DISTRIBUTION OF UNIONID MUSSELS IN THE

BIG THICKET REGION

OF TEXAS

by

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of the requirements for the degree of
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ABSTRACT

The Big Thicket located in Southeast Texas harbors the highest number of regional endemic freshwater mussel species and the highest diversity of unionid mussels in the state, including five state-threatened species. Unfortunately, mussels in this region are threatened by pollution, habitat alteration and destruction due to human impacts caused by petrochemical activities, climatic changes and urbanization. The goals of this project were to (1) survey mussels in the Big Thicket National Preserve, particularly in the poorly surveyed southern portion of the preserve, and (2) to examine historical changes in mussel communities. In addition, DNA samples were taken and the analysis of 97 mussels informed identification of ten species, some of which can be difficult to distinguish morphologically. A total of 39 sites in the Lower Neches River, Village Creek and Pine Island Bayou basins were surveyed. Historical data from 2002 (restricted to Village Creek) and 2014 were available for sub-set of these sites. The survey showed that species richness and mussel densities generally increased from upstream tributaries towards lower Village Creek and the mainstream Neches, where rare and threatened species were mostly found. Evidence for recruitment was mainly found in the backwaters of the lower Neches, which may act as a refuge during flooding. Declines between 2014 and 2018 were most severe in the parts of the Neches basin that most likely experienced the highest shear stress during flooding based on the channel morphology. Declines were also detected when data from 2002 were compared with 2014 suggesting that the exceptional drought in 2011 may have also contributed to long-term declines in Village Creek. Future studies should examine the role of backwaters for recruitment of threatened mussels.

I. INTRODUCTION

The Big Thicket of Southeast Texas is known as one of the most extraordinarily biodiverse regions in North America (Moring, 2003). Unfortunately, Big Thicket National Preserve (BTNP) is also recognized as the most at-risk of the “crown jewel” parks in the national parks system (Callicott et al., 2006). Historically the Neches River basin has seen the most extensive loss of contiguous coastal wetlands in the state of Texas. Past and continued local subsurface resource withdrawals (petrochemical, water, natural gas) have contributed to extensive wetland subsidence / compaction. The construction of a ship channel through Sabine Lake in the early 1900s, along with innumerable pipeline canals, has promoted saltwater intrusion (White & Tremblay, 1995). Presently, economic and population growth have led to planned and proposed projects that, alone and in combination with the stressors caused by global climate change, threaten the availability and quality of aquatic habitat in the Big Thicket, including the abundance and diversity of endemic freshwater mussel species.

Freshwater mussels (Bivalvia: Unionidae), which are an important component of freshwater ecosystems, are highly threatened and rapidly declining in North America (Strayer, 2008). The Neches River basin is considered to be the “hot spot” of Texas unionid diversity (Burlakova et al., 2011; Dascher et al., 2018; Howells, 2010). Six state-threatened species (STS) have been documented in the region: *Fusconaia askewi* (Texas pigtoe); *Fusconaia lananensis* (Triangle pigtoe); *Lampsilis satura* (Sandbank pocketbook); *Obovaria arkansasensis* (Southern hickorynut); *Pleurobema riddellii* (Louisiana pigtoe); and *Potamilus amphichaenus* (Texas heelsplitter) (Howells, 2010). However, recent molecular phylogenetic analysis has shown *F. lananensis* to be a junior synonym of *F. askewi* because it does not differ genetically from *F. askewi* (Pieri et al., 2018). Historical and previous surveys found that the upper portions of the BTNP include areas of exceptional mussel diversity (Howells, 1997). The lower Neches River, downstream from B. A. Steinhagen reservoir, was noted as recently as 2007 to hold the most abundant and diverse assemblage of mussels in Texas (Karatayev & Burlakova, 2007). Unfortunately, the upstream reaches of the larger streams that flow through the BTNP are heavily modified (Benke, 1990). Ford (2015) suggested that extensive amounts of water released in 2013 from B. A. Steinhagen reservoir resulted in the loss of a large mussel bed formerly documented below the dam, and that habitat along the Lower Neches River no longer appears to support the historic diverse population of mussel species.

Currently the distribution and diversity of mussels in the Big Thicket is largely unknown. To the best of our knowledge, only one freshwater mussel survey was carried out within the past ten years within the region by Ford (2015). Karatayev and Burlokova (2007) attempted to survey Village Creek but were unable to complete their work due to unsafe hydraulic conditions (velocities) from flooding. The most intensive survey of the Village Creek sub-basin to date was conducted by Bordelon and Harrel (2004).

While Ford (2015) noted that mussel diversity and abundance were highest in the backwater-type habitats of the region, with few exceptions, his selected survey sites were located at easy access locations like bridges and boat ramps. Backwater areas in the lower portions of the BTNP may act as flow refuges protecting mussels from extreme high and low flow events, and the numerous backwaters within the lower BTNP could be vital to mussel recruitment within the region. Although prior mussel surveys have been conducted in the region, none have specifically focused on backwater habitats in the lower part of the Neches basin.

Extreme climatic events may have affected the distribution and diversity of mussels in the Big Thicket during the last two decades. The storm surge from Hurricane Ike (2008) allowed saltwater to breach the Lower Neches Valley Authority (LNVA) saltwater barrier and inundate the lower reaches of the Neches River and Pine Island Bayou (Figure 1). During 2010 and 2011 the region experienced the most severe drought of record (Nielsen-Gammon, 2011). Average annual streamflow at the USGS 08041500 Village Creek gage near Kountze, Texas, fell to a record low of 84.1 cfs during 2011. Mean discharge for Village Creek from 1940 to 2017 was 899 cfs. In contrast, high rainfall in 2016 caused the largest flood ever recorded in the region at that time: the maximum daily discharge rose to 24,600 cfs. This was surpassed by high flows caused by the unprecedented precipitation during Hurricane Harvey in 2017. Daily discharge at the same station rose from a daily mean of 268 cfs on August 24, 2017, to an estimated maximum discharge of 182,000 cfs (gage failed during flood event) on August 30, 2017 (USGS, 2019). While the tropical cyclone stalled on land over the Big Thicket, Harvey inundated sections of Jefferson County, Texas, with more than 153 cm of rain between August 25-30, exceeding the annual average of ~152 cm for the region. This represents the most rainfall produced by any tropical cyclone in United States' history (NOAA, 2018). Van Oldenborgh et al. (2017) concluded that global warming made the precipitation about 15% more intense, and a similar study showed that extremely high ocean heat values, attributed to human-induced climate change, not only intensified the storm but also increased the rain amount (Trenberth et al., 2018). Although this was an extremely rare event, the occurrence of extreme rainfall events will likely increase with climate change (van Oldenborgh et al., 2017).

The objectives of this study were to: (1) survey mussels in under-sampled areas of the BTNP, particularly in the southern portion of the preserve. This region contains numerous backwaters that are likely critical to mussel recruitment within the BTNP and can potentially provide refuge from high flow events; (2) examine historical changes in mussel communities and document the response of known mussel communities to the 2011 drought and to the recent extreme flooding as a consequence of Hurricane Harvey's delivering record-breaking rain amounts (Trenberth et al., 2018). These objectives were facilitated through a comparison of surveys conducted during this study with past survey data (Bordelon & Harrel, 2004; Ford, 2015).

II. METHODOLOGY

Study Area

The Big Thicket is located in the Coastal Plains region of the Southeastern US (Figure 1, Michener et al., 1998) and generally described as the area of Southeast Texas delineated on the west by the Trinity River and on the east by the Sabine River. The Big Thicket supports one of the most biodiverse ecosystems in North America (Callicott et al., 2006) due to its location where four biomes converge: humid eastern hardwood forests, southwestern deserts, southeastern swamps, and the Central Prairie (NPS, 2017). Soils are typical of the Coastal Plain region and consist of alluvium loam and acidic clay (Hall & Harcombe, 2001). Streams in this region generally have soft, acidic, slow-moving waters surrounded by predominantly forested watersheds (> 60%) that contain moderate (< 8%) urbanization (Burlakova et al., 2011). The first preserve of the United States National Park System (NPS), the BTNP occupies sections of Hardin, Jasper, Jefferson, Liberty, Orange, Polk, and Tyler Counties, Texas, and protects over 43,790 hectares of land (NPS, 2017).

The study area encompassed ~7.4 km of the Neches River upstream of the confluence with Village Creek to ~18.2 km downstream to the confluence of Pine Island Bayou. The study area also included ~137.4 km of the Village Creek sub-basin, ~23.4 km of Pine Island Bayou and ~11 km of its tributary Little Pine Island Bayou (Figure 1).

Sampling Sites

A total of 39 survey sites distributed among six reaches in the region (Upper Village Creek Sub-basin, mid-Village Creek, lower Village Creek, Neches River, Little Pine Island Bayou, and Pine Island Bayou) were sampled between August 2017 and July 2018 (Figure 1). Three sites (triangles in Figure 1) were sampled in 2017 but were subsequently abandoned due to lack of site access from flood debris after Hurricane Harvey. The focus of this was study was on backwater habitat. Google Earth imagery was used to identify sites which did not dry out during the drought in 2011. Site accessibility further reduced the number of backwaters selected for surveys. In addition, tributaries that went dry in 2011 were not sampled. Sites for which historical survey data were available were sampled if they were within the BTNP and were accessible (15 sites of the 39 sites sampled, Figure 1). Access to sampling sites was made by motor boat, kayak, vehicle, and foot as conditions required. The length of each sample site varied between 50 and 140 meters and depended on the extent of the uniform mesohabitat type.

Sampling Mussels

At each site a minimum of 0.25 person-hours was employed for detecting mussels by tactile searches. When mussels were detected, time was extended for up to two person-hours. In general, total sampling efforts ranged between one and two person-hours based on detection of threatened, rare, small (<30 mm), and/or number of individuals conducting the search. Sampling proceeded from the shoreline outward until either the opposite bank was reached or water depths exceeded 3 meters. The length and width of the sampled area was measured with a Nikon laser range finder. The site was georeferenced and photographed. All specimens located were identified, counted, and returned to the stream. STS were photographed and shell characteristics measured (L x W x H). When mussels with exceptionally small or unique characteristics were encountered, they were also photographed and measured. After juvenile mussels were found in sediment within dead shells in backwaters of the lower Neches mainstem, sediment was rinsed from dead shells through a 500 µm mesh to detect juvenile mussels. In addition, genetic samples were collected by swabbing the mantle with a small brush and analyzed by a genetics lab (Stephen Harding and David Rodriguez, Texas State University) to inform identification of species, which can be difficult to distinguish by external morphology. The analysis of DNA from 97 mussels informed identification of ten species. Occasionally, when specimens of apparent recent mortalities were encountered, tissue was separated from the shells, preserved in ethanol and refrigerated.

Comparison with Historical Data

In order to examine historical changes in mussel communities in our study area, we compared survey data collected at the same sites from previous studies in 2014 (Ford, 2015) and 2002 (Bordelon and Harrel, 2004). Surveys in 2014 were conducted in the Village Creek sub-basin, Pine Island Bayou sub-basin and the Lower Neches River (Figure 1). Surveys in 2002 were from the Village Creek sub-basin only (Big Sandy Creek and its tributaries along with mid and lower Village Creek) only (Figure1). Several assessments were carried out by comparing sites which were surveyed during different years: 1) to assess potential impacts of drought, survey data from ten sites that were surveyed both in 2002 and 2014 (or 2017 pre-storm) were compared (available sites were restricted to the Village Creek sub-basin); 2) to assess the impact of severe flooding in 2017 due to Hurricane Harvey, survey data from 15 sites that were surveyed both in 2014 or 2017 and 2018 were compared; 3) to assess long-term changes (including impacts of drought and flooding events) survey data from ten sites that were surveyed both in 2002 and 2018 were compared (available sites were restricted to the Village Creek sub-basin). To facilitate these comparisons, the number of mussels reported in the previous surveys were normalized by search effort to number of mussels per one person-hour (p-H).

Environmental Parameters

At each sampling location, habitat was characterized as one of six mesohabitat classes: run, riffle, pool, large backwater (area > 8000 m2), medium backwater (1000 m2 > area < 8000 m2), small backwater (area < 1000 m2), mean depth, channel wetted width, and visual estimates of the percent substrate composition based on the modified Wentworth scale. In addition, adjacent land use, anthropogenic influences, presence of exotic species, percent shade, and shoreline and aquatic vegetation composition were also recorded. These data were supplemented by reach level characteristics for each stream segment with channel sinuosity, slope, structural index, mean bank slope, bank height, mean wetted channel width, mean bank-full channel width, channel incision, drainage area, and percent urbanized land use in 1990 (Moring, 2003).

III. RESULTS

Mussel Distribution

Mussel communities differed among different parts of the lower Neches River basin (Figure 2, Table 4). Species richness and mussel densities generally increased longitudinally towards the mainstem Neches River. Rare and threatened species were mostly found in the mainstem Neches and in the lower Village Creek near the confluence with the Neches River. The smallest tributaries, Big Sandy Creek in the upper Village Creek sub-basin [7.6 mussels per person-hour (mph)] and Little Pine Island Bayou (8.3 mph), displayed low species richness with only two species found in Big Sandy Creek, *Toxolasma sp.* and *Potamilus purpuratus* (Figure 2) comprising 89% and 11% of the relative abundance respectively. Little Pine Island Bayou was also dominated by *Toxolasma sp.*, comprising 76% of the relative abundance (Figure 2); whereas two other species *Pyganodon grandis* and *Lampsilis hydiana* contributed 6% relative abundance each. In total, eight species were found, but five of them only occasionally and in low numbers.

Downstream from Big Sandy Creek, mid Village Creek displayed a slight increase in overall mussel abundance (11 mph) and species abundance (11 species total). The four most abundant species were *Toxolasma sp.* (29%), *Lampsilis teres* (25%), *L. hydiana* (16%), and *F. askewi* (14%) (Figure 2). The trend of increasing mussel abundance and species richness continued within Village Creek with both increasing as distance to the Neches River decreased. Eighteen species were found in the lower reach of Village Creek. Abundance of individuals increased as well (57 mph). In addition, species richness was highest in this segment. *Amblema plicata* (23%), *Plectomerus* *dombeyanus* (17%), *L. hydiana* (13%), and *Quadrula sp.* (10% *Q. apiculata* or *Q. nobilis*) were the dominant species with the remaining species making up <10% each of the total (Figure 2). Three STS were found in this reach, contributing ≤6% each to the community composition: *F. askewi* (3%), *O. arkansasensis* (5%) and *L. satura* (6%). This segment of Village Creek was the only location where *O. arkansasensis* was documented.

Though overall abundance was high (142 mph) in Pine Island Bayou, species richness was low. Of the 12 total bivalve species noted in this reach, the salinity tolerant *Glebula rotundata* was dominate, composing 60% of the total. *Quadrula sp.* (14%) was the second most abundant with all other species representing less than 10% each of the total (Figure 2).

Overall species richness was highest in the Neches River (25 species total) and comparable to lower Village Creek. However, though overall abundance was highest (mph =154) in the Neches, species evenness was lower than that of lower Village Creek (Table 4). *Quadrula apiculata* (21%), *G. rotundata* (20%), *P. dombeyanus* (17%), and *L. teres* (9%) were the dominant species (Figure 2). Two STS were found in this reach, *L. satura* and *P. amphichaenus*. *P. amphichaenus* were found only in backwater habitats of the Neches River, including individuals that measured <30mm in length. In addition, two species noted as rare for the region, *Arcidens confragosus* and *Truncilla donaciformis*, were found only in this reach.

Associations with Environmental Factors

The increase in diversity and abundance of mussels from the mid Village Creek sub-basin to lower Village Creek (Figure 1) was associated with a considerable decline in slope (2 orders of magnitude), a slight decline in the ratio of bank-full channel width to mean wetted channel width (from 2.8 to 1.9 in the mid and lower Village Creek respectively), and a lower index of incision, signifying that lower Village Creek likely experiences less shear stress during high flow events. In addition, reach structure index as a measure of in-channel structures such as woody snags (Moring, 2003) increased from 57 in mid Village Creek to 176 in the downstream reach (Table 5). Sinuosity increased from 100 (overall lowest value) in the most upstream reach to 249 (overall highest value) in lower Village Creek (Table 5). Dominant substrate composition varied from 44% clay and 15% sand in mid Village Creek to 26% clay and 27% sand in lower Village Creek. Average channel width and average depth increased from 22.5 m and 1 m in mid Village Creek to 48 m and 1.3 m in lower Village Creek (Table 6).

At the three most downstream sites of mid Village Creek, the stream channel was relatively straight and was surrounded by high, entrenched, steep banks that appear to have been subjected to high flows and extensive erosion (Figure 3). Also, the substrate was predominately sand in this reach with very few pockets of clay or organic matter, resulting in very little suitable mussel habitat. Although channel morphology changed in the lower Village Creek, an increase in mussel abundance was observed only downstream of the three most upstream sites in the lower Village Creek. At the most upstream sites in the lower Village Creek, the stream appeared to provide very little suitable habitat. The channel was incised with few bends and backwaters within this segment. Further, this reach has been subject to strong anthropogenic influence (private residences with docks, bulkheads, other similar bank modifications, and high recreational use). Further downstream to its mouth at the Neches River, Village Creek provided suitable mussel habitat in the form of backwater areas, large bends, large logjams, clay / sand substrate, hardwood (Cypress trees), and other riparian vegetation.

Both Big Sandy Creek (upper Village Creek) and Little Pine Island Bayou had the smallest drainage areas, and average stream mean wetted width values were lower (9.4 m and 5.1 m respectively) compared to all other sites surveyed in the basin (Table 5), indicative of their upstream location within the basin (Figure 1). Both tributaries also had the highest values (4.1 and 3.5 respectively) for the ratio of mean channel wetted width to mean bank-full wetted width. In comparison, the Neches River was 0.9 (Table 5). Big Sandy Creek (upper Village Creek) displayed the lowest reach sinuosity value (100) of all stream segments and the 0.055 channel incision index (compared to 0.011 in lower Village Creek) was the highest of all segments (Table 5). However, both tributaries were rated with a relatively high USGS structure index (300 and 182 for upper Village Creek and Little Pine Island respectively), and both displayed a comparable substrate mixture of clay (30%), sand (29%), roots (19%), and woody debris (10%). Similarly, substrate at Little Pine Island was also dominated by clay (33%), woody debris (25%), and leaf litter (15%) (Table 6). However, at the two downstream sites in Little Pine Island Bayou, the first 16 cm of substrate depth was composed of 90% dead mussel shells (mostly unionid mussels) and 10% small wood debris, leaf litter, and golf balls.

In contrast, the Lower Neches River section, which occupies the largest drainage area (23600 km2) in the region, exhibited the greatest channel width (96.5 m) while maintaining a moderate (0.047) slope value (Table 5). It should be noted that while the highest diversity and abundance of mussels (also the largest number of smaller individuals/recruits) occurred at sites in this segment, all sites were in slack-water areas off the main channel. Substrate was characterized by large amounts of woody debris (10-40%) and emergent vegetation (0-15%) within the backwater sites. Although the Neches mainstem displayed the lowest bank-full to wetted width ratio (0.918), the mainstem Neches had higher current velocities, a structure index of 0, substrates almost exclusively consisting of coarse sand with a few pockets of clay, and water depths >12 m, suggesting the mainstem likely experienced more shear stress than "backwater" areas.

The Pine Island Bayou section also had a structure index of 0, but it displayed higher values for both incision (0.04) and bank height (7.5) (Table 5). The reach sinuosity (177) was high and only surpassed by that of lower Village Creek (249) and the adjacent portion of the Neches River (178) (Table 5). Though the riparian corridor was heavily vegetated and the littoral zone contained plentiful emergent vegetation including cypress trees (variables usually associated with mussel beds in the region), the substrate composition in Pine Island Bayou contained the highest percentage of silt (17%) of all stream segments and a large amount of leaf litter (9%), conditions known to lead to anoxic conditions in this bayou, particularly in times of low flow (Kleinsasser & Linam, 1987).

Overall signs of erosion were high throughout the study area, especially in sections where riparian vegetation was lacking or was mainly composed of pine trees, but little or no erosion was detected in sections (mostly those of the Neches River backwaters, Pine Island Bayou, and Lower Village Creek) that were comprised of Cypress trees. In all sections monitored by USGS there has been little urban development (2.2 to 0.63%).

Temporal Changes in Mussel Communities

Assessing the impact of drought: 2002-2014 - Village Creek Sub Basin

Ten of the sites surveyed in 2014 were also surveyed in 2002, though all sites were confined to the Village Creek sub-basin. Both species richness and mph were significantly lower in 2014 compared to 2002 (Table 1), but it should be noted that the search effort in 2014 was also lower compared to 2002 (11.2 and 21.8 p-H search effort in 2014 and 2002 respectively). Species richness (mean ± SD) declined from 7.7 ± 3.4 species in 2002 to 3.9 ± 3.6 species in 2014, and the average number of mussels (mean ± SD) decreased from 51.8 ± 48.7 mph (range: 0.4-177 mph) in 2002 to 15.7 ± 31 mph (range 0-106 mph) in 2014.

In 2014 *F. askewii* remained a dominant species, but the proportion *of Quadrulini* species (such as *C. mortoni*) declined considerably (Table 7). Instead, a higher proportion of *Lampsilis hydiana* (7% vs. 5% in 2002) and *P. dombeyanus* was found (18% vs. 2% in 2002) (Table 7). In 2002, four STS were found: *F. askewi* (8 sites), *L. satura* (1 site), *P. riddellii* (3 sites), and *O. arkansasensis* (1 site). *P. riddellii* was not found in 2014, but three other STS--*F. askewii* (five sites), *O. arkansasensis* (two sites), and *L. satura* (one site)--were. In both years, all STS except *F. askewi*, were found in low numbers (1% or less each of the total).

Assessing the impact of flooding: 2014-2018

Fourteen of the sites surveyed in 2018 (total search effort: 13.6 p-H) were also surveyed in 2014 (total search effort:14.9 p-H). Eight sites were located in the Village Creek sub-basin, one site in the Neches River and five sites in the Pine Island Bayou sub-basin (Table 2).

Pine Island Bayou. Both overall species' richness and individual abundances doubled in the Pine Island Bayou sub-basin from 2014 to 2018 (Table 2), except for one site where no individuals were found in 2018. Though species' richness increased slightly at the most upstream site in the sub-basin, the greatest decrease in abundance (>5 times) was seen here. At the four sites in Pine Island Bayou, *F. askewi* (52%) and *P. dombeyanus* (39%) dominated the community composition, and *P. grandis, Q. apiculata, Toxolasma sp., L. teres*, and *Leptodea fragilis* composed <5% each of the total in 2014 (Table 8). In contrast, in 2018 *G. rotundata* was the most dominant species (60%); *Quadrula sp*. (15%), and *P. dombeyanus* (8%) were dominant with the remaining species making up 5% or less of the total (Table 8). It should be noted that *G. rotundata* was not reported in 2014 and that no *F. askewi*, the dominant species in 2014, were found in 2018. The identification of *G. rotunda* was confirmed by DNA analysis, but no DNA analyses were done in 2014. Thus *G. rotunda* in 2018 was misidentified in 2014 as *F. askewi* because they look morphologically similar especially when they are small.

Village Creek. A different pattern emerged when comparing sites in the Village Creek sub-basin. While search efforts were similar (8.2 vs. 7.5 p-H in 2014 and 2018 respectively), species' richness decreased at six out of eight sites surveyed in both years and stayed constant at two sites in upper Village Creek (Table 2). Only *Toxolasma sp.* were found in 2018.

No mussels were found in 2018 at four sites where mussels were found in moderate to high abundances in 2014 (Table 2), including STS *O. arkensensis, F. askewi,* and *L. satura.* Two of these sites were located near bridges; one of the bridges was destroyed during the flooding in 2017 (Figures 6 and 7). The extreme flooding in 2017 and associated scour decimated what was formerly the largest documented bed of *Fusconaia sp.* in the region and at which other STS (*L. satura* and *O. arkansasensis*) were collected in 2014 (Ford, 2015).

One site in mid Village Creek was surveyed before and after the flooding from Hurricane Harvey in 2017, and species' richness declined from 11 to 8 species, whereas abundance increased slightly from 39 to 50 mph. No STS were found at this site post Harvey, although two STS (*F. askewi* and *O. arkansasensis*) were noted in 2017. An attempt by kayak was made to resurvey additional sites established during this study before the 2017 flooding event. The other sights were not accessible due to extensive downed trees, logjams, and shifted sandbanks not noted pre-flood at the sites sampled in 2017.

Neches River Site. The survey in 2018 found considerably more species (16 species, including STS *L. satura*) at the Neches River site compared to 2014 (7 species) and abundances were also ten times higher (Table 2). In 2014, the dominant species were *L. teres* (48%) and *P. dombeyanus* (29%), and in 2018 *P. dombeyanus* (22%), *Q. apiculata* (21%), and *G. rotundata* (17%) were dominant. One individual of the STS *L. satura* was found in 2018. No *F. askewi* were found in the Neches River in 2018. It is likely that *G. rotunda* was misidentified as *F. askewi* in 2014 as they look morphologically similar (see above).

Assessing long-term changes

Nine sites that were surveyed in the Village Creek sub-basin in 2018 were also surveyed in 2002 (Bordelon & Harrel, 2004), and considerable declines in both species' richness and abundance were detected in seven out of the nine sites (Table 3). The most drastic declines in species' richness occurred in the upper and mid Village Creek sub-basin, where no mussels were found at one site that previously contained 10 species, and only 1-2 species were found at three other sites where 9-13 species were found in 2002 (Table 3). Mean per site abundance declined from 79 mph 2002 to 18 mph in 2018. Species' richness and abundance increased at two sites in lower Village Creek, where 15 species were found in 2018, but only 6 to 9 species in 2002, and abundance nearly doubled by 2018 (Table 3).

In 2002 at the most upstream site in this comparison, *F. askewi* and *Toxolasma sp.* dominated the community composition, and STS *P. riddellii* (1%) was also noted. At the same site in 2018, six individual *Toxolasma sp.* were the only living mussels found. In the mid reach of Village Creek, *C. mortoni* (37%), *F. askewi* (24%), and *Toxolasma sp*. (21%) were dominant in 2002, and the presence of STS *L. satura, O. arkansasensis* and *P. riddellii* were documented. In 2018 only four individual mussels composed of two species, *Toxolasma sp.* (75%) and *L. hydiana* (25%), were found among two sites. No STS were found at this reach in 2018.

In the lower reach of Village Creek, *F. askewi* (30%), *C. mortoni* (32%), *Toxolasma sp.* (11%), *A. plicata* (8%), *L. hydiana* (6%), and *Q. nobilis* (5%) were abundant in 2002. In 2018 most of the same species--*A. plicata* (21%), *L. hydiana* (12%), *Toxolasma sp.* (12%), and *Quadrula sp.* (7%)--remained abundant, where the relative abundance of *P. dombeyanus* increased (19% in 2018) and *F. askewi* decreased (4% in 2018). In addition, STS *L. satura* and *O. arkansasensis* were found in 2002 and 2018, but *P. riddellii* (<1%) only in 2002 (Table 9). The absence of *P. riddellii* and the increase in *P. dombeyanus* was also observed at a site surveyed in 2002 and pre-storm in 2017.

IV. DISCUSSION

This is the first study to assess changes in mussel communities following record flooding from a tropical cyclone. The effects on the mussel community from these types of events can vary according to the hydraulic properties of a stream and its basin (Hastie et al., 2003). The most severe declines occurred in the Village Creek sub-basin, which most likely experienced the highest shear stress during flooding based on the channel morphology (see below). The post-hurricane survey showed that species richness and mussel abundance generally increased from upstream tributaries toward lower Village Creek and the mainstem Neches River. Rare and threatened species were mostly found in the lower Village Creek and lower Neches River, especially in backwaters, which also showed signs of recruitment. The backwaters in the lower Neches basin likely act as important refuge during floods (Moriarty & Winemiller, 1997) and conservation efforts should focus on protecting these habitats.

Furthermore, the importance of backwater habitats for recruitment was supported by the presence of small unionids ranging from <5 mm to <30 mm in length in backwaters of the lower Neches River (25 individuals were found), indicating recent recruitment for several species including *P. amphichaenus*. By closely examining the sediment built up on the inside of the valves of dead mussels by rinsing in a fine mesh bag, extremely small (to <5mm) living unionids were detected, including several that are likely the smallest documented specimens of the species for *P. amphichaenus* (Figure 4) and *L. hydiana* (Figure 5). It appears this is the first time this technique has been used to locate individuals of small size. With the number of small individuals found inside of and / or attached to the valves of large, dead individuals, it seems very small unionids may receive protection and refuge in such locations. Furthermore, given the small size, it appears that the STS *P. amphichaenus* is reproducing in the lower Neches River. Future studies should focus on unionid mussel recruitment within backwater habitats of the Lower Neches River basin.

One threat for these backwater habitats is severe drought, such as the one that occurred in 2011. Previous studies have shown that droughts can increase mortality and decrease mussel richness (Gagnon et al., 2004; Golladay et al., 2004; Haag & Warren, 2008; Sousa et al., 2018). There is anecdotal evidence indicating that several backwaters and stream segments were dry or near dry in 2011. During droughts, mussels can be subjected to thermal stressors and, as water levels decrease, can become stranded on dry land where they are exposed to terrestrial predation and desiccation (Archambault et al., 2014; Bond et al., 2008; Walters & Ford, 2013). Declines in mussel species richness and abundance were detected when data from 2002 were compared with data from 2014, suggesting that the exceptional drought in 2011 negatively impacted the mussel community.

Since the historical mussel surveys in 2002, not only have extreme dry years (2011, the second driest year of record since recording began in 1901) and warm years (2012 and 2016, sixth and third warmest year respectively) occurred, but also extreme wet years (2017, 2018, the first and second wettest years on record respectively) took place (NWS, 2019). Although mussels may evade high-flow events by burrowing into the substrate (Schwalb & Pusch, 2007), during extreme high-flow events stream bed components, including benthic fauna, can become dislodged and transported downstream. Major floods are assumed to have an adverse effect on unionid populations, although few studies have examined these effects (Hastie et al., 2001; Strayer, 1999; Vaughn and Taylor, 1999; Watters, 1999). In a study of the effects of a 100-year flood on a well-documented freshwater mussel population, Hastie et al. (2001) noted a total mortally of ~50,000 individual mussels, and some transects suffered a loss of at least 40% of the population resulting from the flood. Hurricane Harvey provided an opportunity to aid our comprehension of the role major flooding plays in shaping stream habitat and how its impacts can differ across a basin due to differences in geomorphology. While we found a decline in Village Creek, we detected an increase at most sites in Pine Island Bayou. Interestingly, mussels in Pine Island Bayou showed marks of physical damage, which may have occurred during downstream transport during the flooding, and the increase could be the results of dispersal from upstream.

Because of the BTNP, much of the floodplain and riparian area in the Lower Neches basin is heavily forested and undisturbed. Exceptions exist where physical structures like highways, bridges, and culverts alter overland and in-channel flow. In such locations (example, US 96 bridge at Village Creek), we observed amplified damage from erosion resulting in damage to the stream bed and to mussel communities (Figure 6 and 7). High flows can alter the stream channel and cause the loss of mussel beds at such locations through scour or by depositing sediment onto mussel habitat. Field observations and channel morphology characteristics indicate that shear stress was high throughout the Village Creek sub-basin. Accordingly, the most severe mussel population declines occurred here with both species' richness and abundance increasing as distance to the mainstem of the Lower Neches River decreased. This is likely due to the high degree of connection between the Lower Neches and its floodplains.

Stream segments in the upper portions of the Village Creek sub-basin are relatively straight and surrounded by rather steep banks in addition to being shallow and narrow; erosion was observed at study sites in this part of the basin. Shear stress in this part of the basin is likely much higher, which has been shown to limit mussel abundance (Gangloff & Feminella, 2007). The lack of connected backwater habitats resulted in the absence of refugia and likely low survival of mussel communities. Around the area of Village Creek State Park and downstream to the Neches River, the stream contained ample large wooded debris and was well connected to the densely forested floodplain. These conditions likely decreased bed scour during the catastrophic flooding events. This section appeared to be the only part of Village Creek that still contained dense patches of mussel beds. Log-jams may provide additional local flow refuges, which are often the only stable instream structures in Coastal Plain streams (Michener et al., 1998). Mussels were often found downstream of log-jams, and *P. amphichaenus* was often found in log-jams.

Degraded water quality seemed to restrict the abundance of mussels in other parts of the Neches River basin. For example, the lack of mussel diversity and abundance in Little Pine Island Bayou was likely due to multiple upstream effluent outflows, a lack of flow, and a high organic load from the surrounding riparian vegetation making it unsuitable for many species of mussels. Species such as *Utterbackia imbecellis* found here are more adapted for lentic environments (Haag, 2012). Near the most upstream site in Little Pine Island Bayou, surface dissolved oxygen levels as low as 2.17mg/L have been recorded during times of high temperatures (Kleinsasser & Linam, 1987).

Similarly, Pine Island Bayou seemed to provide suitable habitat for mussels

(Ford, 2015), but did not support the diversity of species seen in the similarly sized reach of Village Creek. Given the history of water quality issues in this section of the Lower Neches River basin, the absence of mussels is not surprising. Predating pollution abatement, the lower reach of Pine Island Bayou and the far downstream portion of the Neches River (downstream from the mouth of Village Creek to Sabine Lake) was the second most polluted waterway in the state and considered a dead zone. At times, due to upstream abstraction and flow diversions, the only notable current was either a result of effluent released upstream or of tidal action (Harrel & Smith, 2002). As a consequence of the establishment and enforcement of state and federal water quality regulations in the 1970s, the water quality improved, and by the mid-1980s the reach began to support a diverse macrobenthic assemblage (Harrel & Hall, 1991). However, Pine Island Bayou presently remains listed as a 303(d) stream segment by the Texas Commission on Environmental Quality (TCEQ), indicating that it is an impaired waterway not meeting criteria for aquatic life due to continued reports of low dissolved oxygen (TCEQ, 2019). In contrast, several of the Neches River sites established in 2018, that are downstream of Village Creek but upstream of the mouth of Pine Island Bayou, were found to support dense and diverse unionid populations (including rare and STS).

Another limiting factor and threat for mussels in the lower Neches River basin is saltwater intrusion. As few unionid mussel species can tolerate high levels of salinity, survey sites were restricted to the stream reaches upstream of the saltwater barrier. Interestingly, in 2018, *G. rotundata*, a species known to be tolerant of brackish water, was the most abundant species in the Pine Island Bayou sub-basin. In addition, *Rangia cuneata* (Atlantic Rangia), an estuarian bivalve species that requires saline water to complete transformation through the larval stage (Hopkins et al., 1973), has historically occupied this reach and the adjacent reach of the Neches River (Darville & Harrel, 1980). Some smaller individuals of *R. cuneata* were noted in this reach in 2018, but not 2014, which may indicate a recent spread triggered by saltwater intrusion.

The synergistic effects of interior wetland subsidence and shoreline erosion have caused the Neches River basin to be subject to the most extensive loss of contiguous coastal wetlands in the state, including those of the lower Neches River (White & Tremblay, 1995). These wetlands compose the backwaters refuges where rare and threatened species (along with signs of recruitment) were predominantly found in this study. These backwaters may act as crucial refuges for extreme climatic events such as the recent Hurricane Harvey. Unfortunately, the likelihood of a similar event happening in the future has increased as anthropogenic activities (mainly greenhouse gas emissions) continue to amplify the effects of climate. During the last century, precipitation intensity along the Gulf Coast increased by 15% while the return period of extreme weather events decreased, making such events three or more times more likely to occur (van Oldenborgh et al., 2017). In order to protect threatened mussels in this region, it will be crucial to protect these wetlands and to carefully evaluate the impacts of infrastructure and oil and gas operations in the region.

Table 1. *Changes in species richness, number of mussels per person hour and sampling effort at study sites sampled in 2002 and 2014.*

	Species richness			# individuals / p-H			Sampling effort	
Reach	2002	2014	Change	2002	2014	Change	2002	2014
UVC	4	0	-4	20	0	-20	1.5	1.3
UVC	1	0	-1	0.4	0	-0.4	2.3	1.3
UVC	4	2	-2	20.5	2	-18.5	2	1.3
UVC	8	3	-5	16.7	2.3	-14.4	3	1
UVC	9	1	-8	43.7	0.8	-42.9	3	0.7
MVC	9	10	1	26.5	14	-12.5	2	1.1
MVC	9	2	-7	73.3	0.9	-72.4	1.5	0.8
MVC	10	7	-3	56	6.1	-49.9	2	1.16
MVC	13	4	-9	177	25	-152	3	1.1
LVC	10	10	0	84	106	22	1.5	1.4
M	7.7	3.9	-3.8	51.8	15.7	-36.1	2.2	1.1
SD	3.4	3.6	3.2	48.7	31	46.1		
						Sampling effort (p-H)	21.8	11.2

Note. Upper Village Creek= UVC, Mid Village Creek= MVC, Lower Village Creek= LVC

Table 2. *Changes in species richness, number of mussels per person hour and sampling effort at study sites sampled in 2014 and 2018.*

	Species richness			# individuals / p-H			Sampling effort	
Reach	2014	2018	Change	2014	2018	Change	2014	2018
UVC	2	0	-2	1.5	0	-1.5	0.7	1
UVC	1	1	0	0.8	6	5.2	0.7	0.5
UVC	0	0	0	0	0	0	1.3	1
MVC	6	5	-1	13.3	21	7.7	0.8	1
MVC	4	0	-4	7	0	-7	1.1	1
MVC	7	0	-7	6.1	0	-6.1	1.1	1
MVC	4	2	-2	25	3	-22	1.1	1
LVC	10	0	-10	106	0	-106	1.4	1
Neches	7	16	9	27	300	273	1	2
LPI	2	3	1	77.5	14	-63.5	1.3	1
PIB	2	10	8	32	132	100	0.5	0.5
PIB	4	8	4	7.7	66	58.3	1.3	0.8
PIB	1	0	-1	17.7	0	-17.7	1.3	1
PIB	2	6	4	15.9	84	68.1	1.3	0.8
M	3.7	3.6	-0.1	24.9	44.7	19.9	1.1	1
SD	2.8	4.7	5	31.8	80.9	86.8		
				Sampling effort (p-H)			14.9	13.6

Note. Upper Village Creek= UVC, Mid Village Creek= MVC, Lower Village Creek= LVC, Little Pine Island Bayou= LPIB, PIB= Pine Island Bayou

Table 3. *Changes in species richness, number of mussels per person hour and sampling effort at study sites sampled in 2002 and 2018 and sites sampled in 2002 and 2017.*

	Species richness			# individuals / p-H			Sampling effort	
Reach	2002	2018	Change	2002	2018	Change	2002	2018
UVC	9	1	-8	43.7	6	-37.7	3	0.5
MVC	10	0	-10	56	0	-56	1.2	1
MVC	13	2	-11	177	3	-174	3	1.3
MVC	13	1	-12	37.3	1	-36.3	3	2
LVC	10	0	-10	84	0	-84	1.5	1
LVC	10	4	-6	76.5	17	-59.5	2	1
LVC	6	15	9	38	98	60	2	1
LVC	9	7	-2	80.7	9.5	-71.2	1.5	1
LVC	9	15	6	55.3	98	42.7	1.5	1
M	10	4.1	3.4	78.5	18.3	-47.4	2.1	1.1
SD	2.3	5	6.8	44	33	64		
				Sampling effort (p-H)			18.7	9.8
	2002	2017		2002	2017		2002	2017
MVC	11	8	-3	39	50	11	1	1
MVC	12	11	-1	71	50	-21	2	1.5
LVC	13	10	-3	53	18.2	-34.8	3	3
M	11.7	7.3	-4.3	61.5	23.1	-38.4	2.22	1.8
SD	1.2	4.5	3.4	7.4	20.3	15.9		
				Sampling effort (p-H)			7.0	5.5

Note. Upper Village Creek= UVC, Mid Village Creek= MVC, Lower Village Creek= LVC

Table 4. *Number of mussel species found in different segments of the Neches River basin in 2018 and their relative abundance (%).*

Species	% UVC	% LPIB	% MVC	% LVC	% PIB	% LNR
*Fusconaia askewi**	0.0	0.0	16.0	3.2	0.0	0.0
*Lampsilis satura**	0.0	0.0	0.0	5.9	0.0	0.6
*Obovaria arkansasensis**	0.0	0.0	0.0	5.3	0.0	0.0
*Potamilus amphichaenus**	0.0	0.0	0.0	0.0	0.0	0.6
Amblema plicata	0.0	0.0	1.3	21.2	1.8	4.0
Utterbackiana suborbiculata	0.0	0.0	2.7	0.0	0.0	0.2
Arcidens confragosus	0.0	0.0	0.0	0.0	0.0	0.4
Glebula rotundata	0.0	0.0	0.0	0.6	60.1	19.8
Lampsilis hydiana	0.0	6.1	8.0	15.0	0.4	1.8
Lampsilis teres	0.0	0.0	28.0	5.6	1.1	8.6
Leptodea fragilis	0.0	0.0	0.0	0.6	0.7	0.6
Ligumia subrostrata	0.0	1.5	0.0	0.6	0.0	0.0
Megalonaias nervosa	0.0	0.0	0.0	0.0	0.0	1.5
Obliquaria reflexa	0.0	0.0	0.0	0.3	0.0	4.2
Plectomerus dombeyanus	0.0	0.0	1.3	15.6	7.8	17.1
Potamilus purpuratus	10.5	0.0	2.7	5.3	0.0	4.0
Pyganodon grandis	0.0	6.1	5.3	0.0	2.5	2.6
Quadrula apiculata	0.0	3.0	0.0	0.3	2.1	21.4
Cyclonaias mortoni	0.0	0.0	2.7	1.2	0.0	0.8
Quadrula nobilis	0.0	0.0	0.0	0.0	0.0	4.4
Cyclonaias nodulata	0.0	0.0	0.0	0.0	0.0	1.2
Quadrula sp.	0.0	0.0	0.0	9.4	14.5	2.9
Tritogonia verrucosa	0.0	3.0	6.7	0.6	0.0	0.1
Toxolasma	89.5	78.5	25.3	7.6	4.9	2.9
Truncilla donaciformis	0.0	0.0	0.0	0.0	0.0	1.0
Uniomerus tetralasmus	0.0	3.0	0.0	0.0	0.0	0.0
U. imbecillis	0.0	1.5	0.0	0.0	0.0	0.1
Unknown	0.0	0.0	0.0	1.8	3.2	0.2
***Rangia cuneata*	0.0	0.0	0.0	0.0	1.1	0.1
Individuals per p-H	7.6	8.3	10.7	56.7	141.5	154.4

Note. *indicates state-threatened species, **indicates non-unionid bivalve, UVC=Upper Village Creek, LPIB= Little Pine Island Bayou, MVC= Mid Village Creek, LVC= Lower Village Creek, PIB= Pine Island Bayou

Table 5. *USGS (2003) environmental characteristics at study sites by defined reaches.*

Reach	Reach slope	Mean bank slope	Mean wetted channel width (m)	Mean bank-full channel width (m)	Channel ratio	Drainage area (km2)	Land-use: % urban (1990s)	Channel incision	Bnk hgt (m)	Reach sinuosity	Structure index
UVC	1.65 x 10-5	0.074	11.8	21.9	1.856	280	0.63	0.055	3.7	100	300
UVC	1.95 x 10-4	0.082	9.36	38.7	4.135	389	0.78	0.026	3.3	155	197
MVC	6.95 x 10-5	0.094	8.51	23.9	2.808	700	0.98	0.047	3.6	174	157
MVC	1.22 x 10-4	0.074	23.4	36.3	1.551	838	1.01	0.044	5.6	125	57.2
LVC	7.79 x 10-6	0.053	41	78.2	1.907	1120	1.75	0.011	4.1	249	176
NR	6.44 x 10-5	0.047	67.4	91.8	1.362	20400	1.8	0.025	6.0	145	0
NR	3.20 x 10-5	0.065	96.5	88.6	0.918	23600	1.82	0.029	7.2	178	0
LPIB	1.34 x 10-4	0.067	5.1	17.8	3.49	239	0.92	0.032	2.2	172	182
PIB	1.06 x 10-5	0.079	40.9	58.7	1.435	1620	2.2	0.039	7.5	177	0

Note. Upper Village Creek= UVC, Mid Village Creek= MVC, Lower Village Creek= LVC, Little Pine Island Bayou= LPIB, PIB= Pine Island Bayou, NR= Neches River

Table 6. *Percent substrate composition, width and depth within study reaches*

Reach	% Substrate composition: Clay	Silt	Sand	Gravel	Cobble	Roots	Other	Shell	Leaflitter	Wooded debris	Ave W (m)	Ave D (m)
PIB	33	17	9.8	2.5	1.3	12	2.5	4.4	9.0	10	62	0.9
LPIB	33	0	5	2.5	2.5	6.3	0	12	15	25	13	0.7
LVC	26	9.5	27	4	4	16	2	0.2	3.5	7.9	48	1.3
MVC	44	7.8	15	0	0	11	0.3	3.1	7.5	11	22.5	1
UVC	30	7.5	29	5	0	19	0	0	0	10	16	1.5
NR	30	7.5	18	0	0	0	0	15	5	25	90	1
NR	31	2.9	22	0	0	7.9	0	10	7.9	18	102	1.1

Note. Upper Village Creek= UVC, Mid Village Creek= MVC, Lower Village Creek= LVC, Pine Island Bayou, Little Pine Island Bayou, NR= Neches River

Table 7. *Comparison of relative abundance (%) of mussels in Village Creek between 2002 and 2014.*

Species	% 2002	% 2014	Change
*Fusconaia askewi**	35.9	48.4	12.5
*Lampsilis satura**	0.3	0.4	0.2
*Obovaria arkansasensis**	0.4	1.1	0.7
*Pleurobema riddellii**	0.5	0.0	-0.5
Amblema plicata	10.2	4.0	-6.2
Lampsilis hydiana	4.7	7.2	2.4
Lampsilis teres	2.7	0.9	-1.8
Leptodea fragilis	0.0	1.0	1.0
Obliquaria reflexa	0.4	1.3	0.9
Plectomerus dombeyanus	1.8	17.5	15.7
Potamilus purpuratus	0.1	0.0	-0.1
Pyganodon grandis	0.0	0.2	0.2
Cyclonaias mortoni	31.3	4.3	-27.0
Quadrula nobilis	6.1	0.0	-6.1
Tritogonia verrucosa	0.7	0.0	-0.7
Toxolasma	4.8	9.9	5.1
Uniomerus tetralasmus	0.2	1.1	0.9
Unknown	0.0	2.7	2.7
Individuals per p-H	51.8	15.7	

Note. *indicates state-threatened species

Table 8. *Comparison of relative abundance (%) of mussels in Pine Island Bayou between 2014 and 2018.*

Species	% 2014	% 2018	Change
*Fusconaia askewi**	52.4	0.0	-52.4
Amblema plicata	0.0	1.8	1.8
Glebula rotundata	0.0	60.0	60.0
Lampsilis hydiana	0.0	0.4	0.4
Lampsilis teres	4.5	1.1	-3.4
Leptodea fragilis	0.8	0.7	-0.1
Plectomerus dombeyanus	39.1	7.8	-31.4
Pyganodon grandis	1.0	2.5	1.4
Quadrula apiculata	1.0	2.1	1.1
Quadrula sp.	0.0	14.5	14.5
Toxolasma	1.0	4.9	3.9
Uniomerus tetralasmus	0.0	0.0	0.0
Unkown	0.0	3.2	3.2
***Rangia cuneata*	0.0	1.1	1.1
Individuals per p-H	18.3	141.5	

Note. *indicates state-threatened species, **indicates non-unionid bivalve

Table 9. *Comparison of relative abundance (%) of mussels in Village Creek between 2002 and 2018.*

Species	% 2002	% 2018	Change
*Fusconaia askewi**	29.5	2.8	-26.7
*Lampsilis satura**	1.8	5.1	3.3
*Obovaria arkansasensis**	0.5	4.6	4.1
*Pleurobema riddellii**	0.4	0.0	-0.4
Amblema plicata	7.1	18.7	11.6
Utterbackiana suborbiculata	0.0	0.5	0.5
Glebula rotundata	0.0	0.5	0.5
Lampsilis hydiana	6.8	12.8	6.0
Lampsilis teres	2.9	9.7	6.8
Leptodea fragilis	0.6	0.5	-0.1
Ligumia subrostrata	0.0	0.5	0.5
Obliquaria reflexa	0.3	0.3	0.0
Plectomerus dombeyanus	1.5	13.8	12.3
Potamilus purpuratus	0.3	4.6	4.4
Pyganodon grandis	0.0	1.0	1.0
Quadrula apiculata	0.0	0.3	0.3
Cyclonaias mortoni	31.7	1.5	-30.2
Quadrula nobilis	5.0	0.0	-5.0
Quadrula sp.	0.0	8.2	8.2
Tritogonia verrucosa	0.3	0.5	0.2
Toxolasma	11.4	12.3	1.0
Unkown	0.0	1.5	1.5
Individuals per p-H	72.0	39.0	

Note. *indicates state-threatened species

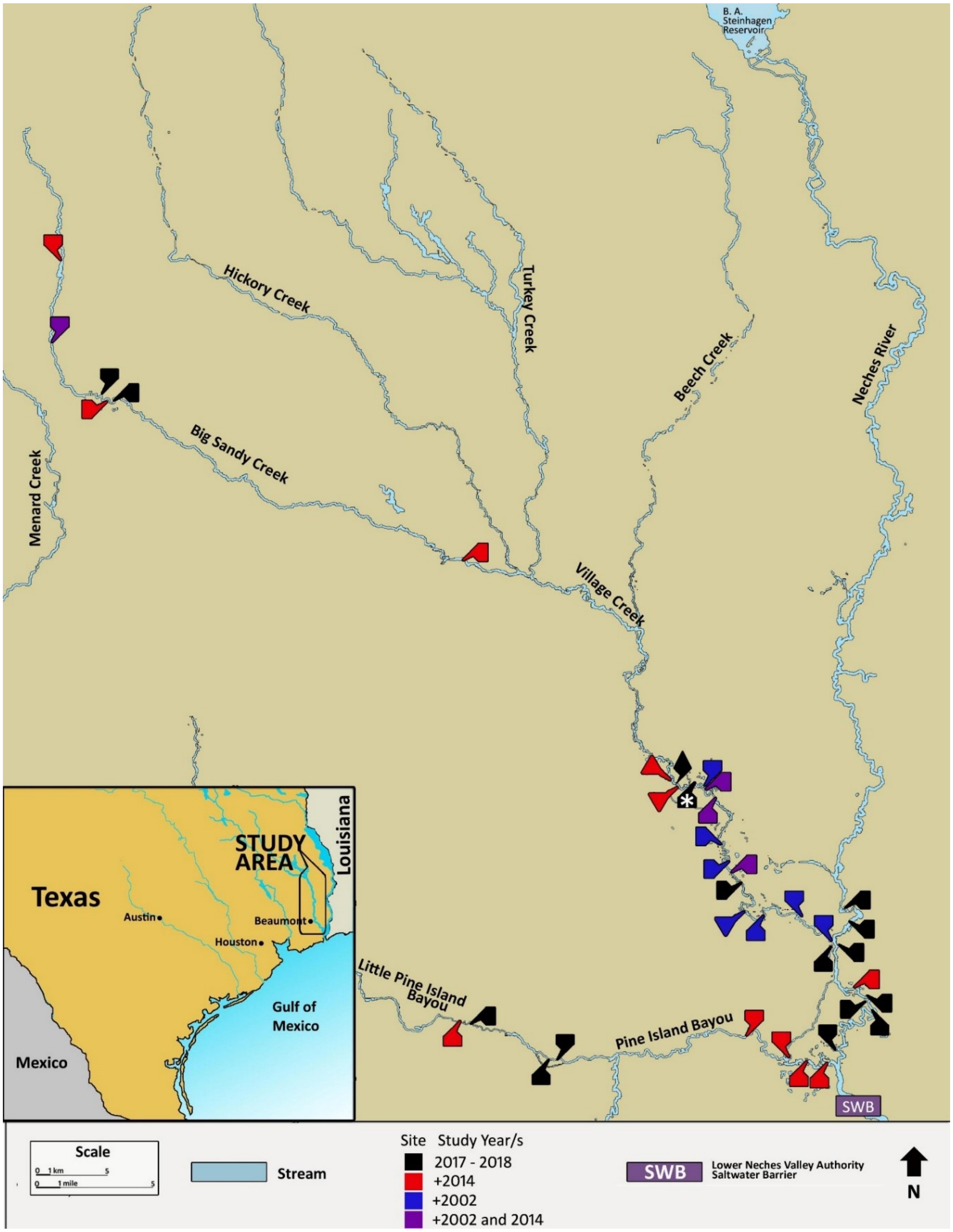

Figure 1. *Study region and 39 sampling sites in the lower Neches River basin. Black labels indicate sites sampled in this survey only (2017-2018). Triangles indicate sites sampled in 2017. An asterisk indicates a site which was sampled in 2017 and 2018. Blue labels: historical data available for 2002; red labels: historical data available for 2014; purple labels: historical data available for 2002 and 2014.*

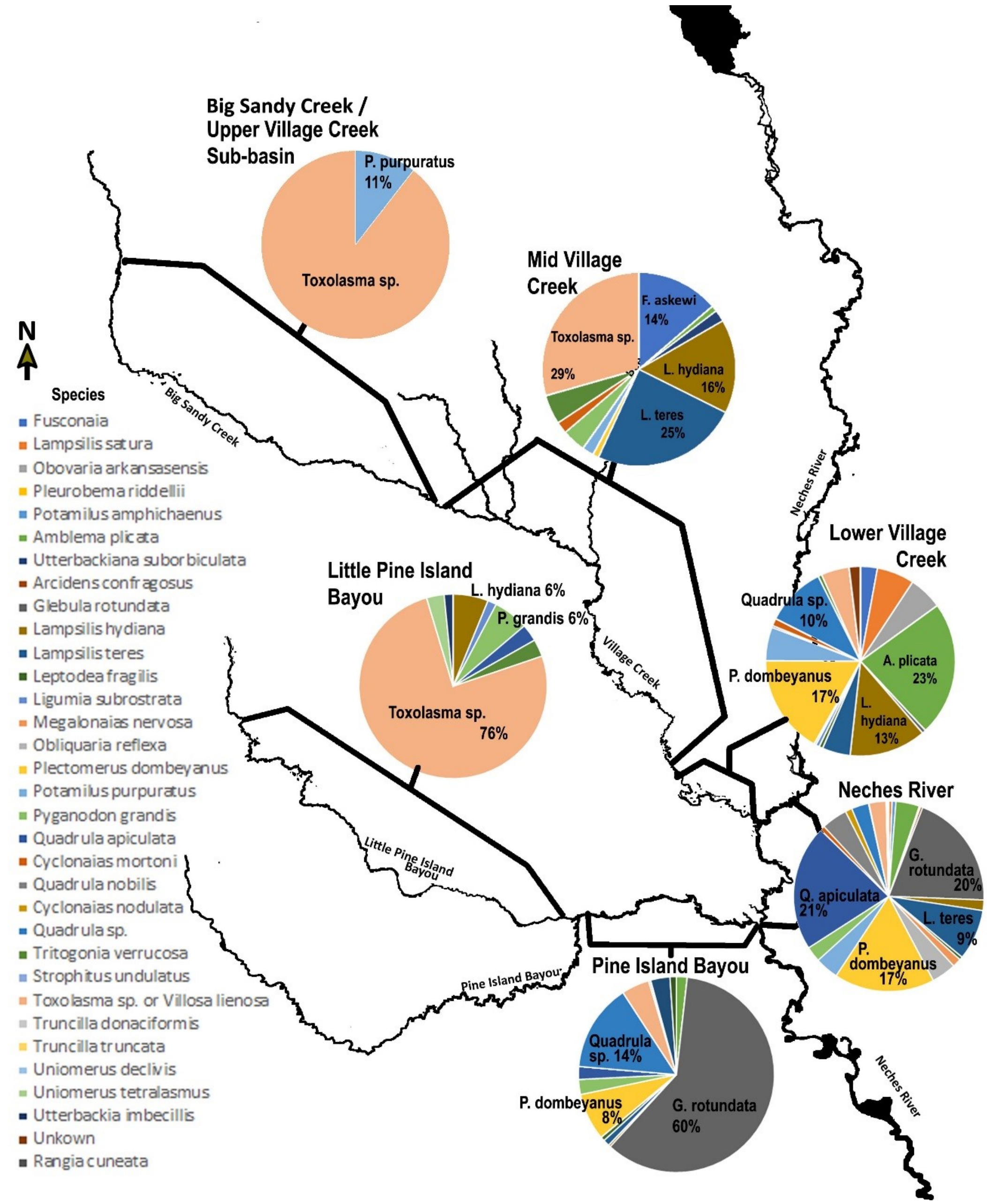

Figure 2. *2018 mussel community composition by stream segment. The species contributing most to the species composition are noted on the pie charts.*

Note: Toxolasma sp. looks morphologically similar to *Villosa lineosa*, but all individuals that could not be clearly idenfied morphologically were identified as *Toxolasma sp.* by genetic analyses (n=5).

Figure 3. *Post flooding erosion in the mid-reach of Village Creek.*

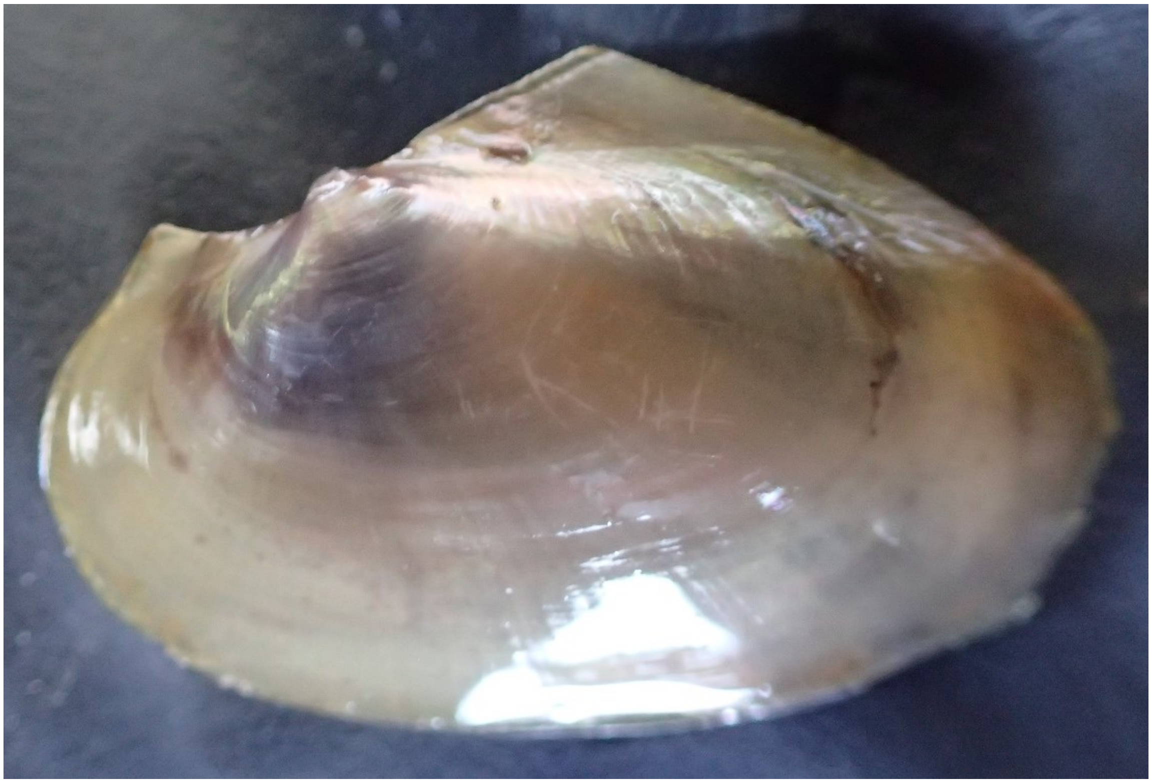

Figure 4. *Potamilus amphichaenus* (Texas heelsplitter) 9.3x2.1x6.3mm – *This is likely the smallest documented specimen of the species. The field identification was confirmed through genetic analysis.*

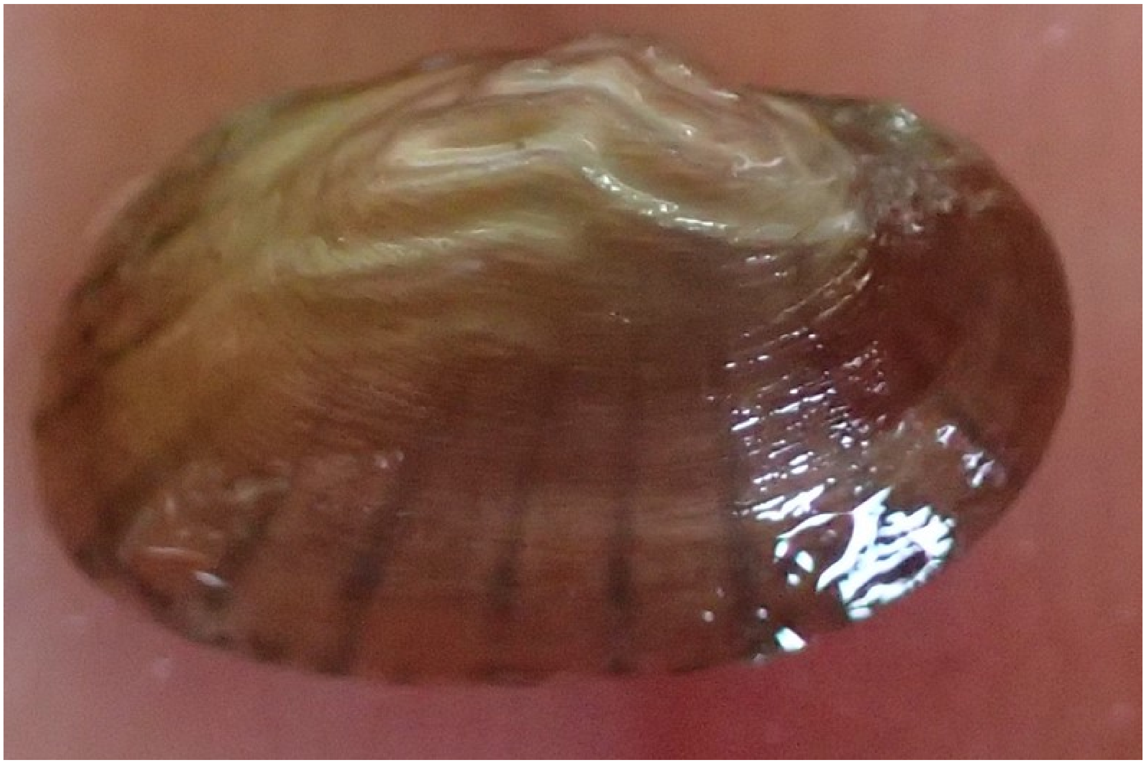

Figure 5. *Lampsilis hydiana* (Louisiana fatmucket) 8.1x3.29x5.7mm - *This is likely the smallest documented specimen of the species.*

Figure 6. *US 96 partial bridge collapse due to 2017 flooding.*
https://kfdm.com/news/local/bridge-between-lumberton-silsbee-partially-collapses

Figure 7. *Post hurricane road construction repair activity on US 96 bridge.*
https://www.beaumontenterprise.com/news/weather/article/Road-updates-in-Southeast-Texas-12171566.php

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