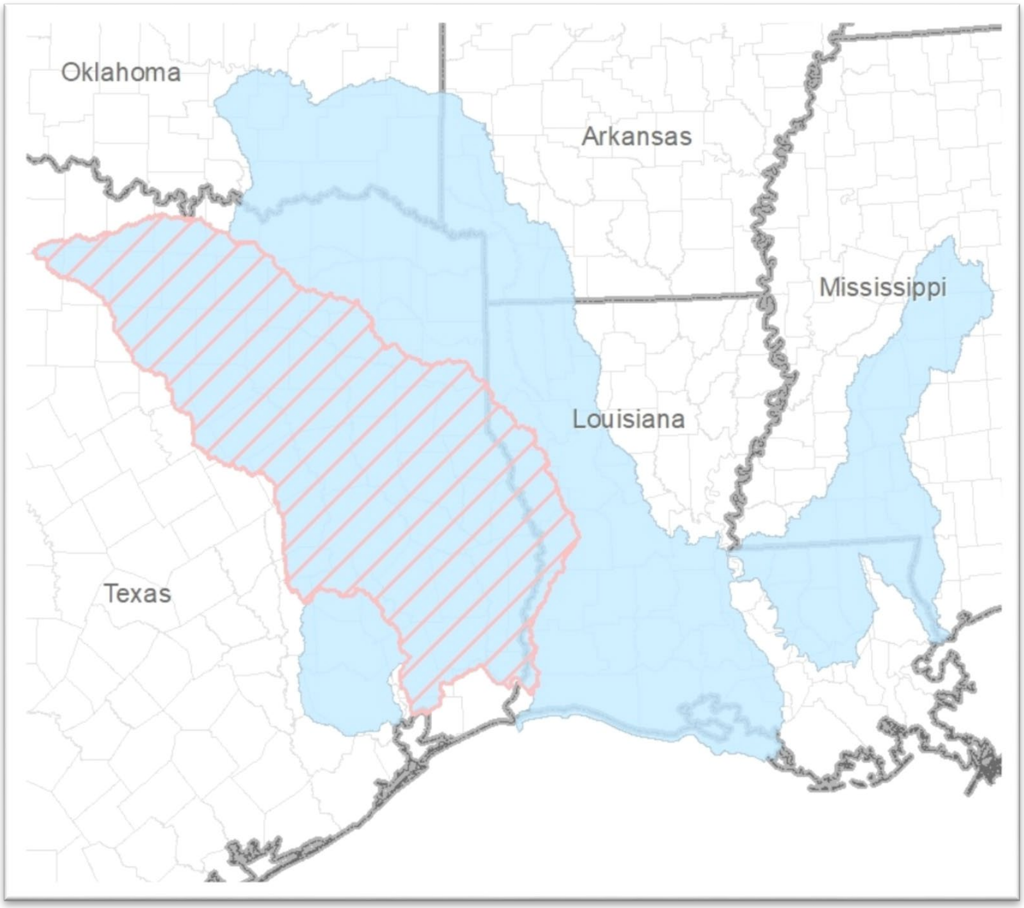
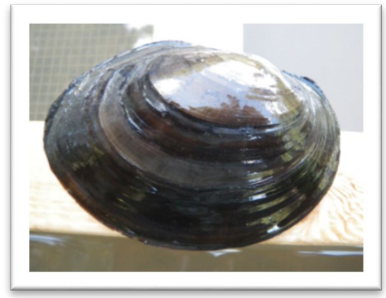
DRAFT Species Status Assessment Report for Two East Texas Mussels





TEXAS HEELSPLITTER (*POTAMILUS AMPHICHAENUS)* (HISTORICAL RANGE SHOWN IN RED HATCH)

LOUISIANA PIGTOE (*PLEUROBEMA RIDDELLII)* (HISTORICAL RANGE SHOWN IN BLUE)

Version 1.0

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U.S. Fish and Wildlife Service
Region 2
Albuquerque, NM

This document was prepared by the U.S. Fish and Wildlife Service's East Texas Mussel SSA Team and supporting staff, comprised of the core USFWS team (Jacob Lewis, Robert Allen, Susan Oetker, Erik Orsak, and Gary Pandolfi), and individuals from a variety of state and federal agencies, including Charrish Stevens, David Martinez, Chris Davidson, Dave Oster, Amy Trahan, and Mike Dick from the USFWS, Clint Robertson from the Texas Parks and Wildlife Department, Bill Posey from the Arkansas Game and Fish Commission, and Beau Gregory, Jared Streeter, and Kerui Lejeune from the Louisiana Department of Wildlife and Fisheries.

The following conservation partners, researchers, and independent peer reviewers provided valuable input on the content and accuracy of this SSA report: Dr. Charles Randklev, Dr. Kentaro Inoue, Dr. Neil Ford, Lance Williams, Debra Bills, Chis Harper, Glenn Clingenpeel, Webster Mangham, Terry Corbett, Mark Fisher, Colin McDonald, Kimberly Horndeski, Jennifer N. Khan, and Stephanie Ni.

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Note about this draft document **January 2020**

This is a preliminary draft document of the U.S. Fish and Wildlife Service. At this time it is intended for the sole purpose of soliciting reviews from expert peer reviewers selected by the Service, from State and Federal partners with expert knowledge of the species and their habitat, and internal review by Department of Interior staff. It is not intended to solicit comment from the public at large. For additional information contact Erik_Orsak@fws.gov.

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U.S. Fish and Wildlife Service. 2020. Species status assessment report for the Texas heelsplitter (*Potamilus amphichaenus*) and Louisiana pigtoe (*Pleurobema riddellii*). Version 1.0. January 2020. Arlington, Texas.

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CHAPTER 1. INTRODUCTION

The U.S. Fish and Wildlife Service (Service) is responsible for identifying those species that are in need of protection under the Endangered Species Act of 1973, as amended (Act), due to ongoing threats such as habitat loss, and increasing concerns that a species may become extinct. The framework used by the Service to review the status of a species, known as a Species Status Assessment (SSA, Smith et al. 2018, entire), is intended to be an in-depth review of the species' biology, an evaluation of its biological status and threats to survival, and an assessment of the resources and conditions needed to maintain long-term viability. Information contained in the SSA Report is used to support a decision by the Service as to whether a species should be listed as threatened or endangered, and thereby afforded protection under the Act. If listing is warranted, the SSA Report becomes a living document that can be updated as new information on a species becomes available, and continues to support a myriad of other regulatory actions under the Act, such as recovery, section 7 consultation, section 10 permits, and reclassification decisions.

This document contains information collected as part of a review of the status of two freshwater mussels occurring in east Texas, the Louisiana pigtoe (*Pleurobema riddellii*) and Texas heelsplitter (*Potamilus amphichaenus*). Both species were petitioned for federal listing under the Act in 2007 by Forest Guardians, which resulted in substantial 90-day findings published in 2009. The Louisiana pigtoe and Texas heelsplitter are freshwater mussels in the Family *Unionidae*. Like most mussels they occur in the gravel and coarse sandy substrates of rivers, streams, and in the case of the Texas heelsplitter, reservoirs. Mussels are filter feeders that rely on clean flowing water of sufficient volume to support their life cycle, and that of their host fishes, which are essential for reproduction. Previous status reviews indicated that these two freshwater mussel species face threats including habitat loss, changes to water quality, changes to hydrology, and riverbank destabilization. Although both species are found in east Texas rivers, the range of the Louisiana pigtoe is more expansive, extending into portions of east Oklahoma, southeast Arkansas, south Louisiana, and west Mississippi. The Texas heelsplitter is currently known to occur in portions of three major river basins in Texas (Trinity, Neches, and Sabine), and the Louisiana pigtoe currently occupies areas within five states across seven major river basins (San Jacinto, Neches, Sabine, Big Cypress-Sulphur, Red, Calcasieu-Mermentau, and Pearl). This SSA Report will refer to the species collectively as "East Texas mussels" and individually by common name and by scientific name (i.e., genus and specific epithet), where appropriate.

The Service will be using this SSA Report to form the biological basis for whether these two species of freshwater mussels warrant protection under the Act. Importantly, the SSA Report is not a decisional document, rather it provides a review of available information strictly related to the biological status of the species. A listing decision is made by the Service after reviewing this document and all relevant laws, regulations, and policies, and after the results of a proposed decision are announced in the Federal Register, with appropriate opportunity for public input. If listing is not warranted, we will continue to support conservation efforts, where appropriate. If listing is warranted, there are two possible outcomes based on both the level and timing of threats, including 1) Endangered – defined as a species that is in danger of extinction throughout all or a significant portion of its range (i.e., risk of extinction is high and imminent), or 2) Threatened – defined as a species that is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range (i.e., risk of extinction is high but not imminent).

For the purpose of this assessment, we generally define viability as the ability of the East Texas mussels to sustain populations in natural river systems over time. Using the SSA framework (Figure 1.1), we consider what the species needs to maintain viability by characterizing the status of the species in terms of its resiliency, redundancy, and representation (i.e., the 3Rs, Smith et al. 2018, entire). The 3Rs are defined as:

Resiliency reflects a species' ability to withstand stochastic events (e.g., droughts, floods). Demographic measures that reflect the health of each population, such as fecundity (e.g., birth rate), survival, and population size, are some of the metrics used to evaluate resiliency. A resilient population is better able to withstand and recover from disturbances such as random fluctuations in birth rates (demographic stochasticity), variations in rainfall (environmental stochasticity), and the effects of anthropogenic activities.

Redundancy reflects a species' ability to withstand catastrophic events (such as a rare destructive natural event or episode involving many populations). Redundancy is about spreading the risk of such an event across multiple, resilient populations. As such, redundancy can be measured by the number and distribution of resilient populations across the range of the species.

Representation describes the ability of a species to adapt to changing environmental conditions over time. Representation is measured by the breadth of genetic or environmental diversity within and among populations across the range of the species by gauging the probability that a species is capable of adapting to environmental changes. The more representation, or diversity, a species has, the more it is capable of adapting to changes (natural or human-caused) in its environment. In the absence of species-specific genetic and ecological diversity information, we evaluate representation based on the extent and variability of habitat characteristics across the geographical range.

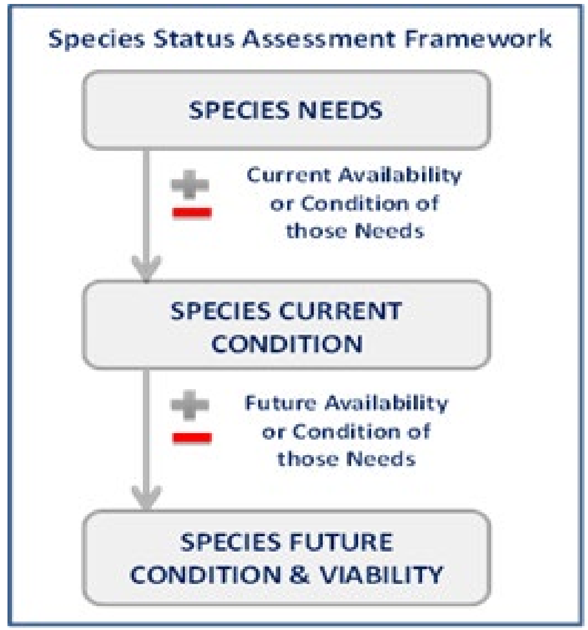


Figure 1.1. *Species Status Assessment Framework (USFWS, 2016).*

To evaluate the biological status of the East Texas mussels both currently and into the future, we assessed a range of conditions to allow us to consider the species' resiliency, redundancy, and representation. This SSA Report provides a thorough assessment of existing information on these species, including the biology and natural history, demographic risks, stressors, and limiting factors in the context of determining their viability and risk of extinction, as well as estimates of how these variables will change in the future.

The format for this SSA Report includes: a description of the resource needs of individuals (Chapter 2); current and historical species distribution, and factors affecting population resiliency, redundancy, and representation (Chapter 3); estimates of current condition (Chapter 4); risk factors affecting species viability (Chapter 5); and estimates of future condition and population viability (Chapter 6). This document is a compilation of the best scientific and commercial information available, and a description of past, present, and likely future risk factors (i.e., threats) to the East Texas mussels.

Appendix A includes all references cited, which are available upon request, in portable document format (pdf), from the Arlington Texas Ecological Services Field Office[1]. Appendix B contains Cause and Effects Tables, which evaluate the stressors to the species historically and into the future. Appendix C contains detailed narratives, tables, and maps for each population based on our analysis and model output for future condition.

[1] 2005 NE Green Oaks Blvd, Suite 140, Arlington, Texas, 76006 or call 817-277-1100

CHAPTER 2 - INDIVIDUAL NEEDS

This chapter reviews the basic biological and ecological information about the East Texas mussels. This information includes taxonomy, phylogenetic relationships, morphology, and a description of known life history traits, with an emphasis on life history traits that are important to the viability of the species now and in the future. We then outline the resource needs at the level of the individual. Basic information is included about freshwater mussels in general, to the East Texas mussels in particular, and characteristics that are unique to individual species where appropriate.

2.A. EAST TEXAS MUSSELS – GENERAL INDIVIDUAL NEEDS

2.A.1. TAXONOMY OF EAST TEXAS MUSSELS

Both species of East Texas mussels belong to the Family Unionidae, also known as the naiads and pearly mussels, a group of bivalve mollusks that have been in existence for over 400 million years (Howells et al. 1996, p.1) and now represent over 600 species worldwide, of which over 250 species occur in North America (Strayer et al. 2004, p. 429; Lopes-Lima et al. 2018, pp. 2-3).

This report follows the most recently published and accepted taxonomic treatment of North American freshwater mussels as provided by Williams et al. (2017a, entire) which applies to the East Texas mussels assessed in this report.

PHYLUM	**Mollusca Linnaeus, 1758**
CLASS	**Bivalvia Linnaeus, 1758**
ORDER	**Unionida Gray, 1854**
FAMILY	**Unionidae Rafinesque, 1820**
SUBFAMILY	**Ambleminae Rafinesque, 1820**

The East Texas mussels, along with approximately 85% of North American mussel species, belong to the subfamily Ambleminae. Generally speaking, members of this group share the following common characteristics: 1) are typically slow-growing and commonly live for more than twenty years, with growth rates typically between 1–5mm/year, depending on conditions (Howells et al. 1996, p.17), 2) are frequently summer breeders (Howells et al. 1996, p. 9) although the Lampsilini (e.g., Texas heelsplitter) typically spawn in fall and brood through the winter, 3) possess either unhooked or axe-head-type glochidia; may brood larvae in either all six or the outer two (lateral) demibranchs (McMahon and Bogan 2001, p. 342), 4) glochidia attach primarily to gills of the host fish (Barnhart et al. 2008, p. 375), 5) produce and store conglutinates in their mantle to facilitate rapid discharge of glochidia when fish attempt to feed (Barnhart et al. 2008, p. 375) and 6) free glochidia (not attached) may be released to water for hours or weeks prior to host infestation (Barnhart et al. 2008, p. 375).

2.A.2. LIFE HISTORY OF EAST TEXAS MUSSELS

Freshwater mussels, including the East Texas mussels, have a complex life history (Figure 2.1) involving an obligate parasitic larval life stage, called glochidia, which are wholly dependent on host fish. As freshwater mussels are generally immobile, dispersal is accomplished primarily through the behavior of host fish and their tendencies to travel upstream and against the current (positive rheotaxis) in rivers and streams. Mussels are broadcast spawners; males release sperm into the water column, which is taken in by the female through the incurrent siphon (the tubular structure used to draw water into the body of the mussel). The sperm fertilizes the eggs, which are held during maturation in an area of the gills called the marsupial chamber. The developing larvae remain in the marsupial chamber until they mature and are ready for release as glochidia, to attach on the gills, head, or fins of fishes (Vaughn and Taylor 1999, p. 913; Barnhart et al. 2008, pp. 371-373). Glochidia die if they fail to find a host fish, attach to the wrong species of host fish, attach to a fish that has developed immunity from prior infestations, or attach to the wrong location on a host fish (Neves 1991, p. 254; Bogan 1993, p. 599). Glochidia encyst (enclose in a cyst-like structure) on the host's tissue, draw nutrients from the fish, and develop into juvenile mussels weeks or months after attachment (Arey 1932, pp. 214-215). The glochidia will remain encysted for about a month through a transformation to the juvenile stage. Once transformed, the juveniles will excyst (release) from the fish and drop to the substrate. Freshwater mussel species vary in both onset and duration of spawning, how long developing larvae are held in the marsupial gill chambers, and which fish species serve as hosts. The mechanisms employed by mussel species to increase the likelihood of interaction between host fish and glochidia also vary by species.

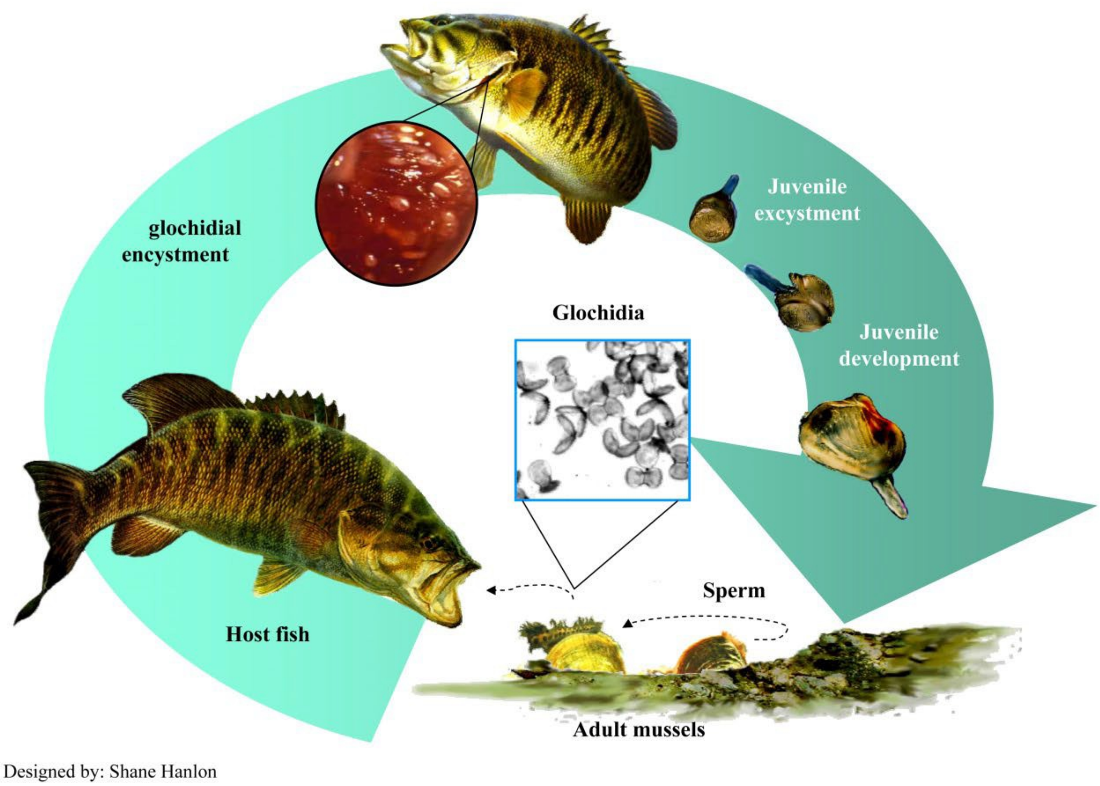


Figure 2.1. *Generalized freshwater mussel life cycle. Freshwater mussels, including the East Texas mussels, have a complex life history involving an obligate parasitic larval life stage, called glochidia, which are wholly dependent on host fish. (Image courtesy of Shane Hanlon, USFWS).*

Although mature mussels are capable of moving short distances using a muscular foot appendage, they are generally sedentary and therefore experience their primary opportunity for dispersal and movement within a stream as glochidia attached to a mobile host fish (Smith 1985, p. 105). Upon release from the host, newly transformed juveniles drop to the substrate on the bottom of the stream. Those juveniles that drop in unsuitable substrates die because their immobility prevents them from relocating to more favorable habitat. Juvenile freshwater mussels burrow into interstitial substrates and grow to a larger size that is less susceptible to predation and displacement from high flow events (Yeager et al. 1994, p. 220). Adult mussels typically remain within the same general location where they drop~~ped~~ off (excyst~~ed) of~~ their host fish as juveniles.

Host specificity can vary across mussel species, which may have specialized or generalized relationships with one or more taxa of fish. Mussels have evolved a wide variety of adaptations to facilitate transmission of glochidia to host fish including: 1) display of mantle lures that mimic fish or invertebrates, 2) packages of glochidia (conglutinates) that mimic worms, insect larvae, larval fish, or fish eggs, and 3) release of glochidia in mucous webs that entangle fish (Strayer et al. 2004, p. 431). Polymorphism of mantle lures and conglutinates frequently exists within mussel populations (Barnhart et al. 2008, p. 383), representing important adaptive capacity in terms of genetic diversity and ecological representation.

Freshwater mussels are generally considered to be long-lived and slow-growing (but see Haag and Rypel 2010, p. 2), with some individuals estimated to be decades or even centuries old based on measured growth rates (Strayer et al. 2004, p. 433). Due in part to their long life spans, recruitment is episodic and populations may be slow to recover from disturbance. Thin-shelled mussels (like Texas heelsplitter) often live 4–10 years while thick-shelled mussels (like Louisiana pigtoe) can live for 20–40 years, or longer (Howells et al. 1996, p.17).

Fast-growing species (like Texas heelsplitter) may mature as early as their first year, while slow-growing species (like Louisiana pigtoe) may take as long as 5–20 years to mature (Haag and Rypel 2010, p. 19). Fast-growing, short-lived species may be better adapted to more variable environments and therefore better suited to recover from high-mortality events than slower-growing long-lived species that are better adapted to more stable environments (Haag and Rypel 2010, p. 20). Nevertheless, growth rates and longevity often vary somewhat within and among populations of the same species.

2.A.3. Resource (Habitat) Needs of Individuals

Here we describe general habitat needs common to both East Texas mussels. We describe the specific needs of each species in section 2.B (Species-Specific Needs of East Texas Mussels).

The East Texas mussels generally occur in medium to large streams and rivers, requiring 1) flowing water of sufficient quantity and quality (i.e., low or no contaminants) to meet their life history requirements and that of their host fishes, 2) adequate food supply, 3) habitat that provides refugia from both high- and low-flow events, 4) appropriate substrate that is generally characterized as stable and free of excessive fine sediment, 5) access to appropriate fish hosts, and 6) habitat connectivity (i.e., lack of excessive impoundments and barriers to fish passage) (Figure 2.2, Table 2.1).

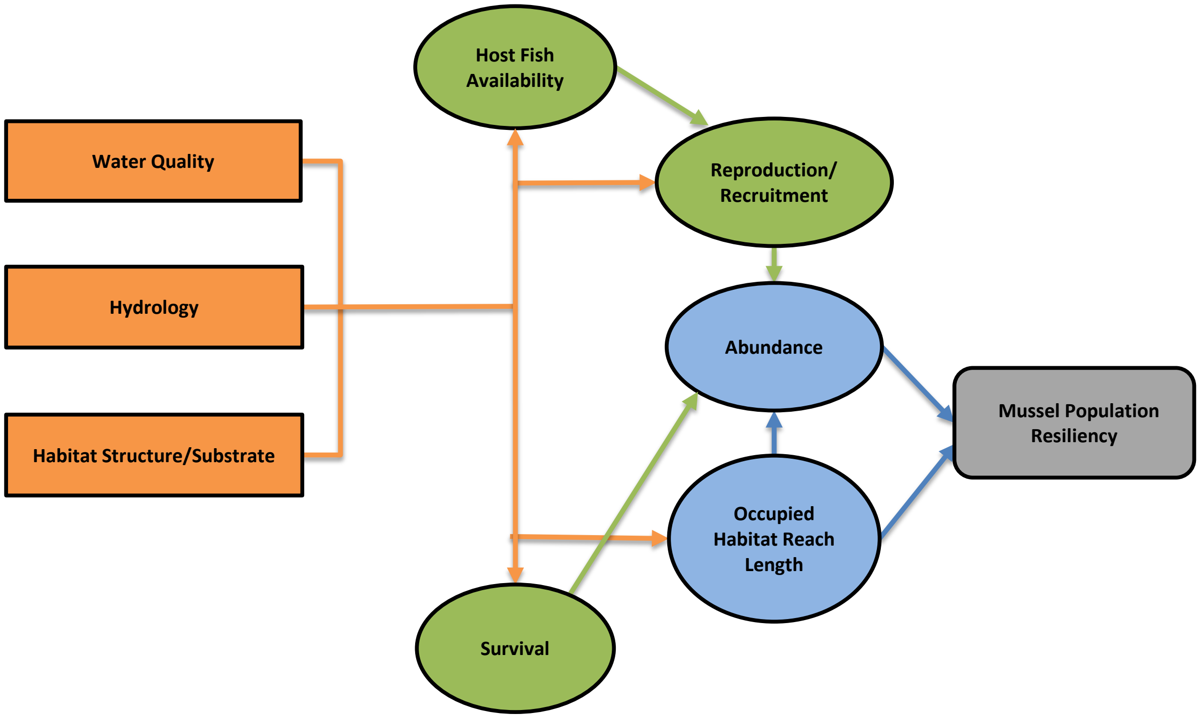


Figure 2.2. *Influence diagram representing the general population needs of the East Texas mussels. Habitat factors (orange boxes) influence demographic factors (green ~~boxes~~) that affect population attributes (blue ~~boxes~~) which influence overall resiliency of East Texas mussel populations.*

<u>Flowing water and protection from low-flow (dry or dewatering) events</u>. Louisiana pigtoe are not adapted to lentic or non-flowing environments (e.g., reservoirs and impoundments) and do not persist or thrive in habitats unless they are free-flowing (lotic), such as unimpeded stream and river reaches. Texas heelsplitter, however, are able to persist in lentic conditions, inhabiting several impoundments in North and East Texas. Nevertheless, both species of freshwater mussels in this report are considered to be lotic-habitat specialists, with Texas heelsplitter tolerant of lentic-habitats.

Since the East Texas mussels evolved in, and are adapted to, free-flowing environments, they require unaltered rivers and streams that are free from major impoundments and other structures that impede flow. Free-flowing water provides appropriate oxygenation, nutrition, thermal buffering, and access to fish hosts for reproduction and dispersal. East Texas mussels require adequate, but not excessively high flows, which may lead to scouring of suitable substrates.

East Texas mussels generally do not tolerate exposure to a non-watered environments. Dewatering of occupied habitat can lead to reduced reproduction, health, body condition, or fitness, and can result in eventual death or stranding of mussels, along with exposure to predation. Dewatering can also affect, limit, or prevent mussel-host fish interaction. As such, East Texas mussels require habitats and meso-habitats that consistently provide minimum flows necessary to meet life history requirements. Preferred habitat for East Texas mussels will maintain the necessary minimum flows and are protected from dewatering throughout the year. While some mussel species in other regions of Texas are more tolerant of dewatering, or have adaptations to avoid stranding (Bonner et al 2018, p. 196), East Texas mussels are not well adapted to persist in habitats subject to rapid and frequent dewatering (Mitchell et al. 2018, p. 16).

Protection from high-flow (scour) events. Both species of East Texas mussels live in the substrate of rivers and streams, also known as the benthic environment (stream bed and bank habitats). Benthic habitats are typically comprised of a mix of sediments and cobble that are subject to periodic disturbance from high storm flows. The increased velocity of these storm flows can scour sediments and dislodge mussels, transporting them downstream to locations that may or may not be suitable habitat. Although mussels have adapted to increased flows associated with natural storm events, changing land uses such as increases in impervious cover and storm run-off from urban areas, may exceed their capacity to ~~stay attached to~~ substrates and result in mortality. Therefore, East Texas mussels require microhabitats (flow refugia) that are naturally protected from scouring high-flow events that may occur during flood conditions. Some examples of flow refugia include boulders, crevices, bedrock shelves, bends, meanders, undercut banks, eddies, riffles, and living or dead vegetation (i.e., tree roots and coarse woody debris). In summary, East Texas mussels require a balance between periods of low flow where the volume must be sufficient to meet their basic life history needs (discussed in the previous paragraph) and high flows that must not reach levels capable of scouring substrate, or otherwise degrading or destroying their habitat.

Water quality. The East Texas mussels require naturally clean water and are sensitive to both point and non-point source contaminants that deteriorate water quality and degrade their habitat. Contaminants are capable of altering the chemical, physical, and biological characteristics of a stream to the point where mussels or their host fish can no longer survive. A variety of pollutants can cause lethal and sub-lethal effects in aquatic biota, but mussel-specific data are generally lacking regarding their sensitivity to the more than 80,000 chemical compounds and their metabolites that are currently in commerce and are routinely released into the environment. Contaminants that are sometimes elevated in rivers and are a concern to mussel health include excess nutrients such as ammonia (NH_3), which is highly toxic to aquatic organisms, chemicals related to wastewater disinfection such as chlorine (Cl), trace metals like copper or cadmium (March et al. 2007, p. 270, Wang et al. 2010, p. 2057), dissolved solids (e.g., salinity), pharmaceuticals and personal care products (e.g., musks, fragrances, growth hormones, estradiol), and a variety of pesticides commonly used for residential and commercial applications; these pollutants, individually or collectively (i.e., synergism) can interfere with the ability of mussels or their host fishes to feed, breed, or otherwise meet their life history needs (Cope et al. 2008, p. 452). Augsperger et al. (2003) estimated a safe range of ammonia concentrations for all mussel life stages of 0.3-0.7 mg/L total ammonia as N at pH 8 (p. 2574) and noted that "sediment pore-water concentrations of ammonia typically exceed those of overlying surface water" (p. 2574). Healthy mussel populations need naturally clean, high-quality water that is free of pollutants, has appropriate water chemistry including desirable oxygenation (generally expressed as mg/L dissolved oxygen), and is within appropriate upper and lower thermal limits (Khan et al. in press, entire). It is worth noting that water quality and water quantity are interrelated and interdependent, so as water quantity decreases, the concentration of pollutants introduced to streams generally increases as does the likelihood that pollutants may reach levels ~~that are~~ harmful to aquatic biota.

Firm and stable substrate. Since east Texas mussels live in the substrate of benthic environments, the composition of the substrate material is vital to their ability to properly anchor and remain firmly in place. A firm and stable substrate comprised of the appropriate mix of materials is necessary for mussels to withstand changes in stream flow such as perturbations associated with storm events and prevent ~~being~~ transport~~ed~~ downstream. Sediments such as shifting sands and unconsolidated silts generally do not provide appropriate anchoring substrate, and thus appropriate habitat, for East Texas mussels.

Nutrition and food supply. Adult freshwater mussels, including East Texas mussels, are filter-feeders, siphoning suspended phytoplankton, zooplankton, rotifers, protozoans, detritus and dissolved organic matter from the water column (Strayer et al. 2004, p. 430) and from sediment; juvenile mussels are capable of using their foot to collect food items from sediments (pedal feeding; Vaughn et al. 2008, pp. 409-411). Glochidia derive what little nutrition they need from their obligate fish hosts (Barnhart et al. 2008, p. 372). Stable isotope studies suggest some mussel species feed on coarse particulate organic matter (CPOM)~~,~~ or bacteria and fungi a~~dhered to~~ and decomposing CPOM (Bonner et al. 2018, pp. 7, 215). Freshwater mussels must keep their shells open (gaped) to obtain food and facilitate gas exchange. They are sometimes able to sense perturbations to water quality and may respond by temporarily closing their shells (Bonner et al. 2018, p. 141). Food supply is not generally considered limiting in the environments inhabited by East Texas mussels.

Fish hosts. East Texas mussels have an obligate parasitic relationship with their respective host fishes. Nearly all freshwater mussels including East Texas mussels cannot successfully reproduce or disperse in the absence of appropriate host fish. Host fish are necessary to facilitate dispersal and represent the only mechanism to do so in a free-flowing environment, although downstream movement of individuals may occur during high flow events if they become dislodged from the substrate. Both large and small run of river impoundments act as barriers to fish passage, and therefore inhibit mussel dispersal and recolonization. In some cases, freshwater mussels may be more tolerant of water quality degradation than their host fish. For example, mussels generally prefer dissolved oxygen concentrations greater than 3 mg/L and will begin to experience respiratory distress below approximately 2 mg/L (Bonner et al. 2018, p. 131), but dissolved oxygen below 5 mg/L is generally considered to be harmful to many fish species, and fish mortality is almost certain below 2 mg/L (Francis-Floyd 2011, p. 1).

Table 2.1. General life history and resource needs of East Texas mussels.		
Life Stage	**Resource Need(s) - Habitat Requirements**	**Reference(s)**
All life Stages	**Water Quality**: Naturally clean, high-quality water with little or no harmful pollutants (i.e., harmful constituents and toxicants are absent or below tolerance limits of mussels, their host fishes, and host fish prey). Desirable conditions include: - Natural, unaltered ambient water temperature; generally below 27°C (80.6°F) is considered protective but sensitivity can vary and many species have not been tested for thermal tolerance - Dissolved oxygen generally > 3 mg/L or parts per million (ppm) -Low salinity/total dissolved solids (TDS) (e.g., trends for TDS and/or conductivity within watershed are stable (not increasing due to anthropogenic activity)) -No excess nutrients (e.g., nitrogen and ammonia levels are low (NH_3 below 0.3–0.7 mg/L NH_3-N at pH 8 and 25°C (77°F) cited by Augspurger as generally protective)) -Low levels of copper, nickel, and other potentially harmful trace metals -No or low levels of pesticides, sulfate, chloride, potassium, and other potentially harmful constituents -No or low pollutants related to municipal and industrial wastewater or urban run-off, including pharmaceuticals, hormones, coliform bacteria, antibiotics, disinfection by-products (e.g., chlorine), petroleum hydrocarbons, and other environmental contaminants common to wastewater	Khan et al. in press, entire. Gascho-Landis and Stoeckel 2015, p. 8; Gascho-Landis et al. 2013, pp. 76, 79; Augspurger et al. 2003, pp. 2569, 2571, 2574; Augspurger et al. 2007, p. 2,025; Cope et al. 2008, p. 454, 456.
	Water Quantity: Flowing water in sufficient quantity to support the life history requirements of mussels and their host fishes	Galbraith and Vaughn 2009, p. 46; Allen and Vaughn 2010, p. 390; Randklev et al. 2013b, p. 269. Randklev et al. 2017a, pp. 1, 5.
Gamete (broadcast sperm, egg development, to fertilization)	Sexually mature male and female mussels with appropriate water temperatures for spawning, fertilization, and brooding. Temperature is a primary cue for spawning. Low temperatures can suspend reproduction and high temperatures can lead to premature expulsion of glochidia	Haag 2012, pp. 38–39; Galbraith and Vaughn 2009, p. 45-46; Randklev et al. 2013a, pp. 3, 19.
Glochidium (from attachment through excystment)	Presence of host fish with sufficient flows to allow attachment, encystment, relocation, excystment, and dispersal of glochidia. Note that glochidia can be up to four times more sensitive to pollutants in water than juveniles	Barnhart et al. 2008, p. 372; Randklev et al. 2013b, p. 269.
	Stable substrates appropriate for burrowing	
Juvenile, sub-adult, and Adult (from excystment through maturity)	Stable substrates comprised of suitable sediment types and appropriate for burrowing	Allen and Vaughn 2010, pp. 384-385.
	Appropriate food source in adequate supply	

2.B. SPECIES-SPECIFIC NEEDS OF EAST TEXAS MUSSELS

2.B.1. LOUISIANA PIGTOE, PLEUROBEMA RIDDELLII (LEA, 1862)

Figure 2.3. *Louisiana pigtoe observed from Neches River, Angelina/Trinity Counties, Texas (USFWS photo).*

2.B.1.A. TAXONOMIC AND MORPHOLOGICAL DESCRIPTIONS

The Louisana pigtoe (Figure 2.3) was originally described as the species *Unio riddellii* by Isaac Lea (1862, p. 228) from the Trinity River near the City of Dallas, Dallas County, Texas; however, a recent study has suggested the type specimen may be a misidentified, more common species known as pimpleback (*Cyclonaias pustulosa*) based on shell morphology (Khan et al. 2018, p. 9). Simpson (1914), Vidrine (1993), and Howells et al. (1996) recognized the following synonyms:

Unio friersoni Wright (1896);
Quadrula friersoni (Wright) of Simpson (1914) and Frierson (1927);
Fusconaia friersoni (Wright) of Stern (1976) and Vidrine (1985);
Quadrula ridelli (Lea) of Strecker (1931);
Pleurobema riddelli (Lea) of Vidrine (1993), Howells et al. (1996), Turgeon et al. (1998), and others.

The current recognized scientific name for Louisiana pigtoe is *Pleurobema riddellii*, and this report refers to it as such. The following taxonomic treatment follows Williams et al. (2017a, pp. 35, 42).

CLASS	**Bivalvia Linnaeus, 1758**
ORDER	**Unionida Gray, 1854**
FAMILY	**Unionidae Rafinesque, 1820**
SUBFAMILY	**Ambleminae Rafinesque, 1820**
TRIBE	**Pleurobemini Hannibal, 1912**
GENUS	***Pleurobema* Rafinesque, 1819**
SPECIES	***Pleurobema riddellii* Lea, 1861**

The Louisiana pigtoe is a medium-sized freshwater mussel (shell lengths to greater than 62 mm) with a brown to black, triangular to subquadrate shell without external sculpturing, sometimes with greenish rays. Burlakova et al. (2011a, p. 158) considered the species rare throughout its range. For a detailed description see Howells et al. 1996 (pp. 91-92) and Howells 2014 (p. 65). Other native mussel species (e.g. pimpleback, *Cyclonaias pustulosa*; Texas pigtoe, *Fusconaia askewi*; Trinity pigtoe, *F. chunii*; and Wabash pigtoe, *F. flava*) can easily be mistaken for Louisiana pigtoe when identified by shell morphology alone. A recent survey suggested experienced malacologists had a 76% success rate accurately identifying the species in the Little River, Oklahoma, when field identifications were compared with genetic analysis results (Inoue 2019, p. 1).

2.B.1.B. GENETIC DIVERSITY

Williams et al. (2017a, p. 51) recognized 23 species from the genus *Pleurobema*. Recent genetic work supports the monophyly of genus *Pleurobema* and subgenus *Pleurobema* (*Sintoxia*), with *P. cordatum*, *P. plenum*, *P. riddellii* (Louisiana pigtoe), *P. rubrum*, and *P. sintoxia* forming a single clade, and all other *Pleurobema* species in a second clade (Inoue et al. 2018, pp. 694, 698; Williams 2017a, p. 51). Inoue et al. (2018, p. 669) also suggested divergence within the *P. riddellii* complex due to phylogenetic distinction between *Pleurobema cf. riddellii* from the Ouachita River drainage and *Pleurobema riddellii* from the Red River and west Gulf Coast drainages, although additional samples would be required to assess *P. cf. riddellii* as a possible new species.

2.B.1.C. REPRODUCTION AND FISH HOST INTERACTIONS

Louisiana pigtoe are considered bradytictic (spawning occurs during the summer, glochidia are held by the female over winter and released the following spring); however, gravid females have been observed in July (Marshall 2014, pp. 46-47). Freshwater mussel recruitment does not occur every year (Ford 2016b, p. 28).

The host fish for Louisiana pigtoe has not been confirmed. Marshall (2014, pp. 59-60) suggested bullhead minnow (*Pimephales vigilax*), red shiner (*Cyprinella lutrensis*), and blacktail shiner (*Cypinella venusta*) as potential fish hosts based on a fish host distribution modeling effort. When modeled individually, bullhead minnow, red shiner, dusky darter (*Percina sciera*), and blacktail shiner accounted for 47%, 59%, 75%, and 77% of the gain of the full mussel model, respectively (Marshall 2014, pp. 57, 59-60). In this same study, and as part a model validation effort, encysted Louisiana pigtoe glochidia were collected from wild bullhead minnow and red shiner from the Neches River; however, none were found encysted on blacktail shiner or dusky darter. Marshall (2014, p. 60) proposed that since blacktail shiner and red shiner are closely related and are known to hybridize, they likely serve as hosts to the same freshwater mussel species. Hinkle (2018) collected glochidia infected wild fish from the upper Neches River and kept them under laboratory conditions through glochidia metamorphosis. Results indicated 6 genetically confirmed Louisiana pigtoe juveniles excystised from blacktail shiners (Hinkle 2018, p. 9, 11).

Hinkle (2018) reported male gametogenesis occurred from mid-July through mid-August with peak production occurring at 30°C (p. 19). Male gametes were flagellated and had an average length of 4.2 micrometers (µm), average width of 1.96 µm, and were found in concentrations ranging from 500,000 to approximately 20,000,000 gametes per milliliter. Female gametogenesis occurred from March through September with peak production at 25°C in early September through early October (Hinkle 2018, p. 19, 21). In females, concentrations of gametes ranged from 0 (but with clusters of oogonia and oocytes) up to 219,400 nonviable ova and 173,200 viable ova and averaged 12,500 nonviable and viable ova among sampled sexually mature females (Hinkle 2018, p. 19).

2.B.1.D. AGE AND GROWTH

A single Louisiana pigtoe juvenile from the Neches River, Texas, was reported to grow 15 mm during its first year from an initial shell length of 2 mm (Ford et al. 2016b, p. 30). Sexual maturity is achieved at shell lengths around 40 mm and mature adults grow approximately 2.5 mm in shell length per year (Ford et al. 2016b, pp. 28, 30). At these growth rates, juvenile Louisiana pigtoe could reach maturity in 3-4 years. Sexually mature males were estimated to be between 9 and 12 years old based on external valve annuli and were between 37-50 mm in shell length (Hinkle 2018, p. 19). Based on ova production, sexually mature females were estimated by external annuli to be between 4 and 12 years of age with shell lengths ranging from 29-59 mm (Hinkle 2018, p. 19).

2.B.1.E. HABITAT

Louisiana pigtoe occur in medium to large-sized streams and rivers in flowing waters (0.3-1.4 m/s) over substrates of cobble and rock or sand, gravel, cobble, and woody debris; they are often associated with riffle, run, and sometimes larger backwater tributary habitats (Ford et al. 2016b, pp. 42, 52; Howells 2010a, p. 3-4; Williams et al. 2017a, p. 21). Specimens have been found as deep as 3.1 m (Zara 2015, Appendix A, p. 1), but are typically found in shallower waters (0.1-1.2 m in depth) (Howells 2010a, p. 3). Specimens collected from the Neches River occupied substrates of gravel mixtures at depths between 0.57-1.12 m in run habitat with flow velocities of 0.44-0.66 m/s (Glen 2017, p. 17).

Table 2.2. Louisiana pigtoe Life History Characteristics and Resource Needs

Life Stage	Resource Needs	Reference
Glochidia: through host fish attachment	**Potential Hosts:** red shiner (*Cyprinella (Notropis) lutrensis*), blacktail shiner (*Cyprinella venusta*), bullhead minnow (*Pimephales vigilax*)	Ford and Oliver 2015, p. 6; Bertram 2015, p. 32; Marshall 2014, p. 37 Hinkle 2018, p. 9, 11)
Juveniles: excystment through sexual maturity	Habitat requirements assumed to be similar to adults	
	Growth rate: One 2 mm individual grew 15 mm in the first year	Ford et al. 2016b, p. 30
	Growth rate: May grow to 35 mm during first 3 years	Ford et al. 2016b, p. 30
	Size at maturity: Approximately 40 mm	Ford et al. 2016b, p. 28
Adults	**Stream flow:** Intermediate flow volume; 0.3-1.4 m/s in Neches River, TX; larger backwater tributaries of Neches River upper reaches	Ford et al. 2016b, p. 42; Howells 2010c, pp. 3-4; Williams et al. 2017b, p. 21; Vaughan 2017, p. 9
	Depth: Found as deep as 3.1 m in Trinity River, TX	Zara 2015, Appendix A, p. 1
	Substrate: Riffles of cobble and rock; sand, gravel, cobble, woody debris; runs with subdominant gravel mixtures	Ford et al. 2016b, p. 52; Howells 2010a, p. 3; Glen 2017, p. 17.
	Growth rate: approximately 2.5 mm shell length per year	Ford et al. 2016b, p. 30
	Abundance: Considered rare	Ford et al. 2016b, p.4

Figure 2.4. *Texas heelsplitter observed from Neches River, Angelina/Trinity Counties, Texas (USFWS photo).*

2.B.2. TEXAS HEELSPLITTER, POTAMILUS AMPHICHAENUS

2.B.2.A. TAXONOMIC AND MORPHOLOGICAL DESCRIPTION

The Texas heelsplitter (Figure 2.4) was first described as the species *Unio (Lampsilis) amphichaenus* by Frierson (1898, p. 109) from the Sabine River near Logansport, Louisiana. Vidrine (1993), Neck and Howells (1995, p. 4), and Howells (1996, p. 95) recognized the following synonyms (Howells 2010b, p. 4):

Unio (Lampsilis) amphichaenus of Frierson (1898);
Lampsilis (Proptera) amphichaenus (Frierson 1898) of Simpson (1900);
Lampsilis (Proptera) amphichaena (Frierson 1898) of Simpson (1914);
Proptera amphichaena (Frierson 1898) of Frierson (1927) and Haas (1969);
Leptodea amphichaena (Frierson 1898) of Burch (1975);
Lastena amphichaena (Frierson 1898) of Hoggarth (1988);
Potamilus amphichaenus (Frierson 1898) of Turgeon (1988), Williams et al. (2017a), and others.

The recognized scientific name for Texas heelsplitter is *Potamilus amphichaenus*, and this report refers to it as such. The following taxonomic treatment follows Williams et al. (2017a, pp. 35, 42).

CLASS Bivalvia Linnaeus, 1758

CLASS	**Bivalvia Linnaeus, 1758**
ORDER	**Unionida Gray, 1854**
FAMILY	**Unionidae Rafinesque, 1820**
SUBFAMILY	**Ambleminae Rafinesque, 1820**
TRIBE	**Lampsilini Ihering, 1901**
GENUS	***Potamilus* Rafinesque, 1818**
SPECIES	***Potamilus amphichaenus* Frierson, 1898**

The Texas heelsplitter is a medium to large-sized freshwater mussel (up to 177 mm shell length) that has a tan to brown or black elliptical shell, with lighter coloration on the beaks. The hinge line is relatively straight. Texas heelsplitter exhibit slight sexual dimorphism; females have a broadly rounded posterior margin and males are more pointed (Howells 2010b, p. 2). The base of the anterior margin exhibits a long, narrow gape, while a shorter, much wider gape is located along the posterior margin, presumably to accommodate the incurrent and excurrent apertures (Neck and Howells 1995, p. 4). Burlakova et al. (2011, p. 158) considered the species rare throughout its range. For a detailed morphological description see Neck and Howells (1995, p. 5-6), Howells et al. (1996, p. 95) and Howells (2014, p. 69).

2.B.2.B. GENETIC DIVERSITY

Ford et al. (2016b, p. 48) sequenced the mitochrondrial gene ~~known as~~ ND1 from 6 Texas heelsplitters, 6 pink papershells (*Potamilus ohiensis*), and 1 suspected Texas heelsplitter/pink papershell hybrid. Results showed that the suspected hybrid had a mix of both species characteristics preventing positive species level identification. The hybrid morphology also exhibited a blending of the two species. Texas heelsplitter and pink papershell are known to co-occur in the Trinity River drainage but the extent to which Texas heelsplitter populations have been compromised by pink papershell genetics is currently unknown (Ford et al. 2016b, p. 49).

2.B.2.C. REPRODUCTION AND FISH HOST INTERACTIONS

Members of the Lampsilini tribe can expel conglutinates and are known to use mantle lures to attract sight feeding fishes that attack and rupture the marsupium, thereby becoming infested by glochidia (Barnhart et al. 2008, p. 377, 380). These species are long-term brooders (bradytictic) (p. 384). Howells (2010b) observed eggs and glochidia from two females during ~~the month of~~ January from the Neches River; however, 13 others collected in January, July, and August were not gravid (p. 3). A single female, 90 mm in shell length, was estimated to have 6,665 eggs and 871,665 glochidia while another female with a 104 mm in shell length had 599,375 eggs and 646,250 glochidia (Howells 2010b, p. 3). Freshwater drum (*Aplodinotus grunniens*) were confirmed as host fish for Texas heelsplitter (Bosman et al. 2015, p. 15). Freshwater mussel recruitment does not occur every year (Ford 2016b, p. 28).

2.B.2.D. AGE AND GROWTH

A congener (*Potamilus purpuatus* (common name Bluefer)) from the southeast United States was reported by Haag and Rypel (2011) to reach a maximum age of 9–26 years (Table 1, p. 229) and members of tribe Lampsilini ranged from 4–50 years (p. 234) with a higher growth rate compared to other tribes (p. 239). Texas Heelsplitter has been reported mature at approximately 60 mm and juvenile presence has been confirmed in the Sabine River (Ford et al. 2016b, p. 31).

2.B.2.E. HABITAT

Texas heelsplitter occur in streams and rivers of the Trinity, Neches, and Sabine River drainages on substrates consisting of "firm mud, sand, or finer gravels bottoms, in still to moderate flows" and sometimes associated with fallen timber (Howells 2014, p. 69; Howells 2010b, p. 3, and Table 2.3). Vaughan (2017, p.15) collected specimens in substrates with high organic matter content. Dickson (2018, p. 23) reported Texas heelsplitter were found in areas of large channel widths, with at least one low bank, in sandy substrates, at depths of 10 cm and deeper within the substrate, and in areas prone to bankfall. Texas heelsplitter can tolerate man-made impoundments and have been found in several east Texas reservoirs (Howells 2010b, p. 3).

Table 2.3. Texas heelsplitter Life History Characteristics and Resource Needs		
Life Stage	**Resource Needs**	**Reference**
Glochidia: through host fish attachment	**Host:** Freshwater drum (*Aplodinotus grunniens*)	Bosman et al. 2015, p. 15
Juveniles: excystment through sexual maturity	Habitat requirements assumed to be similar to adults	
	Size at maturity: Approximately 60mm	Ford et al. 2016b, p. 31
Adults	**Stream flow:** Slow to moderately flowing streams; tolerates impoundments	Howells 2010b, p. 3
	Depth: Deeper pools with sand	Ford et al. 2010, p. 13
	Substrate: Mud, sand, finer gravels, and mixtures of those with high organic matter content; sometimes associated with fallen timber	Howells 2010b, p. 3 Vaughan 2017, p. 15
	Brooding: Both eggs and glochidia found in 2 females in Neches River in January, glochidia found in one from Sabine River in July, others collected in January, July, and August not gravid	Howells 2010b, p. 3
	Fecundity: 90 mm sl (shell length) female (6,665 eggs, 871,665 glochidia), 104 mm sl female (599,375 eggs, 646,250 glochidia)	Howells 2010b, p. 3
	Habitat availability: Not declining in east TX rivers	Williams et al. 2017b, p. 21
	Species abundance: Considered very rare	Howells 2010b, pg. 7; Williams et al. 2017b, p. 21
	Hybridization: May hybridize with pink papershell (*Potamilus ohiensis*) in Trinity basin; hybridized offspring morphology a mixture of both species characteristics	Ford et al. 2016b, p.48

2.C. SUMMARY

This report considers two species of East Texas mussels, Louisiana pigtoe and Texas heelsplitter, both of which belong to the subfamily Ambleminae of the family Unionidae. The two species occur in three or more of the following seven basins in Arkansas, Louisiana, Oklahoma, and Texas: Little River, Calcasieu River, Big Cypress Bayou, Sabine River, Angelina River, Neches River, and Trinity River. The Louisiana pigtoe and Texas heelsplitter are among the ~~fifteen~~ mussel species ~~that were~~ added to the list of Texas state threatened species by the Texas Parks and Wildlife Department in 2009 (TPWD 2009, pp. 1-2).

Species needs for each of the East Texas mussels generally include water environs with suitable substrate, adequate but not scouring flows, high-quality water (within optimal thermal and dissolved oxygen limits, and without harmful pollutants or contaminants), refuge from high and low flow events, stable substrates, access to appropriate host fishes, and appropriate nutrition (adequate but not excessive levels of CPOM and associated bacteria and fungi, or suspended phytoplankton).

CHAPTER 3 – SPECIES NEEDS AT THE INDIVIDUAL AND POPULATION LEVEL

This chapter considers the current and historical distribution of the Louisiana pigtoe and Texas heelsplitter, and evaluates factors important to assessing the viability of each species. Along with species distribution, we examine the needs of the species as they pertain to population resiliency, redundancy, and representation, which support species viability and reduce the likelihood of extinction.

For the purposes of this assessment, a mussel population is defined as a stream reach that is occupied by a collection of mussel beds through which host fish infested with glochidia may travel freely, allowing for dispersal of juveniles among and within mussel beds. Viability is defined as the ability of the species to sustain populations in the wild over time, in this case, 50 years. Fifty years represents up to five mussel generations and reflects the approximate forecasting horizon for climate projections and estimates of future development. This assessment considers the viability of each species following the SSA framework based on "the conservation biology principles of representation, resiliency, and redundancy (the 3Rs) to evaluate the current and future conditions of a species" as described by Smith et al. (2018, p. 7).

3.A. HISTORICAL RANGE AND CURRENT DISTRIBUTION

3.A.1. LOUISIANA PIGTOE

The range of the Louisiana pigtoe is comprised of multiple river drainages throughout portions of east Texas, Louisiana, west Mississippi, southeast Oklahoma, and southwest Arkansas (Vidrine 1993, p.66; Howells et al. 1997, p.22; Randklev et al. 2013b, p. 269; Randklev 2018, entire). The type locality specimen was described by Lea in 1861 from the Trinity River near Dallas (Lea 1862, p. 392) and recently confirmed as Louisiana pigtoe through genetic analysis (Randklev 2019b, p. 3).

In Texas, the Louisiana pigtoe has been recorded from several east Texas rivers, including the Big Cypress-Sulphur, Neches-Angelina, Sabine, San Jacinto, and Trinity River basins (Strecker 1931, p.29; Howells et al. 1996, p. 91; Howells 1997, p. 22; Howells 2006, p. 98; Burlakova et al. 2012, p. 12; Ford 2013a, pp. 75 – 80; Ford et al. 2014, p. 10; Ford et al. 2016b, p. 20; Randklev 2018, entire) (see Figure 3.1). In Louisiana, the species has been recorded within the Amite, Bayou Boeuf, Calcasieu, Red, Sabine, and Pearl River systems (Vidrine 1993, p.66; Randklev et al. 2013b, p. 269; LNHP 2018, entire; Randklev 2018, entire; Johnson et al. 2019, p. 11). In Mississippi, the species has been observed from the Pearl River (Johnson et al. 2019, p. 11). In Arkansas, the species has been recorded in the Cossatot, Mountain Fork, Saline, Rolling Fork, and Little Rivers (USFWS 2014, p. 29; USFWS 2015, p. 5; USFWS 2017, p. 8; Randklev 2018, entire). In Oklahoma, the species has been recorded in the mainstem of the Little River (Inoue 2018, p. 1). Reported populations from the Ouachita River system in Arkansas were determined to be phylogenetically distinct from Louisiana pigtoe and are not considered in this report (Inoue et al. 2018, p. 699). We assume the historical distribution of the species would have included the entirety of the river basins described above where connectivity was not an issue and conditions were suitable (see stream segments highlighted black on Figure 3.1).

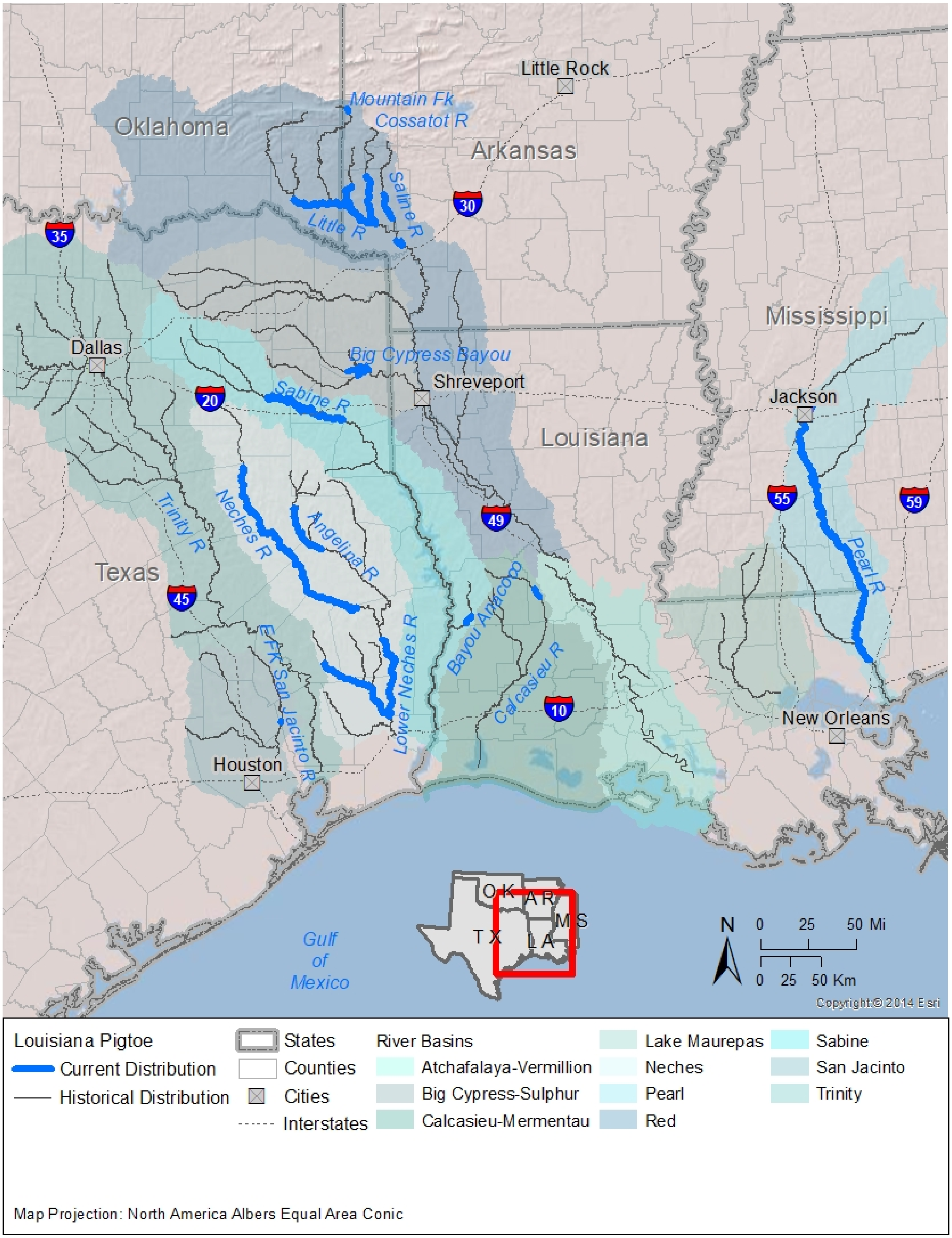


Figure 3.1. *Louisiana pigtoe current and historical distribution.*

For this assessment, a current Louisiana pigtoe population, also referred to as a focal area and labeled "Current Distribution on Figure 3.1 (see stream segments highlighted blue), is a contiguous (hydrologically connected) reach of stream containing freshwater mussel beds with live or recent dead individuals observed in surveys performed from the year 2000 to present. Recent dead refers to dead individuals with valves still attached by the hinge, lustrous nacre, and intact periostracum; soft tissues may or may not be present. Since mussels are likely to occur beyond known sampled areas, estimates of the upper and lower extent of populations were determined by extending 0.5 miles beyond the most upstream or downstream location with live or recent dead observations since 2000. Populated tributaries (tributaries with live or recent dead observations since 2000) that were hydrologically connected (i.e., no impoundments or other barriers to host fish passage) to another population were considered a single population; if appropriate, the lower extent was then determined by extending the population line approximately 0.5 river miles downstream of the confluence of the populated streams. Specific survey location information was not available for the Pearl River population as of the writing of this report other than at the Hydrologic Unit Code 10 (HUC10) scale. This population was delineated from the upper boundary of the most upstream occupied HUC10 to the lower boundary of the most downstream occupied HUC10. Table 3.1 displays the estimated length of each population in river miles, extracted from the U.S. Geological Survey's National Hydrography Dataset (USGS 2014a).

Table 3.1. Current known populations of Louisiana pigtoe and estimated length of occupied reach.

Louisiana Pigtoe Focal Areas			
River Basin	**State**	**Population**	**Length of Occupied Reach (miles)**
Red	AR	**Mountain Fork**	2.3
	AR	**Little River /Rolling Fork**	103.6
	AR	**Cossatot River**	41.9
	AR	**Saline River**	27.9
	AR	**Lower Little River**	8.5
Big Cypress-Sulphur	TX	**Big Cypress Bayou**	32.3
Calcasieu-Mermentau	LA	**Upper Calcasieu River**	9.9
Pearl	LA/MS	**Pearl River**	280.8
Sabine	TX	**Sabine River**	86.8
	LA	**Bayou Anacoco**	9.1
Neches	TX	**Angelina River**	53.2
	TX	**Neches River**	203.0
	TX	**Lower Neches River**	160.4
San Jacinto	TX	**East Fork San Jacinto**	1.3

3.A.1.A. Mountain Fork Population (Red River Basin)

The headwaters of the Mountain Fork River originate in the Ouachita Mountains of southeast Oklahoma, flowing southeast into Arkansas before turning southwest, reentering Oklahoma and eventually flowing into Broken Bow Reservoir. Five Louisiana pigtoe were first detected in Mountain Fork above Broken Bow Reservoir in 2018 at a single location in Polk County, Arkansas (Posey 2018, p. 2). Spooner and Vaughn (2007, p.14) previously surveyed 23 sites in Arkansas and Oklahoma above Broken Bow Reservoir without detecting Louisiana pigtoe, however, Wabash pigtoe (*Fusconaia flava*), a morphologically similar species, was detected. Voucher specimens were retained in both survey efforts but genetic confirmation was not reported. The Mountain Fork population, based on detections at only 1 site, is approximately 2.3 river miles in length.

3.A.1.B. Little River/Rolling Fork Population (Red River Basin)

The Rolling Fork reach of this population extends from the confluence of the Rolling Fork with the Little River near Horatio, Arkansas, upstream to approximately 1.4 miles below DeQueen Lake. The Little River reach begins near Alleene, Arkansas and continues upstream to near Garvin, Oklahoma. Multiple survey efforts have observed a total of 280 Louisiana pigtoe in the Little River/Rolling Fork population from 2013 to 2018 (Bouldin et al. 2013, entire; Davidson et al. 2014, entire; AGFC 2018, entire; Davidson 2017, entire; Inoue 2018, p. 1). The combined length of the Little River/Rolling Fork population is approximately 103.6 river miles within McCurtain County, Oklahoma, and Sevier and Little River Counties, Arkansas.

3.A.1.C. Cossatot River Population (Red River Basin)

The Cossatot River population begins near its confluence with Little River at Millwood Lake and extends upstream to approximately 5 miles below Gillham Lake. In 2013, Louisiana pigtoe were first recorded from the Cossatot River at 39 sites with 148 detections (AGFC 2018, entire). The length of the Cossatot River population is estimated at 41.9 river miles in Sevier County, Arkansas.

3.A.1.D. Saline River Population (Red River Basin)

The Saline River population extends approximately 28 miles upstream from its confluence with the Little River at Millwood Lake. In 2013, the Saline River was sampled for the first time at 8 sites resulting in 18 Louisiana pigtoe detections (Bouldin et al. 2013, entire; AGFC 2018, entire). The Saline River population occupies an estimated 27.9 river miles in Sevier and Howard Counties, Arkansas.

3.A.1.E. Lower Little River Population (Red River Basin)

The Lower Little River population extends approximately 8.5 miles downstream of the Millwood Dam. The freshwater mussel community of the lower Little River was sampled only in 2012 resulting in 2 live and 2 recent dead Louisiana pigtoe detections at 3 sites (AGFC 2018, entire). The Lower Little River population is approximately 8.5 river miles in length within Little River and Hempstead Counties, Arkansas.

3.A.1.F. Big Cypress Bayou Population (Big Cypress-Sulphur Basin)

The Big Cypress Bayou portion of the Big Cypress Bayou population extends from approximately 0.5 miles downstream of the confluence with Little Cypress Bayou to approximately 4.5 miles downstream of Ferrell's Bridge Dam on Lake O' the Pines. The Little Cypress Bayou reach of the population extends approximately 10.6 miles upstream of its confluence with Big Cypress Bayou. From 2011 to 2016, 27 Louisiana pigtoe were observed at 12 sites from this population (Randklev 2018, entire). The length of the entire Big Cypress Bayou Population is estimated at 32.3 river miles in Marion and Harrison Counties, Texas.

3.A.1.G. Pearl River Population (Pearl Basin)

The Pearl River population extends from a point approximately 2.5 miles northwest of Nicholson, Mississippi, to the Ross Barnett Reservoir dam located approximately 8 mile northeast of Jackson, Mississippi. From 2005 to 2018, 7 Louisiana pigtoe were observed from 3 sites on the Pearl River (Johnson et al. 2019, p. 11). Additional surveys are needed, but based on the limited information available we estimate the length of the Pearl River population at 280.8 river miles encompassing portions of St. Tammany and Washington Parishes, Louisiana, and Copiah, Hinds, Lawrence, Marion, Pearl River, Rankin, and Simpson Counties, Mississippi.

3.A.1.H. Calcasieu River Population (Calcasieu-Mermentau Basin)

The Calcasieu River population extends upstream from approximately 1.3 miles south of Calcasieu, Louisiana, to 0.5 miles upstream of the State Highway 121 bridge south of Hineston, Louisiana. During a survey effort conducted in 2000, "several" Louisiana pigtoe were reported from 2 sites (LNHP 2018, entire). In a 2019 survey effort, 14 Louisiana pigtoe were recorded at 2 sites (Kinney 2019, p. 2). The Calcasieu River population extends for an estimated 9.9 river miles in Rapides Parish, Louisiana.

3.A.1.I. Sabine River Population (Sabine River Basin)

The Sabine River population begins approximately 3 miles upstream of the State Highway 43 bridge in Harrison and Rusk Counties and continues 86.8 river miles upstream through Gregg, Upshur, Smith, and Wood Counties, Texas, to approximately 1 mile downstream of the Farm-to-Market Road 14 bridge south of Hawkins, Texas. From 2010 to 2018, 39 live and 1 recently dead Louisiana pigtoe were reported from 12 sites within this population (Ford et al. 2016b, p. 27; Randklev 2018, entire).

3.A.1.J. Bayou Anacoco Population (Sabine River Basin)

The Bayou Anacoco population, located in Vernon Parish, is comprised of 9.1 river miles located west of Rosepine, Louisiana. In 2010, 14 Louisiana pigtoe were collected from 2 sites within this population (Randklev 2013b, p. 269; LNHP 2018, entire).

3.A.1.K. Angelina River Population (Neches River Basin)

The Angelina River population, located in Angelina, Cherokee, and Nacogdoches Counties, Texas, begins approximately 1.3 miles downstream of the U.S. Highway 59 bridge and extends upstream 53.2 river miles to approximately 0.8 miles upstream of Farm-to-Market Road 343. From 2006 to 2018, 16 sites were surveyed with 36 live and 1 recently dead Louisiana pigtoe observations (Randklev 2018, entire).

3.A.1.L. Neches River Population (Neches River Basin)

The Neches River population runs 203.0 river miles through portions of Anderson, Angelina, Cherokee, Houston, Jasper, Polk, Trinity, and Tyler Counties, Texas. The upper extent of this population is immediately downstream of Lake Palestine's Blackburn Crossing Dam and continues downstream to approximately 0.7 miles below the U.S. Highway 69 bridge south of Nancy, Texas. From 2006 to 2018, 1,030 live and 3 recently dead Louisiana pigtoe were recorded at 147 sites within the delineated Neches River population (Randklev 2018, entire; Ford et al. 2016b, p. 27; and Ford et al. 2018), making it the largest known population both in terms of occupied river miles and number of individuals detected.

3.A.1.M. Lower Neches River Population (Neches River Basin)

The Lower Neches River population is comprised of portions of the Neches River below B.A. Steinhagen Lake's Town Bluff Dam, Big Sandy Creek, and Village Creek within Hardin, Jasper, Polk, and Tyler

Counties, Texas. The Big Sandy segment begins at its confluence with Kimball Creek, which then becomes Village Creek and continues upstream to approximately 4 miles west of Dallardsville, Texas. The population includes Village Creek in its entirety. The Neches River segment of this population starts approximately 0.5 mile downstream of the confluence with Village Creek and continues upstream for approximately 53 miles. The combined length of the Lower Neches River Population is 160.4 river miles. From 2000 to 2018, 123 live and 8 recently dead Louisiana pigtoe were collected from 28 sites within this population (Randklev 2018, entire).

3.A.1.N. East Fork San Jacinto River Population (San Jacinto River Basin)

The East Fork San Jacinto River population's lower extent is approximately 0.9 mile downstream of Farm-to-Market Road 2090 near Plum Grove, Texas, and continues up the East Fork San Jacinto River to its upper extent, located approximately 0.4 mile upstream of the same bridge crossing. The length of this population is 1.3 river miles. In 2019, 3 live Louisiana pigtoe were recorded at 1 site within the East Fork San Jacinto River population segment (Randklev 2019c, p. 1).

3.A.2. TEXAS HEELSPLITTER

The Texas heelsplitter is endemic to the Neches, Sabine, and Trinity River drainages of east Texas (Howells et al. 1997, pg. 22). The type locality specimen was described by Frierson in 1898 from the Sabine River on the Texas – Louisiana border near Logansport, Louisiana (Frierson 1898, pg. 109).
Within the Neches River drainage, the Texas heelsplitter has been recorded at multiple locations throughout the system below Lake Palestine, including areas downstream of B.A. Steinhagen Reservoir (Vidrine 1993, pg.159; Howells et al. 1996, pg. 96; Howells et al. 1997, pg. 8, 22; Howells 2006, pp. 25-33; Ford et al. 2014, pg. 10; Ford et al. 2016b, p. 22; Randklev 2018, entire) (see Figure 3.2). Within the Sabine River drainage, the species has been recorded at several locations throughout the system from Lake Tawakoni to below Toledo Bend Reservoir (Vidrine 1993, pg. 159; Howells et al. 1996, pg. 96; Howells 2006 pp. 17-21, 83; Ford et al.2010, pg. 6; Hollis 2013, pg. 68; Ford 2016b, pg. 22; Randklev 2018, entire). Within the Trinity River drainage, the species has been recorded at several locations throughout the system, including reservoirs, from Lake Lewisville and Lake Grapevine to Lake Livingston (Howells 2006, pg. 42, 48; Bosman et al. 2015, pg. 15; Randklev 2018, entire). We assume the historical distribution of the species would have included the entirety of the river basins described above where connectivity was not an issue and conditions were suitable (see stream segments highlighted black on Figure 3.2).

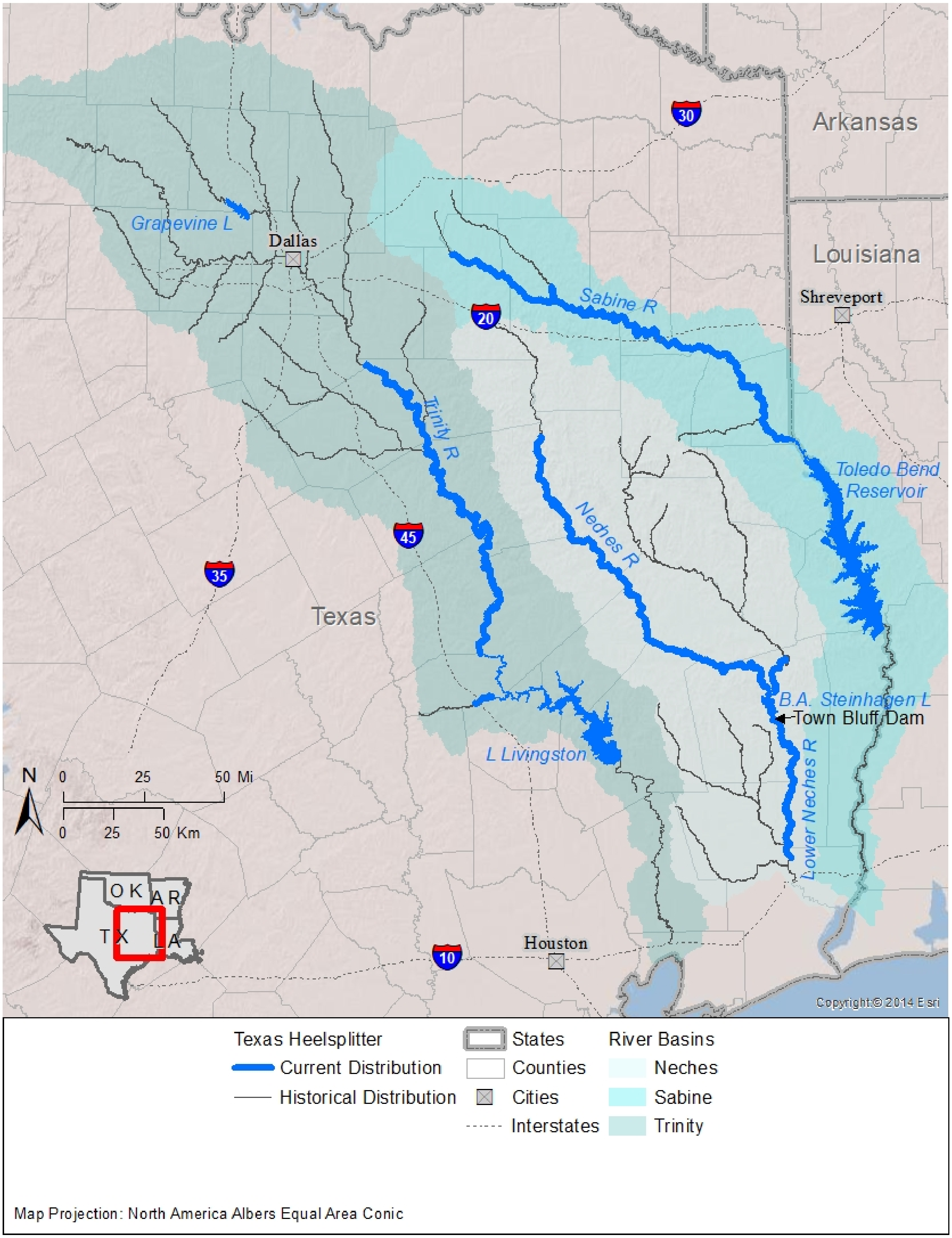


Figure 3.2. *Texas heelsplitter current and historical distribution.*

Current Texas heelsplitter populations (also referred to as focal areas and labeled "Current Distribution" on Figure 3.2 (see stream segments highlighted blue) were determined utilizing the same methodology described above for the Louisiana pigtoe (i.e., by identifying stream reaches with live or recent dead observations since the year 2000) with the exception of the inclusion of impoundments. Impoundments with live or recent dead observations since 2000 were considered occupied in their entirety (due to a paucity of reservoir survey data). No attempt was made to quantify a surrogate parameter for occupied habitat reach length for impoundments.

Table 3.2. Current known populations of Texas heelsplitter and estimated length of occupied reach.

Texas Heelsplitter Focal Areas			
River Basin	**State**	**Population**	**Length of Occupied Reach (miles)**
Sabine	TX/LA	**Sabine River/Toledo Bend**	245.8
Neches	TX	**Neches R/B.A. Steinhagen**	240.9
	TX	**Lower Neches River**	74.2
Trinity	TX	**Grapevine Lake**	n/a
	TX	**Trinity River/Lake Livingston**	203.4

3.A.2.A. Sabine River/Toledo Bend Population (Sabine River Basin)

The Sabine River/Toledo Bend population includes Toledo Bend Reservoir, Sabine River upstream to Lake Tawakoni's Iron Gate Dam, and 7.9 river miles of Lake Fork Creek upstream from its confluence with the Sabine River. From 2005 to 2018, 82 live and 25 recently dead Texas heelsplitters were collected at 88 sites from this population (Randklev 2018, entire; Ford et al. 2016b, p. 27). The Sabine River/Toledo Bend population occupies an estimated 245.8 river miles of the Sabine River in De Soto and Sabine Parishes, Louisiana, and Gregg, Harrison, Newton, Panola, Rains, Rusk, Sabine, Shelby, Smith, Upshur, Van Zandt, and Wood Counties, Texas.

3.A.2.B. Neches River/B.A. Steinhagen Lake Population (Neches River Basin)

The Neches River/B.A. Steinhagen Lake population includes B.A. Steinhagen Lake and the mainstem of the Neches River upstream 240.9 river miles to approximately 0.5 miles upstream of the Farm-to-Market 320 bridge southwest of Cuney, Texas. The population is located in Anderson, Angelina, Cherokee, Houston, Jasper, Polk, Trinity, and Tyler Counties, Texas. Surveys of this population from 2005 through 2018 recorded 54 live and 88 recently dead Texas heelsplitter at 48 sites (Randklev 2018, entire).

3.A.2.C. Lower Neches River Population (Neches River Basin)

The Lower Neches River population in Hardin, Jasper, and Tyler Counties, Texas, extends 52.3 river miles downstream from Lake B.A. Steinhagen's Town Bluff Dam to approximately 2.2 miles upstream of the State Highway 96 bridge, east of Evadale, Texas. Texas heelsplitter observations from this population include 5 live and 12 recently dead individuals collected from 2004 to 2016 at 18 sites (Randklev 2018, entire).

3.A.2.D. Grapevine Lake Population (Trinity River Basin)

The Grapevine Lake population is contained completely within Grapevine Lake (an impoundment on Denton

Creek, a tributary of Elm Fork of the Trinity River) in Denton and Tarrant Counties, Texas. A sampling effort in 2014 found at least 2 gravid female Texas heelsplitter from this population (Randklev 2018, entire).

3.A.2.E. Trinity River/Lake Livingston Population (Trinity River Basin)

The Trinity River/Lake Livingston population occupies a total of 203.4 river miles in portions of Anderson, Ellis, Freestone, Henderson, Houston, Leon, Madison, Navarro, Polk, San Jacinto, Trinity, and Walker Counties, Texas. This population includes Lake Livingston, the Trinity River 193.1 river miles upstream to Ennis, Texas, and 10.3 river miles of Bedias Creek (a tributary of the Trinity River). From 2005 to 2017, 55 live and 6 recently dead Texas heelsplitter were recorded at 25 sites within the Trinity River/Lake Livingston population (Randklev 2018, entire).

3.B. NEEDS OF THE LOUISIANA PIGTOE AND TEXAS HEELSPLITTER

3.B.1. POPULATION RESILIENCY

For these species to maintain viability, their populations or some portion thereof must be resilient to disturbance from stochastic events that vary in duration and intensity. Stochastic events that have the potential to affect mussel populations include 1) high flow events that result in scouring, mobilization of substrates, and burial of mussel beds by large amounts of sediment (these events include flash floods following heavy rains, bank collapse events, etc.), 2) extended droughts and other dewatering events, 3) changes to water quality, including the ongoing or episodic discharge of environmental pollutants or hazardous materials (e.g., oil spill), 4) large-scale depredation events (e.g., collection, natural predation), 5) disease outbreaks, and 6) changes to basic water chemistry (e.g., high water temperature, episodes of low dissolved oxygen). A number of factors influence the resiliency of populations, including occupied stream length, abundance, and recruitment. Elements of occupied habitat also influence resiliency by controlling whether mussel populations can grow to maximize habitat occupancy, thereby increasing the resiliency of populations. These factors and habitat elements are discussed in greater detail below in the context of how they meet the needs of mussels.

POPULATION FACTORS INFLUENCING RESILIENCY

Occupied Stream Length – Most freshwater mussels, including the Louisiana pigtoe and Texas heelsplitter, are found in aggregations called mussel beds that vary in size from about 50 to >5000 square meters (m^2) and are separated by stream reaches in which mussels are absent or rare (Vaughn 2012, p. 2). As discussed above, we define a mussel population at a larger scale than a single mussel bed; it is the collection or series of mussel beds within a stream reach between which infested host fish may travel, allowing for ebbs and flows in mussel bed density and abundance over time throughout the population's occupied reach. Therefore, resilient mussel populations must occupy stream reaches long enough such that stochastic events that adversely affect individual mussel beds do not eliminate the entire population. In other words, repopulation by glochidia-infested fish from other mussel beds within the reach allow the population to recover from the temporary loss of individuals due to occasional disruptive events. We consider populations extending greater than 50 miles to have a high probability of persistence to stochastic events because a single event is unlikely to affect the entire population. Populations occupying reaches between 20 and 50 river miles have a moderate ~~of~~ probability of persistence to stochastic events, while populations occupying reaches less than 20 miles have a low probability of persistence (Table 3.3). We consider probability of persistence a reflection of a species resiliency. Note that, by definition, an extirpated or functionally extirpated population occupies a stream length of approximately (or approaching) zero miles.

Table 3.3. Occupied stream length and corresponding rankings for probabilities of persistence for Louisiana pigtoe and Texas heelsplitter populations.

	Probability of Persistence			
	High	**Moderate**	**Low**	**Functionally Extirpated/Extirpated**
Occupied Stream Length	> 50 river miles	20-50 river miles	<20 river miles	none

Abundance – Populations require a minimum number of individuals to ensure stability and persistence. This threshold is often referred to as the minimum viable population and is generally calculated through a population viability analysis that estimates extinction risk given a number of input variables. There are no published minimum viable population estimates for the Louisiana pigtoe or Texas heelsplitter; therefore, it is unknown how many individuals are required to sustain populations of these mussels. However, population health is dependent on species abundance as well as water availability and the ability for mussels to meet life history needs within their habitats, which can be assessed and was evaluated as part of this report.

It is important to recognize that Louisiana pigtoe observations used to determine abundance in this report may include misidentified individuals. Inoue suggested that without genetic confirmation, identification of Louisiana pigtoe in the field based on shell morphology is questionable, with seasoned experts accurately identifying the species only 76% of the time (2019, p. 1). Unfortunately, previous mussel surveys relied solely on shell morphological characteristics for species identification and genetic confirmation was not available for the majority of reported Louisiana pigtoe historical observations (Randklev 2018, entire). Since there is no way to know the margin of error or to otherwise account for potential misidentifications, we determined abundance based on reported observations (as is). We do not consider misidentification to be an issue for Texas heelsplitter observations, since they are recognizable based on morphological characteristics observed in the field and not easily confused with other species.

Mussel abundance in a given stream reach is a product of the number of mussel beds and the density of mussels within those beds. For populations of Louisiana pigtoe and Texas heelsplitter to be healthy (i.e., resilient), mussel beds of sufficient number and density must be present to allow recovery from natural and local stochastic events, allowing the mussel bed to persist and the overall local population to survive within a stream reach. Mussel abundance is indicated by the number of individuals found during a sample event; mussel surveys are rarely a complete census of the population, but density can be estimated by the number of individuals found during a survey effort using various statistical techniques (i.e., estimate the total population from a subset of surveyed individuals). Since population estimates are not available for all Louisiana pigtoe and Texas heelsplitter populations, and techniques for available surveys are not always directly comparable (i.e., same area size searched, similar search time, etc.), when available we used the number of individuals captured relative to the amount of time surveys were conducted to estimate population abundance, hereafter referred to as catch per unit effort (CPUE). Although CPUE was the preferred metric to estimate population abundance, when CPUE was not available, the number of individuals detected during surveys was used as a surrogate metric. Abundance was calculated per the following guidelines, 1) Overall CPUE was calculated by adding the total number of live individuals detected during surveys since 2000 divided by total survey effort (in person-hours), 2) Negative surveys (where no mussels were found) were not included in the calculations, nor were surveys that did not report time (person-hours), and 3) individuals detected per survey were used to calculate abundance for populations where CPUE data were not available. For sites with survey data spanning several years, abundance was based on the number of individuals detected during the most recent year's comprehensive survey effort. Calculation of abundance in this manner is intended to be an estimate and is considered the best available information when precise population abundance cannot be determined. Using these methods, we are able to estimate if the species is dominant at a site or rare, and examine trends over time. Table 3.4 displays how estimates of relative abundance for each species were defined and used to rank the probability of persistence for populations from high to functionally extirpated.

Table 3.4. Population abundance and corresponding rankings for probability of persistence for Louisiana pigtoe and Texas heelsplitter populations.

	Probability of Persistence			
	High	**Moderate**	**Low**	**Functionally Extirpated/Extirpated**
Population Abundance	Overall CPUE ≥ 4.0 (or ≥100 individuals found per population survey)	Overall CPUE ≥ 2.0 and < 4.0 (or ≥25 and <100 individuals found per population survey)	Overall CPUE ≥ 0.5 and < 2.0 (or ≥3 and <25 individuals found per population survey)	Overall CPUE <0.5 (or <3 individuals found per population survey)

Reproduction/Recruitment – Resilient Louisiana pigtoe and Texas heelsplitter populations must also be reproducing and recruiting young individuals into the population to replace individuals lost to old age, disease, or predation. Population size and abundance are a reflection of habitat conditions, environmental stressors, and other past influences on the population. The ability of populations to successfully reproduce and recruit will determine if a population may be stable, increasing, or decreasing over time. For example, a large, dense mussel population that contains mostly old individuals is not likely to remain large and dense into the future if there are few young individuals to sustain the population over time (i.e., death rates exceed birth rates resulting in negative population growth). Conversely, a population that is less dense but has many young and/or gravid individuals is likely to grow, becoming more densely populated in the future (i.e., birth rates, and subsequent recruitment of reproductive adults, exceed death rates resulting in positive population growth). Detection rates of very young juvenile mussels during routine abundance and distribution surveys are extremely low due to sampling bias because sampling involves tactile searches and mussels < 35 mm ~~are very~~ difficult to detect (Strayer and Smith 2003, pp. 47-48). For this evaluation, we concluded there was evidence of reproduction/recruitment for a population when surveys detected small-sized individuals (near the low end of the detectable range or approximately 35 mm in size) since the year 2000 or gravid females (eggs visible) were observed during the reproductively active time of year (Table 3.5). Sites lacking survey information specific to the presence of gravid females or juveniles due to inadequate effort default to a ranking of low in Table 3.5.

Table 3.5. Reproduction/recruitment and corresponding rankings for probability of persistence for populations of Louisiana pigtoe and Texas heelsplitter.

	Probability of Persistence			
	High	**Moderate**	**Low**	**Functionally Extirpated/ Extirpated**
Reproduction/ Recruitment	50% or more sites with juveniles (<35mm) or gravid females present during breeding season. Fish host(s) present.	25-50% of sites inhabited by juveniles (<35mm) and or gravid females present during breeding season. Fish host(s) present in moderate abundance.	< 25% of sites inhabited by juveniles (<35mm) or gravid females present during breeding season. Fish host(s) present in low numbers and/or ability to disperse is reduced.	No gravid or juvenile individuals present

HABITAT FACTORS INFLUENCING RESILIENCY

Habitat Structure/Substrate – Suitable habitat structure and substrates vary among species of freshwater mussels, including between the Louisiana pigtoe and Texas heelsplitter. All mussel species need stable substrate in which to anchor. The Louisiana pigtoe occurs primarily in stream segments composed of riffle and run habitat where suitable substrates are present. Typical substrates utilized by the Louisiana pigtoe include gravel and cobble, but the species has also been observed in finer substrates including sand and silt. Sedimentation can negatively impact Louisiana pigtoe populations by burying individuals and degrading anchoring habitat. The Texas heelsplitter occurs in river systems and lentic waters (lakes or other non-flowing systems) primarily in pools and backwater habitats. Substrates providing adequate anchoring habitat for the Texas heelsplitter include mud, sand, and silt. Sedimentation can also negatively impact Texas heelsplitter populations by burying individuals. The habitat structure and substrate needs of both species are displayed in Table 3.6.

Table 3.6. Habitat structure and substrate conditions and corresponding rankings for probability of persistence for populations of Louisiana pigtoe and Texas heelsplitter.

	Probability of Persistence			
	High	**Moderate**	**Low**	**Functionally Extirpated/ Extirpated**
Habitat Structure/Substrate for Louisiana pigtoe	Riffle and run habitat common. Substrates are stable. Gravel and cobble substrate sufficient to provide anchoring habitat. Low levels of sedimentation on substrate.	Riffle and run habitat uncommon. Substrates are mostly stable. Gravel and cobble substrate sufficient to provide anchoring habitat with some mobilization of particles and light sedimentation on substrate.	Riffle and run habitat rare or absent; substrates are mostly unstable; habitat eroded, or being buried by mobilized sediments from upstream.	No suitable habitat present
Habitat Structure/Substrate for Texas heelsplitter	Pool and backwater habitats common. Stable mud, sand, and silt substrates sufficient to provide anchoring habitat. Low levels of sedimentation on substrate.	Pool and backwater habitats uncommon. Mud, sand, and silt substrates mostly stable and sufficient to provide anchoring habitat with some mobilization of particles and light sedimentation on substrate.	Pool and backwater habitat absent; substrates mostly unstable, habitat eroded, or being buried by mobilized sediments from upstream.	No suitable habitat present

Hydrological Regime – Freshwater mussels need water for survival. Some species are more resilient to low-velocity water than others and inhabit lentic waters (lakes or other non-flowing systems) including the Texas heelsplitter. Neither Louisiana pigtoe nor Texas heelsplitter are able to persist in or tolerate areas that are regularly dewatered. High stream flows can degrade mussel habitat by producing shear stress capable of dislodging mussels and scouring stream bed substrates. Low stream flows can reduce the amount of anchoring habitat and negatively influence water quality parameters necessary for freshwater mussel persistence. Both high and low flows can also influence the presence or absence of host fish. The hydrological needs of both mussel species are displayed in Table 3.7.

Table 3.7. Hydrological regimes and corresponding rankings for probability of persistence for populations of Louisiana pigtoe and Texas heelsplitter.

	Probability of Persistence			
	High	**Moderate**	**Low**	**Functionally Extirpated/Extirpated**
Hydrological Needs of Louisiana pigtoe	Flowing water present year-round. No recorded periods of zero flow days, even during droughts. High flows and shear stress capable of causing bed movement or dislocation of mussels minimally impacts population (or habitat).	Flowing water present year-round (no zero flow days). High flows and shear stress capable of causing bed movement or dislocation of mussels moderately impacts population (or habitat).	Flowing water is not present year-round. River may become isolated pools or dry river bed seasonally. Zero flow days occur and riffles become dry. High flows and shear stress capable of causing bed movement or dislocation of mussels significantly impacts population (or habitat).	Dry stream bed or zero flow days occur often enough to preclude survival. Substrates are mostly unstable; high flows and shear stress are routinely capable of causing bed movement or dislocation of mussels (i.e., occurs frequently), resulting in unsuitable habitat for mussels.
Hydrological Regime of Texas heelsplitter	Slow to moderate flowing water present year-round. No recorded periods of zero flow days, even during droughts. Extremely high, low, and/or erratic (e.g. significant fluctuations in flow over a short time) flows are rare. Little fluctuation of water levels in occupied reservoirs.	Slow to moderate flowing water present year-round (no zero flow days), however, extremely high, low, and/or erratic flows occur infrequently. Moderate fluctuation of water levels in occupied reservoirs.	Slow to moderate flowing water is not present year-round. River may become isolated pools or dry river bed seasonally. Zero flow days occur and riffles become dry. Extremely high, low, and/or erratic flows are routine. High fluctuation of water levels in occupied reservoirs.	Dry stream bed or zero flow days occur often enough to preclude survival. Extremely high, low, and/or erratic flows are frequent, resulting in unsuitable habitat for mussels. Large magnitude reservoir drawdowns occur frequently.

Water Quality – Freshwater mussels, as a group, are very sensitive to changes in water quality, including parameters such as temperature, dissolved oxygen, salinity, ammonia, pH and a variety of environmental pollutants. Habitats with naturally clean water that is free of pollutants and contains appropriate levels of these parameters are considered suitable, while habitats with levels outside of the appropriate range for mussels are considered unsuitable or degraded habitat. Basic water quality conditions for the Louisiana pigtoe and Texas heelsplitter as they relate to our estimates of probability of persistence are displayed in Table 3.8.

Table 3.8. Water quality conditions and corresponding rankings for probability of persistence for populations of Louisiana pigtoe and Texas heelsplitter.

	Probability of Persistence			
	High	**Moderate**	**Low**	**Functionally Extirpated/Extirpated**
Water Quality	Overall WQ is good or excellent. No known contaminants, dissolved oxygen sufficient, and no thermal extremes documented. Total dissolved solids (TDS) stable or decreasing.	Overall WQ is good to fair. Contaminants known, moderate to low dissolved oxygen, and occasional temperature extremes documented. Not believed to be at levels that threaten mussel survival. TDS stable or slightly increasing.	Overall WQ is fair to poor. Contaminants known, low dissolved oxygen, and temperature extremes documented. TDS increasing. Levels sufficient enough to threaten mussel survival.	Overall WQ is limiting for aquatic life. Water quality degraded enough to preclude mussel habitation.

3.B.2. SPECIES REPRESENTATION

Maintaining species representation in the form of genetic and ecological diversity is important in safeguarding the ability of Louisiana pigtoe and Texas heelsplitter populations to adapt to future environmental changes. Mussel species like the Louisiana pigtoe and Texas heelsplitter need to retain populations throughout their range to maintain their overall potential, both genetically and ecologically (i.e., across habitats with varying capacity to meet life history attributes), to appropriately buffer the species against stochastic events and maintain their ability to respond to environmental changes over time (Jones et al. 2006, p. 531). The genetic diversity of populations of Louisiana pigtoe and Texas heelsplitter is ~~not currently available~~, although both species may have lost genetic diversity as populations have contracted over time or been reduced or extirpated by human activities. As such, maintaining the remaining representation in the form of genetic and ecological diversity will be important to preserving the capacity of these populations to adapt to future environmental change.

The major river basins within the historical distribution of the Louisiana pigtoe described in section 3.A.1. span across multiple states and ecoregions, including Blackland Prairie, East Central Plains, and South Central Plains in Texas, the Ouachita Mountains of Oklahoma and Arkansas, and the Rolling and Coastal Plains of Mississippi. The major river basins within the historical distribution of the Texas heelsplitter described in section 3.A.2. span multiple ecoregions in Texas, including Cross Timbers, Blackland Prairie, East Central Plains, and South Central Plains. Maintaining this ecological and spatial diversity in the future will be important to preserve representation for both species.

3.B.3. SPECIES REDUNDANCY

Both the Louisiana pigtoe and Texas heelsplitter need multiple resilient populations distributed throughout their range to provide adequate redundancy. The more populations that exist, particularly densely populated populations, and the wider the distribution of those populations, the more redundancy the species will exhibit. Redundancy reduces the risk that a large portion of the species' range will be negatively affected by a single catastrophic natural or anthropogenic-induced event at any given point in time. Species that are well-distributed across their historical range are considered less susceptible to extinction and more likely to remain viable compared to species that are confined to a small portion of their historical range (Carroll et al. 2010, entire; Redford et al. 2011, entire). Historically, populations of both mussel species were hydrologically connected by fish migration within each river basin including their tributaries. Impoundments and other barriers to fish movement, such as river reaches with unsuitable water quality (e.g., high salinity or temperature), effectively isolate populations from one another, making repopulation of extirpated locations from nearby populations unlikely without human intervention (i.e., active restocking).

Chapter 4 - Current Condition of East Texas Mussels

This assessment defines a mussel population as a stream reach that is occupied by a collection of mussel beds through which host fish infested with glochidia may travel freely, allowing for dispersal of juveniles among and within mussel beds. This chapter discusses the current condition of East Texas Mussel populations for each species and evaluates the resiliency of those populations.

4.A. Methodology for Population Resiliency Assessment

For each species and each population, we developed and assigned condition categories for three population factors (Occupied Stream Length, Abundance, Reproduction/Recruitment) and three habitat factors (Habitat Structure/Substrate, Hydrological Regime, and Water Quality); see "Chapter 3.B. Needs of the Louisiana pigtoe and Texas heelsplitter." Occupied stream length was calculated for populations of both species using ArcGIS by summing the stream miles between locations known to be occupied since 2000 (based on available survey data). The five remaining factors were scored by U.S. Fish and Wildlife Service and state wildlife agency biologists based on consensus using a combination of expert opinion and information available from our files, including information that was provided to our office by other agencies and academia. For each population, the six categories were assigned a numerical value: "3" for healthy (high condition), "2" for moderately healthy (moderate condition), "1" for unhealthy (low condition), and "0" for extirpated or functionally extirpated. Values for the six factors were then averaged, resulting in an overall condition value that was compared back to the individual category value for population abundance. This comparison was necessary to ensure that the overall condition values did not exceed the population abundance value (i.e., overall population condition was capped at the population abundance condition value) because abundance is considered a direct measure of fecundity and reproductive success, versus the other factors which are indirect measures of condition, like water quality or hydrology. The resulting current condition value or category for each population is a qualitative estimate based on the analysis of the three population factors and three habitat elements. Table 4.1 displays the presumed probability of persistence and probability of extirpation over 20 years (approximate time needed for at least three to five generations of East Texas mussels) for populations that fall into one of four current condition categories. For example, for our analysis we assumed that a mussel population rated as having a high overall current condition would have less than a 10% probability of becoming extirpated or functionally extirpated over 20 years into the future.

Table 4.1. Presumed probabilities of persistence and extirpation for each overall current condition category over 20 years.

Likelihood of Persistence:	High	Moderate	Low	Extirpated/Functionally Extirpated
Range of Presumed Probability of Persistence over ~20 years	>90%	60 – 90%	10 – 60%	< 10%
Range of Presumed Probability of Extirpation over ~20 years	<10%	10 – 40%	40 – 90%	> 90%

4.B. LOUISIANA PIGTOE

4.B.1. CURRENT CONDITIONS

Based on our analysis, the total combined stream length currently occupied by the 14 remaining Louisiana pigtoe populations described in Chapter 3 is 1,021 river miles, which is approximately 15% of the presumed historical range for the species (6,716 river miles). Although a precise historical range for the species is unknown, and occupied areas would likely fluctuate naturally due to a variety of environmental conditions, this represents an 85% reduction to the range of the species.

To summarize the overall current conditions of Louisiana pigtoe populations, we assigned each population to one of four condition categories (high, moderate, low, or extirpated/functionally extirpated) based on an evaluation of the six population and habitat factors discussed in Chapter 3. Table 4.2 provides the definitions we used to assign conditions for the six factors. Table 4.3 presents the condition we assigned for all six factors as well as the overall condition for each of the 14 remaining Louisiana pigtoe populations. The overall condition of each population is also displayed graphically within a map of the historical range of the species in Figure 4.1. To evaluate the overall condition for each population, Appendix B, Table B.1 was developed. Within Table B.1, the cause and effects of stressors for each factor were considered through a combination of literature pertinent to specific factors and the elicitation of subject matter experts within the SSA working group.

Table 4.2. Definitions for population and habitat characteristics used to assign the current condition of Louisiana pigtoe populations (see Table 4.3).

	Population Factors			Habitat Factors		
Condition	**Occupied Habitat** (stream length)	**Abundance**	**Reproduction/ Recruitment**	**Habitat Structure/ Substrate**	**Hydrology**	**Water Quality**
High	> 50 river miles	Catch per unit effort (CPUE) ≥ 4.0 *(or ≥100 individuals found per population survey)	50% or more sites with juveniles (<35mm) and gravid females present during breeding season. Fish hosts present (i.e., not limiting).	Riffle and run habitat common. Substrates are stable. Gravel and cobble substrate sufficient to provide lodging. Low levels of sedimentation on substrate.	Flowing water present year-round. No recorded periods of zero flow days, even during droughts. High flows and shear stress capable of causing bed movement or dislocation of mussels minimally impacts population (or habitat).	Overall WQ is good or excellent. No known contaminants, dissolved oxygen sufficient, and no thermal extremes documented. Pollutants indicative of anthropogenic degradation, such as total dissolved solids (TDS), are stable or decreasing.
Moderate	20–50 river miles	4.0 > CPUE ≥ 2.0 *(or ≥25 and <100 individuals found per population survey)	25-50% of sites inhabited by juveniles (<35mm) and gravid females present during breeding season. Fish hosts present in moderate abundance.	Riffle and run habitat uncommon. Substrates are mostly stable. Gravel and cobble substrate sufficient to provide lodging with some mobilization of particles and light sedimentation on substrate.	Flowing water present year-round (no zero flow days). High flows and shear stress capable of causing bed movement or dislocation of mussels moderately impacts population (or habitat).	Overall WQ is fair. Contaminants known; low dissolved oxygen, and temperature extremes documented. Not believed to be at levels that threaten mussel survival. TDS stable or slightly increasing.
Low	< 20 river miles	2.0 > CPUE ≥ 0.5 *(or ≥3 and <25 individuals found per population survey)	< 25% of sites inhabited by juveniles (<35mm) and gravid females present during breeding season. Fish host present in low numbers and/or ability to disperse is reduced.	Riffle and run habitat rare or absent; Substrates are mostly unstable; habitat eroded or being buried by mobilized sediments from upstream.	Flowing water is not present year-round. River may become isolated pools or dry river bed seasonally. Zero flow days occur and riffles become dry. High flows and shear stress capable of causing bed movement or dislocation of mussels significantly impacts population (or habitat).	Overall WQ is poor. Contaminants known; low dissolved oxygen, and temperature extremes documented. TDS increasing. Pollutant levels sufficient to threaten mussel survival.
Extirpated/ Functionally Extirpated	none	CPUE <0.5 *(or <3 individuals found per population survey)	No gravid or juvenile individuals present	No suitable habitat present.	Dry stream bed or zero flow days occur often enough to preclude survival. Substrates are mostly unstable; high flows and shear stress are routinely capable of causing bed movement or dislocation of mussels (i.e., occurs frequently), resulting in unsuitable habitat for mussels.	Overall WQ is limiting for aquatic life. Water quality degraded enough to preclude mussel habitation.

*the number of individuals found per most recent comprehensive population survey were used to rank Abundance when CPUE information was not available.

Table 4.3. The estimated current condition of known Louisiana pigtoe populations*; where high condition = 3 (green box), moderate condition = 2 (yellow box), low condition = 1 (red box), and extirpated/functionally extirpated = 0 (grey box).
*See Appendix B, Table B.1 for supporting information used to score population and habitat factors.

		Population Factors			Habitat Factors			Overall Condition (Viability)
River Basin	**Population**	**Occupied Habitat**	**Abundance**	**Reproduction/ Recruitment**	**Habitat Structure/ Substrate**	**Hydrology**	**Water Quality**	
Red	Mountain Fork	1	1	1	1	2	1	1
	Little River/Rolling Fork	3	2	3	2	2	2	2
	Cossatot River	2	3	3	3	2	2	3
	Saline River	2	1	1	1	2	2	1
	Lower Little River	1	0	1	1	1	1	0
Big Cypress	Big Cypress Bayou	2	2	1	2	2	2	2
Calcasieu-Mermentau	Calcasieu River	1	1	1	3	2	2	1
Pearl	Pearl River	3	1	1	2	2	2	1
Sabine	Sabine River	3	0	1	3	2	2	0
	Bayou Anacoco	1	2	1	3	2	2	2
Neches	Angelina River	3	1	1	3	3	2	1
	Neches River	3	3	2	3	3	2	3
	Lower Neches River	3	2	2	3	2	2	2
San Jacinto	East Fork San Jacinto River	1	1	1	1	2	2	1

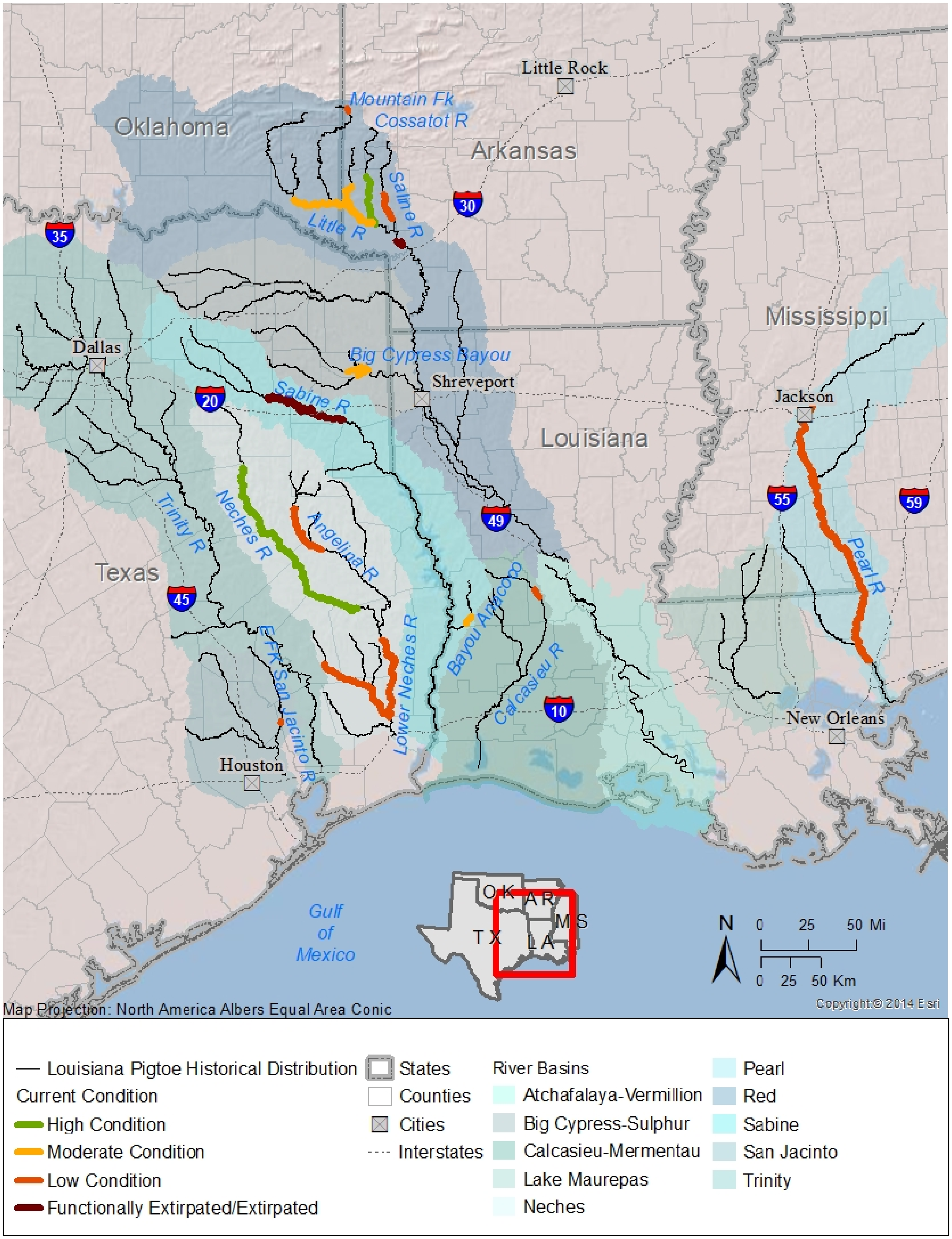


Figure 4.1. *Location and estimated current condition of 14 remaining populations of Louisiana pigtoe within the historical range of the species.*

4.B.2. CURRENT POPULATION RESILIENCY

Resiliency describes the ability of a species to withstand stochastic disturbance. Resiliency is positively related to population size and growth rate and may be influenced by connectivity among populations. Generally speaking, populations need abundant individuals within habitat patches of adequate area and quality to maintain survival and reproduction in spite of natural and anthropogenic disturbance. Resilient populations have the ability to rebound from events that cause mortality or otherwise temporarily reduce fedundity to restore the overall population back to pre-disturbance levels within a relatively short amount of time (e.g., 2-5 years, depending on the magnitude of the event). Based on our analysis, the Louisiana pigtoe currently persists as 14 populations across 5 states and within portions of 7 separate river basins (Big Cypress-Sulphur, Calcasieu-Mermentau, Neches, Pearl, Red, Sabine, and San Jacinto; Chapter 3).

Within the Big Cypress-Sulphur River basin in northeast Texas, Louisiana pigtoe currently occupy portions of Big Cypress Bayou, a drainage that extends approximately 150 miles. The Big Cypress Bayou population occupies approximately 32 miles of river at the confluence of Big Cypress Bayou and Little Cypress Bayou located between Lake O' the Pines and Caddo Lake. The current condition evaluation for this population determined that occupied habitat reach length, abundance, habitat structure/substrate, hydrology, and water quality were in moderate condition (Tables 4.2 and 4.3). Reproduction/ recruitment was determined to be in low condition due to a lack of reported juveniles or gravid females (Randklev 2018, entire). This single population is estimated to have a moderate overall current condition and, therefore, moderate resiliency (Table 4.3).

Louisiana's Calcasieu-Mermentau River basin has a single population on a small portion of the upper mainstem Calcasieu River. The Calcasieu River is approximately 200 miles long but Louisiana pigtoe are currently only known to occur along a 10 mile section in Calcasieu Parish. The current condition evaluation for this population determined that habitat structure/substrate was in high condition while hydrology and water quality were in moderate condition (Tables 4.2 and 4.3). Occupied habitat reach length, abundance, and reproduction/recruitment were found to be in low condition, primarily due to the low number and distribution of surveys performed within the Calcasieu River basin and resulting lack of data (LNHP 2018, entire). This population has a low overall current condition, which corresponds to low resiliency.

The Neches River basin in Texas has 3 populations of Louisiana pigtoe, one each in the Angelina River, Neches River (above B.A. Steinhagen reservoir), and Lower Neches River (below B.A. Steinhagen). These 3 populations combined encompass over 400 miles of river in a basin that many experts believe contains some of the best remaining habitat for freshwater mussels in Texas. The Neches River and Lower Neches River populations are hydrologically isolated from each other by an impoundment that forms B.A. Steinhagen Lake known as Town Bluff Dam, while the Angelina River population is isolated from the Neches River population by Sam Rayburn Dam and Reservoir. The Angelina River population current condition evaluation (Tables 4.2 and 4.3) found that occupied habitat reach length, habitat structure/substrate, and hydrology were high condition; water quality was in moderate condition; and abundance and reproduction/recruitment were in low condition, due to low CPUE and lack of juvenile or gravid female presence data, respectively (Randklev 2018, entire). The Neches River population current condition evaluation determined that occupied reach habitat length, abundance, habitat structure/substrate, and hydrology were in high condition, while reproduction/recruitment and water quality were in moderate condition. No population or habitat current condition factors were determined to be low for the Neches River population. The Lower Neches River population current condition evaluation found occupied habitat reach length and habitat structure/substrate in high condition while reproduction/recruitment, hydrology, and water quality were moderate condition. The Lower Neches River population abundance was in low condition due to low CPUE (Randklev 2018, entire). The Angelina River population and Lower Neches River population have a low overall current condition, and the Neches River population has a high overall current condition; resiliency for these populations is low, low, and high respectively.

The Pearl River basin in Louisiana and Mississippi has a single population of Louisiana pigtoe within the mainstem Pearl River that extends approximately 150 miles below Ross Barnett Dam near Jackson MS to Picayune MS (upstream of Interstate 59). A new impoundment proposed by the Rankin-Hinds Pearl River Flood and Drainage Control District 9 miles downstream of Ross Barnett Reservoir intended for flood control is still under review. The current condition evaluation for the Pearl River population determined that occupied habitat reach length was in high condition; habitat structure/substrate, hydrology, and water quality were in moderate condition; and abundance and reproduction/recruitment were in low condition due to the few ~~number of~~ individuals observed and lack of juvenile or gravid female presence (Johnson et al. 2019, p.11). The Pearl River population has an estimated overall low current condition and low resiliency.

The Red River basin contains 5 distinct populations, all within the upper reaches of the Little River drainage in Arkansas and Oklahoma, including populations in the Cossatot River, Little River/Rolling Fork, Lower Little River, Mountain Fork, and Saline River. Millwood Lake, located in southwest Arkansas, hydrologically separates the Cossatot River, Saline River, Little River/Rolling Fork, and Lower Little River populations from one another. The Mountain Fork population, located near the headwaters, is hydrologically isolated from the Little River/Rolling Fork population by Broken Bow Lake, an impoundment on Mountain Fork of the Little River in southeast Oklahoma. The Cossatot River population current conditions evaluation found that abundance, reproduction/recruitment, and habitat structure/substrate were in high condition; occupied habitat reach length, hydrology, and water quality were in moderate condition; and no habitat or population factors were determined to be in low condition (Tables 4.2 and 4.3). The Little River/Rolling Fork population current condition evaluation determined occupied habitat reach length and reproduction/recruitment were high condition. All other population and habitat factors were in moderate condition. The Mountain Fork population current condition evaluation determined that only hydrology was in moderate condition while all other habitat and population factors were in low condition primarily due to low abundance, high agricultural land use within this headwaters river system, and resulting impacts to other habitat factors, such as water quality and habitat structure/substrate (Tables 4.2 and 4.3). The Saline River population current condition evaluation found occupied habitat reach length, hydrology, and water quality in moderate condition while abundance, reproduction/recruitment, and habitat structure/substrate were in low condition. The Lower Little River population current conditions evaluation determined that all population and habitat factors were in low condition except abundance, which was functionally extirpated due low numbers of individuals observed in this focal area (AGFC 2018, entire). In summary, the Cossatot River population has a high overall current condition, the Little River/Rolling Fork Population has a moderate overall current condition, the Mountain Fork and Saline River populations have a low overall current condition, and the Lower Little River population is considered functionally extirpated. The predicted resiliency for these populations matched the current condition (e.g., high current condition = high resiliency, etc.)

There are two known Sabine River populations, one located along 85 miles of river between State Highway 14 near Hawkins, Texas downstream to above the State Highway 43 crossing near Tatum, Texas, and a second population within a 9 mile segment of Bayou Anacoco in Louisiana. These populations are hydrologically separated by Toledo Bend Dam and Reservoir. The Sabine River population current condition evaluation determined that occupied habitat reach length and habitat structure/substrate were high condition; hydrology and water quality were moderate condition; and reproduction/recruitment in low condition. However, abundance was functionally extirpated due to low reported CPUE (Randklev 2018, entire). The Bayou Anacoco population current conditions evaluation found habitat structure/substrate was high condition; abundance, hydrology, and water quality were in moderate condition; and occupied habitat reach length and reproduction/recruitment were low condition due to the distribution of observed individuals and lack of reported juveniles or gravid females (Randklev 2018, entire). The Sabine River population is considered functionally extirpated due to the very low number of individual mussels found during recent surveys, and therefore has little to no resiliency. The Bayou Anacoco population is in moderate current overall condition and has moderate resiliency.

The East Fork San Jacinto River population located, near Plum Grove, Texas, occupies a 1.3 mile segment of stream. The population current condition evaluation found hydrology and water quality were moderate condition while the other population and habitat factors were low condition (Tables 4.2 and 4.3). The East Fork San Jacinto River population was determined to be in overall low condition due to the limited number of individuals found. This population was estimated to have low resiliency.

4.B.3. CURRENT SPECIES REPRESENTATION

Representation describes the ability of a species to adapt to changing environmental conditions over time. It is characterized by the breadth of genetic and environmental diversity within and among populations. Our analysis explores the relationship between the species life history and the influence of genetic and ecological diversity and the species ability to adapt to changing environmental conditions over time.

We consider Louisiana pigtoe to have representation in the form of genetic, ecological, and geographical diversity between each of 7 river basins: Big Cypress-Sulphur, Calcasieu-Mermentau, Neches, Pearl, Red, Sabine, and San Jacinto. Because there are no un-impounded, freshwater connections that allow movement between the 7 basins, for our analysis we treated each river basin as a separate area of representation.

4.B.4. CURRENT SPECIES REDUNDANCY

Redundancy describes the ability of a species to withstand and recover from catastrophic events. High redundancy is achieved through multiple populations that serve to spread risk, thereby reducing the impact that any one event might have in terms overall loss to the species. Redundancy is characterized by having multiple healthy, resilient populations distributed across the range of the species. It can be measured by population number, resiliency, spatial extent, and degree of connectivity. Our analysis explored the influence of the number, distribution, and connectivity of populations on the species' ability to withstand catastrophic events.

Within identified representation areas, the Big Cypress-Sulphur, Calcasieu-Mermentau, Pearl, and San Jacinto River basins each have only 1 known current population and therefore lack redundancy. The Sabine River basin has 2 separate populations but lacks redundancy due to one population being functionally extirpated. The Neches and Red River basins each currently have 4 viable populations (the Lower Little River population in the Red River basin is considered functionally extirpated), however each population is hydrologically isolated within their respective river basins and are, therefore, considered to provide only limited redundancy.

4.C. TEXAS HEELSPLITTER

4.C.1. CURRENT CONDITIONS

The stream length currently occupied by the 5 known Texas heelsplitter populations (see Chapter 3) combined equals 764 river miles including 4 reservoirs, which equates to 24.3% of more than 3,146 river miles that the species once occupied historically. This approximate range reduction assumes the species continuously occupied its entire historical range, which is unlikely given the species' specialized habitat preferences. Due to a lack of research into Texas heelsplitter habitat needs in lacustrine environments and uncertainty whether those populations function as viable populations, no attempt was made to quantify occupied habitat in reservoirs.

To summarize the overall current conditions of Texas heelsplitter populations, we assigned each population to one of four condition categories based on an assessment of six factors, as described in Section 4.B.1 above and as displayed in Table 4.4. Table 4.5 presents the estimated overall condition of Texas heelsplitter populations, which is also displayed geographically across the range of the species in Figure 4.2. To evaluate the overall condition for each population, Appendix B, Table B.1 was developed. Within Table B.1, the cause and effects of stressors for each factor were considered through a combination of literature pertinent to specific factors and the elicitation of subject matter experts within the SSA working group.

Table 4.4. Definitions for population and habitat characteristics used to assign the current condition of Texas heelsplitter populations (see Table 4.5)

	Population Factors			Habitat Factors		
Condition	**Occupied Habitat** (stream length)	**Abundance**	**Reproduction/ Recruitment**	**Habitat Structure/ Substrate**	**Hydrology**	**Water Quality**
High	> 50 river miles	Catch Per Unit Effort (CPUE) ≥ 4.0 *(or ≥100 individuals found per population survey)	50% or more sites with juveniles (<35mm) and gravid females present during breeding season. Fish hosts present (i.e., not limiting).	Pool and backwater habitats common. Stable mud, sand, and silt substrates sufficient to provide lodging. Low levels of sedimentation on substrate.	Slow to moderate flowing water present year-round. No recorded periods of zero flow days, even during droughts. Extremely high, low, and/or erratic flows are rare. Little fluctuation of water levels in occupied reservoirs (i.e., little to no drying of occupied habitat).	Overall WQ is good or excellent. No known contaminants, dissolved oxygen sufficient, and no thermal extremes documented. Pollutants indicative of anthropogenic degradation, such as total dissolved solids (TDS) are stable or decreasing.
Moderate	20–50 river miles	4.0 > CPUE ≥ 2.0 *(or ≥25 and <100 individuals found per population survey)	25-50% of sites inhabited by juveniles (<35mm) and gravid females present during breeding season. Fish hosts present in moderate abundance.	Pool and backwater habitats uncommon. Mud, sand, and silt substrates mostly stable and sufficient to provide lodging with some mobilization of particles and light sedimentation on substrate.	Slow to moderate flowing water present year-round (no zero flow days), however, extremely high, low, and/or erratic flows occur infrequently. Moderate fluctuation of water levels in occupied reservoirs.	Overall WQ is fair. Contaminants known, low dissolved oxygen, and temperature extremes documented. Not believed to be at levels that threaten mussel survival. TDS stable or slightly increasing.
Low	< 20 river miles	2.0 > CPUE ≥ 0.5 *(or ≥3 and <25 individuals found per population survey)	< 25% of sites inhabited by juveniles (<35mm) and gravid females present during breeding season. Fish host present in low numbers and/or ability to disperse is reduced.	Pool and backwater habitat absent; substrates mostly unstable, habitat eroded, or being buried by mobilized sediments from upstream.	Slow to moderate flowing water is not present year-round. River may become isolated pools or dry river bed seasonally. Zero flow days occur and riffles become dry. Extremely high, low, and/or erratic flows are routine. High fluctuation of water levels in occupied reservoirs.	Overall WQ is poor. Contaminants known, low dissolved oxygen, and temperature extremes documented. TDS increasing. Pollution levels sufficient to threaten mussel survival.
Extirpated/ Functionally Extirpated	none	CPUE <0.5 *(or <3 individuals found per population survey)	No gravid or juvenile individuals present	No suitable habitat present	Dry stream bed or zero flow days high enough to preclude survival. Extremely high, low, and/or erratic flows are frequent, resulting in unsuitable habitat for mussels. Large magnitude reservoir drawdowns occur frequently, resulting in drying of occupied habitat and morality.	Overall WQ is limiting for aquatic life. Water quality degraded enough to preclude mussel habitation.

*the number of individuals found per most recent comprehensive population survey were used to rank Abundance when CPUE information was not available.

Table 4.5. The estimated current condition of Texas heelsplitter populations; ~~where~~ high condition = 3 (green box), moderate condition = 2 (yellow box), low condition = 1 (red box), and extirpated/functionally extirpated = 0 (grey box).

		Population Factors			Habitat Factors			
River Basin	**Population**	**Occupied Habitat**	**Abundance**	**Reproduction/ Recruitment**	**Habitat Structure/ Substrate**	**Hydrology**	**Water Quality**	**Overall Condition** (Viability)
Sabine	**Sabine River/ Toledo Bend**	3	0	1	3	2	3	0
Neches	**Neches River/ B.A. Steinhagen**	3	2	1	3	3	2	2
	Lower Neches River	3	1	1	3	2	2	1
Trinity	**Grapevine Lake**	**na**	0	1	3	2	2	0
	Trinity River/ Lake Livingston	3	1	1	1	1	1	1

*See Appendix B, Table B.1 for supporting information used to score population and habitat factors.

na = not applicable (i.e., not applicable to reservoirs).

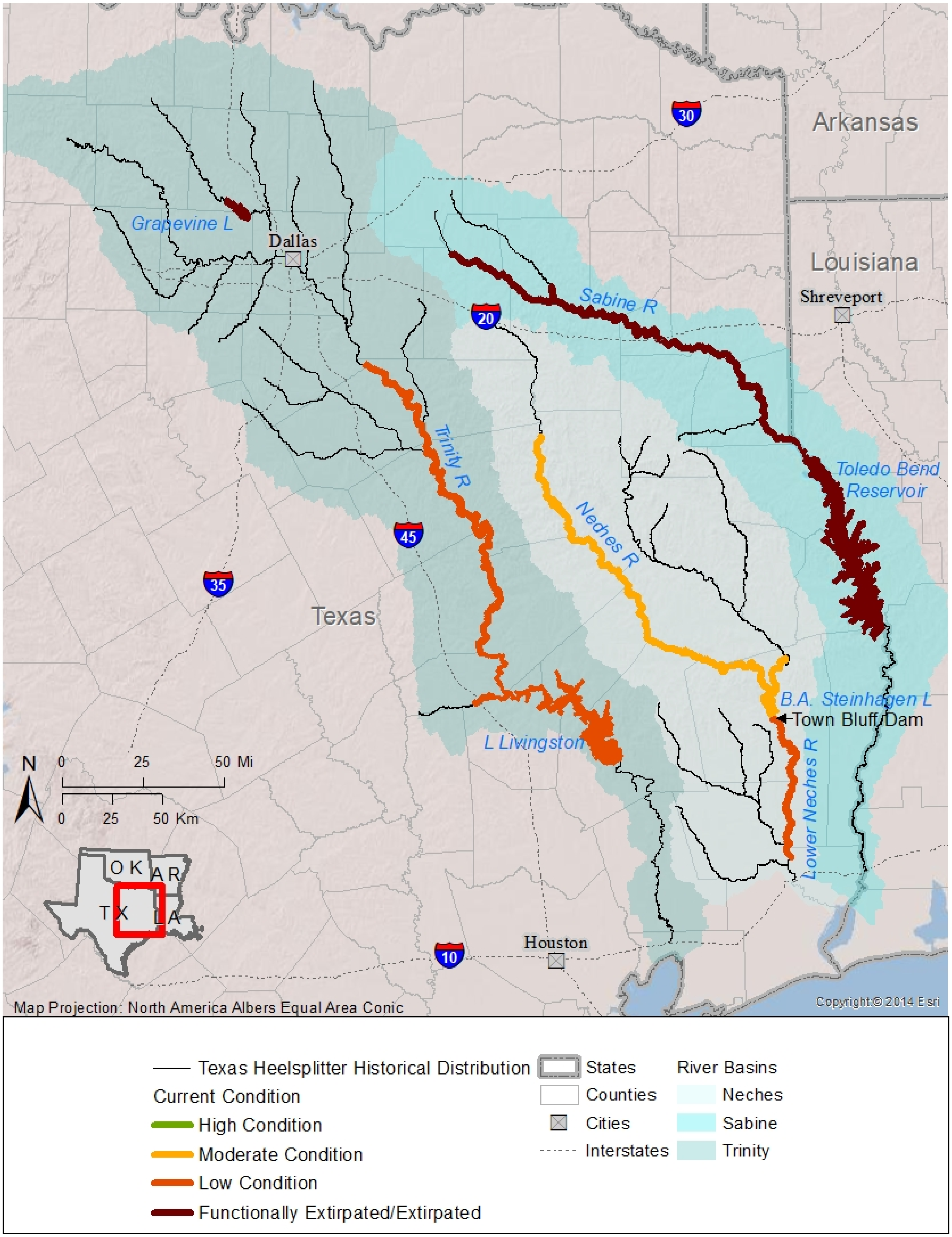


Figure 4.2. *Location and estimated condition of 5 remaining Texas heelsplitter populations within the historical range of the species.*

4.C.2. CURRENT POPULATION RESILIENCY

Currently, the Texas heelsplitter is known to exist as 5 populations occurring in 3 separate river basins: the Neches, Sabine, and Trinity. The Neches River basin in Texas has 2 populations of Texas heelsplitter: Neches River/B.A. Steinhagen population and Lower Neches River population. The Neches River/B.A. Steinhagen and Lower Neches River populations are hydrologically isolated from each other by Town Bluff Dam, an impoundment that forms B.A. Steinhagen Reservoir. The Neches River population extends 225 miles on the mainstem from just below Lake Palestine to B.A. Steinhagen reservoir. The Neches River population current condition evaluation determined occupied reach habitat length, habitat structure/substrate, and hydrology were high condition; abundance and water quality in moderate condition; and reproduction/recruitment in low condition due to lack of reported juvenile or gravid female observations (Randklev 2018, entire). The Lower Neches River population includes 40 miles of the mainstem below B.A. Steinhagen to the confluence with Village Creek, including 50 miles upstream within Village Creek from the confluence. The Lower Neches River population current condition evaluation found that occupied habitat reach length and habitat structure/substrate were in high condition; hydrology and water quality were in moderate condition; and abundance and reproduction/recruitment were in low condition due to low reported CPUE and numbers of reported juveniles or gravid females (Tables 4.4 and 4.5). The Neches River population has a moderate overall current condition and the Lower Neches River population has a low overall current condition, resulting in moderate and low resiliency, respectively.

The Sabine River basin has 1 Texas heelsplitter population in Texas, which marginally extends into Louisiana. The Sabine River/Toledo Bend population occupies an estimated 243 river miles from below Iron Bridge Dam to approximately 5 miles upstream of Logansport, ~~Texas~~. The Sabine River population current conditions evaluation determined that water quality, habitat structure/substrate, and occupied habitat reach length were high condition; hydrology in moderate condition; reproduction/recruitment in low condition due to a lack of reported juvenile or gravid female presence data; and abundance condition was determined to be functionally extirpated due to low CPUE (Tables 4.4 and 4.5; Randklev 2018, entire). The current condition of this population is functionally extirpated and; therefore, has little to no resiliency.

The Grapevine Lake and Trinity River/Lake Livingston populations, located within the Trinity River basin in Texas, are hydrologically isolated from one another by the dam that forms Grapevine Lake. The Trinity River population occupies approximately 200 river miles from below highway 34 near Ennis, Texas to just upstream of the highway 21 crossing near Midway, Texas. The Grapevine Lake population current condition evaluation found habitat structure/substrate to be in high condition; hydrology and water quality in moderate condition; reproduction/recruitment in low condition; and abundance was determined to be functionally extirpated due to low number of individuals observed (Randklev 2018, entire). The Trinity River population current condition evaluation resulted in occupied habitat reach length found in high condition and habitat structure/substrate in moderate condition; the remaining population and habitat factors were determined to be low condition, primarily attributed to impacts associated with hydrology changes within the Trinity River basin (Tables 4.4. and 4.5). The Grapevine Lake population is considered functionally extirpated, while the Trinity River/Lake Livingston population has a low overall current condition and low resiliency.

4.C.3. CURRENT SPECIES REPRESENTATION

We consider the Texas heelsplitter to have representation in the form of genetic, geographic, and ecological diversity in the 3 currently occupied river basins. Because there are no freshwater connections between the 3 basins, we treated each river basin as separate areas of representation.

4.C.4. CURRENT SPECIES REDUNDANCY

Within the identified representation areas (Neches, Sabine, and Trinity River basins), only the Neches and

Trinity River basins have at least 1 known current viable population (the Sabine River/Toledo Bend population in the Sabine River basin and Grapevine Lake in the Trinity River basin are considered functionally extirpated). The Neches River basin has 2 currently viable populations (Neches River and Lower Neches River populations); however, these populations are hydrologically isolated, and therefore provide only minimal redundancy.

4.D. SUMMARY OF CURRENT CONDITIONS OF EAST TEXAS MUSSELS

Both species of East Texas mussels exhibit various levels of resiliency, redundancy, and representation across the major river basins in which they occur. However, no population seems to contain all of the ~~necessary~~ habitat and population factors necessary to warrant ~~a~~ strong, healthy mussel populations. Given our analysis of current condition, only 2 Louisiana pigtoe populations were considered to have high current condition overall (i.e., Neches and Cossatot ~~R~~ivers; Table 4.3), and no Texas heelsplitter populations are in high condition (Table 4.5). While other populations have aspects, or factors, that are in high condition (such as occupied habitat length or habitat structure/substrate) none of those populations have all of the factors necessary to support a highly resilient population. Four populations of the East Texas mussels are considered ~~currently~~ functionally extirpated, meaning abundance is too low to support viability of the population, including the Lower Little River (tributary to the Red River) and Sabine River populations for the Louisiana pigtoe, and Sabine River/Toledo Bend and Grapevine Lake populations for the Texas heelsplitter.

CHAPTER 5 - FACTORS INFLUENCING VIABILITY

This chapter evaluates the past, current, and future factors that may affect the long-term viability of East Texas mussels. Each factor is discussed below and explored further in the "Cause and Effects Tables" attached to this report (Appendix B**)**. The Cause and Effects Tables analyze, in detail, the pathways through which each factor influences a species at both the individual and population level. Each factor is also examined temporally to determine the magnitude of potential impacts on the status of the species from a historical, current, and future perspective. These factors include: 1) changes to water quality, 2) altered hydrology, 3) changes to substrate, 4) habitat fragmentation, 5) direct mortality, and 6) invasive species. Climate change, which has the unique ability to influence all six factors, is also briefly mentioned toward the end of the chapter and is a key component of our analysis in Chapter 6 where we take a closer look at future conditions.

The current and potential future effects of the six factors, along with current estimates of distribution and abundance, determine present viability, and therefore future vulnerability to extinction. The factors we chose to examine are based on known stressors that either influence the East Texas mussels directly or influence the resources upon which mussels rely for survival, growth, and reproduction, as well as a discussion on the sources of those stressors. For more information about how each factor influences species survival, see Appendix B. Environmental stressors that are not known to affect East Texas mussel populations are not discussed in this SSA report.

5.A. CHANGES IN WATER QUALITY

Freshwater mussels require water in sufficient quantity and quality on a consistent basis to complete their life cycles and those of their host fishes. Like many rare species, along with natural perturbations that exert pressure on populations and influence survival, habitat for freshwater mussels is impacted by a myriad of anthropogenic activities. These activities, such as residential development and agriculture, place increasing demands on natural resources, particularly water, which can have deleterious effects on both water quality and quantity.

Water quality can be degraded through contamination or alteration of water chemistry. Environmental contaminants include a broad array of natural, synthetic, and chemical substances introduced to the environment that can be hazardous to living organisms. Chemical contaminants are ubiquitous throughout the environment and are a major contributor to the current declining status of freshwater mussel species nationwide (Augspurger et al. 2007, p. 2025). Contaminants that enter the environment are generally categorized by their origin as either coming from point sources such as hazardous spills, industrial wastewater, and municipal effluents, or non-point sources such as urban stormwater and agricultural runoff. These discharges can introduce a variety of pollutants to air, water and soil, including organic compounds, trace metals, pesticides, plastics, petroleum hydrocarbons, flame retardants, and a wide variety of emerging contaminants (e.g., pharmaceuticals and personal care products) that comprise some 85,000 chemicals in commerce today and are routinely released into the aquatic environment (EPA 2018, p. 1). The extent to which environmental contaminants adversely affect aquatic biota can vary depending on many site-specific variables (e.g., the concentration of the pollutant, the volume discharged, and the timing of the release), but species diversity and abundance consistently ranks lower in waters that are known to be polluted or otherwise impaired by contaminants. For example, freshwater mussels are not generally found for many miles downstream of municipal wastewater treatment plants (WWTP)(Gillis et al. 2017, p. 460; Goudreau et al. 1993, p. 211; Horne and McIntosh 1979, p. 119). Transplanted common freshwater mussels (*Amblema plicata* and *Corbicula fluminea*) showed reduced growth and survival below a wastewater treatment plant (WWTP) outfall relative to sites located upstream of the WWTP in Wilbager Creek (a tributary to the Colorado River in

Travis County, Texas); water chemistry was altered by the wastewater flows at downstream sites, with elevated constituents in the water column that included copper, potassium, magnesium, and zinc (Nobles and Zhang 2015, p.11; Duncan and Nobles 2012, p. 8).

Although municipal wastewater effluents are nutrient rich and contain a variety of pollutants that can affect water quality, ammonia is of particular concern below wastewater treatment plant outfalls because freshwater mussels have been shown to be particularly sensitive to increases in ammonia levels (Augspurger et al. 2003, p. 2569). Elevated concentrations of un-ionized ammonia (NH_3) in the interstitial spaces of benthic habitats (> 0.2 parts per billion) have been implicated in the reproductive failure of eastern elliptio (*Elliptio complanata*) freshwater mussel populations (Strayer and Malcom 2012, pp. 1787-8), and sub-lethal effects (valve closures) have recently been described as total ammonia nitrogen (TAN) approaches 2.0 milligrams per liter (mg/L or ppm; Bonner et al. 2018, p. 186). Waters near intensive agricultural operations such as poultry farms, processing plants, and confined animal feeding operations that house large concentrations of animals producing ammonia waste are also at risk of contamination. Quantitative estimates of the effects of un-ionized ammonia in the water column are currently unknown, and relationships between total ammonia N and un-ionized ammonia (NH_3) are dependent on pH and temperature (see inset). Recent laboratory studies suggest that for pimpleback (*Cyclonaias pustulosa*; a species native to the eastern United States and entire Mississippi drainage), the revised EPA ammonia benchmarks are sufficient to protect from short-term effects of ammonia on resting metabolic rate and ability to extract oxygen even under low oxygen conditions (Bonner et al. 2018, p. 151). However, some sources are continuous and the long-term effects of chronic ammonia exposure (i.e., years or decades) to freshwater mussels has yet to be experimentally investigated.

Ammonia toxicity ~~as~~ explained ~~by Dr. Jim Stoeckel of Auburn University~~ *in* Bonner et al. 2018, p. 147-8:

"Ammonia in surface waters is typically reported as total ammonia nitrogen (TAN). This refers to the combined concentration of nitrogen (mg/L) occurring in the two co-existing forms of ammonia, ionized (NH_4^+) and un-ionized (NH_3). Un-ionized ammonia is the most toxic form. The proportion of un-ionized to ionized ($NH_3:NH_4^+$) ammonia increases with increasing pH and temperature. Thus, ammonia becomes more toxic with increases in temperature and/or pH even if the concentration of ammonia, measured as TAN, remains the same. The U.S. EPA 2013 ammonia benchmark is 17 mg TAN/L for acute (1 hour average) exposure and 1.9 mg TAN/L for chronic (30 day rolling average) exposure. These benchmarks are referred to as "criterion minimum concentrations" (CMC) and represent a concentration that is expected to be lethal to < 50% of individuals in sensitive species. They specifically apply to a pH of 7 and a temperature of 20°C during the summer months. The toxicity of 17 (acute) and 1.9 (chronic) mg TAN/L benchmark concentrations would therefore increase and may no longer be sufficiently protective of unionid mussels. The EPA is cognizant of this issue and provides tables to adjust benchmark concentrations for specific temperature and pH values. Un-ionized ammonia can affect organisms such as mussels via multiple mechanisms that increase ventilation rates (volume of water passing through gills per unit time), gill damage, and a reduction in the ability of blood (hemolymph) to carry oxygen."

Although a comprehensive review of ammonia related impacts to the East Texas mussels is beyond the scope of this document, municipal wastewater is known to contain both ionized and un-ionized ammonia and wastewater discharge permits issued by Texas Commission on Environmental Quality (TCEQ) do not always impose limits on ammonia, particularly for smaller volume dischargers. Thus, at a minimum there are likely to be elevated concentrations of ammonia in the immediate mixing zone of some WWTP outfalls, and in some cases, impacts will persist for some distance downstream. To give insight into the potential scope of WWTP related impacts, there are approximately 386 discharge permits issued for the Trinity River basin alone from its headwaters above the Dallas-Fort Worth metroplex down to the Gulf of Mexico (TCEQ 2018b, entire). The San Jacinto Basin, although geographically smaller than most other basins in Texas, has approximately 1,052 WWTP outfalls, while the Neches and Sabine Rivers have 218 and 191 outfalls

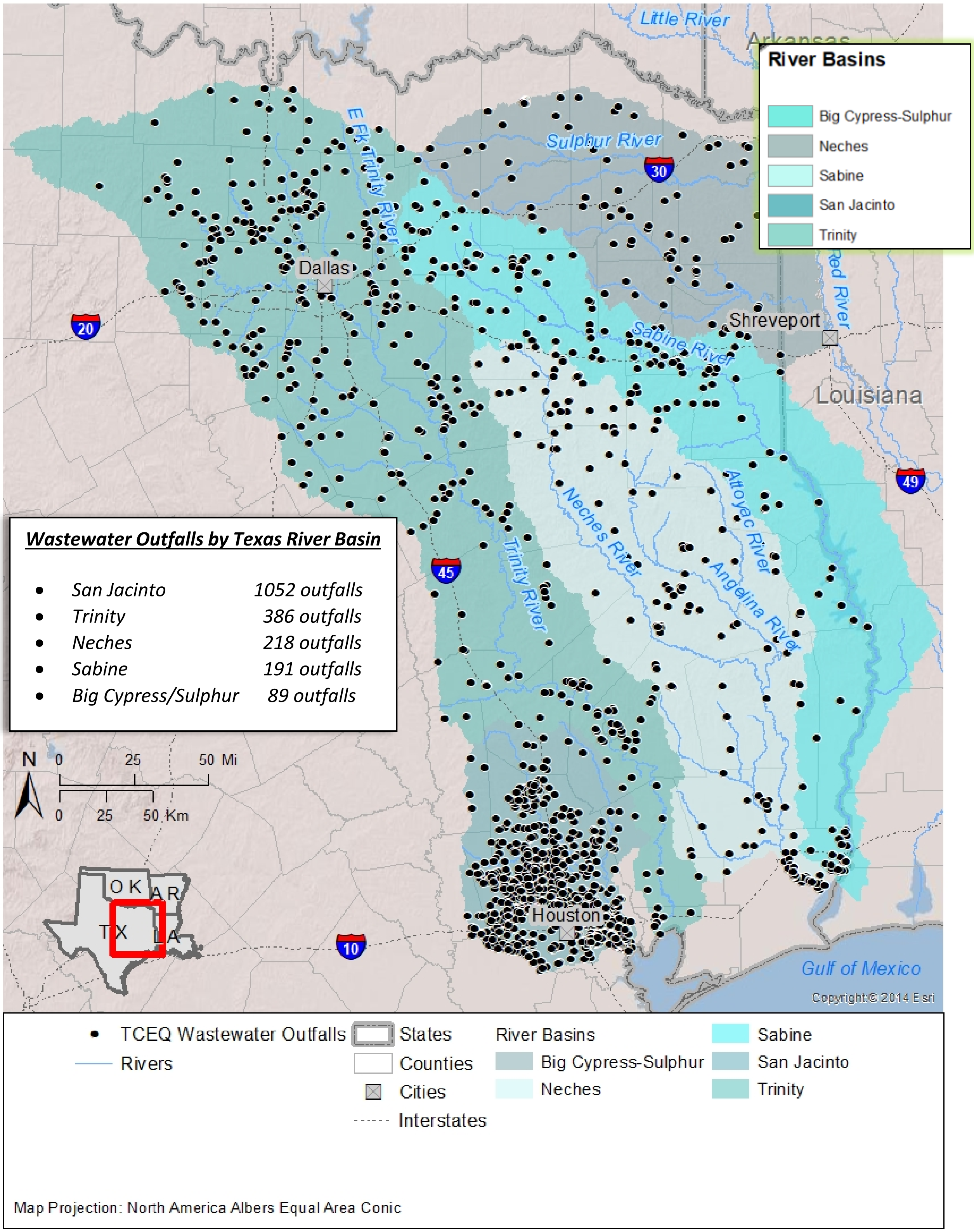


Figure 5.1. *Wastewater discharge permits issued by the Texas Commission on Environmental Quality within the range of East Texas mussels (analysis limited to Texas; TCEQ 2018b, entire)*

respectively (Figure 5.1). In addition, some industrial permits such as animal processing facilities can discharge millions of gallons per day and have ammonia limits in the range of 4 mg/L, which exceeds levels that inhibited growth in juvenile fatmucket (Lampsiis siliquoidea) and rainbow mussel (Villosa iris) during 28 day chronic tests (0.37 to 1.2 mg total ammonia N/L; no-observed-effect concentration and lowest-observed-effect concentration, respectively) (Wang et al. 2007, entire). Immature mussels (i.e., juveniles and glochidia) are especially sensitive to water quality degradation and contaminants (Cope et al. 2008, p. 456, Wang et al. 2017, p. 791-792; Wang et al. 2018, p. 3041).

Another common type of water quality degradation is the alteration of basic water chemistry, including changes to water quality parameters such as dissolved oxygen, temperature, total dissolved solids (TDS) and salinity. Dissolved oxygen levels are influenced by temperature (i.e, as temperatures increase, dissolved oxygen levels decrease) and may be reduced from increased nutrient inputs or other sources of organic matter that increase the biochemical oxygen demand in the water column as microorganisms decompose waste. Organic waste can originate from stormwater, agriculture, irrigation runoff or wastewater effluent, and juvenile mussels seem to be particularly sensitive to low dissolved oxygen with sub-lethal effects evident at 2 ppm and lethal effects at 1.3 ppm after just 48 hours (Sparks and Strayer 1998, pp. 132-133). Although some aquatic organisms tolerate dissolved oxygen levels below 3 ppm, most prefer levels somewhere between 4 ppm and supersaturation (i.e., excessively high dissolved oxygen). Increases in water temperature (≥27° C for sensitive species) resulting from water diversions, climate change, or low flows during droughts can increase the toxicity of many pollutants and exacerbate low dissolved oxygen levels, in addition to other drought-related effects on both juvenile and adult mussels. Total dissolved solids, a measure of the mineral content of water (i.e., inorganic salts, metals, cations or anions dissolved in water, including calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates), is commonly elevated in watersheds impacted by a variety of industrial, commercial, urban and agricultural activities, and has been associated with acute and chronic toxicity to aquatic organisms. Total dissolved solids are a good overall indicator of water quality and can be measured indirectly using conductivity; therefore, watersheds with increasing trends in conductivity or TDS are experiencing declines in water quality that can be harmful to mussels and other aquatic organisms. Increasing trends in TDS are not uncommon in watersheds impacted anthropogenic activities. For example, water quality samples taken on segment 0402 of the Big Cypress near the confluence with Little Cypress Bayou showed a significant increasing trend in conductivity, with values rising from 120 uS/cm in 1998 to 190 uS/cm in 2012, likely due to changing land uses and subsequent increases in point and non-point source pollution (TCEQ 2014, pp. 20-21). Mussels are also sensitive to elevated salinity, which is a measure of dissolved salts like chloride and sodium that are a component of TDS, such that, the distribution of mussels is naturally limited in the lower basins where conditions become unfavorable from the intrusion of brackish and saline water near the coast. Freshwater areas within these lower basins can be affected by storm surges or inclement weather, such as hurricanes, as saline water is carried inland. These salt water deposits can harm freshwater biota, including mussels, depending largely on the volume introduced and the amount of time saline conditions persist. Salinity in river water is diluted by surface flow and as surface flow decreases the influence of salt concentrations increase, resulting in adverse effects on freshwater mussels. Even low levels of salinity (2-4 parts per thousand (ppt)) can have substantial negative effects on reproductive success, metabolic rates, and survival of freshwater mussels (Blakeslee et al. 2013, p. 2853). Bonner et al. (2018, pp. 155-6) suggest that the behavioral response of valve closure to high salinity concentrations (> 2 ppt) is the likely mechanism for reduced metabolic rates, reduced feeding, and reduced reproductive success based on reported sub-lethal effects of salinity > 2 ppt for Texas pimpleback, which closed tightly when exposed to salinity > 4 ppt for 7 days. The extent to which salinity currently affects freshwater mussel survival and reproduction near coastal areas is unknown, but the impacts will likely increase with climate change as weather related events increase the frequency and intensity of storms.

Contaminants released during accidental spills of chemicals, crude oil, or other hazardous materials are also a concern to water quality, as they often impact adjacent rivers, stream and waterbodies. Texas leads the nation in crude oil and natural gas production with more than 270,000 active oil and gas wells, in addition to 448,446 miles of pipelines and associated infrastructure that is needed to move product from wells to refineries for processing (Figure 5.2). Various chemicals, refined fuels like diesel, and wastewater related to oil and natural gas exploration are also routinely transported along Texas highways. These facilities and equipment used for extraction, transportation and refinement of hazardous materials are all potential sources of hazardous spills, which occur with regularity throughout the state and can originate from human error, equipment failure, or catastrophic events like industrial accidents, fires or floods. Although spills are relatively short-term events and may be localized, depending on the types of substances and volume released, water resources nearby can be severely impacted and degraded for years after the incident along with the biological resources that inhabit the area.

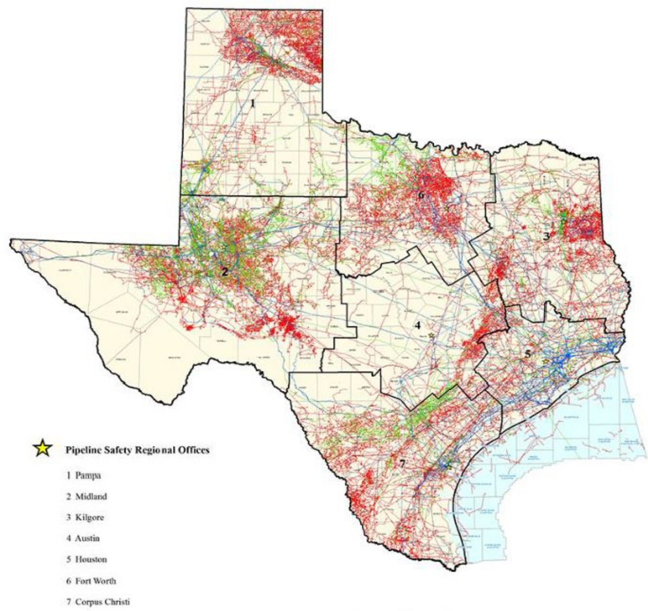


Figure 5.2. *Texas Railroad Commission map showing extensive pipeline network used to carry natural gas (red), crude oil (green), and hazardous liquids (blue) throughout the state (as of January 2018).*

Water quality and quantity are interdependent, so reductions in surface flow caused by drought, instream diversions, or groundwater extraction serve to concentrate contaminants from point and non-point source pollution that would otherwise be diluted. For example, point source discharges of industrial or municipal wastewater inherently pose a greater risk to aquatic biota under low flow conditions as concentrations of pollutants and water temperatures increase. Drought conditions can place additional stressors on stream systems beyond reduced flows by exacerbating contaminant related effects to aquatic biota, including East Texas mussels. Not only can temperature be a biological, physical, and chemical stressor, the toxicity of many pollutants to aquatic organisms increases at higher temperatures (e.g., ammonia, mercury), which is further exacerbated by the increased metabolic activity (e.g., higher respiration rates) experienced by organisms as they try to adapt to hotter conditions within the water column. We foresee threats to water quality increasing into the future due to the effects of climate change as demand and competition for limited water resources grows. For additional information and a more comprehensive discussion of water quality requirements for aquatic species in Texas, the reader is referred to USFWS (2006, entire).

5.B. ALTERED HYDROLOGY

In this report, altered hydrology refers to anthropogenic changes to historical flow regimes that result in degradation of East Texas mussel habitat. The changes to flow originate from a variety of activities, resulting in either an increase or decrease in flows (e.g., magnitude, duration, intensity) beyond natural fluctuations that occurred historically, and in some cases these changes exceed levels tolerated by mussels. While we recognize changes to flow occur naturally, such as floods and droughts, the focus of our discussion is related to changes to flow that occur directly or indirectly related to human activity. Altered hydrology (leading to inundation, low flow, or high flow conditions) may reduce the quality of affected habitats to the point where they are no longer suitable for East Texas mussels. While both species have adapted to survive natural fluctuations in flows, populations that experience sustained higher than normal flows, prolonged flooding or unnatural fluctuations in the frequency or intensity of high/low flows, or extended (or repeated) drying events, will not persist. Although some watersheds have been more heavily impacted than others, virtually every watershed in Texas experienced some level of anthropogenic-induced change to the hydrology during the 20th century, a trend that will likely continue into the 21st century, particularly in areas with rapid population growth.

Inundation of previously free-flowing rivers and streams by impoundments has arguably had the single largest human-related impact on the distribution of freshwater mussels to date. The construction of reservoirs and other impoundments permanently alters the hydrology, and hence, the ecology of rivers, often with deleterious effects to water quality, water quantity, host fish movement and dispersal of mussel glochidia, nutrient cycling, sediment deposition, fate and transport of contaminants, and numerous other changes to the physical, chemical, and biological characteristics of affected areas (upstream and downstream). In this section, we discuss how the close relationship of flow to mussels makes them uniquely vulnerable to changes to hydrology.

East Texas mussels are adapted to flowing water (lotic habitats) rather than standing water (lentic habitats). Louisiana pigtoe require free-flowing water to survive and prolonged inundation in non-flowing conditions is not suitable habitat for the species. Like the Louisiana pigtoe, the Texas heelsplitter evolved in flowing conditions but they have also been observed in lentic habitats and appear to be tolerant of reservoir conditions. There is, however, uncertainty about whether populations that occur in lacustrine environments function in the same manner as those in lentic habitats, and the mechanisms that allow the Texas heelsplitter to tolerate reservoirs is poorly understood (Randklev 2019a, p. 2). Some have suggested Texas heelsplitter may occur in higher densities, and hence favor, areas of reservoirs that are influenced by stream inflows where conditions more closely resemble their preferred riverine habitat (Whisenant 2019, p. 1; Neck and Howells 1995, p. 15).

Inundation of mussel habitat has primarily occurred upstream of dams, including large structures on public land such as Toledo Bend Reservoir and other major flood control and water supply reservoirs, and smaller structures like low water vehicle crossings and diversion dams typically found along tributaries on privately-owned land. These structures alter the hydrology of rivers by slowing, impeding or diverting normal flow patterns, causing a myriad of other changes to the aquatic environment. Inundation alters natural sediment deposition by increasing deposition in some areas and eliminating the interstitial spaces that East Texas mussels inhabit. Inundation also includes the effects of reservoir releases where the frequency and magnitude of flows and variations in surface water elevation can make habitat unsuitable for East Texas mussels. In large reservoirs that release water from the hypolimnion, the deeper water is cold and often devoid of oxygen and necessary nutrients, which can adversely affect mussel survival. Cold water can stunt mussel growth and delay or hinder spawning (Vaughn and Taylor 1999, p. 917). Reservoirs like Broken Bow Lake in southeast Oklahoma that release cold water from the bottom of the reservoir (in part to support a non-native rainbow and brown trout recreational fishery), can affect water temperatures for miles downstream. These cold releases create an extinction gradient, where freshwater mussels are absent or presence is low near the dam, and abundance does not rebound until some distance downstream where ambient conditions raise the water temperature to within the tolerance limits of mussels (Davidson et al. 2014, p. 29; Vaugh and Taylor 1999, pp. 915, 916).

The construction of dams for flood control and drinking water supply, and the subsequent management of water releases from those reservoirs (e.g., timing, intensity, and duration), has significant impacts on the natural function and hydrology of rivers and streams. For example, dams trap sediment in reservoirs and managed releases typically do not conform to the natural flow regime, often resulting in higher base flows, and peak flows of reduced intensity but longer duration. The additional shear stress caused by these sustained high base flows can incise channels, erode river banks, scour mussel beds, and remove substrate preferred by mussels. Over time, the physical force of these higher base flows can dislodge mussels from the sediment and permanently alter the geomorphology of rivers. Rivers transport not only water but also sediment, which is transported mostly as solids suspended in the water column. The majority of sediment transport occurs during floods (Kondolf 1997, p.533; Clark and Mangham 2019, pp. 6-7). The increase in flooding severity results in greater sediment transport, with important effects to substrate stability and benthic habitats for freshwater mussels, as well as other organisms that are dependent on stable benthic habitats. Further, water released by dams is usually clear due to reduced sediment load, and is considered “hungry water because the excess energy is typically expended on erosion of the channel bed and banks…resulting in incision (downcutting of the bed) and coarsening of the bed material until a new equilibrium is reached" (Kondolf 1997, p.535). The extent to which downcutting and erosion occurs as a result of dam releases varies depending on the volume of flows and geomorphology of the river downstream, but in some cases leads to bank collapse, burial of mussel beds, and mortality. Conversely, depending on how dam releases are conducted, reduced flood peaks can lead to accumulations of fine sediment in the river bed (i.e., loss of flushing flows, Kondolf 1997, pp. 535, 548).

Operation of reservoirs for flood-control, water-supply, and recreation results in altered hydrologic regimes, including an attenuation of both high- and low-flow events. Flood control dams store flood waters and then release them in a controlled manner. Extended release of these flood waters can result in significant scour, and loss of substrates that provide mussel habitat. The changes to flood flows also alter sediment dynamics, as sediments are trapped above and scoured below major impoundments. These changes in water and sediment transport negatively affect freshwater mussels and their habitats. Evidence that Texas heelsplitter are able to tolerate reservoir conditions leads us to believe the overall impacts of reservoirs may be more pronounced for Louisiana pigtoe; however, this is speculative since to our knowledge there have been no studies to elucidate this issue.

Flow loss and scour - Very low flows and water levels are also detrimental to East Texas mussel populations. Droughts that occurred in the recent past led to extremely low flows in several East Texas rivers. Some rivers, or portions thereof, are resilient to drought because they are spring-fed (Calcasieu, Neches), contain large volumes of water (Trinity), have large reservoirs in the upper reaches that release water for downstream users (all, excluding Calcasieu and Mountain Fork), or have significant return flows (Pearl, Sabine, Trinity); however, drought in combination with increasing trends in groundwater extraction may lead to lower river flows of longer duration than previously recorded. Reservoir releases can be managed to some extent during drought conditions to prevent complete dewatering below reservoirs, but in many cases dam operators must stop releases during droughts to conserve water and protect water supplies, leaving mussels vulnerable to desiccation. The same limitation applies during major floods, where dam operators have little choice but to maximize flood releases to protect public safety and property, which can negatively affect mussels downstream.

Streamflow and overall discharge for rivers inhabited by East Texas mussels are expected to decline due to climate change and projected increases in temperatures and evaporation rates, resulting in more frequent and intense droughts (Lafontaine et al. 2019, entire). Return flows, consisting primarily of treated municipal wastewater, are projected to continue to increase in areas with population growth and may serve to ameliorate some of the effects of climate change downstream of metropolitan areas, albeit with notable impacts to water quality; however, these benefits may become less significant as municipalities increase wastewater reuse as a conservation measure. The Trinity River, for example, has been a significantly modified, highly controlled and regulated system since the 1960s, with low flows steadily increasing as the population has grown, resulting in base flows that are significantly higher compared to historical flows (Clark and Mangham 2019, p. 9). The increase in base flows can be attributed to substantial return flows from Dallas/Fort Worth metropolitan area wastewater treatment plants and are projected to continue to increase in the future. Surface and alluvial aquifer groundwater withdrawals will likely increase in the future due to the effects of more intense droughts, with reductions in streamflows putting an additional strain on aquatic resources. With the exception of stream segments where municipal effluent return flows supplement base flows, most streams experience lower base flows and reduced high flow events after major reservoirs are constructed (USGS 2008, pp. 964, 966).

Many streams in Texas receive significant groundwater inputs from multiple springs associated with aquifers. As spring flows decline due to drought, climate change or groundwater pumping, habitat for East Texas mussels in affected streams is reduced and could eventually cease to exist. While East Texas mussels may survive short periods of low flow, as low flows persist, mussels can be subjected to oxygen deprivation, increased water temperature, and, ultimately, stranding, which leads to reduced survivorship, reproduction, and recruitment to the population. Likewise, high-flow events can lead to increased risk of mortality through physical removal, transport, or burial of mussels as unstable substrates are transported downstream by flood waters (entrainment) and dislodged mussels are later redeposited in locations that may not be suitable habitat. Low flow events also lead to an increased risk of desiccation (physical stranding and drying) and exposure to elevated water temperature and other water quality degradations, such as more concentrated contaminants, as well as to predation.

The distribution of mussel communities and their habitats is affected by large floods returning at least once during the typical life span of an individual mussel (generally from 3 to 30 years), as mediated by the presence of flow refuges, where shear stress is relatively low, sediments are relatively stable, and mussels "must either tolerate high-frequency disturbances or be eliminated and can colonize (only) areas that are infrequently disturbed between events" (Strayer 1999, pp. 468-9). Shear stress and relative substrate stability (RSS) are limiting to mussel abundance and species richness (Randklev et al. 2017a, p. 7) and riffle habitats may be more resilient to high flow events than littoral (bank) habitats.

East Texas mussels undoubtedly evolved in the presence of extreme hydrological conditions to some degree, including severe droughts leading to dewatering, and heavy rains leading to damaging scour events and movement of mussels and substrate, although the frequency, duration, and intensity of these events may be different from what is observed today. The natural drought/flood cycle in East Texas can be characterized by long periods of time with little or no rain, interrupted by short periods of heavy rain that often result in flooding. These same patterns led to the development of flood control and storage reservoirs throughout Texas in the twentieth century. Howells (2000) provides a summary of drought conditions in Texas from 1995-1999, characterized by prolonged drought conditions punctuated by severe floods, and their impacts on native unionids, reporting that "although no sampling efforts were mounted to document [the] impact on rare endemic unionids…, [some] species… were almost certainly reduced in numbers, especially at sites that dried completely" (p.ii). It follows that given the variable climate of East Texas; mussels must have life history strategies, and other adaptations, that allow them to persist by withstanding severe conditions, and/or repopulating during more favorable conditions. However, there are limits to the ability of mussels to respond to increasing variability, frequency, and severity of extreme weather events, which is believed to be a contributing factor to the contraction of populations for both species.

Another source of alteration to hydrology is from sand and gravel mining. Sand and gravel can be mined directly from rivers or from adjacent alluvial deposits, and instream gravels often require less processing and are thus more attractive from a business perspective (Kondolf 1997, p. 541). Instream mining directly impacts river habitats by removal of substrates used by mussels, and can indirectly affect river habitats through channel incision, bed coarsening, and lateral channel instability (Kondolf 1997, p. 541). Excavation of pits in or near to the channel can create a knickpoint, which can contribute to erosion (and mobilization of substrate) associated with head cutting (Kondolf 1997, p. 541). Pits associated with off-channel mining of the floodplain can become involved during floods, such that the pits become hydrologically connected, and thus can affect sediment dynamics in the stream or river (Kondolf 1997, p. 545). Sand and gravel mines occurred historically and continue to operate in some basins throughout the range of East Texas mussels, including two operations noted within the Bayou Anacoco focal area and one within the San Jacinto focal area during our review.

Due to the importance of hydrology to East Texas mussels, in 2018 the Service contracted ~~the~~ Texas A&M University's Natural Resources Institute to conduct research on hydrologic changes that have occurred in East Texas rivers and examine potential impacts to freshwater mussels. This two year study entitled "Assessment and Review of Hydrological Relationships for Mussels in East Texas" utilized historical U.S. Geological Survey stream gage data to evaluate changes to eleven flow parameters known as Indices of Hydrologic Alteration (IHA) at 43 gages over a 50 year period (1968 – 2018)(Figure 5.3). Preliminary findings contained in the 2019 Interim Report indicate significant changes to specific measured hydrologic parameters in all four river basins reviewed, with basins experiencing change ranked from high to low as follows: Trinity River, Sabine River, Big Cypress, and Neches River (see Figure 5.4). To determine the influence these changes to flow had on East Texas mussels (i.e., clarify mussel-flow relationships), the gage data were paired with records from approximately 500 mussel surveys conducted within 20 kilometers of the 43 gages (24 gages for the Trinity, 9 for the Neches, 6 for the Sabine, and 4 for ~~the~~ Cypress). Although evaluation of mussel-flow relationships is ongoing and a final report is not due until the Fall of 2020, based on quantile regression models there are flow parameters that appear to be limiting to East Texas mussels. Specifically, changes to the number of days with zero flow was limiting for Louisiana pigtoe, and the number of high pulses was limiting for Texas heelsplitter. In summary, results to date indicate natural flow regimes have been altered in East Texas rivers, as was expected, which has led to modification of instream habitats and contributed to declines in freshwater mussels. These findings agree with the opinion of many experts who believe 1) portions of the Trinity River have been significantly modified and may no longer support mussels (particularly in the upper basin where stream hydrology and geomorphology have been permanently altered), and 2) the Neches River is least altered and has some of the best remaining mussel habitat, along with the most abundant and diverse mussel populations, left in East Texas.

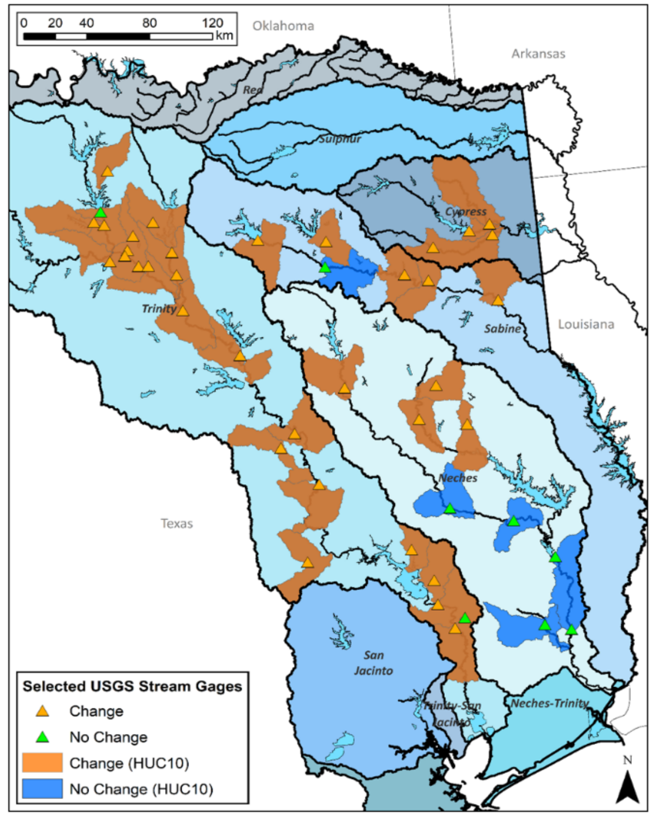


Figure 5.3. *Map of USGS stream gages evaluated for changes to flow from 1968-2018 based on HUC10 watersheds. HUCs highlighted in orange indicate at least one gaging station showed a significant change over time in one or more of the 11 flow parameters analyzed.(HUCs in blue show no change in any of the 11 flow parameters). (Khan and Randklev, 2019 Interim Report, pg. 7).*

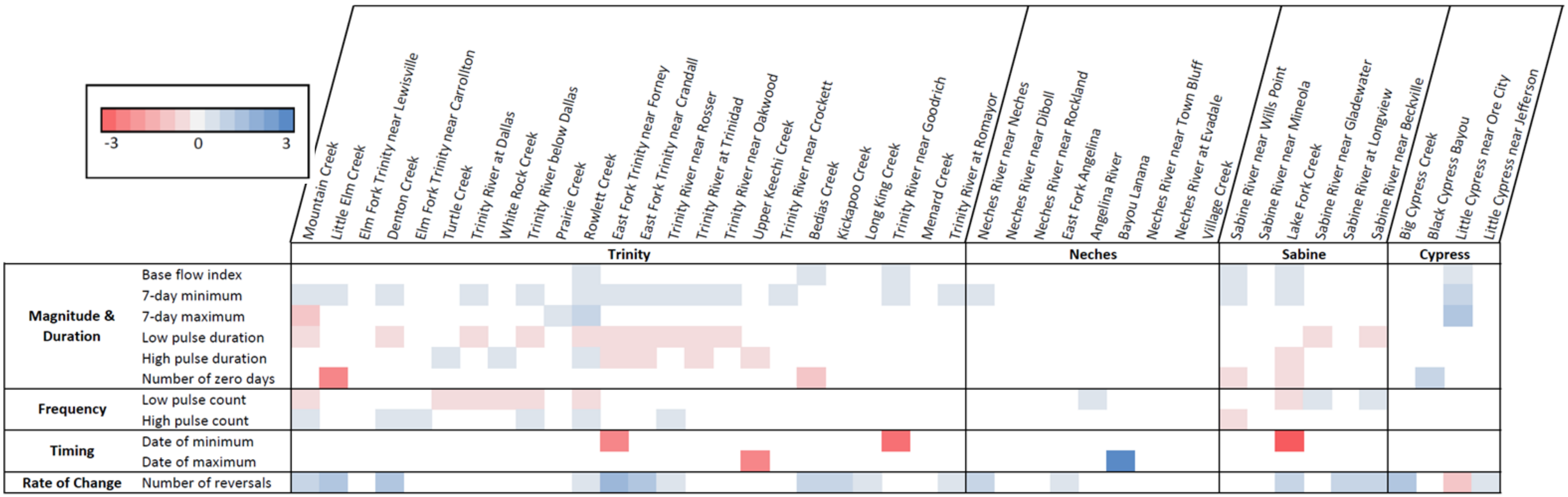


Figure 5.4. *Changes to eleven flow metrics (Indices of Hydrolic Alteration (IHA)) over time at 43 gages within multiple drainage basins of four East Texas rivers. Red denotes a statistically significant ($p \leq 0.05$) decrease in flow metric over time, and blue denotes a significant ($p \leq 0.05$) increase in flow metric over time. The degree of the slope is indicated by a color gradient, with darker colors representing more substantial changes to flow. White spaces indicate no significant change in flow parameter over time, representing mussel habitat that has been least impacted by hydrologic alterations (Khan and Randklev, 2019 Interim Report, pg. 8). See Appendix D for IHA definitions*

5.C. CHANGES TO HABITAT STRUCTURE/SUBSTRATE

Juvenile and adult East Texas mussels inhabit microsites along river stream beds that have abundant interstitial spaces or small openings in an otherwise closed matrix of substrate, created by gravel, cobble, boulders, bedrock crevices, tree roots, and other vegetation, with some amount of fine sediment (i.e., clay and silt) necessary to provide appropriate shelter. However, excessive amounts of fine sediments can reduce the number of appropriate microsites in an otherwise suitable mussel bed by filling in these interstitial spaces, effectively smothering mussels in place. East Texas mussels generally require stable substrates, and loose silt deposits do not generally provide adequate substrate stability. Interstitial spaces provide essential habitat for juvenile mussels in particular, offering protection from predation and vital nutrients. Juvenile freshwater mussels burrow into interstitial substrates, making them particularly susceptible to degradation of this habitat feature. When clogged with sand or silt, interstitial flow rates and spaces may become reduced (Brim Box and Mossa 1999, p. 100) and no longer provide suitable habitat for juveniles. While adult mussels can be physically buried by excessive sediment, "the main impacts of excess sedimentation on unionids are often sublethal" and include interference with feeding mediated by valve closure (Brim Box and Mossa 1999, p. 101). Many land use activities can result in excessive erosion, sediment production and channel instability, including, but not limited to oil and gas development, logging, crop farming, ranching, mining, and urbanization (Arm et al. 2014, p. 114; Howells 2010b, p. 14; Arbuckle and Downing 2002, p. 311; Brim Box and Mossa 1999, p. 102).

Under a natural flow regime, a river or stream is in equilibrium in the context of sediment load, so that sediments are naturally washed away from one microsite to another, the amount of sediment in the substrate is relatively stable, and different reaches within a river or stream may be aggrading or degrading sediment at any given time (Poff et al. 1997, pp. 770-2). Current (and past) human activities often result in enhanced sedimentation in river systems and legacy sediment, resulting from past land disturbances and reservoir construction. These activities continue in many basins occupied by East Texas mussels, influencing river processes and sediment dynamics (Wohl 2015, p. 31, pp. 39), with legacy effects that can result in degradation of mussel habitat. Fine sediments collect on the streambed and in crevices during low flow events, and much of the sediment is washed downstream during high flow events (also known as cleansing flows) and deposited elsewhere. However, increased frequency of low flow events (from groundwater extraction, instream surface flow diversions, and/or drought) combined with a decrease in cleansing flows (from reservoir management and drought) causes sediment to accumulate. Sediments deposited by large scale flooding or other disturbance may persist for several years until adequate cleansing flows can redistribute that sediment downstream. When water velocity decreases, which can occur from reduced streamflow or inundation, water loses its ability to carry sediment in suspension and sediment falls to the substrate, eventually smothering mussels not adapted to soft substrates (Watters 2000, p. 263). Sediment accumulation can be exacerbated when there is a simultaneous increase in the sources of fine sediments in a watershed. In the range of the East Texas mussels, these sources include streambank erosion from development, agricultural activities, livestock and wildlife grazing, in-channel disturbances, roads, and crossings, among others (Poff et al. 1997, p. 773). In areas with ongoing development, runoff can transport substantial amounts of sediment from ground disturbance related to construction activities with inadequate or absent sedimentation controls. While these construction impacts can be transient (lasting only during the construction phase), the long-term effects of development on water quantity and quality are long lasting and can result in hydrological alterations as increased impervious cover increases run off and resulting shear stress causes streambank instability and additional sedimentation.

5.D. HABITAT FRAGMENTATION

Historically, the Louisiana pigtoe and Texas heelsplitter were likely distributed throughout the river basins described in Chapter 3. Given the reproductive ecology of both species, new areas of suitable habitat would have been colonized through movement of infested host fish, as newly metamorphosed juveniles would excyst from host fish and become established in new locations.

Today, the remaining Louisiana pigtoe and Texas heelsplitter populations are isolated from one another by major reservoirs such that natural recolonization of areas previously extirpated is extremely unlikely, if not impossible, due to barriers to host fish movement. There is currently no opportunity for interaction among extant Louisiana pigtoe and Texas heelsplitter populations as they are all fragmented from one another by reservoirs.

Instream barriers, such as reservoirs, low water crossings, and sections of dry stream bed during periods of prolonged drought, have multiple impacts on stream ecosystems. The impacts of reservoirs in particular are significant, causing permanent changes to fish movement, water quality, and hydrology, with cascading effects to river ecology and aquatic species that utilize areas downstream. Reductions in the diversity and abundance of mussels are primarily attributed to habitat shifts caused by impoundments (Neves et al. 1997, p.63), including the drastic alteration in resident fish populations and the inability of host fish to move freely between mussel populations resulting in the genetic isolation. The overall distribution of mussels is, in part, a function of the dispersal of their host fish. There is limited potential for immigration between populations other than through attached glochidia being transported to a new area or to another population. Small populations are more affected by this limited immigration potential because they are susceptible to genetic drift (random loss of genetic diversity) and inbreeding depression. At the species level, populations that are eliminated due to stochastic events cannot be recolonized naturally, leading to reduced overall redundancy and representation.

The confirmed or assumed primary host fish species for both the Louisiana pigtoe and Texas heelsplitter are known to be common and widespread throughout the range of both mussel species, and are therefore not believed to be a limiting factor to dispersal at this time. If fish host species are indeed abundant, existing dams and the construction new major dams and reservoirs, and other barriers to fish movement are the primary mechanism in which remaining population are isolated. Furthermore, reservoir impacts to river ecosystems can be difficult and costly to manage or minimize. For instance, it is possible to manage dam releases to mimic natural fluctuations in flows to benefit wildlife; however most reservoirs function primarily to provide water supply and/or flood control, and meeting those objectives typically involves holding on to as much water as possible (i.e., not releasing); this limits the ability of reservoir managers to modify releases for the purpose of meeting wildlife conservation or recovery goals. Although dams have been managed to allow fish passage for spawning, to our knowledge, fish passage has not been facilitated specifically to allow movement of host fish for the benefit of freshwater mussels, nor would this be cost-effective considering host fish for the East Texas mussels are believed to be abundant; nevertheless, reservoirs represent a permanent barrier to freshwater mussel dispersal. The overall impacts of reservoirs is believed to be greater for the Louisiana pigtoe relative to the Texas heelsplitter, which is able to persist in reservoir conditions although questions remain about their reproductive success in lacustrine environments.

5.E. DIRECT MORTALITY

Direct mortality includes any activity or event, whether human induced or natural, that results in the death of mussels within a localized area due to removal, crushing, burying, consumption, dessication, or poisoning. Potential activities or events causing direct mortality include, but are not limited to, development projects (such as bridge replacement, stream channelization, and impoundment construction), undeveloped low water crossings with vehicular traffic that intersect mussel beds, bank collapse, accidental release of hazardous materials, predation, vandalism, and collection (whether for scientific purposes, recreation, or by collectors). Although we expound on only a subset of possible activities and events that may cause direct mortality in this report, the above activities, and others not mentioned, are presumed to occur with some regularity in most watersheds occupied by the East Texas mussels and impact populations from time to time. The frequency, intensity, and magnitude of these impacts likely vary in time and by location, and are difficult to quantify with any certainty other than to acknowledge that they exist and negatively affect mussel survival to some degree.

Predation on freshwater mussels is a natural ecological interaction. Raccoons, snapping turtles, and fish are known to prey upon mussels. Under natural conditions, the level of predation occurring within these mussel species populations is not likely to pose a significant risk to any given population. However, during periods of low flow, terrestrial predators have increased access to portions of the river that are otherwise too deep under normal flow conditions, resulting in unnaturally high levels of predation that can decimate mussel populations. Predation during drought has been observed for the Texas heelsplitter on the Sabine River (Walters and Ford 2013, p. 479). Drought and low flow conditions are predicted to occur more often and for longer periods due to the effects of future climate change; therefore, the tributaries and upper portions of focal areas for East Texas mussels are expected to experience additional predation pressure into the future. Increased predation pressure may become especially problematic during summer months due to projected reductions in summer minimum base flows (Lafontaine et al. 2019, entire). Predation is expected to be less of a problem for the lower portions of the main stem river populations where the rivers are significantly larger than the tributary streams and these species are less likely to be located in exposed or very shallow habitats.

Certain mussel beds within some populations, due to ease of access, are vulnerable to over-collection and vandalism. These areas have well known and well documented mussel beds that are often sampled multiple times annually by various researchers for various scientific projects. Populations subjected to repeated sampling or monitoring may experience increased stress or higher rates of mortality. Mortality may also occur in areas with intense recreation where local fishing enthusiasts have been observed using freshwater mussels as bait. The risk of direct mortality from recreation or over collection for scientific purposes are compounded by the additional stressors discussed in this chapter, which can influence mussel survival in a cumulative manner. Service biologists recently hosted a meeting with State biologists, consultants, and academia who are involved in mussel research to discuss ongoing monitoring and scientific collections and to reduce the likelihood of over harvesting mussels from any given population (USFWS 2018, p.1). We anticipate this collaboration among researchers will continue into the future with ongoing coordination and annual meetings.

5.F. INVASIVE SPECIES

Invasive species, such as Asian clam (*Corbicula fluminea*), zebra mussel (*Dreissena polymorpha*), feral hog (*Sus scrofa*), floating water hyacinth (*Eichhornia crassipes*), giant salvinia (*Salvinia molesta*), and hydrilla (*Hydrilla verticillata*), occur throughout the range of East Texas mussels and can negatively impact mussel survival. These impacts include predation (feral hog), habitat destruction or modification (feral hog, floating waterhyacinth, giant salvinia, hydrilla), changes to water quality (feral hog, zebra mussel), increased resource competition (Asian clam, zebra mussel), or physical impairment (zebra mussel, hydrilla) (Howells 2010a, p. 13; Howells 2010b, pp. 14-15; Kaller et al. 2007, pp. 173-174).

Zebra mussels have attached to this young Higgins eye pearlymussel, an endangered species found in the Mississippi river. Photo by USFWS

Asian clams are common in river basins across the range of the East Texas mussels, often at high densities, and likely compete with native unionids for food, oxygen, physical space, and other environmental resources (USGS 2019a, entire; Howells 2010a, p. 13; Howells 2010b, p. 14; Cherry et al. 2005, p. 369). However, they are sensitive to low flow, increased silt loads, temperature extremes, and low dissolved oxygen, and can experience rapid die-offs (Cherry et al. 2005, p. 369). Tissue decomposition associated with Asian clam die-offs can cause spikes of ammonia in the water column and impact native mussels, especially during early life stages (Cherry et al. 2005, pg. 378); Cooper et al. (2005, p. 392) concluded concentrations of ammonia in substrate pore water (i.e., water contained in the interstitial spaces located between particles comprising the substrate) can be greater than that of the water column during Asian clam die-offs, potentially impacting glochidia survival.

Although zebra mussel infestations occur in several Texas reservoirs, including Lake Lewisville and Lake Livingston, populations have not become established in nearby river habitats occupied by the East Texas mussels (TPWD 2019, entire; USGS 2019e, entire; Ford et al. 2016b, p. 47). The distribution of zebra mussels may be limited to lacustrine environments in part due to the fragility of zebra mussel veligers (larval stage) and the higher turbulence and velocities associated with reservoir discharge (Churchill and Quigley 2018, p. 1123). Where native mussels and zebra mussels co-occur, zebra mussels compete with native mussels for dissolved oxygen and food resources, although the extent to which this competition limits the growth or survival of native mussels is poorly understood. Zebra mussels reproduce prolifically and attach to virtually any surface, including the shells of native mussels, which impedes mobility and further reduces resource uptake. Native mussels and zebra mussels prefer the unicellular cyanobacteria Microcystis as a food source; however, native mussels are less efficient at selecting Microcystis over less nutritious detritus particles than zebra mussels. Therefore, where zebra mussels are present, food quality available to native mussels decreases, contributing to native mussel mortality (Baker and Levinton 2003, pp. 103-104).

Feral hogs occur throughout the range of both East Texas mussels and are known to engage in a variety of activities that disturb soils and degrade water quality, including the contribution of waste (i.e., excrement) that elevates nutrient and fecal coliform levels within streams and rivers (USDA 2019, entire; Gregory et al. 2014, p. 35; Kaller et al. 2007, p. 173). Feral hogs may also consume native mussels in shallow waters (Kaller et al. 2007, p. 174). Bank and stream bed damage from feral hogs contributes to erosion and increased sedimentation, and their presence appears to cause native mussel diversity and abundance to decrease through organic enrichment of the water column and unfavorable changes to microbial community composition (Howells 2010b, p. 10; Kaller et al. 2007, p. 174).

Invasive macrophyte infestations of floating waterhyacinth, hydrilla, and giant salvinia negatively impact native mussels and their host fish throughout the southern half of the ranges of East Texas mussels by creating hypoxic conditions through respiration and during decay (USGS 2019b, entire; USGS 2019c, entire; USGS 2019d, entire; Karateyev and Burlakova 2007, p. 298). Dense mats of hydrilla, an aquatic plant rooted to substrate, can also impede native mussel movement during periods of fluctuating surface water levels, leaving them stranded as water levels recede. In Texas, attempts to control these exotic species has led to periodic partial drawdowns of B.A. Steinhagen Lake, a reservoir known to be occupied by Texas heelsplitter (Howells 2010b, p. 14), which likely led to mussel mortalities in areas where substrates were exposed for extended periods.

5.G. CLIMATE CHANGE

Most experts agree climate change has been underway for decades with mounting impacts to humans, wildlife, infrastructure, and communities, particularly in coastal areas; continued greenhouse gas emissions at or above current rates will cause further warming with broad implications for living organisms across the planet and the habitat on which they depend (Intergovernmental Panel on Climate Change (IPCC) 2013, pp. 11-12). Warming in Texas is expected to be greatest in the summer (Maloney et al. 2014, p. 2236, Fig. 3), with the number of extremely hot days (high temperatures exceeding 95º Fahrenheit) projected to double by around 2050 (Kinniburgh et al. 2015, p. 83). The effects of climate change are expected to be more pronounced in the naturally dry climates of West Texas (Diffenbaugh et al. 2008, p. 3), although impacts to water resources are projected throughout the state. Changes in stream temperatures are expected to reflect changes in air temperature, at a rate of approximately 0.6 – 0.8°C increase in stream water temperature for every 1°C increase in air temperature (Morrill et al. 2005, pp. 1-2, 15), with implications for temperature-dependent water quality parameters such as dissolved oxygen and ammonia toxicity. Given that freshwater mussels in Texas exist at or near the ecophysiogical edge of climate and habitat gradients of unionid biogeography in North America, they may be particularly vulnerable to future climate changes in combination with current and future stressors (Burlakova et al. 2011a, pp. 156, 161, 163; Burlakova et al. 2011b, pp. 395, 403).

While projected changes to rainfall in Texas may seem relatively small (USGCRP 2017, p. 217), higher temperatures caused by anthropogenic activity will lead to increased soil water deficits because of higher rates of evapotranspiration. In turn, higher evapotranspiration rates will likely to result in increasing drought severity in future climate scenarios at a time when "extreme precipitation, one of the controlling factors in flood statistics, is observed to have generally increased and is projected to continue to do so across the United States in a warming atmosphere" (USGCRP 2017, p. 231). Even if precipitation and groundwater recharge remain at current levels, increased groundwater pumping and resulting aquifer shortages due to increased temperatures are nearly certain (Loaiciga et al. 2000, p. 193; Mace and Wade 2008, pp. 662, 664-665; Taylor et al. 2013, p. 3).

Higher temperatures are also expected to lead to increased evaporative losses from reservoirs, diminishing overall water supply and negatively affecting downstream releases and flows (Friedrich et al. 2018, p. 167). Effects of climate change, such as changes to seasonal rainfall patterns, air temperature increases, and increases in drought frequency and intensity, have been shown to be occurring throughout the range of East Texas mussels (USGCRP 2017, p. 188; Andreadis and Lettenmaier 2006, p. 3); these effects are expected to exacerbate several of the stressors discussed above, such as water temperature and flow loss (Wuebbles et al. 2013, p. 16). A recent review of future climate projections for Texas concludes that both droughts and floods could become more common in East Texas, with droughts like ~~the one seen in~~ 2011 (the warmest on record) becoming commonplace by the year 2100 (Mullens and McPherson 2017, pp. 3, 6). This trend of more frequent droughts is driven by increases in hot temperatures (e.g., daily maximum) and the number of days projected to be at or above 100°F, which is set to "increase in both consecutive events and the total number of days" (Mullens and McPherson 2017, p. 14-15). Similarly, floods and extreme runoff are projected to become more common and severe in the 21st century as the frequency, magnitude and intensity of heavy precipitation events increase (Mullens and McPherson 2017, p. 20, USGCRP 2017, p. 224).

In the analysis of the future condition for East Texas mussels~~, which follows~~ in Chapter 6, climate change is considered further under various likely future scenarios, serving to exacerbate already deteriorating conditions through an increase of fine sediments, changes to water quality, loss of flowing water, and predation, among others.

5.G. SUMMARY

Our analysis of the past, current, and future variables that influence East Texas mussel needs for long-term viability revealed that there are four factors that pose the largest risk to future viability, namely degradation of water quality, altered hydrology, changes to substrate, and habitat fragmentation; all of which are exacerbated by climate change.

All the factors affecting viability, including degradation of water quality, altered hydrology, changes to substrate, habitat fragmentation, direct mortality, and invasive species, are carried forward in Chapter 6 where we assess the future condition of East Texas mussel populations and the viability of each species as the influence of each factor changes into the foreseeable future.

CHAPTER 6 – SPECIES VIABILITY IN THE FUTURE

This report has considered what the East Texas mussels need for viability and the current condition of those needs (Chapters 2, 3 and 4), and reviewed the risk factors that are driving the historical, current, and future conditions of the species (Chapter 5 and Appendix B). In this Chapter we ~~will~~ consider potential changes to risk factors in the foreseeable future, and the implications of those changes on the viability of each species. In keeping with the SSA framework, we will apply our ~~future~~ forecasts using the concepts of species resiliency, redundancy, and representation to describe future viability of the East Texas mussels.

6.A. INTRODUCTION

Relative to historical conditions (i.e., historical range), the East Texas mussels have declined significantly in terms of overall distribution and abundance over the past 100 or more years. Most ~~of the~~ known populations are isolated and currently exist in very low numbers (i.e., low abundance), have limited evidence of recruitment, and are believed to occupy much less habitat than in the past (range contraction). Furthermore, existing available habitats are experiencing additional stressors and are reduced in terms of water quality and quantity relative to historical conditions.

Efforts to create new infrastructure for flood control and water supply continued throughout the mid ~~twentieth~~ century, and by 1975 major dams and reservoirs had been constructed in every river basin occupied by the East Texas mussels; in some cases, multiple reservoirs were established along the same river. Only the upper most reaches of a few rivers were spared, including the Calcasieu River and Mountain Fork populations of Louisiana pigtoe, which are not currently impacted by upstream impoundments. The inundation and subsequent alteration of hydrology and sediment dynamics associated with the operation of these flood-control, hydropower, and municipal supply reservoirs has resulted in irreversible changes to the natural flow regime of these rivers and ultimately re-shaped the aquatic ecosystems they provide, including the fisheries and invertebrate communities that depend on them, as well as populations of the East Texas mussels.

With the advent of the industrial revolution and before Congress enacted laws like the Clean Water Act to protect the environment, water quality impacts were common in many Texas rivers. Prior to the implementation of modern sanitation, impacts could be severe, leading the Texas Department of Health to call the Trinity a "mythological river of death" in 1925 (USGS 1998, p. 19). Fortunately today, water quality has improved dramatically utilizing enhanced treatment technology and centralized wastewater treatment, and fish populations have rebounded, although not to historical levels (Perkin and Bonner 2016, p. 97). Nevertheless, water quality in many watershed remains largely altered from pre-industrial revolution condition, and degradation continues to affect mussels and their habitats. These impacts become more pronounced during low flow conditions, when water chemistry and geomorphological constraints diminish instream habitats. The timing, frequency, and intensity of high flow events has also been altered, generating shear stress that mobilizes substrates, scours mussel beds, and erodes river banks.

Additionally, while host fish may still be adequately represented in contemporary fish assemblages, access to fish hosts can be reduced during critical reproductive times by barriers such as low-water crossings, reservoirs, and low-head dams that are relatively common on the landscape. Low flows can lead to dewatering of habitats, desiccation of individuals, elevated water temperatures (above 30°C and approaching 40°C) and other water quality degradations (low dissolved oxygen and elevated TAN), as well as increased exposure to predation. Diminished access to host fish leads to reduced reproductive success just as barriers to fish passage impede the movement of fish, and thus compromise the ability of mussels to disperse and colonize new habitats following a disturbance (Schwalb et al. 2013, p. 446). Lastly, freshwater mussels have long been utilized by humans, for food and bait, for pearls and buttons, for scientific collection, and to create artificial pearls; even today rare mussels are vulnerable to human collection (Bogan 1993, pp. 604-5), even though other threats like habitat modification pose a greater risk.

Populations of East Texas mussels are faced with a myriad of stressors from natural and anthropogenic sources that pose a risk to their survival in both large and small river segments. In Texas, as elsewhere, climate change has the noteworthy distinction of being able to directly or indirectly exacerbate the most relevant stressors to freshwater mussels wherever they occur. Climate projections suggest persistent droughts over the continental United States that are longer, cover more area, and are more intense than what has been experienced in the 20th century (APA 2019, pg. 4). Humans are likely to respond to climate change in predictable ways to meet their needs, such as increased groundwater pumping and surface water diversions, and increased use of reverse osmosis to treat sources of water that are of poor quality (thereby generating increasing volumes of reject wastewater). These activities will increase overall demand for freshwater resources at a time when those very resources are strained and less abundant (reviewed in Banner et al. 2010, entire). We expect climate change impacts to occur throughout the range of both East Texas mussels.

These risks, acting alone or in combination with each other and climate change, could result in the extirpation of additional mussel populations, further reducing the overall redundancy and representation of the East Texas mussels. Historically, each species, bolstered by large interconnected populations (i.e., with meta-population dynamics), would have been more resilient to stochastic events such as drought, excessive sedimentation, and scouring floods. As locations became extirpated by catastrophic events, they could be recolonized over time by dispersal from nearby surviving populations, facilitated by movements of "affiliate species" of host fish (Douda et al. 2012, p. 536). This connectivity across potential habitats made for highly resilient species overall, as evidenced by the long and successful evolutionary history of freshwater mussels as a taxonomic group, and in North America in particular. However, under current conditions, restoration of that connectivity on a regional scale is not feasible. As a consequence of these current conditions, the viability of the East Texas mussels now primarily depends on maintaining the remaining isolated populations and potentially restoring new populations where feasible.

6.B. Future Scenarios and Considerations

Because of significant uncertainty regarding the location, magnitude, and duration of impacts related to flow loss, water quality degradation, extreme flooding and scour/substrate mobilizing events, or new impoundment construction, we began forecasting future viability for the East Texas mussels in terms of resiliency, redundancy, and representation under 3 plausible future scenarios (maintain current trends, moderate increase in stressors, and severe increase in stressors). However, during our evaluations it became apparent that our approach lacked the resolution to distinguish any meaningful difference between the "maintain current trends" and the "moderate increase in stressors" scenarios. As a result, the SSA team decided to limit the future forecasts analyzed in this report to two scenarios, a moderate increase in stressors and a severe increase in stressors (Table 6.1). Both scenarios were evaluated at 3 time internals into the future, where future risks were considered to determine the biological status of mussel populations and their habitats in 10, 25, and 50 years. Ten years represents 1 to 2 generations of mussels, assuming an average reproductive life span of 5 to 10 years. Twenty-five years similarly represents 2 to 4 mussel generations and 50 years represents 5 or more generations of mussels.

Table 6.1. Two future scenarios (moderate and severe increase in stressors) evaluated under associated moderate and severe climate change emission scenarios (i.e., a 4.5 and 8.5 Representative Concentration Pathways (RCP*), respectively), at each of three time steps.

Future Scenario	RCP*	10–years	25-years	50-years
Scenario 1: moderate increase in stressors	4.5	0–10 yrs	10–25 yrs	25–50 yrs
Scenario 2: severe increase in stressors	8.5	0–10 yrs	10–25 yrs	25–50 yrs
*RCP = Representative Concentration Pathway Scenario (IPCC 2014, pp. 9, 57)				

The future scenarios included the interactive effects of future climate change using emissions projected at 4.5 and 8.5 RCP scenarios contributed by the Working Group III to the Fifth Assessment Report and described in the most recent Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC 2014, pp. 9, 22, 57). The IPCC Report describes four alternative trajectories for carbon dioxide emissions (RCPs) and the resulting atmospheric concentrations from the year 2000 to 2100 (van Vuuren et al. 2011, p.5). Scenario 1 assumed RCP 4.5, a medium stabilization scenario where CO_2 emissions continue to increase through mid-21st century, but then decline and atmospheric carbon dioxide concentrations are between 580 and 720 ppm CO_2 from 2050 to 2100, representing an approximate +2.5 ºC temperature change relative to 1861-80 (IPCC 2014, p. 9, Figure SPM.5). Scenario 2 assumed RCP 8.5 where atmospheric carbon dioxide concentrations are above 1000 ppm CO_2 between 2050 and 2100, representing an approximate +4.5 ºC temperature change relative to 1861-80 (IPCC 2014, p. 9, Figure SPM.5). The most recent IPCC Synthesis Report projects global temperature change to 2100 and beyond (IPCC 2014, p. 8). A recent study suggests that, because of uncertainty in long-run economic growth rates, there is "a greater than 35% probability that emissions concentrations will exceed those assumed in the most severe of the available climate change scenarios (RCP8.5)" by 2100 (Christensen et al. 2018, p. 1).

This SSA is based on the following assumptions, which are from the most recent Synthesis Report of the IPCC (IPCC 2014, entire) and other scientific studies. The IPCC Synthesis Report considers RCP 4.5 as an intermediate scenario and RCP 8.5 as having "very high" greenhouse gas emissions (IPCC 2014, p. 8). Under RCP 4.5, current conditions, including a continued trend towards increased warming, frequency and severity of extreme weather events, such as droughts and floods, are expected to continue. Global mean surface temperature change is projected "*more likely than not*" to exceed 1.5 ºC by 2100, relative to 1850-1900 (IPCC 2014, p. 60). Under RCP 8.5, future conditions include a more dramatic increasing trend with more significant increases in the frequency and severity of extreme weather events, such as droughts and floods, under future climate projections. Global mean surface temperature change is projected "*likely*" to exceed 2.0 ºC by 2100, perhaps as high as 4.8 ºC, relative to 1850-1900 (IPCC 2014, p. 60). It is important to remember that two of the most powerful environmental forces that influence the presence of living organisms in any given area are temperature and the presence of water; therefore, even minor shifts in global temperatures will have dramatic worldwide effects on species distribution and abundance. Because of the influence of temperature on water, including evapotranspiration, climate change is expected to result in drier soils with less runoff and under RCP 8.5 by 2100, "no region of the planet is projected to experience significantly higher levels of annual average surface soil moisture…even though much higher precipitation is projected in some regions" (USGCRP 2017, pp. 232-8).

For all IPCC RCP scenarios, extreme precipitation events over most mid-latitude land masses (like North

America) will very likely become more intense and frequent as global mean surface temperatures increase (IPCC 2014, p. 60) and, as such, future temperature and precipitation patterns are likely to become more variable and extreme, with drought and flooding events occurring more frequently and with higher severity in the southwestern United States (Seager et al. 2007, pp. 1183-4). In the southeastern United States, most rivers will experience lower annual minimum 7-day base flows and summer minimum base flows with fewer high flow events of longer duration (Lafontaine et al. 2019, entire). The magnitude of these changes is expected to increase with time even without increasing greenhouse gas emissions as even steady-state (i.e., no change in greenhouse emissions) or slightly reduced emissions would produce increased atmospheric concentrations. Given the inertia of the climate system and regardless of future emissions, the risk of flooding is expected to increase over the next 25-50 years. These increases in the severity of extreme floods are expected to affect human systems (reviewed in Willner et al. 2018, entire; Hirabayashi et al. 2013, entire), as well as marine and freshwater ecosystems and the aquatic organisms that depend on them, including freshwater mussels and their host fishes.

Future human demand for water resources, due to projected human population growth and limitations of existing supplies, is expected to increase and interact with climate effects to exacerbate the effects of drought on surface water resources in Texas. These effects are expected to occur throughout the range of the East Texas mussels, and are likely to impact the ability of water managers to provide “environmental flows” that are designed to provide the minimum flow needed by freshwater mussels and other aquatic dependent organisms (Wolaver et al. 2014, pp. 1-2).

The upper portions of the basins, including tributaries, will be more sensitive to changes in precipitation patterns and withdrawals, relative to the lower portions of the basins, where flows are generally larger and are supplemented by municipal wastewater (or other) return flows; senior water rights located at the “bottom” of the basin also help protect flows in the lower reaches. However, while minimum flows may be maintained, other artifacts of altered hydrology may have deleterious effects to mussels and their habitats through altered water quality. Changes to sediment transport (more extreme deposition and scour) will also lead to reductions in habitat quality and quantity.

This SSA report evaluates two plausible future scenarios (Table 6.1). Scenario 1 considers a moderate increase in stressors resulting in a moderate decline of current conditions projected across the next 10, 25, and 50 years. Scenario 1 assumes RCP 4.5 climate change predictions, representing fairly optimistic emissions conditions and resulting climate impacts, with an overall moderate decline in current population trends. Scenario 2 projects a severe decline in current population trends and condition categories in the future under RCP 8.5 predictions. Further, Scenario 2 also includes anthropogenic actions, such as the construction of new reservoirs, wastewater treatment plants, and other currently proposed projects. Scenario 2 manifests as a future where the hydrological conditions of many of the rivers and streams currently occupied by East Texas mussels are altered such that base flows are diminished, floods are more severe if not more frequent, and mussels and their habitats are adversely affected through degradation of water quality and quantity. These altered hydrological conditions are primarily caused by a combination increasing anthropogenic stressors and climate change.

We examined the resiliency, representation, and redundancy of the East Texas mussel species under two plausible future scenarios for each of the three time periods. The resiliency of mussel populations depends on future conditions providing water of sufficient quality and quantity to meet the life history needs of the East Texas mussels and their host fishes. Resiliency requires good water quality, flowing water, and suitable substrates because these habitat factors directly influence species reproduction and abundance, which determines the amount of occupied habitat. We expect the extant populations of these mussel species to experience changes to critical aspects of their habitat in different ways under the different scenarios. We projected the future resiliency of each population based on events that were likely to occur under each scenario. We then projected the overall condition for each population based on expert opinion and anticipated changes to habitat and population factors. For these projections, populations in high (healthy) condition are expected to have high resiliency at that time period; i.e., they occupy habitat of sufficient size to allow for ebbs and flows in density of mussel beds within the population over time without significantly impacting the overall health of the population. Populations in high condition are expected to persist into the future (> 90 % chance of persistence beyond 20 years), and they have the ability to withstand stochastic events that may occur. Populations in moderate (moderately healthy) condition have lower resiliency than those in high condition, but the majority (60–90 %) are expected to persist beyond 20 years. Populations in moderate condition are smaller and less dense than those in high condition. Populations in low (unhealthy) condition have low resiliency and are not necessarily able to withstand stochastic events. As a result, they are less likely to persist beyond 20 years (10–60 % chance). Finally, we considered populations extirpated when they either lacked individuals (i.e., surveys yielded no observations) or there was no evidence of reproduction (functionally extinct); these populations have very low resiliency and have less than a 10 % chance of persistence beyond 20 years.

In an effort to maintain consistency throughout the scenario evaluation process for each East Texas mussel population, the SSA team developed a population resiliency model to determine the direction and magnitude of change to population resiliency under each future scenario and time step. This unweighted additive model, based on the effects pathway flowchart, shows how threats under the different scenarios influence habitat factors (habitat structure/substrate, hydrological regime, and water quality), population factors (occupied habitat reach length, abundance, and reproduction/recruitment), host fish availability, and survival (Figure 6.1). However, if two of the three habitat factors (habitat structure/substrate, hydrological regime, or water quality) were determined to be in severe decline, we considered population resiliency to also be in severe decline regardless of model output. The final output value represented the impact of all forecasted threats to population resiliency.

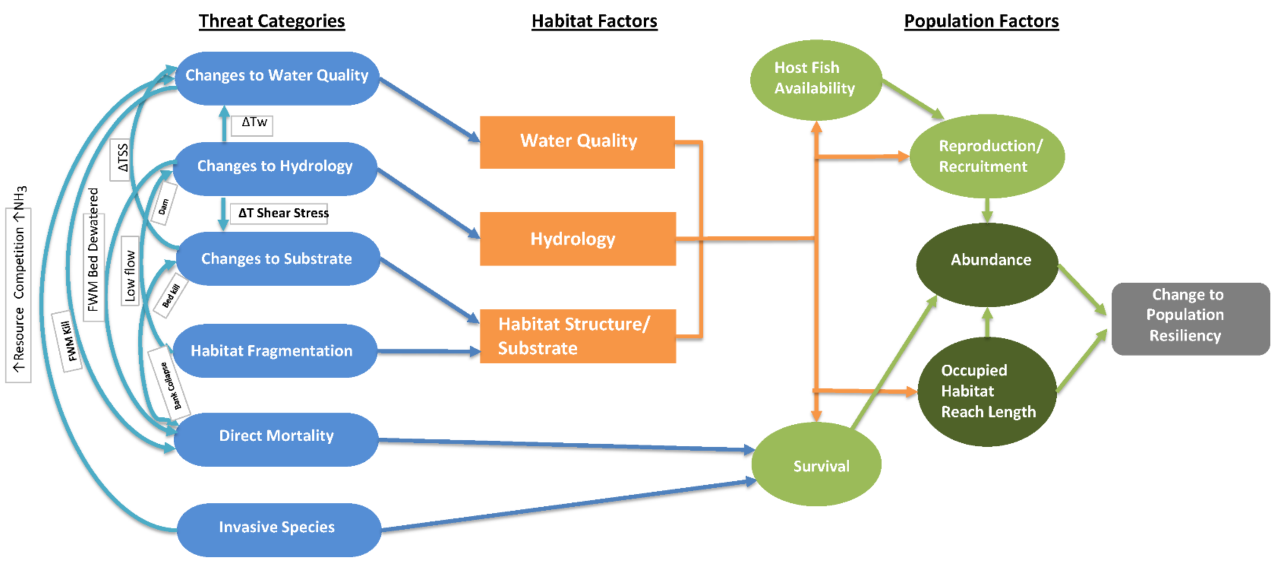


Figure 6.1. Effects pathway flowchart for East Texas mussels. Threats (blue elliptical circles on the left side of the chart) influence Habitat Factors (orange boxes in middle) and Population Factors (green circles at right), which ultimately determines population resiliency (grey box at far right). White boxes (on far left) provide examples of how a change to one threat category can influence other threat categories.

Inputs to the population resiliency model were determined by SSA team consensus on the projected magnitude of change to the six threat categories (water quality, hydrology, habitat structure/substrate, fragmentation, direct mortality, and invasive species) and classified as either significant improvement, moderate improvement, maintain current trend, moderate decline, or severe decline (see Appendix C, tables C.1 and C.2 for classification criteria). Each threat category projection was then assigned a numerical value corresponding to the previous classifications. Input values ranged from 2 to -2: where 2 represents significant improvement; 1, moderate improvement; 0, maintain current trend; -1, moderate decline; and -2, severe decline. The algorithm for the population resiliency model was expressed as follows:

$$\triangle \mathbf{Resilience} = \mathbf{5}(\triangle \mathbf{wq} + \triangle \mathbf{hr} + \triangle \mathbf{s} + \triangle \mathbf{f}) + \triangle \mathbf{m} + \triangle \mathbf{i}$$

Where: △Resilience = change to population resilience
△wq = threat of changes to water quality
△hr = threat of changes to hydrological regime
△s = threat of changes to substrate
△f = threat of changes to habitat fragmentation
△m = threat of changes to direct mortality
△i = threat of changes to invasive species

Population Resiliency Model assumptions:

- All threat categories are equal in importance (unweighted); however, those threats (or their products) used more frequently in the algorithm have more influence on model output than those used less.
- Each threat category can influence one or many other threat categories (see fig. 6.1).
- Current condition was considered to follow a continuing declining trend and additional conservation, if implemented, would at best negate the current decline in future scenarios.

Model output values ranged from 44 to -45, with positive numbers indicative of an overall improvement in population resiliency, 0 indicating no change from current trend, and negative values showing an overall decline in population resiliency. Scenarios with two of the three habitat factors (water quality, hydrology, and substrate) projected to be in severe decline from the current trend were considered to result in a severe decline in population resilience and identified with an output value of -45. Output values were categorized as shown in Table 6.2.

Table 6.2. Population resiliency model output classifications

Model output	Classification
44 ≥ △Resiliency > 22	Significant improvement in population resiliency
22 ≥ △Resiliency > 0	Moderate improvement in population resiliency
△Resiliency= 0	Maintain current population resiliency
0 > △Resiliency ≥ (-22)	Moderate decline in population resiliency
(-22) > △Resiliency > (-44)	Severe decline in population resiliency

Note: △Resiliency = (-45) indicates two of the three habitat factors are severely declining; therefore, △Resiliency = severe decline.

For each future scenario and time step, the population resiliency model output was compared to the population's current condition, as described in Chapter 4. SSA team consensus was then used to evaluate the effect of the projected change in population resilience over time to the current population condition, resulting in a projected population condition for each future scenario and time step.

6.B.1. Future Scenario 1 – Moderate Decline in Conditions

Scenario 1 considers a future where conditions moderately decline from present trends under current population conditions. Scenario 1 assumes intermediate climate effects, including more frequent and intense droughts, where droughts are broken by major flooding. Scenario 1 also considers additional groundwater and surface water demands associated with human population growth and decreased water availability that is compounded by intermediate climate effects. Reductions in streamflow, due to decreased inputs and enhanced evapotranspiration, are expected to occur in all streams and rivers, and those effects will likely be more pronounced in the upper basins.

Scenario 1 considers additional water projects, like new wastewater treatment plant outfalls or proposed new reservoirs, only if currently proposed or planned. Under Scenario 1, proposed new reservoirs are constructed in the next 10–25 years, and any effects from completion of the associated dams are manifest in the next 25–50 years. Necessary routine maintenance as well as repair and replacement of existing old dams occurs in the next 10–25 years, and any effects from those repairs are manifest in the next 25–50 years.

6.B.2. Future Scenario 2 – Severe Decline in Conditions

Scenario 2 considers a future where conditions severely decline from the status quo (i.e., current conditions). Scenario 2 considers severe climate effects, including more frequent and intense droughts, where droughts are broken by major flooding. Scenario 2 considers additional groundwater and surface water demands associated with increased human demand and decreased water availability due to severe climate effects. Scenario 2 considers additional water projects, like new wastewater treatment plant outfalls, even if not currently proposed, as well as possible new reservoirs and other construction projects affecting water quality or quantity.

6.C. Future Viability (Resiliency, Redundancy, and Representation)

This section generally reviews the viability of the East Texas mussel species under each of the two scenarios. The output of the scenarios at each time step for each species, as well as a synopsis of the effects to the populations over time are included in Appendix C.

6.C.1. Future Scenario 1 – Moderate Increase in Stressors

Resiliency

Under Scenario 1, populations of the East Texas mussels decline in resiliency over time as the factors that are having an influence on populations moderately decline from current rates (Table 6.4). The effects of current levels of climate change continue to result in low streamflows, which lead to increased sedimentation, reduced water quality, and occasional desiccation. Population extirpations occur to both species, with only the Cossatot River population of Louisiana pigtoe in moderate condition in 50 years. The remaining populations are in low condition and are particularly vulnerable to extirpation.

Table 6.4. Condition of the East Texas mussel populations under Future Scenario 1.

Future Scenario 1: Moderate increase in stressors Climate Change Model RCP 4.5						
SPECIES	**Representation Areas (River Basin)**	**POPULATIONS (Focal Areas)**	**Current Condition**	10-yrs	25-yrs	50-yrs
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	Extirpated	Extirpated	Extirpated	Extirpated
	Neches	Neches R/BA Steinhagen	Moderate	Moderate	Low	Low
		Lower Neches R	Low	Low	Low	Extirpated
	Trinity	Grapevine LK	Extirpated	Extirpated	Extirpated	Extirpated
		Trinity R/Livingston	Low	Low	Low	Extirpated
Louisiana pigtoe	Red	Mountain FK	Low	Low	Low	Extirpated
		Little R/Rolling FK	Moderate	Moderate	Low	Low
		Cossatot R	High	High	High	Moderate
		Saline R (Little)	Low	Low	Low	Low
		Lower Little R	Extirpated	Extirpated	Extirpated	Extirpated
	Big Cypress	Big Cypress Bayou	Moderate	Moderate	Moderate	Low
	Calcasieu-Mermentau	Upper Calcasieu R	Low	Low	Low	Extirpated
	Pearl	Pearl R	Low	Low	Low	Low
	Sabine	Sabine R	Extirpated	Extirpated	Extirpated	Extirpated
		Bayou Anacoco	Moderate	Low	Moderate	Low
	Neches	Angelina R	Low	Low	Low	Extirpated
		Neches R	High	High	Low	Low
		Lower Neches R	Low	Low	Low	Low
	San Jacinto	E FK San Jacinto R	Low	Low	Low	Extirpated

Redundancy

Both of the East Texas mussels lose redundancy under Scenario 1 (Tables 6.4 and 6.5). Under our projections, the Louisiana pigtoe would have 1 population in moderate condition, 7 in low condition, and 6 functionally extirpated or extirpated populations across 6 representation areas in 50 years. Of the 5 populations evaluated for Texas heelsplitter, all but one (Neches River/B.A. Steinhagen population) are projected to become extirpated or functionally extirpated in 50 years under this scenario.

Representation

Under Scenario 1, both species of East Texas mussels lose two areas of representation, diminishing the overall adaptive capacity of each species to future environmental change in the next 50 years (Tables 6.4 and 6.5). The Louisiana pigtoe would lose the Upper Calcasieu River and San Jacinto River populations, and the Texas Heelsplitter would lose the Sabine River and Trinity River populations.

Table 6.5. Summary of condition for the East Texas mussel populations under Future Scenario 1.

Projected condition	Number of Louisiana pigtoe populations (n=14 within 6 representation areas)			Number of Texas heelsplitter populations (n=5 within 3 representation areas)		
	10-year	25-year	50-year	10-year	25-year	50-year
High	2	1	0	0	0	0
Moderate	2	2	1	1	0	0
Low	8	9	7	2	3	1
Extirpated/ functionally extirpated	2	2	6	2	2	4
Number of representation areas	6	6	4	2	2	1

6.C.2. Future Scenario 2 – Severe Increase in Stressors

Resiliency

Under Scenario 2, populations of the East Texas mussels would decline in resiliency over time as the effects of severe climate change begin to impact populations (Table 6.6). The effects of severe climate change result in even lower stream flows, with a proportionally severe increase in sedimentation, reduction in water quality, and increase in potential for desiccation of habitat. All Texas heelsplitter populations are projected to become extirpated or remain functionally extirpated in 50 years. A total of 8 populations of Louisiana pigtoe are expected to remain functionally extirpated or become extirpated in 50 years, with the remaining 6 populations in low condition. The populations that remain in low condition are particularly vulnerable to extirpation.

Table 6.6. Condition of East Texas mussel populations under Future Scenario 2.

Future Scenario 2: Severe Increase in Stressors - Climate Change Model RCP 8.5						
SPECIES	**Representation Areas (River Basin)**	**POPULATIONS (Focal Areas)**	**Current Condition**	10-yrs	25-yrs	50-yrs
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	Extirpated	Extirpated	Extirpated	Extirpated
	Neches	Neches R/BA Steinhagen	Moderate	Moderate	Low	Extirpated
		Lower Neches R	Low	Low	Low	Extirpated
	Trinity	Grapevine LK	Extirpated	Extirpated	Extirpated	Extirpated
		Trinity R/Livingston	Low	Low	Low	Extirpated
Louisiana pigtoe	Red	Mountain FK	Low	Low	Low	Extirpated
		Little R/Rolling FK	Moderate	Moderate	Low	Low
		Cossatot R	High	High	High	Low
		Saline R (Little)	Low	Low	Low	Low
		Lower Little R	Extirpated	Extirpated	Extirpated	Extirpated
	Big Cypress	Big Cypress Bayou	Moderate	Moderate	Moderate	Low
	Calcasieu-Mermentau	Upper Calcasieu R	Low	Low	Low	Extirpated
	Pearl	Pearl R	Low	Low	Low	Extirpated
	Sabine	Sabine R	Extirpated	Extirpated	Extirpated	Extirpated
		Bayou Anacoco	Moderate	Low	Moderate	Extirpated
	Neches	Angelina R	Low	Low	Low	Extirpated
		Neches R	High	High	Low	Low
		Lower Neches R	Low	Low	Low	Low
	San Jacinto	E FK San Jacinto R	Low	Low	Extirpated	Extirpated

Redundancy

Both East Texas mussels lose redundancy under Scenario 2 with a particularly severe outcome for Texas heelsplitter populations, which are extirpated throughout the range of the species (Table 6.6 and 6.7). Under our projections, Louisiana pigtoe would have 4 remaining populations within the Red River basin and 2 in the Neches River basin in 50 years. The remaining Louisiana pigtoe populations are projected to be in low condition and vulnerable to extirpation.

Representation

Under Scenario 2, Louisiana pigtoe lose 4 of the 6 current representation areas in 50 years (Table 6.6 and 6.7), with 8 of 14 populations remaining or becoming extirpated; therefore, the adaptive capacity and representation of this species is projected to be severely reduced from future environmental change. The populations of Louisiana pigtoe projected to remain in 50 years are in low condition. Texas heelsplitter are projected to be extirpated throughout their range in 50 years (i.e, extinct), and the remaining Louisiana pigtoe populations are extremely vulnerable to extinction under Scenario 2.

Table 6.7. Summary of condition of the East Texas mussel populations under Future Scenario 2.

Projected condition	Number of Louisiana pigtoe populations (n=14 within 6 representation areas)			Number of Texas heelsplitter populations (n=5 within 3 representation areas)		
	10-year	25-year	50-year	10-year	25-year	50-year
High	2	1	0	0	0	0
Moderate	2	2	0	1	0	0
Low	8	8	6	2	3	0
Extirpated/ functionally extirpated	2	3	8	2	2	5
Number of representation areas	6	5	2	2	2	0

6.D. Status Assessment Summary

Using the best available information, this report used scenario planning to forecast the likely future condition of the East Texas Mussels across their current ranges. The goal of this report is to describe the viability of each species in terms of resiliency, representation, and redundancy. This report considers the possible future condition of each species, and a range of potential scenarios that include important influences on the current and future status of Louisiana pigtoe and Texas heelsplitter. The results of this analysis describe a range of possible future conditions to determine whether or not populations of these species are likely to persist into the future.

Both of these species face a variety of risks from a variety of environmental stressors, including hydrological alterations to their habitat (loss of flow leading to dewatering, excessive flows leading to scouring), water quality degradation, loss of suitable substrates due to excessive sedimentation and other processes, and inundation leading to habitat fragmentation and population isolation. Other factors contribute, or exacerbate exposure, to these risks but are not directly driving population condition. These secondary factors include: depredation, invasive species, over-collection and/or vandalism, and host fish interactions, among others.

These risks together substantially affect the future viability of the East Texas mussels. If population resiliency (the ability to withstand stochastic events and described by demographic factors including population size and growth rate) is diminished, populations are more vulnerable to extirpation. Population extirpations result in losses to redundancy (the ability of a species to withstand catastrophic events) and diminished species representation (important breadth of genetic and ecological diversity).

Louisiana pigtoe is currently represented by 2 high condition populations, 3 moderate condition populations, 7 low condition populations, and 2 functionally extirpated populations. Within 50 years, even under the best conditions and with additional conservation, given the ongoing effects of climate change and human activities on altered hydrology and habitat degradation, 6 populations are expected to remain functionally extirpated or become functionally extirpated, 7 are expected to be in an overall low condition, and 1 population is expected to be in moderate condition (Table 6.5). Given the likelihood of increased climate and anthropogenic effects in the foreseeable future, 8 populations are expected to remain functionally extirpated or become extirpated, with 6 low condition populations remaining in 50 years (Table 6.7).

Texas heelsplitter is currently represented by 1 moderate condition population, 2 low condition populations, and 2 functionally extirpated populations. Within 50 years, even under the best conditions and with additional conservation, given the ongoing effects of climate change and human activities on altered hydrology and habitat degradation, only 1 population remains in low condition while 4 are functionally extirpated or extirpated (Table 6.5). Given the likelihood of increased climate and anthropogenic effects in the foreseeable future, all Texas heelsplitter populations are expected to remain or become functionally extirpated in 50 years (Table 6.7).

See Figures 6.2 and 6.3 for a series of maps that represents the forecasted future condition of each population by species relative to current condition. Larger maps are provided in Appendix C.

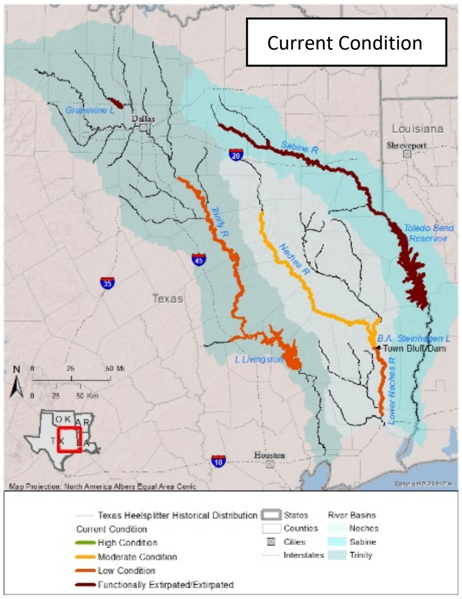
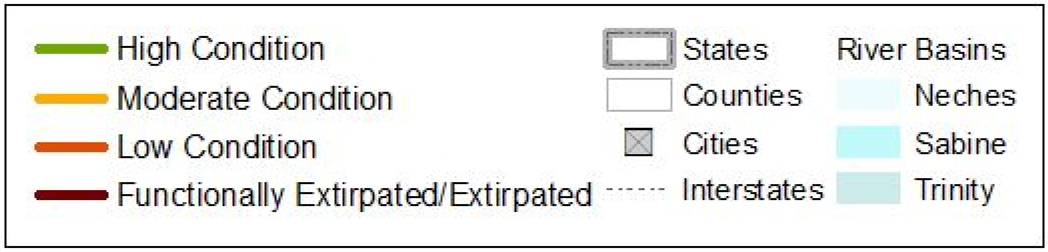
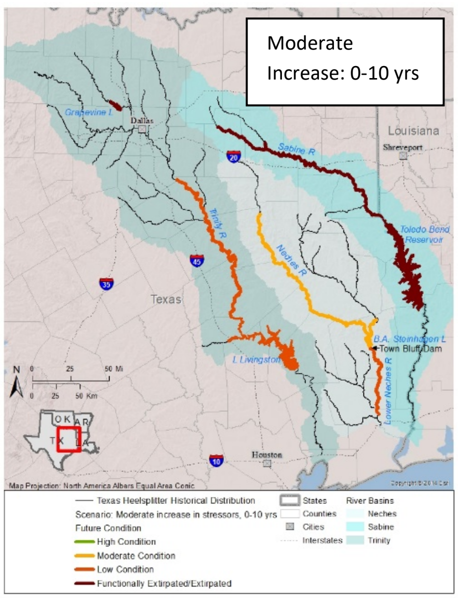
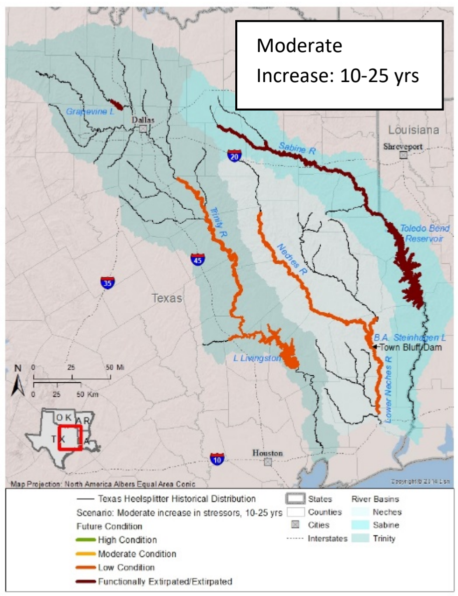
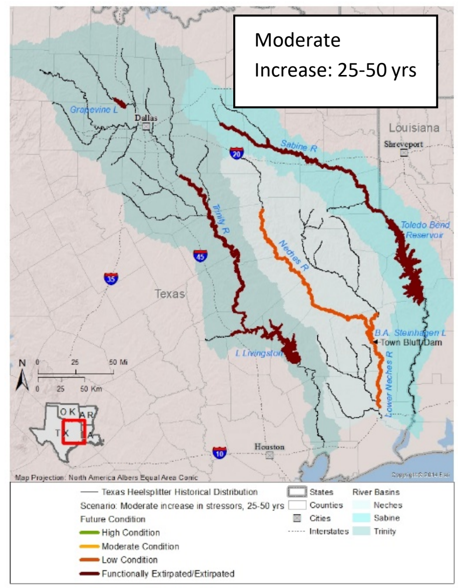


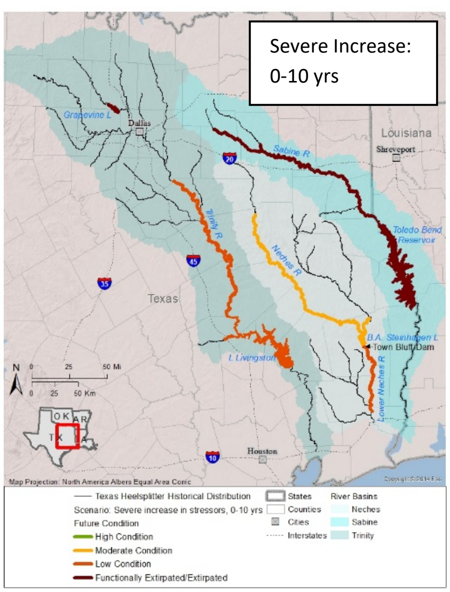
FIGURE 6.2. SUMMARY OF CURRENT AND FUTURE POPULATION CONDITIONS FOR TEXAS HEELSPLITTER (SEE APPENDIX C FOR LARGER MAPS)

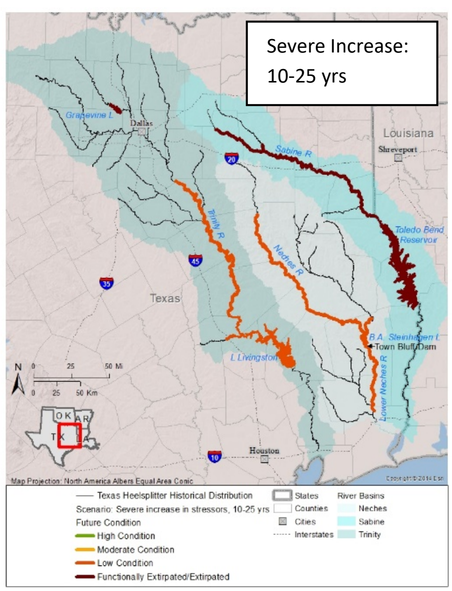


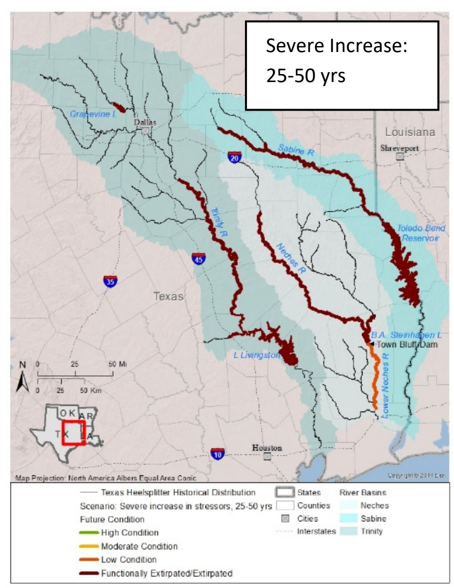












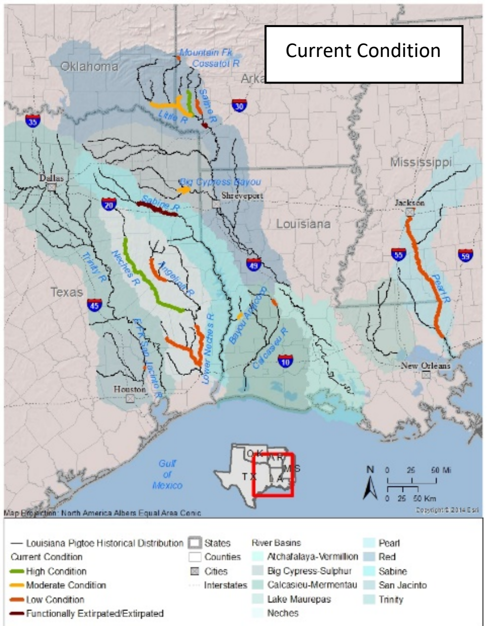
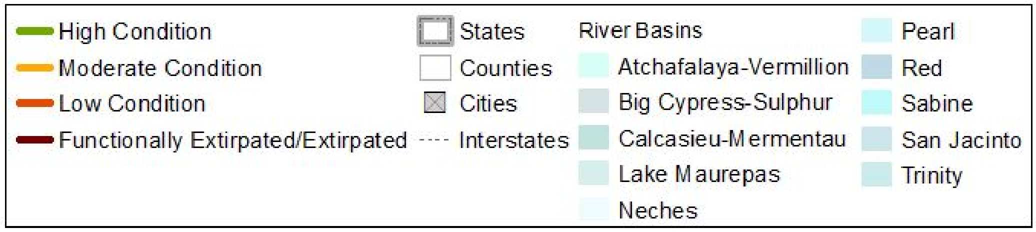
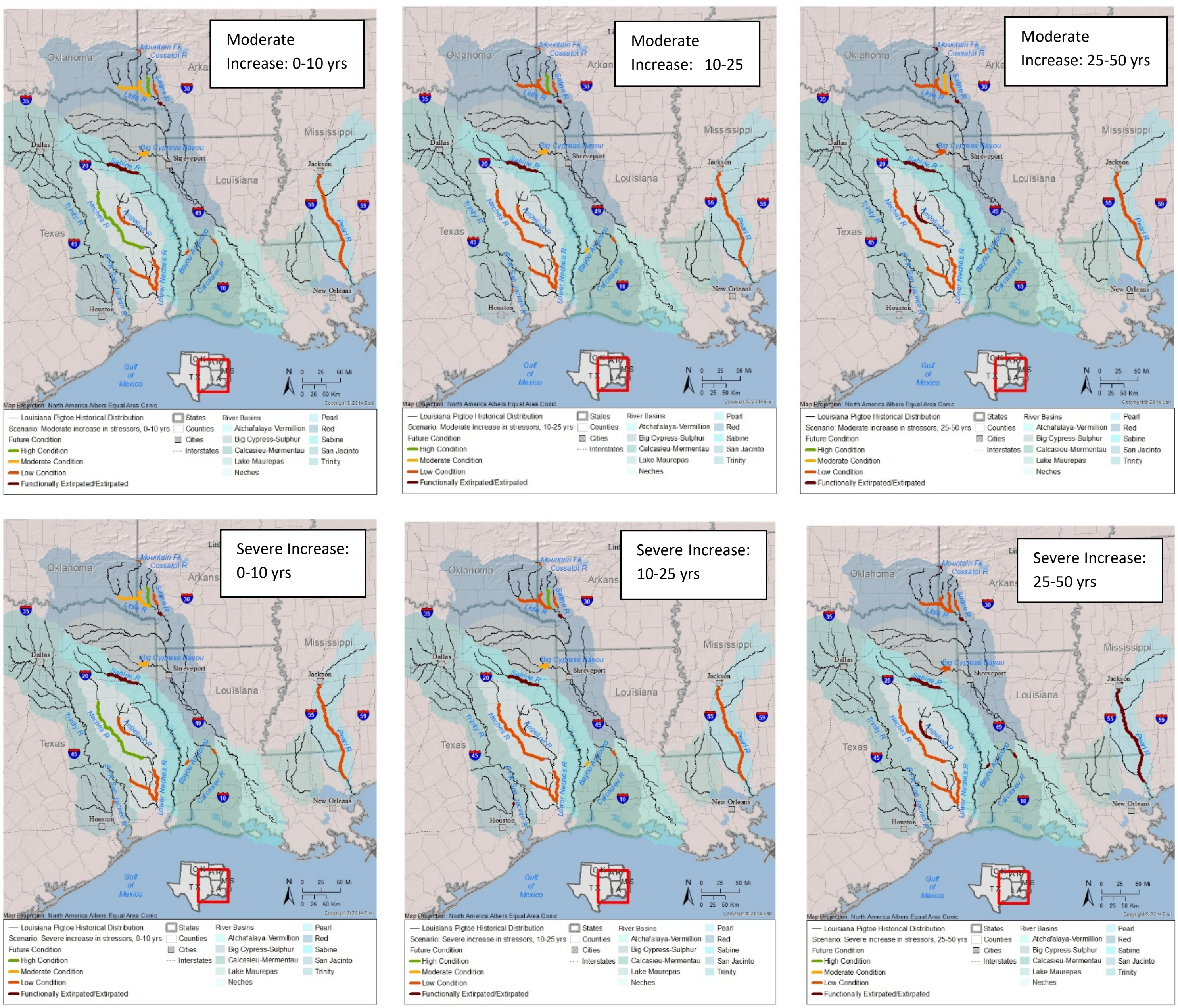


FIGURE 6.3. SUMMARY OF CURRENT AND FUTURE POPULATION CONDITIONS FOR LOUISIANA PIGTOE (SEE APPENDIX C FOR LARGER MAPS)





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Appendix B. Cause and Effects Analysis for the East Texas Mussels

Template for Cause and Effects Evaluation

THEME: ?			
[ESA Factor(s): ?]	**Analysis**	Confidence / Uncertainty	Supporting Information
SOURCE(S)	*What is the ultimate source of the actions causing the stressor? Ie, Urban Development, Oil and Gas Development, Agriculture*	See next page for confidences to apply at each step.	Literature Citations, with page numbers , for each step. Use superscript to delineate which statement goes with which citation. These can be repeated per theme, but not within a theme.
- Activity(ies)	*What is actually happening on the ground as a result of the action? Be specific here.*		
STRESSOR(S)	*What are the changes in environmental conditions on the ground that may be affecting the species? For example, removal of nesting habitat, increased temperature, loss of flow*		
- Affected Resource(s)	*What are the resources that are needed by the species that are being affected by this stressor? Or is it a direct effect on individuals?*		
- Exposure of Stressor(s)	*Overlap in time and space. When and where does the stressor overlap with the resource need of the species (life history and habitat needs)? This is not the place to describe where geographically it is occuring, but where in terms of habitat.*		
- Immediacy of Stressor(s)	*What's the timing and frequency of the stressors? Are the stressors happening in the past, present, and/or future?*		
Changes in Resource(s)	*Specifically, how has(is) the resource changed(ing)?*		
Response to Stressors: - INDIVIDUALS	*What are the effects on individuals of the species to the stressor? (May be by life stage)*		
POPULATION & SPECIES RESPONSES	*[Following analysis will determine how do individual effects translate to population and species-level responses? And what is the magnitude of this stressor in terms of species viability?]*		
Effects of Stressors: - POPULATIONS [RESILIENCY]	*What are the effects on population characteristics (lower reproductive rates, reduced population growth rate, changes in distribution, etc)?*		
- GEOGRAPHIC SCOPE	*What is the geographic extent of the stressor relative to the range of the species/populations? In other words, this stressor effects what proportion of the rangewide populations?*		
- MAGNITUDE	*How large of an effect do you expect it to have on the populations?*		
SUMMARY	*What is the bottom line- is this stressor important to carry forward in your analysis, or is it only having local effects, or no effects?*		

This table of Confidence Terminologies explains what we mean when we characterize our confidence levels in the cause and effects tables on the following pages.

Confidence Terminology	Explanation
Highly Confident	We are more than **90% sure** that this relationship or assumption accurately reflects the reality in the wild as supported by documented accounts or research and/or strongly consistent with accepted conservation biology principles.
Moderately Confident	We are **70 to 90% sure** that this relationship or assumption accurately reflects the reality in the wild as supported by some available information and/or consistent with accepted conservation biology principles.
Somewhat Confident	We are **50 to 70% sure** that this relationship or assumption accurately reflects the reality in the wild as supported by some available information and/or consistent with accepted conservation biology principles.
Low Confidence	We are less than **50% sure** that this relationship or assumption accurately reflects the reality in the wild, as there is little or no supporting available information and/or uncertainty consistency with accepted conservation biology principles. Indicates areas of high uncertainty.

Theme: Changes to water quality			
[ESA Factor(s): A, E]	Analysis	Confidence / Uncertainty	Supporting Information
SOURCE(S)	Population growth, human activity, and changing land uses are the drivers. Examples include Urban Development, Oil and Gas Development, Agriculture, confined animal feeding operations, etc.[1] Attoyac bacteria sources: on-site sewage facilities, wildlife, cattle, dogs, feral hogs, poultry litter, hunting camps, horses, and wastewater treatment facilities[2].	Highly confident	[1]Ford et al. 2014, p. 9. [2]Gregory et al. 2014, p. xii.
- Activity(ies)	Lost ecosystem functionality as forests and grasslands are denuded or converted for other uses. Increases in water demand for agriculture and human consumption results in increased groundwater pumping, reservoir construction, altered hydrology, and lower water quality from point and nonpoint sources. Pulp and paper mill effluent may contribute to absence of freshwater mussels near the mouth of Anacoco Bayou[1]. Oil extraction, WWTP effluent, and surrounding agriculture impact E TX rivers[2].	Highly confident	[1]Randklev et al. 2013b, p. 272. [2]Williams et al. 2017b, p. 17.
STRESSOR(S)	Heavy shell erosion observed in waters with pH = 5.6[1]. Erosion, lower streambank stability, and lower water quality, which includes a variety of potentially harmful constituents, such as changes to basic water chemistry (e.g., increase in temperature (which increases toxicity of many pollutants), increase in total dissolved solids/salinity (as measured by Conductivity), elevated ammonia and nitrogen, and low dissolved oxygen), persistent, bioaccumulative, and toxic substances such as pesticides and trace metals., and hormonally active compounds (i.e., emerging contaminants). Tanker truck and other transportation related spills can adversely effect water quality[3].	Highly confident	[1]Burlakova et al. 2012, p. 6. [2]Augspurger et al. 2003, p. 2569. [3]Jones et al. 2001.
- Affected Resource(s)	Watershed-level effects can occur, including loss of riparian habitat, increase in invasive species, lower biodiversity, altered stream functionality (changes to chemical, physical, and biological processes).	Moderately confident	
- Exposure of Stressor(s)	Contaminants from point and nonpoint sources, including hazardous spills, may affect water quality with magnitude varying by volume of discharge, dilution capacity of receiving waters, duration of exposure, life stage of mussel exposed, and whether stressor acts in isolation or simultaneously with other stressors that may compound the effects. Contaminants in water may be short-term acute exposures resulting in immediate mortality, or sub-lethal long-term exposures. Persistent, bioaccumulative and toxic (PBT) compounds may accumulate in sediments, resulting in sediment toxicity. Contaminants may also exert toxicity on host fishes and interfere with life cycle requirements of mussels. Sediment pore-water concentrations of NH_3 typically exceed that of the surface water[1].	Highly confident	[1]Augspurger et al. 2003, p. 2574.

- Immediacy of Stressor(s)	Varies by stream segment depending on point and nonpoint sources in the watershed, hydrology (e.g., frequency of low flow conditions), etc. This has happened in the past, is currently happening, and will continue to happen in the future. Although efforts under the CWA have generally improved water quality conditions in the U.S. compared to the mid-20th century post-industrial era, human population growth along with increasing demand for limited water resources, as well as increasing demand for wastewater disposal, continues to deteriorate remaining water resources.	Highly confident	
Changes in Resource(s)	Contaminants in water and sediment may inhibit mussel survival, growth and reproduction, or that of their host fishes.	Highly confident	
Response to Stressors: **- INDIVIDUALS**	May be sub-lethal, such as inhibiting growth or reproduction, or cause mortality of individuals. DNA damage occurs in the mussel *Unio pictorum*, when found downstream of paper mills and oil refineries[1]. Heavy metals may inhibit glochidial attachment[2]. Juveniles more susceptible to anthropogenic disturbances [3].	Highly confident	[1]Ford 2013a, p. 4. [2]Arm et al. 2014, p. 114. [3]Ford et al. 2018, p. 14.
POPULATION & SPECIES RESPONSES	*[Following analysis will determine how ~~do~~ individual effects translate to population and species-level responses~~?~~ ~~And what is~~ the magnitude of this stressor in terms of species viability~~?~~]*		
Effects of Stressors: **- POPULATIONS** **[RESILIENCY]**	Will vary by nature and magnitude of local stressors, but capable of causing population declines, lowering resiliency, or even extirpation. Low levels of salinity can have dramatic effect on reproduction, physiology, and survival in *Elliptio complanata*[1].	Highly confident	[1]Blakeslee et al. 2013, p. 2853.
- GEOGRAPHIC SCOPE	Little River: freshwater mussel declines in Little R have been attributed to impoundments and degraded WQ from point source effluents, these impacts likely affect host fish thereby limiting recruitment[1]. Pulp and paper mill effluent may contribute to absence of freshwater mussels near the mouth of Anacoco Bayou[2]. Portions of the Calcasieu R impacted by paper mill wastes and sand mining[3]. Big Cypress CR is listed 303d for elevated Hg in fish tissues, low pH, and low DO. pH impairment may be removed by the state due to the standard being met since 2014; Little Cyprees Bayou listed for low DPO and elevated bacteria[4]. Large portions of the Trinity and Neches Rivers have legacy contamination, including PCBs and Dioxins (polychlorinated dibenzofurans and dibenzo-p-dioxins (PCDFs/PCDDs) in the Trinity, and mercury and dioxins in the Neches [5,7] Several lakes along the Sabine River have mercury contamination, including Hills Lake, Clear Lake, and Toledo Bend Reservoir (Panola County), as do Big Cypress Creek and Caddo Lake[6].	Highly confident	[1]Davidson et al. 2014, p. 1. [2]Randklev et al. 2013b, p. 272. [3]Vidrine 1993. [4]WMS 2018, pp. 16, 37. [5]TDSHS 201[illegible] [6]TCEQ 2018. [7]Perkin and Bonner 2016.
- MAGNITUDE	Attoyac Bayou: fecal coliforms often exceeded standards in the late 1990s and elevated ammonia levels were rountinley observed in 2008[1].	Highly confident	[1]Gregory et al. 2014, p. xi.
SUMMARY	Carry stressor forward. Not localized or isolated.	Highly confident	

THEME: Changes to hydrology (altered flow regime)			
[ESA Factor(s): A, E]	**Analysis**	Confidence / Uncertainty	Supporting Information
SOURCE(S)	Urban development[1], reservoir operation, agriculture (diversion, ground water extraction, etc.) and climate change[2] (flood/scour from very large rainfall events).	Highly confident	[1]Ford et al. 2014, p. 9. [2]Archambault et al. 2013, p. 230, 247.
- Activity(ies)	Hydroloelectric dam operations[1], out-of-basin water transfers. Climate change is likely to result in more extreme flooding and droughts and lead to changes in surface water, soil moisture, and groundwater[2].	Highly confident	[1]Davidson 2017, p. 3; Ford 2013b, p. 3; Randklev et al. 2013b, p. 272. [2]Taylor et al. 2013, entire.
STRESSOR(S)	Altered flow regimes (more frequent peak flows, increased scouring in channel, loss of water due to pumping and out-of-basin transfers), inundation of habitat upstream of dams, decrease in water temperature down stream of hydroelectric dams[1].	Highly confident	[1]Randklev et al. 2013b, p. 272.
- Affected Resource(s)	Water temperature, stability of stream sediments, stability of stream banks, water availability, inundation of stream habitat.	Moderately confident	
- Exposure of Stressor(s)	Inundation occurs upstream of dam and seasonally with changing water levels, temperature effects of hydroelectric operations occur downstream of dam, altered flows due to dam operations primarily occurs downstream of dam, altered flows due to climate change, altered flows due to pumping and out-of-basin transfers[1].	Highly confident	[1]Ford 2013b, p. 3; Ford et al. 2016b, p. 47.
- Immediacy of Stressor(s)	Impacts from hydroelectric dams can be expected to continue. Water basin transfers are likely to increase in the future. Climate change effects are expected to intensify into the future.	Moderately confident	
Changes in Resource(s)	Unstable banks and substrates, reduction in water temperature downstream of hydroelectric dams, fluctuating water levels of impounded areas. Changes in flow rates and volume due to impoundments can cause scouring and deposition impacting mussels[1]. Overgrazing since mid-1800's caused loss of vegetative cover and soils, which allows runoff from precipitation to increase contributing to scouring in streams; also, changes in rainfall patterns to fewer light and moderate showers and longer periods of drought with heavy, damaging floods contribute to scouring impacts[2]. After inundation, flows are altered which can lead to increased sedimentation, organic material deposition, decreased oxygen levels due to lack of flow and increased oxygen demand due to decomposition, increase in water depth, a possible lack of suitable nutrients available to mussels that may impact reproduction[3].	Moderately confident	[1]Howells 1997, p. 32. [2]Howells 2010a, p. 9. [3]Neck and Howells 1995, p. 14.

Response to Stressors: **- INDIVIDUALS**	High shear stress dislodges small, lightweight juveniles from the substrate without displacing the heavier adults[1]. Oxbows and tribs provide refugia from main channel high flows (BA Steinhagen releases)[2]. Excysted juveniles dispersal distance influenced by the magnitude of velocity and velocity gradients[3]. Individuals deposited downstream will likely die. Those smothered with deposited sediment will die.	Highly confident	[1]Bakken 2013, p. 5. [2]Ford 2013b, p. 10. [3]Daraio et al. 2012, p. 601.
POPULATION & SPECIES RESPONSES	*[Following analysis will determine how do individual effects translate to population and species-level responses? And what is the magnitude of this stressor in terms of species viability?]*		
Effects of Stressors: **- POPULATIONS [RESILIENCY]**	Diversity and abundance are negatively impacted by hydropower generation in the lower Sabine River due to altered flow, temperature, and sediment regimes; sinuosity and connectivity with the floodplain may lessen these impacts[1].	Highly confident	[1]Randklev et al. 2014, pp. 9-10.
- GEOGRAPHIC SCOPE	Entire extent of range. 20km downstream of Pine Creek Dam and Broken Bow Dam[1]. In TX, negative correlation between human population density and the proportion of rare species in the watershed[2]. Flow variability likely accounts for 14% of the variability in mussel community composition[3]. Substrate scouring occurred in the uppermost Sabine R mussel sanctuary due to highwater releases from LK Tawakoni, beds only found in mid and lower sanctuaries[4]. Impoundments constructed in the early 1900s on East FK, Elm FK, West FK, and Clear FK Trinity River may have acutley impacted mussel distribution in the DFW area, compounded by other anthropogenic impacts[5]. Discharge below Toledo Bend Dam is high pulsed during periods of power generation[6]. CR- Anthropogenic hydrologic alteration is prevelant throughout the entire range of Louisiana pigtoe and Texas heelsplitter. These systems are impacted by mainstem reservoirs, tributary reservoirs, and surfacewater and groundwater extraction. The magnitude of the impacts of these flow alterations varies by type, which impacts being localized (small weir) or impacting many river kilometers (large hydropower reservoir).	Highly confident	[1]Davidson 2017, p. 10. [2]Burlakova and Karatayev 2011b, p. 403. [3]Dascher et al. 2017, p. 3. [4]Ford et al. 2009, p. 290-291. [5]Randklev 2011, pp. 36-39. [6]Randklev et al. 2011, p. 3.
- MAGNITUDE	The overall range, and distribution of East Texas mussels have been significantly altered due to hydrological alterations, including large hydropower operations. These effects of current and historical stressors will continute to persits[1].	Highly confident	[1]Haag 2012, p. 328-330.
SUMMARY	Affects all populations. Carry stressor forward, combine with Hydrology (low flow). These reservoirs act as large scale barriers that isolate populations, prevent host fish movements, and preclude genetic exchange.	Highly confident	

THEME: Changes to hydrology (inundation, low flow conditions)			
[ESA Factor(s): A, E]	**Analysis**	Confidence / Uncertainty	Supporting Information
SOURCE(S)	Dams, drought, pumping/groundwater extraction, potential climate change	Highly confident	
- Activity(ies)	Municipal and agricultural water demands - Reservoirs throughout the range of both species provided municipal water supply. Southern Neches River water extraction for rice and crawfish farming. Flood Control - Reservoirs in Neches Basin (other?) limit number and severity of pulse flows. Climate Change - May result in periods of extreme drought thus reducing surface flows. In one East Texas reservoir [likely BA Steinhagen] that was brought down by 2 m every second year, stranded individuals (Texas heelsplitter) were observered burrowing into sand and mud substrates or following the declining water line[1].	Highly confident	[1]Howells 2010b, p. 3.
STRESSOR(S)	Loss of flow due to drought reduces the amount of available habitat as a result of narrowing stream bed[1]. Loss of flow results in habitat degradation from lack pulse flows, increase in fine sediment[3,8], DO reduction[1,5,6], increased water temperatures[7], increased contaminate exposure[4], ammonia[9], stranding of individuals[2], increased exposure to predation[1], and reduction of nutrients into system.	Highly confident	[1]Galloday et al. 2004, p. 501, 503; Haag and Warren 2008, p. 1172-1173. [2]Howells 2010b, p. 3. [3]Brim Box and Mossa 1999, p. 100. [4]Augspurger et al. 2007, p. 2025. [5]Sparks and Strayer 1998, pp. 132–133. [6]Johnson 2001. [7]Pandolfo et al. 2010. [8]Kondolf 1997, pp. 535, 548. [9]Augspurger et al. 2003, p. 2569.
- Affected Resource(s)	Adequate water quality, wide stream bed, substrate enhancement, cover from predation	Highly confident	
- Exposure of Stressor(s)	Low flows result in reduction in anchoring habitat for adults and juveniles, documented predator access to adults and juveniles cover from predation[1]. Low flows are important for reproduction (egg fertilization, host fish/mussel interaction, juvenile anchoring, glochidia niche).	Highly confident	[1]Thorp and Covich 2010.

- Immediacy of Stressor(s	Reservoirs in these stream systems for decades. Managed water releases from dams presently result in extended periods of low flow. Likely to continue into the future without release strategies. Effects of climate change are only expected to increase into the future as droughts become more frequent and air temperatures increase, resulting in more surface water extraction and additional water demands arise.	Moderatley confident	
Changes in Resource(s)	Low flows have reduced available habitat to narrow stream beds, stranded individuals, increased exposure to predation. Additionally may lower fitness or cause mortality due to reduced water quality.	Highly confident	
Response to Stressors: **- INDIVIDUALS**	Byssus production in juvenile Lampsilis was more impacted by low flow (drought) regime with 93-99% reduction when compared to the watered regime[1]. Glochidia survival effected by increased water temp[2]. Mortality. Sub-lethal effects[3]	Highly confident	[1]Archambault et al. 2013, p. 236, 244. [2]Pandolfo et al. 2010, pg. 961 - 963. [3]Gagnon et al. 2004, p. 675.
POPULATION & SPECIES RESPONSES	*[Following analysis will determine how do individual effects translate to population and species-level responses? And what is the magnitude of this stressor in terms of species viability?]*		
Effects of Stressors: **- POPULATIONS** **[RESILIENCY]**	Populations may be reduced or eliminated as a result of habitat loss, reduction in breeding age adults from predation, lowered fitness or mortality of all lifestages due to water quality/contaminants. Thermal stress associated with low water levels -> observed declines in abundance and species richness[1]	Moderately confident	[1]Galbraith et al. 2010, p. 1180.
- GEOGRAPHIC SCOPE	Toledo Bend tributaries/Sabine R low flow/drought in 2010-2011, many [illegible] populations in Sabine Nat'l Forest were dewatered[1]. B.A. Steinhagen Reservoir drawdown decimated the largest known P. amphichaenus population in 2006 through 2007[2]. This reoccured in 2019. LA-Calcasieu, Vermillion, Mermentau, and lower Sabine: Increased water abstraction during low rainfall periods due to agricultural practices[3].	Moderately confident	[1]Arnold et al. 2013, p. 24. [2]Howells 2010b, p. 11, 16. [3]Kelso et al. 2011, p. 14.
- MAGNITUDE	High E TX rivers are large enough and rainfall is more consistant minimizing impacts due to inadequate flow resulting from a lack of precipitation[1]. Projected TX population growth from 2010 to 2060 is 80% (25 to 46 million), water demand increase of ~20%, water supply decrease up to 10% due to groundwater depletion[2]	Somewhat confident	[1]Williams et al. 2017b, p. 17. [2]Wolaver et al. 2014, p. 1081.
SUMMARY	As low flows are mostly the result of dams and have altered the natural flow regimes range wide for both and can be exacerbated by drought. Affects all populations. Carry stressor forward, combine with Hydrology (flow changes).	Highly confident	

THEME: Changes to substrate (sedimentation)			
[ESA Factor(s): A, E]	**Analysis**	Confidence / Uncertainty	Supporting Information
SOURCE(S)	Tributary and streambed scouring, streambank erosion, land development and resulting erosion of uplands brought by runoff	Highly confident	
- Activity(ies)	Land use changes[1], urbanization, hydrological modifications	Highly confident	[1]Arbuckle and Downing 2002, p. 311; Arm et al. 2014, p. 45.
STRESSOR(S)	Filling in of substrate, smothering, toxicity from contaminants bound to substrate particles[1].	Highly confident	[1]Ford 2013a, p. 2., Allen and Vaughn 2010, p. 383.
- Affected Resource(s)	Direct smothering of individuals, changing suitability of anchoring habitat, reducing feeding of juveniles[1]. Also coarse gravel, cobble moving through system changing habitat. Contaminants bound to substrate particles compromising metabolic processes.	Highly confident	[1]Ford 2013a, p. 2.
- Exposure of Stressor(s)	Juvenile and adults living in substrate, potential loss of host fish use of habitat[1].	Highly confident	[1]Ford 2013a, p. 2.
- Immediacy of Stressor(s)	Historical, current, future. After high flow events, as water velocity decreases, particles drop to substrate.	Highly confident	
Changes in Resource(s)	Summary statement- fine and coarse sediment moving through system, changing habitat for existing pops and preventing recruitment. FWM require a stable environment due to limited mobility and age of sexual maturation[1]. Observed localized siltation on mussel beds due to riaprian clearing[2].		[1]Randklev et al. 2014, p. 9. [2]Galbraith et al. 2010, p. 1181.
Response to Stressors: **- INDIVIDUALS**	Clogged gills, reduced fitness and growth rates, mortality, recruitment failure, changed host fish interactions.	Highly confident	[1]Sparks and Strayer 1998, p. 129. [2]Brim Box and Mossa 1999, pp. 99, 100.
POPULATION & SPECIES RESPONSES	*[Following analysis will determine how do individual effects translate to population and species-level responses? And what is the magnitude of this stressor in terms of species viability?]*		
Effects of Stressors: **- POPULATIONS** **[RESILIENCY]**	Substrate changes can result in population level response- these changes are not highly localized. Can affect recruitment, population growth rates, etc. Poor substrate quality can lead to low resiliency[1].		[1]Allen and Vaughn 2010. p. 390.

- GEOGRAPHIC SCOPE	Mussel beds appear generally stable from 1996 to 2014 in Saline R (Ouachita R trib)[1]. International Paper purchased 9000 ac for timber harvest between STHY 46 and STHY 167[2]. Large mussel bed downstream of BA Steinhagen covered by shifting sands due to altered flows by dam operations[3]. Large percentage of the mid sanctuary (Sabine R) had severve erosion and numerous bankfalls[4]. S. Sulphur R was realigned and channelized, N. Sulphur channelized in 1920, sedimentation occurring throughout Sulphur R drainage[5]. Sandy soils in east TX are subject to any distrubance of natural cover resulting in extensive erosion and increased deposition in streams[6]. Sabine R below Toledo Bend Reservoir - prevalent substrate is sand[7]. Diversity and abundance are negatively impacted by hydropower generation in the lower Sabine R. due to altered flow, temperature, and sediment regimes; sinuosity and connectivity with the floodplain may lessen these impacts[8]. Lower parts of Calcasieu R and Sabine R heavily impacted; "increased sedimentation resulting from erosion in adjacent riparian and upland habitats is a common characteristic of virtually all streams in southern Louisiana."[9]. Portions of the Calcasieu R impacted by paper mill wastes and sand mining[10]. The mainstem of the Trinity, Neches, and Sabine Rivers are on the 303(d) list for contaminants. There is potential for these contaminants to impact survival, growth, and reproduction in mussel communities in these systems[11]. In addition to substrate contamination, substrate scouring from increased high flow events in the Trinity River is impacting bank stability and sediment along bank habitats where TH occurs[12]. In addition, mainstem reservoirs in the Sabine River have caused downstream declines in mussel richness and abundance ~~which~~ one factor for these declines could be ~~attributed to~~ changes in sediment dynamics[13].	**Moderately Confident**	[1]Davidson 2015, p. 29. [2]Davidson and Clem 2002, p. 26. [3]Ford 2013b, pp. 9-10. [4]Ford et al. 2009, p. 282. [5]Heffentrager 2013, p. 4-5. [6]Howells 1997, p. 31. [7]Karatayev and Burlakova 2008, p. 24. [8]Randklev et al. 2014, pp. 9-10. [9]Kelso et al. 2011, pp. 11-12. [10]Vidrine 1993. [11] TCEQ 2018a. [12]Randklev et al. 2017b, p. 5. [13]Randklev et al. 2015, p. 16.
- MAGNITUDE	Sediment accumulation is a pervasive problem throughout the range of East Texas mussels.	Highly confident	[1]Ford 2013b, p. 10.
SUMMARY	Sediment accumulation in the substrates occupied by East Texas mussels has reduced habitat availability for ~~all~~ both species historically and is expected to continue ~~into the future~~. Conversely, high flows (e.g. flooding) have scoured ~~out~~ mussel habitat and resulted in bank collapse. These stressors will be carried forward in our analysis of future conditions of the species.	Moderately Confident	

THEME: Invasive species			
[ESA Factor(s): C]	**Analysis**	Confidence / Uncertainty	Supporting Information
SOURCE(S)	Zebra mussels, giant salvinia, asian clams Direct competition for resources with LP and TH from invasive Zebra Mussels. Habitat alterations from non-native aquatic plants (i.e. Giant Salvinia, Hydrilla, etc…)	Somewhat confident	Howells 2010a, p. 13 Howells 2010b, pp. 14-15 Kaller et al. 2007, pp. 173-174
- Activity(ies)	Zebra Mussels are present in the Trinity and Red River basins in Texas (other river basins in the other states as well) and there is potential for them to continue to spread to other river basins, or further expansion within basins they are currently present. Aquatic invasive plant species are prevelant throughout the range of LP and TH.	Somewhat confident	Howells 2010a, p. 13 Howells 2010b, pp. 14-15 Kaller et al. 2007, pp. 173-174
STRESSOR(S)	Hydrilla and Giant Salvinia can become too dense for mussels to use lake habitats and alter water quality.	Somewhat confident	
- Affected Resource(s)	Dissolved oxygen reduced due to blocked sunlight and decomposition of plant matter[1]. Asian clam die-offs can cause water column ammonia to increase to levels that could impact native mussels[2].	Somewhat confident	[1]TPWD 2018. [2]Cherry et al. 2005, p. 378; Cooper et al. 2005, p. 392.
- Exposure of Stressor(s)	Zebra mussels and exotic macrophytes prefer lacustrine, backwater, and very low flow areas in east Texas. Asian clam is most sucessful in flowing water[1].	Somewhat confident	[1]Howells 2014, p. 125.
- Immediacy of Stressor(s)	Timing and frequency of invasive threats existing today are likley to increase in severity over time due to climate change impacts.	Somewhat confident	
Changes in Resource(s)	Resource competition, degradation of habitat, increased predation.	Somewhat confident	
Response to Stressors: **- INDIVIDUALS**	Reduced food quality due to zebra mussels being more efficient at sorting food particles[1].	Somewhat confident	[1]Baker and Levinton 2003, p. 103.
POPULATION & SPECIES RESPONSES	*[Following analysis will determine how do individual effects translate to population and species-level responses? And what is the magnitude of this stressor in terms of species viability?]*		
Effects of Stressors: **- POPULATIONS [RESILIENCY]**	What are the effects on population characteristics (lower reproductive rates, reduced population growth rate, changes in distribution, etc)?	Somewhat confident	

- GEOGRAPHIC SCOPE	Physical evidence of zebra mussels not found in ETX rivers[1]. Mill CR, LA: Given that hogs spend considerable time in aquatic habitat[2] and appear to contribute E. coli into streams, we believe that it is logical that the previously measured high fecal coliform counts in the Mill Creek watershed[34] were probably the result of the large numbers of feral and free-ranging hogs rather than deer, turkeys, beavers, horses, or other potential sources. The DNA data potentially implicate feral hogs as the primary source of fecal coliforms that were negatively associated with freshwater mussels and important nutrient processing insects in the Mill Creek watershed[5]. Feral hogs appear to decrease freshwater mussel (members of the family Unionidae commonly known as pearly mussels) diversity and abundance by creating organic enrichment and changes in microbial community composition[5]. Feral hogs may compound existing perturbations leading to further declines or localized extirpation[6]. Invasive aquatic species are prevelant throughout the range of LP and TH. Reservoir habitats currently appear to be disproportionately affected by these aquatic invasice species so they may impact TH populations disproportionately. Feral hogs destabilize banks, leading to further erosion and sloughing during high flows[7].	Somewhat confident	[1]Ford et al. 2016b, p. 47. [2]Mersinger and Silvy 2007. [3]Kaller and Kelso 200[illegible] [4]Kaller 2005, p. 114. [5]Kaller and Kelso 2006. [6]Kaller et al. 2007, pp. 173-174. [7]Timmons et al. 2011, entire.
- MAGNITUDE	Invasives are present throughout the range, though more severe in southern portions.	Somewhat confident	
SUMMARY	Invasives compete directly with mussels for space and food resources, can impact water quality, degrade habitat.	Somewhat confident	

THEME: Direct mortality			
[ESA Factor(s): A, C, E]	**Analysis**	Confidence / Uncertainty	Supporting Information
SOURCE(S)	For Louisiana pigtoe, 1) human collection for fish bait[1], 2) human collection for scientific purposes, 3) dewatering/ dessication, 4) WQ/acute & chronic toxicity. Texas heelsplitter is difficult to find and rarely collected in the field so direct mortality by collection is not known to be a stressor for the species; however, dewatering/desiccation and WQ/toxicity are likely stressors. Mammalian predation.	Highly Confident	[1]Orsak, personal observation, Little River OK, May 2018.
- Activity(ies)	1-4) direct mortality. Decresasing stream flows result in increasing predation by terrestrial predators due to increased access, reducing populations. Collection and sampling of both species at known sites can impact population sizes.	Highly Confident	
STRESSOR(S)	**Collection**. Increased temperature and loss of flow may contribute to conditions that allow collection; increased concern regarding the status of mussels has led to increased interest in research, increased funding for studies and increased collection for science, although impacts are thought to be minor. Collection for fish bait is believed to be localized but may impact affected populations heavily in areas popular for recreational sports. **Predation** on freshwater mussels is a natural ecological interaction. Raccoons, river otters, snapping turtles, and fish are known to prey upon east Texas mussels. Under natural conditions, the level of predation occurring within populations is not likely to be a significant risk to that population. However, during periods of low flow, terrestrial predators have increased access to portions of the river that are generally too deep under normal flow conditions. Muskrats and raccoons are known to prey upon live mussels, as evidenced by freshly fragmented valves scattered along vegetated riverbank margins.	Somewhat confident	
- Affected Resource(s)	Direct on Individuals but currently disease and predation do not appear to be problematic to *P. riddellii* [1] or *P. amphichaenus* [2].	Somewhat confident	[1]Howells 2010a, p. 12. [2]Howells 2010b, p. 13.

- Exposure of Stressor(s)	**Collection.** Scientific collection is not thought to be widespread; the extent to which collection for fish bait occurs across the range is unknown. **Hydrology.** Dewatering/desiccation will vary by season, watershed, and climatic conditions. **Water quality** and risk of acute or chronic toxicity will vary by location and watershed, including land uses and proximity of mussel beds to sources of point and nonpoint pollution. Age of exposure will also affect toxicity, with early life stages being most vulnerable. **Predation.** As stream flows decline, access by terrestrial predators increases, increasing predation rates by raccoons[1] and muskrats[2]. Adults are more susceptible to predation and collection than juveniles, as they are larger and easier to find.	Somewhat confident	[1]Walters and Ford 2013, p. 479. [2]Golladay et al 2004, p. 503.
- Immediacy of Stressor(	Mortality of Texas heelsplitter due to predation have been observed during low flow periods. Raccoons have preyed on individual Texas heelsplitters stranded by low waters or deposited in shallow water or on bars following flooding or low water periods[1]. As drought and low flow are predicted to occur more often and for longer periods due to climate change, populations are expected to experience additional predation pressure in the future.	Somewhat confident	[1]Walters and Ford 2013, p. 479.
Changes in Resource(s)	Depredated and collected mussels removed from breeding population, thus reducing current and potential future number of individuals.	Highly confident	
Response to Stressors: - INDIVIDUALS	Removal from population and loss of breeding potential	Highly Confident	
POPULATION & SPECIES RESPONSES	*[Following analysis will determine how do individual effects translate to population and species-level responses? And what is the magnitude of this stressor in terms of species viability?]*		
Effects of Stressors: - POPULATIONS [RESILIENCY]	Loss of individuals of both species from combined effect of collection, dewatering/desiccation, predation, water quality will result in populations possessing less resiliency and increasing risk of extirpation. Future models predict decreasing water volumes/stream flows thus exacerbating current trends.	Highly Confident	
- GEOGRAPHIC SCOPE	Mammalian predation at ponds on Camp Maxey was up to 19% exacerbated by fluctuating water levels[1]. Sabine R upstream of Toledo Bend: 58 of 79 recently deceased *P. amphichaenus* exhibited signs of predation, all were <100mm in length, raccoon suspected[2]. While the threat of direct mortality extends throughout the entire range of *P. riddellii* and *P. amphichaenus*-, these specific stressors are limited to specific areas.	Moderately confident	[1]Burlakova and Karatayev 2007, p. 291. [2]Walters and Ford 2013, pp. 479-480.
- MAGNITUDE	Predation/collection is an exacerbating factor on populations already under pressure from various other stressors. Could potentially impact some populations reducing resiliancy.	Somewhat confident	

SUMMARY	Mortality from dewatering events and resulting dessication are expected to continue for some populations of TH in reservoirs and LP in canal systems. Reduced stream flows in the future would expose both species to increases in predation. These effects will be carried forward in our analysis of effects to East Texas mussels into the future. Collection for LP is localized and could effect populations and is thus carried forward. Collection for TH is not expected to have an effect due to its rarity, thus it is not carried forward.	Moderately confident	

THEME: Fragmentation			
[ESA Factor(s): A, E]	**Analysis**	Confidence / Uncertainty	Supporting Information
SOURCE(S)	Impoundments, transportation structures, dewatered stream segments.	Highly Confident	
- Activity(ies)	Dam construction, flood control, low-water crossings, reduced flow resulting in barrier to movement	Highly Confident	
STRESSOR(S)	These activities result in deep impounded waters reducing available streambed habitat[2] as well as function as barriers to host fish movement/disperal upstream and potentially downstream of mussel populations thereby isolating populations[12]. Impoundments can significantly decrease genetic variability in mussel populations[3]. Isolated populations are susceptible to genetic drift (change of gene frequencies in a population over time) and inbreeding depression which may cause death, reduced fertility, reduced fitness and morphological chromosomal abnormalities.	Highly Confident	[1]Watters 1996. p. 83. [2]Newton et al. 2008, p.430. [3]Reagan 2008, p.72.
- Affected Resource(s)	Dam construction fragments the range of *P. riddellii* , leaving remaining habitats and populations isolated by the structures as well as by extensive areas of deep uninhabitable, impounded waters. Dams impound river habitats throughout almost the entire range of the species, and these impoundments have left isolated patches of remnant habitat between impounded reaches. While *P. amphichaenus* inhabitats reservoirs as well as streams, historically the species only occurred in streams and sloughs as lakes/reservoirs did not occur naturally within its range[1].	Highly Confident	[1]Howells 2014, p. 69.
- Exposure of Stressor(s)	Impounded Water - permanent stream bed habitat loss to adults and juvenile *P. riddellii* . Barriers - permanently precludes movement of adults, juveniles, glochidia and host fish, thereby isolating populations.	Highly Confident	
- Immediacy of Stressor(s)	Reservoirs (impounded water plus barrier) have historically and currently acted as stressors upon these species. Existing reservoirs will continue to act as stressors into the future and proposed new reservoirs could exacerbate current conditions. Impacts from these stressors occur in the recent past, present, and expected to continue into the future.	Highly Confident	
Changes in Resource(s)	As existing populations are isolated from one another, genetic exchange between populations has been eliminated and any populations that may be extirpated through stochastic events will not be naturally recolonized.	Moderately Confident	
Response to Stressors: - INDIVIDUALS	Habitat fragmentation acts on the population level. Individuals are unaffected.	Highly Confident	
POPULATION & SPECIES RESPONSES	*[Following analysis will determine how do individual effects translate to population and species-level responses? And what is the magnitude of this stressor in terms of species viability?]*		
Effects of Stressors: - POPULATIONS [RESILIENCY]	Reduced range/distribution due to stream bed loss, lack of gene flow between fragmented populations with the potential for genetic drift and/or inbreeding depression.	Highly Confident	

- GEOGRAPHIC SCOPE	Watersheds throughout the entire range of both species have been fragmented by large dams, reservoirs and smaller barriers[1].	Highly Confident	[1]Randklev et al. 2016.
- MAGNITUDE	Population fragmentation due to barriers to fish movement has occurred for both mussel species historically. Currently, and into the future this fragmentation reduces the ability of all populations to rebound from stochastic events.	Highly Confident	`
SUMMARY	Fragmentation severes gene exchange through a river system, prevents recolonization upstream of barries, reduces available habitat, and increases the number of isolated populations. Additional barriers associated with water development are proposed within the range of both species. Carry Forward in analysis.	Highly Confident	

Appendix C – Discussion of future scenario model forecasts, evaluation criteria and future condition tables for East Texas mussels

Texas Heelsplitter

The range of the Texas heelsplitter is currently represented by five focal areas within three river basins: the Sabine River/Toledo Bend population in the Sabine River basin; the Neches River/B.A. Steinhagen reservoir and Lower Neches River populations in the Neches River basin; and Grapevine Lake and the Trinity River/Lake Livingston in the Trinity River basin.

Sabine Basin

Sabine River/Toledo Bend Reservoir Focal Area – Current Condition

The currently extirpated Sabine River/Toledo Bend focal area (Table C.2.14) is expected to remain extirpated in the next 50 years in all future scenarios. Two segments within the focal area are on the 303(d) list of impaired waterbodies for bacteria. A new poultry processing plant has been permitted to release wastewater in the upper portion of the focal area downstream of Lake Tawakoni. Wastewater releases are permitted at 2.18 million gallons per day with an ammonia limit of 3.94 mg/L, which is beyond the threshold for freshwater mussel tolerances. The construction of Lake Tawakoni and Toledo Bend Reservoir has impacted natural hydrologic conditions and dam releases causing substrate scouring eliminating mussel habitat downstream until sheer stress dissipates. An additional off-channel reservoir in the middle of the focal area and a water diversion project are proposed to meet future water demand. When constructed, water quality and hydrologic conditions would further degenerate from current conditions. Bank erosion is prevalent throughout the focal area, resulting in elevated inputs of sediment impacting suitable substrates for mussel beds.

Sabine River/Toledo Bend Reservoir Focal Area - Moderate Increase in Stressors

In the **Moderate 10-year scenario (**Table C.2.2), the focal area is projected to endure a moderate decline in water quality due to degradation resulting from a general increase in point and non-point source discharges, including significant wastewater effluent flows from a new poultry processing plant into a portion of the river with documented mussel beds. This degradation in water quality is expected to negatively influence overall mussel survival and reproductive success, potentially affecting both mussel and host fish movement, and subsequently causing fragmentation of suitable habitat. In some cases, water quality degradation may result in increased direct mortality of Texas heelsplitters, contributing to a moderate decline in this focal area. Changes to hydrology, substrate and invasive species are expected to maintain their current condition of moderate decline. The changes to threat conditions described above negatively affected modelled Texas heelsplitter habitat and population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected moderate decline in population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, hydrology, substrate, fragmentation, and direct mortality are expected to continue in tandem with population growth and associated impacts (e.g., habitat loss, increased demand for water supply, and increased generation of wastewater). Declining conditions of water quality, fragmentation, and direct mortality would be exacerbated by the effects of climate change. The moderate decline in hydrology is expected, in part, from future predicted reductions in flow, as represented by reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate (Lafontaine et al. 2019, entire). Subsequently, a moderate decline in substrate condition is anticipated as sediments accumulate on mussel beds from a lack of adequate cleansing flows. The threat posed by invasive species is expected to maintain current condition. The changes to threat conditions described above negatively affected modelled Texas heelsplitter habitat and population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected moderate decline in population resiliency (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality, substrate, fragmentation, and direct mortality will continue due to the threats described above. Hydrology is expected to severely decline due to climate change, including significant reductions in 7-day minimum and summer minimum base flows, as well as the construction of an off-channel reservoir in the middle Sabine River basin; these changes to hydrology and flow will further degrade water quality. Threats from invasive species are expected to maintain current condition. The changes to threat conditions described above negatively affected modelled Texas heelsplitter habitat and population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected severe decline in population resiliency (Table C.2.7).

Sabine River/Toledo Bend Reservoir Focal Area - Severe Increase in Stressors

In the **Severe 10-year scenario** (Table C.2.8), we anticipate moderate declines in water quality in this focal area due to degradation in general, and specifically resulting from discharges of effluent from a new poultry processing plant. This degradation in water quality is expected to negatively influence overall mussel survival and reproductive success, potentially affecting both mussels and host fish movement, and subsequently causing fragmentation of suitable habitat. In some cases, water quality degradation will result in increased direct mortality of Texas heelsplitters, contributing to a moderate decline in this focal area. Changes to hydrology, substrate and invasive species are expected to maintain their current condition. The changes to threat conditions described above negatively affected modelled Texas heelsplitter habitat and population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected moderate decline in population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, substrate, fragmentation, and direct mortality continue. Conditions of water quality, fragmentation and direct mortality would be exacerbated by the same stressors described above. A moderate decline in substrate condition is expected as sediments accumulate on mussel beds from a lack of adequate cleansing flows. This change in substrate condition is correlated with an expected severe decline in hydrological condition from reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate in addition to an off-channel reservoir constructed in the middle of the Sabine River basin; these changes to hydrology and flow will further degrade water quality. Invasive species condition is expected to maintain current condition. The changes to threat conditions described above negatively affected modelled Texas heelsplitter habitat and population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected severe decline in population resiliency (Table C.2.11).

In the **Severe 50-year scenario** (Table C.2.12), severe declines in water quality and hydrology are anticipated resulting from increasing demands for waters supply and increasing point and non-point source pollution. Changes to flow include an estimated 30% reduction in minimum base flows as well as the construction of an off-channel reservoir in the middle Sabine River basin. Moderate declines in substrate, fragmentation, and direct mortality are anticipated from the same sources described in the Severe 25-year scenario. Invasive species condition is expected to maintain current condition. The changes to threat conditions described above negatively affected modelled Texas heelsplitter habitat and population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected severe decline in population resiliency (Table C.2.13).

Neches Basin

Neches River/B.A. Steinhagen Focal Area – Current Condition

The Neches River/B.A. Steinhagen focal area currently has a moderate probability of persistence. Tributaries and segments of the focal area are on the 303(d) impaired water bodies list for dioxin and mercury in edible tissue, bacteria, and depressed dissolved oxygen. Numerous segments had concerns for nutrients, particularly ammonia and total phosphorus; however, decreasing trends for these parameters were often observed. Stream flows are influence by Lake Palestine in the upper portion of the focal area and B.A. Steinhagen in the southern portion of the focal area. Drawdowns of B.A. Steinhagen resulted in direct mortality of Texas heelsplitters in 2006 through 2007 and again in 2019.

Neches River/B.A. Steinhagen Focal Area – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario (**Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, substrate, fragmentation, and direct mortality are anticipated. Water quality degradation is expected from a general increase in point and non-point source pollution, with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels; these water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural stream flows with some increases to municipal wastewater effluent return flows). Sediment accumulation on mussel beds is projected to increase from a lack of adequate cleansing flows. The proposed Rockland reservoir on the main channel of the Neches River, which would function as a fish passage barrier, is anticipated to be operational at this time-step. Direct mortality is expected to increase due to water quality degradation, reductions in water volume, and habitat loss from reservoir construction. A severe decline in hydrology is attributed to three proposed water delivery projects within the focal area combined with an overall reduction in stream flows. Lake Columbia is an off-channel reservoir proposed in the upper portion of the focal area, a run-of river water diversion is proposed for the middle of the focal area, and Rockland reservoir is proposed near the downstream end of the focal area. Additionally, reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate are expected. The invasive species factor is expected to maintain current condition. The projected moderate and severe decline in habitat and population factors (i.e., water quality and quantity, fish host availability, reproduction/recruitment, occupied habitat, and abundance) is expected to result in a severe decline in population resiliency (Table C.2.5). Low population condition is anticipated during this time-step.

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality, substrate, fragmentation, and direct mortality are expected to continue as the threats discussed in the Moderate 25-year scenario are realized and exacerbated by further reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate. Severe declines in host fish availability, reproduction/recruitment, occupied habitat, and abundance population factors continue, as well as declines to habitat factors, contributing to a projected severe decline in population resiliency (Table C.2.7). Extirpation is expected during this time-step.

Neches River/B.A. Steinhagen Focal Area – Severe Increase in Stressors

Change from the current moderate population condition is not expected as no change to habitat factors occur during the **Severe 10-year scenario** (Table C.2.8). Thus, no change in population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area is projected to maintain its current population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, substrate, fragmentation, and direct mortality are anticipated. Water quality degradation is expected from a general increase in point and non-point source pollution, with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels; these water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural steam flows with some increases to municipal wastewater effluent return flows). Sediment accumulation on mussel beds is projected to increase from a lack of adequate cleansing flows. The proposed Rockland reservoir on the main channel of the Neches River, which would function as a fish passage barrier, is anticipated to be operational at this time-step. Direct mortality is expected to increase due to water quality degradation, reductions in water volume, and habitat loss from reservoir construction. A severe decline in hydrology is attributed to three proposed water delivery projects within the focal area combined with an overall reduction in stream flows. Lake Columbia is an off-channel reservoir proposed in the upper portion of the focal area, a run-of river water diversion is proposed for the middle of the focal area, and Rockland reservoir is proposed near the downstream end of the focal area. Additionally, reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate are expected. The invasive species factor is expected to maintain current condition. The projected moderate and severe decline in habitat and population factors (i.e., water quality and quantity, fish host availability, reproduction/recruitment, occupied habitat, and abundance) is expected to result in a severe decline in population resiliency (Table C.2.11). Low population condition is anticipated during this time-step.

In the **Severe 50-year scenario** (Table C.2.12), moderate declines in substrate, fragmentation, and direct mortality are expected to continue as the threats discussed in the Severe 25-year scenario are realized and exacerbated by further changes to hydrology, including reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate. Both water quality and quantity undergo a severe decline as summer minimum base flows are projected to decrease by 30% from present levels (Lafontaine et al. 2019, entire), in addition to the other water volume reductions considered in the Severe 25-year scenario. Severe declines in host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance population factors, as well as declines to habitat factors, contribute to a continuing severe decline in population resiliency (Table C.2.13). Extirpation is expected during this time-step.

Lower Neches River Focal Area – Current Condition

The Lower Neches River focal area currently has a low current condition/probability of persistence. Tributaries and segments of the focal area are on the 303(d) impaired water bodies list for dioxin and mercury in edible tissue, bacteria, and depressed dissolved oxygen. Numerous segments had concerns for nutrients, particularly ammonia and total phosphorus; however, decreasing trends for these parameters were often observed. Stream flows are influence by B.A. Steinhagen Reservoir in the upper portion of the focal area. Substrates below the reservoir are subjected to sheer stress from water releases, causing shifting sediments to impact mussel beds. No impoundments are proposed within the focal area.

Lower Neches River Focal Area – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.3) and low population condition.

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, hydrology, and direct mortality are anticipated. Water quality degradation is expected from a general increase in point and non-point source pollution, with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels; these water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural stream flows with some increases to municipal wastewater effluent return flows). Hydrologic impacts related to climate change, including a reduction in 7-day minimum flows and summer minimum base flows, are expected. Direct mortality is expected to increase as a result of these and other changes to habitat factors. Substrate, fragmentation and invasive species continue to maintain current condition. The moderate declines in water quality and hydrology habitat factors, coupled with moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulted in a projected moderate decline in population resiliency (Table C.2.5). Low population condition is anticipated during this time-step.

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality and direct mortality continue due to the same sources described in the Moderate 25-year scenario. Hydrologic alterations driven by climate change will experience a severe decline due to further reductions in 7-day minimum flows and summer minimum base flows. Substrate, fragmentation and invasive species continue to maintain current condition. The moderate declines in water quality and direct mortality combined with the severe decline in hydrology habitat factors, along with moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulted in a projected moderate decline in population resiliency (Table C.2.7). Extirpation is expected during this time-step.

Lower Neches River Focal Area – Severe Increase in Stressors

Change from the current low population condition is not expected as no change to habitat factors occur during the **Severe 10-year scenario** (Table C.2.8). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency and low population condition (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, hydrology, and direct mortality are anticipated. Water quality degradation is expected from a general increase in point and non-point source pollution, with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels; these water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural stream flows with some increases to municipal wastewater effluent return flows). Hydrologic impacts related to climate change, including reductions in 7-day minimum and summer minimum base flows, are expected. Direct mortality is expected to increase as a result of these and other changes to habitat factors. Substrate, fragmentation and invasive species continue to maintain current condition. The moderate declines in water quality and hydrology habitat factors, coupled with moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance), resulted in a projected moderate decline in population resiliency (Table C.2.11). Low population condition is anticipated during this time-step.

In the **Severe 50-year scenario** (Table C.2.12), both water quality and hydrology undergo severe decline as ongoing water quality degradation is exacerbated by a greater than 30% reduction in 7-day minimum flows and summer minimum base flows from present-day levels. Direct mortality is expected to continue in moderate decline as a result. Substrate, fragmentation and invasive species continue to maintain current condition. The focal area is projected to experience severe declines in water quality and hydrology habitat factors, coupled with moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) (Table C.2.13). Since two of the three habitat factors are in severe decline, the focal area is expected to experience a severe decline in population resiliency resulting in extirpation during this time-step.

Trinity Basin

Grapevine Lake Focal Area – Current Condition

The Texas heelsplitter population in the Grapevine Lake focal area is currently considered functionally extirpated and is expected to remain so over the next 50 years in all future scenarios. Lake Grapevine functions as local water supply source and receives municipal wastewater is discharges. The focal area is on the 303(d) impaired water bodies list for pH. The aquatic invasive zebra mussel has been documented in the lake.

Grapevine Lake Focal Area – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in population factors (i.e., host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, hydrology, direct mortality, and invasive species are anticipated. Water quality degradation is expected as Grapevine Lake is in a highly urbanized area and thus will be subjected to general increasing point and non-point source pollution with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels. These water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural stream flows with some increases to municipal wastewater effluent return flows). Lake elevation is expected to fluctuate due to reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate in addition to increasing water demand. As water levels fluctuate from hydrologic impacts, direct mortality is expected to increase from stranding and predation as well as from fluctuations in water quality and other habitat factors. Zebra mussels are anticipated to infest Lake Grapevine, resulting in increased competition for space and nutrients. Substrate and fragmentation continue to maintain current condition. The moderate declines in water quality and hydrology habitat factors coupled with those for direct mortality and invasive species project to moderate declines in host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance population factors resulted in a projected moderate decline in population resiliency (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality, direct mortality and invasive species continue due to the same sources described in the Moderate 25-year scenario, while hydrology undergoes a severe decline. Hydrologic alterations driven by climate change will experience a severe decline due to further reductions in 7-day minimum flows and summer minimum base flows. Substrate and fragmentation continue to maintain current condition. The moderate declines in water quality and the severe decline in hydrology habitat factors combined with the moderate decline in direct mortality and invasive species project to moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance population) ~~which~~ result~~ed~~ in a projected moderate decline in population resiliency (Table C.2.7).

Grapevine Lake – Severe Increase in Stressors

Change from extirpated population condition is not expected as no change to habitat factors occur during the **Severe 10-year scenario** (Table C.2.8). Thus, no change in population factors (i.e., host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, hydrology, direct mortality, and invasive species are anticipated. Water quality degradation is expected as Grapevine Lake is in a highly urbanized area and would be subjected to general increasing point and non-point source pollution with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels; these water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural stream flows with some increases to municipal wastewater effluent return flows). Lake elevation is expected to fluctuate due to reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate in addition to increasing water demand. As water levels fluctuate, direct mortality is expected to increase from stranding and predation as well as from fluctuations in water quality and other habitat factors. Zebra mussels are anticipated to infest Lake Grapevine, resulting in increased competition for space and nutrients. Substrate and fragmentation continue to maintain current condition. The moderate declines in water quality and hydrology habitat factors coupled with moderate declines for direct mortality and invasive species projected to moderate declines in host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance population factors resulting in a projected moderate decline in population resiliency (Table C.2.11).

In the **Severe 50-year scenario** (Table C.2.12), moderate declines in water quality, direct mortality and invasive species are expected to continue, while hydrology undergoes a severe decline. Declines in water quality, direct mortality and invasive species continue due to the same sources described in the Severe 25-year scenario. Hydrology is anticipated to experience a severe decline due to further reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate. Substrate and fragmentation continue to maintain current condition. The moderate decline in water quality and the severe decline in hydrology habitat factors coupled with the moderate decline in direct mortality and invasive species project to moderate declines in host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance population factors resulting in a projected moderate decline in population resiliency (Table C.2.13).

Trinity River/Lake Livingston – Current Condition

The Trinity River/Lake Livingston focal area currently has a low current condition/probability of persistence. Point sources are significant in the upper Trinity (large daily volumes of treated municipal wastewater discharged), with contaminants typical of effluent dominated waters near urban centers and some distance downstream, including elevated nutrients (e.g., nitrogen, phosphorus), dissolved solids, disinfection by-products, total organic carbon, haloacetic acid, and trihalomethane (TWDB 2015 p. 1.45, 1.46); contaminants of emerging concern like pharmaceuticals, fragrances, and musks are also present. Non-point source pollution typical of urban and rural areas also impacts water quality. Legacy contamination including dioxins, PCBs, furans, and chlordane have affected large areas of the upper Trinity with fish consumption advisories/bans in place. Fluctuations in dissolved oxygen occur; low dissolved oxygen is typically not a problem but can drop to levels stressful for fish (2 - 3 mg/L) in some segments during low flows and warm weather; elevated nutirents may cause algal blooms and fish kills due to phytotoxins or large diurnal fluctuations in dissolved oxygen (TRA 2018, p. 47). Urban run-off and non-point sources may contribute a variety of trace metals (e.g. lead), pesticides, and other pollutants that can harm aquatic life, some of which accumulate in fish and other biota (TWDB 2015, p. 1.50). Reservoir development, groundwater drawdown, and return flows of treated wastewater have greatly altered natural flow patterns in the focal area. Portions of the focal area are on the 303(d) impaired water bodies list for nutrients, bacteria, ammonia and chlorine. Elevated base flows from wastewater returns have resulted in increased shear stress, bank instability, and scouring to bedrock in areas (Clark and Mangham 2019, p.13).

Trinity River/Lake Livingston – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.3) and maintain low population condition.

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, hydrology, substrate and direct mortality are anticipated. Water quality degradation is expected as the Trinity River is impacted by increasing urbanization and a 1.5 times increase in water demand; thus, the focal area will be subjected to general increasing point and non-point source pollution with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels. These water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural stream flows with some increases to municipal wastewater effluent return flows). Erratic hydrologic conditions are expected due to reductions in 7-day minimum flows and summer minimum base flows combined with periods of flooding attributed to urban run-off from increases in impervious surfaces and increasingly intense storm events attributed to climate change. These intense high flows are expected to scour the stream bed removing suitable mussel substrate habitat. Direct mortality is expected to increase due to the negative changes in water quality, hydrology and substrate. The moderate declines in water quality, hydrology, and substrate habitat factors as well as direct mortality project to moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) ~~factors~~ resulting in a projected moderate decline in population resiliency. Despite the increase in stressors, the population maintains **low** condition (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), severe declines in water quality, hydrology, and direct mortality are expected as ongoing water quality degradation exacerbated increasing water demands and a greater than 30% reduction in 7-day minimum flows and summer minimum base flows from present-day levels. Substrate is expected to continue in moderate decline as those threats described in the Moderate 25-year scenario continue. Fragmentation and invasive species continue to maintain current condition. The severe declines in direct mortality as well as in the water quality and hydrology habitat factors projected to severe decline for all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance). A severe decline in resiliency is anticipated, ultimately resulting in extirpation within the time-step of this scenario (Table C.2.7).

Trinity River/Lake Livingston – Severe Increase in Stressors

Change from the current low population condition is not expected as no change to habitat factors occur during the **Severe 10-year scenario** (Table C.2.8). Thus, no change in population factors (i.e., host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency and maintain low population condition (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, hydrology, substrate and direct mortality are expected from the same stressors described in the Moderate 25-year scenario, but higher in magnitude. The moderate declines in water quality, hydrology, and substrate habitat factors as well as direct mortality project to moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) ~~factors~~ resulting in a projected moderate decline in population resiliency (Table C.2.11). Despite the increase in stressors, the population maintains **low** condition.

In the **Severe 50-year scenario** (Table C.2.12), a severe decline in water quality, hydrology, and direct mortality is anticipated from the same stressors described in the Moderate 50-year scenario, but with greater magnitude. Substrate is expected to continue in moderate decline as those threats described in the Severe 25-year scenario continue. Fragmentation and invasive species continue to maintain current condition. The severe declines in direct mortality ~~as~~ well as in the water quality and hydrology habitat factors projected to severe decline for all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance)(Table C.2.13). A severe decline in resiliency is anticipated, ultimately resulting in extirpation within the time-step of this scenario.

Louisiana Pigtoe

The range of the Louisiana pigtoe is currently represented by 14 focal areas within six river basins: the Mountain Fork, Little River/Rolling Fork, Cossatot River, Saline River, Lower Little River and Big Cypress Bayou in the Red River basin; Upper Calcasieu River in the Calcasieu-Mermentau River basin; Pearl River in the Pearl River basin; Sabine River and Bayou Anacoco in the Sabine River basin; Angelina River, Neches River and Lower Neches River in the Neches River basin; and East Fork San Jacinto River in the San Jacinto River basin.

Red River Basin

Mountain Fork Focal Area – Current Condition

The Mountain Fork focal area currently has a low current condition/probability of persistence. Tributaries and portions of the focal area are listed as impaired on the 303(d) list for zinc, silver, lead, pH, dissolved oxygen, cadmium, and turbidity.

Mountain Fork Focal Area – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated with the focal area maintaining current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, hydrology, and direct mortality are anticipated. Water quality degradation is expected as the impairments described in the Moderate 10-year scenario are exacerbated by reductions in stream flow. Hydrologic impacts related to climate change, including a reduction in 7-day minimum flows and summer minimum base flows are expected (Lafontaine et al. 2019, entire). The reductions in minimum base flows contribute to increased direct mortality from dewatering of habitat causing desiccation and increased exposure to predators. Substrate, fragmentation and invasive species continue to maintain current condition. The moderate declines in water quality and hydrology habitat factors as well as direct mortality, coupled with moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulted in a projected moderate decline in population resiliency. Despite the increase in stressors, the population maintains **low** condition as the decline in resiliency was not considered severe enough to result in extirpation (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality and direct mortality are expected to continue, while hydrology undergoes a severe decline. Declines in water quality and direct mortality continue due to the same sources described in the Moderate 25-year scenario. Hydrology is anticipated to experience a severe decline due to further reductions in 7-day minimum flows and an approximate 20% reduction in summer minimum base flows arising from a changing climate (Lafontaine et al. 2019, entire). Substrate, fragmentation and invasive species continue to maintain current condition. The moderate declines in water quality and direct mortality in conjunction with the severe decline in the hydrology habitat factors project to moderate declines in host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance population factors resulting in a projected moderate decline in population resiliency. Due to the reductions in summer base flows and resulting effects of dewatered habitat, extirpation is anticipated ~~as~~ this time-step (Table C.2.7).

Mountain Fork Focal Area – Severe Increase in Stressors

Change from the current low population condition is not expected as no change to habitat factors occur during the **Severe 10-year scenario** (Table C.2.8). Thus, no change in population factors (i.e., host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, hydrology, and direct mortality are expected from the same stressors described in the Moderate 25-year scenario, but higher in magnitude as the effects for climate change on stream flow is more pronounced. The moderate declines in water quality and hydrology habitat factors as well as direct mortality project to moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) factors resulting in a projected moderate decline in population resiliency (Table C.2.11). Despite the increase in stressors, the population maintains **low** condition.

In the **Severe 50-year scenario** (Table C.2.12), severe declines in water quality and hydrology are anticipated from the same stressors described in the Moderate 50-year scenario, but greater in magnitude. Water quality degradation is expected as the impairments described in the Moderate 10-year scenario are intensified by reductions in stream flow. Seven-day minimum flows and summer minimum base flows are project to decrease by < 30% (Lafontaine et al. 2019, entire). Direct mortality is expected to continue in moderate decline as those threats in the Severe 25-year scenario continue. Fragmentation and invasive species continue to maintain current condition. The severe declines in water quality and hydrology habitat factors as well as direct mortality projected to moderate declines for all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) (Table C.2.13). Because two of the three habitat factors are in severe decline, the focal area is expected to experience a severe decline in population resiliency resulting in extirpation during this time-step.

Little River/Rolling Fork – Current Condition

The Little River/Rolling Fork focal area currently has a moderate population condition/~~-~~probability of persistence. Tributaries and portions of the focal area are listed as impaired on the 303(d) list for mercury, zinc, lead, silver, pH, dissolved oxygen, and turbidity. ~~A total of s~~ix wastewater permits discharge into the Little River for a combined total of 4.7 million gallons per day.

Little River/Rolling Fork – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in hydrology and substrate are anticipated. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (13 – 25%) and summer minimum base flows (7 – 14%) while the durations of high flow events increase (up to 16%) (Lafontaine et al. 2019, entire). The increasing duration of high flows are expected to cause scouring of the stream bed, removing suitable mussel substrate habitat and sediment deposition in mussel beds. Water quality, fragmentation, direct mortality, and invasive species continue to maintain current condition. The moderate declines in hydrology and substrate habitat factors project to moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected moderate decline in population resiliency shifting the population into low condition (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality, substrate, fragmentation, and direct mortality are expected as hydrology undergoes severe decline as the impacts discussed in the Moderate 25-year scenario intensify, causing cascading effects to other habitat factors. Water quality degrades due to increasing concentrations of pollutants attributed to the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. Reduction in summer minimum base flows would subject substrates to more frequent and profound drying events from channel narrowing or complete loss of flowing water. Periodic fragmentation would occur as a result of streambed drying and direct mortality is expected from desiccation and exposure to predators. With the moderate decline in water quality, substrate, fragmentation, and direct mortality coupled with the severe decline in hydrology, severe declines in population factors host fish availability, reproduction/recruitment, occupied habitat, and abundance are projected, resulting in a severe decline in population resiliency. Low population condition is anticipated during this time-step (Table C.2.7).

Little River/Rolling Fork – Severe Increase in Stressors

Change from the current moderate population condition is not expected as no change to habitat factors occur during the **Severe 10-year scenario** (Table C.2.8). Thus, no change in population factors (i.e., host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in hydrology and substrate are anticipated. Changes in hydrologic conditions attributed to climate change are expected with a reduction in 7-day minimum flows between 30 – 40% and summer minimum base flows 26 – 33%, while durations of high flow events increase up to 16% (Lafontaine et al. 2019, entire). The effects to substrate are anticipated to manifest somewhere between the Moderate 25 and 50 year scenarios described above. Water quality, fragmentation, direct mortality, and invasive species continue to maintain current condition. The moderate declines in hydrology and substrate habitat factors project to moderate declines in all population factors resulting in a projected moderate decline in population resiliency shifting the population into low condition (Table C.2.11).

In the **Severe 50-year scenario** (Table C.2.12), severe declines in water quality and hydrology are anticipated from the same stressors described in the Moderate 50-year scenario, but greater in magnitude. Water quality degrades due to increasing concentrations of pollutants attributed to a 30 – 40% drop in 7-day minimum flows, 26 – 33% drop in summer minimum base flows (Lafontaine et al. 2019, entire) and increasing water demand. Flashiness (intense flow of short duration) in the stream system is expected to increase the occurrence of harmful shear stresses and sediment deposition, thus a continuation of moderate decline in substrate. With the drop in minimum base flows, fragmentation would intensify beyond the level described in the Moderate 50-year scenario. Direct mortality moves to moderate decline as desiccation and exposure to predation is expected to increase from streambed narrowing and drying. Invasive species maintains current condition. Severe declines in water quality and hydrology coupled with moderate declines in substrate, fragmentation, and direct mortality project to severe declines in all population factors (Table C.2.13). It is projected that the upper reaches of the focal area will experience a severe decline while more stable conditions in the lower portion will persist avoiding extirpation, thus maintaining the population in low condition.

Cossatot River – Current Condition

The Cossatot population currently has a high population condition/probability of persistence. No 303(d) impairments are listed for this focal area, but mercury in fish tissue is beyond EPA recommended consumption level. More than 60 wastewater permitted facilities, mostly pig farms, but also sand/gravel mining are in the focal area. Gillham Lake, upstream of the focal area, alters natural stream flows.

Cossatot River – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), a moderate decline in hydrology anticipated. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (16 – 21%) and summer minimum base flows (21 – 23%) while a -5% decrease in flashiness is expected (Lafontaine et al. 2019, entire). Water quality, substrate, fragmentation, direct mortality, and invasive species continue to maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency. The hydrologic impacts were not deemed significant enough to downgrade the population to moderate; therefore, it remains in high condition during this time-step (Table C.2.5).

During the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality and substrate are expected as hydrology undergoes a severe decline as the impacts discussed in the Moderate 25-year scenario intensify, causing cascading effects to other habitat factors. Sand and gravel operations in the watershed are expected to contribute sediment into the system affecting water quality. Run-off from concentrated animal feeding operations, in this instance hog farms, is expected as well. Water quality degrades due to this inputs and the decline in 7-day minimum flows and summer minimum base flows. The combination of decreased flashiness described in the Moderate 25-year scenario and expected sediment deposition would impact substrate as cleansing flows become less frequent. Fragmentation, direct mortality, and invasive species continue to maintain current condition. With the moderate decline in water quality and substrate coupled with the severe decline in hydrology, moderate declines in all population factors are projected to continue. A moderate decline in population resiliency is projected as a result with the population downgraded to moderate condition during this time-step (Table C.2.7).

Cossatot River – Severe Increase in Stressors

Change from the current high population condition is not expected as no change to habitat factors occur during the **Severe 10-year scenario** (Table C.2.8). Thus, no change in population factors (i.e., host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), a moderate decline in hydrology is anticipated. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (35 – 42%) and summer minimum base flows (26 – 30%) while a reduction in flashiness is expected (Lafontaine et al. 2019, entire). Water quality, substrate, fragmentation, direct mortality, and invasive species continue to maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency (Table C.2.11). The hydrologic impacts were not deemed significant enough at this time-step to downgrade the population to moderate; therefore it remains in high condition.

During the **Severe 50-year scenario** (Table C.2.12), a severe decline in hydrology is expected, triggering effects to other habitat factors. Water quality and substrate habitat factors degrade to severe decline and moderate decline respectively. The reductions in 7-day minimum flows and summer minimum base flows intensify, approaching the upper range discussed in the Severe 25-year scenario. The same affects to water quality (increasing concentration on pollutants) and substrate (sediment accumulation on mussel beds) described in the Moderate 50-year scenario occur. Fragmentation, direct mortality, and invasive species continue to maintain current condition. With the severe decline in water quality and hydrology coupled with the moderate decline in substrate, severe declines in host fish availability, reproduction/recruitment, occupied habitat, and abundance population factors are projected (Table C.2.13). A severe decline in population resiliency is projected as a result with the population downgraded to low condition during this time-step.

Saline River (Little) – Current Condition

The Saline River focal area is currently in low condition and is expected to remain in low condition for the next 50 years throughout all future scenarios. Portions of the focal area are not in attainment for dissolved oxygen. Natural flow conditions have been altered by Dierk's Lake in the upstream of the focal area but erratic flow uncommon, while prolonged high water is common for flood control.

Saline River (Little) – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), a moderate decline in hydrology is anticipated. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (18 – 25%) and summer minimum base flows (16 – 19%) (Lafontaine et al. 2019, entire). Water quality, substrate, fragmentation, direct mortality, and invasive species continue to maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency. The hydrologic impacts were not deemed significant enough to downgrade the population to extirpated (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality and substrate are expected as the hydrology undergoes severe decline as the impacts discussed in the Moderate 25-year scenario intensify, causing cascading effects to other habitat factors. Water quality degrades due to increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. Reduction in summer minimum base flows would subject substrates to more frequent and profound drying events from channel narrowing or complete loss of flowing water. With the moderate decline in water quality and substrate coupled with the severe decline in hydrology, moderate declines in population factors host fish availability, reproduction/recruitment, occupied habitat, and abundance are projected, resulting in a moderate decline in population resiliency. The hydrologic impacts were not deemed significant enough to downgrade the population to extirpated (Table C.2.7).

Saline River (Little) – Severe Increase in Stressors

In the **Severe 10-year scenario** (Table C.2.8)**,** no changes from the current condition are expected. Therefore, no change in habitat or population factors is anticipated and the focal area would maintain current population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), a moderate decline in hydrology is anticipated. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (33 – 40%) and summer minimum base flows (28 – 33%) while a reduction in flashiness is expected (Lafontaine et al. 2019, entire). Water quality, substrate, fragmentation, direct mortality, and invasive species continue to maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency (Table C.2.11). The hydrologic impacts were not deemed significant enough at this time-step to downgrade the population to extirpated; therefore it remains in low condition.

During the **Severe 50-year scenario** (Table C.2.12), a severe decline in hydrology is expected, triggering effects to other habitat factors. Severe decline in water quality is anticipated, as substrate and fragmentation habitat factors undergo moderate decline. The reductions in 7-day minimum flows and summer minimum base flows intensify, approaching the upper range discussed in the Severe 25-year scenario. The affects to water quality (increasing concentration on pollutants) and substrate (sediment accumulation on mussel beds) described in the Moderate 50-year scenario occur with more intensity. Decreased flashiness described in the Moderate 25-year scenario would affect substrate as cleansing flows become less frequent. With the drop in summer minimum base flows, fragmentation is expected due to episodic stream bed drying. Direct mortality and invasive species continue to maintain current condition. With the severe decline in water quality and hydrology coupled with the moderate decline in substrate and fragmentation, severe declines in host fish availability, reproduction/recruitment, occupied habitat, and abundance population factors are projected (Table C.2.13). A severe decline in population resiliency is projected, but impacts were not deemed significant enough at this time-step to downgrade the population to extirpated; therefore it remains in low condition.

Lower Little River Focal Area – Current Condition

The Louisiana pigtoe population in the Lower Little River focal area is currently considered functionally extirpated and is expected to remain so over the next 50 years in all future scenarios. A portion of the focal area is on the 303(d) impairment list for temperature.

Lower Little River Focal Area – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors is anticipated and the focal area would maintain current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), a moderate decline in hydrology is anticipated. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (19%) and summer minimum base flows (12%) (Lafontaine et al. 2019, entire). Releases from Millwood Lake dam are expected to buffer losses from minimum base flows described above. Water quality, substrate, fragmentation, direct mortality, and invasive species continue to maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency (Table C.2.5).

During the **Moderate 50-year scenario** (Table C.2.6), a moderate decline in hydrology ~~is~~ persists. Changes in hydrologic conditions described in the Moderate 25-year scenario intensify (Lafontaine et al. 2019, entire) and releases from Millwood Lake dam continue to buffer losses from minimum base flows described above. Water quality, substrate, fragmentation, direct mortality, and invasive species ~~continue to~~ maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency (Table C.2.7).

Lower Little River – Severe Increase in Stressors

In the **Severe 10-year scenario** (Table C.2.8)**,** no changes from the current condition are expected. Therefore, no change in habitat or population factors is anticipated and the focal area would maintain current population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), a moderate decline in hydrology is anticipated. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (39%) and summer minimum base flows (29%) (Lafontaine et al. 2019, entire). Releases from Millwood Lake dam are expected to buffer losses from minimum base flows described above. Water quality, substrate, fragmentation, direct mortality, and invasive species ~~continue to~~ maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency (Table C.2.11).

During the **Severe 50-year scenario** (Table C.2.12), severe declines in water quality and hydrology are anticipated from the same stressors described in the Severe 25-year scenario, but greater in magnitude. Water quality degrad~~es~~ due to increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. Reductions in 7-day minimum flows and summer minimum base flows are project to decrease near or above 30%. Releases from Millwood Lake dam supplements some loss from minimum base flows described above. Substrate, fragmentation, direct mortality, and invasive species ~~continue to~~ maintain current condition. Due to the severe decline in the water quality and hydrology habitat factors, severe declines were projected for all population factors which in turn projected a severe decline in population resiliency (Table C.2.13).

Big Cypress Bayou – Current Condition

The Big Cypress Bayou focal area currently has a moderate population condition/probability of persistence. ~~The a~~ portion of the focal area (0402) was identified on the Texas §303(d) List as having elevated mercury in fish tissue, low pH, and depressed dissolved oxygen in 1998, 2000, and 2010, respectively. The impairments remained on the 2014 Texas §303(d) List. However, pH samples collected since 2014 show that the standard is being met and was removed from the 2016 §303(d) List. Another portion (0409) was identified as impaired for low levels of dissolved oxygen in 2000 and for elevated bacteria (E. coli) levels in 2006. The 2014 and 2016 Texas §303(d) Lists confirmed the impairment. Data collected since 2014 indicate elevated bacteria and low dissolved oxygen levels are still present. Multiple wastewater treatment plants discharge effluent into the focal area. Voluntary instream flows for Cypress Basin in place, but the strategies to meet future water needs of regional water plans and the State Water Plan are not to be limited by these voluntary goals for instream flows. On channel Lake of the Pines and Bob Sandlin upstream of focal areas have altered natural stream flow conditions. A reservoir is proposed that could affect flows in the focal area (Little Cypress Reservoir), but the North East Texas Regional Water Planning Group does not recommend the designation of the potential reservoir site as a unique reservoir site. The invasive/exotic aquatic plant Giant salvinia is established in this watershed.

Big Cypress Bayou – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), a moderate decline in hydrology is anticipated. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (20 – 23%) and summer minimum base flows (16 – 29%) (Lafontaine et al. 2019, entire). Water quality, substrate, fragmentation, direct mortality, and invasive species ~~continue to~~ maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency. The hydrologic impacts were not deemed significant enough to downgrade the population to low condition (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality and direct mortality are expected as the hydrology undergoes severe decline as the impacts discussed in the Moderate 25-year scenario intensify, causing cascading effects to other habitat factors. Water quality degrades due to anthropogenic alterations affecting total maximum daily loads, conductivity and other pollutants attributed to the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. Channel narrowing or complete loss of flowing water due to the reduction in summer minimum base flows would cause desiccation and increased exposure to predation. With the moderate decline in water quality and direct mortality coupled with the severe decline in hydrology, moderate declines in population factors host fish availability, reproduction/recruitment, occupied habitat, and abundance are projected, resulting in a moderate decline in population resiliency. Therefore the population is downgraded to low condition during this time-step (Table C.2.7).

Big Cypress Bayou – Severe Increase in Stressors

In the **Severe 10-year scenario** (Table C.2.8)**,** no changes from the current condition are expected. Therefore, no change in habitat or population factors is anticipated and the focal area would maintain current population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), a moderate decline in hydrology is anticipated. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (27 – 35%) and summer minimum base flows (30 – 40%) (Lafontaine et al. 2019, entire) as well as increasing water demand. Water quality, substrate, fragmentation, direct mortality, and invasive species ~~continue to~~ maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency (Table C.2.11). The hydrologic impacts were not deemed significant enough at this time-step to downgrade the population~~,~~ therefore it remains in moderate condition.

During the **Severe 50-year scenario** (Table C.2.12), severe declines in water quality and hydrology are anticipated from the same stressors described in the Severe 25-year scenario, but greater in magnitude. Water quality degrad~~es~~ due to increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. Reductions in 7-day minimum flows and summer minimum base flows are project to decrease ≤ 30% increasing probability of desiccation and exposure to predation. Substrate, fragmentation, and invasive species ~~continue to~~ maintain current condition. Due to the severe decline in the water quality and hydrology habitat factors, moderate declines were projected for all population factors. Because two of the three habitat factors are in severe decline, the focal area is expected to experience a severe decline in population resiliency resulting in low condition during this time-step (Table C.2.13).

Calcasieu-Mermentau River Basin

Upper Calcasieu River – Current Condition

The Upper Calcasieu River focal area currently has a low current condition/probability of persistence. It is listed as impaired on the 303(d) list ~~by~~ for pH and fecal coliform. Sources of point and non-point pollution include municipal wastewater discharges, paper mill effluent, and sand/gravel mining. Calcasieu River within focal area is designated under Louisiana's Natural and Scenic River System. These waterways are protected by a permit process and certain prohibitions against channelization, impoundment construction, and channel realignment. Continued population growth at the historical rate will likely increase demand for high-quality water supplies for both public supply and industrial uses. Increased water extraction during low rainfall periods to supply local agricultural practices is anticipated.

Upper Calcasieu River Focal Area – Moderate Increase in Stressors

Change from the current condition is expected for hydrology and fragmentation during the **Moderate 10-year scenario** (Table C.2.2). Removal of a low-head dam in the upper portion of the focal area is planned and is anticipated to improve hydrologic conditions and remove a fish passage barrier, thus decreasing fragmentation in the system. All other threats maintain current condition. With the dam removal, moderate improvements to hydrology and habitat structure/substrate habitat factors are expected as stream flows return to more natural conditions. Moderate improvements to all population factors are anticipated as a result and a moderate improvement in population resiliency is projected. The population maintains its low condition despite the improving habitat and population factors as they merely buffer effects from other threats to habitat factors described above (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), a moderate decline in hydrology is anticipated while the moderate improvement to fragmentation continues. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows of 23% and summer minimum base flows 37% (Lafontaine et al. 2019, entire) while demands for surface and groundwater continue their current trend. Positive biological and hydrological responses from reduced fragmentation are expected. Water quality, substrate, direct mortality, and invasive species ~~continue to~~ maintain current condition. With the moderate decline in the hydrology and moderate improvement in fragmentation habitat factors, all population factors are projected to maintain current condition. The focal area would maintain current population resiliency, with the population remaining in low condition (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality and substrate are expected as the hydrology undergoes severe decline as the impacts discussed in the Moderate 25-year scenario intensify, causing cascading effects to other habitat factors. Water quality degrades due to increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. Reduction in summer minimum base flows would subject substrates to more frequent and profound drying events from channel narrowing or complete loss of flowing water as well as sediment accumulate on mussel beds from a lack of adequate cleansing flows. With the moderate decline in water quality and substrate coupled with the severe decline in hydrology, moderate declines in all population factors are projected, resulting in a moderate decline in population resiliency. Extirpation of the population is projected during this time-step (Table C.2.7).

Upper Calcasieu River – Severe Increase in Stressors

Change from the current condition is expected for hydrology and fragmentation during the **Severe 10-year scenario** (Table C.2.8). Moderate improvements to both habitat factors are expected from the reduced threats described in the Moderate 10-year scenario. The population maintains low condition despite improving habitat and population factors as they merely buffer effects from the other threats to habitat factors described in the Moderate increase in Stressors section (Table C.2.9).

During the **Severe 25-year scenario** (Table C.2.10), a severe decline in hydrology is expected, triggering moderate declines in water quality and direct mortality. Moderate improvements to fragmentation are expected as threats are reduced as stream flows return to more natural conditions after dam removal. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows of 35% and summer minimum base flows of 52% (Lafontaine et al. 2019, entire) while demands for surface and groundwater continue their current trend. Water quality degrades due to increasing concentrations of pollutants attributed to the decline in summer minimum base flows. Reduction in summer minimum base flows would subject mussel beds to drying events from channel narrowing or dewatering increasing exposure to predation and desiccation. Positive biological and hydrological responses from reduced fragmentation are expected as stream flows return to more natural conditions. Based on these threats, moderate decline is projected for the water quality habitat factor; severe decline is projected for the hydrology habitat factor; and moderate improvement is projected for the habitat structure/substrate habitat factor. Declines in all population factors are projected as a result, leading to a moderate decline in population resiliency with the population remaining in low condition (Table C.2.11).

In the **Severe 50-year scenario** (Table C.2.12), a severe decline in hydrology is expected as the impacts discussed in the Severe 25-year scenario intensify, causing cascading effects to other habitat factors. A severe decline in water quality and moderate declines in substrate and fragmentation are triggered as a result. Water quality degrades due to increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. Reduction in summer minimum base flows would subject substrates to more frequent and profound drying events from channel narrowing or complete loss of flowing water causing fragmentation. As a result, severe declines in host fish availability, reproduction/recruitment, occupied habitat, and abundance population factors are projected, causing a severe decline in population resiliency (Table C.2.13). Extirpation of the population is projected during this time-step.

Pearl River Basin

Pearl River Focal Area – Current Condition

The Pearl River focal area currently has a low current condition/probability of persistence. The main channel and/or numerous tributaries are on the 303(d) list of impaired waterbodies for various causes including biological impairment, sulfate, pH, dissolved oxygen, and turbidity. Other past and current stressors to water quality include point and non-point source pollution from urban areas and chemical releases from a paper mill near Bogalusa, Louisiana in 2011 causing a substantial fish kill. The Ross R. Barnett Reservoir, construction completed in 1963, influences the current hydrologic condition of the focal area. An additional reservoir on the main channel of the Pearl River below the Ross R. Barnett Reservoir is proposed for flood control.

Pearl River Focal Area – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario (**Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated with the focal area maintaining current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, hydrology, substrate, fragmentation, and direct mortality are anticipated while invasive species maintain current conditions. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (15 – 19%) and summer minimum base flows (12 – 19%) (Lafontaine et al. 2019, entire). In addition, hydrologic conditions would be negatively affected by the construction of a flood control reservoir proposed for the upper portion of the focal area during this time-step. Water quality degrades due to increasing wastewater returns and concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to the decline in 7-day minimum flows, summer minimum base flows. With the reduction in base flows, a moderate decline in substrate condition is anticipated as sediments accumulate on mussel beds from a lack of adequate cleansing flows. The flood control reservoir would function as a fish passage barrier, causing the loss of approximately 20 miles of occupied habitat. Direct mortality is expected to increase due to habitat loss and hydrologic alteration from reservoir construction. As a result of these threats, moderate decline is expected for the water quality, hydrology, and habitat structure/substrate habitat factors as well as all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat and abundance). The focal area would undergo a moderate decline in population resiliency, with the population remaining in low condition (Table C.2.5).

During the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality, hydrologic conditions, substrate, fragmentation and direct mortality are expected to continue. Threats from the same sources described in the Moderate 25-year scenario continue, but with increasing intensity. Invasive species continue to maintain current condition. As a result of these threats, moderate decline is expected for the water quality, hydrology, and habitat structure/substrate habitat factors as well as all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat and abundance). The focal area would undergo a moderate decline in population resiliency, with the population remaining in low condition (Table C.2.7).

Pearl River – Severe Increase in Stressors

In the **Severe 10-year scenario** (Table C.2.8), no changes from the current condition are expected. Therefore, no change in habitat or population factors is anticipated and the focal area would maintain current population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, hydrology, substrate, fragmentation, and direct mortality are anticipated while invasive species maintain current conditions. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (20 – 22%) and summer minimum base flows (14 – 22%) (Lafontaine et al. 2019, entire). With the modeled reductions in base flows as well as the construction of the flood control reservoir, the same threats described in the Moderate 25-year scenario would occur, but with greater intensity. As a result of these threats, moderate decline is expected for the water quality, hydrology, and habitat structure/substrate habitat factors as well as all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat and abundance). The focal area would undergo a moderate decline in population resiliency, with the population remaining in low condition (Table C.2.11).

During the **Severe 50-year Scenario** (Table C.2.12), a severe decline in hydrology is expected as the impacts discussed in the Severe 25-year scenario intensify, causing cascading effects to other habitat factors. With the modeled reductions in base flows as well as the construction of the flood control reservoir, the same threats in the Severe 25-year scenario would occur, but with greater intensity. A moderate decline in water quality, substrate, fragmentation and direct mortality continue as a result. A severe decline in the hydrology habitat factor is projected while water quality and habitat quality/substrate are project to undergo a moderate~~ a~~ decline. Severe declines in host fish availability, reproduction/recruitment, occupied habitat, and abundance population factors are projected, causing a severe decline in population resiliency (Table C.2.13). Extirpation of the population is projected during this time-step.

Sabine River Basin

Sabine River Focal Area – Current Condition

The currently extirpated Sabine River focal area (Table C.2.14) is expected to remain extirpated in the next 50 years in all future scenarios. Two segments within the focal area are on the 303(d) list of impaired waterbodies for bacteria. A new poultry processing plant has been permitted to release wastewater in the upper portion of the focal area downstream of Lake Tawakoni. Wastewater releases are permitted at 2.18 million gallons per day with an ammonia limit of 3.94 mg/L, which is beyond the threshold for freshwater mussel tolerances. The construction of Lake Tawakoni and Toledo Bend Reservoir~~ has~~ impacted natural hydrologic conditions and dam releases caus~~ing~~ substrate scouring eliminating mussel habitat downstream until sheer stress dissipates. An additional off-channel reservoir in the middle of the focal area and a water diversion project are proposed to meet future water demand. When constructed, water quality and hydrologic conditions would further degenerate from current conditions. Bank erosion is prevalent throughout the focal area, resulting in elevated inputs of sediment impacting suitable substrates for mussel beds.

Sabine River Focal Area- Moderate Increase in Stressors

In the **Moderate 10-year scenario (**Table C.2.2), the focal area is projected to endure a moderate decline in water quality due to degradation resulting from a general increase in point and non-point source discharges, including significant wastewater effluent flows from a new poultry processing plant into a portion of the river with documented mussel beds. This degradation in water quality is expected to negatively influence overall mussel survival and reproductive success, potentially affecting both mussel and host fish movement, and subsequently causing fragmentation of suitable habitat. In some cases, water quality degradation may result in increased direct mortality of Louisiana pigtoe, contributing to a moderate decline in this focal area. ~~Changes to h~~ydrology, substrate and invasive species are expected to maintain their current condition of moderate decline. The changes to threat conditions described above negatively affected modelled Louisiana pigtoe water quality and habitat structure/substrate habitat factors and all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected moderate decline in population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, hydrology, substrate, fragmentation, and direct mortality are expected to continue in tandem with population growth and associated impacts (e.g., habitat loss, increased demand for water supply, and increased generation of wastewater). Declining conditions of water quality, fragmentation, and direct mortality would be exacerbated by the effects of climate change. The moderate decline in hydrology is expected, in part, from future predicted reductions in flow, as represented by reductions in 7-day minimum flows (1 – 30%) and summer minimum base flows (10 – 29%) arising from a changing climate (Lafontaine et al. 2019, entire). Subsequently, a moderate decline in substrate condition is anticipated as sediments accumulate on mussel beds from a lack of adequate cleansing flows. The threat posed by invasive species is expected to maintain current condition. The changes to threat conditions described above negatively affected modelled habitat and population factors (moderate declines in host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected moderate decline in population resiliency (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality, substrate, fragmentation, and direct mortality will continue due to the threats described above. Hydrology is expected to severely decline due to climate change, including significant reductions in 7-day minimum and summer minimum base flows, as well as the construction of an off-channel reservoir in the middle Sabine River basin; these changes to hydrology and flow will further degrade water quality. Threats from invasive species are expected to maintain current condition. The changes to threat conditions described above negatively affected modelled habitat with a severe decline in hydrology and moderate declines in water quality and habitat structure/substrate. Population factors of host fish availability, reproduction/recruitment, occupied habitat, and abundance undergo severe decline, resulting in a projected severe decline in population resiliency (Table C.2.7).

Sabine River Focal Area - Severe Increase in Stressors

In the **Severe 10-year scenario** (Table C.2.8), we anticipate moderate declines in water quality, fragmentation and direct mortality based on the same threats assessed in the Moderate 10-year scenario. Changes to hydrology, substrate and invasive species are expected to maintain their current condition. The changes to threat conditions described above negatively affected modelled Louisiana pigtoe water quality and habitat structure/substrate habitat factors and all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected moderate decline in population resiliency (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, substrate, fragmentation, and direct mortality continue. Conditions of water quality, fragmentation and direct mortality would be exacerbated by the same stressors described above. A moderate decline in substrate condition is expected as sediments accumulate on mussel beds from a lack of adequate cleansing flows. This change in substrate condition is correlated with an expected severe decline in hydrological condition from reductions in 7-day minimum flows (20 – 22%) and summer minimum base flows (14 – 22%) (Lafontaine et al. 2019, entire) arising from a changing climate in addition to an off-channel reservoir constructed in the middle of the Sabine River basin; these changes to hydrology and flow will further degrade water quality. Invasive species condition is expected to maintain current condition. The changes to threat conditions described above negatively affected modelled habitat factors with a severe decline in hydrology and moderate declines in water quality and habitat structure/substrate. Population factors of host fish availability, reproduction/recruitment, occupied habitat, and abundance undergo severe decline, resulting in a projected severe decline in population resiliency (Table C.2.11).

In the **Severe 50-year scenario** (Table C.2.12), severe declines in water quality and hydrology are anticipated resulting from increasing demands for waters supply and increasing point and non-point source pollution. Changes to flow include an estimated 30% reduction in minimum base flows as well as the construction of an off-channel reservoir in the middle Sabine River basin. Moderate declines in substrate, fragmentation, and direct mortality are anticipated from the same sources described in the Severe 25-year scenario. Invasive species condition is expected to maintain current condition. The changes to threat conditions described above negatively affected modelled Louisiana pigtoe habitat and population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected severe decline in population resiliency (Table C.2.13).

Bayou Anacoco Focal Area – Current Condition

The Bayou Anacoco focal area currently has a moderate current condition/probability of persistence. It is currently on the 303(d) impaired water bodies list for total dissolved solids and fecal coliform. Municipal and Industrial wastewater discharges into Bayou Anacoco including Boise Packing and Newsprint-Deridder Paper Mill (39 million gallons per day) and City of Leesville Wastewater Treatment Facility (2.1 million gallons per day). Lake Vernon and Anacoco Lake are upstream of the focal area. The two impoundments and wastewater discharges have altered natural hydrologic and water quality conditions throughout the focal area.

Bayou Anacoco Focal Area- Moderate Increase in Stressors

In the **Moderate 10-year scenario (**Table C.2.2), the focal area is projected to endure a moderate decline in hydrology due to reduced stream flows from dam repairs and filling of Vernon Lake. Subsequently, a moderate decline in substrate condition is anticipated as sediments accumulate on mussel beds from a lack of adequate cleansing flows. Threats to water quality, fragmentation, direct mortality and invasive species are expected to maintain their current condition. The changes to threat conditions described above resulted in moderate decline in hydrology and habitat structure/substrate habitat factors. All population factors are projected to undergo moderate decline as a result and a projected moderate decline in population resiliency is expected. The population is downgraded to low condition during this time-step (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), a moderate decline in hydrology is expected to continue due to a modelled 35% reduction in 7-day minimum flows and 30% reduction in summer minimum base flows (Lafontaine et al. 2019, entire). All other threat categories are expected to maintain current condition. Due to the moderate decline in the hydrology habitat factor, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency. The hydrologic impacts were not deemed significant enough to downgrade the population and the system is expected to recover from Vernon Lake dam repairs/filling resulting in a projected upgrade of the population to moderate condition (Table C.2.5).

During the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality and substrate are expected as hydrology undergoes severe decline as the impacts discussed in the Moderate 25-year scenario intensify, causing cascading effects to other habitat factors. Water quality degrades due to increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. Reduction in summer minimum base flows would subject substrates to more frequent and profound drying events from channel narrowing or complete loss of flowing water as well as sediment accumulation on mussel beds from a lack of adequate cleansing flows. With the moderate decline in water quality and substrate coupled with the severe decline in hydrology, moderate declines in all population factors are projected, resulting in a moderate decline in population resiliency. The population is downgraded to low condition during this time-step (Table C.2.7).

Bayou Anacoco Focal Area- Severe Increase in Stressors

In the **Severe 10-year scenario** (Table C.2.8), we anticipate moderate declines in hydrology and substrate based on the same threats assessed in the Moderate 10-year scenario. Changes to water quality, fragmentation, direct mortality and invasive species are expected to maintain their current condition. The changes to threat conditions described above negatively affected modelled Louisiana pigtoe hydrology and habitat structure/substrate habitat factors and all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulting in a projected moderate decline in population resiliency. The population is downgraded to low condition during this time-step (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), a severe decline in hydrology is expected to continue due to a modelled 41% reduction in 7-day minimum flows and 36% reduction in summer minimum base flows (Lafontaine et al. 2019, entire). A moderate decline in water quality is expected due to threats from increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to paper mill and municipal wastewater effluent and the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. These water quality impacts are expected to increase threats in direct mortality. Substrate, fragmentation, and invasive species are expected to maintain current condition. Due to the severe decline in the hydrology and moderate decline in water quality habitat factors, moderate declines were projected for all population factors which in turn projected a moderate decline in population resiliency (Table C.2.11). The decline in population resiliency was not deemed significant enough to downgrade the population and the system is expected to recover from Vernon Lake dam repairs/filling resulting in a projected upgrade of the population to moderate condition.

During the **Severe 50-year scenario** (Table C.2.12), a severe decline in water quality and moderate decline in substrate is expected as hydrology undergoes severe decline as the impacts discussed in the Severe 25-year scenario intensify, causing cascading effects to other habitat factors. Water quality degradation described in the Severe 25-year scenario intensify. Reduction in summer minimum base flows would subject substrates to more frequent and profound drying events from channel narrowing or complete loss of flowing water as well as sediment accumulation on mussel beds from a lack of adequate cleansing flows. With the moderate decline substrate coupled with the severe decline in hydrology and water quality, severe declines in host fish availability, reproduction/recruitment, occupied habitat, and abundance population factors are projected (Table C.2.13). A severe decline in population resiliency is projected and extirpation is expected during this time-step.

Neches River Basin

Angelina River Focal Area – Current Condition

The Angelina River focal area currently has a low population condition/probability of persistence. Segments of the focal area are on the 303(d) impaired water bodies list for bacteria. Fecal coliform often exceeded standards in the late 1990s and elevated ammonia levels were routinely observed in 2008. No impoundments are on Angelina River upstream or within the focal area. Two reservoirs, Lake Columbia and Lake Ponta, are proposed in on a major tributary to the focal area. Both would be constructed on Mud Creek in the upper watershed of the focal area, altering hydrology and substrates.

Angelina River Focal Area – Moderate Increase in Stressors

In the **Moderate 10-year scenario (**Table C.2.2), the focal area is projected to endure a moderate decline in substrate and direct mortality from threats associated with underwater seismic testing. Seismic tests involve explosive charges placed in “shot” holes. Drilling ~~of the~~ shot holes into the substrate and subsequent explosi~~ve~~ are expected to result in direct mortality of individuals and degraded substrate habitat. Threats to water quality, hydrology, fragmentation, and invasive species are expected to maintain their current condition. The changes to threat conditions described above resulted in moderate decline in the habitat structure/substrate habitat factor. All population factors are projected to undergo moderate decline as a result and a projected moderate decline in population resiliency is expected. The population maintains low condition during this time-step (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), increasing stressors result in severe declines in hydrology and substrate and moderate declines in water quality, fragmentation, and direct mortality. Declining condition~~s of water quality~~ attributed to the moderate decline in hydrology is expected, in part, from future predicted reductions in flow, as represented by reductions in 7-day minimum flows (25 – 32%) and summer minimum base flows (28 – 29%) arising from a changing climate (Lafontaine et al. 2019, entire). Stream flow reductions from reservoir development in the upper watershed of the focal area are expected as well. These reductions in stream flow are expected to cause temporary fragmentation due to dry periods. Subsequently, a severe decline in substrate condition is anticipated as sediments accumulate on mussel beds from a lack of adequate cleansing flows. Direct mortality from seismic testing is anticipated. Threats from invasive species are expected to maintain current condition. Due to the increase in stressors, severe decline in the hydrology and habitat structure/substrate habitat factors and a moderate decline in the water quality habitat factors is projected. As a result, severe declines were projected for all population factors which in turn projected a severe decline in population resiliency. The population continues to maintain low condition during this time-step (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), severe declines in water quality, hydrology, substrate and fragmentation are expected while direct mortality continues in moderate decline. Hydrology threats intensify, causing cascading threats to the other habitat factors described in the Moderate 25-year scenario. Due to the increase in stressors, severe declines in all habitat factors and population factors are projected, which in turn projected a severe decline in population resiliency. Extirpation is anticipated during this time-step (Table C.2.7).

Angelina River Focal Area – Severe Increase in Stressors

In the **Severe 10-year scenario** (Table C.2.8), we anticipate moderate declines in substrate and direct mortality based on the same threats assessed in the Moderate 10-year scenario. ~~Changes to w~~ater quality, hydrology, fragmentation and invasive species are expected to maintain their current condition. The changes to threat conditions described above negatively affected modelled Louisiana pigtoe habitat structure/substrate habitat factor and all population factors, resulting in a projected moderate decline in population resiliency. The population maintains low condition during this time-step (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), increasing stressors result in severe declines in hydrology and substrate and moderate declines in water quality, fragmentation, and direct mortality. Declining conditions of water quality attributed to the moderate decline in hydrology is expected, in part, from future predicted reductions in flow, as represented by reductions in 7-day minimum flows (34 – 35%) and summer minimum base flows (42%) arising from a changing climate (Lafontaine et al. 2019, entire). Stream flow reductions from reservoir development in the upper watershed of the focal area are expected as well. These reductions in stream flow are expected to cause temporary fragmentation due to dry periods. Subsequently, a severe decline in substrate condition is anticipated as sediments accumulate on mussel beds from a lack of adequate cleansing flows. Direct mortality from seismic testing is anticipated. Threats from invasive species are expected to maintain current condition. Due to the increase in stressors, severe decline in the hydrology and habitat structure/substrate habitat factors and a moderate decline in the water quality habitat factors is projected. As a result, severe declines were projected for all population factors which in turn projected a severe decline in population resiliency (Table C.2.11). The population continues to maintain low condition during this time-step.

In the **Severe 50-year scenario** (Table C.2.12), severe declines in water quality, hydrology, substrate and fragmentation are expected while direct mortality continues in moderate decline. Hydrology threats intensify, exacerbating threats to the other habitat factors described in the Severe 25-year scenario. Due to the increase in stressors, severe declines in all habitat factors and population factors are project, which in turn projected a severe decline in population resiliency (Table C.2.13). Extirpation is anticipated during this time-step.

Neches River Focal Area – Current Condition

The Neches River focal area currently has a high population condition/probability of persistence. Tributaries and segments of the focal area are on the 303(d) impaired water bodies list for dioxin and mercury in edible tissue, bacteria, and depressed dissolved oxygen. Numerous segments had concerns for nutrients, particularly ammonia and total phosphorus, however, decreasing trends for these parameters were often observed. Stream flows are influence by Lake Palestine in the upper portion of the focal area and B.A. Steinhagen Reservoir in the southern portion of the focal area.

Neches River Focal Area – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency. The population continues to maintain high condition during this time-step (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, substrate, fragmentation, and direct mortality are anticipated. Water quality degradation is expected from a general increase in point and non-point source pollution, with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels; these water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural stream flows with some increases to municipal wastewater effluent return flows). Sediment accumulation on mussel beds is projected to increase from a lack of adequate cleansing flows. The proposed Rockland reservoir on the main channel of the Neches River, which would function as a fish passage barrier, is anticipated to be operational at this time-step. Direct mortality is expected to increase due to water quality degradation, reductions in water volume, and habitat loss from reservoir construction. A severe decline in hydrology is attributed to three proposed water delivery projects within the focal area combined with an overall reduction in stream flows. Lake Columbia is an off-channel reservoir proposed in the upper portion of the focal area, a run-of river water diversion is proposed for the middle of the focal area, and Rockland reservoir is proposed near the downstream end of the focal area. Additionally, reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate are expected. The invasive species factor is expected to maintain current condition. The projected moderate and severe decline in habitat and population factors (i.e., water quality and quantity, fish host availability, reproduction/recruitment, occupied habitat, and abundance) is expected to result in a severe decline in population resiliency. The population is downgraded to low condition during this time-step (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate declines in water quality, substrate, fragmentation, and direct mortality are expected to continue as the threats discussed in the Moderate 25-year scenario are realized and exacerbated by further reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate. Severe declines in host fish availability, reproduction/recruitment, occupied habitat, and abundance population factors continue, as well as declines to habitat factors, contributing to a projected severe decline in population resiliency. The population continues to maintain low condition during this time-step (Table C.2.7).

Neches River Focal Area – Severe Increase in Stressors

Change from the current moderate population condition is not expected as no change to habitat factors occur during the **Severe 10-year scenario** (Table C.2.8). Thus, no change in population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area is projected to maintain its current population resiliency. The population continues to maintain high condition during this time-step (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, substrate, fragmentation, and direct mortality are anticipated. Water quality degradation is expected from a general increase in point and non-point source pollution, with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels; these water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural steam flows with some increases to municipal wastewater effluent return flows). Sediment accumulation on mussel beds is projected to increase from a lack of adequate cleansing flows. The proposed Rockland reservoir on the main channel of the Neches River, which would function as a fish passage barrier, is anticipated to be operational at this time-step. Direct mortality is expected to increase due to water quality degradation, reductions in water volume, and habitat loss from reservoir construction. A severe decline in hydrology is attributed to three proposed water delivery projects within the focal area combined with an overall reduction in stream flows. Lake Columbia is an off-channel reservoir proposed in the upper portion of the focal area, a run-of river water diversion is proposed for the middle of the focal area, and Rockland reservoir is proposed near the downstream end of the focal area. Additionally, reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate are expected. The invasive species factor is expected to maintain current condition. The projected moderate and severe decline in habitat and population factors (i.e., water quality and quantity, fish host availability, reproduction/recruitment, occupied habitat, and abundance) is expected to result in a severe decline in population resiliency (Table C.2.11). The population is downgraded to low condition during this time-step.

In the **Severe 50-year scenario** (Table C.2.12), moderate declines in substrate, fragmentation, and direct mortality are expected to continue as the threats discussed in the Severe 25-year scenario are realized and exacerbated by further changes to hydrology, including reductions in 7-day minimum flows and summer minimum base flows arising from a changing climate. Both water quality and quantity undergo a severe decline as summer minimum base flows are projected to decrease by 30% from present levels (Lafontaine et al. 2019, entire), in addition to the other water volume reductions considered in the Severe 25-year scenario. Severe declines in host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance population factors, as well as declines to habitat factors, contribute to a continuing severe decline in population resiliency (Table C.2.13). The population continues to maintain low condition during this time-step.

Lower Neches River Focal Area – Current Condition

The Lower Neches River focal area currently has a low population condition/probability of persistence. See the information in the Neches River focal area for current water quality information. Stream flows are influenced by B.A. Steinhagen in the upper portion of the focal area.

Lower Neches River Focal Area – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality and hydrology are anticipated. Water quality degradation is expected from a general increase in point and non-point source pollution, with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels; these water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural stream flows with some increases to municipal wastewater effluent return flows). Hydrologic impacts related to climate change, including a reduction in 7-day minimum flows (21 – 25%) and summer minimum base flows (24 – 32%) (Lafontaine et al. 2019, entire), are expected. Substrate, fragmentation, direct mortality, and invasive species ~~continue to~~ maintain current condition. The moderate declines in water quality and hydrology habitat factors, coupled with moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulted in a projected moderate decline in population resiliency. The population continues to maintain low condition during this time-step (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), moderate decline in water quality continue due to the same sources described in the Moderate 25-year scenario. Hydrologic alterations driven by climate change will experience ~~a severe decline due to~~ further reductions in 7-day minimum flows and summer minimum base flows. Substrate, fragmentation, direct mortality, and invasive species ~~continue to~~ maintain current condition. The moderate decline in water quality combined with the severe decline in hydrology habitat factors, along with moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) resulted in a projected moderate decline in population resiliency. The population continues to maintain low condition during this time-step (Table C.2.7).

Lower Neches River Focal Area – Severe Increase in Stressors

Change from the current low population condition is not expected as no change to habitat factors occur during the **Severe 10-year scenario** (Table C.2.8). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency. The population ~~continues to~~ maintain low condition during this time-step (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality and hydrology are anticipated. Water quality degradation is expected from a general increase in point and non-point source pollution, with increasing concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels; these water quality impacts will be exacerbated by changes to hydrology (i.e., general decrease in natural stream flows with some increases to municipal wastewater effluent return flows). Hydrologic impacts related to climate change, including reductions in 7-day minimum (30 – 36%) and summer minimum base flows (32 – 41%) (Lafontaine et al. 2019, entire), are expected. Substrate, fragmentation, direct mortality, and invasive species ~~continue to~~ maintain current condition. The moderate declines in water quality and hydrology habitat factors, coupled with moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance), resulted in a projected moderate decline in population resiliency (Table C.2.11). The population ~~continues to~~ maintain low condition during this time-step.

In the **Severe 50-year scenario** (Table C.2.12), both water quality and hydrology undergo severe decline as ongoing water quality degradation is exacerbated by a greater than 30% reduction in 7-day minimum flows and summer minimum base flows from present-day levels (Lafontaine et al. 2019, entire). Substrate, fragmentation, direct mortality, and invasive species ~~continue to~~ maintain current condition. The focal area is projected to experience severe declines in water quality and hydrology habitat factors, coupled with moderate declines in population factors (host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance). Since two of the three habitat factors are in severe decline, the focal area is expected to experience a severe decline in population resiliency resulting in extirpation during this time-step (Table C.2.13).

San Jacinto River Basin

East Fork San Jacinto River Focal Area – Current Condition

The East Fork San Jacinto focal area currently has a low population condition/probability of persistence. It is on the 303(d) impaired water bodies list for bacteria. No impoundments are on the East Fork San Jacinto upstream or within the focal area. Lake Houston is downstream of the focal area. No new impoundments are proposed within or upstream of the focal area. Sand mining, in particular, has led to increased nutrient loads in the San Jacinto River which can result in an increase in cyanobacteria levels (Region H water plan pg 1-23).

East Fork San Jacinto Focal Area – Moderate Increase in Stressors

Change from the current condition is not expected for any threats during the **Moderate 10-year scenario** (Table C.2.2). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency. The population ~~continues to~~ maintain low condition during this time-step (Table C.2.3).

In the **Moderate 25-year scenario** (Table C.2.4), moderate declines in water quality, hydrology, substrate, and direct mortality are anticipated while fragmentation and invasive species maintain current condition. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (9%) and summer minimum base flows (30%) (Lafontaine et al. 2019, entire). Water quality degrad~~es~~ due to increasing wastewater returns and concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects to basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to the decline in 7-day minimum flows, summer minimum base flows and increased water demand. With the reduction in base flows, a moderate decline in substrate condition is anticipated as sediments accumulate on mussel beds from a lack of adequate cleansing flows. Direct mortality is expected to increase due to the threats above as well as desiccation and increased exposure to predation during dry periods. As a result of these threats, moderate decline is expected for the water quality, hydrology, and habitat structure/substrate habitat factors as well as all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat and abundance). The focal area would undergo a moderate decline in population resiliency, with the population remaining in low condition (Table C.2.5).

In the **Moderate 50-year scenario** (Table C.2.6), severe declines in water quality, hydrology, and substrate are expected while direct mortality continues in moderate decline. Fragmentation and invasive species threats maintain current condition. Hydrology threats described in the Moderate 25-year scenario intensify, causing cascading threats to the other habitat factors described in the Moderate 25-year scenario. Due to the increase in stressors, severe declines in water quality and hydrology and a moderate decline in habitat structure/substrate habitat factors are projected. Severe declines in all population factors are projected as a result, which in turn projected a severe decline in population resiliency. Extirpation is anticipated during this time-step (Table C.2.7).

East Fork San Jacinto Focal Area – Severe Increase in Stressors

Change from the current condition is not expected for any threats during the **Severe 10-year scenario** (Table C.2.8). Therefore, no change in habitat or population factors (i.e., water quality and quantity, host fish availability, reproduction/recruitment, survival, occupied habitat, and abundance) is anticipated and the focal area would maintain current population resiliency. The population ~~continues to~~ maintain low condition during this time-step (Table C.2.9).

In the **Severe 25-year scenario** (Table C.2.10), moderate declines in water quality, hydrology, substrate, and direct mortality are anticipated while fragmentation and invasive species maintain current condition. Changes in hydrologic conditions attributed to climate change are expected due to reductions in 7-day minimum flows (24%) and summer minimum base flows (36%) (Lafontaine et al. 2019, entire) and increasing water demand. Water quality degrades due to increasing wastewater returns and concentrations of some pollutants (e.g., ammonia and bacteria) and deleterious effects on basic water chemistry (e.g., dissolved oxygen) that can negatively affect mussels attributed to the decline in 7-day minimum flows, summer minimum base flows and increasing water demand. With the reduction in base flows, a moderate decline in substrate condition is anticipated as sediments accumulate on mussel beds from a lack of adequate cleansing flows. Direct mortality is expected to increase due to the threats above as well as desiccation and increased exposure to predation during dry periods. As a result of these threats, moderate decline is expected for the water quality, hydrology, and habitat structure/substrate habitat factors as well as all population factors (host fish availability, reproduction/recruitment, survival, occupied habitat and abundance) (Table C.2.11). The focal area would undergo a moderate decline in population resiliency, with extirpation occurring during this time-step.

In the **Severe 50-year scenario** (Table C.2.12), severe declines in water quality, hydrology, substrate, and direct mortality are expected. Fragmentation and invasive species threats maintain current condition. Hydrology threats described in the Severe 25-year scenario intensify, causing cascading threats to the other habitat factors described in the Severe 25-year scenario. Due to the increase in stressors, severe declines in water quality and hydrology and a moderate decline in habitat structure/substrate habitat factors are projected. Severe declines in all population factors are projected as a result, which in turn projected a severe decline in population resiliency (Table C.2.13). Extirpation is anticipated during this time-step.

C.1 Future scenario evaluation criteria for East Texas mussels

Table C.1.1: Louisiana pigtoe threat matrix definitions used to determine population resiliency model input values. ND indicates not defined.

Habitat Parameters	Significant Conservation/Research	Moderate Improvement	Maintain Current Condition	Moderate Decline	Severe Decline
Condition Value	2	1	0	-1	-2
Water Quality Changes	ND	WQ is good or excellent. Point and non-point sources of contaminants within watershed are low. No known contaminant concerns (e.g., dissolved oxygen sufficient, no thermal extremes documented). If available, total dissolved solids (TDS) or other indicators of anthropogenic alteration are stable or decreasing.	WQ is moderately impacted. Point and non-point sources of contaminants within watershed are present at moderate levels. TDS or other indicators of anthropogenic alteration are stable or slightly increasing.	WQ is highly impacted. Point and non-point sources of contaminants within watershed are at high levels. TDS or other indicators of anthropogenic alteration are increasing.	WQ is limiting for aquatic life. Point and non-point sources of contaminants within watershed are at levels that preclude mussel or host fish survival.
Hydrology Changes	ND	Hydrology remains unaltered from natural conditions; fully meets requirements of mussels. No impacts to flow components (subsistence, base, high flow pulses, overbanking) from impoundments, reservoirs, diversions, groundwater extraction, or other anthropogenic activities. Flowing water is present year-round with no recorded zero-flow days, even during droughts.	Hydrology moderately impacted. One or more flow components (subsistence, base, high flow pulses, overbanking) impacted from impoundments, reservoirs, diversions, groundwater extraction, or other anthropogenic activity. Biological and geomorphic functions mostly intact. Extremely high, low, or erratic flows are infrequent.	Hydrology highly impacted. One or more flow components (subsistence, base, high flow pulses, overbanking) severely altered from impoundments, reservoirs, diversions, groundwater extraction, or other anthropogenic activity. Biological and geomorphic functions highly impacted. Extremely high, low, or erratic flows are routine; zero flow days occur. PRMS model estimates less than 20% reduction in flows are considered moderate.	Dry stream bed / zero flow days occur frequently, hydrology severely altered; frequency of high flows and shear stress is sufficient to scour substrate and dislocate mussels; substrates are unstable, resulting in unsuitable habitat for mussels. PRMS model estimates greater than 20% reduction in flows and/or changes to hydrology severe enough to impact survival.
Substrate Changes	ND	Riffle and run habitat common. Substrates are stable. Gravel and cobble substrate sufficient to provide anchoring habitat. Low levels of sedimentation on substrate.	Riffle and run habitat uncommon. Substrates are moderately stable. Gravel and cobble substrate sufficient to provide anchoring habitat with some mobilization of particles and light sedimentation on substrate.	Riffle and run habitat rare. Substrates are highly unstable; habitat eroded, or being buried by mobilized sediments from upstream.	No suitable habitat present.
Fragmentation	ND	No impoundments/ barriers limiting mobility of host fish.	New or existing impoundments/ barriers moderately reducing mobility of host fish and impacting dispersal range of glochidia.	New or existing impoundments/ barriers severely reducing mobility of host fish and impacting dispersal range of glochidia.	New or existing impoundments/ barriers has limited mobility of host fish and impacted dispersal of glochidia at level causing extirpation/extinction.
Direct Mortality	ND	Predation, collection, or other actions resulting in direct mortality are not impacting populations.	Predation, collection, or other actions resulting in direct mortality are moderately impacting populations.	Predation, collection, or other actions resulting in direct mortality are severely impacting populations.	Predation, collection, or other actions resulting in mortality have caused extirpation/extinction
Invasive Species	ND	No invasive species present.	Invasive species moderately impacting populations.	Invasive species highly impacting populations.	Invasive species limiting to mussels or host fish. Invasive species present and severely impacting populations.

Table C.1.2: Texas heelsplitter threat matrix definitions used to determine population resiliency model input values. ND indicates not defined.

Habitat Parameters	Significant Improvement	Moderate Improvement	Maintain Current Condition	Moderate Decline	Severe Decline
Condition Value	2	1	0	-1	-2
Water Quality Changes	ND	WQ is good or excellent. Point and non-point sources of contaminants within watershed are low. No known contaminant concerns (e.g., dissolved oxygen sufficient, no thermal extremes documented). If available, total dissolved solids (TDS) or other indicators of anthropogenic alteration are stable or decreasing.	WQ is moderately impacted. Point and non-point sources of contaminants within watershed are present at moderate levels. TDS or other indicators of anthropogenic alteration are stable or slightly increasing.	WQ is highly impacted. Point and non-point sources of contaminants within watershed are at high levels. TDS or other indicators of anthropogenic alteration are increasing.	WQ is limiting for aquatic life. Point and non-point sources of contaminants within watershed are at levels that preclude mussel or host fish survival.
Hydrology Changes	ND	Hydrology remains unaltered from natural conditions; fully meets requirements of mussels. No impacts to flow components (subsistence, base, high flow pulses, overbanking) from impoundments, reservoirs, diversions, groundwater extraction, or other anthropogenic activities. Flowing water is present year-round with no recorded zero-flow days, even during droughts.	Hydrology moderately impacted. One or more flow components (subsistence, base, high flow pulses, overbanking) impacted from impoundments, reservoirs, diversions, groundwater extraction, or other anthropogenic activities. Biological and geomorphic functions mostly intact. Occupied reservoirs maintain stable water levels or experience moderate fluctuations. Extremely high, low, or erratic flows are infrequent.	Hydrology highly impacted. One or more flow components (subsistence, base, high flow pulses, overbanking) severely altered from impoundments, reservoirs, diversions, groundwater extraction, or other anthropogenic activities. Biological and/or geomorphic functions highly impacted. Frequency and magnitude of water fluctuations in occupied reservoirs is high. Extremely high, low, or erratic flows are routine; zero flow days occur. PRMS model estimates less than 20% reduction in flows are considered moderate.	Extremely high, low, and/or erratic flows are frequent, resulting in unsuitable habitat for mussels. Large magnitude reservoir drawdowns occur frequently. PRMS model estimates greater than 20% reduction in flows are considered significant and/or changes to hydrology severe enough to impact survival.
Substrate Changes	ND	Pool and backwater habitats common. Stable mud, sand, and silt substrates sufficient to provide anchoring habitat. Low levels of sedimentation on substrate.	Pool and backwater habitats uncommon. Mud, sand, and silt substrates moderately stable, providing anchoring habitat with some mobilization of particles and light sedimentation on substrate.	Pool and backwater habitat rare; substrates highly unstable, habitat eroded, or being buried by mobilized sediments from upstream.	No suitable habitat present.
Fragmentation	ND	No impoundments/ barriers limiting mobility of host fish.	New or existing impoundments/ barriers moderately reducing mobility of host fish and impacting dispersal range of glochidia.	New or existing impoundments/ barriers severely reducing mobility of host fish and impacting dispersal range of glochidia.	New or existing impoundments/ barriers has limited mobility of host fish and impacted dispersal of glochidia at level causing extirpation/extinction.
Direct Mortality	ND	Predation, collection, or other actions resulting in direct mortality are not impacting populations.	Predation, collection, or other actions resulting in direct mortality are moderately impacting populations.	Predation, collection, or other actions resulting in direct mortality are severely impacting populations.	Predation, collection, or other actions resulting in direct mortality have caused extirpation/extinction
Invasive Species	ND	No invasive species present.	Invasive species moderately impacting populations.	Invasive species highly impacting populations.	Invasive species limiting to mussels or host fish. Invasive species present and severely impacting populations.

C.2 Future condition tables by scenario and time step for the East Texas mussels

Table C.2.1: Population resiliency model input and output definitions for all scenarios and time steps

Forecasted Change in State	Input Value	Output	Change to Population Resiliency
Significant improvement	2	44 ≥ Resiliency > 22	Significant improvement in population resiliency
Moderate improvement	1	22 ≥ Resiliency > 0	Moderate improvement in population resiliency
Maintain Current Condition	0	Resiliency= 0	Maintain current population resiliency
Moderate Decline	-1	0 > Resiliency ≥ (-22)	Moderate decline in population resiliency
Severe Decline	-2	(-22) > Resiliency > (-44)	Severe decline in population resiliency

Resiliency = (-45) indicates two of the three Habitat Factors are severely declining, therefore Resiliency = severe decline.

Table C.2.2: Scenario 1 – 10 year time step stressors evaluation model input

ETX FWM Scenario Development			Threats					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality Changes	Hydrology Changes	Substrate Changes	Fragmentation	Direct Mortality	Invasive Species
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	0	0	-1	-1	0
		LK Tawakoni	0	0	0	0	0	0
	Neches	Neches R/BA Steinhagen	0	0	0	0	0	0
		Lower Neches R	0	0	0	0	0	0
	Trinity	LK Lewisville	0	0	0	0	0	0
		Grapevine LK	0	0	0	0	0	0
		Trinity R/Livingston	0	0	0	0	0	0
Louisiana pigtoe	Red	Mountain Fork	0	0	0	0	0	0
		Little R/Rolling FK	0	0	0	0	0	0
		Cossatot R	0	0	0	0	0	0
		Saline R (Little)	0	0	0	0	0	0
		Lower Little R	0	0	0	0	0	0
		Big Cypress Bayou	0	0	0	0	0	0
	Calcasieu	Upper Calcasieu R	0	1	0	1	0	0
	Pearl	Pearl R	0	0	0	0	0	0
	Sabine	Sabine R	-1	0	0	-1	-1	0
		Bayou Anacoco	0	-1	-1	0	0	0
	Neches	Angelina R	0	0	-1	0	-1	0
		Neches R	0	0	0	0	0	0
		Lower Neches R	0	0	0	0	0	0
	San Jacinto	E FK San Jacinto R	0	0	0	0	0	0

Table C.2.3: Scenario 1 – 10 year time step stressors evaluation model output

			Habitat Factors			Population Factors					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality	Hydrology	Habitat Structure/ Substrate	Host Fish Availability	Reproduction/ Recruitment	Survival	Occupied Habitat	Abundance	Change to Resiliency
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	0	-1	-2	-4	-3	-2	-9	-11
		LK Tawakoni	0	0	0	0	0	0	0	0	0
	Neches	Neches R/BA Steinhagen	0	0	0	0	0	0	0	0	0
		Lower Neches R	0	0	0	0	0	0	0	0	0
	Trinity	LK Lewisville	0	0	0	0	0	0	0	0	0
		Grapevine LK	0	0	0	0	0	0	0	0	0
		Trinity R/Livingston	0	0	0	0	0	0	0	0	0
Louisiana pigtoe	Red	Mountain Fork	0	0	0	0	0	0	0	0	0
		Little R/Rolling FK	0	0	0	0	0	0	0	0	0
		Cossatot R	0	0	0	0	0	0	0	0	0
		Saline R (Little)	0	0	0	0	0	0	0	0	0
		Lower Little R	0	0	0	0	0	0	0	0	0
		Big Cypress Bayou	0	0	0	0	0	0	0	0	0
	Calcasieu	Upper Calcasieu R	0	1	1	2	4	2	2	8	10
	Pearl	Pearl R	0	0	0	0	0	0	0	0	0
	Sabine	Sabine R	-1	0	-1	-2	-4	-3	-2	-9	-11
		Bayou Anacoco	0	-1	-1	-2	-4	-2	-2	-8	-10
	Neches	Angelina R	0	0	-1	-1	-2	-2	-1	-5	-6
		Neches R	0	0	0	0	0	0	0	0	0
		Lower Neches R	0	0	0	0	0	0	0	0	0
	San Jacinto	E FK San Jacinto R	0	0	0	0	0	0	0	0	0

Table C.2.4: Scenario 1 – 25 year time step stressors evaluation model input

ETX FWM Scenario Development			Threats					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality Changes	Hydrology Changes	Substrate Changes	Fragmentation	Direct Mortality	Invasive Species
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	-1	-1	-1	-1	0
		LK Tawakoni	-1	-1	0	0	-1	-1
	Neches	Neches R/BA Steinhagen	-1	-2	-1	-1	-1	0
		Lower Neches R	-1	-1	0	0	-1	0
	Trinity	LK Lewisville	-1	-1	0	0	-1	-1
		Grapevine LK	-1	-1	0	0	-1	-1
		Trinity R/Livingston	-1	-1	-1	0	-1	0
Louisiana pigtoe	Red	Mountain Fork	-1	-1	0	0	-1	0
		Little R/Rolling FK	0	-1	-1	0	0	0
		Cossatot R	0	-1	0	0	0	0
		Saline R (Little)	0	-1	0	0	0	0
		Lower Little R	0	-1	0	0	0	0
		Big Cypress Bayou	0	-1	0	0	0	0
	Calcasieu	Upper Calcasieu R	0	-1	0	1	0	0
	Pearl	Pearl R	-1	-1	-1	-1	-1	0
	Sabine	Sabine R	-1	-1	-1	-1	-1	0
		Bayou Anacoco	0	-1	0	0	0	0
	Neches	Angelina R	-1	-2	-2	-1	-1	0
		Neches R	-1	-2	-1	-1	-1	0
		Lower Neches R	-1	-1	0	0	0	0
	San Jacinto	E FK San Jacinto R	-1	-1	-1	0	-1	0

Table C.2.5: Scenario 1 – 25 year time step stressors evaluation model output

			Habitat Factors			Population Factors					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality	Hydrology	Habitat Structure/ Substrate	Host Fish Availability	Reproduction/ Recruitment	Survival	Occupied Habitat	Abundance	Change to Resiliency
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	-1	-2	-4	-8	-5	-4	-17	-21
		LK Tawakoni	-1	-1	0	-2	-4	-4	-2	-10	-12
	Neches	Neches R/BA Steinhagen	-1	-2	-2	-5	-10	-6	-5	-21	-26
		Lower Neches R	-1	-1	0	-2	-4	-3	-2	-9	-11
	Trinity	LK Lewisville	-1	-1	0	-2	-4	-4	-2	-10	-12
		Grapevine LK	-1	-1	0	-2	-4	-4	-2	-10	-12
		Trinity R/Livingston	-1	-1	-1	-3	-6	-4	-3	-13	-16
Louisiana pigtoe	Red	Mountain Fork	-1	-1	0	-2	-4	-3	-2	-9	-11
		Little R/Rolling FK	0	-1	-1	-2	-4	-2	-2	-8	-10
		Cossatot R	0	-1	0	-1	-2	-1	-1	-4	-5
		Saline R (Little)	0	-1	0	-1	-2	-1	-1	-4	-5
		Lower Little R	0	-1	0	-1	-2	-1	-1	-4	-5
		Big Cypress Bayou	0	-1	0	-1	-2	-1	-1	-4	-5
	Calcasieu	Upper Calcasieu R	0	-1	1	0	0	0	0	0	0
	Pearl	Pearl R	-1	-1	-2	-4	-8	-5	-4	-17	-21
	Sabine	Sabine R	-1	-1	-2	-4	-8	-5	-4	-17	-21
		Bayou Anacoco	0	-1	0	-1	-2	-1	-1	-4	-5
	Neches	Angelina R	-1	-2	-3	-6	-12	-7	-6	-25	-31
		Neches R	-1	-2	-2	-5	-10	-6	-5	-21	-26
		Lower Neches R	-1	-1	0	-2	-4	-2	-2	-8	-10
	San Jacinto	E FK San Jacinto R	-1	-1	-1	-3	-6	-4	-3	-13	-16

Table C.2.6: Scenario 1 – 50 year time step stressors evaluation model input

ETX FWM Scenario Development			Threats					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality Changes	Hydrology Changes	Substrate Changes	Fragmentation	Direct Mortality	Invasive Species
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	-2	-1	-1	-1	0
		LK Tawakoni	-1	-1	0	0	-1	-1
	Neches	Neches R/BA Steinhagen	-1	-2	-1	-1	-1	0
		Lower Neches R	-1	-2	0	0	-1	0
	Trinity	LK Lewisville	-1	-2	0	0	-1	-1
		Grapevine LK	-1	-2	0	0	-1	-1
		Trinity R/Livingston	-2	-2	-1	0	-2	0
Louisiana pigtoe	Red	Mountain Fork	-1	-2	0	0	-1	0
		Little R/Rolling FK	-1	-2	-1	-1	-1	0
		Cossatot R	-1	-2	-1	0	0	0
		Saline R (Little)	-1	-2	-1	0	0	0
		Lower Little R	0	-1	0	0	0	0
		Big Cypress Bayou	-1	-2	0	0	-1	0
	Calcasieu	Upper Calcasieu R	-1	-2	-1	0	0	0
	Pearl	Pearl R	-1	-1	-1	-1	-1	0
	Sabine	Sabine R	-1	-2	-1	-1	-1	0
		Bayou Anacoco	-1	-2	-1	0	0	0
	Neches	Angelina R	-2	-2	-2	-2	-1	0
		Neches R	-1	-2	-1	-1	-1	0
		Lower Neches R	-1	-2	0	0	0	0
	San Jacinto	E FK San Jacinto R	-2	-2	-2	0	-1	0

Table C.2.7: Scenario 1 – 50 year time step stressors evaluation model output

			Habitat Factors			Population Factors					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality	Hydrology	Habitat Structure/ Substrate	Host Fish Availability	Reproduction/ Recruitment	Survival	Occupied Habitat	Abundance	Change to Resiliency
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	-2	-2	-5	-10	-6	-5	-21	-26
		LK Tawakoni	-1	-1	0	-2	-4	-4	-2	-10	-12
	Neches	Neches R/BA Steinhagen	-1	-2	-2	-5	-10	-6	-5	-21	-26
		Lower Neches R	-1	-2	0	-3	-6	-4	-3	-13	-16
	Trinity	LK Lewisville	-1	-2	0	-3	-6	-5	-3	-14	-17
		Grapevine LK	-1	-2	0	-3	-6	-5	-3	-14	-17
		Trinity R/Livingston	-2	-2	-1	-5	-10	-7	-5	-22	-45
Louisiana pigtoe	Red	Mountain Fork	-1	-2	0	-3	-6	-4	-3	-13	-16
		Little R/Rolling FK	-1	-2	-2	-5	-10	-6	-5	-21	-26
		Cossatot R	-1	-2	-1	-4	-8	-4	-4	-16	-20
		Saline R (Little)	-1	-2	-1	-4	-8	-4	-4	-16	-20
		Lower Little R	0	-1	0	-1	-2	-1	-1	-4	-5
		Big Cypress Bayou	-1	-2	0	-3	-6	-4	-3	-13	-16
	Calcasieu	Upper Calcasieu R	-1	-2	-1	-4	-8	-4	-4	-16	-20
	Pearl	Pearl R	-1	-1	-2	-4	-8	-5	-4	-17	-21
	Sabine	Sabine R	-1	-2	-2	-5	-10	-6	-5	-21	-26
		Bayou Anacoco	-1	-2	-1	-4	-8	-4	-4	-16	-20
	Neches	Angelina R	-2	-2	-4	-8	-16	-9	-8	-33	-45
		Neches R	-1	-2	-2	-5	-10	-6	-5	-21	-26
		Lower Neches R	-1	-2	0	-3	-6	-3	-3	-12	-15
	San Jacinto	E FK San Jacinto R	-2	-2	-2	-6	-12	-7	-6	-25	-45

Table C.2.8: Scenario 2 – 10 year time step stressors evaluation model input

ETX FWM Scenario Development			Threats					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality Changes	Hydrology Changes	Substrate Changes	Fragmentation	Direct Mortality	Invasive Species
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	0	0	-1	-1	0
		LK Tawakoni	0	0	0	0	0	0
	Neches	Neches R/BA Steinhagen	0	0	0	0	0	0
		Lower Neches R	0	0	0	0	0	0
	Trinity	LK Lewisville	0	0	0	0	0	0
		Grapevine LK	0	0	0	0	0	0
		Trinity R/Livingston	0	0	0	0	0	0
Louisiana pigtoe	Red	Mountain Fork	0	0	0	0	0	0
		Little R/Rolling FK	0	0	0	0	0	0
		Cossatot R	0	0	0	0	0	0
		Saline R (Little)	0	0	0	0	0	0
		Lower Little R	0	0	0	0	0	0
		Big Cypress Bayou	0	0	0	0	0	0
	Calcasieu	Upper Calcasieu R	0	1	0	1	0	0
	Pearl	Pearl R	0	0	0	0	0	0
	Sabine	Sabine R	-1	0	0	-1	-1	0
		Bayou Anacoco	0	-1	-1	0	0	0
	Neches	Angelina R	0	0	-1	0	-1	0
		Neches R	0	0	0	0	0	0
		Lower Neches R	0	0	0	0	0	0
	San Jacinto	E FK San Jacinto R	0	0	0	0	0	0

Table C.2.9: Scenario 2 – 10 year time step stressors evaluation model output

			Habitat Factors			Population Factors					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality	Hydrology	Habitat Structure/ Substrate	Host Fish Availability	Reproduction/ Recruitment	Survival	Occupied Habitat	Abundance	Change to Resiliency
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	0	-1	-2	-4	-3	-2	-9	-11
		LK Tawakoni	0	0	0	0	0	0	0	0	0
	Neches	Neches R/BA Steinhagen	0	0	0	0	0	0	0	0	0
		Lower Neches R	0	0	0	0	0	0	0	0	0
	Trinity	LK Lewisville	0	0	0	0	0	0	0	0	0
		Grapevine LK	0	0	0	0	0	0	0	0	0
		Trinity R/Livingston	0	0	0	0	0	0	0	0	0
Louisiana pigtoe	Red	Mountain Fork	0	0	0	0	0	0	0	0	0
		Little R/Rolling FK	0	0	0	0	0	0	0	0	0
		Cossatot R	0	0	0	0	0	0	0	0	0
		Saline R (Little)	0	0	0	0	0	0	0	0	0
		Lower Little R	0	0	0	0	0	0	0	0	0
		Big Cypress Bayou	0	0	0	0	0	0	0	0	0
	Calcasieu	Upper Calcasieu R	0	1	1	2	4	2	2	8	10
	Pearl	Pearl R	0	0	0	0	0	0	0	0	0
	Sabine	Sabine R	-1	0	-1	-2	-4	-3	-2	-9	-11
		Bayou Anacoco	0	-1	-1	-2	-4	-2	-2	-8	-10
	Neches	Angelina R	0	0	-1	-1	-2	-2	-1	-5	-6
		Neches R	0	0	0	0	0	0	0	0	0
		Lower Neches R	0	0	0	0	0	0	0	0	0
	San Jacinto	E FK San Jacinto R	0	0	0	0	0	0	0	0	0

Table C.2.10: Scenario 2 – 25 year time step stressors evaluation model input

ETX FWM Scenario Development			Threats					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality Changes	Hydrology Changes	Substrate Changes	Fragmentation	Direct Mortality	Invasive Species
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	-2	-1	-1	-1	0
		LK Tawakoni	-1	-1	0	0	-1	-1
	Neches	Neches R/BA Steinhagen	-1	-2	-1	-1	-1	0
		Lower Neches R	-1	-1	0	0	-1	0
	Trinity	LK Lewisville	-1	-1	0	0	-1	-1
		Grapevine LK	-1	-1	0	0	-1	-1
		Trinity R/Livingston	-1	-1	-1	0	-1	0
Louisiana pigtoe	Red	Mountain Fork	-1	-1	0	0	-1	0
		Little R/Rolling FK	0	-1	-1	0	0	0
		Cossatot R	0	-1	0	0	0	0
		Saline R (Little)	0	-1	0	0	0	0
		Lower Little R	0	-1	0	0	0	0
		Big Cypress Bayou	0	-1	0	0	0	0
	Calcasieu	Upper Calcasieu R	-1	-2	0	1	-1	0
	Pearl	Pearl R	-1	-1	-1	-1	-1	0
	Sabine	Sabine R	-1	-2	-1	-1	-1	0
		Bayou Anacoco	-1	-2	0	0	-1	0
	Neches	Angelina R	-1	-2	-2	-1	-1	0
		Neches R	-1	-2	-1	-1	-1	0
		Lower Neches R	-1	-1	0	0	0	0
	San Jacinto	E FK San Jacinto R	-1	-1	-1	0	-1	0

Table C.2.11: Scenario 2 – 25 year time step stressors evaluation model output

			Habitat Factors			Population Factors					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality	Hydrology	Habitat Structure/ Substrate	Host Fish Availability	Reproduction/ Recruitment	Survival	Occupied Habitat	Abundance	Change to Resiliency
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-1	-2	-2	-5	-10	-6	-5	-21	-26
		LK Tawakoni	-1	-1	0	-2	-4	-4	-2	-10	-12
	Neches	Neches R/BA Steinhagen	-1	-2	-2	-5	-10	-6	-5	-21	-26
		Lower Neches R	-1	-1	0	-2	-4	-3	-2	-9	-11
	Trinity	LK Lewisville	-1	-1	0	-2	-4	-4	-2	-10	-12
		Grapevine LK	-1	-1	0	-2	-4	-4	-2	-10	-12
		Trinity R/Livingston	-1	-1	-1	-3	-6	-4	-3	-13	-16
Louisiana pigtoe	Red	Mountain Fork	-1	-1	0	-2	-4	-3	-2	-9	-11
		Little R/Rolling FK	0	-1	-1	-2	-4	-2	-2	-8	-10
		Cossatot R	0	-1	0	-1	-2	-1	-1	-4	-5
		Saline R (Little)	0	-1	0	-1	-2	-1	-1	-4	-5
		Lower Little R	0	-1	0	-1	-2	-1	-1	-4	-5
		Big Cypress Bayou	0	-1	0	-1	-2	-1	-1	-4	-5
	Calcasieu	Upper Calcasieu R	-1	-2	1	-2	-4	-3	-2	-9	-11
	Pearl	Pearl R	-1	-1	-2	-4	-8	-5	-4	-17	-21
	Sabine	Sabine R	-1	-2	-2	-5	-10	-6	-5	-21	-26
		Bayou Anacoco	-1	-2	0	-3	-6	-4	-3	-13	-16
	Neches	Angelina R	-1	-2	-3	-6	-12	-7	-6	-25	-31
		Neches R	-1	-2	-2	-5	-10	-6	-5	-21	-26
		Lower Neches R	-1	-1	0	-2	-4	-2	-2	-8	-10
	San Jacinto	E FK San Jacinto R	-1	-1	-1	-3	-6	-4	-3	-13	-16

Table C.2.12: Scenario 2 – 50 year time step stressors evaluation model input

ETX FWM Scenario Development			Threats					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality Changes	Hydrology Changes	Substrate Changes	Fragmentation	Direct Mortality	Invasive Species
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-2	-2	-1	-1	-1	0
		LK Tawakoni	-1	-2	0	0	-1	-1
	Neches	Neches R/BA Steinhagen	-2	-2	-1	-1	-1	0
		Lower Neches R	-2	-2	0	0	-1	0
	Trinity	LK Lewisville	-1	-2	0	0	-1	-1
		Grapevine LK	-1	-2	0	0	-1	-1
		Trinity R/Livingston	-2	-2	-1	0	-2	0
Louisiana pigtoe	Red	Mountain Fork	-2	-2	0	0	-1	0
		Little R/Rolling FK	-2	-2	-1	-1	-1	0
		Cossatot R	-2	-2	-1	0	0	0
		Saline R (Little)	-2	-2	-1	-1	0	0
		Lower Little R	-2	-2	0	0	0	0
		Big Cypress Bayou	-2	-2	0	0	-1	0
	Calcasieu	Upper Calcasieu R	-2	-2	-1	-1	0	0
	Pearl	Pearl R	-1	-2	-1	-1	-1	0
	Sabine	Sabine R	-2	-2	-1	-1	-1	0
		Bayou Anacoco	-2	-2	-1	0	0	0
	Neches	Angelina R	-2	-2	-2	-2	-1	0
		Neches R	-2	-2	-1	-1	-1	0
		Lower Neches R	-2	-2	0	0	0	0
	San Jacinto	E FK San Jacinto R	-2	-2	-2	0	-2	0

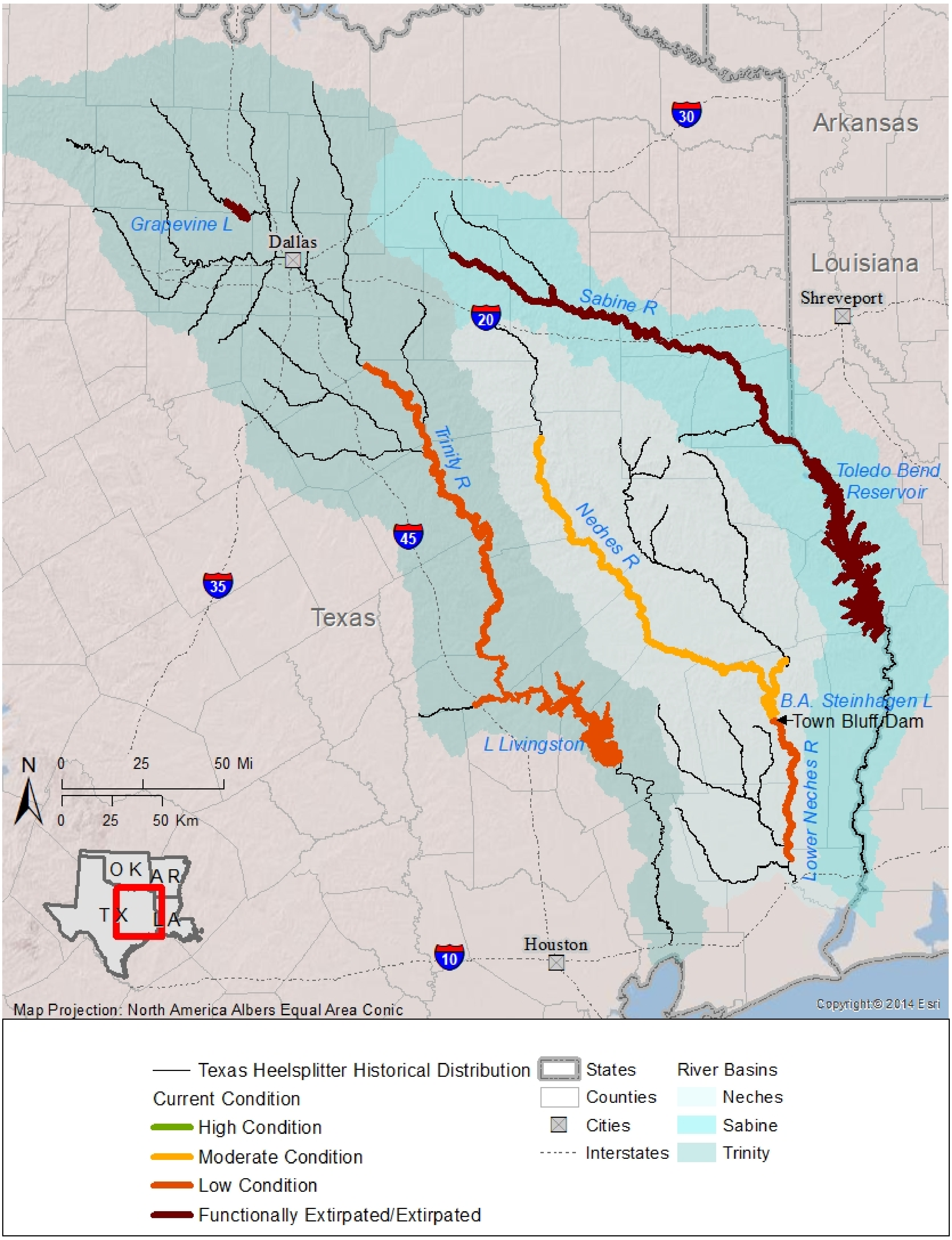
Table C.2.13: Scenario 2 – 50 year time step stressors evaluation model output

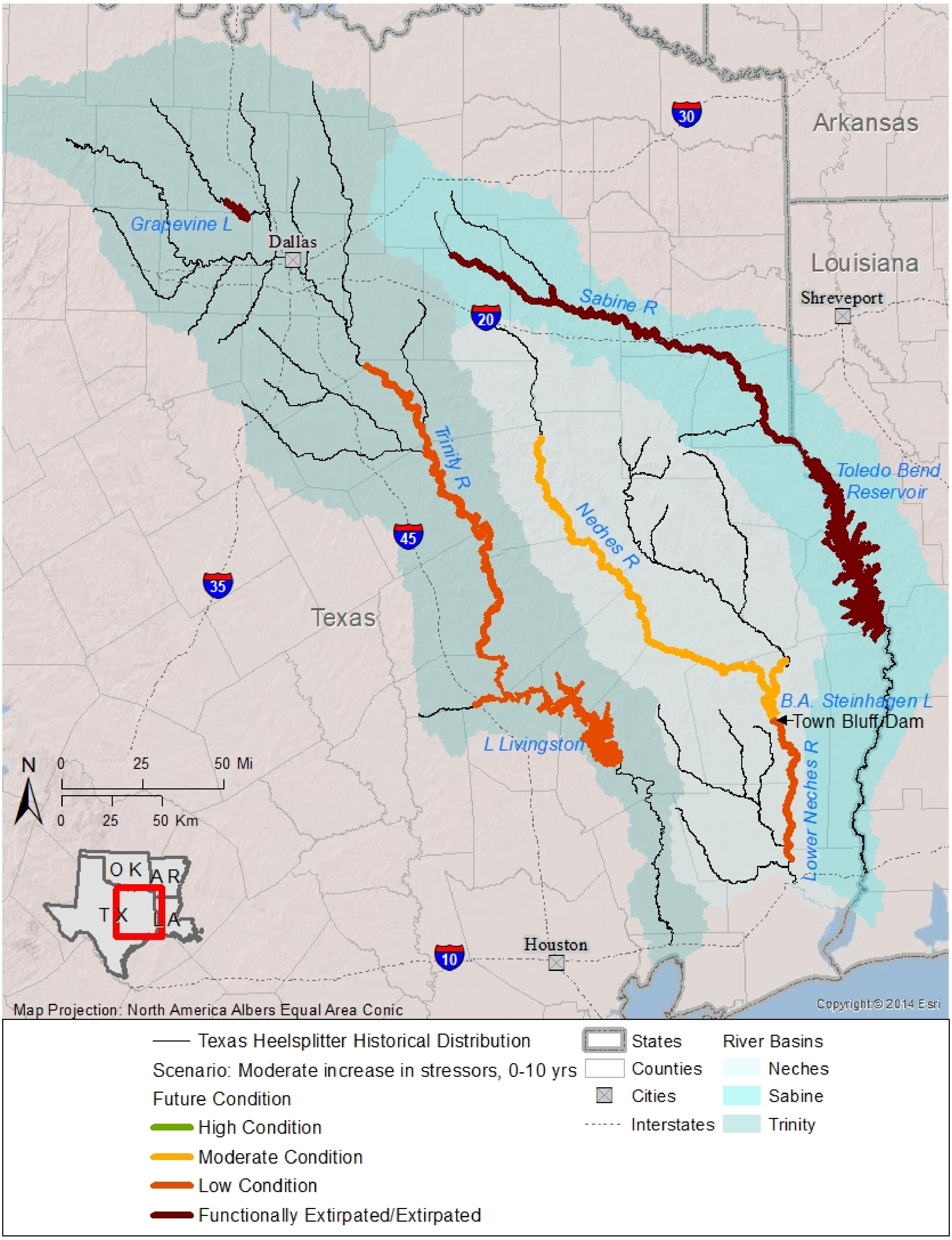
			Habitat Factors			Population Factors					
SPECIES	Representation Areas	POPULATIONS (Focal Area)	Water Quality	Hydrology	Habitat Structure/ Substrate	Host Fish Availability	Reproduction/ Recruitment	Survival	Occupied Habitat	Abundance	Change to Resiliency
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	-2	-2	-2	-6	-12	-7	-6	-25	-45
		LK Tawakoni	-1	-2	0	-3	-6	-5	-3	-14	-17
	Neches	Neches R/BA Steinhagen	-2	-2	-2	-6	-12	-7	-6	-25	-45
		Lower Neches R	-2	-2	0	-4	-8	-5	-4	-17	-45
	Trinity	LK Lewisville	-1	-2	0	-3	-6	-5	-3	-14	-17
		Grapevine LK	-1	-2	0	-3	-6	-5	-3	-14	-17
		Trinity R/Livingston	-2	-2	-1	-5	-10	-7	-5	-22	-45
Louisiana pigtoe	Red	Mountain Fork	-2	-2	0	-4	-8	-5	-4	-17	-45
		Little R/Rolling FK	-2	-2	-2	-6	-12	-7	-6	-25	-45
		Cossatot R	-2	-2	-1	-5	-10	-5	-5	-20	-45
		Saline R (Little)	-2	-2	-2	-6	-12	-6	-6	-24	-45
		Lower Little R	-2	-2	0	-4	-8	-4	-4	-16	-45
		Big Cypress Bayou	-2	-2	0	-4	-8	-5	-4	-17	-45
	Calcasieu	Upper Calcasieu R	-2	-2	-2	-6	-12	-6	-6	-24	-45
	Pearl	Pearl R	-1	-2	-2	-5	-10	-6	-5	-21	-26
	Sabine	Sabine R	-2	-2	-2	-6	-12	-7	-6	-25	-45
		Bayou Anacoco	-2	-2	-1	-5	-10	-5	-5	-20	-45
	Neches	Angelina R	-2	-2	-4	-8	-16	-9	-8	-33	-45
		Neches R	-2	-2	-2	-6	-12	-7	-6	-25	-45
		Lower Neches R	-2	-2	0	-4	-8	-4	-4	-16	-45
	San Jacinto	E FK San Jacinto R	-2	-2	-2	-6	-12	-8	-6	-26	-45

Table C.2.14: Future population condition for East Texas mussel resiliency

Future Scenarios				Scenario 1: Moderate Increase in Stessors - (RCP 4.5)			Scenario 2: Severe Increase in Stressors - (RCP 8.5)		
SPECIES	**Representation Areas**	**POPULATIONS (Focal Areas)**	**Current Condition**	10-yrs	25-yrs	50-yrs	10-yrs	25-yrs	50-yrs
Texas heelsplitter	Sabine	Sabine R/Toledo Bend	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated
	Neches	Neches R/BA Steinhagen	Moderate	Moderate	Low	Low	Moderate	Low	Extirpated
		Lower Neches R	Low	Low	Low	Extirpated	Low	Low	Extirpated
	Trinity	Grapevine LK	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated
		Trinity R/Livingston	low	Low	Low	Extirpated	Low	Low	Extirpated
Louisiana pigtoe	Red	Mountain FK	Low	Low	Low	Extirpated	Low	Low	Extirpated
		Little R/Rolling FK	Moderate	Moderate	Low	Low	Moderate	Low	Low
		Cossatot R	High	High	High	Moderate	High	High	Low
		Saline R (Little)	Low	Low	Low	Low	Low	Low	Low
		Lower Little R	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated
		Big Cypress Bayou	Moderate	Moderate	Moderate	Low	Moderate	Moderate	Low
	Calcasieu	Upper Calcasieu R	Low	Low	Low	Extirpated	Low	Low	Extirpated
	Pearl	Pearl R	Low	Low	Low	Low	Low	Low	Extirpated
	Sabine	Sabine R	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated	Extirpated
		Bayou Anacoco	Moderate	Low	Moderate	Low	Low	Moderate	Extirpated
	Neches	Angelina R	Low	Low	Low	Extirpated	Low	Low	Extirpated
		Neches R	High	High	Low	Low	High	Low	Low
		Lower Neches R	Low	Low	Low	Low	Low	Low	Low
	San Jacinto	E FK San Jacinto R	Low	Low	Low	Extirpated	Low	Extirpated	Extirpated

Figure C.1 Large-sized Current and Future Population Condition Maps for Texas Heelsplitter





Arkansas
Louisiana
Shreveport
Dallas
Grapevine L
Sabine R
Trinity R
Neches R
Toledo Bend Reservoir
Texas
B.A. Steinhagen L
Town Bluff Dam
L Livingston
Lower Neches R
Houston
30
20
45
35
10
N
0 25 50 Mi
0 25 50 Km
OK
AR
TX
LA
Map Projection: North America Albers Equal Area Conic
Copyright:© 2014 Esri
Texas Heelsplitter Historical Distribution
Scenario: Moderate increase in stressors, 0-10 yrs
Future Condition
High Condition
Moderate Condition
Low Condition
Functionally Extirpated/Extirpated
States
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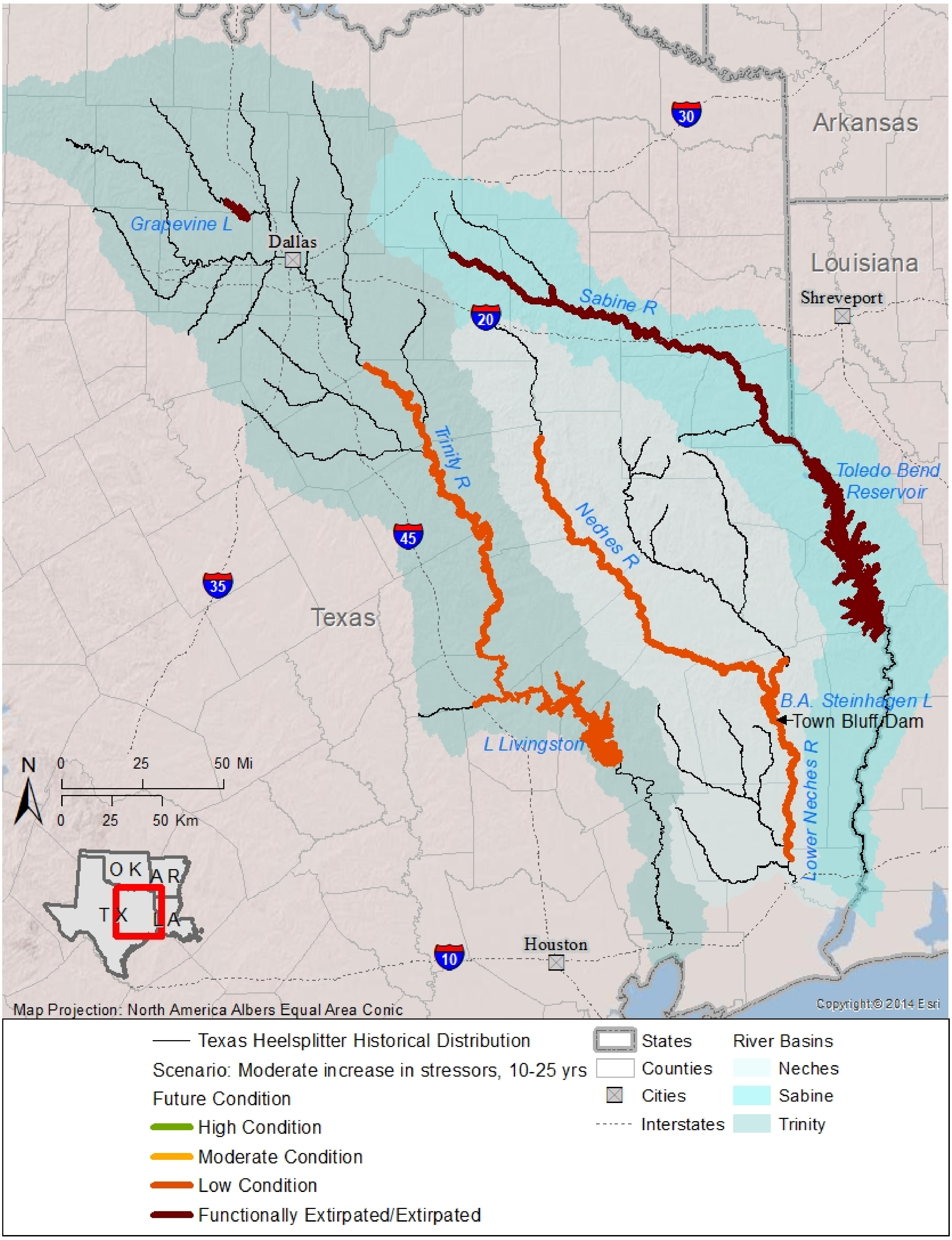
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Map Projection: North America Albers Equal Area Conic
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Texas Heelsplitter Historical Distribution
Scenario: Moderate increase in stressors, 10-25 yrs
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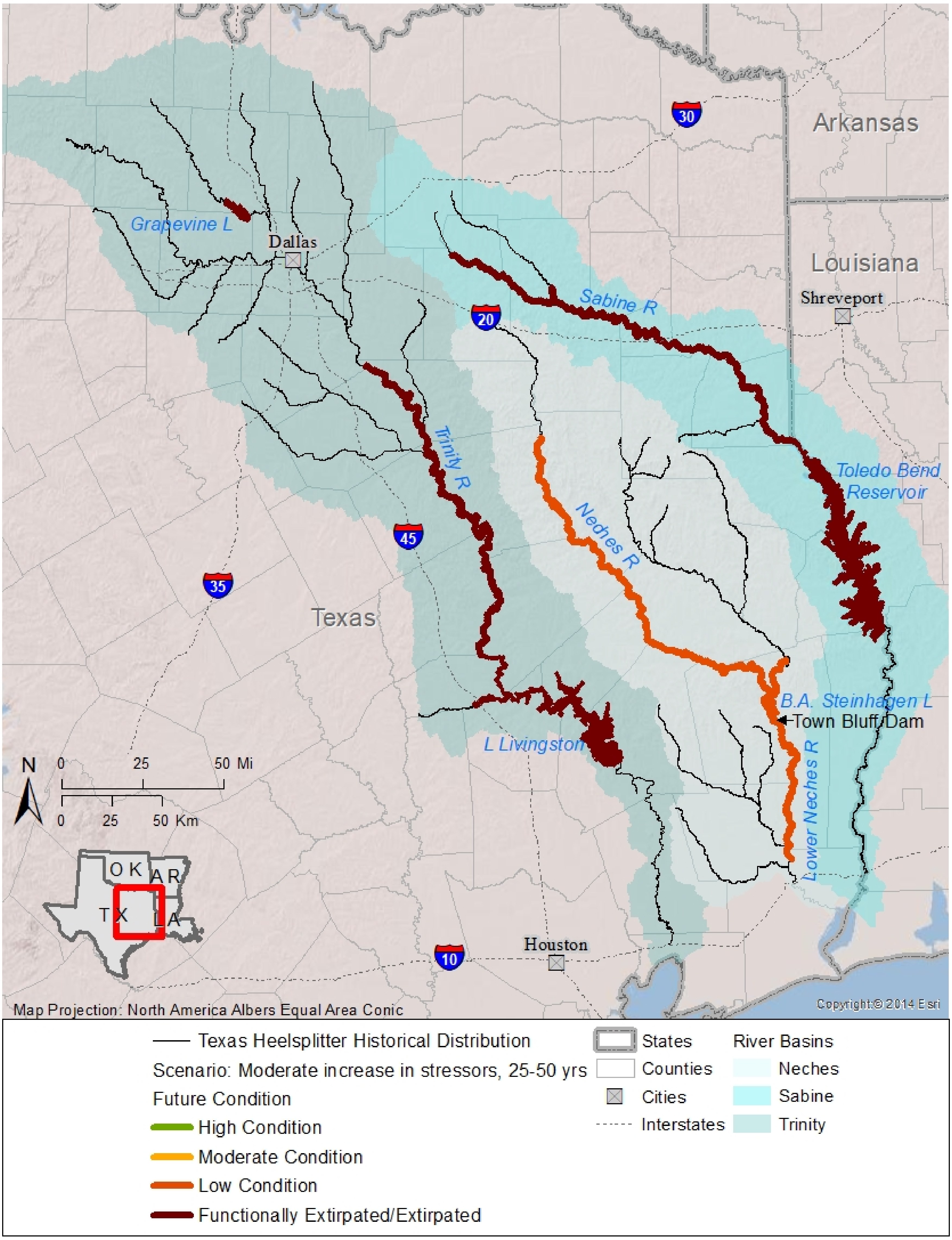

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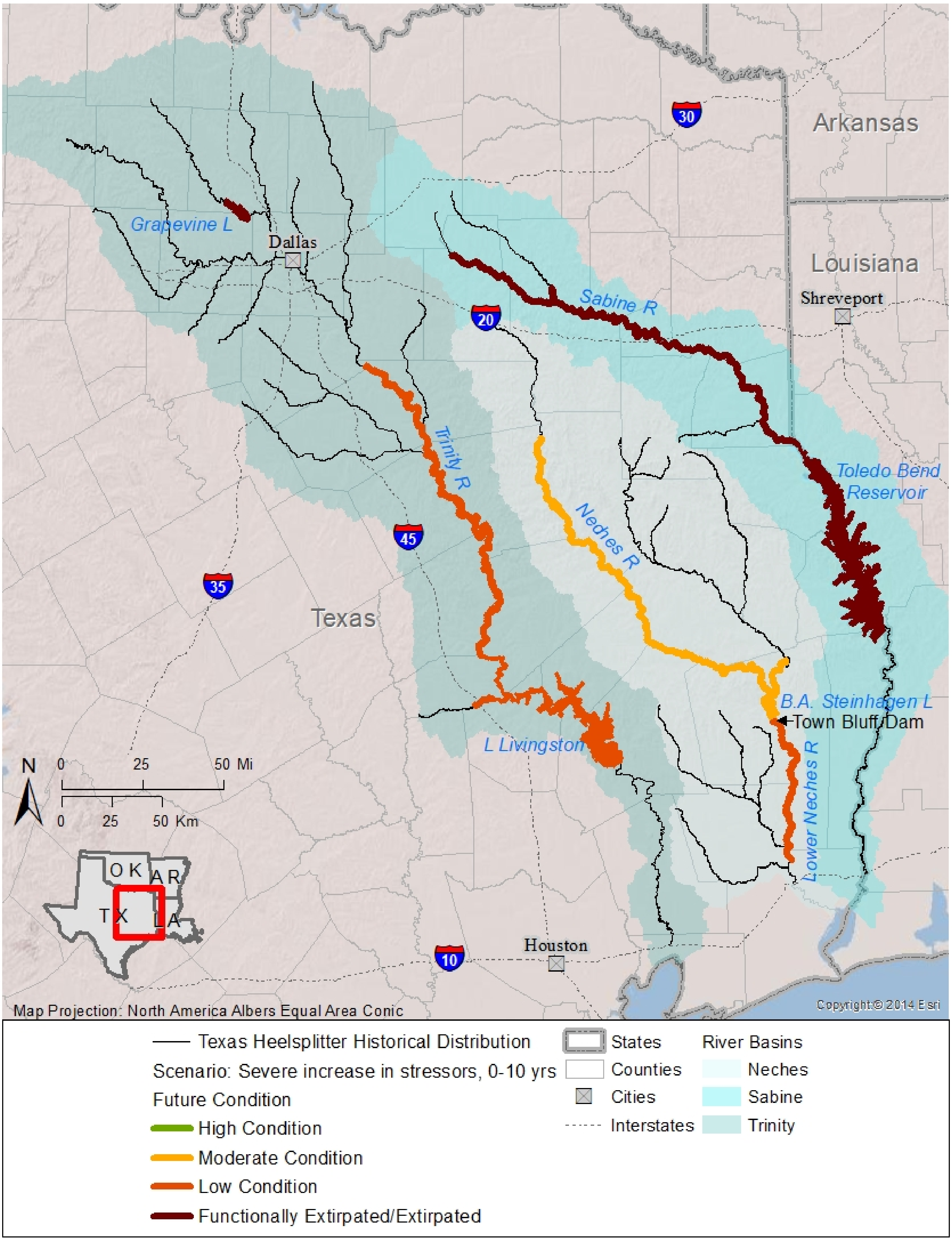
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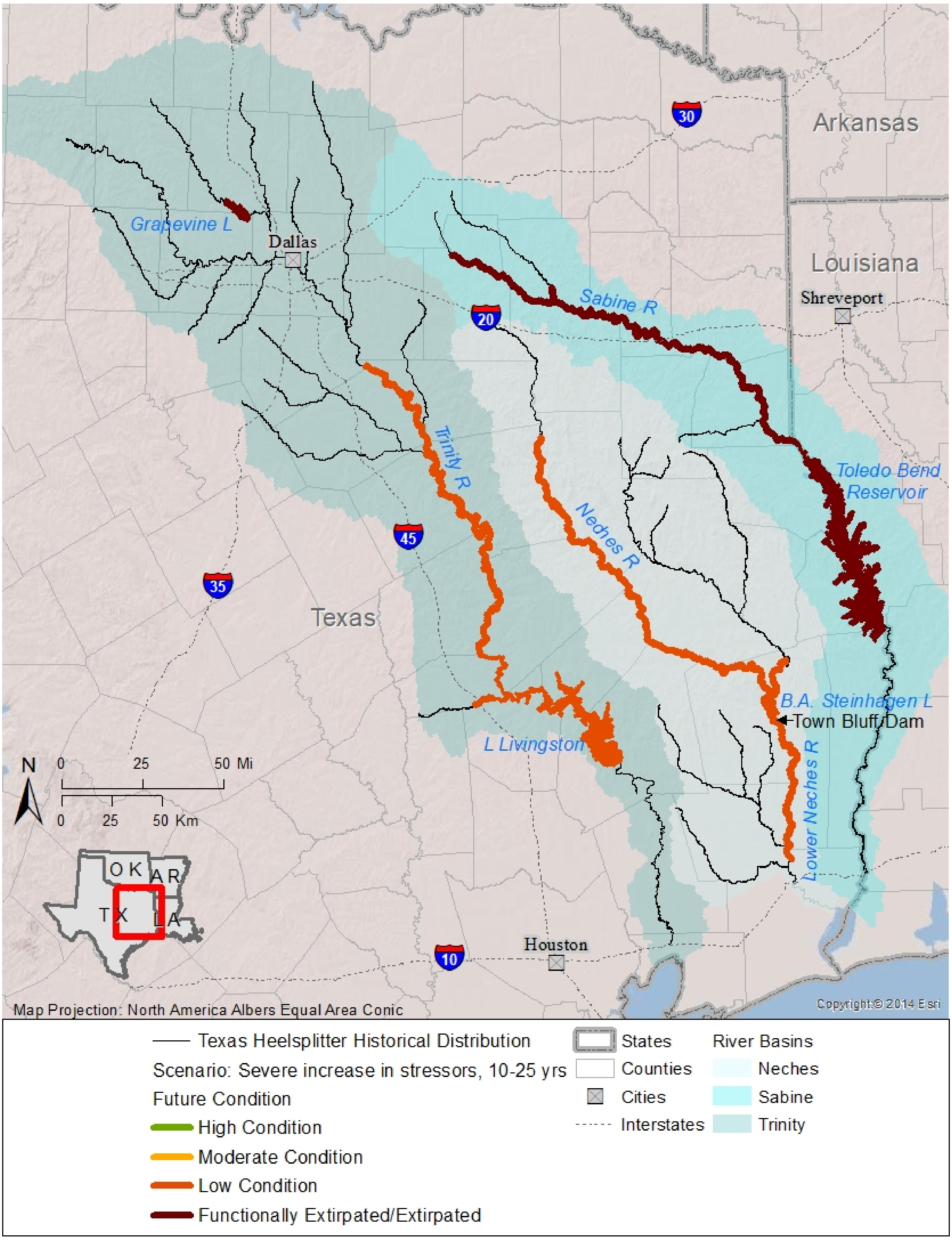

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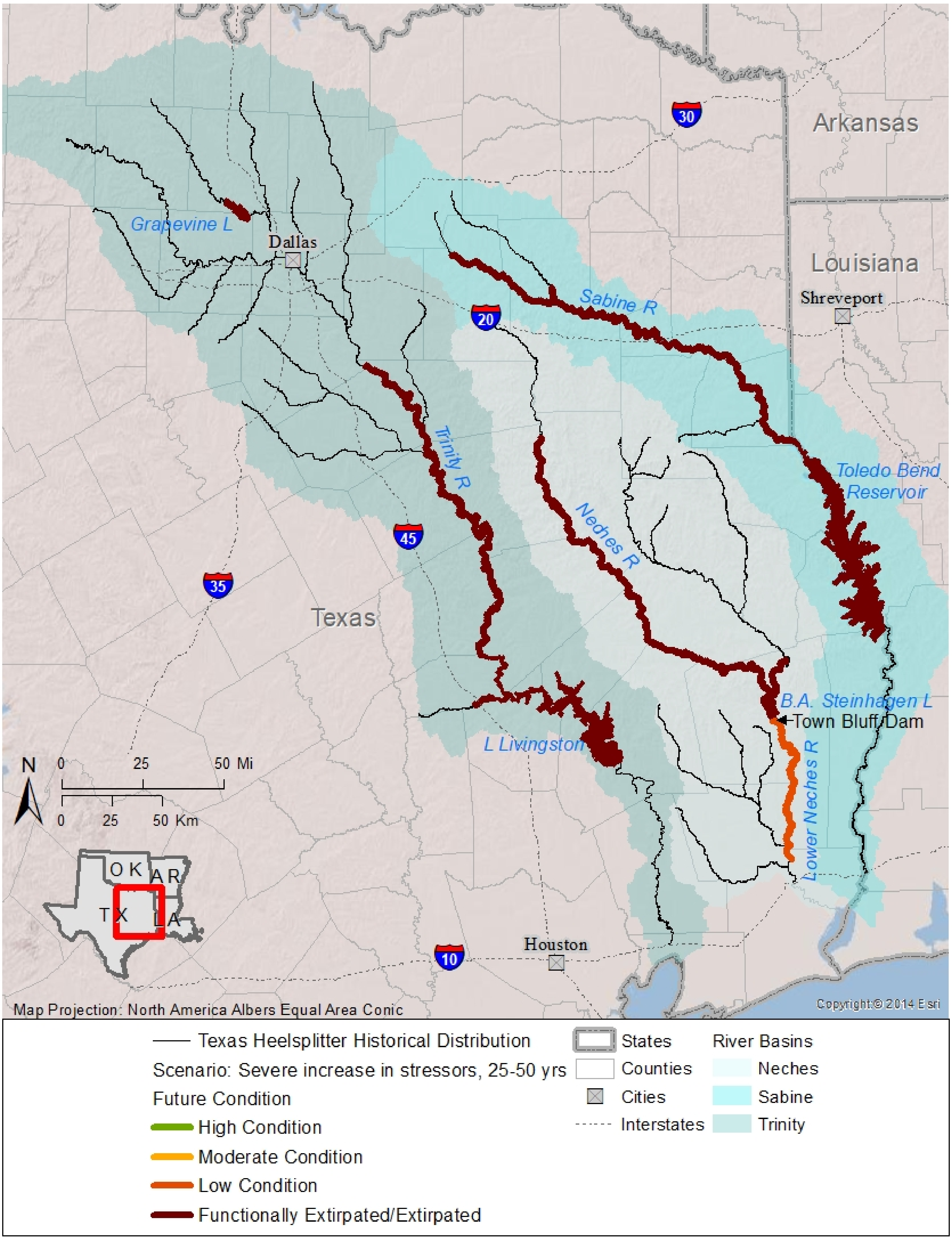
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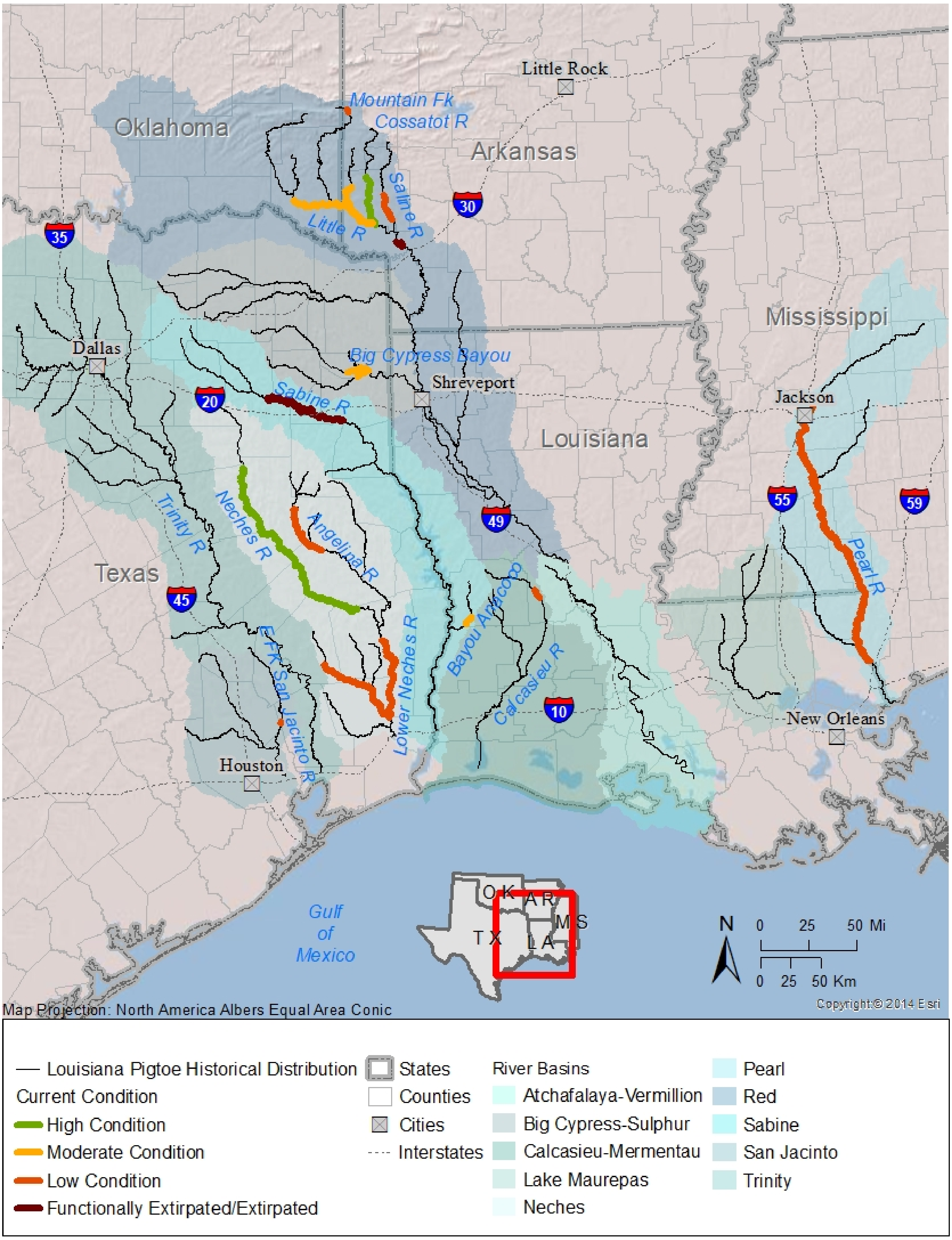
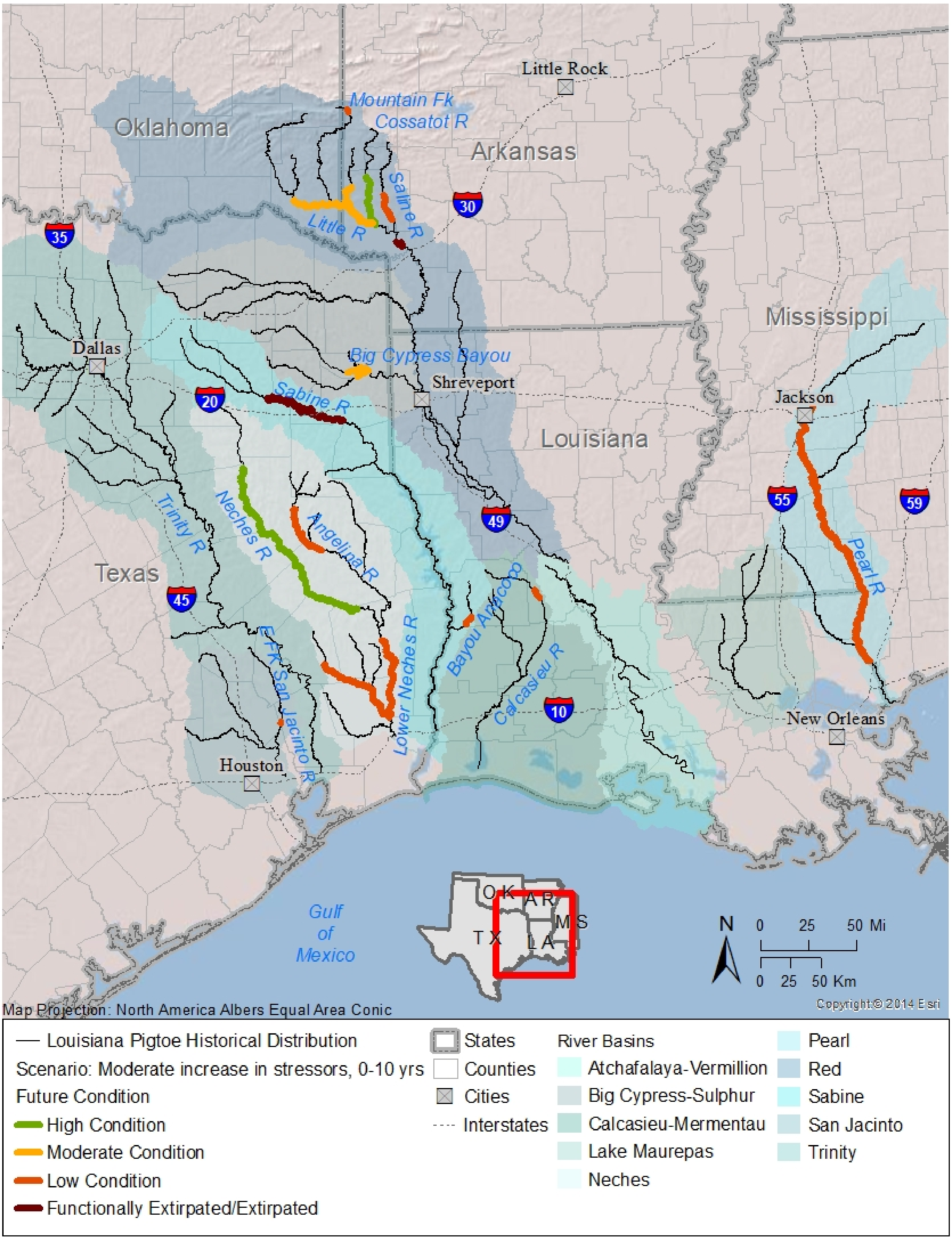
Figure C.2 Large-sized Current and Future Population Condition Maps for Louisiana Pigtoe





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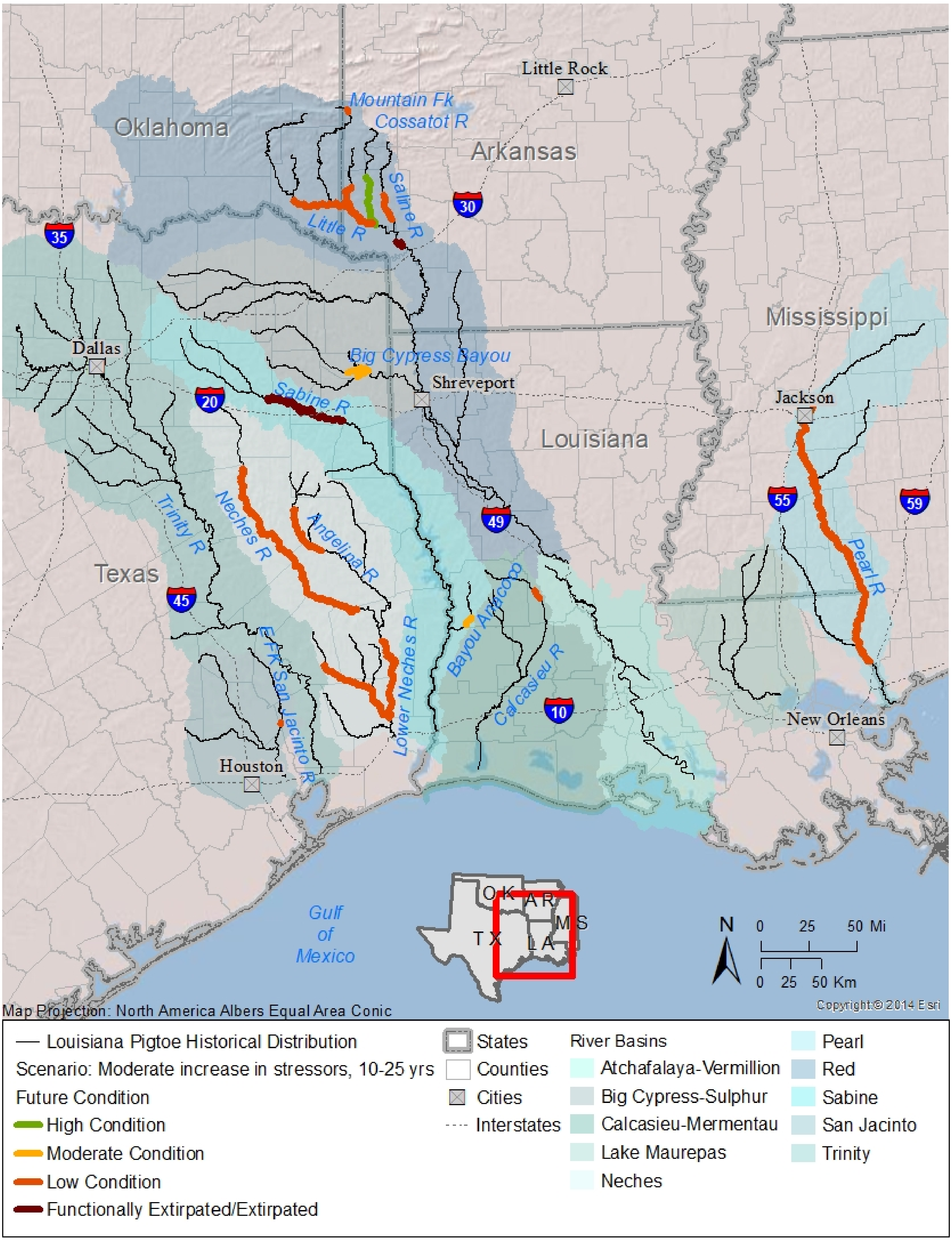

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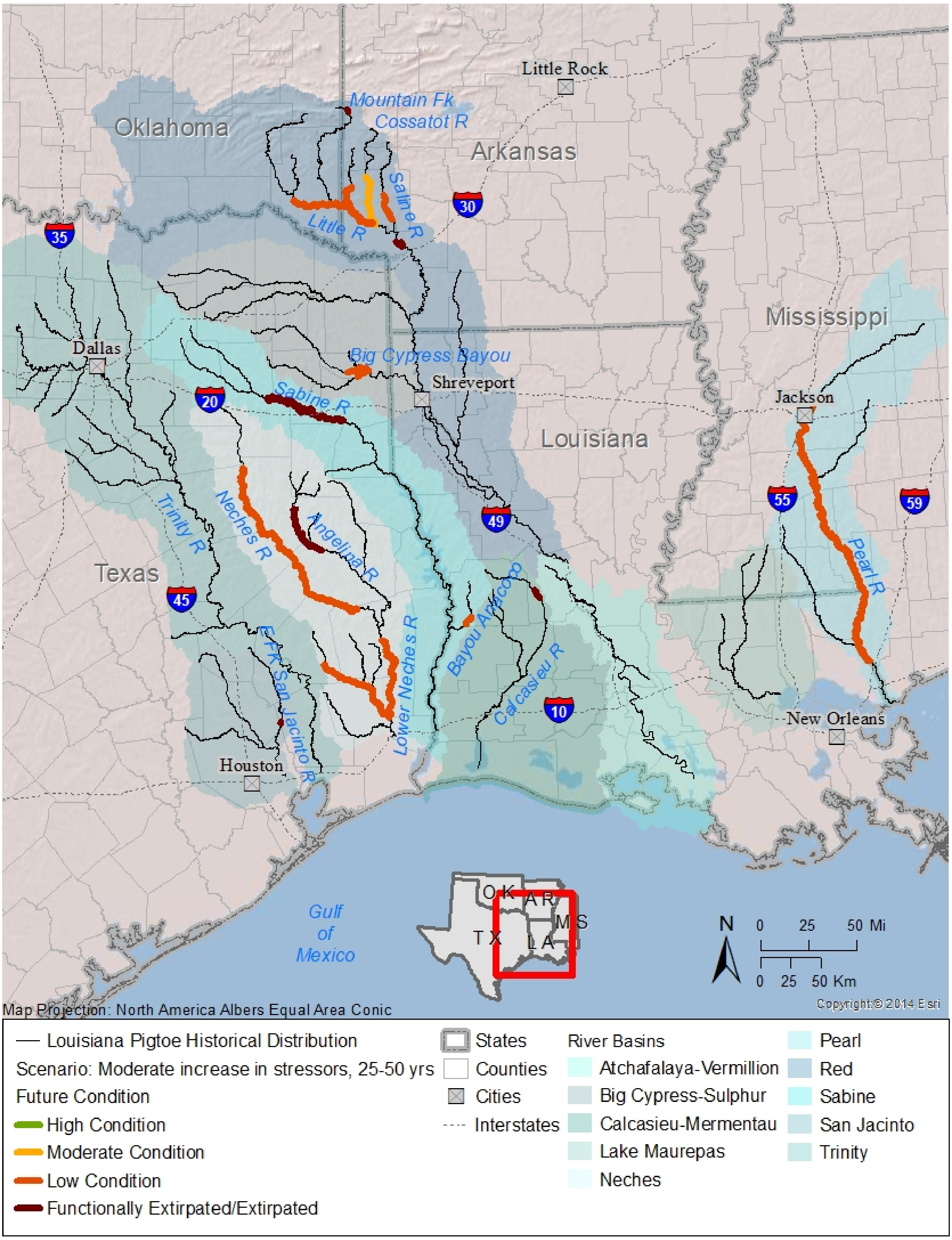
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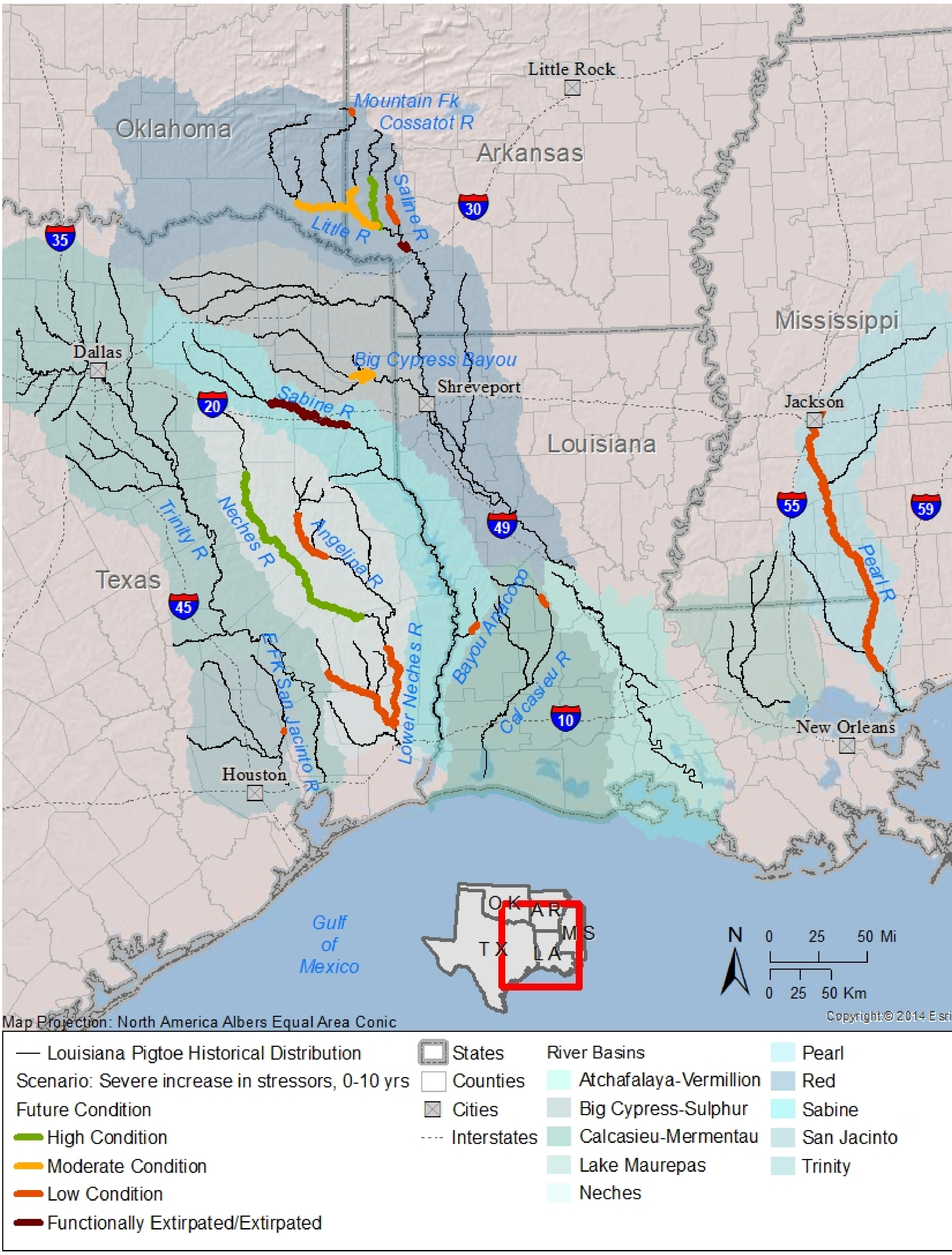

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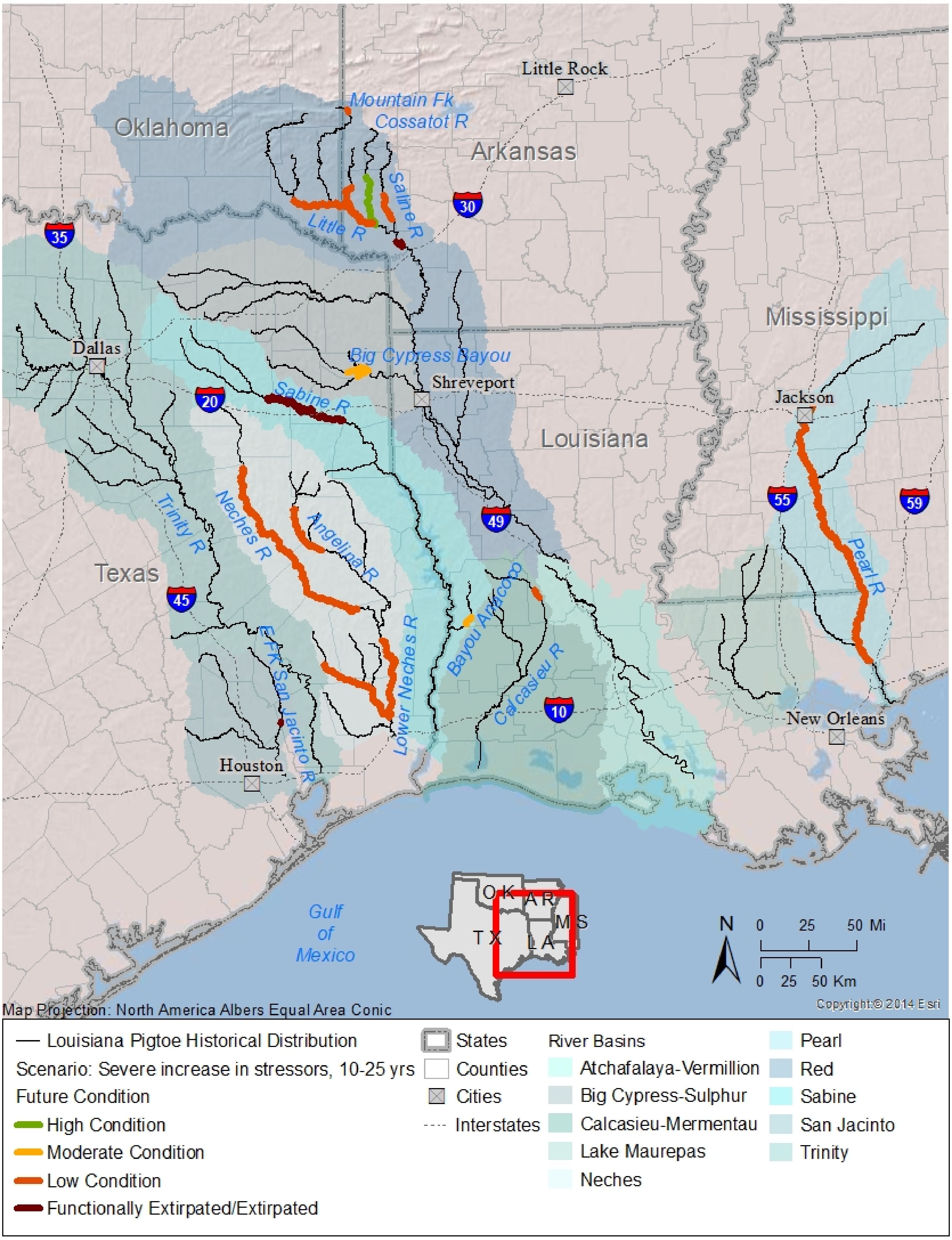
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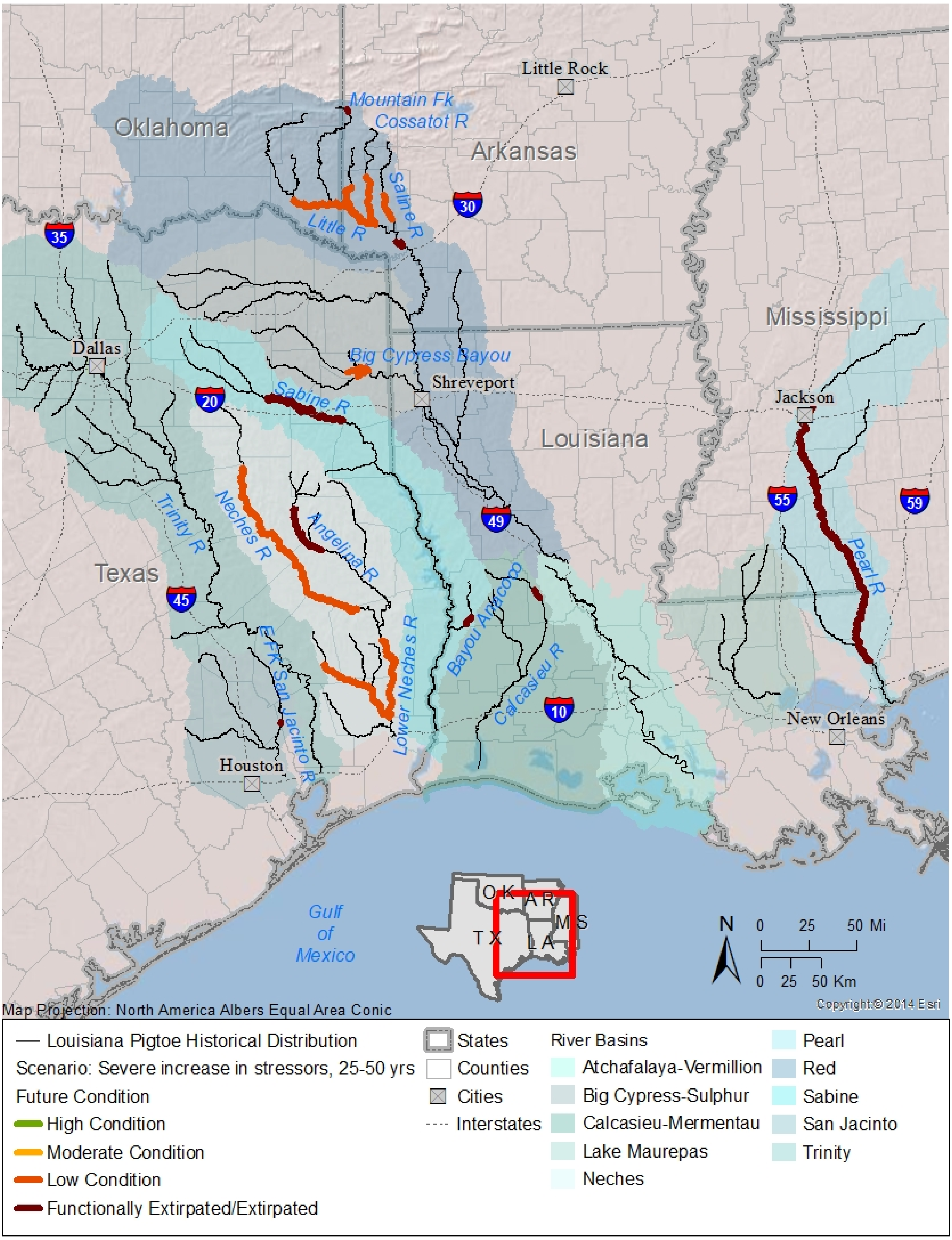

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Neches
Pearl
Red
Sabine
San Jacinto
Trinity

Appendix D: Descriptions for Select Indices of Hydrologic Alteration Evaluated (red boxes).

Group 2: Magnitude and duration of annual extreme flow conditions		
1-day minimum	Annual minimum 1-day mean discharge	ft^3/s
3-day minimum	Annual minimum 3-day mean discharge	ft^3/s
7-day minimum	Annual minimum 7-day mean discharge	ft^3/s
30-day minimum	Annual minimum 30-day mean discharge	ft^3/s
90-day minimum	Annual minimum 90-day mean discharge	ft^3/s
1-day maximum	Annual maximum 1-day mean discharge	ft^3/s
3-day maximum	Annual maximum 3-day mean discharge	ft^3/s
7-day maximum	Annual maximum 7-day mean discharge	ft^3/s
30-day maximum	Annual maximum 30-day mean discharge	ft^3/s
90-day maximum	Annual maximum 90-day mean discharge	ft^3/s
Number of zero days	Number of days having a discharge of zero for each year	Count
Base flow index	Minimum 7-day mean divided by mean annual flow for each year	ft^3/s
Group 3: Timing of annual minimum and maximum flow conditions		
Date of minimum	Julian date of each annual 1-day maximum	Julian date
Date of maximum	Julian date of each annual 1-day minimum	Julian date
Group 4: Frequency and duration of low- and high-flow pulses		
Low pulse count	Number of low-flow pulses within each year	Count
Low pulse duration	Duration of low-flow pulses within each year	Days
High pulse count	Number of high-flow pulses within each year	Count
High pulse duration	Duration of high-flow pulses within each year	Days
Parameter Group 5: Rate and frequency of change in flow		
Rise rate	Median of all positive differences between consecutive daily means	ft^3/s
Fall rate	Median of all negative differences between consecutive daily means	ft^3/s
Number of reversals	Median number of times in which flow switched from a rising period to a falling period or from a falling period to a rising period	Count