± 1.68) in upper Sabine River and 0.84 mussels/p-hr (± 1.68) within in occupied reach. Mean CPUE of federal candidate Texas Heelsplitter was 0.04 mussels/p-hr (± 0.16) overall and 0.06 mussels/p-hr (± 0.20) in upper Sabine River.

Habitat associations

Mussels were collected from riffle, run, pool, and backwater habitats with mean depths ranging from 0.5 to 1.5 m and benthic current velocities ranging from <0.01 to 0.21 cm/s among samples (Table 5). Principal component (PC) axes I and II explained 42% of the variation in habitat measurements collected among 46 samples (Figure 3). Axis I explained 29% of the variation and described a current velocity, depth, and substrate gradient, contrasting samples having swifter current velocities, shallower depths, and more gravel substrates from those having slower current velocities, deeper depths, and more silt substrates. Mean scores of samples collected from lower Sabine River with slower benthic current velocities, deeper depths, and more silt substrates were positively associated with PC axis I, whereas mean scores of samples collected from upper Sabine River, Lake Fork Creek, Anacoco Bayou, and Toro Bayou with swifter benthic current velocities, shallower depths, more gravel substrates were negatively associated with axis I. Axis II explained 13% of the variation and described a substrate gradient, contrasting samples having more sand and bedrock substrates from those having more cobble and gravel substrates. Mean scores of samples collected from lower Sabine River and Lake Fork Creek with more cobble and gravel substrates were negatively associated with PC axis II, whereas mean scores of samples collected from upper Sabine River, Anacoco Bayou, and Toro Bayou with more sand and bedrock substrates were positively associated with axis II.

Canonical correspondence (CC) axes I and II explained 69% ($P < 0.01$) of the variation in the mussel communities among reaches (Figure 4). Pure effects of habitat variables explained 34% (P = 0.02) of the variation and pure effects of reach explained 12% ($P < 0.01$) of the variation. Strongest loadings for CC axis I were lower Sabine River (0.91), silt (0.88), gravel (-0.77), upper Sabine River (-0.73) and benthic velocity (-0.71). Strongest loadings on CC axis II were sand (0.57), edge habitat (0.45), pool (0.36), detritus (0.34), mid-channel (-0.45), and gravel (-0.33). Among mussels associated with CC axis I, Round Pearlshell, Gulf Mapleleaf *Tritogonia nobilis*, Giant Floater *Pyganodon grandis*, and Louisiana Fatmucket were associated with slower current velocities and greater depths with silt substrates in the lower Sabine River, whereas Deertoe *Truncilla truncata*, Louisiana Pigtoe, and Washboard *Megalonaias nervosa* were associated with swifter current velocities and shallower depths with gravel substrates in the upper Sabine River. Among mussels associated with CC axis II, Texas Heelsplitter, Bleufer *Potamilus purpuratus*, and Yellow Sandshell *Lampsilis teres* were associated with sand and bedrock substrates at moderate current velocities and depths.

Among univariate assessments, mean (± 1 SD) benthic current velocity ranged between 0.17 (± 0.01) m/s for Gulf Mapleleaf to 0.35 (± 0.04) m/s for Louisiana Pigtoe. Mean (± 1 SD) depth ranged between 0.66 (± 0.03) m for Deertoe to 1.8 (± 0.20) m for Round Pearlshell (Figure 5). Eleven of the 18 species were collected from all four habitat types ranging from rare (<5% in species relative abundance) to common (50 - 74% in species relative abundance) (Appendix 1). Sandbank Pocketbook was collected from all four habitat types, frequently (25 – 49%) collected in riffle and run mesohabitats. Louisiana Pigtoe was commonly collected from run habitats and frequently collected from riffle habitats. Texas Heelsplitter was commonly collected from riffle habitat and occasionally (5 – 24%) collected from run and pool habitat. Among all samples, dominant substrates were sand (30%), gravel (28%), and silt (27%) (Appendix 2). All mussels were rare to abundant in the dominant substrates with many rare to occasional in clay, cobble, boulder, bedrock, and detritus substrates. Among river morphologies, 78% of the species were frequent to abundant in straightaways (39% of the samples), 66% were frequent to abundant behind point bars (20% of the samples), and 28% were frequent to abundant in outside bends (37% of the samples) (Appendix 3). Between river positions (59% of samples were edge, 41% were mid-channel), 83% of the species were frequent to abundant in the mid-channel and 61% were frequent to abundant on the edge (Appendix 4).

Trends in water quality within the Sabine River Basin

For Lake Fork Creek (Segment 515), water quality datasets consisted of 444 measurements among 13 water quality variables but only the following 11 variables had < 30% of years with missing data: Cl^-, DO, hardness, pH, SO_4^{2-}, alkalinity, TDS, TOC, P, turbidity, and water temperature. Principal component I and PC II axes explained 60% of the variation in water quality, contrasting primarily turbidity, SO_4^{2-}, and alkalinity gradients along PC I and primarily DO and water temperature gradients along PC II (Figure 6a). Decades differed along PC 1 ($F_{4,39} = 16.1$; P <0.01) and PC 2 ($F_{4,39} = 9.3$; P <0.01) axes. Among pairwise contrasts, 1990s and 2010s with lower SO_4^{2-} and alkalinity differed from the other decades along PC 1, and 1970s with greater DO and lower water temperatures differed from the other decades along PC 2. Five variables (i.e., NH_3-N, Cl^-, DO, pH, and TDS) exceeded TCEQ screening levels, ranging from 0.2% of the time for pH to 2.7% of the time for NH_3-N (Table 6; Figure 6b).

For upper Sabine River (Segment 506), water quality datasets consisted of 994 measurements among 13 water quality variables with all water quality variables having <30% of the years with missing data. Principal component I and PC II axes explained 41% of the variation in water quality, contrasting primarily turbidity, TDS, and Cl^- gradients along PC I and primarily hardness, TOC, and NO_3-N gradients along PC II (Figure 7a). Decades differed along PC 1 ($F_{4,46} = 8.1$; P <0.01) and PC 2 ($F_{4,46} = 3.7$; P = 0.01) axes. Among pairwise contrasts, 1980s with greater TDS and Cl^- differed from the other decades along PC I and 1970s and 1980s with greater hardness, TOC, and lesser NO_3-N differed from the other decades along PC II. Eight variables (i.e., NH_3-N, Cl^-, DO, NO_3-N, pH, SO_4^{2-}, TDS, and P) exceeded TCEQ screening levels, ranging from 0.2% of the time for SO_4^{2-} and to 5.4% of the time for TDS (Figure 7b).

For upper Sabine River (Segment 505), water quality datasets consisted of 706 measurements among 13 water quality variables with all water quality variables having <30% of the years with missing data. Principal component I and PC II axes explained 56% of the variation in water quality, contrasting primarily a DO and Cl^- gradient on PCI and primarily an NH_3-N and pH gradient on PC II (Figure 8a). Decades differed along PC 1 ($F_{4, 44} = 3.1$; $P = 0.03$) and PC 2 ($F_{4,44} = 3.4$; $P = 0.02$) axes. Among pairwise contrasts, 1980s with grater Cl^- and TDS differed from other decades along PC I and the 1970s with greater NH_3-N differed from the other decades along PC II. Nine variables (i.e., NH_3-N, Cl^-, DO, NO_3-N, pH, SO_4^{2-}, TDS, P, and water temperature) exceeded TCEQ screening levels ranging from 0.02% of the time for water temperature to 6.8% of the time for TDS (Figure 8b).

For the lower Sabine River (Segment 503) water quality datasets consisted of 1,984 measurements among 13 water quality variables with 12 water quality variables having <30% of the years with missing data: NH_3-N, Cl^-, DO, hardness, pH, SO_4^{2-}, alkalinity, TDS, TOC, P, turbidity, and water temperature. Principal component I and PC II axes explained 51% of the variation in water quality, contrasting primarily a NH_3-N and SO_4^{2-} gradient on PCI and primarily a TOC and DO on PC II (Figure 9a). Decades differed along PC 1 ($F_{4, 47} = 5.9$; $P < 0.01$) and PC 2 ($F_{4,47} = 5.9$; $P < 0.01$) axes. Along a pairwise the 1980s through the 2010s had grater SO_4^{2-} and differed from other decades along PC I and the 2000 and 2010s had higher temperatures other decades along PC II. Eight variables (i.e., NH_3-N, Cl^-, DO, pH, SO_4^{2-}, TDS, P, and water temperature) exceeded TCEQ screening levels ranging from 0.1% of the time for Cl^- to 6.3% of the time for SO_4^{2-} (Figure 9b).

For the lower Sabine River (Segment 502) water quality datasets consisted of 964 measurements among 13 water quality variables with all water quality variables having <30% of the years with missing data. Principal component I and PC II axes explained 43% of the variation in water quality, contrasting primarily a SO_4^{2-} and turbidity gradient on PC I and primarily a DO and temperature gradient on PC II (Figure 10a). Decades were not different ($F_{4,43}$ = 1.9; P = 0.12) along PC I but differed ($F_{4,43}$ = 6.9; P < 0.01) along PC II. Along a pairwise the 1980s had higher DO than other decades along PC II. Six variables (i.e., NH_3-N, Cl^-, DO, pH, SO_4^{2-}, and TDS) exceeded TCEQ screening levels ranging from 0.1% of the time for Cl^- to 2.3% of the time for pH (Figure 10b).

For Anacoco Bayou water quality datasets consisted of 280 measurements among 13 water quality variables with 10 water quality variables having <30% of the years with missing data: Cl^-, DO, NO_3-N hardness, pH, P, SO_4^{2-}, alkalinity, TDS, and water temperature. PC I and PC II axes explained 65% of the variation in water quality, contrasting primarily a DO and TDS gradient on PC1 and primarily Cl- and temperature gradient on PC 2 (Figure 11a). Decades differed along PC 1 ($F_{5, 48}$ = 5.7; P < 0.01) and PC 2 ($F_{5, 48}$ = 6.9; P < 0.01) axes. Along a pairwise contrast, the 2000 to 2010 had higher SO_4^{2-} than the other decades on PC I, while the 2000 and 2010 had higher temperatures that other decades on PC II. Seven variables (i.e., NH_3-N, Cl-, DO, pH, SO_4^{2-}, and TDS, P) exceeded TCEQ screening levels ranging from 0.5% of the time for P to 57% of the time for SO_4^{2-} (Figure 11b).

Discussion

Although this study targeted priority reaches for Louisiana Pigtoe and Texas Heelsplitter, the number of mussel species (S = 28) collected among five reaches was greater than the number of species reported in nearby Sulphur River (S = 10 – 11 from two sites), a tributary of the Red River (Karatayev and Burlakova 2007), Neches River (S = 16 – 25; 1 to 45 sites; Karatayev and Burlakova 2007, Ford et al. 2016), and Neches River tributaries (S = 15 – 19; 2 to 22 sites; Bordelon 2003, Karatayev and Burlakova 2007, Ford et al. 2016). In this study, upper Sabine River mean CPUE and lower Sabine River mean CPUE were higher than previous studies reports of CPUE (26) in upper Sabine River and in the Lower Sabine River (10) (Karatayev and Burlakova 2007; Randklev 2011). Combining results of this study and those reported by Karatayev and Burlakova (2007) and Randklev (2011) for a total of 58 sites, mean CPUE per site ranged from 1.8 to 83. In comparison to the adjacent Neches River where Louisiana Pigtoe is considered in high condition (USFWS 2020), CPUE ranges between 4.7 and 85 among 100 total sites (Bordelon 2003; Karatayev and Burlakova 2007; Ford et al. 2016). Despite Louisiana Pigtoe being consider in low condition in the upper Sabine River, the mussel community, based on species richness and CPUE, is similar to the Neches River.

The initial prediction of Texas Heelsplitter being functionally extirpated (< 0.50 CPUE, < 3 individuals per population survey) per USFWS (2020) definition was supported by this study with a mean CPUE (± 1 SD) of 0.06 (± 0.16) in the upper Sabine River, although the number of individuals (N = 7) exceeded the functionally extirpated definition. The initial prediction of Louisiana Pigtoe being functionally extirpated was not supported with a mean CPUE (± 1 SD) of 0.51 ± 1.68 and abundance of 57 individuals in the upper Sabine River. Range-wide estimates of CPUE range from 0.15 to 1.8 for Texas Heelsplitter and 0.22 to 5.23 for Louisiana Pigtoe, and range-wide estimates of abundances range from 2 to 377 for Texas Heelsplitter and 3 to 192 for Louisiana Pigtoe (USFWS 2020). Although Louisiana Pigtoe and Texas Heelsplitter ranked low in relative abundance and CPUE (ranked 18th and 23rd, respectively), state-listed Texas Pigtoe was ranked the most abundant mussel species and had the highest CPUE among the five reaches of this study. Likewise, the Sabine River supported the state-listed Sandbank Pocketbook with a 17th rank in relative abundance and CPUE.

Quantified habitat associations reported herein generally follow habitat descriptions for several of the abundant mussels collected in this study and for the candidate or listed species. Texas Pigtoe, Pistolgrip, and Pimpleback were associated with mid-channel, run and riffle habitats with sand to gravel substrates at generally swifter current velocities than available and at shallower depths than available. Previously, Texas Pigtoe was reported to associate with loose substrates and run habitats (Glen 2017), Pistolgrip was reported to associate with riffle habitats and swift current velocities (Gooding et al. 2019), and Pimpleback was reported as a habitat-generalist species (Vaughan et al. 2020). In this study, state-listed Sandbank Pocketbook (N = 75) was associated with edge and mid-channel, riffle and run habitats with gravel substrates but occasionally found in pool and backwater habitats with silt and sand substrates. In a previous description, Sandbank Pocketbook similarly occur in low flowing and pool habitats with silt, sand, and gravel substrates (Howell et al. 1996). Louisiana Pigtoe (N =

57) was associated with mid-channel, riffle and run habitats with swift current velocities, shallow depths, and gravel substrates, similar to previous habitat descriptions (Glen 2017, Vaughn et al. 2020). Texas Heelsplitter, based on a small sample size (N = 7), was associated with mid-channel, riffle habitats with swift current velocities and shallow depths and sand and gravel substrates. In previous habitat descriptions, Texas Heelsplitter is associated with sand and silty substrates (Walters et al. 2017, Dickson 2018). Recently, 66 Texas Heelsplitters were reported in Steinhagen Reservoir (Neches River drainage) during a dewatering event (Texas Parks and Wildlife 2019, unpublished report), suggesting perhaps a strong association with backwater, off-channel, or reservoir habitats. Within their reported occupied range in the upper Sabine River, backwater habitats comprised a small percentage (4%) of the sampled habitats. Targeted sampling of backwater habitats might yield greater numbers of Texas Heelsplitter.

The initial prediction of water quality improving was partially supported among three (upper Sabine, Lake Fork Creek, and lower Sabine) of the four reaches of the Sabine basin assessed in this study. Chloride and NH_3-N decreased below TCEQ screening levels between 1970 and 2020 in all or part of three reaches while P decreased within the upper and lower Sabine. Collective decreases in water quality variables (NH_3-N, P, Cl^-, and NO_3-N) indicate increasing water quality through time and have broadly been reported in other rivers (Perkin and Bonner 2016; Parker et al. 2016; Smith et al. 2018). Water quality initiatives or regulations, such as the Clean Water Act (1972), are connected to decreases in harmful levels of water quality variables and increases in fish and macroinvertebrates communities (Perkin and Bonner 2016; Gibson-Reinemer et al. 2017; Smith et al. 2018).

Variables SO_4^{2-}, TDS, and CL^- exceeded TCEQ screening levels within the Sabine basin since 2010. Chlorides exceeded screening levels in the upper Sabine River, and SO_4^{2-} and TDS exceeded screening levels in the lower Sabine River and Anacoco Bayou. Most notably, SO_4^{2-} in lower Sabine River (mean ± 1 SD; 37 mg/l ± 36.4; max: 185) and Anacoco Bayou (120 mg/l ± 108.2; max: 515 mg/l) exceeded TCEQ screening levels (>100 mg/l). Sulfates are toxic for a variety of species (Griffith et al. 2020) at levels as low as 129 mg/L for algae (Elphick et al. 2011), although limited data indicated that mussels might have a higher tolerance (>1,350 mg/l; Wang et al. 2017). Sulfate occurs naturally but recent increases in sulfate in the lower Sabine River and Anacoco Bayou suggest an anthropogenic sources, which are commonly elevated wastewater from oil, gas, mining, sewage and papermills (Thompson et al. 2001; Sievert et al 2007; Allen 2008; Rubright et al. 2017).

Within the Sabine River basin, lack of historical mussel occurrence and abundance data preclude mussel trend assessments relating to water quality changes through time. Nevertheless, baseline occurrence and abundance data in this study can serve as a baseline for future trend assessments and conservation goals (Strayer et al. 2019). At this time and among the variables assessed in this study, it does not appear that water quality is a limiting factor for the mussel community, especially species of conservation concern, given that the basin supports four mussel species of conservation concern with one (i.e., Texas Pigtoe) being the most abundant species in the basin. If legacy effects of poor water quality (i.e., pre-1960s, which lack water quality data) limited some of the Sabine River basin mussels, then increasing numbers of these species might be expected with improvement of water quality, defined herein as generally conforming to TCEQ water quality screening levels, as previously observed with macroinvertebrate and fish communities (Perkin and Bonner 2016; Whitten and Gibson-Reinemer 2018; Artz et al. 2020). Future monitoring, at appropriate spatial and temporal scales, would be beneficial in the understanding of contemporary processes regulating the Sabine River mussel community (Moniruzzaman et al. 2021) and enable assessments of current and future threats to the aquatic biota of the Sabine River basin.

Table 1: Reach names, corresponding Texas Commission Environmental Quality segment names, which is lacking for Anacoco Bayou, and first year of recorded water quality data used in this study for areas with water quality assessments in Sabine River basin.

Reach	Segment number-name	First year of record
Lake Fork Creek	515-Lake Fork Creek	1977
Upper Sabine River	506-Sabine River below Tawakoni	1970
	505-Sabine River above Toledo Bend	1972
Lower Sabine River	503-Sabine River above Caney Creek	1968
	502-Sabine River above Tidal	1973
Anacoco Bayou	Anacoco Bayou	1967

Table 2: Texas Commission of Environmental Quality (TCEQ) screening levels within the Sabine River basin along with summary of reported tolerances of freshwater mussels.

Variable	TCEQ Screening levels	Mussel information	Source for mussel information
NH_3-N (mg/l)	>0.33	>1.5	Wang et al. 2017
Cl^- (mg/l)	>100	>1,035	Wang et al. 2017
DO (mg/l)	<4	<3	Chen et al. 2001
NO_3-N (mg/l)	>1.95	>56	Soucek and Dickinson 2012
pH	<6, >8.5	<6, >9	Berezina 2001
SO_4^{2-} (mg/l)	>100	>1,350	Wang et al. 2017
TDS (mg/l)	>400	>940	Ciparis et al. 2015
Temperatures °C	>33	>33	Pandolfo et al. 2010
P (mg/L)	>0.69		

Table 3. Relative abundances (%) of mussels overall and among five reaches of the Sabine River basin sampled during June 2020 through September 2021.

Scientific Name	Overall %	Lake Fork Creek %	Upper Sabine River %	Lower Sabine River %	Toro Bayou %	Anacoco Bayou %
Amblema plicata	0.4	-	0.24	0.81	-	-
Arcidens confragosus	0.4	0.18	0.56	0.07	-	-
Cyclonaias pustulosa	12	-	13	17	18	57
Fusconaia askewi	21	9.2	35	1.8	35	7.1
Glebula rotundata	6.8	-	-	22	-	-
Lampsilis hydiana	2.7	-	0.32	7.4	21	14
Lampsilis satura	0.8	-	1.0	0.85	-	7.1
Lampsilis teres	7.2	0.54	6.6	11	5.9	7.1
Leaunio lienosa	1.0	-	0.06	3.0	1.5	-
Leptodea fragilis	1.2	0.54	1.3	1.2	-	-
Megalonaias nervosa	1.3	0.98	2.1	-	-	-
Obliquaria reflexa	2.8	2.3	3.3	2.37	-	-
Plectomerus dombeyanus	5.7	18	0.98	9.40	-	-
Pleurobema riddellii	0.63	-	1.1	-	-	-
Potamilus amphichaenus	0.08	-	0.14	-	-	-
Potamilus purpuratus	2.0	2.2	2.9	0.42	-	-
Pyganodon grandis	1.4	0.27	0.12	4	-	-
Quadrula quadrula	7.3	8.3	7.5	6.8	-	-
Sagittunio subrostrata	0.01	0.09	-	-	-	-
Strophitus undulatus	0.01	-	0.02	-	-	-
Toxolasma parvum	0.04	-	-	0.14	-	-
Toxolasma sp.	0.02	-	-	0.07	-	-
Toxolasma texasiense	0.03	-	-	0.11	-	-
Tritogonia nobilis	3.4	-	-	11	-	-
Tritogonia verrucosa	18	47	22	0.67	19.1	7.1
Truncilla truncate	2.9	9.9	2.94	-	-	-
Uniomerus tetralasmus	0.02	-	-	0.07	-	-
Utterbackia imbecillis	0.17	-	-	0.53	-	-
Utterbackiana suborbiculata	0.11	-	-	0.35	-	-
Total	9,244	1,335	4,998	2,829	68	14

Table 4. Mean catch-per-unit effort (mussels/person-hour) of mussels overall and among five reaches of the Sabine River basin (Toro Bayou has a single sample) sampled during June 2020 through September 2021.

	Overall		Lake Fork Creek		Upper Sabine River		Lower Sabine River		Toro Bayou	Anacoco Bayou	
Species	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Total	Mean	SD
Amblema plicata	0.19	0.4	-	-	0.11	0.25	0.52	0.61	-	-	-
Arcidens confragosus	0.17	0.32	0.13	0.25	0.25	0.38	0.05	0.15	-	-	-
Cyclonaias pustulosa	7.26	10.2	13.6	19.8	5.62	7.36	10.7	12.4	3	1	1.41
Fusconaia askewi	10.4	21.1	6.44	11.2	15.4	25.6	1.16	1.99	6	0.13	0.18
Glebula rotundata	3.34	16.9	-	-	-	-	14	33.5	-	-	-
Lampsilis hydiana	1.3	2.72	-	-	0.14	0.48	4.73	3.81	3.5	0.25	0.35
Lampsilis satura	0.41	0.58	-	-	0.45	0.63	0.55	0.55	-	0.13	0.18
Lampsilis teres	3.55	3.59	0.38	0.32	2.96	3.14	7.05	3.18	1	0.13	0.18
Leaunio lienosa	0.48	1.6	-	-	0.03	0.1	1.91	2.91	0.25	-	-
Leptodea fragilis	0.59	0.84	0.38	0.13	0.62	0.88	0.75	0.93	-	-	-
Megalonaias nervosa	0.63	1.26	0.69	1.38	0.94	1.46	-	-	-	-	-
Obliquaria reflexa	1.39	3.19	1.63	1.96	1.46	2.84	1.52	4.72	-	-	-
Plectomerus dombeyanus	2.8	6.2	12.6	11.2	0.44	0.8	6.05	8.13	-	-	-
Pleurobema riddellii	0.31	1.32	-	-	0.51	1.68	-	-	-	-	-
Potamilus amphichaenus	0.04	0.16	-	-	0.06	0.2	-	-	-	-	-
Potamilus purpuratus	0.99	1.36	1.56	1.26	1.29	1.55	0.27	0.33	-	-	-
Pyganodon grandis	0.66	2.64	0.19	0.38	0.05	0.17	2.57	5.09	-	-	-
Quadrula quadrula	3.6	4.94	5.81	7.16	3.37	4.77	4.36	5.14	-	-	-
Sagittunio subrostrata	0.01	0.04	0.06	0	-	-	-	-	-	-	-
Strophitus undulatus	0.01	0.04	-	-	0.01	0.05	-	-	-	-	-
Toxolasma parvum	0.02	0.1	-	-	-	-	0.09	0.2	-	-	-
Toxolasma sp.	0.01	0.05	-	-	-	-	0.05	0.1	-	-	-
Toxolasma texasiense	0.02	0.06	-	-	-	-	0.07	0.12	-	-	-
Tritogonia nobilis	1.66	7.75	-	-	-	-	6.95	15.2	-	-	-
Tritogonia verrucosa	8.9	16.6	33.1	38.3	9.6	13.1	0.43	0.64	3.25	0.13	0.18
Truncilla truncata	1.4	3.52	6.94	0	1.31	2.01	-	-	-	-	-
Uniomerus tetralasmus	0.01	0.05	-	-	-	-	0.05	0.1	-	-	-
Utterbackia imbecillis	0.08	0.35	-	-	-	-	0.34	0.66	-	-	-
Utterbackiana suborbiculata	0.05	0.3	-	-	-	-	0.23	0.6	-	-	-
N of samples	46		4		28		11		1	2	
Mean CPUE	50.2		83		45		64		17	1.8	
Total effort (h)	184		16		112		44		4	8	

Table 5: Summary of habitat characteristics at 46 samples among five reaches within the Sabine River basin sampled during June 2020 through September 2021.

	Lake Fork Creek	Upper Sabine River	Lower Sabine River	Toro Bayou	Anacoco Bayou
N of samples	4	28	11	1	2
Mesohabitat (%)					
riffle	-	32	-	-	-
run	75	39	-	100	100
pool	25	25	55	-	-
backwater	-	4	45	-	-
Mean depth (m)	0.8	1	1.5	0.5	0.6
Mean benthic current velocity (m/s)	0.21	0.18	<0.01	0.15	0.15
Substrate (%)					
clay	7.5	2.3	4.5	-	-
silt	13	13	74	-	-
sand	18	35	14	40	65
gravel	63	34	1.8	10	35
cobble	-	6	5.5	-	-
boulder	-	3.2	-	-	-
bedrock	-	5.9	0.9	50	-
detritus	-	0.4	-	-	-
River morphology (%)					
straightaway	50	46	18	100	-
outside bend	-	21	27	-	-
behind point bar	50	32	55	-	100
River position (%)					
mid-channel	25	57	18	-	-
edge	75	43	82	100	100

Table 6: Percentage of the time that a variable exceeded the Texas Commission of Environmental Quality (TCEQ) screening level by reach and segment in the Sabine River basin. For consistency across segments, TCEQ screening levels were used for Anacoco Bayou, although Anacoco Bayou outside of TCEQ jurisdiction. Water quality acronyms are as follows: ammonia (NH_3-N; mg/l), chloride (Cl^-; mg/l), dissolved oxygen (DO; mg/l), nitrate (NO_3-N; mg/l), pH, sulfate (SO_4^{2-}; mg/l), total dissolved solids (TDS; mg/l), total phosphorus (P; mg/l), and water temperature (°C).

Variable	Lake Fork Creek, Segment 515	Upper Sabine River, Segment 506	Upper Sabine River, Segment 505	Lower Sabine River, Segment 503	Lower Sabine River, Segment 502	Anacoco Bayou
NH_3-N	2.7	3.2	3.7	2.3	1.5	6.6
Cl^-	0.8	3.8	1.1	0.1	0.1	11
DO	3	3.7	2.9	0.7	1.7	1.6
NO_3-N	0	0.4	0.4	0	0	0
pH	0.2	0.4	1.5	0.3	2.3	1.8
SO_4^{2-}	0	0.2	0.1	6.3	0.9	57
TDS	0.5	5.4	6.8	4	0.6	51
P	0	0.7	1.2	0	0	0.53
Temperature	0	0	0.02	0.3	0	0

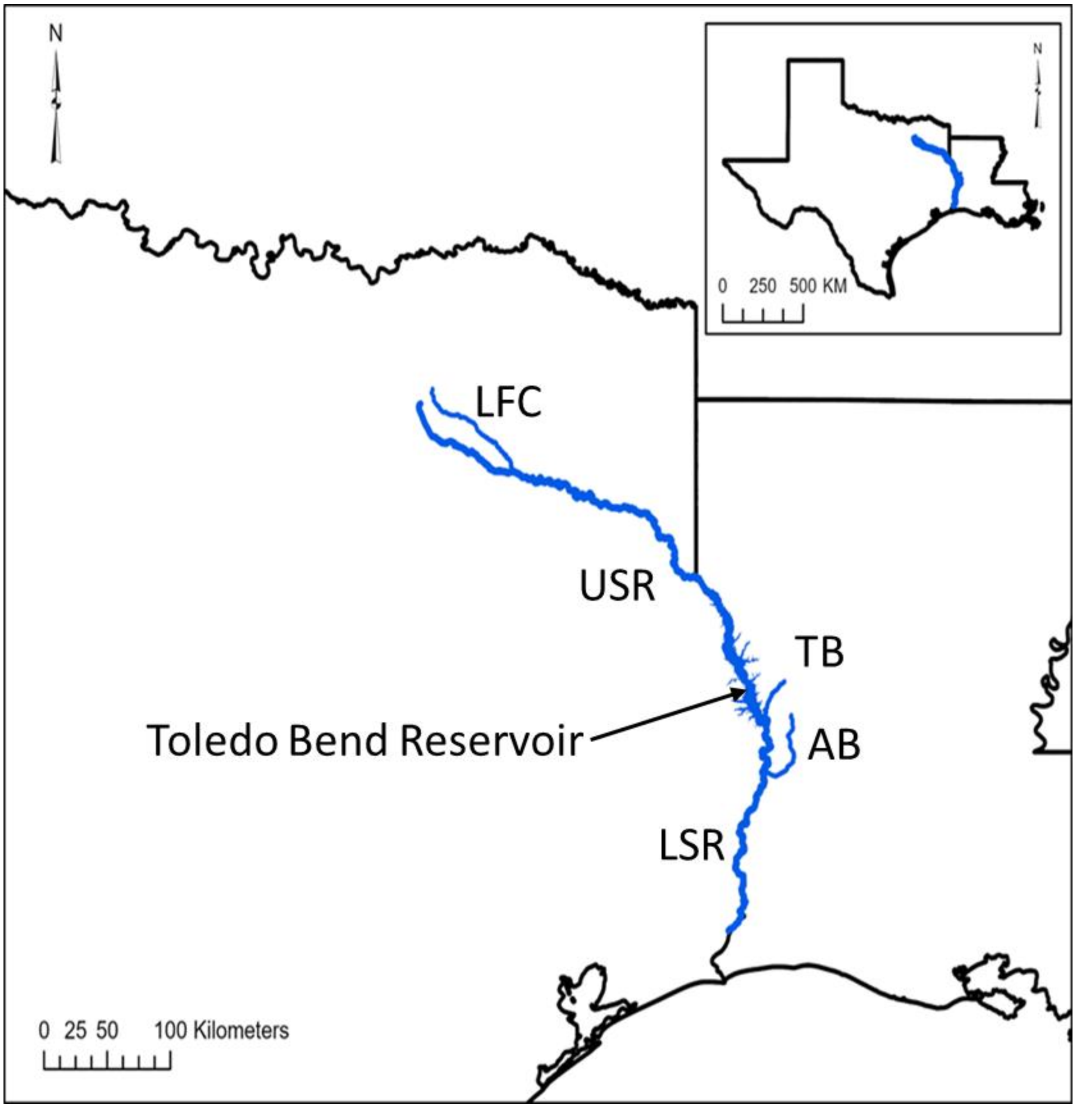

Figure 1: The five reaches sampled within the Sabine River basin from June 2020 through September 2021 includes Lake Fork Creek (LFC), upper Sabine River (USR), lower Sabine River (LSR), Toro Bayou (TB), and Anacoco Bayou (AB).

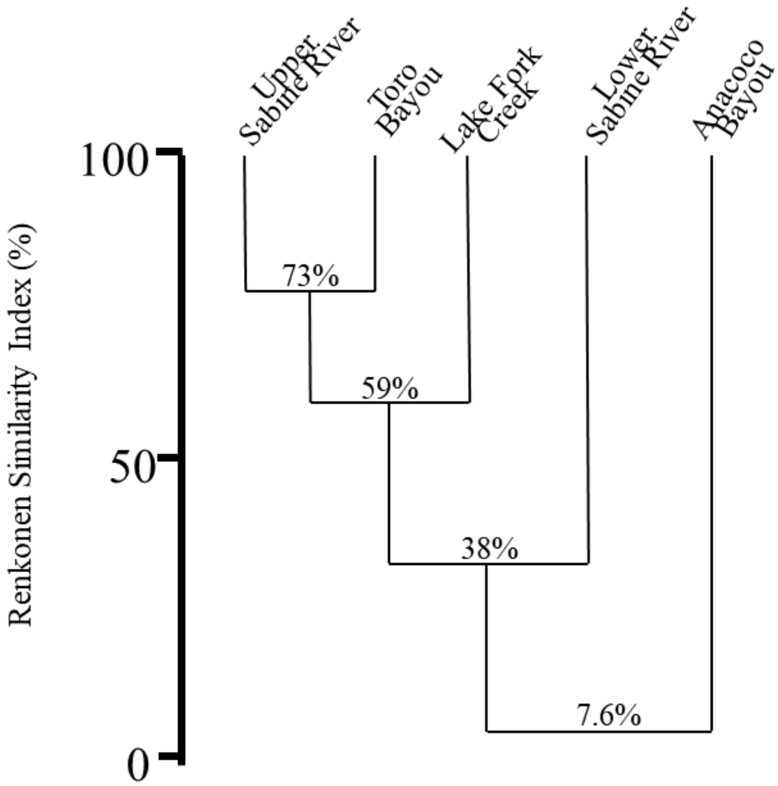

Figure 2. Dendrogram illustrating mussel community similarities among five reaches and 46 samples within the Sabine River drainage. Percent similarity values were calculated using the Renkonen Similarity Index and are based on relative abundance per species.

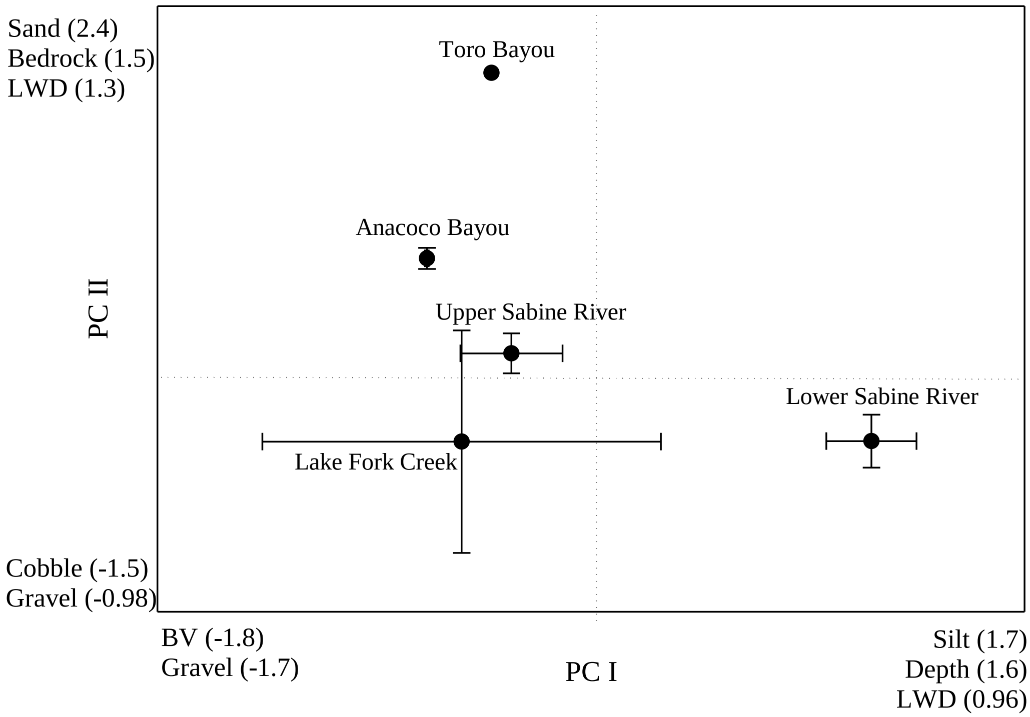

Figure 3. Plot of principal component axes I and II for habitat measurements collected among five reaches and 46 samples within the Sabine River drainage. Only habitat variables with the strongest loadings on PC axes I and II are provided. Black circle represents mean PC scores among sub-basins. Error bars denote 1 SE.

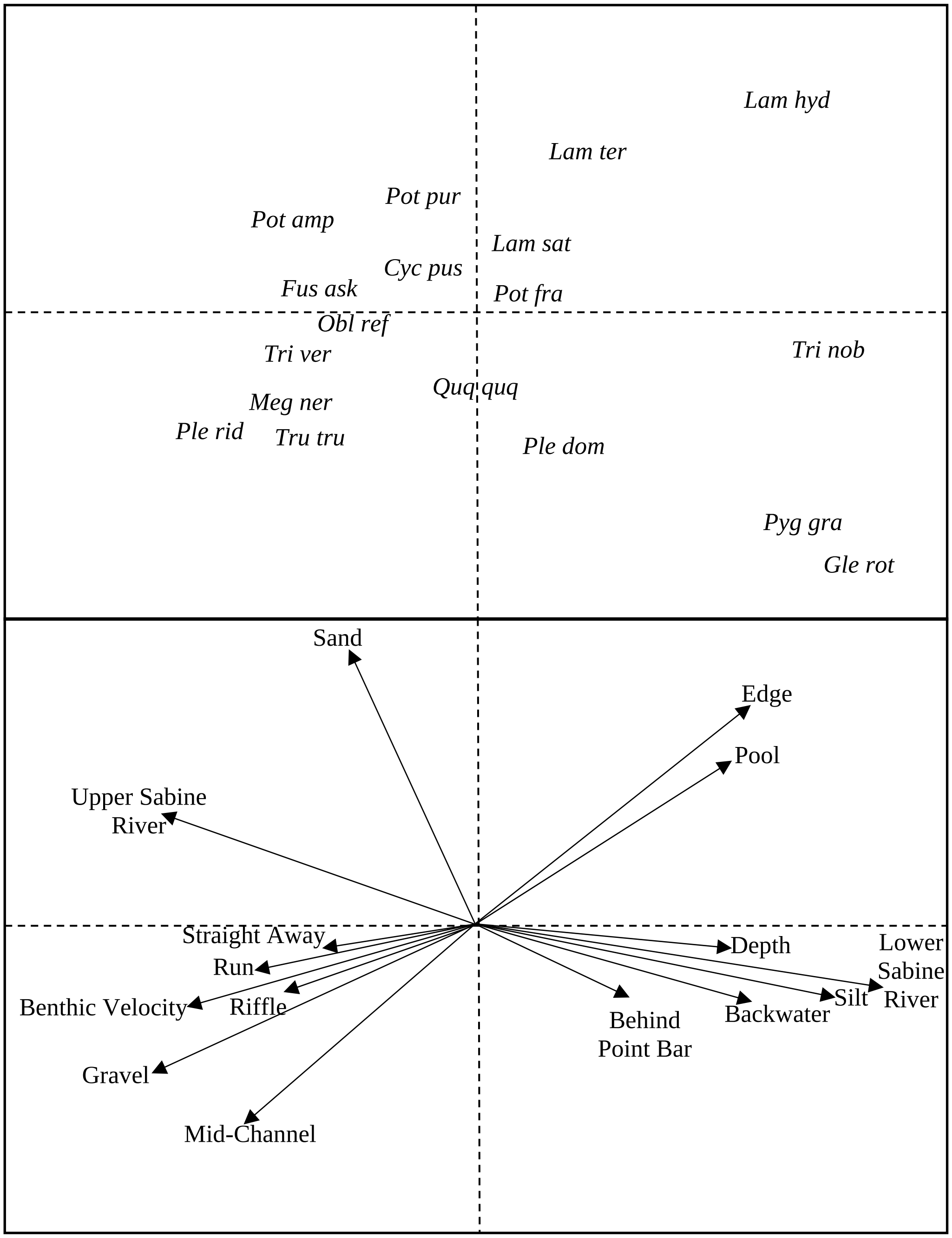

Figure 4. Plot of canonical correspondence axes I and II for habitat measurements and species (i.e., abundant, candidate, or listed species) collected among five reaches and 46 samples within the Sabine River drainage during June 2020 through September 2021.

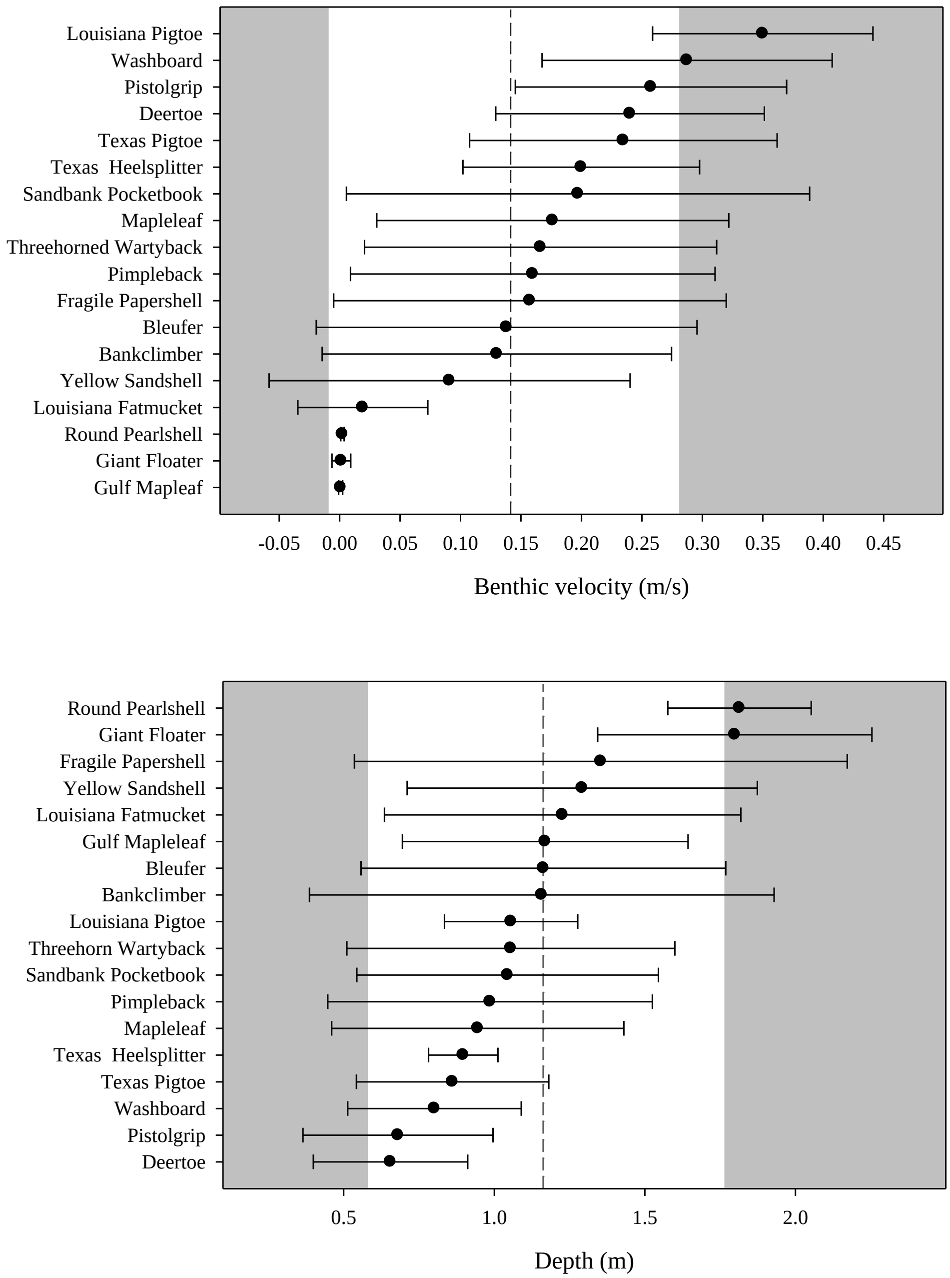

Figure 5. Weighted mean (black circle) and 1 SD (whiskers) of benthic current velocities (top panel) and depths (bottom panel) for mussels collected among five reaches within the Sabine River drainage from June 2020 through September 2021. Dashed vertical line represents the mean of all available habitats and the white area represents ± 1 SD of the mean for all available habitats.

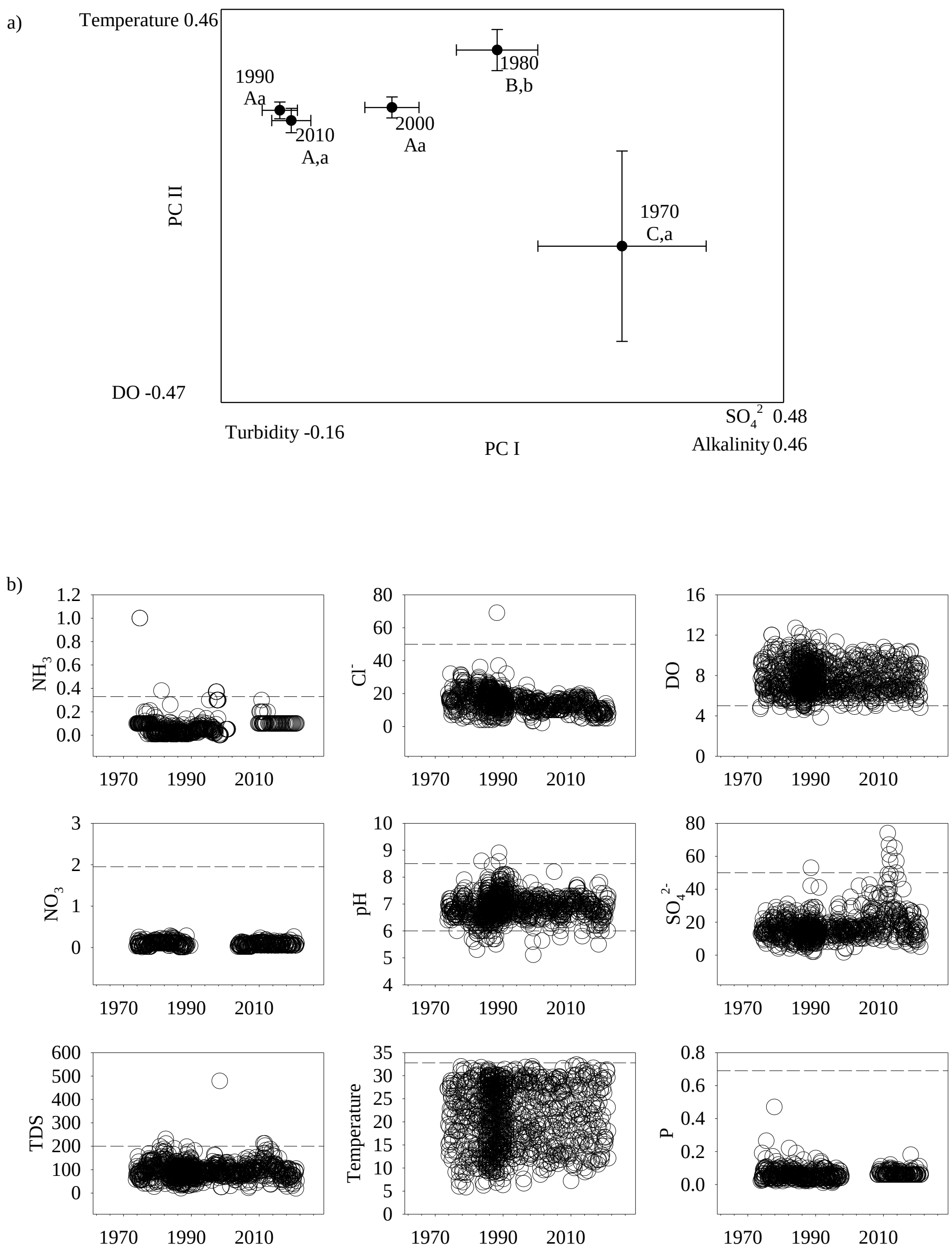

Figure 6. a) Means (black circle; ± 1 SE, whisker) of PC scores grouped by decade for water quality variables extracted from Lake Fork Creek Segment 515; b) univariate plots to visually assess water quality variables in context of Texas Commission of environmental Quality screening levels (dashed lines), 1977 to 2020.

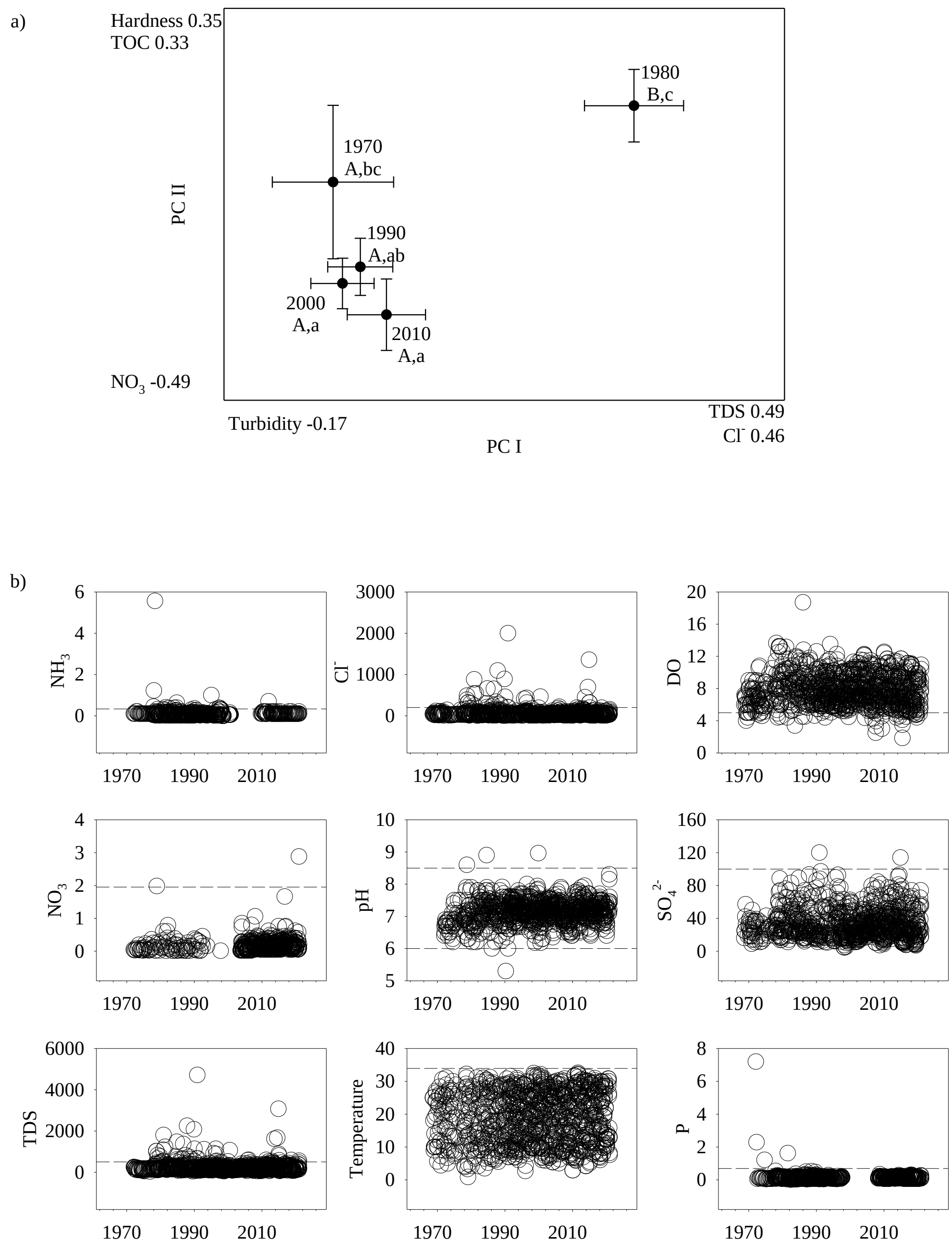

Figure 7. a) Means (black circle; ± 1 SE, whisker) of PC scores grouped by decade for water quality variables extracted from upper Sabine River Segment 506; b) univariate plots to visually assess water quality variables in context of Texas Commission of environmental Quality screening levels (dashed lines), 1970 to 2020.

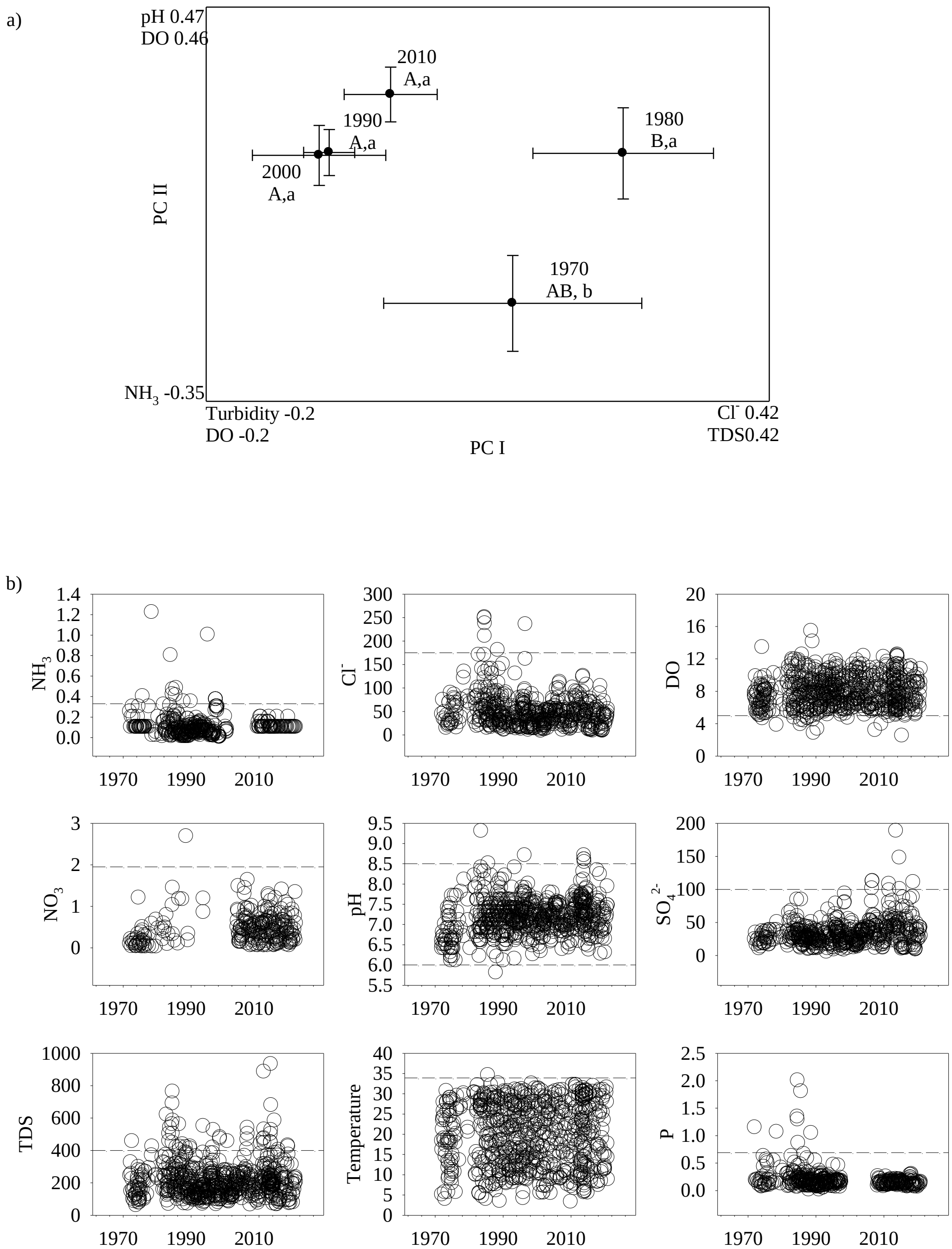

Figure 8. a) Means (black circle; ± 1 SE, whisker) of PC scores grouped by decade for water quality variables extracted from upper Sabine River Segment 505; b) univariate plots to visually assess water quality variables in context of Texas Commission of environmental Quality screening levels (dashed lines), 1972 to 2020.

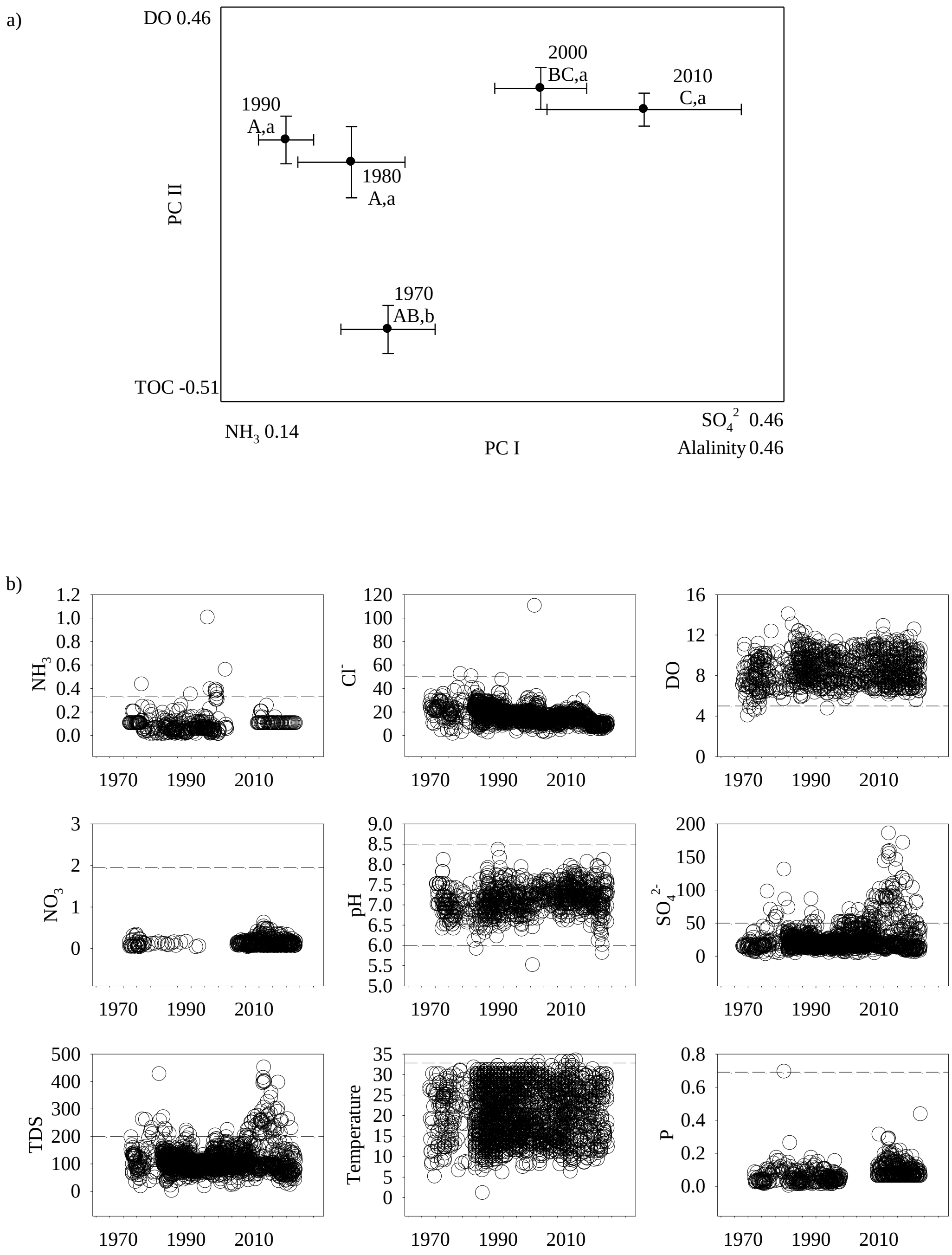

Figure 9. a) Means (black circle; ± 1 SE, whisker) of PC scores grouped by decade for water quality variables extracted from lower Sabine River Segment 503; b) univariate plots to visually assess water quality variables in context of Texas Commission of environmental Quality screening levels (dashed lines), 1970 to 2020.

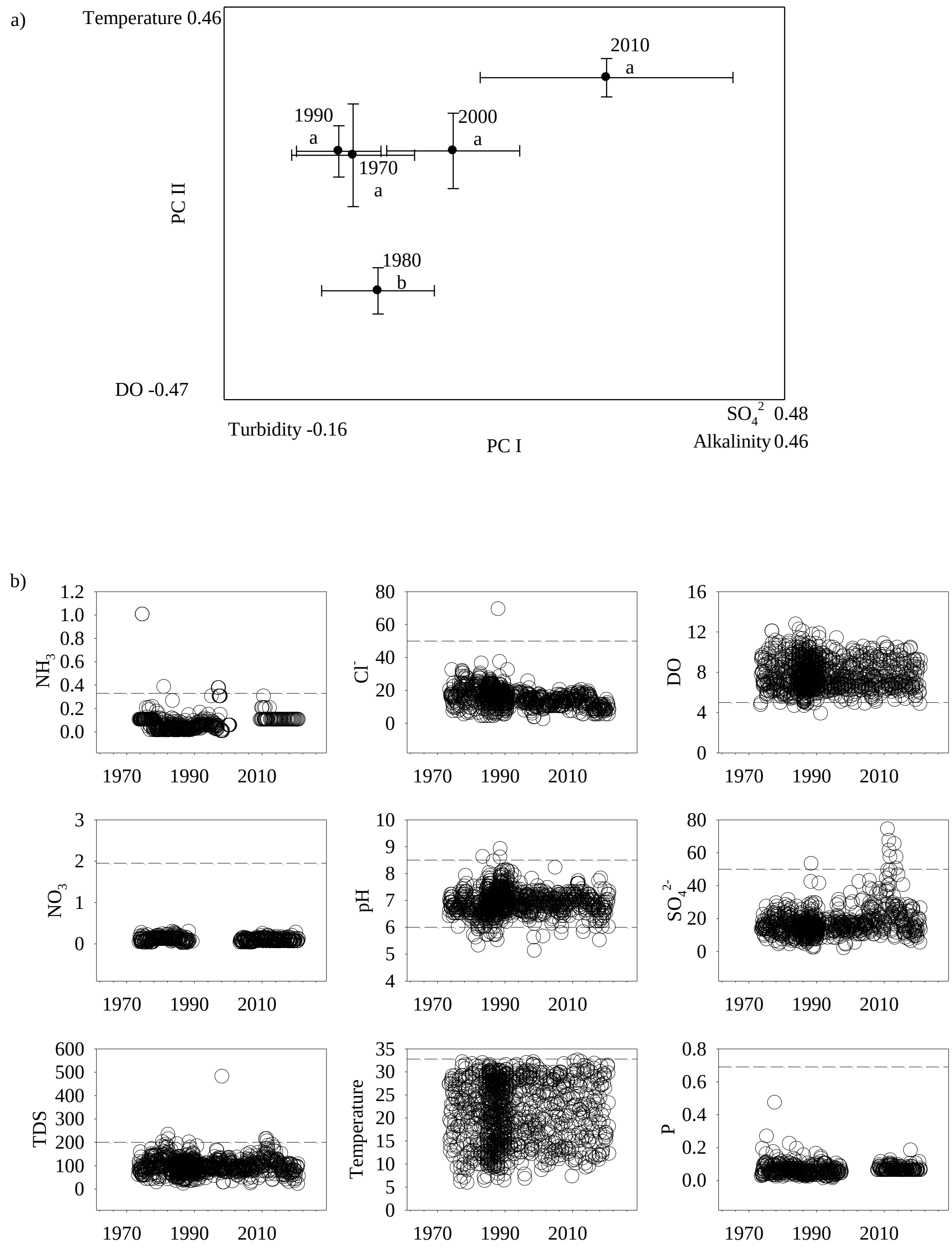

Figure 10. a) Means (black circle; ± 1 SE, whisker) of PC scores grouped by decade for water quality variables extracted from lower Sabine River Segment 502; b) univariate plots to visually assess water quality variables in context of Texas Commission of environmental Quality screening levels (dashed lines), 1973 to 2020.

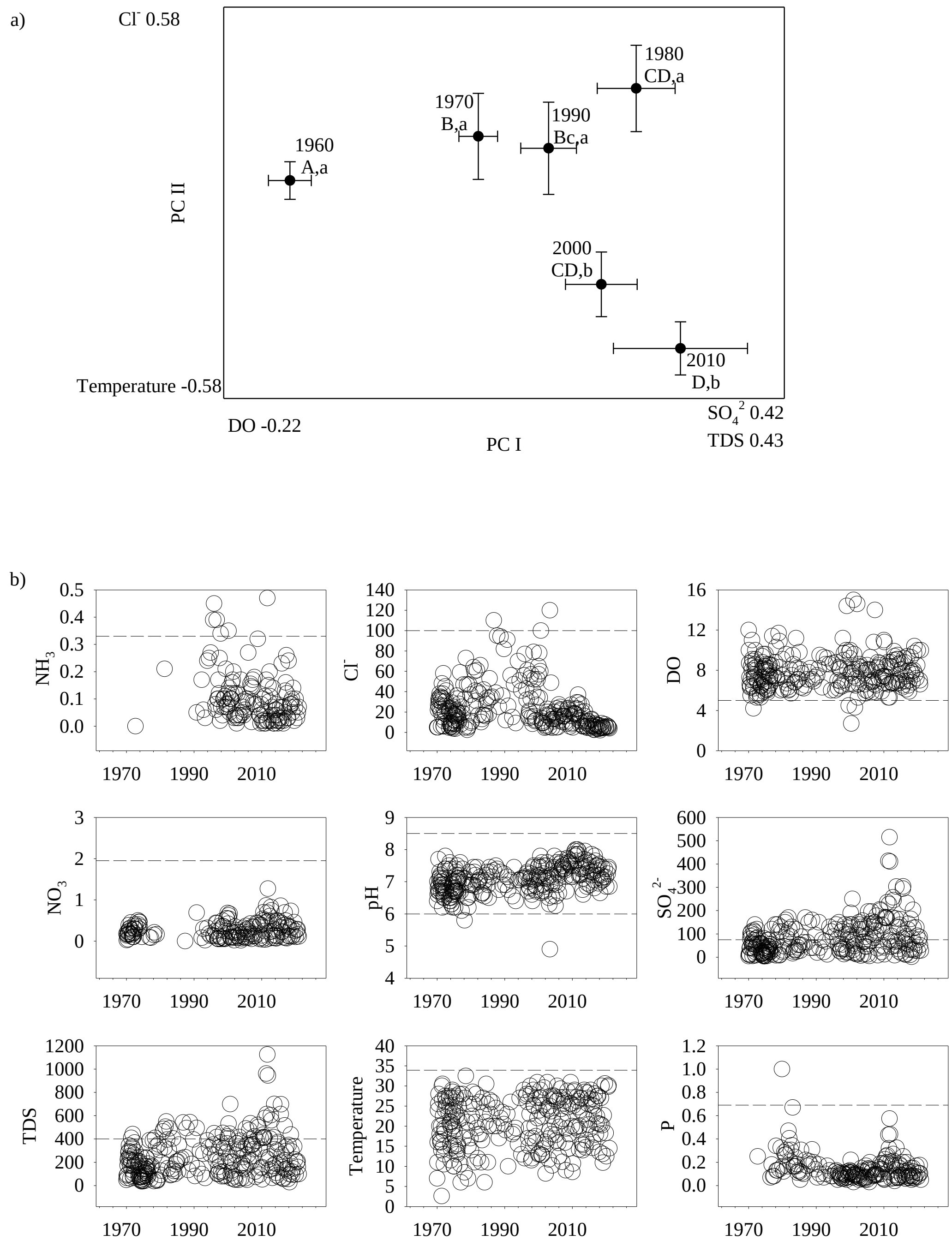

Figure 11. a) Means (black circle; ± 1 SE, whisker) of PC scores grouped by decade for water quality variables extracted from Anacoco Bayou; b) univariate plots to visually assess water quality variables in context of Texas Commission of environmental Quality screening levels (dashed lines), 1967 to 2020.

APPENDIX SECTION

Appendix 1. Mussel species name, counts, and qualitative descriptions of mussel-mesohabitat type associations observed in the Sabine River drainage using ACFOR scale: abundant (75–100% of all individuals observed), common (50–74%), frequent (25–49%), occasional (5–24%), and rare (>0–4%). Percentages listed in column titles represent the percentages of mesohabitat type available.

Scientific Name	total	Riffle (20%)	Run (37%)	Pool (30%)	Backwater (13%)
Fusconaia askewi	1906	common	frequent	rare	rare
Tritogonia verrucosa	1638	frequent	common	rare	rare
Cyclonaias pustulosa	1335	frequent	frequent	occasional	occasional
Quadrula quadrula	662	frequent	frequent	occasional	occasional
Lampsilis teres	653	occasional	occasional	common	occasional
Glebula rotundata	614	-	-	common	frequent
Plectomerus dombeyanus	516	occasional	common	common	occasional
Tritogonia nobilis	306	-	-	occasional	abundant
Truncilla truncata	258	frequent	common	-	-
Obliquaria reflexa	256	occasional	common	frequent	rare
Lampsilis hydiana	240	rare	occasional	frequent	frequent
Potamilus purpuratus	182	occasional	frequent	frequent	occasional
Pyganodon grandis	122	-	rare	frequent	common
Megalonaias nervosa	116	common	frequent	rare	-
Leptodea fragilis	108	frequent	occasional	frequent	occasional
Lampsilis satura	75	frequent	frequent	occasional	occasional
Pleurobema riddellii	57	frequent	common		-
Potamilus amphichaenus	7	common	occasional	occasional	-

Appendix 2. Mussel species name, counts, and qualitative descriptions of mussel-substrate associations observed in the Sabine River drainage using ACFOR scale: abundant (75–100% of all individuals observed), common (50–74%), frequent (25–49%), occasional (5–24%), and rare (>0–4%). Percentages listed in column titles represent the percentages of mesohabitat type available.

Scientific Name	total	Clay (3%)	Silt (27%)	Sand (30%)	Gravel (28%)	Cobble (5%)	Boulder (2%)	Bedrock (5%)	Detritus (>1%)
Fusconaia askewi	1906	rare	rare	frequent	frequent	occasional	rare	occasional	rare
Tritogonia verrucosa	1638	rare	rare	frequent	common	occasional	rare	occasional	-
Cyclonaias pustulosa	1335	occasional	frequent	occasional	frequent	occasional	rare	rare	-
Quadrula quadrula	662	rare	frequent	occasional	frequent	occasional	rare	rare	-
Lampsilis teres	653	rare	frequent	frequent	occasional	occasional	rare	rare	rare
Glebula rotundata	614	rare	abundant	rare	rare	rare	-	-	-
Plectomerus dombeyanus	516	occasional	frequent	occasional	frequent	rare	rare	rare	-
Tritogonia nobilis	306	rare	abundant	rare	rare	occasional	-	-	-
Truncilla truncata	258	rare	-	occasional	common	occasional	rare	rare	-
Obliquaria reflexa	256	occasional	occasional	occasional	frequent	occasional	rare	rare	rare
Lampsilis hydiana	240	occasional	common	occasional	rare	occasional	rare	rare	rare
Potamilus purpuratus	182	rare	frequent	frequent	frequent	rare	rare	occasional	rare
Pyganodon grandis	122	rare	abundant	rare	rare	-	-	rare	-
Megalonaias nervosa	116	rare	rare	occasional	common	occasional	rare	occasional	-
Potamilus fragilis	108	rare	frequent	occasional	frequent	occasional	occasional	occasional	-
Lampsilis satura	75	occasional	occasional	occasional	frequent	occasional	rare	rare	rare
Pleurobema riddellii	57	rare	-	occasional	common	occasional	-	rare	-
Potamilus amphichaenus	7	occasional	occasional	frequent	frequent	rare	-	occasional	-

Appendix 3: Mussel species name, counts, and qualitative descriptions of mussel-stream morphology associations observed in the Sabine River drainage using ACFOR scale: abundant (75–100% of all individuals observed), common (50–74%), frequent (25–49%), occasional (5–24%), and rare (>0–4%). Percentages listed in column titles represent the percentages of mesohabitat type available.

Scientific Name	total	Straightaway (39%)	Outside Bend (37%)	Behind Point Bar (20%)	Point Bar (4%)
Fusconaia askewi	1906	common	occasional	frequent	rare
Tritogonia verrucosa	1638	common	occasional	frequent	rare
Cyclonaias pustulosa	1335	frequent	occasional	frequent	-
Quadrula quadrula	662	frequent	occasional	frequent	rare
Lampsilis teres	653	frequent	frequent	frequent	rare
Glebula rotundata	614	rare	abundant	rare	-
Plectomerus dombeyanus	516	frequent	occasional	common	occasional
Tritogonia nobilis	306	rare	occasional	abundant	-
Truncilla truncata	258	abundant	rare	occasional	occasional
Obliquaria reflexa	256	common	frequent	occasional	rare
Lampsilis hydiana	240	occasional	frequent	common	-
Potamilus purpuratus	182	frequent	occasional	frequent	rare
Pyganodon grandis	122	occasional	rare	abundant	-
Megalonaias nervosa	116	common	occasional	occasional	-
Potamilus fragilis	108	common	occasional	frequent	rare
Lampsilis satura	75	frequent	occasional	frequent	-
Pleurobema riddellii	57	common	occasional	occasional	-
Potamilus amphichaenus	7	common	frequent	-	-

Appendix 4. Mussel species name, counts, and qualitative descriptions of mussel-stream position associations observed in the Sabine River drainage using ACFOR scale: abundant (75–100% of all individuals observed), common (50–74%), frequent (25–49%), occasional (5–24%), and rare (>0–4%). Percentages listed in column titles represent the percentages of mesohabitat type available.

Scientific Name	**total**	**edge (59%)**	**mid-channel (41%)**
Fusconaia askewi	1906	occasional	abundant
Tritogonia verrucosa	1638	occasional	abundant
Cyclonaias pustulosa	1335	common	frequent
Quadrula quadrula	662	occasional	common
Lampsilis teres	653	common	frequent
Glebula rotundata	614	occasional	abundant
Plectomerus dombeyanus	516	frequent	common
Tritogonia nobilis	306	abundant	occasional
Truncilla truncata	258	frequent	common
Obliquaria reflexa	256	frequent	common
Lampsilis hydiana	240	abundant	occasional
Potamilus purpuratus	182	common	frequent
Pyganodon grandis	122	abundant	occasional
Megalonaias nervosa	116	rare	abundant
Potamilus fragilis	108	frequent	common
Lampsilis satura	75	frequent	common
Pleurobema riddellii	57	-	abundant
Potamilus amphichaenus	7	occasional	abundant

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