U.S. Department of the Interior – Fish and Wildlife Service
South Atlantic-Gulf & Mississippi Basin Unified Regions

Species Status Assessment Report for Western Fanshell (*Cyprogenia aberti*) and "Ouachita" Fanshell (*Cyprogenia* cf. *aberti*)

Version 1.1

Photo credit: Ed Miller

December 2020

This document was prepared by U.S. Fish and Wildlife Service biologists Chris Davidson (Arkansas Field Office), Josh Hundley (Missouri Field Office), and David Martinez (Oklahoma Field Office) with assistance from Steve Choy and Barbara Hosler (Great Lakes Regional Office) and Brian Evans (South Atlantic-Gulf & Mississippi Basin Unified Regional Office) and individuals from state agencies, including Kendall Moles (Arkansas Game and Fish Commission), Steve McMurray (Missouri Department of Conservation), Matt Fullerton (Oklahoma Department of Wildlife Conservation), and Ed Miller (Kansas Department of Wildlife, Parks, and Tourism).

The following individuals provided valuable peer review: Teresa Newton (USGS) and Adam Terando (USGS) with additional review from Steve McMurray (MDC) and Nathan Eckert (USFWS). We appreciate the time and advice of the individuals above, as well as the researchers listed in the Literature Cited section.

Suggested reference:

U.S. Fish and Wildlife Service. 2020. Species status assessment report for Western Fanshell (*Cyprogenia aberti*) and “Ouachita” Fanshell (*Cyprogenia* cf. *aberti*). December 2020 (Version 1.1). Columbia, Missouri.

Executive Summary

This species status assessment (SSA) reports the results of the comprehensive status review for two freshwater mussels, Western Fanshell (*Cyprogenia aberti* (Conrad 1850)) and "Ouachita" Fanshell (*Cyprogenia* cf. *aberti*), collectively Fanshell mussels, documenting the species' historical condition and providing estimates of current and future conditions. The Western Fanshell has a historical range comprising multiple rivers within the Neosho-Verdigris, lower Arkansas, Lower Mississippi–St. Francis, and upper White river drainages of Arkansas, Missouri, Kansas, and Oklahoma. There are reported records from archeological sites within four river basins in Mississippi. Mississippi recognizes Western Fanshell and ranks it as presumed extirpated, but because of the genetic uncertainties of *Cyprogenia* and the lack of live individuals, we do not include these records within the Western Fanshell historical range for this SSA report. The historical range of "Ouachita" Fanshell comprises multiple rivers within the Ouachita River basin in southern Arkansas and northern Louisiana.

Western Fanshell currently occupies 11 of 26 historical management units, and "Ouachita" Fanshell occupies four of five historical management units. Forty-five percent of the Western Fanshell management units (MUs) are currently in low condition (i.e., are predominantly composed of populations that are small with no evidence of recruitment or age class structure). Fifty percent of "Ouachita" Fanshell MUs are in low condition. The Western Fanshell and "Ouachita" Fanshell also have suffered a 60% and 47% reduction in stream length occupation, respectively.

Our analysis of the past, current, and future variables that influence the Fanshell mussels' needs for long-term viability (likelihood of persistence) revealed that there are four factors that pose the largest risk to future viability: water quality degradation, altered flow, landscape changes, and habitat fragmentation, all of which are exacerbated by climate change. All the factors affecting viability carry forward in Chapter 6 where we assess the future condition of Fanshell mussel populations and the viability of each species as the influence of each factor changes in the foreseeable future.

The Fanshell mussels face a variety of risks from water quality degradation, altered flow, landscape changes, and habitat fragmentation. These risks play a large role in the future viability of the Fanshell mussels. If populations lose resiliency, they are more vulnerable to extirpation, with resulting losses in representation and redundancy.

In projecting the future viability of the Fanshell mussels, two scenarios were considered: (1) current conditions moderately decline over 40 years into the future; and (2) negative influences increase severely over 40 years. Historical, current, and future population projections are summarized below in Table ES-1. Our analysis articulates the ability of the species to withstand catastrophic events (through redundancy), its adaptive potential across the six river basins where it is extant (representation/diversity), and the capability of populations to withstand stochastic disturbance (resiliency).

Table ES-1 Fanshell mussels current population conditions and population conditions in 40 years under two scenarios.

HUC4	Management Unit	Current Condition	Scenario 1 – Moderate Effects	Scenario 2 – Severe Effects
Western Fanshell				
Neosho–Verdigris	Fall	Medium	Medium	Low
	Middle Verdigris	High	Medium	Low
	Spring	Low	Likely Extirpated	Likely Extirpated
Upper White	Black	High	Medium	Low
	Buffalo	Low	Likely Extirpated	Likely Extirpated
	Little Red	Medium	Low	Low
	Middle White	Low	Likely Extirpated	Likely Extirpated
	Strawberry	Low	Likely Extirpated	Likely Extirpated
	Spring	Medium	Low	Low
Lower Mississippi–St. Francis	Lower St. Francis	Low	Likely Extirpated	Likely Extirpated
	Upper St. Francis	High	Medium	Low
“Ouachita” Fanshell				
Lower Red–Ouachita	Caddo	Low	Likely Extirpated	Likely Extirpated
	Ouachita Headwaters	Low	Likely Extirpated	Likely Extirpated
	Saline	High	Medium	Low
	Upper Ouachita	Medium	Low	Low

Under Scenario 1, the moderate decline in condition option, we predicted a decline of resiliency, representation, and redundancy is expected over time. Under this scenario, we predicted that no MUs would remain in high condition, four Western Fanshell and one “Ouachita” Fanshell MUs would exist in moderate condition, two Western Fanshell and one “Ouachita” Fanshell MUs would exist in low condition, and the remaining MUs would be likely extirpated. Redundancy would be reduced with likely extirpation in five of eleven currently extant Western Fanshell MUs and two of four currently extant “Ouachita” Fanshell MUs. Representation would be reduced with the lost MUs, but neither species loses any full areas of representation (HUC4 river basins).

Under Scenario 2, the severe decline in condition option, we predicted substantial decline of resiliency, representation, and redundancy. Redundancy would be reduced to six Western Fanshell MUs (i.e., likely extirpation of five MUs) and two “Ouachita” Fanshell MUs (i.e., likely extirpation of two MUs) and the resiliency of those populations is expected to be low. Representation would be reduced with the lost MUs, but neither species loses any full areas of representation.

Table of Contents

Executive Summary ii

Chapter 1 – Introduction 6

1.1 Background 6

1.2 Analytical Framework 6

1.3 Methodology 7

Chapter 2 – Individual Needs: Life History and Biology 9

2.1 Taxonomy 9

2.2 Description 10

2.3 Reproduction 10

2.4 Diet 12

2.5 Habitat 12

2.6 Individual Resource Needs 12

Chapter 3 –Population and Species Needs 16

3.1 Population Resiliency 16

3.1.A Demographic Factors 17

3.1.B Habitat Factors 18

3.2 Species Representation 19

3.3 Species Redundancy 20

Chapter 4 – Current Condition of Western Fanshell and “Ouachita” Fanshell 21

4.1 Historical Range and Current Distribution 21

4.1.A Western Fanshell 21

4.1.B “Ouachita” Fanshell 29

4.2 Methodology for Population Resiliency Assessment 31

4.2.A Population Factors 31

4.2.B Habitat Factors 33

4.3 Current Condition 36

4.3.A Western Fanshell Current Condition 36

4.3.B “Ouachita” Fanshell Current Condition 46

Chapter 5 – Factors Influencing Viability 51

5.1 Water Quality 51

5.2 Flow 56

5.3 Landscape Changes 57

5.4 Habitat Fragmentation 59
5.5 Climate Change 60
5.6 Invasive Species 62
5.7 Summary 63
Chapter 6 – Species Projected Viability in the Future 64
6.1 Future Scenarios Methodology and Considerations 64
6.1.A Future Scenario 1 – Moderate Decline in Conditions 67
6.1.B Future Scenario 2 – Severe Decline in Conditions 67
6.2 Future Viability (Resiliency, Redundancy, and Representation) 69
6.2.A Future Scenario 1 – Moderate Increase in Stressors 69
6.2.B Future Scenario 2 – Severe Increase in Stressors 70
6.3 Status Assessment Summary 71
Literature Cited 76
Appendices I – V 99

Chapter 1 – Introduction

1.1 Background

This report summarizes the results of a species status assessment (SSA) conducted for two freshwater mussels, Western Fanshell (*Cyprogenia aberti*) and “Ouachita” Fanshell (*Cyprogenia* cf. *aberti*). The Center for Biological Diversity, Alabama River Alliance, Clinch Coalition, Dogwood Alliance, Gulf Restoration Network, Tennessee Forests Council, and West Virginia Highlands Conservancy petitioned the U.S. Fish and Wildlife Service to list 404 aquatic, riparian, and wetland species, including the Western Fanshell, as endangered or threatened under the Endangered Species Act of 1973, as amended (Act) on April 20, 2010. In September 2011, we found the petition presented substantial scientific or commercial information that indicated listing 374 species, including Western Fanshell, may be warranted (76 FR 59836). The “Ouachita” Fanshell is currently an undescribed species, now recognized by species and taxonomic experts as distinct from Western Fanshell (Williams *et al*. 2017, p. 47). This SSA Report will refer to the species collectively as “Fanshell mussels” and individually by common name and by scientific name (i.e., genus and specific epithet), where appropriate.

Both species are freshwater mussels in the Family Unionidae. Western Fanshell (*Cyprogenia aberti*) occurs in portions of three major river basins (Lower Mississippi-St. Francis, Neosho-Verdigris, and upper White) in Arkansas, Kansas, Missouri and Oklahoma; and “Ouachita” Fanshell (*Cyprogenia* cf. *aberti*) occurs in one major river basin (lower Red-Ouachita) in Arkansas and Louisiana (Figure 1.1). For this assessment, we used information about the species’ historical ranges to partition Fanshell Mussels into these four geographical units (river basins).

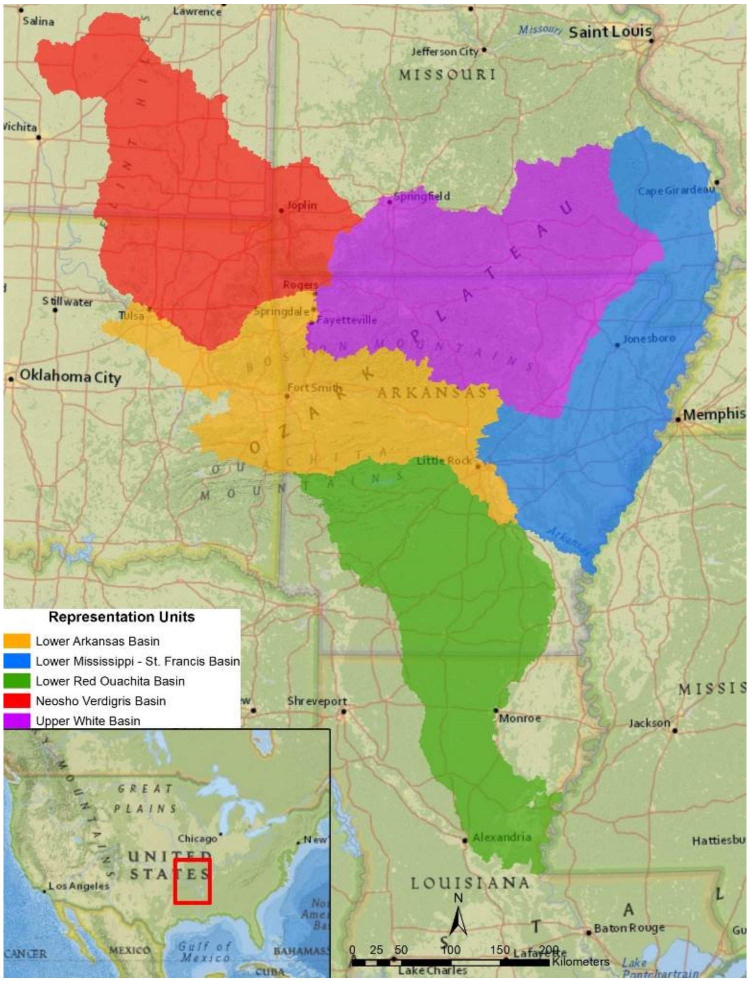


Figure 1.1 Western and “Ouachita” Fanshell major river basin range map.

1.2 Analytical Framework

The SSA framework (Service 2016a, entire) is a concise review of the species’ biology, an evaluation of its biological status and threats to survival, and an assessment of resources and conditions needed to maintain long-term viability. The intent is for the SSA Report to become a living document easily updated as new information becomes available and to support all functions of the Endangered Species Program, such as listing, recovery, section 7 consultation, section 10 permits, and reclassification decisions.

This SSA report is intended to provide the biological support for the decision on whether these two freshwater mussel species warrant listing under the Act and, if so, to determine whether to propose designating critical habitat. Importantly, the SSA Report is not a decisional document; rather it provides a review of available information strictly related to the species biological status. The Service will make a listing decision after reviewing this document and all relevant laws, regulations, and policies. If a decision is made that listing is warranted, then the Service will announce that proposed decision in the *Federal Register*, with appropriate opportunity for public input.

For the purpose of this assessment, we generally define viability as the ability of Fanshell mussels to sustain populations in natural river systems over time. Using the SSA framework (Figure 1.2), we consider what the species needs to maintain viability by characterizing the species status in terms of its resiliency, redundancy, and representation (i.e., the 3Rs; Shaffer *et al.* 2002, pp. 139-140; Shaffer and Stein 2000, pp. 308-311; Smith *et al*. 2018, entire; Wolf *et al.* 2015, entire). The 3Rs are defined as:

Resiliency reflects a species' ability to withstand disturbance. Demographic measures that reflect the health of each population, such as fecundity (birth rate), survival, and population size, are some 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 effects of anthropogenic activities.

Redundancy reflects a species' ability to withstand catastrophic events (destructive events or episodes involving many populations). Redundancy is about spreading the risk of such an event across multiple, resilient populations. As such, the number and distribution of resilient populations across the species range is a measure of redundancy.

Representation is an indicator of the species' ability to adapt to changing environmental conditions over time. Representation is a measure of the breadth of genetic or ecological diversity within and among populations across the species' range. Generally, 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.

1.3 Methodology

To evaluate the biological status of the Fanshell 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 related to the status of these species, including biology and natural history, demographic risks, stressors, and limiting factors in the context of determining their viability and extinction risk, as well as estimates/projections of how these variables are likely to change in the future.

The format for this SSA Report includes a description of the individual's resource needs (Chapter 2); current and historical species distribution, and factors affecting population resiliency, redundancy, and representation, including estimates of current condition (Chapter 3 – 4); risk factors affecting species viability (Chapter 5); and projections 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 (threats) to the Fanshell mussels.

Chapter 2 – Individual Needs: Life History and Biology

This chapter reviews biological and ecological information about the Fanshell 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 their viability now and in the future. We then outline the resource needs at the individual level. Basic information is included about freshwater mussels in general, and characteristics that are unique to the Fanshell mussels specifically when available or known.

2.1 Taxonomy

Cyprogenia aberti (Conrad, 1850) Western Fanshell

Synonymy:

Unio aberti Conrad, 1850 (Conrad 1850, p. 10)

Unio lamarckianus Lea, 1852 (Lea 1852, p. 266)

Margaron (*Unio*) *lamarckianus* Lea, 1852 (Lea 1852, p. 23)

Margaron (*Unio*) *aberti* (Conrad, 1850) (Lea 1870, p. 34)

Cyprogenia aberti (Conrad, 1850) (Simpson 1900, p. 610)

Unio popenoi Call, 1885 (Call 1885, p. 48)

Conrad lists the type locality as "Chambers' Ford rapids of Verdigris River, Arkansas", which is incorrect. Chambers' Ford is located in Oklahoma.

Recent molecular analysis of *Cyprogenia* identified three independent evolutionary lineages, *C. aberti* in the White, St. Francis, Verdigris, and Neosho river basins (Arkansas, Kansas, Missouri, Oklahoma) and *C.* cf. *aberti* ("Ouachita" Fanshell) from the Ouachita River basin (Arkansas, Louisiana) (Chong *et al*. 2016, pp. 2445 – 2449; Grobler *et al*. 2011, p. 203; Serb 2006, pp. 428 – 432; Serb and Barnhart 2008, pp. 257 – 259). Confusion regarding the type locality of *Unio lamarckianus* requires resolution to determine whether the name is available for the Ouachita River drainage, but Williams *et al*. (2017, p. 47) recognized the distinctiveness of this species. A third lineage, *C. stegaria*, occurs in the Ohio River basin. Sub-fossil shells of *Cyprogenia* also exist from Mississippi, but information pertaining to proper classification is lacking. This report follows the most recently published and accepted taxonomic treatment of North American freshwater mussels (Williams *et al*. 2017, entire).

PHYLUM	Mollusca Linnaeus, 1758
CLASS	Bivalvia Linnaeus, 1758
ORDER	Unionida Gray, 1854
FAMILY	Unionidae Rafinesque, 1820
SUBFAMILY	Ambleminae Rafinesque, 1820
TRIBE	Lampsilini Ihering, 1901

2.2 Description

The lifespan for the Fanshell mussels is unknown, but Jones and Neves (2002, p.81) aged 84 *Cyprogenia stegaria* individuals with a range of 6 to 26 years and a mean age at death of 12-13 years. Fanshell mussels have a thick, compressed to moderately inflated, round to triangular shell (up to 3 inches (76 millimeters)). The posterior ridge is prominent and raised with a shallow sulcus from umbo to middle of the ventral margin. Periostracum is a dull tan with a distinctive ray pattern from bands of tiny pigment flecks. The shell has a wrinkled or rough appearance. The pseudocardinal teeth are large and lateral teeth short and slightly curved. The beak cavity is moderately deep with somewhat pointed beaks extending slightly above the hinge line. The nacre is white (Conrad 1850, p. 10; McMurray *et al.* 2012, p. 30; Oesch 1995, pp. 143 – 144; Roe 2004, pp. 4 – 5;). Chamberlain (1934, entire) provides the first description of the brightly colored worm-like conglutinates--specialized mucilaginous packets of glochidia (larvae) and unfertilized eggs--of Western Fanshell from the St. Francis River in Arkansas, also further described by Barnhart (1997, entire) and Eckert (2003, pp. 28 – 29; Figure 2.2). Eckert (2003, p. 61) reports mean glochidia length/height ratio of 1.37 ± 0.05 (Arkansas River basin), 1.32 ± 0.04 (St. Francis River basin), and 1.33 ± 0.03 (Ouachita River basin).

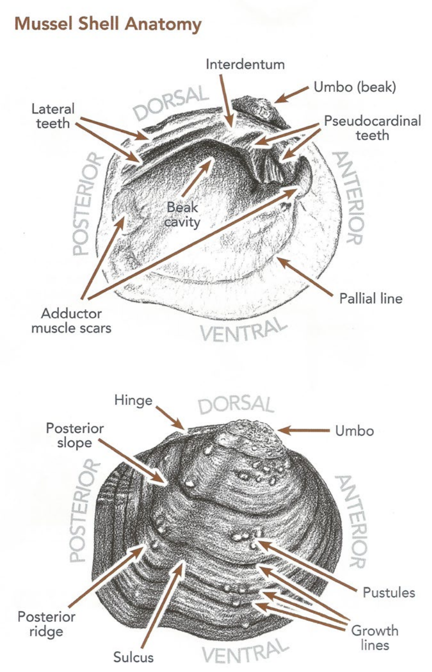


Figure 1.1 Generalized mussel shell anatomy (McMurray *et al.* 2012, p. 12).

2.3 Reproduction

As with most freshwater mussels, the Fanshell mussels have a unique life cycle that relies on fish hosts for successful reproduction (Figure 2.3). Freshwater mussels are generally immobile. They disperse 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 females take in through the incurrent siphon (the tubular structure used to draw water into the body of the mussel). The sperm

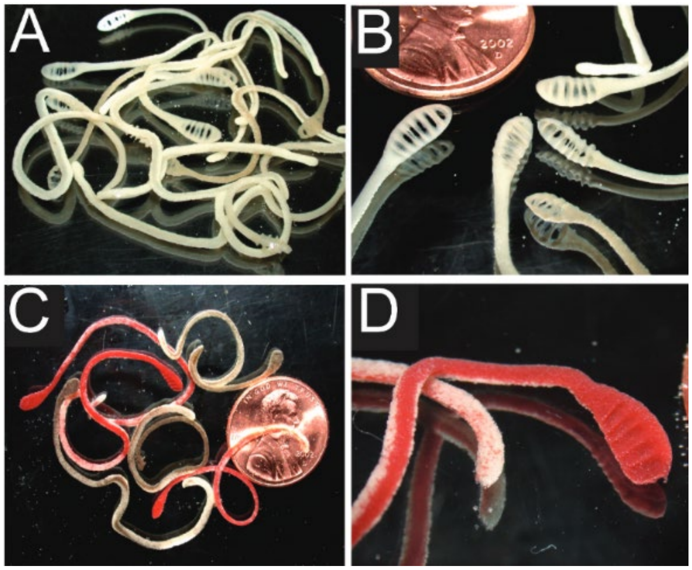


Figure 2.2 Variation in conglutinate morphology. A – B. White conglutinates produced by females in the Arkansas River basin, Kansas. C – D. Red and brown conglutinates produced by females in the St. Francis and Ouachita River basins (Serb and Barnhart 2008, p. 251; Eckert 2003, pp. 67 – 68).

fertilizes the eggs, which the female holds until 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 (Barnhart *et al.* 2008, pp. 371 – 373; Vaughn and Taylor 1999, p. 913). 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 (Bogan 1993, p. 599; Neves 1991, p. 254). 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 for the Fanshell mussels remain encysted for about a month until transformation to the juvenile stage (Figure 2.4; Barnhart 1997, p. 12). Once transformed, the juveniles 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 remain 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.

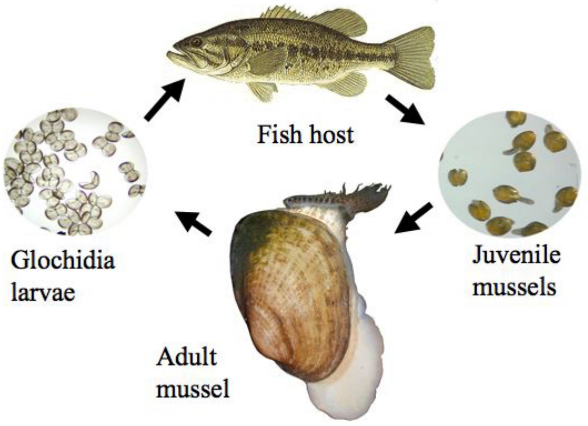


Figure 2.3 Generic illustration of the freshwater mussel reproductive cycle (FMCS 2015)

Jones and Neves (2002, p. 81) report sexual maturity for *Cyprogenia stegaria* from ages 5 to 9 and Haag (2012, Appendix A) suggests that *Cyprogenia stegaria* do not reach sexual maturity until age 7. However, the exact age of sexual maturity for the Fanshell mussels is unknown. The Fanshell mussels are bradytictic (long-term) brooders typically spawning from August – October and release conglutinates in early spring (Barnhart 1997, p. 13; N. Eckert 2020, pers. comm.). Fanshell mussel conglutinates resemble annelid worms, and this resemblance attracts fish hosts (Eckert and Barnhart 2008, p. 12). Females typically release 12 – 33 conglutinates with a mean number of eggs per conglutinate of 23,056 (Barnhart 1997, p. 10; Eckert 2003, p. 62). Barnhart (1997, p. 10) reports mean fecundity as 93,923 offspring per female per year in the Spring River, Kansas. Eckert's (2003, p. 26) mean fecundity ranged from 63,182 (St. Francis River) to 132,363 (Verdigris River), with a mean of 69,634 offspring per female per year in the Ouachita River. Western

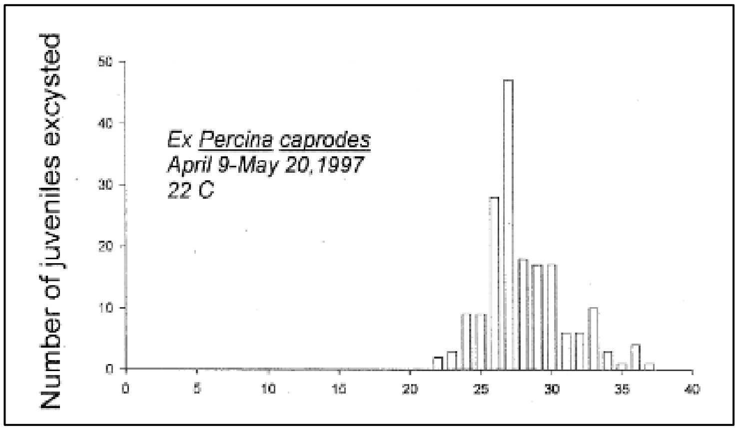


Figure 2.4 Timing of excystment of juvenile Western Fanshell (*Cyprogenia aberti*) from Logperch (*Percina caprodes*) (Barnhart 1997, p. 12)

Fanshell from the Arkansas River basin tend to be larger with larger conglutinates and thus greater fecundity (Eckert 2003, p. 62). Approximately 85% of the eggs in each conglutinate are sterile, apparently providing a structural role in the conglutinate by providing a tough elastic support. The durable core of sterile eggs also serves to increase handling time by fish hosts and theoretically makes conglutinates more palatable to fish hosts (Barnhart 1997, pp. 6 – 10). The mean number of viable glochidia/conglutinate ranges from 2,803 ± 1,263 (Ouachita) to 5,272 ± 2,306 (St. Francis) (Barnhart 1997, p. 10; Eckert 2003, p. 62). The glochidia of *Cyprogenia* are "morphologically depressed" because they have a narrow gape and short dorso-ventral height, which makes it difficult to achieve good rates of initial attachment when pipetting glochidia in suspension onto fish gills. Better glochidia attachment onto fish gills occurs when conglutinates are fed upon by the fish (Barnhart 1997, p. 14).

Conglutinates from Arkansas River basin females are all white (Eckert 2003, p. 16). Females from the St. Francis and Ouachita rivers produce either red or brown conglutinates (Serb and Barnhart 2008, p. 253). Logperch (*Percina caprodes*) is a suitable fish host in all river basins (Eckert 2003, pp. 18 – 19). Rainbow Darter (*Etheostoma caeruleum*) is a good fish host in the St. Francis River, but poor host in the Arkansas River basin (Eckert 2003, p. 19). Slenderhead, Fantail, Rainbow, and Orangebelly darters are suitable hosts only for their respective sympatric Fanshell mussel population (Eckert 2003, p. 33). This adaptation indicates that Fanshell mussels in each river system are ecologically different (Eckert and Barnhart 2008, p. 9). The timing of shedding untransformed glochidia and transformed juveniles varies depending on host species, mussel population, and interaction of host and mussel.

2.4 Diet

Like all mussels, the Fanshell mussels are omnivores that primarily filter feed on a wide variety of microscopic particulate matter suspended in the water column, including phytoplankton, zooplankton, bacteria, detritus, and dissolved organic matter (Haag 2012, p.26). Juveniles likely pedal feed in the sediment, whereas adults filter feed from the water column. A recent nutrition study found that probiotic bacteria (*Bacillus subtilis*) enhanced early juvenile growth and survival (Eads and Levine 2011, p.3).

2.5 Habitat

The Fanshell mussels are typically found in large creeks and rivers with good water quality, moderate to swift current and gravel-sand substrates. Most freshwater mussels, including the Fanshell mussels, occur in aggregations (mussel beds) that vary in size and are often separated by stream reaches where mussels are absent or rare (Vaughn 2012, p. 983). Specific information on microhabitat requirements is lacking. Habitat utilized by Fanshell mussels is not static over time and suitable habitat patches may disappear and re-emerge in different locations.

2.6 Individual Resource Needs

Here we describe general resource needs (Table 2.1) common to both Fanshell mussels. The Fanshell mussels generally require:

1. Stable river channels and banks (e.g., channels that maintain lateral dimensions, longitudinal profiles, and sinuosity patterns over time without an aggrading or degrading bed elevation) during the species' life span with habitats that support a diversity of freshwater mussel and native fish (e.g., stable riffles, sometimes with runs, and mid–channel island habitats that provide flow refuges consisting of gravel and sand substrates with low to moderate amounts of fine sediment and attached filamentous algae).
2. A hydrologic flow regime (the severity, frequency, duration, and seasonality of discharge over time) during the species' life span necessary to maintain benthic habitats where the species are found and to maintain river connectivity with the floodplain, allowing the exchange of nutrients and sediment for maintenance of the mussel's and fish host's habitat, food availability, spawning habitat for native fishes, and the ability for newly transformed juveniles to become established in their habitats.
3. Habitat connectivity (i.e., lack of barriers to fish passage).
4. Water and sediment quality (including, but not limited to, conductivity, hardness, turbidity, temperature, pH, ammonia, heavy metals, and chemical constituents) necessary to sustain natural physiological processes for normal behavior, growth, and viability of all life stages.
5. The presence and abundance of fish hosts necessary for recruitment of the Fanshell mussels.
6. Either no competitive or predaceous invasive (nonnative) species or such species in quantities low enough to have no more than minimal effect on survival of native freshwater mussels.

<u>Flowing water.</u> The Fanshell mussels are not adapted to lentic (non-flowing) environments, such as lakes, and do not persist or thrive in habitats unless they are free flowing (lotic). Free flowing water provides appropriate dissolved oxygen, nutrition, thermal buffering, and access to suitable fish hosts for reproduction and dispersal. The Fanshell mussels require adequate, but not excessively high flows, which may lead to scouring of suitable substrate. They do not tolerate prolonged exposure to non-watered environments, which can reduce reproduction and health. As such, they require minimum flow sufficient to meet life history requirements.

Benthic habitats are typically comprised of sand, gravel and cobble subject to periodic disturbance from high storm flows. Increased discharge and frequency of storm flows may scour sediments and dislodge mussels, leading to unsuitable habitat conditions or displacement to unsuitable habitats. While mussels are adapted to periodic high and low flows, changing land use (e.g., increasing impervious cover in urban areas) and climate change may exceed their capacity to survive higher magnitude and more frequent flooding or prolonged and more frequent lower flows.

<u>Water Quality.</u> The Fanshell mussels require naturally clean water and are sensitive to point and nonpoint source contaminants that deteriorate water quality and habitat. Contaminants are capable of altering the chemical, physical, and biological characteristics of a stream to a point where mussels or their fish hosts cannot survive. A variety of pollutants can cause lethal and sub-lethal effects to mussels and fish. Species-specific data for the Fanshell mussels is lacking regarding their sensitivity to >80,000 chemical compounds and their metabolites commonly

released into the environment. Each life stage (glochidia, juvenile, adult) of mussels have common and unique characteristics that contribute to differences in exposure and sensitivity (Cope *et al*. 2008, p. 451).

Contaminants that sometimes are elevated in rivers and of concern for mussels include excess nutrients such as ammonia (NH_3) (Augspurger *et al*. 2003, p. 2569), chemicals common to wastewater disinfection (e.g., chlorine), trace metals (e.g., copper, cadmium, lead) (Wang *et al*. 2007a, 2007b, 2010, 2013, entire), dissolved solids (e.g., salinity), pharmaceuticals (Cope *et al*. 2008, p. 455; Kolpin *et al*. 2002, pp. 1208 – 1210), and a variety of pesticides (Bringolf *et al* 2007a, p. 2094; 2007b, p. 2086). Wang *et al*. (2007b, pp. 2041 – 2043) report the 28-day half-maximal effective concentration (EC_{50}) for 2-month old juvenile mussels as 0.37 – 0.67 mg total NH_3 nitrogen (TAN)/L. Augspurger *et al*. (2003, p. 2571) provide the acute continuous mg TAN/L protective of all mussel life stages as 0.3 – 1.0 mg TAN/L at pH 8.0 and 25ºC. Gillis *et al*. (2008, pp. 140 – 141) and Wang *et al*. (2010, pp. 2056 – 2059) provide some of the lowest hardness normalized (50 mg/L as $CaCO_3$) EC_{50} data for acute toxicity of multiple mussel species to cadmium, zinc, lead, and copper at 0.014, 0.120, 0.205, and 0.005 mg/L, respectively. Exact critical thermal limits for the Fanshell mussels are unknown, but closely related Lampsilines are classified as thermally sensitive (Spooner and Vaughn 2008, p. 311). High water temperature reduces dissolved oxygen concentrations, which may reduce mussel health and survival (e.g., slows growth, reduces glycogen stores, impairs respiration, shortens glochidial excystment, reduces righting speed, increases oxygen consumption, reduces burrowing and movement responses, and may inhibit reproduction) (Bartsch *et al*. 2000, p. 237; Fuller 1974, pp. 240 – 246; Schwalb and Pusch 2007, p. 261; Watters *et al*. 2001, pp. 544 – 545). Several studies document the influence of temperature on the timing aspects of mussel reproduction (Allen *et al*. 2007, pp. 80 – 85; Gray *et al*. 2002, pp. 155 – 156; Steingraeber *et al*. 2007, p. 297). Peak glochidial releases are associated with water temperature thresholds that can be thermal minimums or maximums, depending on the species (Watters and O'Dee 2000, pp. 136 – 138). Increasing water temperature significantly reduced burrowing behavior and byssus (secreted filaments that assist mussels in attaching to solid surfaces) production, while median lethal temperature for 2 mussel species ranged from 29.9 to 35.6 °C (Archambault *et al*. 2014, p. 601). Mussels generally do not tolerate dissolved oxygen concentrations < 3 mg/L and will begin to experience respiratory distress < 2 mg/L (Bonner *et al*. 2018, p. 131), but dissolved oxygen < 5 mg/L is generally considered to be harmful to many fish species, and fish mortality is almost certain at < 2 mg/L (Francis-Floyd 2011, p. 1).

Fish Hosts. Fanshell mussels have an obligate parasitic relationship with their respective fish hosts. They cannot successfully reproduce or disperse in the absence of appropriate fish hosts. 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. Large and small run of river impoundments and culverted and non-culverted (e.g., concrete pads) low water crossings act as barriers to fish passage, and therefore inhibit mussel dispersal and recolonization.

Table 2.1 General life history and resource needs of Western Fanshell and “Ouachita” Fanshell.

Life Stage	Resource Needs – Habitat Requirements	References
All life Stages	**Water Quality:** Naturally clean, high quality water with little or no harmful pollutants (i.e., pollutants occur below tolerance limits of mussels, fish hosts, prey). These values are based on the best available science and assume mussels respond to average values of a constituent over time (acute or chronic exposure). ➢ D.O. > 3 mg/L ➢ Low salinity/total dissolved solids ➢ Low nutrient concentrations ➢ TAN < 0.3 – 1.0 at pH 8.0 & 25ºC ➢ $NO_3 < 2.0$ mg/L ➢ $NO_2 < 55.8$ mg/L ➢ Low concentrations of metals ➢ Cd < 0.014 mg/L at 50 mg/L $CaCO_3$ hardness ➢ Zn < 0.120 mg/L at 50 mg/L $CaCO_3$ hardness ➢ Pb < 0.205 mg/L at 50 mg/L $CaCO_3$ hardness ➢ Cu < 0.005 mg/L in moderately hard water ➢ Natural, unaltered ambient water temperature generally < 27ºC	Allen *et al*. 2007, pp. 80 – 85; Augspurger *et al*. 2003, p. 2569; Bringolf *et al* 2007a, p. 2094; 2007b, p. 2086; Cope *et al*. 2008, p. 455; Fuller 1974, pp. 240 – 246; Gillis *et al*. 2008, pp. 140 – 141; Gray *et al*. 2002, pp. 155 – 156; Kolpin *et al*. 2002, pp. 1208 – 1210; Spooner and Vaughn 2008, p. 311; Steingraeber *et al*. 2007, p. 297; Wang *et al*. 2007a, 2007b, 2010, 2013, entire.
	Water Quantity: Flowing water in sufficient quantity to support the life history requirements of mussels and their fish hosts.	Galbraith and Vaughn 2009, p. 46; Allen and Vaughn 2010, p. 390; Peterson et al. 2011, p. 115; Daraio et al. 2010, p. 838
Gamete (sperm, egg development, fertilization) **Glochidia**	➢ Sexually mature males and females with appropriate water temperatures for spawning, fertilization, and brooding. ➢ Presence of fish hosts (of appropriate species) with sufficient flow to allow attachment, encystment, relocation, excystment, and dispersal of glochidia. ➢ Glochidia are generally more sensitive than juveniles and adults to pollutants in water.	Haag 2012, pp. 38–39; Galbraith and Vaughn 2009, p. 45-46; Barnhart *et al.* 2008, p. 372.
Juvenile, sub-adult, and adult (from excystment - maturity)	➢ Stable substrate comprised of mixed sand, gravel and cobble, and appropriate for burrowing, pedal feeding, and survival. ➢ Appropriate food sources (phytoplankton, zooplankton, protozoans, detritus, dissolved organic matter) in adequate supply ➢ Presence and abundance of fish hosts available for recruitment ➢ Low numbers of invasive aquatic species with no more than minimal effect on survival	Allen and Vaughn 2010, pp. 384-385; Haag 2012, pp. 26-42; Eckert 2003, pp. 18-19, 33.

Chapter 3 –Population and Species Needs

This chapter considers the Fanshell mussels' historical and current distribution and the factors important to assessing the viability of each species. This chapter reviews the historical information on the range and distribution, considers the population and species level needs, and evaluates factors important to assessing the viability of each species. 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.

The smallest measure of occurrence of the Fanshell mussels is occasional or regular interaction among individuals in different reaches not interrupted by a barrier. In general, interaction is strongly influenced by habitat fragmentation, reproductive aggregations, and distance between occupied river or stream reaches. Available data were organized by named river or stream that was subsequently used as the unit to delineate an individual population. In this context, "river or stream" and "population" are used synonymously herein.

The Fanshell mussels' range includes medium to large rivers with some populations fragmented by dams and creation of navigation channels. Therefore, separate populations are designated for each watershed through which these streams flow (if there was an occurrence record for the stream in that watershed). These watersheds are based on HUC8 watersheds, and are termed management units (MU) in this report. Some of these watersheds have been enlarged because of a lack of dispersal barriers (e.g., Saline MU is upper Saline HUC8 and lower Saline HUC8 combined, Little Missouri HUC8 was combined with Upper Ouachita HUC8) and some divided (e.g., Caddo MU was removed from Upper Ouachita HUC8). MUs represent areas with one or more populations capable of dispersal and interaction. MUs were identified as most appropriate for assessing population-level resiliency because the stream level was determined to be too coarse of a scale to estimate the condition factors influencing resiliency. We used range-wide species occurrence data to create maps indicating the historical and current distribution of Western Fanshell (11 MUs with 14 populations) and "Ouachita" Fanshell (4 MUs with 7 populations) MUs currently known to be extant.

3.1 Population Resiliency

For these species to maintain viability, their populations or some portion thereof must be resilient to disturbances that vary in duration and intensity. Disturbances that have the potential to affect mussel populations include:

1) High flow events (e.g., greater intensity and frequency flooding) that cause scouring, mobilization of substrates, and burial of mussel beds by large amounts of sediment (e.g., bank collapse events, unpaved road erosion, etc.),

2) Extended droughts and other dewatering events,

3) Changes to water and sediment quality (e.g., high water temperature, excessive nutrients, heavy metals, and discharges of other pollutants),

4) Large-scale depredation events (e.g., collection, natural predation),

5) Disease outbreaks,

6) Competition from invasive species, and

7) Reduction in fish host distribution and abundance.

Mussel population health is a product of the extent of stream occupied, abundance within those occupied stream reaches, and recruitment. We discuss these elements of population health and the habitat parameters necessary for mussel population resiliency in detail below.

3.1.A Demographic Factors

Occupied Stream Length – Most freshwater mussels, including the Fanshell mussels, occur in aggregations called mussel beds that vary in size from about 50 to >5,000 m^2 and are separated by stream reaches in which mussels are absent or rare (Vaughn 2012, p. 2). Mussel beds exceeding 5,000 m^2, while uncommon, occur in portions of the "Ouachita" Fanshell range (Davidson and Clem 2002, Appendix 2; 2004, Table 2; Posey 1997, Appendix 1.3). As discussed above, we define a mussel population at a larger scale rather than a single mussel bed; it is the collection or series of mussel beds within a stream reach between which infested fish hosts 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 disturbances 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 used stream length-resiliency relationships reported in other mussel SSAs (Service 2016b, Table 3.1; Service 2018a, Table 5-1; Service 2018b, Table 3.1; Service 2019, Table 5-1; Service 2020, Table 3.3), which we determined to be appropriate for the Fanshell mussels because many of the rivers, habitat, and threats are similar. Based on those examples, populations extending >80 km are more likely to persist after disruptive events because a single event is unlikely to affect the entire population. Likewise, populations occupying 32 – 80 km have a moderate likelihood of persisting after a single disruptive event, while populations occupying <32 km are most susceptible to extirpation following a single disruptive event. Note that, by definition in this SSA, a likely extirpated population occupies a stream length of approximately (or approaching) zero rkm.

Abundance – Mussel abundance in a given stream reach is a product of the number and spatial patterning of mussel beds and mussel density within those beds. For populations of Fanshell mussels to be healthy (i.e., resilient), mussel beds of sufficient number, density and spatial patterning must be present to allow recovery from natural and stochastic events, allowing the mussel bed to persist and the overall local population to survive within a stream reach. We assess mussel abundance by the number of individuals found during a sample event, as mussel surveys are rarely a complete population census.

Population size for each river or stream was based on inventory data collected for freshwater mussels since 2000. Various state and Federal agencies, academic institutions, and non-governmental organizations conducted inventories. Population size was ranked as small (rare in collections or surveys), medium (occasional-to-common in collections or surveys), or large (abundant in collections or surveys) (see Chapter 4).

Reproduction/Recruitment – Resilient Fanshell mussel populations also must 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 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 with many young and/or gravid individuals is likely to grow 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 searches by hand with limited visibility and mussels < 35 mm are very difficult to detect visually (Strayer and Smith 2003, pp. 47-48), unless conducting whole sediment sampling in which juveniles are easily detected.

3.1.B Habitat Factors

Water Quality – Freshwater mussels, as a group, are very sensitive to changes in water quality, including parameters such as temperature, ammonia (NH_3), metals and a variety of environmental pollutants. We consider habitats with naturally clean water with low levels of pollutants (concentrations < values known to cause acute and chronic toxicity) as suitable, while habitats with levels outside of the appropriate range for mussels are unsuitable or degraded habitat.

Flow – 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). The Fanshell mussels are not 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 streambed substrates. Low stream flows can reduce habitat availability and negatively influence water quality parameters (e.g., temperature and other parameters influenced by temperature) necessary for freshwater mussel persistence. Both high and low flows can also influence the presence or absence of fish hosts. While mussels evolved in habitats that experience seasonal fluctuations in discharge, changing global weather patterns can affect normal regimes. Even during naturally occurring low flow events, mussel stress may occur due to water temperature increases (e.g., shallow water warms quicker than deeper water) because they exert significant energy to move to deeper waters, or they may succumb to desiccation. Because low flows generally occur in late summer and early fall and are more likely to induce stress due to warmer temperatures, droughts during this time of year may result in stress and, potentially, an increased rate of mortality. We provide a more detailed analysis of how flow influences viability in Section 5.2.

Flow is also positively related to recruitment. Peterson *et al.* (2011, pp. 115, 119) found minimum and maximum 10-day summer discharge, July maximum discharge, 7-day minimum flow (April – August), and minimum 10-day spring discharge to positively affect recruitment. Low flows during Fanshell mussel spawning periods (August – October) may reduce over dispersal of sperm and increase fertilization success. Spring flows are likely to coincide with Fanshell mussels' glochidial release and juvenile settling. Daraio *et al.* (2010, p. 838) found high velocity flows can prevent juvenile settlement in main channels and cause newly settled juveniles to become re-suspended and deposited in areas with reduced flow. Therefore, the timing and duration of extreme (low and high) flow events (Daraio *et al*. 2010, p. 838; Peterson *et al.* 2011, pp. 115, 119; Ries *et al*. 2016, pp. 711 – 712) likely affect recruitment of Fanshell mussels.

Landscape – Natural vegetative cover stabilizes soil, regulates hydrology, and provides habitat for terrestrial and riparian species. The type, quantity, and structure of the natural vegetation within a watershed have important influences on aquatic habitats. Vegetated landscapes and riparian forests regulate temperature, shading, and input organic matter; retain sediments; and influence surface and ground water hydrology. Whereas, agricultural and urban landscapes increase surface runoff, decrease subsurface infiltration, and are net exporters of sediment and nutrients (EPA 2012, p. 2-4).

The long-term effects of landscape character and change may be among the most important controllers of mussel populations because the landscape affects the physical structure and dynamics of the river bed, the frequency and severity of disturbances such as floods and droughts, the nature and amount of organic matter that reaches the river, and the composition of fish communities (Newton *et al*. 2008, p. 432). The effect of riparian buffer on mussel communities is not definitive, but results suggest that healthy buffers help maintain mussel communities better than modified buffers (Atkinson *et al*. 2012, p. 9). Therefore, the landscape of watersheds where the Fanshell mussels occur is important, but the mechanisms, temporal lag between landscape change and change to the mussel community (including recovery, if not irreversible), and specific thresholds are poorly understood.

Habitat Fragmentation – In the case of mussels, fragmentation can result in barriers to fish host movement, which may affect mussel distributions. Mussels that use smaller host fish (e.g., darters and minnows) are more susceptible to habitat fragmentation effects due to increasing distance between suitable habitat patches and low likelihood of host fish swimming over that distance. Barriers to movement can cause isolated or patchy mussel distribution, which may limit both genetic exchange and recolonization (e.g., after a high flow, scouring event).

3.2 Species Representation

Maintaining species representation in the form of genetic and ecological diversity is important in safeguarding the ability of Fanshell mussel populations to adapt to future environmental changes. The genetic diversity of Fanshell mussel populations is not currently available. In the absence of species-specific genetic information, we can evaluate representation based on the extent and variability of environmental conditions within the species' geographic range. The best available data indicate three representative units (i.e., three HUC4 river basins) where Western Fanshell is currently found: Lower Mississippi-St. Francis, Neosho-Verdigris, and Upper White River basins and one representative unit where “Ouachita” Fanshell is currently found: Lower Red-Ouachita River basin.

We considered geographic range as a surrogate for geographic variation and proxy for potential local adaptation and adaptive capacity. We used hydrographic (management) units (roughly based on the HUC8 level; see additional discussion in Chapter 3) to help define representation because watershed boundaries and natural and artificial barriers constrain ecological processes, such as genetic exchange and ultimately adaptive capacity for aquatic species (Funk *et al*. 2018, p. 14). The best available data indicate “Ouachita Fanshell” has not been extirpated from any major river drainages or basins compared to historical information. Western Fanshell was last reported as relic shell in the Lower Arkansas basin from Big Piney Creek. Therefore, the species has been reduced from four to three major river drainages compared to historical information.

3.3 Species Redundancy

The Fanshell mussels 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 of negatively affecting a large portion of the species’ range by a single catastrophic natural or anthropogenic-induced event at any given point in time. Species well distributed across their historical range are less susceptible to extinction and more likely to remain viable compared to species confined to a small portion of their historical range (Carroll *et al*. 2010, entire; Redford *et al*. 2011, entire). Historically, Fanshell mussel populations were able to disperse by fish migration within each river basin. Impoundments and other barriers to fish movement, such as river reaches with unsuitable water quality (e.g., high concentrations of pollutants 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 Western Fanshell and "Ouachita" Fanshell

This chapter discusses the current condition of Western Fanshell and "Ouachita" Fanshell populations and evaluates the resiliency of those populations.

4.1 Historical Range and Current Distribution

For this assessment, a current population is a continuous stream reach hydrologically connected without major barriers (e.g., dams) containing live or recent dead individuals observed in surveys from 2000 – present. Since malacologists survey rivers at 5 – 10+ year intervals, and surveys may not always be comprehensive (e.g., project-specific), we selected 2000 to present to capture multiple surveys to gain a better understanding of current condition. It is worth noting, it has been half a century or more since many drainages were adequately surveyed and some are virtually unsampled (FMCS 2016, p. 3). Recent (or fresh) dead refers to dead individuals observed with valves still attached to the hinge, a lustrous nacre, and intact periostracum; soft tissue may or may not be present. For description purposes, estimates of upstream and downstream extent of populations extend to the nearest tributary. Tributaries with live or recent dead observations since 2000 connected hydrologically (i.e., no barriers to prevent fish passage) are a single population. If live or recent dead observations occur upstream of the barrier (i.e., isolated hydrologically from downstream reaches), we considered these areas separate populations.

4.1.A Western Fanshell

The Western Fanshell has a historical range comprising multiple rivers within the Neosho-Verdigris, Lower Mississippi–St. Francis, and Upper White river drainages of Arkansas, Missouri, Kansas, and Oklahoma. The Western Fanshell currently occurs in several river basins, including the Black (Rust 1993, Appendix 1.1), Buffalo (Matthews *et al.* 2009, Tables 1 and 3), Little Red (Gordon and Harris 1983, Figure 3; Harris *et al.* 2009, Figure 5; Winterringer 2003, Table 15; C. Davidson 2019, unpublished data), Spring (Gordon and Harris 1983, Figure 3; Harris *et al.* 2009, Figure 5; Rust 1993, Appendix 1.2), Strawberry (Gordon and Harris 1983, Figure 3; Harris *et al.* 2009, Figure 5; Harris *et al*. 2007, Table 6), and White River (Bates and Dennis 1983, Table XXI; Gordon 1980, p. 232; Gordon 1982, Table 1; Harris and Christian 2000, p. 12) in Arkansas (Harris *et al*. 2009, Figure 5; K. Moles 2019, pers. comm.). In Missouri, the Western Fanshell occurs within the Black (Hutson and Barnhart 2004, p. 155, Table 7), St. Francis (Hutson and Barnhart 2004, p. 86, Table 6), and Spring River basins (Buchanan 1980, Table 1; Eckert 2003, Table 1; EcoAnalysts 2018, Table 3-3; Obermeyer 1999, p. 20). In Kansas, the Western Fanshell occurs in the Fall, Spring, and Verdigris River basins (Boeckman and Bidwell 2008, p. 4; Miller and Lynott 2006, p. 386; Obermeyer 1999, p. 19-21; Wolf and Stark 2008, p. 5, 12). Oklahoma considered the Western Fanshell extirpated/extinct (Mather 1990, p. 15, 19; Mather 2005, p. 42) until a 2006 live collection in the Verdigris River near the Kansas/Oklahoma border (Boeckman and Bidwell 2008, p. 4; Bidwell *et al.* 2009, p. 16, Table 2a, Appendix 1:2-4).

Historically, the Western Fanshell occurred in another 14 river basins. In Arkansas, it occurred in the Beaver Reservoir, Dardanelle Reservoir, Eleven Point (K. Moles 2019, pers. comm.; Gordon and Harris 1983, Figure 3; Harris *et al*. 2009, Figure 5), lower White (Bates and Dennis 1983, Table XXI; Gordon 1980, p. 232), Upper White – Village (Christian 1995, Appendix 1.4; Gordon 1980, p. 232; Utterback 1916, p. 322) HUC8 river basins and the Arkansas portion of the lower St. Francis River basin (K. Moles 2019, pers. comm.). In Missouri, it occurred in the Bull Shoals Lake and Whitewater HUC8 river basins, and in the Current River basin (Buchanan 1996, p. 48; McMurray *et al.* 2012, p. 30; MDC 2019; Oesch 1995 p. 144). In Kansas, it occurred in the Elk (Obermeyer *et al*. 1997a, p. 46, Table 1), Middle Neosho, Neosho Headwaters, Upper Neosho (Obermeyer 1999, p. 19-21; Scammon 1906, p. 316), and Upper Verdigris HUC8 river basins (Obermeyer *et al*. 1997a, Figure 4). In Oklahoma, it historically occurred in the Caney (Mather 1990, p. 7, 13) and lower Verdigris (Isely 1924, p.71; Mather 1990, p. 13; Mather 2005, p. 43) HUC8 river basins. We assume the historical distribution of the species included the entirety of these rivers described above (Figure 4.1A – 4.1D). Table 4.1 displays estimated length of each MU in river kilometers (rkm). Utterback (1916, p. 323) noted *C. aberti* was unusually abundant in Native American middens, suggesting historically it was abundant enough to be an important food source.

While it is difficult to determine the historical rkm occupied by the species prior to construction of dams and navigation projects, we assume Western Fanshell occurred throughout the inundated, tailwater, cutoff tributaries, and navigation channel reaches of the Neosho River to Grand Lake O' The Cherokees; Verdigris River from Toronto Lake to the confluence of Fall River; Elk River from Elk City Lake to the Verdigris River; Caney River upstream of Hulah Lake; St. Francis River below Lake Wappapello; War Eagle Creek upstream of Beaver Lake; Big Piney Creek upstream of Lake Dardanelle; White River from Table Rock Lake through Bull Shoals Lake; and the Eleven Point, Current, and St. Francis rivers in Arkansas.

There are reported records from archeological sites within four river basins in Mississippi. These include Western Fanshell valves at three sites on the Big Sunflower River (Mitchell and Peacock 2014, Table 1, Peacock *et al*. 2011, Figure A-5), and one site on Dawson Bayou (Peacock *et al.* 2011, Figure A-5) within the Big Sunflower River basin; one site on Limekiln Creek (Peacock and James 2002, Table 1) within the lower Big Black River basin; two sites on the Yazoo River (Peacock *et al*. 2017, Table 1, Peacock *et al*. 2011, Figure A-5) and one site on O'Neil Creek (Peacock *et al*. 2011, Figure A-5) within the Yazoo River basin; and one site on the Tallahatchie River (Peacock *et al*. 2016, Table 1) within the Tallahatchie River basin. Mississippi recognizes Western Fanshell and ranks it as presumed extirpated (Mississippi Natural Heritage Program 2018). Because of the genetic uncertainties of *Cyprogenia* and the lack of live individuals, we do not include these records within the Western Fanshell historical range for this SSA report.

4.1.A.1 Lower St. Francis Management Unit

The St. Francis River originates in Iron County, Missouri, flows northeast 40.2 rkm, then turns south and flows 643.7 rkm through Missouri and Arkansas to the Mississippi River in the St. Francis National Forest near Helena, Arkansas. Lake Wappapello separates this MU from the Upper St. Francis MU. Historically, Western Fanshell occurred from directly below Wappapello dam in Missouri to the Interstate 40 crossing approximately 3.7 rkm upstream of Madison, Arkansas (approximately 383.9 rkm). Since 2000, Hutson and Barnhart (2004, p. 86) collected five live individuals in the Lower St. Francis River 0.8 rkm downstream of Wappapello Dam (Hutson and Barnhart 2004, p. 86). Within the St. Francis River basin in Arkansas, there are only historical collections (Gordon and Harris 1983, Figure 3; Harris *et al.* 2009, Figure 5; K. Moles 2019, pers. comm.). Because the collections in Arkansas are all historical, we cutoff this MU at the Missouri-Arkansas state line and consider the Arkansas portion likely extirpated.

Table 4.1 Current known populations of Western Fanshell and estimated occupied stream length (river km).

HUC4	Management Unit	State	River	Length of Occupied Reach (rkm)	Number of Sites
Lower Mississippi–St. Francis	Lower St. Francis	Arkansas, Missouri	St. Francis River downstream of Lake Wappapello	<1	1
	Upper St. Francis	Missouri	St. Francis River	80	14
Neosho–Verdigris	Fall	Kansas	Fall River below Fall River Lake	60	8
	Middle Verdigris	Kansas, Oklahoma	Verdigris River above Oologah Lake	80	9
	Spring	Kansas, Missouri	Spring River	25	5
Upper White	Black	Arkansas, Missouri	Black River below Clearwater Lake	105	25
	Buffalo	Arkansas	Buffalo River	145	5
	Middle White	Arkansas	White River	5	2
	Little Red	Arkansas	Beech Fork Little Red River	<1	1
			Middle Fork Little Red River	35	9
	Spring	Arkansas	South Fork Spring River	60	12
			Spring River	50	9
	Strawberry	Arkansas	Strawberry River	65	12

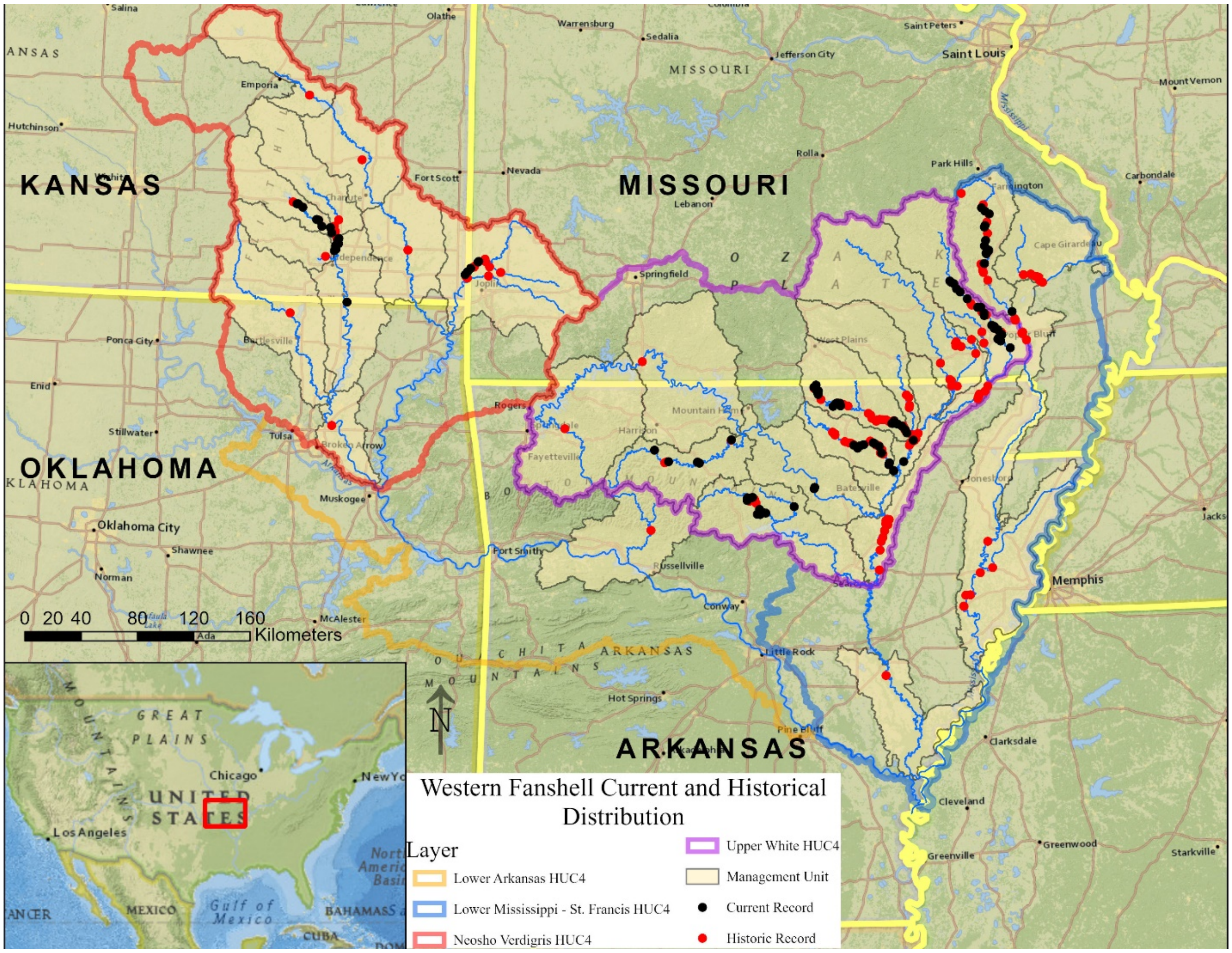


Figure 4.1A Western Fanshell current and historical distribution.

4.1.A.2 Upper St. Francis River Management Unit

The Upper St. Francis River flows approximately 160 rkm from its origin to Lake Wappapello. Historically, Western Fanshell occurred in the Upper St. Francis River from its headwaters 7.7 km north of Pilot Knob, Missouri to Lake Wappapello (approximately 145 rkm). Since 2000, there are reports of 439 live individuals from 13 sites within 80 rkm (Hutson and Barnhart 2004, p. 86, Table 6; MDC mussel database 2019). Hutson and Barnhart (2004, p.86) collected 240 live individuals at 11 sites within 73.9 rkm. The species was actively recruiting and at many sites was locally abundant (Hutson and Barnhart 2004, p. 86).

4.1.A.3 Fall River Management Unit

The Fall River originates in the Flint Hills and flows through the Osage Cuestas to its confluence with the Verdigris River south of Neodesha, Kansas. This MU consists of the Fall River from the Fall River Lake to its confluence with the Verdigris River near Neodesha, Kansas (approximately 82 rkm). Since 2000, 38 live individuals have been collected at 8 sites within 61.5 rkm. Length-frequency histograms suggest recent recruitment (Wolf and Stark 2008, p. 5, 12).

Figure 4.1B Western Fanshell current and historical distribution in the Lower Mississippi-St. Francis Basin. Gray polygons indicate likely extirpated MUs.

4.1.A.4 Middle Verdigris River Management Unit

The Verdigris River originates in the Flint Hills in Kansas and flows through the Osage Cuestas to its confluence with the Arkansas River near Muskogee, Oklahoma. The Middle Verdigris reach begins at the mouth of the Fall River in Kansas and flows south approximately 134.9 rkm to Oologah Lake in Oklahoma. Historically, Western Fanshell occurred from the Toronto Lake Dam in Kansas (Upper Verdigris) to Oologah Lake in Oklahoma (Middle Verdigris) (approximately 215.3 rkm). Since 2000, 498 live individuals have been collected at 9 sites upstream of Oologah Lake in Oklahoma (approximately 80 rkm; Boeckman and Bidwell 2008, p. 4; Bidwell *et al*. 2009, p. 24, Table 2a, Appendix 2:2-4; E. Miller 2019, pers. comm.). Long term monitoring since 1991 shows an increase in relative abundance (E. Miller 2019, pers. comm.; Miller and Lynott 2006, entire) suggesting recruitment is likely occurring.

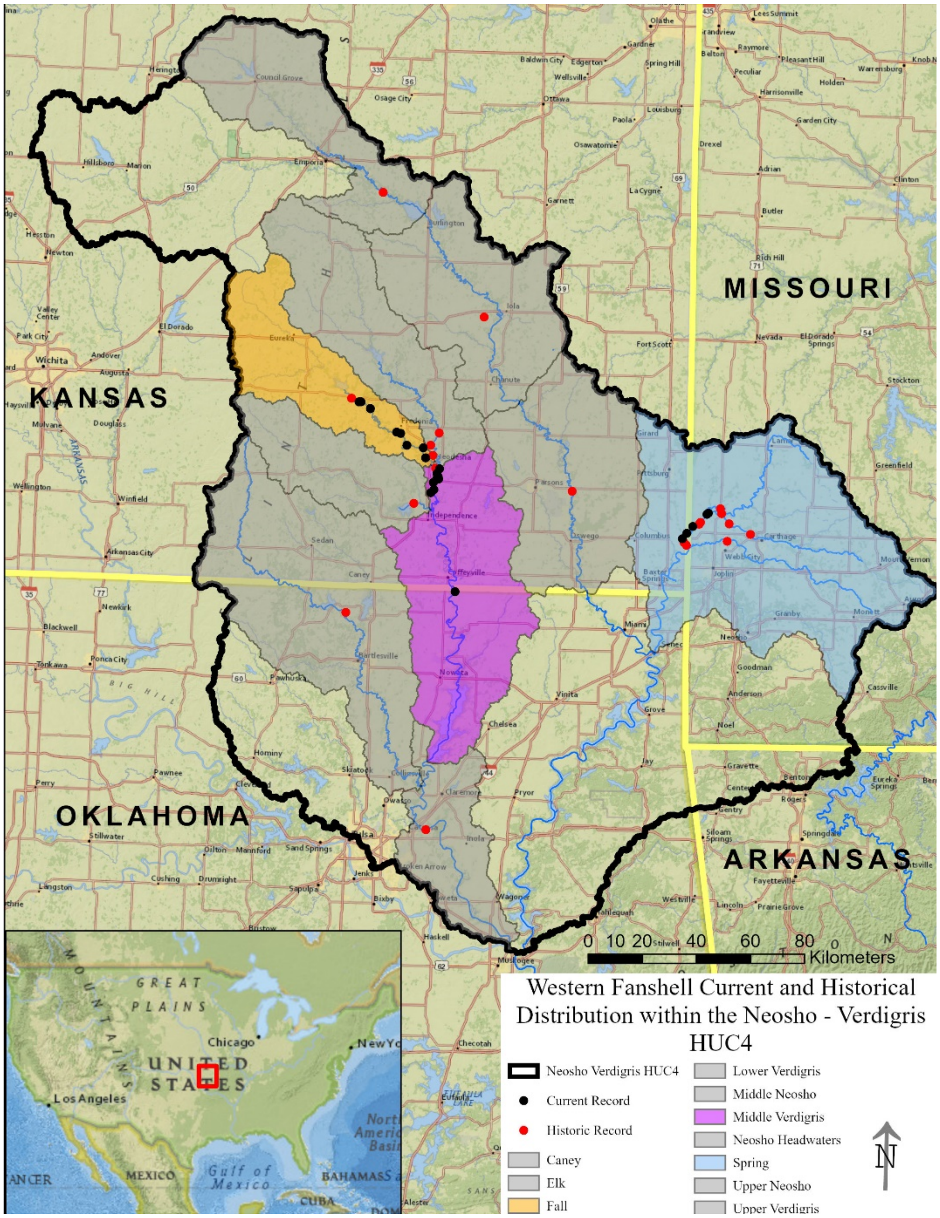


Figure 4.1C Western Fanshell current and historical distribution in the Neosho-Verdigris Basin. Gray polygons indicate likely extirpated MUs.

4.1.A.5 Spring River Management Unit (KS and MO)

The Spring River originates in southwest Missouri, flows west-northwest to its confluence with the North Fork Spring River and then southwest into Kansas and Grand Lake of the Cherokees in Oklahoma (approximately 162.9 rkm). Historically, Western Fanshell occurred from near Carthage, Missouri to the Center Creek confluence at the Missouri-Kansas border (approximately 50.8 rkm). Since 2000, there are records of 10 live individuals from 5 sites within 17.8 rkm (EcoAnalysts 2018, Table 3-3; McMurray and Faiman 2020, p. 18, Table 4; MDC 2019). There also are historical observations from Center Creek and North Fork Spring River (Buchanan 1980, Table 1; MDC 2019).

4.1.A.6 Black River Management Unit

The Black River originates in the St. Francois Mountains in Missouri and flows southwesterly through Arkansas until its confluence with the White River near Newport, Arkansas. Historically, Western Fanshell occurred in the Black River from just below Clearwater Lake Dam to approximately 20.2 river kilometers (rkm) upstream of the Lawrence and Jackson County line (approximately 184.9 rkm). Since 2000, multiple comprehensive survey efforts report observations of 911 individuals from 22 sites within a 75 rkm reach in Missouri (Hutson and Barnhart 2004, p. 155, Table 7; Missouri Department of Conservation (MDC) 2019) and 5 live from 2 sites within a 30 rkm reach in Arkansas (K. Moles 2019, pers. comm.). Hutson and Barnhart (2004, p.155) collected 794 live individuals at 19 sites (37.2% of sites surveyed) and the population appeared to be recruiting.

4.1.A.7 Buffalo River Management Unit

The Buffalo River originates in the Boston Mountains in north-central Arkansas and flows approximately 241 rkm until its confluence with the White River near Buffalo City, Arkansas. Historically, the Western Fanshell occurred at 10 sites in the Buffalo River from the confluence of Mill Creek to 9.6 rkm upstream from its confluence with the White River. Since 2000, nine live or fresh dead specimens have been collected in the Buffalo River at five sites (K. Moles 2019, pers. comm.; Matthews *et al*. 2009, Tables 1 and 3).

4.1.A.8 Little Red River Management Unit

The four main forks (Archey, Middle, South, and Devils forks) of the Little Red River originate in the Boston Mountains in central Arkansas before they converge within Greers Ferry Lake. After Greers Ferry Dam, the main stem Little Red River flows southeast to its confluence with the White River within the Henry Gray/Hurricane Lake Wildlife Management Area. Historically, Western Fanshell occurred in the Middle Fork Little Red River from approximate 6.4 rkm downstream of the Stone and Van Buren County line to the influence of Greers Ferry Lake (approximately 38.8 rkm). Since 2000, 336 live individuals have been collected at 10 sites in the Middle Fork Little Red River within approximately 35 rkm (C. Davidson, 2019, unpublished data; K. Moles 2019, pers. comm.; Winterringer 2003, p. Table 15). Since 2000, there also were 4 individuals collected at 1 site in the Beech Fork Little Red River (part of the Devils Fork) approximately 16.6 rkm upstream from its influence of Greers Ferry Reservoir (C. Davidson 2019, unpublished data; K. Moles 2019, pers. comm.).

4.1.A.9 Middle White River Management Unit

The White River originates in the Boston Mountains, flows northward into Missouri, then southeast through Arkansas to its confluence with the Mississippi River. There are four reservoirs on the main stem White River (Beaver, Table Rock, Taneycomo and Bull Shoals). This MU covers from Bull Shoals Lake dam (the furthest downstream reservoir) to the Black River confluence near Jacksonport, Arkansas. Historically, Western Fanshell likely occurred throughout the White River. Since 2000, there are records of three dead shells at two sites (K. Moles 2019, pers. comm.).

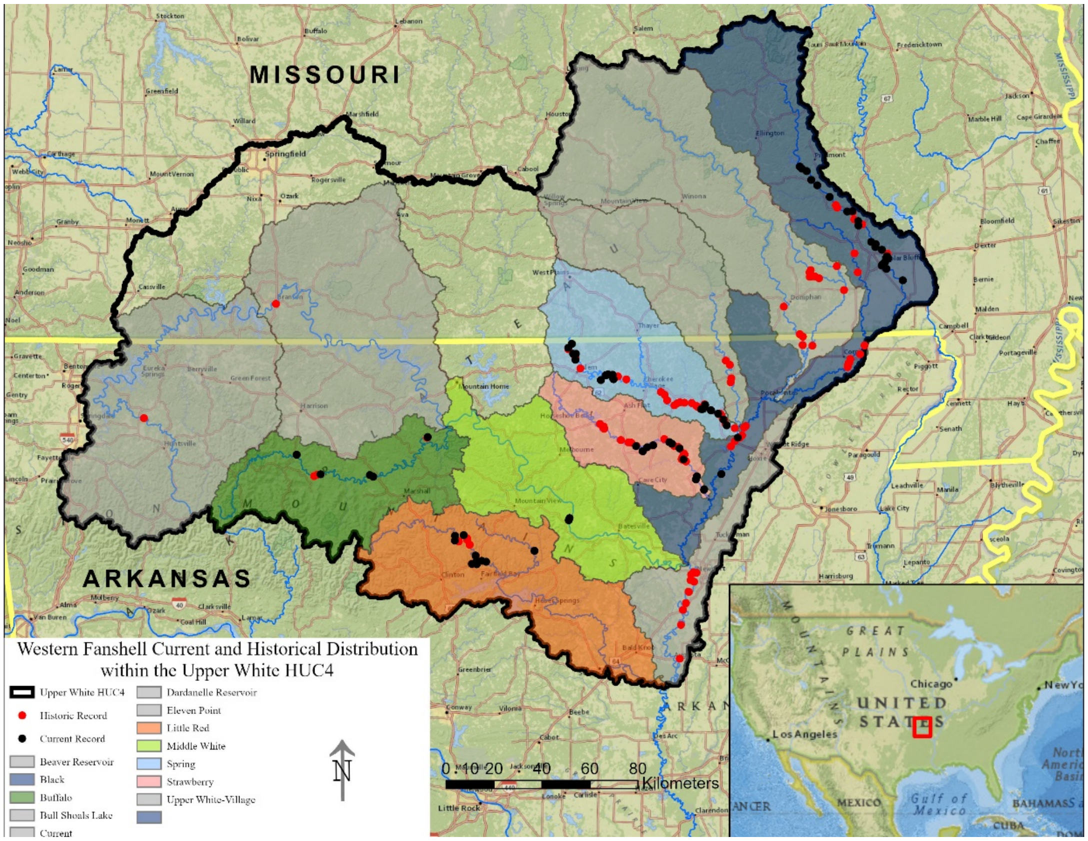


Figure 4.1D Western Fanshell current and historical distribution in the Upper White River Basin. Gray polygons indicate likely extirpated MUs.

4.1.A.10 Spring River Management Unit (AR and MO)

The Spring River originates in the Ozark Highlands in Missouri, flows south to the South Fork Spring River confluence near Hardy, Arkansas, and then flows southwest to the Black River near Black Rock, Arkansas. Historically, Western Fanshell occurred in the Spring River from the Sugar Creek confluence near Hardy, Arkansas to the Eleven Point River confluence north of Black Rock, Arkansas (approximately 48.3 rkm), and in the South Fork Spring River from near the Missouri/Arkansas state line to the confluence with Spring River (approximately 88.4 rkm). Since 2000, there are records of 21 live individuals and 51 dead shells from 12 sites within 58.8 rkm in the South Fork Spring River (Harris *et al*. 2007, Table 5; Martin *et al*. 2009, Table 2). Similarly, there are records of 49 live and 100s of dead shells from 9 sites within 21 rkm in the Spring River (Harris *et al*. 2007, Table 4; K. Moles 2019, pers. comm.).

4.1.A.11 Strawberry River Management Unit

The Strawberry River flows approximately 116.4 rkm from its origin in north central Arkansas to its confluence with the Black River. Historically, Western Fanshell occurred in the Strawberry River from the Arkansas Highway 56 crossing near Franklin, Arkansas to it confluence with the Black River (approximately 116.7 rkm). Since 2000, there are reports of 37 live individuals and 13 dead shells from 11 sites within 65 rkm (Harris *et al*. 2007, Table 6; K. Moles 2019, pers. comm.).

4.1.B “Ouachita” Fanshell

The historical range of “Ouachita” Fanshell comprises multiple rivers within the Ouachita River basin in southern Arkansas and northern Louisiana (Chong *et al*. 2016, p. 2446, 2448; Williams *et al*. 2017, p. 47). In Arkansas, the “Ouachita” Fanshell currently occurs in the main stem Ouachita River upstream and downstream of lakes Ouachita, Hamilton, and Catherine (Harris 1988, Appendix 1; Harris 1999, Attachment D; Harris 2006, Appendix 1; Harris 2017, p. 14; Posey 1997, Appendices 1.3 – 1.4), Caddo River upstream of Lake DeGray (C. Davidson 2019, unpublished data; Harris 1988, Appendix 1), Little Missouri River (Christian and Harris 2004, pp. 12 – 14; Davidson 1997, pp. 128 – 129), Alum Fork Saline River (C. Davidson 2019, unpublished data), and Saline River (Davidson and Clem 2002, p. 13; 2004, p. 17; Davidson and Gosse 2003, pp. 188 – 190; Harris 2006, Appendix 1). Historically, it also occurred in the Antoine River, a tributary of the Little Missouri River (B. Posey 2014, pers. comm.). There are no comprehensive surveys of the Antoine River and there is only one 1983 record from the river. It also historically occurred in the Caddo River downstream of Lake DeGray. In Louisiana, the “Ouachita” Fanshell historically occurred in Bayou Bartholomew (Vidrine 1995, p. 88), but recent surveys failed to locate live specimens (Alley 2005, Appendices 3 – 4; Brooks *et al*. 2008, pp. 13 – 15; Pezold *et al*. 2002, entire). We assume the historical distribution of the species included the entirety of these rivers described above, except Alum Fork Saline River, where connectivity was not an issue and conditions were suitable (Figure 4.2). Table 4.2 displays estimated length of each MU in rkm.

Table 4.2 Current known populations (since 2000) of “Ouachita” Fanshell and estimated occupied stream length (river km).

Management Unit	State	River	Length of Occupied Reach (rkm)	Number of Sites
Caddo	Arkansas	Caddo River (upstream of Lake DeGray)	1 site	1
Ouachita Headwaters	Arkansas	Ouachita River	43.0	14
Saline	Arkansas	Alum Fork Saline River	<2	1
		Saline River	304	153
Upper Ouachita	Arkansas	Ouachita River (Caddo River to Camden, AR)	81	7
		Little Missouri River	35	3

4.1.B.1 Caddo River Management Unit

The Caddo River originates in the Ouachita Mountains in west central Arkansas and flows approximately 64 rkm until its inundation point at Lake DeGray. Historically, the “Ouachita” Fanshell occurred at 6 sites in the Caddo River upstream of Lake DeGray, represented by 26 individuals observed from 1979 – 1988. Since 2000, there are observations of 19 “Ouachita” Fanshell individuals at 1 site near Amity, Arkansas, in 2007, despite multiple comprehensive surveys of the Caddo River from near Caddo Gap, Arkansas, to Lake DeGray (C. Davidson, 2019, unpublished data).

4.1.B.2 Ouachita Headwaters Management Unit

The Ouachita River originates in the Ouachita Mountains near Mena, Arkansas. Three reservoirs (Ouachita, Hamilton, and Catherine) separate this MU from the Upper Ouachita MU. Historically, “Ouachita” Fanshell occurred in the Ouachita River from approximately 17.2 rkm upstream of Pine Ridge, Arkansas, to near Lake Ouachita (approximately 73.9 rkm) (Harris 1988, Appendix 1). Since 2000, there are observations of 46 individuals from 14 sites within a 43 rkm reach (B. Posey 2014, pers. comm.; C. Davidson 2019, unpublished data). The most recent (2014) comprehensive survey of this reach found 29 individuals from 2 sites within 0.8 rkm (C. Davidson 2019, unpublished data).

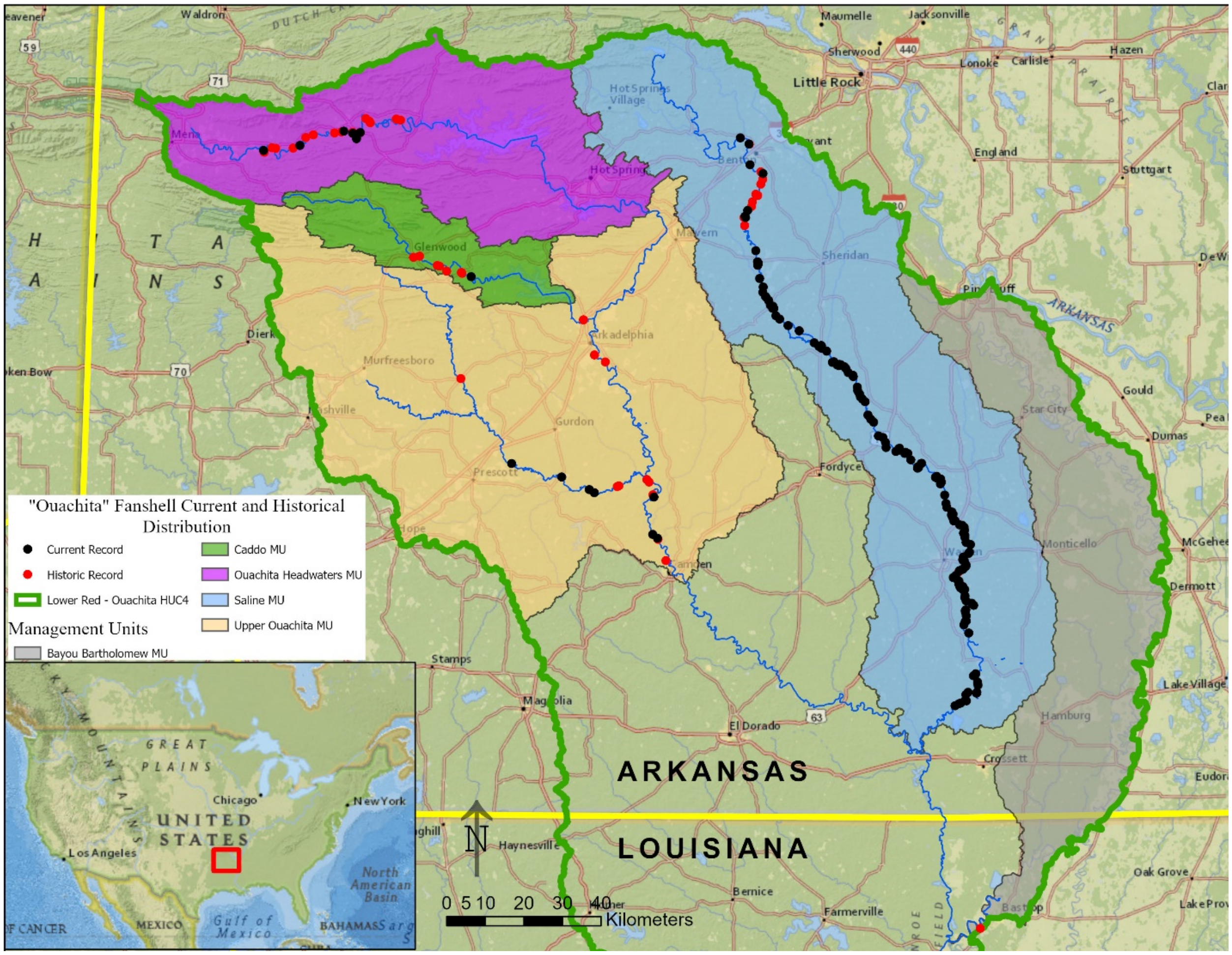


Figure 4.2 “Ouachita” Fanshell current and historical distribution.

4.1.B.3 Saline River Management Unit

The four forks (Alum, Middle, North, and South forks) originate in the Ouachita Mountains in central Arkansas before converging near Benton, Arkansas, to form the main stem Saline River. The Saline River flows unimpeded 328 rkm before converging with the Ouachita River at Felsenthal National Wildlife Refuge near the Arkansas-Louisiana state line. Historically, survey efforts focused on the upper reaches of the Saline River from Benton to Traskwood, Arkansas. From 1987 – 1993, there were 37 individuals reported from 9 sites (B. Posey 2014, pers. comm.).

The only record of "Ouachita" Fanshell from the four forks is a 2006 observation of one individual in the Alum Fork (C. Davidson 2019, unpublished data). Since 2000, 2,651 individuals have been collected from 153 sites. Population estimates per mussel bed, where available, range from 933±654 – 18,800±5,074 individuals (C. Davidson 2019, unpublished data; Davidson and Clem 2002, Appendix 2; 2004, Table 2; Davidson and Gosse 2001, p. 6; 2003, pp. 187 – 191).

4.1.B.4 Upper Ouachita Management Unit

The Ouachita River flows approximately 974 rkm from its origin in west central Arkansas to its confluence with the Red River in Louisiana. Lakes Ouachita, Hamilton and Catherine separate the Upper Ouachita MU from the Ouachita Headwaters MU. The Upper Ouachita MU ends at Camden, Arkansas where the 542 rkm "Ouachita-Black Rivers Navigation Project" begins. Construction for the navigation project, with its six locks and dams began in 1902 and extends to Jonesville, Louisiana. Historically, the "Ouachita" Fanshell likely occurred throughout much of the navigation project. However, there are no records other than one relict valve from Bayou Bartholomew (Vidrine 1995, p. 88), a tributary, in Louisiana and Hunter-Dunbar 1804 – 1805 accounts of shoals extending into northern Louisiana (Jefferson 1806, p. 91). Historical observations of "Ouachita" Fanshell are scant until Posey's (1997, Appendices 1.3 – 1.4) comprehensive survey from the Little Missouri River to the Arkansas-Louisiana stateline.

The Upper Ouachita MU also includes two tributaries, Little Missouri River and Caddo River downstream of Lake DeGray. The only account of live "Ouachita" Fanshell from the lower Caddo River is a 1981 observation of four individuals near Interstate 30 (B. Posey 2014, pers. comm.). There are two historical (1996) observations from the Little Missouri River near its confluence with the Ouachita River (Davidson 1997, Appendix 1.1) and one observation from the Antoine River, a Little Missouri River tributary, near Arkansas Highway 29 in 1982 (B. Posey 2014, pers. comm.).

Since 2000, there are reports of 48 live "Ouachita" Fanshell observations from 7 sites between the Caddo River confluence and Camden, Arkansas (C. Davidson 2019, unpublished data; Harris 2006, Appendices 1e – 1j; Harris 2017, Appendix 1). Christian and Harris (2004, Tables 1 – 3) also report five live individuals from four Little Missouri River sites.

4.2 Methodology for Population Resiliency Assessment

4.2.A Population Factors

Since population estimates are not available for all Fanshell mussel 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 cumulative number of individuals captured since 2000 as an estimate of population abundance. We considered MUs with high abundance to be resilient. We defined high abundance as cumulative counts of over 400 individuals since 2000 as high, 100 – 400 individuals as medium, and 1 – 99 individuals as low (Table 4.3). We consider populations with reasonable survey effort since 2000 and zero individuals captured as likely extirpated.

Table 4.3 Population and habitat condition indicators. *Refer to Section 4.2.B for explanation of scoring for each habitat factor. $^{+}$Refer to Tables 4.6 for parameters. $^{++}$Refer to Table 4.5.

Condition Category	**Demographic Factors**			**Habitat Factors***			
	Population Size	Populations Extent	Reproduction/Recruitment	Water Quality^{+}	Flow	Landscape^{++}	Habitat Fragmentation
High	Cumulative numbers at high end of range (>400) individuals observed since 2000; found at >60% of sites surveyed during reasonable survey effort.	≥80 river km (50 mi)	50% or more sites with sub-adults (<7 years); >5 cohorts present; or gravid females and fish hosts common.	Concentrations at levels below acute toxicity to mussels (1990 – 2019)	Optimal flow regime characteristic of natural conditions, unaltered by anthropogenic factors & sufficient to support food delivery, maximize reproduction & recruitment, and remove excessive fine sediments with minimal effects on population or habitat; < 5th percentile flow >21 but <30 consecutive days rare; multi-year extreme - exceptional droughts rare.	Landscape altered slightly due to anthropogenic factors,	Very little, if any, known habitat fragmentation issues (<10 dams per MU); unpaved road crossing density < 0.21)
Medium	Moderate numbers (100 - 400) of individuals observed since 2000; found at 30 - 60% of all sites surveyed during a reasonable survey effort.	32 - 79 river km (20 - 50 mi)	25-50% of sites inhabited by sub-adults (<7 years); 3 - 5 cohorts present; gravid females and fish hosts present in moderate numbers.	Concentration exceeds acute toxicity levels to mussels <2% of samples (2000 - present), generally exceeds acute toxicity levels <1X/year	Flow regime slightly altered by anthropogenic factors that may affect food delivery, minimize reproduction & recruitment, evidence of increasing fines; flowing water present year round or flows <5th percentile >30 but <45 consecutive days only occur during multi-year extreme-exceptional droughts in suitable habitat	Moderate level of landscape alterations due to anthropogenic factors	Some habitat fragmentation issues (10 - 30 dams per MU); unpaved road crossing density 0.21 - 0.40.
Low	Low numbers (1 - 99) of individuals observed since 2000; found at <30% of all sites surveyed during a reasonable survey effort	<32 river km (20 mi)	<25% of sites inhabited by sub-adults (<7 years); <3 cohorts present; gravid females and fish host present in low numbers.	Concentration exceeds acute toxicity levels >2% of samples (2000 - present), generally exceeds acute toxicity levels multiple times/year	Flow regime impaired to level that puts population at risk of extirpation; multi-years of exceptional drought and flows <5th percentile >45 consecutive days; high shear stress causing bed load movement or dislocation of mussels occurs frequently	Landscape condition severely altered by anthropogenic factors; population at risk of extirpation, habitat severely fragmented	Habitat severely fragmented (30+ dams in MU); unpaved road crossing density >0.40.
Likely Extirpated	Multiple surveys during a reasonable survey effort since 2000 found zero live or fresh dead individuals.	None	No sub-adults or gravid females present; fish host may or may not be present	Water quality limiting aquatic life and degraded to level to preclude mussel survival and recolonization	Flow regime does not support mussel survival	Instream habitat unable to support species survival; habitat extremely fragmented	N/A

For this evaluation, we concluded there was evidence of reproduction/recruitment for a population when surveys detected young individuals (age <7 years; Haag 2012, Appendix A) since the year 2000 at >50% of sites, >5 cohorts present, or gravid females (eggs or glochidia visible) observed during the reproductively active time of year (Table 4.3). We ranked populations with 25 – 50% of sites inhabited by young individuals, three to five cohorts present, or gravid females and fish hosts present in moderate numbers as medium (Table 4.3). Populations ranked low when <25% of sites were inhabited by young individuals, <3 cohorts present, or gravid females and fish hosts present in low numbers (Table 4.3). 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 4.3.

For each species and each MU, we developed and assigned condition categories for three population factors (population size and extent, reproduction/recruitment) and four habitat factors (water quality, flow, landscape, and habitat fragmentation; see Section 3.2.A-B). The current condition is a qualitative estimate based on the analysis of these seven factors. We calculated occupied stream length using ArcGIS for Western Fanshell and Google Earth for “Ouachita” Fanshell by summing rkm between occurrence records since 2000 based on available survey data. We summed all live individuals since 2000 to determine population size. We determined reproduction/recruitment based on number of cohorts, presence of gravid females and fish hosts, or presence of young individuals (age <7 years) where data was available.

We determined overall population condition (PC) ranking by adding population extent (PE) and population size (PS) and then adding reproduction/recruitment (R). For example, a high PE plus low PS equals medium PE+PS. We then added R to PE+PS to determine the overall population condition ranking. We erred conservatively on the species side when two factors scored high + medium or medium + low and selected the lower score. Since population factors are a direct indicator of Fanshell mussel condition, we weighted population factors two times higher than habitat factors (indirect measures) when estimating overall current condition (e.g., PC + PC + habitat condition = overall current condition).

4.2.B Habitat Factors

We evaluated temperature and select nutrient and metals with acute and chronic toxicity data available in the scientific literature as they relate to our likelihood of persistence (Table 4.4). For Western Fanshell, we used ambient water quality data from 1990 – 2018 available from the National Water Quality Monitoring Council’s Water Quality Portal Water Quality Portal. For “Ouachita” Fanshell, we used ambient water quality data from 1990 – 2018 from the Arkansas Department of Environmental Quality’s Water Quality Monitoring Database for occupied stream reaches. If all concentrations for the evaluated water quality parameters were below the most conservative acute toxicity (EC_{50}) values for mussels, we considered water quality suitable (High; Table 4.3). If concentrations exceeded the most conservative acute toxicity values for mussels in <2% of samples (2000 – 2018) and generally exceeded acute toxicity levels < once per year, we considered water quality medium (Table 4.3). Populations with water quality concentrations > acute toxicity levels for >2% of samples (2000 – present) and generally multiple times per year, we ranked water quality low (Table 4.3). Our approach accounts for sensitivity variation across life stages (see Chapter 5). There a several limitations to this approach. First, mussels also may be responding more to sediment quality rather than water quality. However, sediment quality data were generally lacking for both species except in the Spring River basin in Kansas and Missouri (Tri-state Mining District). Second, we do not know of thresholds where any exposure results in 100 percent mortality. Finally, ambient water quality data is generally collected once per month and does not tell us the duration or range of exposure to toxic constituent concentrations for the period between samples. However, in the absence of continuous monitoring data, it provides some insight into environmental conditions experienced by the Fanshell mussels.

Table 4.4 Acute toxicity levels used to evaluate water quality effects on our likelihood of persistence for Western Fanshell and "Ouachita" Fanshell ([1]Augspurger *et al.* (2003, p. 2569); [2]Camargo *et al.* (2005, p. 1255); [3]Wang *et al.* (2010, p. 2059); [4]Gillis *et al.* (2008, p. 143).

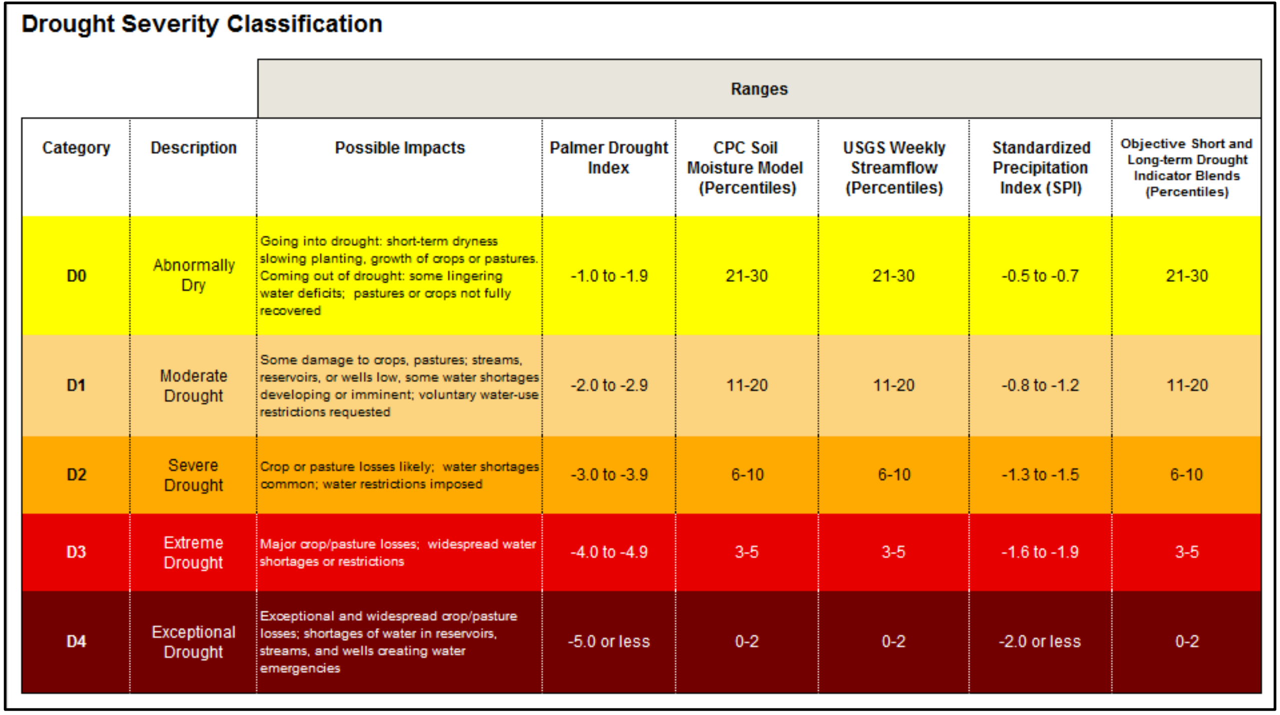
Total Ammonia Nitrogen	**Nitrate + Nitrite**	**Cadmium**	**Copper**	**Zinc**	**Lead**
0.3 - 1.0 mg TAN/L at pH 8 and 25°C[1]	2.0 mg NO_3-N/L[2]	0.014 mg/L[3] (Hardness normalized 50 mg/L $CaCO_3$)	0.014 mg/L[4] (Hardness normalized 50 mg/L $CaCO_3$)	0.120 mg/L[3] (Hardness normalized 50 mg/L $CaCO_3$)	0.205 mg/L[3] (Hardness normalized 50 mg/L $CaCO_3$)

To evaluate how flow influences current condition for the Fanshell mussels, we used a statewide water use vulnerability sub-index score for each MU from the 2016 EPA Preliminary Healthy Watersheds Assessment (PHWA; February 8, 2017 version), known flow issues, and U.S. Drought Monitoring Data. The Water Use Vulnerability Sub-Index characterizes the vulnerability of aquatic ecosystems in a MU to future increases in water use based on 2005 estimates of agricultural, domestic, and industrial water use. We used the US Drought Monitor graphics to assess flow conditions from 2000 – 2019 to identify times that mussels were exposed to consecutive droughts (Appendix V-1 – V-2). We discuss precipitation, flow, and percent impervious cover models used for future conditions in Chapter 5. The flow needs of both mussel species appear in Table 4.3.

To evaluate the effects of various land use activities on our likelihood of persistence, we used a suite of landscape metrics using the National Land Cover Dataset (Dewitz, 2019) to determine percent imperviousness, percent forested riparian (within 108 m of stream banks), percent urban, percent agriculture, and density of unpaved roads. The landscape needs of both mussel species appear in Table 4.3. To evaluate the influence of factors affecting habitat fragmentation in Fanshell mussel MUs, we considered the number of dams from the 2012 National Anthropogenic Barrier Dataset and number of unpaved road crossings (Table 4.5). We assume the majority of unpaved road crossings are barriers to fish dispersal, but acknowledge the number is probably an over estimate since some crossings may be low water fords or bridged. Based on information from current aquatic organism passage projects, we determined barrier removal is 1 – 2 per decade for each MU.

For water quality (WQ), we evaluated ambient water quality data from 1990 – 2018 available from the National Water Quality Monitoring Council for Western Fanshell and Arkansas Department of Environmental Quality for "Ouachita" Fanshell. We only used data available from monitoring stations on streams currently occupied by the Fanshell mussels. We considered using the number of National Pollutant Discharge Elimination System permits (NPDES), but found no additional value in using this information. Using conservative acute toxicity data for mussels available in the scientific literature, we determined the number of occurrences where ambient water quality for select parameters exceeded concentrations known to be protective of mussel life stages (Table 4.4). We selected these parameters because of the extensive data available in the scientific literature. Our results indicated that TAN and cadmium were not stressors to either species now or in future scenarios. Therefore, we include the results from these constituents, but eliminated them from our WQ scores. We recognize other pollutants may be acting on Fanshell mussel populations, and in some instances limited toxicity data may be available, but there is insufficient literature and/or monitoring data available to evaluate other parameters. See Table 4.3 for a description of each WQ category and Table 4.4 for acute toxicity thresholds.

Figure 4.3 U.S. Drought Monitor severity classification system (U.S. Drought Monitor).



Drought Severity Classification

			Ranges				
Category	**Description**	**Possible Impacts**	**Palmer Drought Index**	**CPC Soil Moisture Model (Percentiles)**	**USGS Weekly Streamflow (Percentiles)**	**Standardized Precipitation Index (SPI)**	**Objective Short and Long-term Drought Indicator Blends (Percentiles)**
D0	Abnormally Dry	Going into drought: short-term dryness slowing planting, growth of crops or pastures. Coming out of drought: some lingering water deficits; pastures or crops not fully recovered	-1.0 to -1.9	21-30	21-30	-0.5 to -0.7	21-30
D1	Moderate Drought	Some damage to crops, pastures; streams, reservoirs, or wells low, some water shortages developing or imminent; voluntary water-use restrictions requested	-2.0 to -2.9	11-20	11-20	-0.8 to -1.2	11-20
D2	Severe Drought	Crop or pasture losses likely; water shortages common; water restrictions imposed	-3.0 to -3.9	6-10	6-10	-1.3 to -1.5	6-10
D3	Extreme Drought	Major crop/pasture losses; widespread water shortages or restrictions	-4.0 to -4.9	3-5	3-5	-1.6 to -1.9	3-5
D4	Exceptional Drought	Exceptional and widespread crop/pasture losses; shortages of water in reservoirs, streams, and wells creating water emergencies	-5.0 or less	0-2	0-2	-2.0 or less	0-2

When determining overall WQ scores, we scored each of four parameters ($NO_3 + NO_2$, zinc, copper, and lead) in Table 4.6. When >2 parameters scored low or medium, we assigned an overall WQ score of low or medium, respectively. When one parameter scored low and one parameter medium, we assigned an overall WQ score of medium. If one parameter scored low and three parameters high, we assigned an overall WQ score of medium. When one parameter scored medium and the remaining parameters high, we assigned an overall WQ score of high.

For flow (F), we evaluated known flow issues, drought (Appendix V-1 – V-2), and PHWA Water Use Vulnerability Index (Appendix I-B – I-C). A description of these indicators appears in Table 4-1. When determining current condition F scores, we determined overall H score by adding water use vulnerability, known flow conditions, and drought (e.g., high + medium + low = medium, low + low + high = medium, high + high + medium = high). When two indicators scored the same and the other one level higher or lower, we selected the score of the two scoring the same (e.g., 2 high + 1 medium = high). When two indicators scored the same and the other two levels higher or lower, we selected the intermediate score (e.g., 2 high + 1 low = medium).

For landscape (L), we evaluated condition of riparian forests, percent urban, percent agriculture, percent imperviousness, and unpaved road density (Appendix I-A). A description of these indicators appears in Table 4-5. We weighted each metric equally. When three metrics scored high and three medium (or medium and low), we erred on the side of the species and selected medium. Similarly, three high scores and three low scores results in an overall medium L score.

We followed a similar methodology for habitat fragmentation (HF) (dam count and unpaved road stream crossing density) with each metric weighted equally. When determining overall HF scores, we scored the two elements in Table 4.5. We assigned the lower HF score when within one unit higher or lower (e.g., high HF + medium HF = medium) and intermediate score (medium) when high plus low.

We determined overall habitat factor scores similar to L scores (e.g., 4-5 elements high + 1-2 low = high, 3 elements high + 3 elements medium = medium, 3 elements high + 3 low = medium). The resulting current condition value or category for each population is a qualitative estimate based on the analysis of the three population and four habitat factors. We then consulted state malacologists for each state within both species' ranges for their input to finalize rankings for population and habitat factors.

4.3 Current Condition

4.3.A Western Fanshell Current Condition

Based on our analysis, the total combined stream length currently occupied by the 11 remaining Western Fanshell populations described in this chapter is approximately 1,413.8 rkm. As stated in this chapter, it is difficult to determine the historical rkm occupied by the species prior to construction of dams and navigation projects. We assume Western Fanshell occurred throughout the inundated, tailwater, cutoff tributaries and navigation channel reaches of the Neosho River, Verdigris River, Elk River, Caney River, War Eagle Creek, Big Piney Creek, White River, and the Eleven Point, Current, and St. Francis rivers in Arkansas. The loss of these areas represent approximately 2,113.5 rkm. Therefore, Western Fanshell currently persists in approximately 40% of its historical range.

To summarize the overall current conditions of Western Fanshell populations, we assigned each population to one of four condition categories (high, medium, low, or extirpated) based on an evaluation of the seven population and habitat factors discussed in Chapter 3. Table 4.3 provides the definitions we used to assign conditions for the seven factors. Table 4.7 presents the condition we assigned for the seven factors as well as the overall condition for each of 11 remaining Western Fanshell populations. We also display the overall condition of each population graphically in Figure 4.4. Current condition data for water quality, flow, landscape, and habitat fragmentation appear in Table 4.6 and Appendices I-A – I-B.

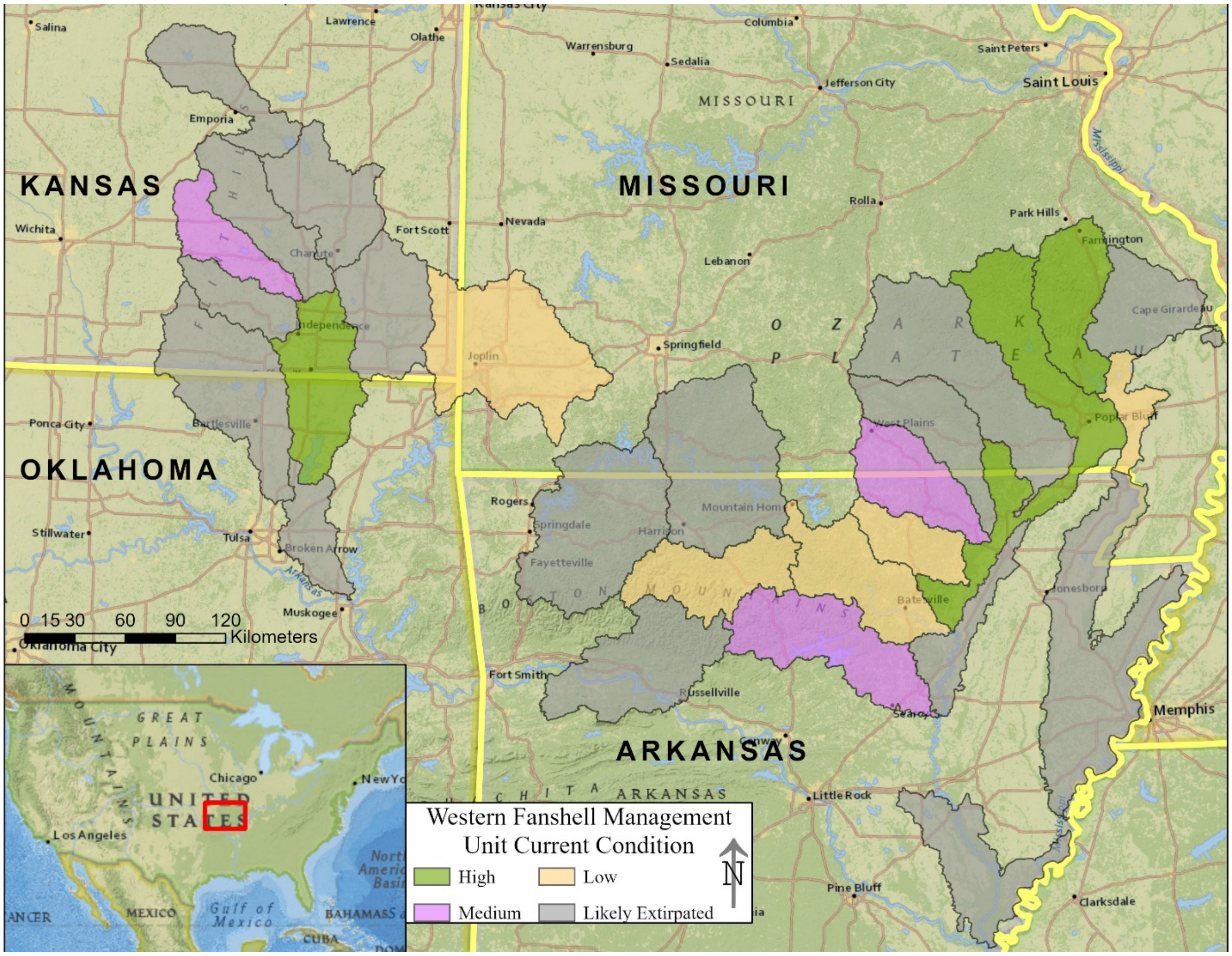


Figure 4.4 Distribution of the current and historically occupied management units (MUs) of Western Fanshell in the United States. Currently occupied MUs are represented with high, medium, low, and likely extirpated condition categories as described in Chapter 3.

4.3.A.1 Current Population Resiliency

Within the Lower Mississippi–St. Francis River basin in Missouri, Western Fanshell currently has two populations, one in the Lower St. Francis River (below Lake Wappapello) and Upper St. Francis River (above Lake Wappapello). The Lower St. Francis River is approximately 456 rkm, but Western Fanshell only occurs at 1 site 0.8 rkm below Wappapello Dam. The current condition evaluation for this population found that population size, extent, and reproduction/recruitment were in low condition (Tables 4.7 and 4.8) despite all habitat factors being in medium condition (Table 4.7, Appendix I-B). This suggests that metrics other than those evaluated in this assessment are influencing population resiliency. We assigned an overall low current condition to this population based on all population factors being low and PE of one site (e.g., PC low + PC low + habitat high = low).

Table 4.5 Landscape, flow, habitat fragmentation and water quality current condition indicators and rankings for Western Fanshell and "Ouachita" Fanshell.

Habitat Factors	Current Condition Indicator	Description of Indicator	High Condition	Moderate Condition	Low Condition
Landscape	% Imperviousness, Mean in WS (2016)	Percent of the MU with developed impervious cover. Calculated as the mean value of percent developed imperviousness in the MU. Stressor: suspended sediment, habitat instability due to altered flow regime	<10	11-15	>15
	% Forested Riparian Remaining in WS	Percent of the MU that is in the Riparian Zone and classified as forest cover by the 2016 NLCD Land Cover dataset. Forest cover classes include 'Deciduous Forest' (code 41), 'Evergreen Forest' (code 42), 'Mixed Forest' (code 43), and 'Woody Wetlands' (code 90) in the 2016 NLCD Land Cover dataset. Calculated as forest area in the Riparian Zone divided by MU area, multiplied by 100. (See also 2016 NLCD Land Cover and Riparian Zone glossary definitions). Stressor: increased suspended sediment, habitat instability	>75	50-75	<50
	Density of Unpaved Roads in WS	km of unpaved road in MU divided by area (km^2) of MU. Stressor: increased suspended sediment	0-0.5	0.6-1.0	>1.0
	% Urban in WS (2016)	Percent of the MU classified as urban cover by the 2016 NLCD Land Cover dataset. Calculated as urban area divided by MU area, multiplied by 100. Stressor: increased suspended sediment, contaminants, habitat instability	<5	5-10	>10
	% Ag in WS (2016)	Percent of the MU classified as agriculture cover by the 2016 NLCD Land Cover dataset. Calculated as agriculture area in the MU divided by MU area, multiplied by 100. Stressor: increased suspended sediment, contaminants, habitat instability	<25	25-40	>40
Flow	PHWA Water Use Vulnerability Sub-Index (2016)	The statewide Water Use Vulnerability Sub-Index score for the MU from the 2016 EPA Preliminary Healthy Watersheds Assessment (PHWA). The Water Use Vulnerability Sub-Index characterizes the vulnerability of aquatic ecosystems in a MU to future increases in water use based on recent (2005) estimates of agricultural, domestic, and industrial water use in the MU. Source data were statewide Water Use Vulnerability Sub-Index scores for MUs developed as part of the 2016 EPA Preliminary Healthy Watersheds Assessment (February 8, 2017 version). (See also PHWA glossary definition). Stressor: habitat instability	0-0.25	0.26-0.49	0.5-1
	Known flow issues	Known flow issues arising from a variety of uses such as hydro-electric, municipal or industrial withdrawals, or irrigation. Stressor: habitat instability, increased contaminant exposure	No	Yes, but affects to mussel community unknown	Yes, with known affects to mussel community
	Drought	Consecutive weeks of extreme low flow (< 10th percentile flow frequency) and multi-year droughts classified as severe/exceptional. Stressor: habitat instability, degradation and availability, DO reduction, increased water temperature	Flows < 5th percentile flow >21 but <30 consecutive days rare, multi-year extreme - exceptional droughts rare	flowing water present year round or flows <5th percentile >30 but <45 consecutive days only occur during multi-year extreme-exceptional droughts in suitable habitat	multi-years of exceptional drought and flows <5th percentile >45 consecutive days
Habitat Fragmentation	Count Dams (2012)	The number of dams in the MU. Source data 2012 National Anthropogenic Barrier Dataset (NABD). Stressor: genetic isolation, fish host dispersal, habitat degradation	<10	10-30	>30
	Unpaved road stream crossing density (# crossings/MU stream length)	The number of unpaved road crossings in the MU divided by stream length in the MU. Stressor: genetic isolation, fish host dispersal, increased suspended sediment, habitat degradation	0 - 0.20	0.21 - 0.40	> 0.40
Water Quality	TAN (mg/L)	Total ammonia nitrogen concentration in surface water (data collected by State water quality monitoring programs, 1990 - present)	Concentrations at levels below acute toxicity to mussels (1990 - 2018).	Concentration exceeds acute toxicity levels to mussels <2% of samples (2000 - present), generally exceeds acute toxicity levels <1X/year	Concentration exceeds acute toxicity levels >2% of samples (2000 - present), generally exceeds acute toxicity levels multiple times/year.

Habitat Factors	Current Condition Indicator	Description of Indicator	High Condition	Moderate Condition	Low Condition
	NO3 + NO2 (mg/L)	Nitrate + nitrite concentration in surface water (data collected by State water quality monitoring programs, 1990 - present)	Concentrations at levels below acute toxicity to mussels (1990 - 2018).	Concentration exceeds acute toxicity levels to mussels <2% of samples (2000 - present), generally exceeds acute toxicity levels <1X/year.	Concentration exceeds acute toxicity levels >2% of samples (2000 - present), generally exceeds acute toxicity levels multiple times/year.
	Cadmium (mg/L)	Hardness normalized cadmium concentration in surface water (data collected by State water quality monitoring programs, 1990 - present).	Concentrations at levels below acute toxicity to mussels (1990 - 2018).	Concentration exceeds acute toxicity levels to mussels <2% of samples (2000 - present), generally exceeds acute toxicity levels <1X/year.	Concentration exceeds acute toxicity levels >2% of samples (2000 - present), generally exceeds acute toxicity levels multiple times/year.
	Copper (mg/L)	Hardness normalized copper concentration in surface water (data collected by State water quality monitoring programs, 1990 - present)	Concentrations at levels below acute toxicity to mussels (1990 - 2018).	Concentration exceeds acute toxicity levels to mussels <2% of samples (2000 - present), generally exceeds acute toxicity levels <1X/year	Concentration exceeds acute toxicity levels >2% of samples (2000 - present), generally exceeds acute toxicity levels multiple times/year.
	Zinc (mg/L)	Hardness normalized zinc concentration in surface water (data collected by State water quality monitoring programs, 1990 - present)	Concentrations at levels below acute toxicity to mussels (1990 - 2018).	Concentration exceeds acute toxicity levels to mussels <2% of samples (2000 - present), generally exceeds acute toxicity levels <1X/year	Concentration exceeds acute toxicity levels >2% of samples (2000 - present), generally exceeds acute toxicity levels multiple times/year.
	Lead (mg/L)	Hardness normalized lead concentrations in surface water (data collected by State water quality monitoring programs, 1990. - present)	Concentrations at levels below acute toxicity to mussels (1990 - 2018).	Concentration exceeds acute toxicity levels to mussels <2% of samples (2000 - present), generally exceeds acute toxicity levels <1X/year.	Concentration exceeds acute toxicity levels >2% of samples (2000 - present), generally exceeds acute toxicity levels multiple times/year.

Table 4.6 Water quality ranges and overall current water quality condition for Western Fanshell (bottom table) and "Ouachita" Fanshell (top table). U is undetected.

MU	# Stations	Period of Record	TAN (mg/L)	NO3 + NO2 (mg/L)	Cadmium (mg/L)	Copper (mg/L)	Zinc (mg/L)	Lead (mg/L)	pH	Hardness (mg/L CaCO3)	Turbidity (NTU)	Overall WQ Score
Saline	7	Sep 1990 - Mar 2018	U - 0.2	U - 7.80	U - 0.0021	U - 0.018	U - 0.123	U - 0.012	4.5 - 8.8	12 - 81	0.8 - 164	Medium
Ouachita Headwaters	3	Sep 1990 - Mar 2018	U - 0.1	U - 1.40	U - 0.0002	U - 0.044	U - 0.031	U - 0.002	4.3 - 8.1	5 - 59	0.9 - 142	High
Upper Ouachita	6	Sep 1990 - Mar 2018	U - 0.3	U - 1.20	U - 0.0026	U - 0.045	U - 0.596	U - 0.029	4.9 - 9.9	11 - 97	1.3 - 390	Medium
Caddo	3	Sep 1990 - Mar 2018	U - 0.20	U - 1.00	U - 0.0028	U - 0.006	U - 0.006	U - 0.001	5.9 - 8.6	10 - 72	0.5 - 85	High

MU	# Stations	Period of Record	TAN (mg/L)	NO3 + NO2 (mg/L)	Cadmium (mg/L)	Copper (mg/L)	Zinc (mg/L)	Lead (mg/L)	pH	Hardness (mg/L CaCO3)	Turbidity (NTU)	Overall WQ Score
Black	10	Jan 1990 - Oct 2019	U - 0.21	U - 1.70	U - 0.003	U - 0.140	U - 0.410	0 - 0.006	6.2 - 8.7	24-226	0.1 - 260	Medium
Buffalo	17	Jan 1990 - July 2019	U - 0.19	U - 1.10	U - 0.003	U - 0.005	U - 0.019	U - 0.020	5.8 - 9.6	12.7 - 202	0.2 - 420	High
Fall	10	Jan 1990 - Oct 2016	U - 0.52	U - 0.92	U - 0.003	U - 0.033	U - 0.19	U - 0.010	6.5 - 8.4	84 - 310	1.0 - 770	High
Little Red	7	Jan 1990 - Mar 2018	U - 0.27	U - 0.90	U - 0.006	U - 0.087	U - 0.114	U - 0.029	5.1 - 9.5	5.95 - 231	0.8 - 497	High
Lower St. Francis	13	Jan 1990 - Jan 2011	U - 0.30	U - 2.43	U - 0.004	U - 0.034	U - 0.138	U - 0.002	6.0 - 8.8	16 - 247	0.1 - 973	Medium
Middle White	3	Jan 1990 - May 2019	U - 0.11	U - 0.87	U - 0.004	U - 0.0243	U - 0.252	U - 0.022	6.3 - 9.6	65.1 - 190	0.5 - 206	Medium
Middle Verdigris	11	Jan 1990 - Jan 2018	U - 0.53	U - 1.50	U - 0.0065	U - 0.049	U - 0.770	U - 0.038	6.8 - 9.1	75 - 290	1.8 - 760	Medium
Spring (MO)	11	Apr 1990 - Nov 2019	U - 1.70	U - 4.11	U - 0.005	U - 0.045	U - 1.200	U - 0.068	6.5 - 9.0	45 - 300	0.2 - 220	Low
Spring (AR)	5	Jan 1990 - Mar 2018	U - 0.18	U - 3.90	U - 0.004	U - 0.074	U - 0.256	U - 0.0068	6 - 10.2	3 - 345	0.6 - 340	Medium
Strawberry	7	Jan 1990 - Mar 2018	U - 0.09	U - 1.50	U - 0.001	U - 0.011	U - 0.052	U - 0.020	5.5 - 9.8	30.4 - 268	0.5 - 397	High
Upper St. Francis	2	Jan 1990 - Oct 2019	U - 0.79	U - 1.30	U - 0.004	U - 0.010	U - 0.065	U - 0.011	5.9 - 8.8	38.3 - 150	0.1 - 90	High

Table 4.7 Resiliency of Western Fanshell populations. See Table 4.3 for a description of condition categories. See Table 4.6 and Appendices 1-A – I-B for values used to determine each habitat factor condition.

HUC4	Management Unit	Population Size	Population Extent (rkm)	Reproduction	Combined Population Factors	Water Quality	Flow	Landscape	Habitat Fragmentation	Combined Habitat Factors	Overall Current Condition
Lower Mississippi–St. Francis	Lower St. Francis	Low	Low	Low	Low	Medium	Medium	Medium	Medium	Medium	Low
	Upper St. Francis	High	High	High	High	High	Medium	High	Medium	Medium	High
Neosho-Verdigris	Fall	Low	Medium	Medium	Medium	High	High	Medium	Medium	Medium	Medium
	Middle Verdigris	High	High	High	High	Medium	High	Medium	Medium	Medium	High
	Spring	Low	Low	Low	Low	Low	Medium	Low	Medium	Medium	Low
Upper White	Black	High	High	High	High	Medium	Medium	Medium	Medium	Medium	High
	Buffalo	Low	Low	Low	Low	High	Medium	High	High	High	Low
	Little Red	Medium	Medium	Medium	Medium	High	High	High	High	High	Medium
	Middle White	Low	Low	Low	Low	Medium	High	Medium	High	High	Low
	Strawberry	Low	Medium	Low	Low	High	High	Medium	High	High	Low
	Spring	Medium	High	Medium	Medium	Medium	High	Medium	Medium	Medium	Medium

The Upper St. Francis River population occupies approximately 80 rkm and is one of the best remaining populations range wide. The current condition evaluation (Tables 4.3, 4.5, Appendix I-B) for this population found that population size, extent, reproduction/recruitment, water quality and landscape were in high condition. Unpaved road stream crossing density, number of dams and drought conditions lowered the flow and habitat fragmentation factors to medium condition (Tables 4.3, AppendicesI-A – I-B). We assigned an overall high current condition to this population based on all population factors being high and an overall medium habitat score (e.g., PC high + PC high + habitat medium = high).

The Neosho-Verdigris River basin has three populations of Western Fanshell, one each in the Fall, Middle Verdigris and Spring rivers. The Spring River population is isolated from the Fall River and Verdigris River populations by multiple reservoirs. The Fall River population currently occupies 8 sites within 61.5 rkm, but collections include only 38 live individuals since 2000. The Fall River population current condition evaluation (Tables 4.7, 4.8, Appendix I-B) found that population extent, water quality and hydrological regime were in high condition and population size was low. Unpaved road density, percent agriculture, percent forested riparian, watershed health index, and number of dams lowered the landscape and habitat fragmentation factors (along with reproduction/recruitment) to medium condition (Tables 4.7, 4.8, Appendix I-A). We assigned an overall medium current condition to this population based on an overall medium population factor score and an overall medium habitat score (e.g., PC medium + PC medium + habitat medium = medium).

The Middle Verdigris River population is one of the best populations left. It currently occupies 80 rkm, mostly in Kansas. Numbers have been increasing since 1991, with a couple substantial increases (E. Miller 2019, pers. comm.), suggesting recruitment is occurring. The current condition evaluation for this population found population size, extent, and reproduction/recruitment in high condition (Table 4.8). Water quality and flow were also in high condition (Tables 4.7, Appendix I-B). Unpaved road density, unpaved road stream crossing density, percent forested riparian, percent agriculture, and number of dams lowered the landscape and habitat fragmentation factors to medium (Tables 4.7, Appendices I-A – I-B). We assigned an overall high current condition to this population based on all population factors being high and an overall medium habitat score (e.g., PC high + PC high + habitat medium = high).

The Spring River population has been declining, and two tributary populations are likely extirpated. This basin is within the Tri-State Mining District with a long history of heavy metal mining; see Chapter 5 for more information. The Spring River population current condition evaluation found that unpaved road density, unpaved road stream crossing density, percent forested riparian, percent agriculture, percent urban, drought, and number of dams cause the flow and habitat fragmentation to score medium and landscape low (Tables 4.7, Appendices I-A – I-B). Population size, extent, and reproduction/recruitment were in low condition (Tables 4.7 & 4.8). Copper concentrations exceed acute toxicity thresholds in <2% of samples and Zinc and $NO_3 + NO_2$ concentrations exceed acute toxicity thresholds in >2% of samples (Table 4.6), resulting in a low water quality condition. We assigned an overall low current condition to this population based on a low combined population factors and a medium combined habitat factor score (e.g., PC low + PC low + habitat medium = low overall condition).

The Upper White River basin has six populations of Western Fanshell including the Black, Buffalo, Little Red, Middle White, Strawberry, and Spring Rivers in Missouri and Arkansas. The Black River population is possibly the best Western Fanshell population. It currently occupies 105 rkm, most of which is within a 75 rkm in Missouri. During the last comprehensive survey (2003), 794 live individuals were collected from 37.2% of the sites sampled (19 sites) and the population appeared to be recruiting. The Black River population current condition evaluation found that population size, extent, reproduction/recruitment, and water quality were in high condition (Tables 4.7 and 4.8). Unpaved road density, unpaved road stream crossing density, percent forested riparian, percent agriculture, drought conditions, known flow issues, and number of dams lowered the landscape, habitat fragmentation, and flow factors to medium (Tables 4.7, Appendices I-A – I-B). We assigned an overall high current condition to this population based on all population factors being high and an overall medium habitat score (e.g., PC high + PC high + habitat medium = high).

The Buffalo River population currently occupies 5 sites within 144.8 rkm, but since 2000, surveyors found only 9 live or fresh dead shells. The Buffalo River population current condition evaluation found that water quality, landscape, and habitat fragmentation were in high condition, while all population factors were in low conditions (Tables 4.7 and 4.8). Recent drought durations lower the flow to a medium condition. We assigned an overall low current condition to this population, despite the habitat factors being high, based on all population factors being low (e.g., PC low + PC low + habitat high = low).

The Little Red River population consists of a 35 rkm reach within the Middle Fork Little Red River and one site in the Beech Fork Little Red River totaling 340 live individuals. The Little Red River population current condition evaluation found that all habitat factors were in high condition, and all population factors were in medium condition. We assigned an overall medium current condition to this population based on an overall medium population factor score and an overall high habitat score (e.g., PC medium + PC medium + habitat high = medium).

The Middle White River population currently consists of two sites in the White River. The Middle White River population current condition evaluation found that occupied habitat water quality, flow, and habitat fragmentation were in high condition, while all population factors were in low condition (Tables 4.7, 4.8, Appendix I-B). Unpaved road density, percent forested riparian, and percent urban lowered the landscape factor to medium (Tables 4.7, Appendices I-A – I-B). We assigned an overall low current condition to this population based on the low population conditions (e.g., PC low + PC low + habitat high = low).

The Spring River population consists of 12 sites within 58.75 rkm in the South Fork Spring River and 9 sites within 21 rkm in the Spring River. The Spring River population current condition evaluation found that occupied habitat population extent and flow were in high condition (Tables 4.7, 4.8, Appendix I-B). Population numbers were close to being high and with multiple age classes, but evidence of recent recruitment is lacking causing population size and

Table 4.8 Resiliency metrics for Western Fanshell population factors. See Table 4.3 for a description of condition categories.

HUC4	Management Unit	Population Size	Population Extent (rkm)	Reproduction	Combined Population Factors
Lower Mississippi–St. Francis	Lower St. Francis River	5	<1	Few individuals, abundance & # sites declining, no evidence of recent recruitment	Low
	Upper St. Francis River	439	80	Multiple age classes documented in 2012	High
Neosho-Verdigris	Fall River	38	60	Low abundance & number of sites, multiple size classes, evidence of recent recruitment	Medium
	Middle Verdigris River	498	80	High abundance & number of sites, multiple size classes, evidence of recent recruitment	High
	Spring River	10	25	Few individuals, abundance & # sites declining, no evidence of recent recruitment	Low
Upper White	Black River	918	75	Multiple age classes documented in 2012	High
	Buffalo River	9	115	Few individuals, abundance & # sites declining, no evidence of recent recruitment	Low
	Little Red River	359	40	High abundance & number of sites, multiple size classes, evidence of recent recruitment	Medium
	Middle White River	3	5	Few individuals, abundance & # sites declining, no evidence of recent recruitment	Low
	Spring River	372	100	Population size medium, # sites low & widely distributed within extant reach, multiple size classes but evidence of recent recruitment lacking	Medium
	Strawberry River	50	65	Population size low, # sites low & widely distributed within extant reach, unknownd data on multiple size classes/recent recruitment	Low

reproduction/recruitment to be in medium condition. Copper, Zinc, and $NO_3 + NO_2$ concentrations exceed acute toxicity thresholds in <2% of samples (Table 4.6), resulting in a medium water quality condition. Unpaved road density, unpaved road stream crossing density, percent forested riparian, percent agriculture, percent urban and number of dams lowered the landscape and habitat fragmentation factors to medium (Tables 4.7, Appendices I-A – I-B). We assigned an overall medium current condition to this population based on the overall medium population and habitat conditions (e.g., PC medium + PC medium + habitat medium = medium). The Strawberry River population currently occupies 11 sites within 65 rkm in the Strawberry River. The Strawberry River population current condition evaluation found that occupied habitat water quality, flow, and habitat fragmentation were in high condition. Unpaved road density, percent forested riparian, percent urban, and percent agriculture lowered the landscape and population extent factors to medium (Tables 4.7, 4.8, Appendices I-A – I-B). Unknown data on recruitment and low numbers cause population size and reproduction/recruitment to be in low conditions. We assigned an overall low current condition to this population based on the low population conditions (e.g., PC low + PC low + habitat high = low).

4.3.A.2 Representation

We used contiguous (hydrologically connected without major barriers) hydrologic units (based on the HUC 4 level; see additional discussion in Chapter 3) as a proxy to help define representation because watershed boundaries and natural and artificial barriers constrain ecological processes, such as genetic exchange and ultimately adaptive capacity for aquatic species (Funk *et al*. 2018, p. 14). We consider Western Fanshell to have representation in the form of genetic, ecological, and geographical diversity between three HUC4 basins: Lower Mississippi–St. Francis, Neosho–Verdigris, and Upper White (refer to section 3.2). The best available data indicates likely extirpation of the Western Fanshell from the Lower Arkansas HUC4, as there is only one collection of a dead shell from Big Piney Creek. The species currently ranges across the three HUC4 basins with high condition MUs in each (Black, Middle Verdigris, and Upper St. Francis) and medium condition MUs within Neosho–Verdigris and Upper White (Fall, Little Red, and Spring). However, it is at the highest risk of losing HUC4 representation in the Lower Mississippi–St. Francis basin, with the Upper St. Francis MU containing the only stable population. Barriers (i.e. dams) prevent movement between the three extant basins.

4.3.A.3 Redundancy

Western Fanshell populations are widely distributed over four states and the redundancy metric we use in this SSA is number of populations and MUs (Tables 4.1, 4.7). The Lower Mississippi–St. Francis River basin contains two populations and two MUs; the Neosho–Verdigris River basin contains three populations and three MUs; and the upper White River basin contains eight populations and six MUs. The total number of extirpated populations and MUs by river basin are: one population (one MU) in the lower Arkansas, four populations (two MUs) in the Lower Mississippi–St. Francis, nine populations (seven MUs) in the Neosho–Verdigris, and six populations (five MUs) in the upper White. Given the current status encompasses 13 populations and 11 MUs throughout its range, the species currently retains redundancy for withstanding and surviving potential catastrophic events. However, it is important to note that a high percentage (45%) of MUs are currently in low condition. Overall, the species has decreased redundancy across its range compared to its historical range caused by the estimated 60% reduction in occupancy and the extirpation of 16 MUs (59%).

4.3.B “Ouachita” Fanshell Current Condition

Based on our analysis, the total combined stream length currently occupied by the four remaining “Ouachita” Fanshell populations described in this chapter is approximately 465 rkm. It is difficult to determine the historical rkm occupied by the species prior to construction of dams and navigation projects. Therefore, we assume “Ouachita” Fanshell occurred throughout the inundated, tailwater, and navigation channel reaches of the main stem Ouachita River extending downstream to at least the confluence of Bayou Bartholomew, throughout at least 50% of Bayou Bartholomew, and in the lower inundated and tailwater reaches of the Caddo River. The loss of these areas represent approximately 415 rkm and hydrologically isolates the remaining populations. Therefore, “Ouachita” Fanshell currently persists in approximately 53% of its historical range with low resiliency in 50% of the extant populations (Table 4.11).

To summarize the overall current conditions of “Ouachita” Fanshell MUs, we assigned each population to one of four condition categories (high, moderate, low, or likely extirpated) based on an evaluation of the seven population and habitat factors discussed in Chapter 3. Table 4.3 provides the definitions we used to assign conditions for the seven factors. Table 4.11 presents the condition we assigned for the seven factors as well as the overall condition for each of the four remaining “Ouachita” Fanshell MUs. We also display the overall condition of each population graphically in Figure 4.5.

4.3.B.1 Current Population Resiliency

We describe resiliency in Section 4.3.A.1. Based on our analysis, the “Ouachita” Fanshell currently persists as five populations within four MUs in Arkansas and within portions of the Ouachita River basin (HUC4). Within the Caddo River MU, “Ouachita” Fanshell currently occupies one site within an area that as recently as the early 1990s included seven sites scattered from approximately Glenwood to Amity, Arkansas (B. Posey 2014, pers. comm.; C. Davidson 2019, unpublished data). The current condition evaluation for this population found that population size, extent, and reproduction/recruitment were in low condition (Tables 4.9 – 4.10) despite all habitat factors being in high condition (Table 4.9). This suggests that metrics other than those evaluated in this assessment are influencing population resiliency. We assigned an overall low current condition to this population based on all population factors being low and PE of one site (e.g., PC low + PC low + habitat high = low).

Since 2000, comprehensive survey efforts in the Ouachita Headwaters report “Ouachita” Fanshell from 14 sites within a 43 rkm reach (B. Posey 2014, pers. comm.; C. Davidson 2019, unpublished data). However, the most recent comprehensive survey (2014) found 29 individuals from 2 sites within 0.8 rkm (C. Davidson 2019, unpublished data). This population continues to

Table 4.9 Resiliency of "Ouachita" Fanshell populations. See Table 4.3 for a description of condition categories. See Table 4.6 and Appendices 1-A and I-C for values used to determine each habitat factor condition.

HUC4	**Management Unit**	**Population Factors**			**Combined Population Factors**	**Habitat Factors**				**Combined Habitat Factors**	**Overall Current Condition**
		Population Size	**Population Extent**	**Reproduction**		**Water Quality**	**Flow**	**Landscape**	**Habitat Fragmentation**		
Lower Red-Ouachita	Caddo	Low	Low	Low	Low	High	High	High	High	High	Low
	Ouachita Headwaters	Low	Medium	Low	Low	High	High	High	Medium	High	Low
	Saline	High	High	High	High	Medium	Medium	High	Medium	Medium	High
	Ouachita	Low	High	Medium	Medium	Medium	Medium	High	Medium	Medium	Medium

experience substantial declines also observed for the entire mussel community in the Ouachita Headwaters. As a result, the current condition evaluation for this population found population size and reproduction/recruitment in low condition, while population extent was in moderate condition (Table 4.10). Water quality, flow, and landscape scored high (Tables 4.9, Appendix I-C). Unpaved road stream crossing density and number of dams lowered the habitat fragmentation factor to medium (Tables 4.11, Appendices I-A & I-C). We assigned an overall low current condition to this population based on low combined population factors and a medium combined habitat factor score (e.g., PC low + PC low + habitat high = low overall condition) (Table 4.9).

Table 4.10 Resiliency metrics for "Ouachita" Fanshell population factors in the Caddo River MU. See Table 4.3 for a description of condition categories.

Management Unit	Population Size	Population Extent (rkm)	Reproduction	Combined Population Factors
Caddo River	19	1 site	Few individuals, abundance & # sites declining, no evidence of recent recruitment	Low
Ouachita Headwaters	46	43.0	Few individuals, abundance & # sites declining, no evidence of recent recruitment	Low
Saline River	2,651	304.2	High abundance & number of sites, multiple size classes, evidence of recent recruitment	High
Upper Ouachita	48	210.8	Population size low, # sites low & widely distributed within extant reach, multiple size classes but evidence of recent recruitment lacking	Medium

The Saline River population is the last stronghold for "Ouachita" Fanshell. The species is widely distributed throughout the main stem except the lowermost 32 rkm affected by Felsenthal Lock and Dam on the Ouachita River (Davidson 1997, Appendices 1.2 – 1.3; 2015, pp. 1 – 2, 28). Since 2000, extensive comprehensive survey efforts of the main stem Saline River report 2,651 individuals from 153 sites. Population estimates per mussel bed, where available, range from 933 ± 654 – 18,800 ± 5,074 individuals (19, unpublished data; Davidson and Clem 2002, Appendix 2; 2004, Table 2; Davidson and Gosse 2001, p. 6; 2003, pp. 187 – 191). Our evaluation of current population factors found the Saline River population in high condition. Copper, Zinc, and NO_3 + NO_2 concentrations exceed acute toxicity thresholds <2% of samples (Table 4.3), resulting in a moderate condition for water quality. Number of dams and unpaved road stream crossing density lowered habitat fragmentation to moderate condition (Table 4.9, Appendices I-A – I-C), while drought and documented mussel die-offs due to low water (C. Davidson 2019, unpublished data) lowered flow condition to moderate (Appendix I-C). Despite all habitat factors being medium, the current size, extent, and evidence of reproduction/recruitment elevate the overall current condition of this population to high (e.g., PC high + PC high + habitat medium = high overall condition; Table 4.10).

Posey (1997, pp. 43 – 59) conducted the last comprehensive survey of the Ouachita River between the Little Missouri River confluence and Camden, Arkansas. He reported population estimates generally from 100 – 1,000 individuals at five locations (Posey 1997, Appendix 1.3). There is no comprehensive survey data available from the Caddo River confluence to the Little Missouri River confluence. Since 2000, there have been observations of 45 live "Ouachita" Fanshell individuals from 13 sites surveyed by Posey (1997) and 1 site between the Caddo and Little Missouri River confluences (C. Davidson 2019, unpublished data; Harris 2006, Appendices 1e – 1j; 2017, p. 14, Appendix A). Christian and Harris (2004, Tables 1 – 3) reported three live individuals from the Little Missouri River at three sites. Based on our evaluation of population factors for the Upper Ouachita MU, population size is low and population extent high (Table 4.10). There is no information available on reproduction for this MU. Therefore, the overall PC is medium (Table 4.10). After consulting state malacologists, we determined that a medium ranking was appropriate. All habitat factors scored medium except landscape was high (Table 4.9), resulting in an overall condition of medium (PC medium + PC medium + habitat medium = overall medium).

The "Ouachita" Fanshell historically occurred in Bayou Bartholomew (Vidrine 1995, p. 88), but recent surveys failed to locate live specimens (Alley 2005, Appendices 3 – 4; Brooks *et al*. 2008, pp. 13 – 15; Pezold *et al*. 2002, entire). We consider this population likely extirpated and did not analyze habitat factors.

4.3.B.2 Representation

We consider "Ouachita" Fanshell to have low adaptive potential in the form of genetic, ecological, and geographical diversity since it occurs only in the Ouachita River basin. Furthermore, dams and a navigation channel isolate the major tributaries and main stem Ouachita River reducing freshwater connections within the river basin. While the species appears to be endemic to the Ouachita River basin (no river basin (HUC 4) variability), its distribution is greatly reduced in three of four MUs (Caddo, Ouachita Headwaters, and Upper Ouachita). In part, the distribution reductions are due to anthropogenic fragmentation of rivers and then more recently by other anthropogenic and natural factors.

4.2.B.3 Redundancy

Within the single representation area, there are currently six populations. The species retains redundancy, albeit in low condition in two populations (Caddo and Ouachita Headwaters), within the Caddo, Ouachita Headwaters, Saline, and Upper Ouachita populations, and only one population (Saline) is highly resilient (Table 4.7). Overall, the species has decreased redundancy across its range due to an estimated 47% reduction in occupancy compared to historical levels and 50% of extant MUs have low resiliency that may further reduce redundancy in the future. Therefore, the overall redundancy for the species is low due to range reductions, two populations with low resiliency, and only two populations currently with moderate to high resiliency. Because of the overall low redundancy, the “Ouachita” Fanshell is more susceptible to catastrophic events.

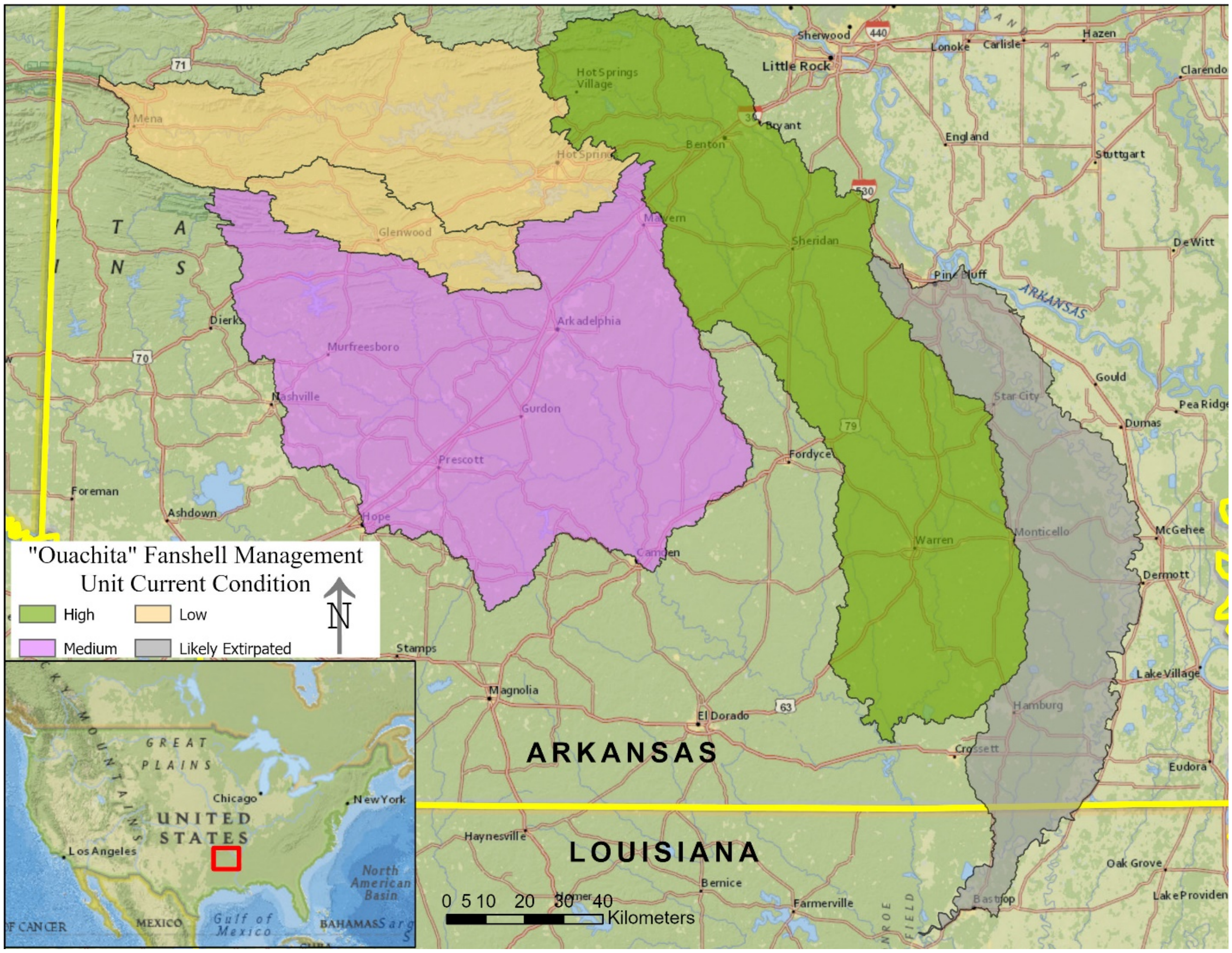


Figure 4.5 Distribution of the current and historically occupied management untis (MUs) of “Ouachita” Fanshell in the United States. Currently occupied MUs are represented with low, medium, and high condition categories as described in Chapter 3.

Chapter 5 – Factors Influencing Viability

This chapter evaluates the risk factors influencing past, current, and future conditions of Fanshell mussels. Existing planned and initiated conservation efforts, such as dam removal, will continue, but are not expected to substantially expand. Aquatic environments face many natural and anthropogenic threats and stressors (Neves *et al*. 1997, p. 44). EPA (2012, p. 2-4) defines six attributes of watershed health (landscape condition, habitat, hydrology, geomorphology, water quality, and biological condition). We identified water quality, hydrology, landscape change, habitat fragmentation, climate change, and invasive species as the primary threats influencing the Fanshell mussels directly or indirectly influencing resources upon which mussels rely for survival, growth, and reproduction (Figure 5.1).

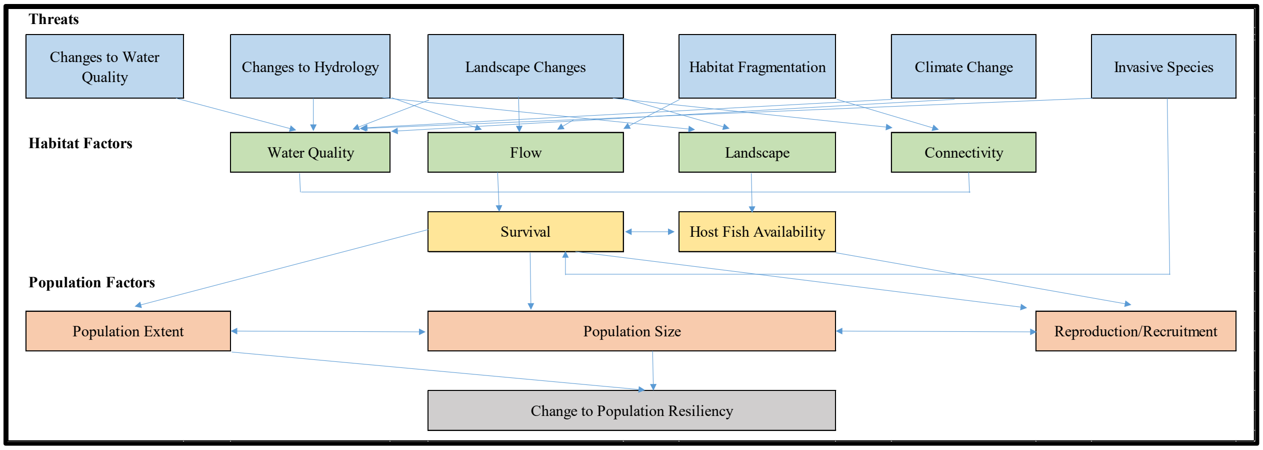


Figure 5.1 Effects pathway flowchart for Western Fanshell and "Ouachita" Fanshell. Threats influence habitat factors and population factors, which ultimately determines population resiliency.

5.1 Water Quality

Freshwater mussels require water in sufficient quantity and quality on a consistent basis to complete their life cycles and those of their fish hosts. Along with natural perturbations that exert pressure on populations and influence survival, a variety of anthropogenic activities affect freshwater mussel habitat. These activities place increasing demands on natural resources, particularly water, which can have deleterious effects on both water quality and quantity.

Hydrology, geomorphology, and landscape condition strongly influence water quality. Assessments of biological condition often integrate chemical and physical water quality information. Chemical and physical characteristics of air also substantially affect aquatic ecosystems (EPA 2012, p. 2-26).

Chemical contaminants are ubiquitous in the environment and a major threat in the decline of mussel species (Cope *et al*. 2008, p. 451; Richter *et al*. 1997, p. 1081; Strayer *et al*. 2004, p. 436; Wang *et al*. 2007a, p. 2029). Chemicals enter rivers through point and nonpoint discharges including spills, industrial and municipal effluents, and residential and agricultural runoff. These sources contribute organic compounds, heavy metals, nutrients, pesticides, and a wide variety of newly emerging contaminants such as pharmaceuticals to the aquatic environment. There are instances where chemical spills resulted in the loss of high mussel numbers (Brown *et al*. 2005, p. 1457; Schmerfeld 2006, pp. 12 – 13). The Fanshell mussels are especially threatened by chemical spills because these spills can occur anywhere that highways or railways, industries, pipelines or mines overlap with their distribution. For example, 93% and 100% of Western Fanshell and “Ouachita” Fanshell occupied streams have highway crossings. Fifty percent of “Ouachita” Fanshell occupied streams have crossings registered as hazardous material road routes. Four “Ouachita” Fanshell occupied streams have gas pipeline crossings, while two have oil and hazardous liquid pipeline crossings within three MUs. Eleven Western Fanshell occupied streams have gas pipeline crossings, while eight have oil and hazardous liquid pipeline crossings within all MUs. These pipelines cross 92% of Western Fanshell occupied streams and 67% of “Ouachita” Fanshell occupied streams.

Cope *et al*. (2008, p. 451) evaluated the pathways of exposure to environmental pollutants for freshwater mollusk life stages (glochidia, juveniles, adults) and found each life stage has common and unique characteristics that contribute to observed differences in exposure and sensitivity. Glochidia can be exposed to waterborne contaminants for up to 36 hours until encystment occurs; between 2 and 36 hours, and then from fish host tissue burdens (for example, atrazine), that last from weeks to months and this could affect transformation success of glochidia into juveniles (Ingersoll *et al*. 2007, pp. 101 – 104). Juvenile mussels typically remain burrowed beneath the sediment surface for two to four years. Residence beneath the sediment surface necessitates deposit (pedal) feeding and a reliance on interstitial water for dissolved oxygen (Watters 2007, p. 56). The relative importance of juvenile mussel exposure to contaminants in overlying surface water, interstitial water, whole sediment, or food needs further assessment. Exposure to contaminants from each of these routes varies with certain periods and environmental conditions (Cope *et al*. 2008, pp. 453, 457). The primary routes of exposure to contaminants for adult mussels are surface water, sediment, interstitial (pore) water, and diet (Cope *et al*. 2008, p. 453). Adult mussels have the ability to detect toxicants in the water and close their valves to avoid exposure (Van Hassel and Farris 2007, p. 6). Adult mussel toxicity and relative sensitivity (exposure and uptake of toxicants) is lower at high toxicant concentrations because uptake is affected by the prolonged or periodic toxicant avoidance responses (when the avoidance behavior of keeping their valves closed can no longer be sustained for physiological reasons (respiration and ability to feed) (Cope *et al*. 2008, p. 454). The duration of any toxicant avoidance response by an adult mussel is likely to vary due to several variables, such as species, age, shell thickness and gape, properties of the toxicant, and water temperature.

Studies conducted in accordance with standard mussel testing methods demonstrated that mussels are among the most sensitive freshwater species to a variety of contaminants, including copper, nickel, chloride, sulfate, potassium, and ammonia (Gillis 2011, p. 137; Wang *et al*. 2007a, p. 2029; b, p. 2036; 2010, p. 2053). Metals occur in industrial and wastewater effluents. Metals from mine water runoff (for example, Tri–State Mining District in southwest Missouri and southeast Kansas) contributed to mussel declines in streams such as Shoal Creek and Spring River in the Arkansas River basin (Angelo *et al*. 2007, p. 467; EcoAnalysts, Inc. 2018, p. 59), which are streams with historical and extant Western Fanshell populations. EcoAnalysts, Inc.

(2018, p. 59) found a negative correlation between mussel community metrics and sediment toxicity, suggesting sediment metal concentrations negatively affect the Spring River basin mussel community. Heavy metals can cause mortality and affect biological processes, for instance, disrupting enzyme efficiency, altering filtration rates, reducing growth, and changing behavior of freshwater mussels (Jacobson *et al*. 1997, p. 2390; Keller and Zam 1991, p. 543; Naimo 1995, pp. 351 – 355; Valenti *et al*. 2005, p. 1244; Wang *et al*. 2007b, pp. 2039 – 2046; c, pp. 2052 – 2055; 2010, p. 2053). Low but chronic heavy metal and other toxicant inputs may reduce mussel recruitment (Ahlstedt and Tuberville 1997, p. 75; Naimo 1995, pp. 347 & 351 – 352; Yeager *et al*. 1994, p. 217). Newly transformed juveniles (age of 5 days) are more sensitive to acute toxicity than glochidia or older juveniles (age of 2 to 6 months) (Wang *et al*. 2010, p. 2062).

WQ data indicate the Fanshell mussels have been exposed to zinc and copper at concentrations that cause acute toxicity (Table 4.6) and may be exposed to toxic levels of lead in the future (Appendix I-D – I-E). Wang *et al*. (2010, p. 2053) found mussels are relatively sensitive to acute toxicity of lead and zinc and to chronic toxicity of lead, but only moderately sensitive to chronic toxicity of zinc. Glochidia were less sensitive than juveniles to these metals. Hardness normalized EC_{50} for lead ranged from 205 – 362 µg/L and zinc 120 – 295 µg/L (Wang *et al.* 2010, p. 2059). Field studies of metal contaminated areas within the Western Fanshell range (Spring River basin) indicate mussel populations decline with increasing concentrations in sediment (Angelo *et al*. 2007, p. 467; Besser *et al*. 2009, p. 525; Wang *et al*. 2010, p. 2062). The 24-h EC_{50} for free glochidia (not encased in a conglutinate) exposed to copper ranges from 6.9 – 36.1 µg/L in soft water; 48-h EC_{50} ranged from 5.2 – 21.6 in soft water (Gillis *et al*. 2008, p. 141). Endangered species were more sensitive (< 10 µg Cu/L) than common species.

Agriculture, timber harvest, and lawn management practices utilize nutrients and pesticides. Nutrients, such as nitrogen and phosphorus, primarily occur in runoff from livestock farms, feedlots, heavily fertilized row crops and pastures (Peterjohn and Correll 1984, p. 1471), post timber management activities, and urban and suburban runoff, including leaking septic tanks, and residential lawns. Studies show that excessive nitrogen concentrations can be lethal to the adult Freshwater Pearl Mussel (*Margaritifera margaritifera*) and reduce the life span and size of other mussel species (Bauer 1988, p. 244; 1992, p. 425).

WQ data indicate the Fanshell mussels have been exposed to $NO_3 + NO_2$ concentrations that may cause acute toxicity (Table 4.6). Camargo *et al*. (2005, p. 1255) found a maximum level of 2 mg NO_3-N/L is appropriate for protecting the most sensitive freshwater species. The 96-h NO_3 concentrations range from 357 (*Lampsilis siliquoidea*) – 937 mg NO_3-N/L (*Megalonaias nervosa*) (Soucek and Dickenson 2012, p. 236). Mollusks are less sensitive to NO_2-N (96-h LC_{50} 55.8 – 176.5 mg NO_2-N/L to NO_2-N) than insects and crustaceans (Soucek and Dickenson 2012, p. 240).

Ammonia is particularly toxic to early life stages of mussels. Sources of ammonia include agricultural wastes (animal feedlots and nitrogenous fertilizers), municipal wastewater treatment plants, and industrial waste (Augspurger *et al*. 2007, p. 2569) as well as precipitation and natural processes (decomposition of organic nitrogen) (Augspurger *et al*. 2003, p. 2569; Goudreau *et al.*

1993, p. 212; Hickey and Martin 1999, p. 44; Newton *et al*. 2003, p. 1243). Ammonia is considered a limiting factor for survival and recovery of some mussel species due to its ubiquity in aquatic environments and high level of toxicity, and because the highest concentrations typically occur in mussel microhabitats (Augspurger *et al*. 2003, p. 2574). Studies show that ammonia toxicity increases with increasing temperature, pH, and low flow conditions (Cherry *et al*. 2005, p. 378; Cooper *et al*. 2005, p. 381; Wang *et al*. 2007a, p. 2045), and may cause ammonia (unionized and ionized) to become more problematic for juvenile mussels (Wang *et al*. 2007a, p. 2045). Sublethal effects include, but may not be limited to, reduced time the valves are open for respiration and feeding, impaired secretion of the byssal thread (used for substrate attachment), reduced ciliary action impairing feeding, depleted lipid, glycogen, and other carbohydrate stores, and altered metabolism (Augspurger *et al*. 2003, pp. 2571 – 2574; Goodreau *et al*. 1993, pp. 216 – 227; Mummert *et al*. 2003, pp. 2548 – 2552). Augspurger *et al*. (2003, p. 2569) found total ammonia nitrogen (TAN) concentrations of 0.3 – 1.0 mg TAN/L at pH 8.0 and 25°C to be protective of freshwater mussels. We analyzed TAN data in rivers occupied by Fanshell mussels, but did not find any concentrations at levels expected to result in acute or chronic toxicity to mussels, nor do our future scenarios predict toxic concentrations (Table 4.6, Appendix I-D – I-E). Therefore, we excluded TAN when determining WQ scores.

Nutrient enrichment increases primary productivity, and the associated algae respiration depletes dissolved oxygen levels. This may be particularly detrimental to juvenile mussels that inhabit the interstitial spaces in the substrate where lower dissolved oxygen concentrations are more likely than on the sediment surface where adults tend to live (Sparks and Strayer 1998, pp. 132 – 133). However, mussels are tolerant of acute (4 days) hypoxia (low dissolved oxygen) with juvenile survival reduced at 0.5 mg/L at 30°C and 0.3 mg/L at 20 – 25°C. Whereas, reduced survival of brooded larvae in chronic (28 day) hypoxia occurred at <3 mg/L at 20°C (Kaiser and Barnhart 2007, poster). WQ data does not indicate that hypoxia is a stressor to the Fanshell mussels.

Pharmaceutical chemicals used in commonly consumed drugs increasingly occur in surface waters. Kolpin *et al*. (2002, pp. 1208 – 1210) detected the presence of numerous pharmaceuticals, hormones, and other organic waste products in nationwide sampling of 139 stream sites in 30 States downstream from urban development and livestock production areas. Another study in northwestern Arkansas found pharmaceuticals or other organic wastewater constituents at 16 of 17 sites in seven streams surveyed in 2004 (Galloway *et al*. 2005, pp. 4 – 22). Toxic levels of exposure to chemicals that act directly on the neuroendocrine pathways controlling reproduction can cause premature release of viable or nonviable glochidia. For example, the active ingredient in many human prescription antidepressant drugs belonging to the class of selective serotonin reuptake inhibitors may exert negative reproductive effects on mussels because of the drug's action on serotonin and other neuroendocrine pathways (Cope *et al*. 2008, p. 455). Pharmaceuticals or organic wastewater constituents are generally greater downstream of wastewater treatment facilities (Galloway *et al*. 2005, p. 28). Pharmaceuticals that alter mussel behavior and influence successful attachment of glochidia on fish hosts may have population-level implications for the Fanshell mussels. However, insufficient data exist to assess whether pharmaceuticals are currently affecting the Fanshell mussels.

Excessive sediments adversely affect riverine mussel populations requiring clean, stable streams (Brim Box and Mossa 1999, p. 99; Ellis 1936, pp. 39 – 40). Specific biological effects include reduced feeding and respiratory efficiency from clogged gills, disrupted metabolic processes, reduced growth rates, limited burrowing activity, physical smothering, and disrupted host fish attraction mechanisms (Ellis 1936, pp. 39 – 40; Hartfield and Hartfield 1996, p. 373; Marking and Bills 1979, p. 210; Vannote and Minshall 1982, pp. 4105 – 4106; Waters 1995, pp. 173 – 175). The physical effects of sediment on mussel habitat appear to be multifold. Effects include changes in suspended and bed material load, bed sediment composition associated with increased sediment production and runoff in the watershed, channel changes in form, position, and degree of stability, changes in depth or the width and depth ratio that affects light penetration and flow regime, actively aggrading (filling) or degrading (scouring) channels, and changes in channel position. These effects to habitat may dislodge, transport downstream, or leave mussels stranded (Brim Box and Mossa 1999, pp. 109 – 112; Kanehl and Lyons 1992, pp. 4 – 5; Vannote and Minshall 1982, p. 4106).

Many Kansas streams (such as Verdigris and Neosho Rivers) supporting Western Fanshell have become increasingly sedimented over the past century, reducing habitat (Obermeyer *et al*. 1997b, pp. 113 – 114). When interstitial spaces are clogged, interstitial flow rates and spaces are reduced (Brim Box and Mossa 1999, p. 100), and this decreases habitat for juvenile mussels. High total suspended solids can interfere with fertilization by reducing the chance of females encountering suspended sperm during filter feeding, or an increase in pseudofeces production could bind sperm in mucus and lead to its egestion before fertilization. Suspended sediment is a potential mechanism to explain the lack of mussel recruitment in many locations (Gascho Landis *et al*. 2013, p. 76). Furthermore, sediment may act as a vector for delivering contaminants, such as nutrients and pesticides.

Our analysis indicates unpaved road density is a threat to the Fanshell mussels (Appendices I-A, II-C and II-D). At the landscape level, unpaved road networks interact with streams delivering sediment runoff and increasing water velocity entering stream channels, thereby increasing stream energy, eroding streambanks, channel scouring, and increasing flooding (Coffin 2007, pp. 397 – 398). Road density is a useful index of several ecological effects of roads in a landscape (e.g., hydrology, aquatic ecosystems; Forman and Alexander 1998, p. 222). DeCantanzaro *et al*. (2009, p. 463) found road density was the dominant factor influencing many water quality variables and an increase of 11.6 m/ha would be expected to decrease water quality index scores considerably. Radwell and Kwak (2005, pp. 806 & 808) found certain physical characteristics (e.g., land use, road density), at the watershed level, in Ozark streams were most influential in discriminating among rivers. They detected that land use might have influenced biota of two rivers (War Eagle Creek and White River) relative to others with higher percentage of forestland, lower road density, and lower nitrate concentrations. Detrimental effects to aquatic macroinvertebrates were evident where roads cover >5% of a California watershed (Forman and Alexander 1998, p. 223). The U.S. Forest Service (2005, p. 58) established a wildlife and fish habitat road density objective of ≤ 1.6 km/2.6 km^2 on the Ouachita National Forest in west central Arkansas, which includes the Ouachita Headwaters and Caddo MUs for “Ouachita” Fanshell. Daigle (2010, Table 3) recommends site-level mitigation techniques to reduce environmental effects of roads. The Arkansas Unpaved Roads Program, authorized by Act 898 of the 90th General Assembly in 2005, establishes a proactive, incentive based management program that results in utilization of best management practices on unpaved roads to minimize erosion and maintain and improve the health of priority lakes and rivers (TNC 2017, entire), including those where both Fanshell mussels occur.

5.2 Flow

Watershed hydrology is driven by climatic processes, surface and subsurface characteristics (e.g., topography, vegetation, geology), and anthropogenic processes (e.g., water and land use; EPA 2012, p. 2-16). Natural flow regimes compose seasonally varying environmental flow components, including high flow, base flow, pulses, and floods. Each flow component serves critical ecological functions (e.g., creating habitat, spawning cues, etc.). Environmental flow characteristics include magnitude, frequency, duration, timing, and rate of change (EPA 2012, p. 2-17).

Reductions in the diversity and abundance of mussels are principally attributed to habitat alteration caused by inundation of free-flowing rivers and streams (Neves *et al.* 1997, p. 60), including portions of the Fanshell mussels range (e.g., White, Ouachita, Caddo, and Neosho rivers). The construction of reservoirs and other impoundments permanently alters the hydrology, and hence, the ecology of rivers, with deleterious effects to water quality, water quantity, fish movement and mussel dispersal, nutrient cycling, sediment deposition, fate and transport of contaminants, and numerous other changes to the physicochemical and biological characteristics of affected areas (upstream and downstream).

In large reservoirs that release water from the hypolimnion, the deeper water is cold and often devoid of oxygen and necessary nutrients, which adversely affects mussel survival. Cold water can stunt mussel growth and delay or hinder spawning (Vaughn and Taylor 1999, p. 917). Reservoirs, like Bull Shoals on the White River in north central Arkansas, that release cold water from the bottom of the reservoir (in part to support a non-native Rainbow and Brown trout recreational fisheries) can affect water temperatures for kilometers downstream. These cold releases create an extinction gradient, where freshwater mussels are absent or present in low numbers 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 (Vaughn and Taylor 1999, pp. 915 – 916).

Recruitment in some species of mussels is significantly related to components of spring and summer flow (Ries *et al*. 2016, p. 711). High velocity flows during spawning can decrease fertilization success (Ries *et al*. 2016, p. 712) and shear stress is the primary determinant of juvenile settling above a range of threshold flow (Daraio *et al*. 2010, p. 838; Hardison and Layzer 2001, p. 77). Hydraulic variables describing substrate stability at high flows are most limiting to mussel species richness and abundance (Allen and Vaughn 2010, p. 390). Mussel beds may be constrained by threshold limits at both flow extremes. Under low flow, mussels may require a minimum hydraulic variable (Reynolds number, Froude number) to transport nutrients, oxygen, and waste products. Under high flow, areas with relatively low boundary shear stress may provide hydraulic refuge (Steuer *et al*. 2008, p. 67). Zigler *et al*. (2008, p. 343) results suggest episodic events such as droughts and floods are important in structuring mussel distribution. Fanshell 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 today. Streamflow and overall discharge for rivers inhabited by Fanshell mussels will likely 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).

The majority of sediment transport occurs during floods (Clark and Mangham 2019, pp. 6-7; Kondolf 1997, p.533). 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 (Kondolf 1997, p.535). The additional shear stress caused by sustained high base flows can incise channels, erode riverbanks, 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 (Clark and Mangham 2019, pp. 6-7; Kondolf 1997, p.533).

Runoff from impervious surfaces prevalent in urban areas affects the natural hydrology of streams by increasing flood magnitude, duration, and frequency (Bressler *et al*. 2009, p.292). Frequent floods in urban areas scour stream substrate and banks, thereby increasing erosion and sedimentation and altering geomorphology. As contributing factors to a sub-basin's impervious area, storm drains and roads are important elements influencing the degradation of water quality with respect to biota (Ourso and Frenzel 2002, p. 117). Geomorphic changes, such as changes in channel width, occur with percent impervious areas as low as 2 –10% (Booth and Jackson 1997, p. 1084; Dunne and Leopold 1978, pp. 275-277; Morisawa and LaFlure 1979, Figure 11). Initial degradation of fish communities and lower larval densities have been associated with percent impervious areas as low as 10% (Limburg and Schmidt 1990, p. 1241-1242; Steedman 1988, p. 498-499). Several thresholds of degradation in streams occur at approximately 10–20% of the catchment in impervious area (Paul and Meyer 2001, p. 335, Figure 1). In 2016, all Fanshell mussels MUs were <2% impervious cover.

5.3 Landscape Changes

Many rivers where the Fanshell mussels occur are threatened by land use activities and change (e.g., increased urbanization, alteration of riparian buffers, improperly designed and maintained unpaved roads). Life history traits of mussels render them poorly adapted to deal with landscape change (Strayer et al. 2004, p. 436). Effects of landscape disturbances, such as increased sedimentation, altered flow regimes, or elevated contaminant concentrations, may be slow and in some cases irreversible (Allan 2004, p. 258 – 260; Newton *et al*. 2008, p. 434).

Urbanization of a watershed results in multiple stressors (e.g., increased pollutant loads from stormwater runoff, altered flow, decreased bank stability, and increased water temperature). Urbanization can also indirectly increase channel erosion and downstream sedimentation by increasing the frequency and volume of channel-altering storm flows (Hammer 1972, p. 1530; Leopold 1968, entire). Long Island urban streams had mean summer temperatures 5 – 8°C warmer and winter temperatures 1.5 – 3°C cooler than forested streams. Seasonal diurnal fluctuations were also greater in urban streams, and summertime storms resulted in increased temperature pulses 10 – 15°C warmer than forested streams, a result of runoff from heated impervious surface (Pluhowski 1970, pp. 1, 57-58).

Urban stressors dramatically affect biological assemblage structure and function in aquatic communities (Bressler *et al*. 2009, p. 292), and are nearly irreversible. Multiple linear regression models indicate that urbanization lowered fish species richness and density and led to predictable changes in species composition. Darters, sculpin, minnows, and endemic fishes declined along the urban gradient (Walters *et al*. 2005, p. 1). They found urban effects on fishes accrue rapidly (<10 years) and are detectable at low levels (~5 – 10% urbanization). Streams with a high development level and nearby construction have less diverse communities with lower abundance than streams with more heavily forested watersheds (Gage *et al*. 2004, p. 345). The Ohio Environmental Protection Agency has a large database of land use and fish abundance that suggests three levels of general fish response to increasing urbanization: with 0 – 5% urban land use, sensitive species are lost; with 5 – 15%, habitat degradation occurs and functional feeding groups (e.g., benthic invertivores) are lost; and with >15% urban land use, toxicity and organic enrichment result in severe degradation of the fish fauna (Yoder *et al*. 1999, p. 22). In 2016, 80% of the Fanshell mussels MUs have ≥5% urban land use, but all are <10% (Appendix I-A).

We discuss imperviousness effects to hydrology in Section 5.2. Percentage impervious surface area also is important in determining stream water quality as defined by ecological indicators such as benthic macroinvertebrate community composition and fish density and abundance (Klein 1979, p. 959, Figure 3; May *et al*. 1997, Figure 16). The percent impervious area where water quality decreases varies, ranging from 4 – 5 to 10 – 12% (Booth and Jackson 1997, p. 1084; Klein 1979, p. 959; May *et al*. 1997, Figure 13). Klein (1979, p. 359) and Yoder *et al*. (1999, p. 22) found precipitous declines in fish metrics with 0 – 15% impervious surface or urban land use. Minimizing total imperviousness to <10 – 15% may be critical to maintaining species assemblages (Gergel *et al*. 2002, p. 122; Groffman *et al*. 2003, p. 319).

The amount of impervious surface and of riparian forest cover are often the focal point of discussions on the link between land use change and stream ecosystem health (Schueler 1994, p. 1; Stewart *et al*. 2001, p. 1481; Weigel *et al*. 2000, p. 99). These two variables influence stream hydrology and water quality (Brabec *et al*. 2002, pp. 505 – 507). Riparian forest cover intercepts and moderates the timing of runoff, buffers temperature extremes (which also reduces toxicity of certain water quality parameters, e.g., NH_3), filters pollutants in runoff, provides woody debris to stream channels that enhances aquatic food webs, and stabilizes excessive erosion. Furthermore, the removal of riparian trees in forested watersheds has a strong influence on stream invertebrate communities (Wallace *et al*. 1997, entire). In a North Carolina statewide analysis, the percent forest strongly correlated with better stream conditions. Forested land cover, at both the watershed and riparian scales, was a statistically significant predictor of benthic macroinvertebrate communities that are less tolerant of stream degradation, and that indicate a greater level of aquatic ecological integrity and better water quality (Potter *et al*. 2004, p. 71). In 2016, forest cover ranged from 70 – 76% in "Ouachita" Fanshell MUs and 12 – 77% in Western Fanshell MUs (Appendix I-A).

Agricultural practices such as livestock grazing and tilling on land adjacent to streams can lead to soil erosion and subsequent runoff of fine sediments, nutrients, and pesticides (e.g., Schulz and Liess 1999, p. 155). Poole and Downing (2004, p. 123) found watersheds with the most habitat converted to farmland had the greatest levels of mussel richness decline. Restoration and long-term protection of mussel biodiversity must address the restoration of riparian zones and increased stream protection from agricultural influences (Poole and Downing 2004, p. 124). In 2016, agriculture land use ranged from 5 – 13% in "Ouachita" Fanshell MUs and 17 – 68% in Western Fanshell MUs and decreased in all MUs for both species from 2011 – 2016 (Appendix I-A).

Roads adversely affect watershed integrity by intercepting, concentrating, and diverting water. The hydrologic and geomorphic consequences resulting from these processes are substantial. Roads directly affect natural sediment and hydrologic regimes by altering stream flow, sediment loading, sediment transport and deposition, channel morphology, channel stability, substrate composition, stream temperature, water quality, and riparian condition (Lee *et al*. 1997, pp. 1102 – 1104). Roads intercept hillslope drainage patterns effectively increasing stream density on the landscape and altering the timing and magnitude of peak flows and base discharge (Furniss *et al*. 1991 p. 301; Harr *et al*. 1975, pp. 440 - 441; King and Tennyson 1984, p. 1162; Wemple *et al*. 1996, p. 1196, 1203) and sub-surface flow (Furniss *et al*. 1991, p. 301; Megahan 1972, pp. 354-355). Hydrologic effects are sensitive to road density, with increased peak flows evident at road densities of 2 – 3 km/km^2 (Forman and Alexander 1998, p. 223). In 2016, unpaved road density in all the Fanshell mussels MUs were ≤1.6 km/km^2.

5.4 Habitat Fragmentation

Hydrologic and geomorphic processes directly relate to habitat extent. The number and distribution of habitat patches and their connectivity influence species population health. Water quality also affects habitat quality. Landscape condition affects water quality and hydrologic processes, which also shape riparian and terrestrial habitat. Thus, habitat condition serves as an integrating indicator of other watershed variables upon which biological condition is dependent (EPA 2012, p. 2-9).

Historically, the Fanshell mussels likely occurred throughout the river basins described in Chapter 4. Given their reproductive ecology, they would colonize new areas of suitable habitat through movement of infested fish hosts. Today, major reservoirs and other anthropogenic effects (e.g., poor water and sediment quality from mining activities, channel maintenance for navigation, road crossings, etc.) isolate many of the remaining populations. These effects can be substantial causing permanent changes to fish movement, water quality, and hydrology. Large-scale reductions in mussel diversity and abundance is largely due to habitat changes caused by impoundments (Neves *et al*. 1997, p. 63). The number of impoundments in "Ouachita" Fanshell MUs ranges from 3 – 51 and 4 – 73 in Western Fanshell MUs. The number of unpaved road crossings/km ranges from 0.11 – 0.56 in the Fanshell mussels MUs. Populations eliminated due to stochastic events cannot naturally recolonize, leading to reduced overall redundancy and representation.

5.5 Climate Change

Based on extensive evidence, the planet is warming and human activities, especially emissions of greenhouse gases, are the dominant cause. There is no convincing alternative explanation aside from human activities that accounts for the warming during the past century (Wuebbles et al. 2017, Executive Summary). The seasonal averages of 30 Coupled Model Intercomparison Project 5 (CMIP5) models from 1950 – 2100 using RCP4.5 and RCP8.5[1] indicate warming air temperatures in the Lower Mississippi River region (Figure 5.2), with a central tendency of < 2 inches change in precipitation (Figure 5.3; Alder and Hostetler 2013, p. 2). The range of potential values for air temperature and precipitation are shown in Figures 5.2 and 5.3 (Alder and Hostetler 2013, p. 2). We expect changes in stream temperatures 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). These water temperature changes will have implications for temperature dependent water quality parameters, such as dissolved oxygen and ammonia toxicity, spawning, and physiological effects to thermally sensitive species. In "Ouachita" Fanshell occupied streams from 1990 – 2018, the percent of water temperature samples exceeding 27°C ranged from 6.9 (Upper Ouachita MU) – 15.4% (Saline MU), with maximum water temperature ranging from 30.3 (Ouachita Headwaters MU) – 36.6°C (Saline MU). In Western Fanshell MUs from 1990 – 2018, the percent of water temperature samples exceeding 27°C ranged from 0 (Middle White MU) – 12.6% (Strawberry MU), with maximum water temperature ranging from 22.0 (Middle White MU) – 35.8°C (Spring MU).

Payton *et al*. (2015, p. 3571) conducted a chronic warming simulation with freshwater mussels performed at predicted IPCC warming scenarios for the southeastern U.S. in 2100. Their data strongly support the conclusion that a thermal increase of 2 – 3°C is sufficient to cause differential species-specific responses in physiology, tissue biochemistry and gene expression, potentially based on species thermal tolerance thresholds. In general, thermally tolerant species mounted stronger responses to their thermal challenge without utilizing critical resources necessary to maintain other cellular, metabolic, and physiological processes. In contrast, the thermally-sensitive species had greater need to utilize these resources in response to thermal stress and ultimately was not able to maintain physiological performance and suffered significant mortality. However, acclimation to future thermal warming may help buffer some negative effects for thermally-sensitive species (Stillman 2003, p. 65).

Exact critical thermal thresholds for survival and normal functioning of many freshwater mussel species are unknown. Several studies documented the influence of temperature on the timing aspects of mussel reproduction (Allen *et al*. 2007, p. 85; Gray *et al*. 2002, p. 156; Steingraeber *et al*. 2007, pp. 303–309). Peak glochidial releases are associated with water temperature thresholds

---

[1] RCP stands for Representative Concentration Pathway. It refers to a greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC) in its 5th Assessment Report to describe potential future climate outcomes, depending on the amount of greenhouse gases that are emitted in the future (IPCC 2014, pp. 126-127).

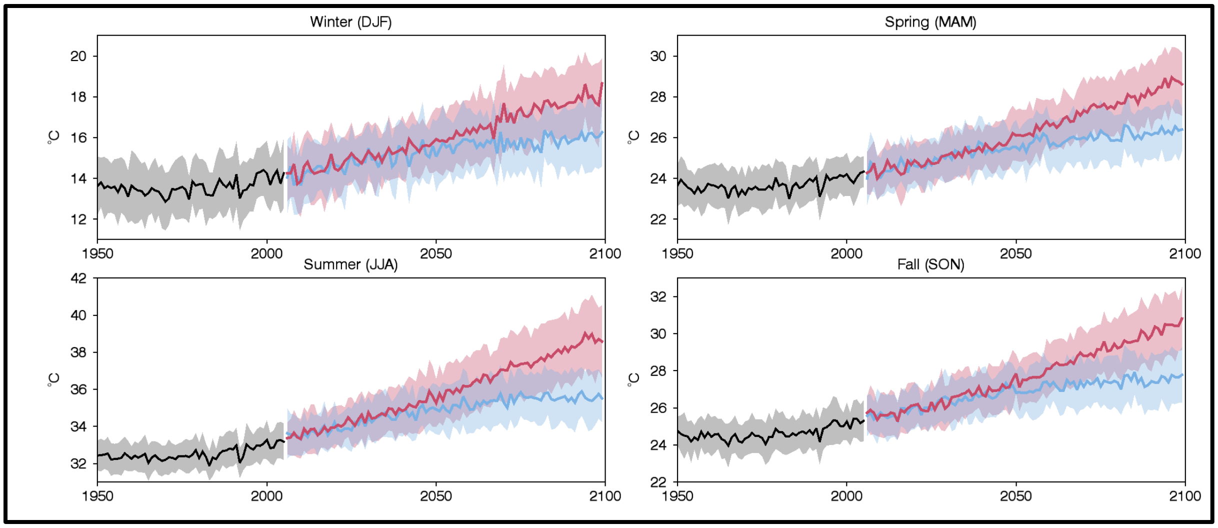


Figure 5.2 Seasonal average time series of maximum 2-m air temperature in the Lower Mississippi River region for historical (black), Representative Concentration Pathway (RCP)4.5 (blue) and RCP8.5 (red). The historical period ends in 2005. The average of 30 Coupled Model Intercomparison Project 5 (CMIP5) models is shown by the solid lines and their standard deviations indicated by the respective shaded envelopes (Alder and Hostetler 2013, p. 2).

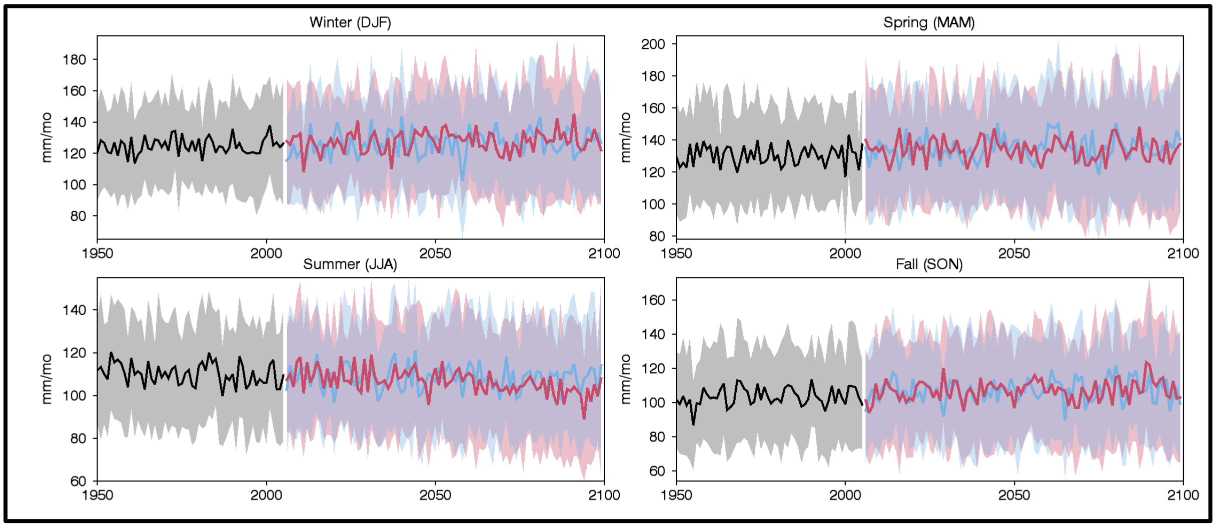


Figure 5.3 Seasonal, average time series of precipitation for four periods for historical (black), RCP4.5 (blue) and RCP8.5 (red) in the Lower Mississippi River region. The historical period ends in 2005. The average of 30 CMIP5 models is shown by the solid lines and their standard deviations indicated by the respective shaded envelopes (Alder and Hostetler 2013, p. 3).

Future increases in the frequency and severity of both extreme drought and extreme rainfall are expected to transform many ecosystems in the Southeast, including Arkansas (Carter et al. 2018, Chapter 19 – Drought and Extreme Rainfall). Haag and Warren (2008, p. 1165) found that mussels are highly sensitive to secondary effects of drought (e.g., water temperature, etc.), but their ability to withstand severe drought is highly dependent on where they occur. In a southeastern Oklahoma study, mussel populations never recovered to pre-drought population levels between 1992 – 2011, likely due to time lag constraints to mussel recovery associated with life span, reduced reproduction and dispersal related to negative density dependence and river fragmentation (Vaughn *et al*. 2015, pp. 1297 – 1298). These studies indicate insufficient time between sequential droughts contribute to mussel declines.

Ficke *et al.* (2005, pp. 67–69; 2007, pp. 603–605) described the general potential effects of climate change on freshwater fish populations worldwide. Overall, they expect the distribution of fish to change, including range shifts and local extirpations. Because freshwater mussels are entirely dependent upon fish hosts for successful reproduction and dispersal, any changes in local fish populations would also affect freshwater mussel populations. Therefore, the Fanshell mussels may reflect local extirpations or decreases in abundance of fish species.

5.6 Invasive Species

Invasive species, such as Asian Clam (*Corbicula fluminea*) and Zebra Mussel (*Dreissena polymorpha*) occur in portions of the Fanshell mussels range and can negatively affect mussel survival. Strayer (1999, pp. 75–80) reviewed in detail the mechanisms by which Zebra Mussels affect native mussels. Zebra Mussels also may affect Fanshell mussels through filtering and removing their sperm and possibly glochidia from the water column, thus reducing reproductive potential. They also may degrade habitat for native mussels by depositing large quantities of Zebra Mussel pseudofeces (undigested waste material passed out of the incurrent siphon) (Vaughan 1997, p. 11).

The Asian Clam competes with native mussels, particularly juveniles, for resources such as food, nutrients, and space (Neves and Widlak 1987, p. 6; Leff *et al.* 1990, p. 414), and may ingest sperm, glochidia, and newly metamorphosed juveniles of native mussels (Strayer 1999, p. 82; Yeager *et al.* 2000, p. 255). Yeager *et al.* (2000, pp. 257–258) determined that high densities of Asian Clams negatively affect the survival and growth of newly metamorphosed juvenile mussels and thus reduced recruitment. Dense Asian Clam populations actively disturb sediments that may reduce habitat for juveniles of native mussels (Strayer 1999, p. 82). Asian Clam density is never high in dense mussel beds, indicating that the clam is unable to successfully invade small–scale habitat patches with high unionid biomass (Vaughn and Spooner 2006, pp. 334–335). The invading clam therefore appears to preferentially invade sites where mussels are already in decline (Strayer 1999, pp. 82–83; Vaughn and Spooner 2006, pp. 332–336). However, an Asian Clam population that thrives in previously stressed, sparse mussel populations might exacerbate mussel decline through competition and by impeding mussel population expansion (Vaughn and Spooner 2006, pp. 335–336). Haag (2019, pp. 55 – 56) suggests that Corbicula is the single most compelling reason for enigmatic mussel declines, but focused research and management is necessary to better evaluate this hypothesis.

The introduced Black Carp (*Mylopharyngodon piceus*), a molluscivore (mollusk eater), is a potential threat to mussels (Strayer 1999, p. 89). Foraging rates for a 4–year–old fish average 1.4–1.8 kg (3 or 4 pounds) a day, indicating that a single individual could consume 9,072 kg (10 tons) of native mollusks during its lifetime (MICRA 2005, p. 1). A diet study found wild caught Black Carp in the Mississippi River from 2009–2017 had a 13.7% incidence of unionids (26.6% for mollusks) (Poulton *et al.* 2019, p. 94). Currently, Black Carp have only been collected in the lower White River within the extant range of Fanshell mussels. However, the species occurs from Baton Rouge, Louisiana to Meyer, Illinois in the Mississippi River (Kroboth *et al.* 2019, p. 1048) and juveniles have been collected in ditches in southeast Missouri (U.S. Geological

Survey Nonindigenous Aquatic Species Database). Kroboth *et al*. (2019, p. 1050) show increased reporting over time and an increase in Black Carp range since 2011.

We acknowledge that invasive species can have individual and in some circumstances population level effects to mussels. However, there is no data available to support that invasive species are a driving force affecting the current or future conditions of Fanshell mussels. Therefore, we did not analyze their potential effects on the future viability of Fanshell mussels in Chapter 6.

5.7 Summary

Our analysis of the past, current, and future variables that influence the Fanshell mussels needs for long-term viability revealed that there are four factors that pose the largest risk to future viability: water quality degradation, altered flow, landscape changes, and habitat fragmentation, all of which are exacerbated by climate change. Existing planned and initiated conservation efforts will continue, but are not expected to substantially expand. The four factors affecting viability carry forward in Chapter 6 where we assess the future condition of Fanshell mussel populations and the viability of each species as the influence of each factor changes in the foreseeable future.

Chapter 6 – Species Projected Viability in the Future

In this chapter, we consider potential changes to risk factors and conservation efforts in the foreseeable future, and implications of those changes on viability of the Fanshell mussels. The current and potential future effects of the five threats, along with current estimates of distribution and abundance, determine present viability, and therefore future vulnerability to extinction. We will apply our future forecasts using the concepts of species resiliency, redundancy, and representation to describe future Fanshell mussels' viability.

6.1 Future Scenarios Methodology and Considerations

Because of substantial uncertainty regarding the location, magnitude, and duration of effects related to altered flow, water quality changes, and habitat degradation, we began forecasting future viability for the Fanshell mussels under three plausible future scenarios (moderate increase in stressors, moderate decrease (improvement) 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 "moderate increase in stressors" and the "moderate decrease in stressors" scenarios. As a result, we limited the future forecasts analyzed in this report to two scenarios, a moderate increase in stressors (Future Scenario 1) and severe increase in stressors (Future Scenario 2). For each scenario, we used best judgement based on the best available scientific and commercial information to determine the likelihood that a particular condition would apply in 40 years. We evaluated both scenarios at 40 years into the future (2060) (approximately 2 – 3 generations), where future threats determine the biological status of mussel populations and their habitat. We limited our evaluation to 40 years primarily due to limitations projecting non-modeled, extrapolated future conditions for water quality, road density (beyond 2050), and habitat fragmentation. The National Climate Change Viewer (NCCV) models for precipitation and air temperature used future projections based on three periods extending through 2099 (Appendix III). Our 40-year period occurs within the 2050 – 2074 period after which there is too much uncertainty to project future conditions. The Precipitation Runoff Modeling System (PRMS) projects hydrologic conditions for one period extending from 2045 – 2075 (Appendix IV). The NCCV and PRMS model outputs are less reliable in forecasting a specific year compared with capturing a mean over many years and model runs. For this reason, the selected NCCV and PRMS model outputs for these time periods is the best available science for our Fanshell mussels projections in 2060. We also note that providing longer-term projections beyond 2060 (e.g., 5 generations) added more uncertainty to our projected future conditions and did not provide much useful information since after 40 years 64% of Western Fanshell and 75% of "Ouachita" Fanshell populations are projected to be in low condition or likely extirpated under the moderate increase scenario.

In this chapter, we consider climate change further under various likely future scenarios (e.g., PRMS and NCCV models), serving to exacerbate already deteriorating conditions through changes to water quality, flow alteration, habitat fragmentation, and changes to the landscape. Climate change directly or indirectly exacerbates the most relevant stressors to freshwater mussels wherever they occur. We expect climate change effects to occur throughout the Fanshell mussel ranges. Climate change, and thus low flow, precipitation and warmer temperatures, is a key component of our future condition analysis. We expect streamflow and overall discharge for rivers inhabited by Fanshell mussels 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).

As discussed in Chapter 5, we expect changes in stream temperatures 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). We used the NCCV to predict air temperature change within the Fanshell mussel ranges. NCCV includes historical (1981 – 2010) and future climate projections from 30 downscaled models for RCP4.5 and RCP8.5 emission scenarios. Appendices III and III-A include NCCV outputs for the Lower Arkansas, Upper White-St. Francis, Neosho-Verdigris, and Lower Red-Ouachita basins. We incorporate temperature data from the NCCV 2050 – 2074 period into our overall WQ score (Appendix I-D – I-G).

The PRMS evaluates the response of various combinations of climate and land use on streamflow and general watershed hydrology using 13 downscaled general circulation models with 4 representative concentration pathways representing a range of potential future changes in climate. The model simulations compute the potential changes in hydrologic response across the southeastern U.S. Results indicate minimum and maximum 10-day summer discharge, July maximum discharge, 7-day minimum flow (April – August), and minimum 10-day spring discharge have a positive relationship with mussel recruitment (Peterson *et al.* 2011, pp. 115, 119). The PRMS does not use these exact flow metrics. Therefore, we selected three PRMS flow metrics (minimum summer flow [June – September], annual minimum 90-day moving average flow, and frequency of low pulse flow events <5% of mean flow for the entire record) likely to influence future change in Fanshell mussel populations. We evaluated spring (April – June) maximum 7-day moving average flows, but PRMS organization of these data into hydrologic response units was not particularly informative for our MUs. The three PRMS metrics we selected account for the spawning period and times when flow and water temperature are likely to stress the Fanshell mussels. Using PRMS, we generated box-whisker plots for each metric to show the percent difference from historical conditions (1950 – 2010) (see Appendix IV). If the median percent difference from historical conditions was < -5%, we assigned the metric a high ranking, -5 – -20% moderate, and > -20% low. We also examined NCCV precipitation data (Appendix III) and percent imperviousness, but neither proved particularly informative in assessing future flow conditions.

We plotted ambient water quality for each selected parameter with time and inserted a trend line extending to 2060 to predict future water quality under Future Scenario 1. In some instances, current water quality trends remained stable or improved slightly under this scenario (Appendix I-D – I-E). We then used the same criteria for determining water quality scores discussed in Chapter 3 and added air temperature. For Future Scenario 2, we applied a 20% increase to our current condition ambient water quality dataset and then used the same criteria for determining scores (Appendix I-F – I-G).

Land-cover change is inherently a local event, yet broader scale socioeconomic and biophysical factors affect how humans make decisions to use the landscape. To determine future landscape condition under Future Scenario 1, we used a simple method to determine future proportions of land cover using the National Land Cover Dataset (2011, 2016) percent change from 2011 – 2016 and extrapolated the rate of change to each 5-year period through 2060 (Appendix II-A). This method assumes future drivers of landscape change remain constant with 2011 – 2016. For Future Scenario 2, we used Forecasting Scenarios (FORE-SCE) (2018), IPCC Special Report on Emissions Scenarios (SRES) Scenario A2, to predict future land cover, except we used EPA's Integrated Climate and Land-Use Scenarios (ICLUS) for imperviousness. ICLUS explores future changes in human population, housing density, and impervious surface based on the IPCC SRES. FORE-SCE uses a modular approach to handle large-scale (national to global) and small-scale (local) drivers of change using several land cover datasets (e.g., National Land Cover Dataset, USGS Land Cover Trends, USDA Census of Agriculture). To predict future changes in unpaved road density and unpaved road stream crossing density, we started with our current condition densities from state datasets (AHTD 2014; KDOT 2012; MoDOT 2019; OKDOT 2020a,b). Meijer *et al*. (2018, p. 1) applied a regression model to future population densities and gross domestic product estimates from the Shared Socioeconomic Pathway scenarios to obtain a best case scenario of 3.2% and worst case scenario of 27.3% increase in road (all types) length km in the U.S. by 2050 (Meijer *et al*. 2018, Table S6). We used the mean of U.S. Global Roads Inventory Project (GRIP) Scenarios SSP1 – SSP5 for Future Scenario 1 and Scenario SSP5 for Future Scenario 2, 15.0 and 27.35% respectively (Meijer 2018; Appendices II-C and II-D). Since GRIP extends to 2050, we added the appropriate fraction of each percent change for 10 years (2050 – 2060) (e.g., 15% + 5.5% = 20.5%) to determine future condition.

We used two metrics for habitat fragmentation, dam count and unpaved road stream crossing density (discussed in previous paragraph). Conservation efforts are ongoing to remove barriers within the Fanshell mussel ranges, and we expect these efforts to continue with a moderate increase in stressors. For dam count under Scenario 1, we projected 1 – 2 dam removals per decade (4 – 8 total) within each MU. However, we projected that despite these efforts to remove dams the overall total would slightly increase per decade under Future Scenario 2.

We examined the resiliency, representation, and redundancy of the Fanshell mussels under two plausible future scenarios for a 40-year period. The resiliency of mussel populations depends on future conditions providing sufficient water quality and quantity to meet life history needs of the mussels and their fish hosts. Resiliency requires good water quality, flowing water, connectivity, and landscape capable of supporting these habitat factors because these habitat factors directly influence species reproduction and abundance, which determine 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, solicited expert opinion, and anticipated changes to habitat and population factors. 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 (Table 6.1).

6.1.A Future Scenario 1 – Moderate Decline in Conditions

Scenario 1 considers a future where conditions moderately decline from current population conditions. Current conservation practices remain in place, but no new measures (except dam removal) occur. Scenario 1 considers climate effects from emissions under RCP4.5 (Appendices III and III-A, RCP4.5; Appendix IV). Throughout the Western Fanshell's range, ≥93% of NCCV models project ±0.5 inch/month change in precipitation by 2074 under Scenario 1. Approximately 70 – 73% of NCCV models project >2°C increase in air temperature throughout the Western Fanshell range. Similarly, 83% and 63% of NCCV models project ±0.5 inch/month change in precipitation and >2°C increase in air temperature, respectively, throughout the "Ouachita" Fanshell's range (Appendix III-A). Minimum summer (June – September) flow is projected to decline in all MUs, except Upper St. Francis and Strawberry, throughout the Fanshell mussel ranges with strong model agreement in the Buffalo, Strawberry, Saline, and Ouachita Headwaters (Appendices IV-A and IV-D). Similarly, annual minimum 90-day moving average flow is expected to decline with very strong model agreement in all MUs (Appendices IV-B and IV-E). Frequency of low pulse flows (<5th percentile) is projected to increase in 27% of Western Fanshell MUs concentrated in the upper White representation unit and 75% of "Ouachita" Fanshell MUs (Appendices IV-C and IV-F). Therefore, we expect reductions in streamflow, due to decreased inputs and enhanced evapotranspiration, to occur in all MUs and those effects will likely be more evident in smaller watersheds (Appendix IV).

We expect overall water quality to decline in all MUs, primarily due to increasing nutrients, metals, and water temperature (Appendices I-F – I-G, III-A). Both species are currently exposed to maximum water temperatures ranging from 30 – 36°C in all MUs, except Middle White. We assume due to their close relationship to Lampsilines that the Fanshell mussels are thermally sensitive. An increase of ~2°C means the Fanshell mussels will be exposed to water temperature >27°C at a greater frequency and duration under this future scenario, which could result in sublethal effects (e.g., slowed growth, reduced fitness, altered timing of reproduction and glochidial excystment) and in extreme cases a higher probability of mortality. Under this scenario, barrier removal continues at the current rate per decade. However, increases in unpaved road crossing density may partially negate improved connectivity associated with dam removal. Influences of landscape change are more apparent in MUs with more socioeconomic drivers.

6.1.B Future Scenario 2 – Severe Decline in Conditions

Factors negatively affecting Fanshell mussel populations worsen with Scenario 2. This scenario magnifies climate effects (RCP8.5; Appendix III) beyond Future Scenario 1. Throughout the Western Fanshell's range, 90 – 93% of NCCV models project ±0.5 inch/month change in precipitation by 2074 under Scenario 2. Approximately 97% of NCCV models project >2°C increase in air temperature throughout the Western Fanshell range. Similarly, 87% and 97% of NCCV models project ±0.5 inch/month change in precipitation and >2°C increase in air

Table 6.1 Future scenario summary table.

Scenario	Future Condition Category Descriptions			
	Water Quality Condition	**Flow Condition**	**Landscape Condition**	**Habitat Fragmentation Condition**
Future Scenario 1 (Moderate stressor increase)	Current water quality trend (1990 - 2019) continues, including same level of water quality standards; majority of models project >2ºC increase by 2060 in annual mean air temperature (RCP4.5)	Current flow trends stable to slight decrease/increase (PRMS Model, except Neosho & Verdigris Basin)	Urbanization, % forested riparian, % imperviousness & % agriculture continue on trend with current levels (2011 - 2016); density of unpaved roads increases 20.5% by 2060, limited improvements to reduce sediment runoff.	Slight reduction in dam count due to restoration efforts; unpaved road crossing density increases 20.5%
Future Scenario 2 (Severe stressor increase)	Declining water quality resulting from increased anthropogenic effects; limited regulations; overall reduced protections; 97% of models project >2°C change in annual mean air temperature by 2074 and many models project increases of 3 – 5°C (RCP 8.5)	Current flow trends decrease substantially (PRMS Model, except Neosho & Verdigris Basins)	Declining habitat quality resulting from increasing conversion rates to urban & imperviousness & declining % forest in the riparian zone compared 2016 based on FORE-SCE A1; density of unpaved roads increases with limited or declining improvements to reduce sediment runoff (worse case GRIP scenario); % forested riparian declines accelerate compared to 2011-2016 trend	Slight increase in level of habitat fragmentation (# dams, unpaved road crossing density), rate of barrier improvement/removal declines

temperature, respectively, throughout the “Ouachita” Fanshell’s range (Appendix III-A). Minimum summer (June – September) flow is projected to decline in all MUs throughout the Fanshell mussel ranges with declines more severe than Scenario 1 (Appendices IV-A and IV-D). Similarly, annual minimum 90-day moving average flow is expected to decline with very strong model agreement in all MUs (Appendices IV-B and IV-E). Frequency of low pulse flows (<5th percentile) is projected to increase beyond Scenario 1 projections, but occur in the same Fanshell mussel MUs as Scenario 1 (Appendices IV-C and IV-F). Therefore, both species experience more frequent and intense droughts broken by more frequent and intense flooding (Appendices III and IV). A greater number of NCCV models predict water temperature will rise 3 – 5.5°C and >2°C is almost certain, increasing the Fanshell mussels exposure to sublethal and potentially lethal temperature at twice the frequency and duration predicted under Future Scenario 1. Landscape changes will likely affect water quality and flow more drastically than Future Scenario 1. Under this scenario dam construction increases slightly per decade, while unpaved road stream crossings increase at a faster rate (Appendix II-D), leading to lower habitat fragmentation. Current conservation measures remain in place, but no new measures occur.

6.2 Future Viability (Resiliency, Redundancy, and Representation)

This section generally reviews the viability of the Fanshell mussel species under each of the two scenarios. The output of the scenarios is included in Tables 6.2 – 6.5. Viability is the species ability to sustain populations in the wild over time, in this case 40 years.

6.2.A Future Scenario 1 – Moderate Increase in Stressors

Resiliency - Under Future Scenario 1, populations of the Fanshell mussels decline in resiliency over time as the factors influencing populations moderately decline from current conditions (Tables 6.2 – 6.3). The effects of climate change lead to flow and temperature changes, which subsequently degrade water quality, and occasionally result in sublethal effects and mortality. Population extirpations likely occur to 55% of Western Fanshell MUs and 50% of “Ouachita” Fanshell MUs, with no MUs in high condition. Thirty-three percent of remaining Western Fanshell and 50% of “Ouachita” Fanshell populations are in low condition and particularly vulnerable to extirpation.

Redundancy - Both Fanshell mussels lose redundancy in Future Scenario 1 (Tables 6.2 and 6.3). Under our projections, the Western Fanshell will have four populations in moderate condition, two in low condition, and five likely extirpated in 40 years across within the Lower Mississippi–St. Francis, Neosho–Verdigris, and upper White River basins. The “Ouachita” Fanshell will have one population in moderate condition, one in low condition, and two likely extirpated in 40 years within the lower Red – Ouachita River basin. These expected losses in number and distribution of resilient populations (both species) will likely make these species more vulnerable to catastrophic events.

Representation - Under Scenario 1, neither species loses any areas of representation. Western Fanshell loses one MU within the Lower Mississippi–St. Francis River basin and Neosho–Verdigris River basin, and loses three MUs within the upper White River basin. However, the “Ouachita” Fanshell has only one area of representation and Western Fanshell has low representation within three areas (Figures 6.1 and 6.2). We do not expect reduced adaptive capacity of either species to future environmental change in the next 40 years (Tables 6.2 and 6.3).

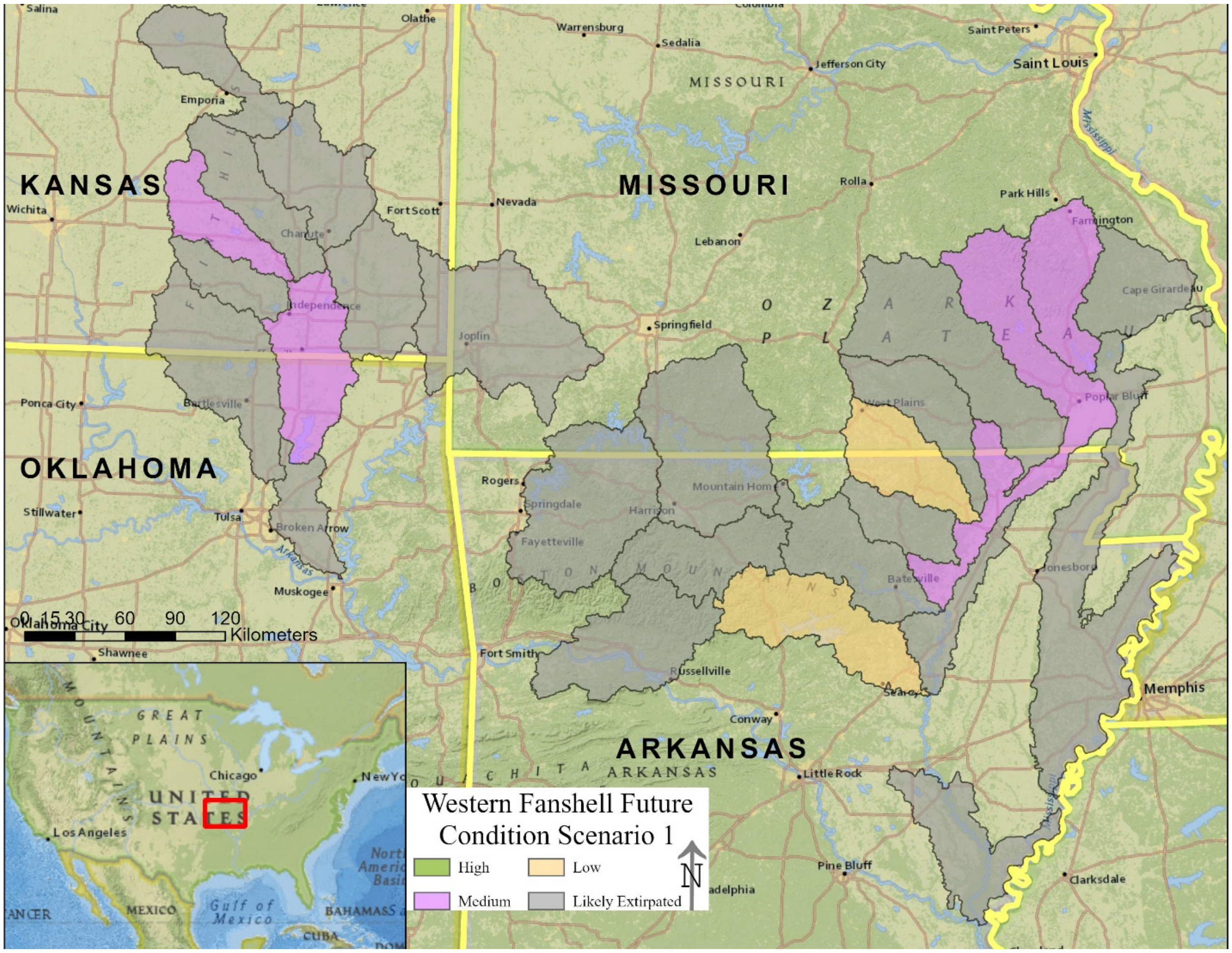


Figure 6.1 Distribution of the current and historically occupied MUs of Western Fanshell under Future Scenario 1.

6.2.B Future Scenario 2 – Severe Increase in Stressors

Resiliency - Under Future Scenario 2, Fanshell mussel populations decline in resiliency over time as the effects of severe climate and landscape change begin to effect populations (Table 6.4 – 6.5). The effects of severe climate and landscape change result in lower stream flows, more frequent and longer duration flooding and degraded water quality and habitat. While our projections do not expect additional extirpations from those observed under Future Scenario 1, we expect all remaining populations of both species to be in low condition in 40 years and particularly vulnerable to extirpation.

Redundancy – Both Fanshell mussels lose redundancy in Future Scenario 2 (Tables 6.4 and 6.5). Under our projections, the remaining 6 Western Fanshell populations will be in low condition, and 5 likely extirpated in 40 years within the Lower Mississippi–St. Francis, Neosho–Verdigris, and upper White River basins (Figure 6.3). The "Ouachita" Fanshell will have two populations in low condition, and two likely extirpated in 40 years within the lower Red – Ouachita River basin

(Figure 6.4). These expected losses in number and distribution of resilient populations (both species) will likely make these species more vulnerable to extirpation.

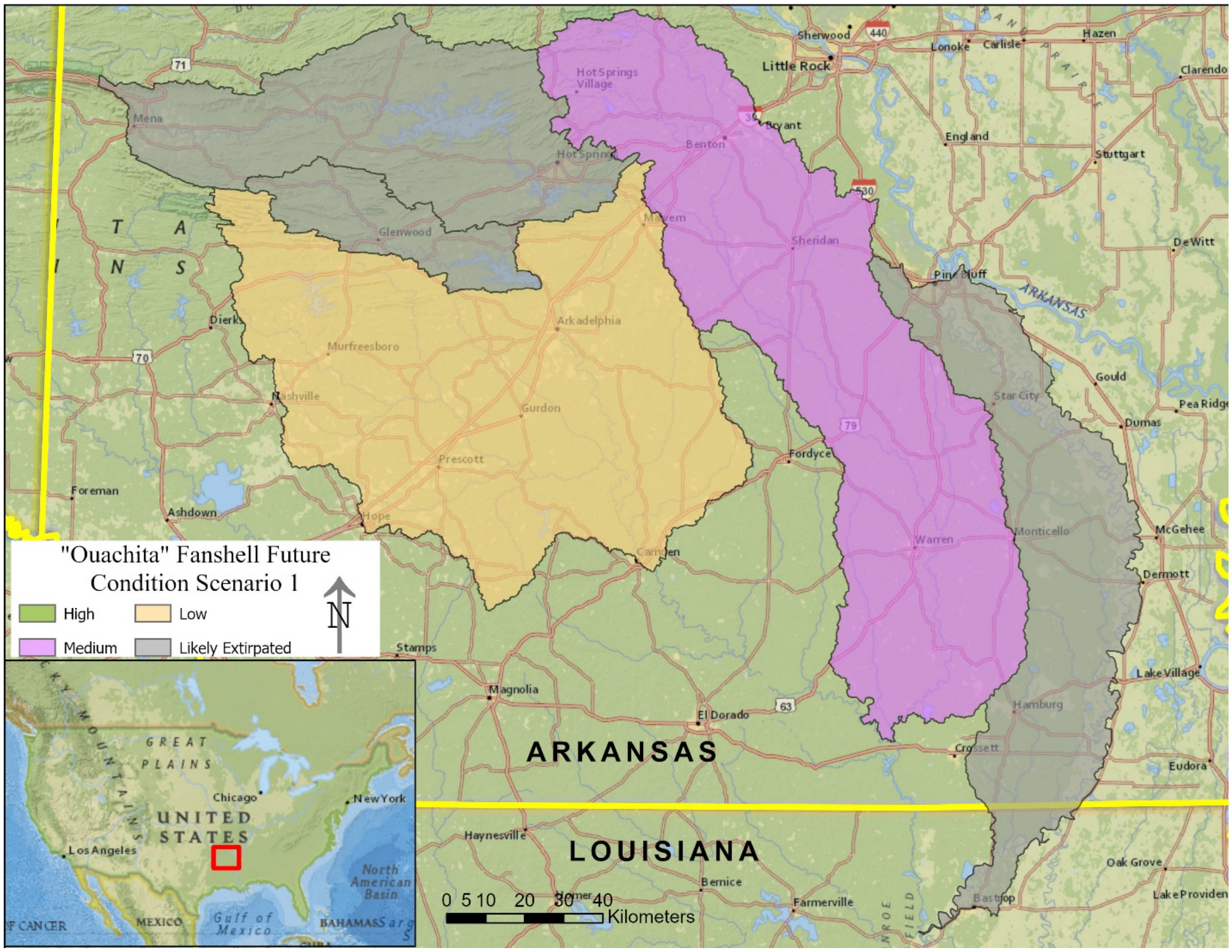


Figure 6.2 Distribution of the current and historically occupied MUs of "Ouachita" Fanshell under Future Scenario 1.

Representation – Neither species loses representation under Future Scenario 2 in 40 years. However, the "Ouachita" Fanshell has only one area of representation and Western Fanshell has low representation within three areas. Western Fanshell does lose five MUs across all three major river basins. We do not expect reduced adaptive capacity of either species to future environmental change in the next 40 years (Tables 6.4 and 6.5).

6.3 Status Assessment Summary

Both species face a variety of environmental stressors, including hydrological alterations to their habitat, water quality degradation, loss of suitable substrates due to excessive sedimentation and other processes, and habitat fragmentation and population isolation.

These risks to Fanshell mussel habitat, acting alone or in combination with each other and climate change, could result in the extirpation of additional populations, further reducing the overall redundancy and representation of Fanshell 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 extirpations due to stochastic or catastrophic events occurred, the Fanshell mussels could recolonize over time by dispersal from nearby surviving populations, facilitated by movements of fish hosts (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. Therefore, the viability of the Fanshell mussels now primarily depends on maintaining the remaining isolated populations and potentially restoring new populations where feasible.

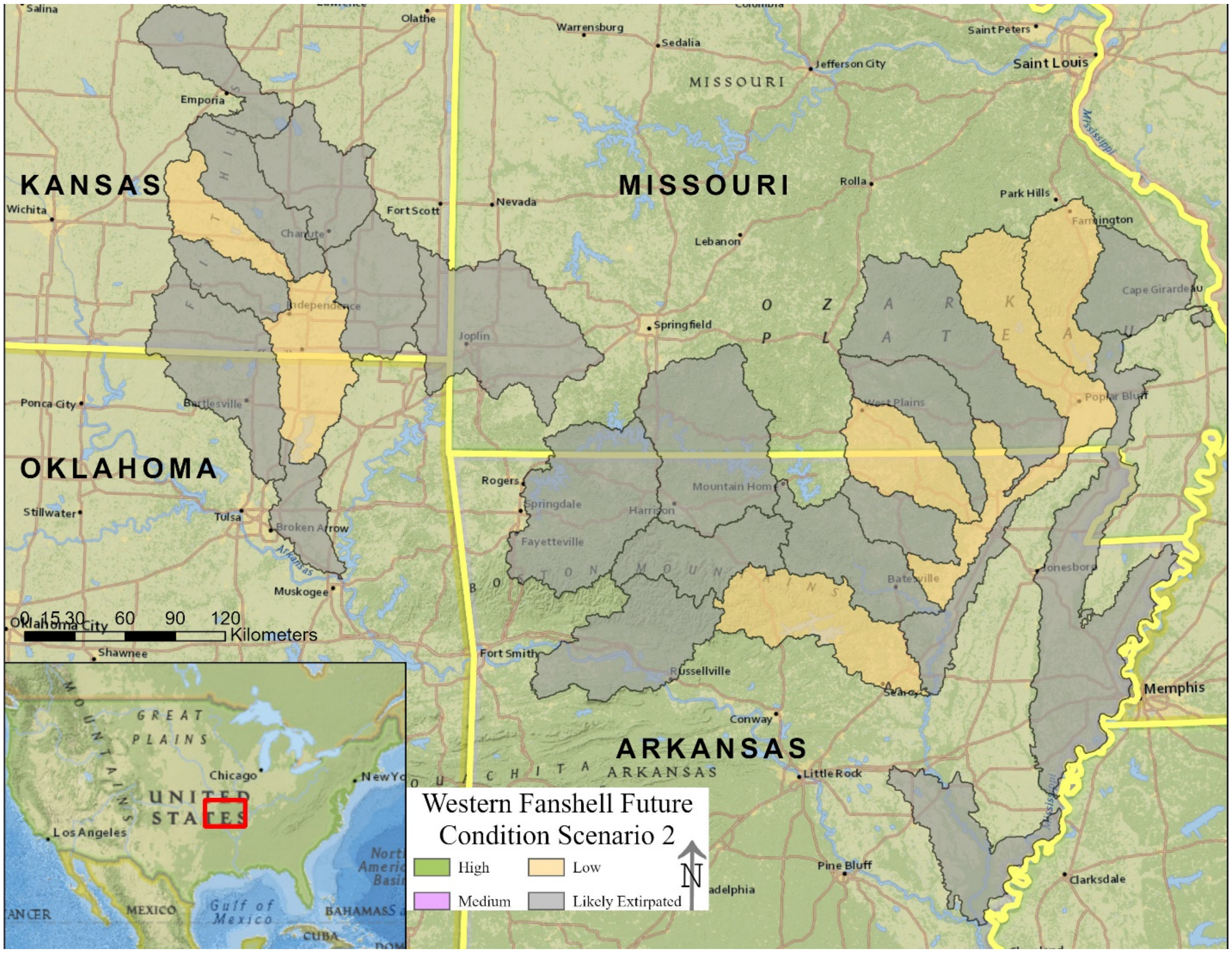


Figure 6.3 Distribution of the current and historically occupied MUs of Western Fanshell under Future Scenario 2.

These risks together substantially affect the future viability of the Fanshell mussels. If population resiliency diminishes, populations are more vulnerable to extirpation. Population extirpation results in losses to redundancy and diminished species representation. Currently, there are three high condition, three moderate condition, and five low condition Western Fanshell populations. Within 40 years, under the best conditions and with additional conservation, given the ongoing effects of climate change and human activities, we expect the likely extirpation of five Western Fanshell populations. Of the remaining Western Fanshell populations, we expect two populations to be in low condition and three populations in moderate condition (Table 6.2, Figure 6.1).

Within 40 years, under the best conditions and with additional conservation, given the ongoing effects of climate change and human activities, we expect the likely extirpation of two “Ouachita” Fanshell populations. Of the remaining “Ouachita” Fanshell populations, we expect one populations to be in low condition and one in moderate condition (Table 6.3, Figure 6.2).

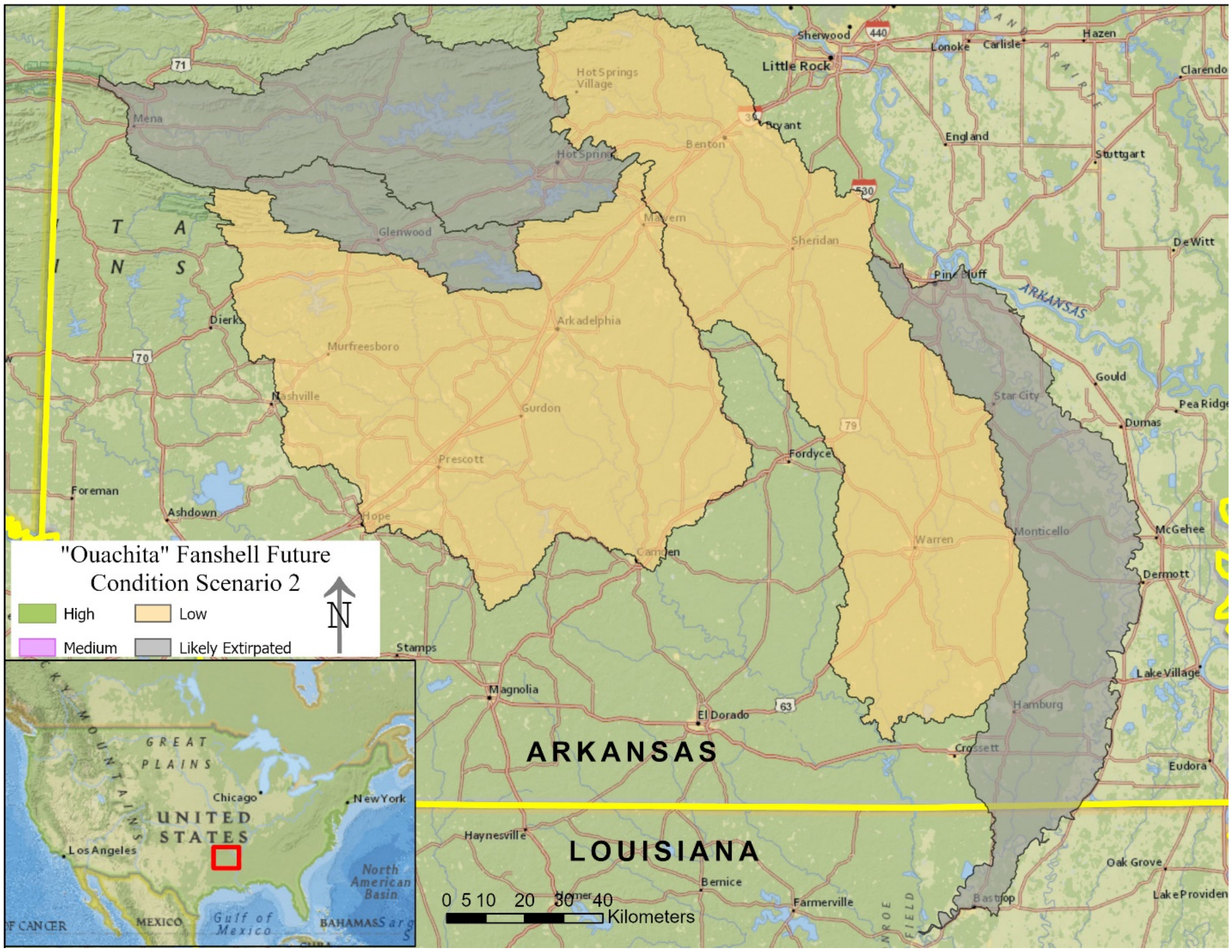


Figure 6.4 Distribution of the current and historically occupied MUs of “Ouachita” Fanshell under Future Scenario 2.

Table 6.2 Condition of Western Fanshell populations under Future Scenario 1. Ø is likely extirpated.

Rep Unit	State	MU	Demographic Factors			Combined Population Score	Habitat Factors				Combined Habitat Score	Overall Future Condition
			Populations Size	Population Extent	Reproduction		Water Quality	Flow	Landscape	Habitat Fragmentation		
Neosho-Verdigris	KS	Fall	Low	Medium	Medium	Medium	Low	Medium	Medium	Low	Low	Medium
	KS, OK	Middle Verdigris	High	Medium	Medium	Medium	Low	Medium	Medium	Medium	Medium	Medium
	KS, MO	Spring	Ø	Ø	Ø	Ø	Low	Medium	Low	Low	Low	Likely Extirpated
Upper White	AR, MO	Black	High	High	Medium	Medium	Medium	Medium	Medium	Low	Medium	Medium
	AR	Buffalo	Ø	Ø	Ø	Ø	Medium	Medium	High	Medium	Medium	Likely Extirpated
	AR	Little Red	Medium	Medium	Low	Low	Medium	High	High	Medium	Medium	Low
	AR	Middle White	Ø	Ø	Ø	Ø	Medium	Medium	High	High	Medium	Likely Extirpated
	AR	Strawberry	Ø	Ø	Ø	Ø	Medium	High	Medium	Medium	Medium	Likely Extirpated
	AR, MO	Spring	Medium	Medium	Low	Low	Medium	Medium	Medium	Medium	Medium	Low
Lower Mississippi-St. Francis	AR, MO	Lower St. Francis	Ø	Ø	Ø	Ø	Low	High	Medium	Low	Low	Likely Extirpated
	MO	Upper St. Francis	High	High	Medium	Medium	Low	High	High	Low	Medium	Medium

Table 6.3 Condition of "Ouachita" Fanshell populations under Future Scenario 1. Ø is likely extirpated.

Rep Unit	State	MU	Demographic Factors			Combined Population Score	Habitat Factors				Combined Habitat Score	Overall Future Condition
			Populations Size	Population Extent	Reproduction		Water Quality	Flow	Landscape	Habitat Fragmentation		
Lower Red-Ouachita	AR	Caddo	Ø	Ø	Ø	Ø	High	Medium	High	Medium	Medium	Likely Extirpated
	AR	Ouachita Headwaters	Ø	Ø	Ø	Ø	Medium	Medium	Medium	Medium	Medium	Likely Extirpated
	AR	Saline	High	High	Medium	Medium	Low	Medium	High	Medium	Medium	Medium
	AR	Upper Ouachita	Low	High	Low	Low	Medium	Medium	High	Medium	Medium	Low

Table 6.4 Condition of Western Fanshell populations under Future Scenario 2. Ø is likely extirpated.

Rep Unit	State	MU	Demographic Factors			Combined Population Score	Habitat Factors				Combined Habitat Score	Overall Future Condition
			Population Size	Population Extent	Reproduction		Water Quality	Flow	Landscape	Habitat Fragmentation		
Neosho-Verdigris	KS	Fall	Low	Low	Low	Low	Low	Medium	Low	Low	Low	Low
	KS, OK	Middle Verdigris	Medium	Low	Low	Low	Low	Medium	Low	Low	Low	Low
	KS, MO	Spring	Ø	Ø	Ø	Ø	Low	Medium	Low	Low	Low	Likely Extirpated
Upper White	AR, MO	Black	Medium	Medium	Low	Low	Medium	Medium	Low	Low	Low	Low
	AR	Buffalo	Ø	Ø	Ø	Ø	Medium	Low	Medium	Medium	Medium	Likely Extirpated
	AR	Little Red	Low	Low	Low	Low	Medium	Medium	Low	Medium	Medium	Low
	AR	Middle White	Ø	Ø	Ø	Ø	Low	Low	Low	Medium	Low	Likely Extirpated
	AR	Strawberry	Ø	Ø	Ø	Ø	Medium	Low	Low	Medium	Low	Likely Extirpated
	AR, MO	Spring	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Lower Mississippi-St. Francis	AR, MO	Lower St. Francis	Ø	Ø	Ø	Ø	Low	Medium	Medium	Low	Low	Likely Extirpated
	MO	Upper St. Francis	Medium	Medium	Low	Low	Low	Medium	Low	Low	Low	Low

Table 6.5 Condition of "Ouachita" Fanshell populations under Future Scenario 2. Ø is likely extirpated.

Rep Unit	State	Population	Demographic Factors			Combined Population Score	Habitat Factors				Combined Habitat Score	Overall Current Condition
			Populations Size	Population Extent	Reproduction		Water Quality	Flow	Landscape	Habitat Fragmentation		
Lower Red-Ouachita	AR	Caddo	Ø	Ø	Ø	Ø	Medium	Low	Low	Medium	Low	Likely Extirpated
	AR	Ouachita Headwaters	Ø	Ø	Ø	Ø	Medium	Low	Low	Low	Low	Likely Extirpated
	AR	Saline	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
	AR	Upper Ouachita	Low	Low	Low	Low	Low	Low	Medium	Low	Low	Low

Literature Cited

Ahlstedt, S.A. & J.D. Tuberville. 1997. Quantitative reassessment of the freshwater mussel fauna in the Clinch and Powell Rivers, Tennessee and Virginia. Pp. 72-97 *in*: K.S. Cummings, A.C. Buchanan, C.A. Mayer, and T.J. Naimo, eds. Conservation and management of freshwater mussels II: initiatives for the future. Proceedings of a UMRCC symposium, October 1995, St. Louis, Missouri. Upper Mississippi River Conservation Committee, Rock Island, Illinois.

[AHTD] Arkansas Highway and Transportation Department. 2014. Arkansas centerline file. Retrieved from http://gis.arkansas.gov/product/arkansas-centerline-file/.

Alder, J.R. & S.W. Hostetler. 2013. USGS National Climate Change Viewer. US Geological Survey. https://www2.usgs.gov/landresources/lcs/nccv/viewer.asp

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology and Systematics 35:257–284.

Allen, D.C. & C.C. Vaughn. 2010. Complex hydraulic and substrate variables limit freshwater mussel species richness and abundance. J. N. Am. Benthol. Soc., 2010, 29(2):383–394.

Allen, D.C., B.E. Sietman, D.E. Kelner, M.C. Hove, J.E. Kurth, J.M. Davis, J.L. Weiss & D.J. Hornbach. 2007. Early life-history and conservation status of *Venustaconcha ellipsiformis* (Bivalvia, Unionidae) in Minnesota. American Midland Naturalist 157:74-91.

Alley, J.L. 2005. Distribution and diversity of freshwater mussels in an unchannelized Mississippi alluvial stream: Bayou Bartholomew, Morehouse Parish, Louisiana. Unpublished M.S. thesis, University of Louisiana at Monroe. 147 pp.

Angelo, R.T., M.S. Cringan, D. L. Chamberlain, A. J. Stahl, S. G. Haslouer & C. A. Goodrich. 2007. Residual effects of lead and zinc mining on freshwater mussels in the Spring River basin (Kansas, Missouri, and Oklahoma, USA). Science of the Total Environment 384: 467-496.

Archambault, J.M., W.G. Cope & T.J. Kwak. 2014. Survival and behaviour of juvenile unionid mussels exposed to thermal stress and dewatering in the presence of a sediment temperature gradient. Freshwater Biology 59:601–613.

Arey, L.B. 1932. The formation and structure of the glochidial cyst. Biological Bulletin 62:212-221.

Atkinson, C.L., J.P. Julian, C.C. Vaughn. 2012. Scale-dependent longitudinal patterns in mussel communities. Freshwater Biology 57:2272 – 2284.

Augspurger, T., A.E. Keller, M.C. Black, W.G. Cope & F.J. Dwyer. 2003. Water quality guidance for protection of freshwater mussels (Unionidae) from ammonia exposure. Environmental Toxicology and Chemistry 22:2569-2575.

Augspurger, T., F.J. Dwyer, C.G. Ingersoll & C.M. Kane. 2007. Advances and opportunities in assessing contaminant sensitivity of freshwater mussel (Unionidae) early life stages. Environmental Toxicology and Chemistry 26(10):2025-2028.

Barnhart 1997. Reproduction and fish hosts of the Western Fanshell, *Cyprogenia aberti* (Conrad 1850). Unpubl. report submitted to Kansas Department of Wildlife, Parks and Tourism. 22 pp.

Barnhart, M.C., Haag, W.R. & W.N. Roston. 2008. Adaptations to host infection and larval parasitism in Unionoida. J. N. Am. Benthol. Soc. 27: 370-394.

Bartsch, M. R., D. L. Waller, W. G. Cope & S. Gutreuter. 2000. Emersion and thermal tolerances of three species of unionid mussels: survival and behavioral effects. Journal of Shellfish Research 19:233-240.

Bates, J.M., and S.D. Dennis. 1983. Mussel (naiad) survey--St. Francis, White, and Cache rivers Arkansas and Missouri. U.S. Army Corps of Engineers, Memphis District, TN. 89 pp. + appendices.

Bauer, G. 1988. Threats to the freshwater pearl mussel *Margaritifera margaritifera* L. in Central Europe. Biological Conservation 45:239-253.

Bauer, G. 1992. Variation in the life span and size of the freshwater pearl mussel. Journal of Animal Ecology 61:425-436.

Besser, J.M., W.G. Brumbaugh, D.K. Hardesty, J.P. Hughes & C.G. Ingersoll. 2009. Assessment of metal-contaminated sediments from the Southeast Missouri (SEMO) mining district using sediment toxicity tests with amphipods and freshwater mussels. Unpublished Administrative Report 08-NRDAR-02 submitted to U.S. Fish and Wildlife Service, Columbia, Missouri. 59 pp.

Bidwell, J.R., C.J. Boeckman & W.L. Fisher. 2009. Status of macroinvertebrate and fish assemblages in the small rivers of the Tallgrass Prairie. Final Report to Oklahoma Department of Wildlife Conservation, Oklahoma City, Oklahoma. Project T-40-P-1, 42 pp. + appendices.

Boeckman, C.J. & J.R. Bidwell 2008 Status of freshwater native mussels (Unionidae) in the Oklahoma section of the Verdigris River after introduction of the zebra mussel (*Dreissena polymorpha* Pallas, 1771). American Malacological Bulletin 25(1):1-8.

Bogan, A.E. 1993. Freshwater Bivalve Extinctions (Mollusca: Unionoida): A Search for Causes American Zoologist, Vol. 33, No. 6 (1993), pp. 599-609.

Bonner, T.H., E.L. Oborny, B.M. Littrell, J.A. Stoeckel, B.S. Helms, K.G. Ostrand, P.L. Duncan & J. Conway. 2018. Multiple freshwater mussel species of the Brazos River, Colorado River, and Guadalupe River basins. CMD 1 - 6233CS. Final Report to Texas Comptroller of Public Accounts. February 28, 2018. 306 pp.

Booth, D.B. & C. Rhett Jackson. 1997. Urbanization of aquatic systems: Degradation thresholds, stormwater detection and the limits of mitigation. Journal of the American Water Resources Association 33(5): 1077-90.

Brabec, E., S. Schulte & P.L. Richards. 2002. Impervious surfaces and water quality: a review of current literature and its implications for watershed planning. Journal of 24 Planning Literature 16(4):499–514.

Bressler, D.W., M.J. Paul, A.H. Purcell, M.T. Barbour, E.T. Rankin & V.H. Resh. 2009. Assessment tools for urban catchments: developing stressor gradients. J. Am. Water Res. Assoc 45(2):291-305.

Brim-Box, J.B. & J. Mossa. 1999. Sediment, land use, and freshwater mussels: prospects and problems. Journal of North American Benthological Society 18:99-117.

Bringolf, R.B., W.G. Cope, S. Mosher, M.C. Barnhart & D. Shea. 2007a. Contaminant sensitivity of freshwater mussels: Acute and chronic toxicity of glyphosphate compounds to glochidia and juveniles of *Lampsilis siliquoidea* (Unionidae). Environmental Toxicology and Chemistry 26:2094-2100.

Bringolf, R.B., W.G. Cope, M.C. Barnhart, S. Mosher, P.R. Lazaro & D. Shea. 2007b. Contaminant sensitivity of freshwater mussels: Acute and chronic toxicity of pesticide formulations (atrazine, chlorpyrifos, and permethrin) to glochidia and juveniles of *Lampsilis siliquoidea*. Environmental Toxicology and Chemistry 26(10):2101-2107.

Brooks, J.A., R.L. Minton, S.G. George, D.M. Hayes, R. Ulmer & F. Pezold. 2008. Diversity and Distribution of Native Freshwater Mussels in Bayou Bartholomew, Arkansas. Proc. Southeastern Fishes Council 50:8-18.

Brown, M.E., M. Kowalewski, R.J. Neves, D.S. Cherry & M.E. Schreiber. 2005. Freshwater mussel shells as environmental chronicles: geochemical and taphonomic signatures of mercury-related extirpations in the North Fork Holston River, Virginia. Environ. Sci. Technol. 39:1455-1462.

Bruenderman, S.A., J.S. Faiman & A.C. Buchanan. 2001. Survey for the Curtis Pearly Mussel, *Epioblasma florentina curtisii* (Utterback 1914) and other mussel species in Little Black River, Missouri. Report to the U.S. Fish and Wildlife Service, Columbia, MO. 78pp.

Buchanan, A.C. 1980. The distribution of *Lampsilis rafinesqueana* and other naiad species in southwestern Missouri. Missouri Department of Conservation, Columbia, MO. 2 pp. + figures and tables.

Buchanan, A.C. 1996. Distribution of naiades in select streams in southern Missouri – A survey conducted during 1981-1982. Missouri Department of Conservation, Columbia, MO. 79 pp.

Call, R.E. 1885. A study of the Unionidae of Arkansas with incidental reference to their distribution in the Mississippi Valley. Transactions of the Academy of Science of St. Louis 7(1):1-65.

Camargo, J.A., A. Alonso & A. Salamanca. 2005. Nitrate toxicity to aquatic animals: a review with new data for freshwater invertebrates. Chemosphere 58(2005):1255-1267.

Carroll, C., J.A. Vucetich, M.P. Nelson, D.J. Rohlf & M.K. Phillips. 2010. Geography and recovery under the U.S. Endangered Species Act. Conservation Biology 24:395-403.

Carter, L., A. Terando, K. Dow, K. Hiers, K.E. Kunkel, A. Lascurain, D. Marcy, M. Osland, and P. Schramm, 2018: Southeast. Pp. 743-808 *in:* Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart eds. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA4.2018.CH19

[CBD] Center for Biological Diversity. 2010. Petition to List 404 Aquatic, Riparian and Wetland Species from the Southeastern United States as Threatened or Endangered Under the Endangered Species Act. Submitted on behalf of CBD, Alabama Rivers Alliance, Clinch Coalition, Dogwood Alliance, Gulf Restoration Network, Tennessee Forests council, West Virginia Highlands Conservancy, Tierra Curry, and Noah Greenwald. Dated April 20, 2010. Pp. 301-304.

Chamberlain, T. K. 1934. The glochidial conglutinates of the Arkansas Fanshell, *Cyprogenia aberti* (Conrad). Biol. Bull., 66:55-61.

Cherry, D.S., J.L. Scheller, N.L. Cooper & J.R. Bidwell. 2005. Potential effects of Asian clam (Corbicula fluminea) die-offs on native freshwater mussels (Unionidae) I: Water-column ammonia levels and ammonia toxicity. Journal of the North American Benthological Society 24: 369-380.

Chong, J.P., J.L. Harris & K.J. Roe. 2016. Incongruence between mtDNA and nuclear data in the freshwater mussel genus *Cyprogenia* (Bivalvia: Unionidae) and its impact on species delineation. Ecology and Evolution 6(8):2439-2452.

Christian, A.D. 1995. Analysis of the commercial mussel beds in the Cache and White rivers in Arkansas. Unpublished M.S. thesis, Arkansas State University, Jonesboro. 197pp.

Christian, A.D. & J.L. Harris, 2004. Status survey for the pink mucket (*Lampsilis abrupta* (Say, 1831)), winged mapleleaf (*Quadrula fragosa* (Conrad, 1835)), and Ouachita rock pocketbook (*Arcidens wheeleri* Ortmann and Walker, 1912) in the Little Missouri River. Unpubl. report submitted to Arkansas Game and Fish Commission, Little Rock, Arkansas. 19 pp. + appendices.

Clark, B. & W. Mangham. 2019. Middle Trinity River research, 2018. White paper. Trinity River Authority, Arlington, Texas. 49 pp.

Coffin, A.W. 2007. From roadkill to road ecology: A review of the ecological effects of roads. Journal of Transport Geography 15 (2007) 396–406.

Conrad, T.A. 1850. Descriptions of new species of fresh water shells. Proceedings of the Academy of Natural Sciences of Philadelphia 5: 10-11.

Cooper, N.L., J.R. Bidwell & D.S. Cherry. 2005. Potential effects of Asian clam (*Corbicula fluminea*) dieoffs on native freshwater mussels (Unionidae) II: porewater ammonia. J. N. Am. Benth. Soc. 24:381-394.

Cope, W.G., R.B. Bringolf, D.B. Buchwalter, T.J. Newton, C.G. Ingersoll, N. Wang, T. Augspurger, F.J. Dwyer, M.C. Barnhart, R.J. Neves & E. Hammer. 2008. Differential exposure, duration, and sensitivity of unionoidean bivalve life stages to environmental contaminants. Journal of North American Benthological Society 27:451-462.

Daigle, P. 2010. A summary of the environmental impacts of roads, management responses, and research gaps: A literature review. BC Journal of Ecosystems and Management 10(3):65–89.

Daraio, J.A., L.J. Weber, & T.J. Newton. 2010. Hydrodynamic modeling of juvenile mussel dispersal in a large river: the potential effects of bed shear stress and other parameters. Journal of the North American Benthological Society, 29(3):838-851.

Davidson, C.L. 1997. Analysis of mussel beds in the Little Missouri and Saline Rivers, Blue Mountain, Ozark and Dardanelle Lakes, Arkansas. Unpublished M.S. thesis, Arkansas State University, Jonesboro. 156pp.

Davidson, C.L. 2015. Status and distribution of freshwater mussels (Bivalvia: Unionoida) inhabiting the Saline River within Felsenthal National Wildlife Refuge. Unpublished report, U.S. Fish and Wildlife Service, Conway, Arkansas. 33pp.

Davidson, C.L. & S.A. Clem. 2002. The freshwater mussel (Bivalvia: Unionacea) resources in a selected segment of the Saline River: location, species composition and status of mussel beds. Unpublished report, Arkansas Tech University, Russellville, for The Nature Conservancy, Little Rock, Arkansas, and Arkansas Game and Fish Commission, Little Rock. 48pp.

Davidson, C.L. & S.A. Clem. 2004. The freshwater mussel (Bivalvia: Unionacea) resources in a selected segment of the Saline River: location, species composition and status of mussel beds. Addendum 2. Unpublished report, Arkansas Tech University, Russellville, for the Arkansas Game and Fish Commission, Little Rock. 23pp.

Davidson, C.L. & D. Gosse. 2001. Status and distribution of freshwater mussels (Bivalvia: Unionacea) inhabiting the Saline River/Holly Creek Bottoms Area, Saline County, Arkansas. Unpubl. report prepared for The Nature Conservancy, Little Rock, Arkansas. 7 pp. + appendices.

Davidson, C.L. & D. Gosse. 2003. Status and distribution of freshwater mussels (Unionacea) inhabiting the Saline River/Holly Creek bottoms area, Saline County, Arkansas. Journal of the Arkansas Academy of Science 57 (2003):187-192.

DeCatanzaro, R., M. Cvetkovic, & P. Chow-Fraser. 2009. The relative importance of road density and physical watershed features in determining coastal marsh water quality in Georgian Bay. Environmental Management 44:456-467.

Dewitz, J. 2019. National Land Cover Database (NLCD) 2016 Products: U.S. Geological Survey data release. https://doi.org/10.5066/P96HHBIE.

Douda, K., P. Horky & M. Bily. 2012. Host limitation of the thick-shelled river mussel: identifying the threats to declining affiliate species. Animal Conservation 15:536-544.

Dunne, T. & L.B. Leopold. 1978. Runoff Process. Pp. 255-277 *in* Water in environmental planning. W.H. Freeman, San Francisco. 818pp.

Eads, C. & J. Levine. 2011. Refinement and Growout Techniques for Four Freshwater Mussel Species. NC State University, Raleigh, NC. 15pp.

Eckert, N.L. 2003. Reproductive biology and host requirement differences among isolated populations of Cyprogenia aberti (Conrad, 1850). M.S. Thesis, Southwest Missouri State University, Springfield. pp. 87.

Eckert, N.L. & M.C. Barnhart. 2008. Conservation status assessment of the Western Fanshell, *Cyprogenia aberti.* Draft Report. 63pp.

EcoAnalysts, Inc. 2018. Final report: Tri-state mining district unionid assessment, Missouri, Kansas, and Oklahoma, 2016 – 2018. Unpubl. report prepared for U.S. Fish and Wildlife Service, Columbia, Missouri. 101 pp.

Ellis, M. M. 1936. Erosion silt as a factor in aquatic environments. Ecology 17:29-42.

[EPA] Environmental Protection Agency. 2012. Identifying and protecting healthy watersheds, Chapter 2 key concepts and assessment approaches. U.S. EPA Office of Water. http://water.epa.gov/healthywatersheds.

[EPA] Environmental Protection Agency. 2016. Preliminary Healthy Watersheds Assessment, February 2017 version. U.S. EPA Office of Water Healthy Watersheds Program. https://www.epa.gov/hwp/download-2017-preliminary-healthy-watersheds-assessments.

Ficke, A.A., C.A. Myrick & L.J. Hansen. 2005. Potential impacts of global climate change on freshwater fishes. World Wide Fund for Nature, Gland, Switzerland.

Ficke, A.A., C.A. Myrick & L.J. Hansen. 2007. Potential impacts of global climate change on freshwater fisheries. Rev. Fish. Biol. Fisheries 17:581-613.

[FMCS] Freshwater Mollusk Conservation Society. 2015. How do mussel reproduce? Retrieved from https://molluskconservation.org/MUSSELS/Reproduction.html.

[FMCS] Freshwater Mollusk Conservation Society. 2016. A national strategy for the conservation of native freshwater mollusks. Freshwater Mollusk Biology and Conservation 19:1-21.

Forman, T.T. &L.E. Alexander 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29:207-231.

Francis-Floyd, R. 2011. Dissolved oxygen for fish production. Publication FA 27. Fisheries and Aquatic Sciences Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. 3 pp.

Fuller, S.L.H. 1974. Clams and mussels (Mollusca: Bivalvia). Pp. 215-273 *in*: C.W. Hart, Jr., and S.L.H. Fuller, eds. Pollution ecology of freshwater invertebrates. Academic Press, New York.

Funk, W.C., B.R. Forester, S.J. Converse, C. Darst & S. Morey. 2018. Improving conservation policy with genomics: a guide to integrating adaptive potential into U.S. Endangered Species

Act decisions for conservation practitioners and geneticists. Conservation Genetics 20:115–134. https://doi.org/10.1007/s10592-018-1096-1.

Furniss, M.J., T.D. Roelofs & C.S. Yee. 1991. Road construction and maintenance. In: Meehan, W.R., ed. Influences of forest and rangeland management on salmonid fishes and their habitats. Spec. Publ. 19. Bethesda, MD: American Fisheries Society: 297-323.

Gage, M.S., A. Spivak, & C.J. Paradise. 2004. Effects of land use and disturbance on benthic insects in headwater streams draining small watersheds north of Charlotte, NC. Southeastern Naturalist 3(2), 345-358.

Galbraith, H.S. & C.C. Vaughn. 2009. Temperature and food interact to influence gamete development in freshwater mussels. Hydrobiologia 636:35-47.

Galloway, J.M., B.E. Haggard, M.T. Meyers & W.R. Green. 2005. Occurrence of Pharmaceuticals and other organic wastewater constituents in selected streams in northern Arkansas, 2004. U.S. Geological Survey Scientific Investigations Report 2005-5140.

Ganser, A. M., T. J. Newton & R. J. Haro. 2015. Effects of elevated water temperature on physiological responses in adult freshwater mussels. Freshwater Biology 60: 1705-1716.

Gascho Landis, A.M., W.R. Haag & J.A. Stoeckel. 2013. High suspended solids as a factor in reproductive failure of a freshwater mussel. Freshwater Science 32:70-81.

Gergel, S.E., M.G. Turner, J.R. Miller, J.M. Melack, & E.H. Stanley. 2002. Landscape indicators of human impacts to riverine systems. Aquatic Sciences 64:118-128.

Gillis P.L. 2011. Assessing the toxicity of sodium chloride to the glochidia of freshwater mussels: implications for salinization of surface waters. 2011. Environ Pollut.159: 1702–8.

Gillis, P.L., R.J. Mitchell, A.N. Schwalba, K.A. McNicholsa, G.L. Mackiea, C.M.Wood & J.D. Ackerman. 2008. Sensitivity of the glochidia (larvae) of freshwater mussels to copper: Assessing the effect of water hardness and dissolved organic carbon on the sensitivity of endangered species. Aquatic Toxicology 88 (2008) 137–145.

Gordon, M.E. 1980. Freshwater Mollusca of the Elk River, White River above Beaver Reservoir, and Frog Bayou drainages of the southwestern Ozarks. M.S. Thesis, University of Arkansas. Fayetteville, AR. 366 pp.

Gordon, M.E. 1982. Mollusca of the White River, Arkansas and Missouri. *Southwestern Naturalist* 27(3):347-352.

Gordon, M.E., and J.L. Harris. 1983. Distribution and status of fourteen species of freshwater mussels considered rare or endangered in Arkansas. Arkansas Natural Heritage Commission, Little Rock, AR. 23 pp. + 2 appendices.

Goudreau, S.E., R.J. Neves & R.J. Sheehan. 1993. Effects of Wastewater Treatment Plant Effluents on Freshwater Mollusks in the Upper Clinch River, Virginia, USA. Hydrobiologia 252: 211-230.

Gray, E.V.S., W.A. Lellis, J.C. Cole & C.S. Johnson. 2002. Host identificaiton for *Strophitus undulatus* (Bivalvia: Unionidae), the Creeper, in the Upper Susquehanna River Basin, Pennsylvania. Am. Midl. Nat. 147:153-161.

Grobler, P.J., J.W. Jones, N.A. Johnson, R.J. Neves & E.M. Hallerman. 2011. Homogeneity at nuclear microsatellite loci masks mitochondrial haplotype diversity in the endangered Fanshell Pearlymussel (Cyprogenia stegaria). Journal of Heredity 102:196-206.

Groffman, P.M., D.J. Bain, L.E. Band, K.T. Belt, G.S. Brush, J.M. Grove, R.V. Pouyat, I.C. Yesilonis, & W.C. Zipperer. 2003. Down by the riverside: urban riparian ecology. Frontiers in Ecology and the Environment 1(6):315-321.

Haag, W.R. 2012. North American freshwater mussels: natural history, ecology, and conservation. Cambridge University Press, New York, New York.

Haag, W.R. 2019. Reassessing enigmatic mussel declines in the United States. Freshwater Mollusk Biology and Conservation 22:43–60.

Haag W.R. & Warren M.L. 2008. Effects of severe drought on freshwater mussel assemblages. Transactions of the American Fisheries Society,137, 1165–1178.

Hammer, T.R. 1972. Stream channel enlargement due to urbanization. Water Resources Research 8(6):1530-1540.

Hardison, B.S. & J.B. Layzer. 2001. Relations between complex hydraulics and the localized distribution of mussels in three regulated rivers. Regul. Rivers: Res. Mgmt. 17:77–84.

Harr, R.D., W.C. Harper, & J.T. Krygier. 1975. Changes in storm hydrographs after road building and clear-cutting in the Oregon Coast Range. Water Resources Research 11(3):436-444.

Harris, J.L. 1988. Status survey of *Lampsilis powelli* (Lea 1852). Unpubl. report submitted to U.S. Fish and Wildlife Service, Jackson, MS. 44 pp. + appendices.

Harris, J.L. 1999. Freshwater mussel survey: Carpenter-Remmel Project, FERC #271. Final Report. Little Rock (AR: Entergy AR). No pagination.

Harris, J.L. 2006. *Quadrula fragosa* population estimates at 10 sites in the Ouachita River drainage, Arkansas. Unpubl. Report submitted to U.S. Fish and Wildlife Service, Arkansas Ecological Services Field Office. 14pp. + appendix.

Harris, J.L. 2017. Sun Bio Products Project Ouachita River Mussel Survey, Clark County, Arkansas. Final report prepared for Crist Engineers, Little Rock, AR. 16 pp. + appendices.

Harris, J.L. & A.D. Christian. 2000. Current status of the freshwater mussel fauna of the White River, Arkansas, River Miles 10-255. Final report prepared for U.S. Army Corps of Engineers, Memphis, TN. 23pp.

Harris, J.L., J.L. Farris, & A.D. Christian. 2007. Status of *Epioblasma florentina curtisii* (Frierson and Utterback 1916), Curtis Pearlymussel, in Arkansas. Final Report to the U.S. Fish and Wildlife Service, Arkansas Ecological Services Field Office. 37 pp. + appendices.

Harris, J.L. W.R. Posey II, C.L. Davidson, J.L. Farris, S.R. Oetker, J.N. Stoeckel, B.G. Crump, M.S. Barnett, H.C. Martin, M.W. Matthews, J.H. Seagraves, N.J. Wentz, R. Winterringer, C. Osborne & A.D. Christian. 2009. Unionoida (Mollusca: Margaritiferidae, Unionidae) in Arkansas, Third Status Review. Journal of the Arkansas Academy of Science 63:50-86.

Hartfield, P.W. & E. Hartfield. 1996. Observations on the conglutinates of *Ptychobranchus greeni* (Conrad 1834) (Mollusca: Bivalvia: Unionoidea). American Midland Naturalist 135:370-375.

Hickey, C.W. & M.L. Martin. 1999. Chronic toxicity of ammonia to the freshwater bivalve *Sphaerium novaezelandiae*. Archives of Environmental Contaminants and Toxicology 36:38-46.

Hutson, C. & M. C. Barnhart. 2004. A survey of endangered and special concern mussel species in the Sac, Pomme de Terre, St. Francis and Black rivers in Southeastern Missouri, 2001-2003. Final report. Missouri Department of Conservation, Endangered Species Grant No. E-1-36. 369 pp.

Ingersoll, C.G., N.J. Kernaghan, T. S. Gross, C. D. Bishop, N. Wang & A. Roberts. 2007. Laboratory toxicity testing with freshwater mussels. Pp.95-134 *in* J.L. Farris and J.H. Van Hassel (editors). Freshwater bivalve ecotoxicology. CRC Press, Boca Raton, Florida and SETAC Press, Pensacola, Florida.

[IPCC] Intergovernmental Panel on Climate Change. 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Isely, F.B. 1924. The fresh-water mussel fauna of eastern Oklahoma. *Proceedings of the Oklahoma Academy of Science* 4:43-118.

Jacobson, P.J., R.J. Neves, D.S. Cherry & J. L. Farris. 1997. Sensitivity of glochidial stages of freshwater mussels (Bivalvia: Unionidae) to copper. Environmental Toxicology and Chemistry 16:2384-2392.

Jefferson, T. 1806. Message from the President of the United States, communicating discoveries made in exploring the Missouri, Red River, and Washita by Captains Lewis and Clark, Doctor Sibley, & Mr. Dunbar. Hopkins and Seymour Printers, New York. 128pp.

Jones, J.W. & R.J. Neves. 2002. Life history and propagation of the endangered Fanshell pearlymussel, *Cyprogenia stegaria* Rafinesque (Bivalvia:Unionidae). Journal of the North American Benthological Society 21(1):76-88.

Kaiser, B. & C. Barnhart. 2007. Effects of hypoxia on immature freshwater mussels. Poster presented at SETAC.

Kanehl, P. & J. Lyons. 1992. Impacts of in-stream sand and gravel mining on stream habitat and fish communities, including a survey on the Big Rib River, Marathon County, Wisconsin. Wisconsin Department of Natural Resources Research Report 155. 32pp.

[KDOT] Kansas Department of Transportation. 2012. Kansas non-state road system. Retrieved from http://www.kansasgis.org/catalog/index.cfm.

Keller, A.E. & S.G. Zam. 1991. The acute toxicity of selected metals to the freshwater mussel, *Anodonta imbecilis*. Environmental Toxicology and Chemistry 10:539-543.

King, J.G. & L.C. Tennyson. 1984. Alterations of streamflow characteristics following road construction in north central Idaho. Water Resources Research 20(8):1159-1163.

Klein, R.D. 1979. Urbanization and stream quality impairment. Water Resource Bulletin 15(4):948-963.

Kolpin, D.W., E. Furlong, M.T. Meyer, E.M. Thurman, S.D. Zaugg, L. B. Barber & H.T. Buxton. 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999-2000: a national reconnaissance. Environmental Science and Technology 36:1202-1211.

Kondolf, G.M. 1997. Hungry Water: Effects of Dams and Gravel Mining on River Channels.

Environmental Management 21:533-551.

Kroboth, P.T., C.L. Cox & D.C. Chapman. 2019. Black carp in North America: a description of range, habitats, time of year, and methods of reported captures. North American Journal of Fisheries Mangement 39:1046-1055.

LaFontaine, J.H., R.M. Hart, L.E. Hay, W.H. Farmer, A.R. Bock, R.J. Viger, S.L. Markstrom, R.S. Regan & J.M. Driscoll. 2019. Simulation of water availability in the Southeastern United States for historical and potential future climate and land-cover conditions. U.S. Geological Survey Scientific Investigations Report 2019–5039, 83 pp. https://doi.org/10.3133/sir20195039

Lea, I. 1852. A synopsis of the family of Naiades. 3rd ed., greatly enlarged and improved. Blanchard and Lea, Philadelphia. 88 pp. https://doi.org/10.3133/sir20195039.Lea 1852.

Lea, I. 1870. A synopsis of the family Unionidae. 4th ed., very greatly enlarged and improved. Henry C. Lea, Philadelphia. 184 pp.

Lee, D.C., J.R. Sedell, B.E. Rieman, [and others]. 1997. Broadscale assessment of aquatic species and habitats. In: Quigley, T.M.; Arbelbide, S.J., tech. eds. An assessment of ecosystem components in the interior Columbia basin and portions of the Klamath and Great Basins: volume III. Gen. Tech. Rep. PNW-GTR-405. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 1057-1496. Chapter 4. (Quigley, T.M., tech. ed.; Interior Columbia Basin Ecosystem Management Project: scientific assessment).

Leff, L.G., J.L. Burch & J.V. McArthur. 1990. Spatial distribution, seston removal, and potential competitive interactions of the bivalves *Corbicula fluminea* and *Elliptio complanata* in a coastal plain stream. Freshwater Biology 24:409-416.

Leopold, L.B. 1968. Hydrology for urban land planning – A guidebook on the hydrologic effects of urban land use. Geological Survey Circular 554. 26pp.

Limburg, K.E. & R. E. Schmidt. 1990. Patterns of fish spawning in Hudson River tributaries: response to an urban gradient? Ecology 71(4):1238-1245.

Marking, L.L. & T.D. Bills. 1979. Acute effects of silt and sand sedimentation on freshwater mussels. Pp. 204-211 *in*: J.R. Rasmussen, ed. Proceedings of the UMRCC symposium on Upper Mississippi River bivalve mollusks. Upper Mississippi River Conservation Committee, Rock Island, Illinois.

Martin, H.C., J.L. Harris & A.D. Christian. 2009. Qualitative freshwater mussel survey of the South Fork Spring River, Missouri and Arkansas. Journal of the Arkansas Academy of

Science 63:106-112.

Mather, C.M. 1990. Status survey of the western Fanshell and the Neosho mucket in Oklahoma. Final Report to Oklahoma Department of Wildlife Conservation, Oklahoma City, Oklahoma. Project E-7, 22 pp.

Mather, C.M. 2005. The freshwater mussels of Oklahoma. Final Report to the Oklahoma Department of Wildlife Conservation, Oklahoma City, Oklahoma. Federal Aid grant No. T-14, 267 pp.

Matthews, M., F. Usrey, S.W. Hodges, J.L. Harris & A.D. Christian. 2009. Species richness, distribution, and relative abundance of freshwater mussels (Bivalvia: Unionidae) of the Buffalo National River, Arkansas. Journal of the Arkansas Academy of Science 63:113-130.

May, C.W., R. Horner, J. Karr, B. Mar, & E. Welch. 1997. Effects of urbanization on small streams in the puget sound lowland ecoregion. Watershed Prot Tech 2(4):483–494.

McMurray, S.E. & J.S. Faiman. 2020. Freshwater mussel survey of the Spring River Basin in southwest Missouri. Missouri Department of Conservation, Columbia, Missouri. 40pp.

McMurray, S.E., J.S. Faiman, A. Roberts, B. Simmons & M.C. Barnhart. 2012. A guide to Missouri's freshwater mussels. Missouri Department of Conservation, Jefferson City, Missouri. 94pp.

[MDC] Missouri Department of Conservation. 2019. Freshwater mussel database. Missouri Department of Conservation, Columbia, MO.

Megahan, W. F. 1972. Subsurface flow interception by a logging road in mountains of central Idaho. National Symposium on Watersheds in Transition, American Water Resources Association and Colorado State University. pp 350-356.

Meijer, J.R., M.A.J. Huijbregts, K.C.G.J. Schotten & A.M. Schipper. 2018. Global patterns of current and future road infrastructure. *Environ. Res. Lett.* 13 (2018) 064006. https://doi.org/10.1088/1748-9326/aabd42.

[MICRA] Mississippi Interstate Cooperative Resource Association. 2005. Black carp risk assessment published. River Crossings (newsletter). 14:1-2.

Miller, E.J. & S.T. Lynott. 2006. Increase of Unionid mussel populations in the Verdigris River, Kansas, from 1991 to 2003. Southeastern Naturalist 5(3):383-392.

Mississippi Natural Heritage Program. 2018. Special animals tracking list. Museum of Natural Sciences, Mississippi Dept. of Wildlife, Fisheries, and Parks, Jackson, MS. 13pp.

Mitchell J. & E. Peacock. 2014. A prehistoric freshwater mussel assemblage from the Big Sunflower River, Sunflower County, Mississippi. Southeastern Naturalist 13(3):626-638.

[MoDOT] Missouri Department of Transportation. 2019. MO 2019 MoDOT roads Oct update. Retrieved from http://msdis-archive.missouri.edu/archive/Missouri_Vector_Data/Transportation_Networks/.

Morisawa, M. & E. LaFlure. 1979. Hydraulic geometry, stream equilibrium and urbanization. Pp. 333-350 i*n:* D. D. Rhodes and G. P. Williams, eds. — Proceedings of the 10th annual Geomorphology Symposium Series. Binghamton, New York.

Morrill, J.C., R.C. Bales & M.H. Conklin. 2005. Estimating stream temperature from air temperature: implications for future water quality. Journal of Environmental Engineering 131. 26 pp.

Mummert, A.K., R.J. Neves, T.J. Newcomb & D. S. Cherry. 2003. Sensitivity of juvenile freshwater mussels (*Lampsilis Fasciola, Villosa Iris*) to total and un-ionized ammonia. *Environmental Toxicology and Chemistry* 22:25-45.

Naimo, T.J. 1995. A Review of the Effects of Heavy Metals on Freshwater Mussels. *Ecotoxicology* 4:341-362.

Neves, R.J. 1991. Mollusks. Pp. 251-319 in: K. Terwilliger, coordinator. Virginia's endangered species. Proceedings of a symposium, April 1989, Blacksburg, Virginia. McDonald & Woodward Publishing Co., Blacksburg.

Neves, R.J. & J.C. Widlak. 1987. Habitat ecology of juvenile freshwater mussels (Bivalvia: Unionidae) in a headwater stream in Virginia. American Malacological Union Bulletin 5:1-7.

Neves, R.J., A.E. Bogan, J.D. Williams, S.A. Ahlstedt & P.W. Hartfield. 1997. Status of aquatic mollusks in the southeastern United States: a downward spiral of diversity. Pp. 43-85 *in*: G. W. Benz and D.E. Collins, eds. Aquatic fauna in peril: the southeastern perspective, March-April 1994, Chattanooga, Tennessee. Special Publication 1, Southeast Aquatic Research Institute, Chattanooga.

Newton, T.J., J.W. Allran, J.A. O'Donnell, M.R. Bartsch & W.B. Richardson. 2003. Effects of ammonia on juvenile unionid mussels (*Lampsilis cardium*) in laboratory sediment toxicity tests. Environmental Toxicology and Chemistry 22(11):2554–2560.

Newton, T.J., D.A. Woolnough, & D.L. Strayer. 2008. Using landscape ecology to understand and manage freshwater mussel populations. J. N. Am. Benthol. Soc., 2008, 27(2):424–439.

Obermeyer, B.K. 1999. Recovery plan for four freshwater mussels in southeast Kansas: Neosho mucket (*Lampsilis rafinesqueana)*, Ouachita kidneyshell (*Ptychobranchus occidentalis)*, rabbitsfoot (*Quadrula cylindrica cylindrica)* and wester Fanshell (*Cyprogenia aberti)*. Kansas Department of Wildlife and Parks, Pratt, Kansas, 83pp.

Obermeyer, B.K., D.R. Edds, C.W. Prophet, & E.J. Miller. 1997a. Freshwater mussels (Bivalvia: Unionidae) in the Verdigris, Neosho, and Spring River basins of Kansas and Missouri, with emphasis on species of concern. American Malacological Bulletin 14(1):41-55.

Obermeyer, B.K., D.R. Edds, E.J. Miller & C.W. Prophet. 1997b. Range reductions of southeast Kansas unionids. Pages 108-116 in K.S. Cummings, A.C. Buchanan, C.A. Mayer, and T.J. Naimo, eds. Conservation and management of freshwater mussels II: initiatives for the future. Proceedings of a UMRCC symposium, 16-18 October 1995, St. Louis, Missouri. Upper Mississippi River Conservation Committee, Rock Island, Illinois.

Oesch, R.D. 1995. Missouri naiades: a guide to the mussels of Missouri. Missouri Department of Conservation, Jefferson City, Missouri. 271pp.

[OKDOT] Oklahoma Department of Transportation. 2020a. Local Roadways. Retrieved from http://gis-okdot.opendata.arcgis.com/search?groupIds=ba4c7d77c5f24b1bba7e5027176b9ab6.

[OKDOT] Oklahoma Department of Transportation. 2020b. Roadways. Retrieved from http://gis-okdot.opendata.arcgis.com/search?groupIds=ba4c7d77c5f24b1bba7e5027176b9ab6.

Ourso, R.T. & S.A. Frenzel 2002. Identification of linear and threshold responses in streams along a gradient of urbanization in Anchorage, Alaska. Hydrobiologia 501:117–131.

Paul, M.J. & J.L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecological Systems 32:333-365.

Payton, S.L., P.D. Johnson & M.J. Jenny. 2015. Comparative physiological, biochemical and molecular thermal stress response profiles for two unionid freshwater mussel species. Journal of Experimental Biology 219:3562-3574.

Peacock, E. & T.R. James. 2002. A prehistoric Unionid assemblage from the Big Black River drainage in Hinds County, Mississippi. Journal of the Mississippi Academy of Sciences 47(2):121-125.

Peacock, E., C. Jenkins, P.F. Jacobs, & J. Greenleaf. 2011. Archaeology and biogeography of prehistoric freshwater mussel shell in Mississippi. BAR International Series 2297. Archaeopress, British Archaeological Reports. Oxford, UK. 154pp.

Peacock, E., J. Mitchell, & C. Jenkins. 2016. Pre-Columbian freshwater mussel assemblages from the Tallahatchie River in the Lower Mississippi River alluvial basin, U.S.A. American Malacological Bulletin 34(2):121-132.

Peacock, E., J. Mitchell, & C.A. Buchner. 2017. Applied zooarchaeology of freshwater mussel (Bivalvia: Unionidae) shell from Golson (22HU508), a Deasonville-Period site on the Yazoo River, Mississippi. Environmental Archaeology 23(2):152-159.

Peterjohn, W.T. & D. Correll. 1984. Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of a Riparian Forest. Ecology 65: 1466-1475.

Peterson, J.T., J.M. Wisniewski, C.P. Shea, & C.R. Jackson. 2011. Estimation of Mussel Population Response to Hydrologic Alteration in a Southeastern U.S. Stream. Environmental Management (2011) 48:109–122.

Pezold, F., P. Aku, A. Hill, J.L. Harris, J. Alley, M. Antwine & H. Ray. 2002. Fish and freshwater mussel surveys of Bayou Bartholomew and Bayou DeLoutre Arkansas and Louisiana. Final Report. The Nature Conservancy, AR & LA Offices. 43pp.

Pluhowski, E.J. 1970. Urbanization and its effects on the temperatures of streams on Long Island, New York. Department of the Interior. Geological Survey Professional Paper 627-D. 110 pp.

Poole, K.E. & J.A. Downing. 2004. Relationship of declining mussel biodiversity to stream-reach and watershed characteristics in an agricultural landscape. J. N. Am. Benthol. Soc. 23(1):114-125.

Posey, W.R., Jr. 1997. Location, species composition, and community estimates for mussel beds in the St. Francis and Ouachita rivers in Arkansas. Unpublished M.S. thesis, Arkansas State University, Jonesboro. 178pp.

Potter, K.M., F.W. Cubbage, G.B. Blank, & R.H. Schaberg. 2004. A watershed-scale model for predicting nonpoint pollution risk in North Carolina. Environmental Management 34(1):62-74.

Poulton, B.C., P.T. Kroboth, A.E. George, D.C. Chapman, J. Bailey, S.E. McMurray, and J.S. Faiman. 2019. First examination of diet items consumed by wild-caught Black Carp (*Mylopharyngodon piceus)* in the U.S. American Midland Naturalist 182:89–108.

Radwell, R.J & T.J. Kwak 2005. Assessing ecological integrity of Ozark rivers to determine suitability for protective status. Environmental Management 35(6):799–810.

Redford, K.H., G. Amoto, J. Baillie, P. Beldomenico, E.L. Bennett, N. Clum, R. Cook, G. Fonseca, S. Hedges, F. Launay, S. Lieberman, G. M. Mace, A. Murayama, A. Putnam, J.G. Robinson, H. Rosenbaum, E.W. Sanderson, S.N. Stuart, P. Thomas & J. Thorbjarnarson. 2011. What does it mean to successfully conserve a (vertebrate) species? Bioscience 61:39–48.

Richter, B.D., D.P. Braun, M.A. Mendelson & L.L. Master. 1997. Threats to imperiled freshwater fauna. Conservation Biology 11:1081-1093.

Ries, P.R., T.J. Newton, R.J. Haro, S.J. Zigler & M. DAVIS. 2016. Annual variation in recruitment of freshwater mussels and its relationship with river discharge. Aquatic Conserv: Mar. Freshw. Ecosyst. 26: 703–714.

Roe, K.J. 2004. *Conservation Assessment for* Western Fanshell (*Cyprogenia aberti*) Conrad, 1850. Final report submitted to U.S.D.A. Forest Service, Eastern Region. 12 pp.

Rust, P.J. 1993. Analysis of the commercial mussel beds in the Black, Spring, Strawberry and Current Rivers in Arkansas. Unpublished M.S. thesis, Arkansas State University, Jonesboro. 116pp.

Scammon, R.E.1906. The Unionidae of Kansas, Part I. An illustrated catalogue of the Kansas Unionidae. *Kansas University Science Bulletin* 3(9):279-373 + 21 plates.

Schmerfeld, J. 2006. Reversing a Textbook Tragedy. Endangered Species *Update* 23: 12-13.

Schueler. 1994. The importance of imperviousness. Watershed Protection Techniques. 1(3): 100-111.

Schulz, R. & M. Liess. 1999. A field study of the effects of agriculturally derived insecticide input on stream macroinvertebrate dynamics. Aquatic Toxicology 46(3–4): 155-176.

Schwalb, A N. & M.T. Pusch. 2007. Horizontal and vertical movements of unionid mussels in a lowland river. Journal of the North American Benthological Society 26:261-272.

Serb, J.M. 2006. Discovery of genetically distinct sympatric lineages in the freshwater mussel *Cyprogenia aberti* (Bivalvia: Unionidae). Journal of Molluscan Studies 72:425–434.

Serb, J.M. & M.C. Barnhart 2008. Congruence and conflict between molecular and reproductive characters when assessing biological diversity in the western Fanshell *Cyprogenia aberti* (Bivalvia, Unionidae). Annals of the Missouri Botanical Garden 95(2):248-261.

[Service] U.S. Fish and Wildlife Service. 2016a. U. S. Fish and Wildlife Service Species Status Assessment Framework: an integrated analytical framework for conservation. Version 3.4, dated August 2016.

[Service] U.S. Fish and Wildlife Service. 2016b. Species Status Assessment for the Texas Hornshell. Version 1.0. June 2016. Albuquerque, New Mexico.

[Service] U.S. Fish and Wildlife Service. 2018a. Species Status Assessment for the Longsolid Mussel (*Fusconaia subrotunda*). Version 1.3. October 2018. Asheville, North Carolina.

[Service] U.S. Fish and Wildlife Service. 2018b. Species Status Assessment for the Central Texas Mussels. Version 1.1. Draft Report, June 2018. Albuquerque, New Mexico.

[Service] U.S. Fish and Wildlife Service. 2019. Species Status Assessment for the Round Hickorynut Mussel (*Obovaria subrotunda*). Version 1.0. October 2019. Asheville, North Carolina.

[Service] U.S. Fish and Wildlife Service. 2020. Species Status Assessment for the Two East Texas Mussels: Louisiana Pigtoe (*Pleurobema riddellii*) and Texas Heelsplitter (*Potamilus amphichaenus*). Version 1.1. Draft Report, May 2020. Albuquerque, New Mexico.

Shaffer, M.L. & M.A. Stein. 2000. Safeguarding our precious heritage. Pp. 301-321 *in*: B.A. Stein, L.S. Kutner & J.S. Adams, eds. Precious heritage: the status of biodiversity in the United States. Oxford University Press, New York.

Shaffer, M. L., L. H. Watchman, W.J. Snape III, & I. K. Latchis. 2002. Population viability analysis and conservation. Pp. 123–145 *in:* S.R. Beissenger and D. R. McCullough, eds. Population viability analysis, University of Chicago Press, Chicago.

Simpson, C.T. 1900. Synopsis of the naiades, or pearly fresh-water mussels. Proceedings of the United States National Museum 22: 501-1044. Available electronically at: https://biodiversitylibrary.org/page/32021246.

Smith, D.R., N.A. Allen, C.P. McGowan, J.A. Szymanski, S.R. Oetker & H.M. Bell. 2018. Development of a species status assessment process for decisions under the U.S. Endangered Species Act. Journal of Fish and Wildlife Management 9:1-19.

Soucek, D.J. & A. Dickinson. 2012. Acute toxicity of nitrate and nitrite to sensitive freshwater insects, mollusks, and a crustacean. Arch Environ Contam. Toxicol. (2012) 62:233-242.

Sparks, B.L. & D.L. Strayer. 1998. Effects of low dissolved oxygen on juvenile *Elliptio complanata* (Bivalvia: Unionidae). Journal of the North American Benthological Society 17:129-134.

Spooner, D.E. & C.C. Vaughn 2008. A trait-based approach to species' roles in stream ecosystems: climate change, community structure, and material cycling. Oecologia 158:307–317.

Steedman, R.J. 1988. Modification and assessment of an index of biotic integrity to quantify stream quality in southern Ontario. Canadian Journal of Fish and Aquatic Sciences 45:492-501.

Steingraeber, M.T., M.R. Bartsch, J.E. Kalas & T.J. Newton. 2007. Thermal Criteria for Early Life Stage Development of the Winged Mapleleaf Mussel (*Quadrula fragosa*). American Midland Naturalist 157:297–311.

Steuer, J.J., T.J. Newton & S.J. Zigler. 2008. Use of complex hydraulic variables to predict the distribution and density of unionids in a side channel of the Upper Mississippi River. Hydrobiologia (2008) 610:67–82.

Stewart, J.S., L. Wang, J. Lyons, J.A. Horwatich, & R. Bannerman. 2001. Influences of watershed, riparian-corridor, and reach-scale characteristics on aquatic biota in agricultural watersheds. Journal of the American Water Resources Association 37(6):1475-1487.

Stillman, J.H. 2003. Acclimation Capacity Underlies Susceptibility to Climate Change. Science 301:65.

Strayer, D. 1999. Effects of alien species on freshwater mollusks in North America. Journal of the North American Benthological Society 18(1):74-98.

Strayer, D.L. & D. R. Smith. 2003. A guide to sampling freshwater mussel populations. American Fisheries Society, Monograph 8. 101 pp.

Strayer, D. L., J.A. Downing, W.R. Haag, T.L. King, J.B. Layzer, T.J. Newton & S.J. Nichols. 2004. Changing perspectives on pearly mussels, North America's most imperiled animals. BioScience 54:429-439.

[TNC] The Nature Conservancy. 2017. Better unpaved roads for nature and people. Brochure. The Nature Conservancy, Arkansas Field Office, Little Rock, AR. 4 pp.

U.S. Forest Service. 2005. Final Environmental Impact Statement: Ouachita National Forest Land Resource Management Plan – Chapter 3. U.S. Forest Service, Ouachita National Forest, Hot Springs, AR. 263 pp.

Utterback, W.I. 1916. The naiades of Missouri – V. Amercian Midland Naturalist 4(7):311-327. https://www.biodiversitylibrary.org/page/29527633#page/357/mode/1up.

Valenti, T. W., D.S. Cherry, R.J. Neves & J. Schmerfeld. 2005. Acute and chronic toxicity of mercury to early life stages of the rainbow mussel, *Villosa iris* (Bivalvia: Unionidae). Environmental Toxicology and Chemistry 24:1242-1246.

Van Hassel, J.H. & J.L. Farris. 2007. A review of the use of unionid mussels as biological indicators of ecosystem health. Pages 19–49 in Freshwater Bivalve Ecotoxicology, edited by J. L. Farris and J. H. Van Hassel. CRC Press, Pensacola, FL.

Vannote, R.L. & G.W. Minshall. 1982. Fluvial processes and local lithology controlling abundance, structure, and composition of mussel beds. Proceedings of the National Academy of Science USA 79:4103-4107.

Vaughan, P.W. 1997. Winged mapleleaf mussel (*Quadrula fragosa)* recovery plan. U.S. Fish and Wildlife Service, Fort Snelling, Minnesota. 71 pp.

Vaughn, C.C. 1997. Regional patterns of mussel species distributions in North American rivers. Ecography 20:107-115

Vaughn, Caryn C. 2012. Life history traits and abundance can predict local colonization and extinction rates of freshwater mussels. Freshwater Biology 57:982-992.

Vaughn, C.C. & C.M. Taylor. 1999. Impoundments and the decline of freshwater mussels: a case study of an extinction gradient. Conservation Biology 13:912-920.

Vaughn, C.C. & D. E. Spooner. 2006. Scale-dependent associations between native freshwater mussels and invasive Corbicula. Hydrobiologia 568:331-339.

Vaughn, C.C., C.L. Atkinson & J.P. Julian. 2015. Drought-induced changes in flow regimes lead to long-term losses in mussel-provided ecosystem services. Ecology and Evolution 5(6):1291–1305.

Vidrine, M.F. 1995. River survey of freshwater mollusks of Bayou Bartholomew in northeastern Louisiana. Final report submitted to Louisiana Department of Wildlife and Fisheries. 119 pp. + plates.

Wallace, J.B., S.L. Eggert, J.L. Meyer, J.R. Webster. 1997. Multiple trophic levels of a forest stream linked to terrestrial litter inputs. Science 277:102-104.

Walters, D.M., M.C. Freeman, D.S. Leigh, B.J. Freeman & C.M. Pringle. 2005. Urbanization Effects on Fishes and Habitat Quality in a Southern Piedmont River Basin. American Fisheries Society Symposium 47. 423 pp.

Wang, N., T. Augspurger, M.C. Barnhart, J.R. Bidwell, W.G. Cope, F.J. Dwyer, S. Geis, I.E. Greer, C.G. Ingersoll, C.M. Kane, T.W. May, R.J. Neves, T.J. Newton, A.D. Roberts & D.W. Whites. 2007a. Intra- and interlaboratory variability in acute toxicity tests with glochidia and juveniles of freshwater mussels (Unionidae). Environmental Toxicity and Chemistry 26:2029-2035.

Wang, N., C.G. Ingersoll, D.K. Hardesty, C.D. Ivey, J.L. Kunz, T.W. May, F.J. Dwyer, A.D. Roberts, T. Augspurger, C.M. Kane, R.J. Neves & M.C. Barnhart. 2007b. Acute toxicity of copper, ammonia, and chlorine to glochidia and juveniles of freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26:2036-2047.

Wang, N., C.G. Ingersoll, I.E. Greer, D.K. Hardesty, C.D. Ivey, J.L. Kunz, W.G. Brumbaugh, F.J. Dwyer, A.D. Roberts, T. Augspurger, C.M. Kane, R.J. Neves, and M.C. Barnhart. 2007c. Chronic toxicity of copper and ammonia to juvenile freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10):2048–2056.

Wang, N., C.G. Ingersoll, C.D. Ivey, D.K. Hardesty, T.W. May, T. Augspurger, AD. Roberts, E. Van Genderen & M. C. Barnhart. 2010. Sensitivity of early lifestages of freshwater mussels (Unionidae) to acute and chronic toxicity of lead, cadmium, and zinc in water. Environmental Toxicology and Chemistry 29:2053-2063.

Wang N, C.G. Ingersoll, C.D. Ivey, W.G. Brumbaugh, J.M. Besser, E. Hammer, C.R. Bauer, T. Augspurger, S. Raimondo, B. Shephard, J. Bartoszek, M.C. Barnhart & N. Eckert. 2013. Acute sensitivity of freshwater mollusks and commonly tested invertebrates to select chemicals with different toxic modes of action. Presented at the 34th meeting of SETAC North America, Nashville TN, November 17-21, 2013.

Waters, T.F. 1995. Sediment in streams: sources, biological effects, and control. American Fisheries Society Monograph 7. 251 pp.

Watters, G.T. 2007. A brief look at freshwater mussel (Unionaceae) biology, p. 51-64. *in:* J.L. Farris and J.H. Van Hassel eds. Freshwater bivalve ecotoxicology. CRC Press.

Watters, G.T. & S.H. O'Dee. 2000. Glochidial release as a function of water temperature: Beyond bradyticty and tachyticty. Pp. 135-140 *in:* R.A. Tankersley *et al.,* eds. Proceedings of the Conservation, Captive Care, and Propagation of Freshwater Mussels Symposium, 1998. Ohio Biological Survey Special Publications, Columbus, Ohio.

Watters, G.T., S.H. O'Dee & S. Chordas III. 2001. Patterns of Vertical Migration in Freshwater Mussels (Bivalvia: Unionoida), Journal of Freshwater Ecology, 16(4):541-549.

Watters, G., M. Hoggarth & D. Stansbery. 2009. The Freshwater Mussels of Ohio. The Ohio State Press.

Weigel, B. M., J. Lyons, L. K. Paine, S. I. Dodson, & D. J. Undersander. 2000. Using stream macroinvertebrates to compare riparian land use practices on cattle farms in south- western Wisconsin. Journal of Freshwater Ecology 15(1): 93-106.

Wemple, B.C., J.A. Jones, & G.E. Grant. 1996. Channel network extension by logging roads in two basins, Western Cascades, Oregon. Water Resources Bulletin 32(6):1195-1207.

Williams, C. 1999. Summary of Scientific Findings on Roads and Aquatic Ecosystems. Unpubl. report accessed at https://docsbay.net/summary-of-scientific-findings-on-roads-and-aquatic-ecosystems.

Williams, J.D., A.E. Bogan, R.S. Butler, K.S. Cummings, J.T. Garner, J.L. Harris, N.A. Johnson & G.T. Watters. 2017. A revised list of the freshwater mussels (Mollusca: Bivalvia: Unionida) of the United States and Canada. Freshwater Mollusk Biology and Conservation 20:33-58.

Winterringer, R. 2003. Population dynamics and reproductive patterns of the endangered freshwater mussel, *Lampsilis streckeri* (Frierson 1927). M.S. Thesis, Arkansas State University, Jonesboro. 74 pp. + appendices.

Wolf, C. & B. Stark. 2008. Survey of freshwater mussels (Bivalvia: Unionidea) in the Marais des Cygnes River, Fall River, and Grouse Creek. Transactions of the Kansas Academy Science 111:1-20.

Wolf, S., B. Hartl, C. Carroll, M.C. Neel, and D.N. Greenwald. 2015. Beyond PVA: Why recovery under the Endangered Species Act is more than population viability. BioScience 65(2):200–207.

Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, B. DeAngelo, S. Doherty, K. Hayhoe, R. Horton, J.P. Kossin, P.C. Taylor, A.M. Waple, and C.P. Weaver, 2017. Executive summary. *in:* Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock eds. Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program, Washington, DC, USA, pp. 12-34, https://doi.org/10.7930/J0DJ5CTG

Yeager, M.M., D.S. Cherry & R.J. Neves. 1994. Feeding and burrowing behaviors of juvenile rainbow mussels, *Villosa iris* (Bivalvia: Unionidae). Journal of the North American Benthological Society 13:217-222.

Yeager, M.M., R.J. Neves & D.S. Cherry. 2000. Competitive interactions between early life stages of *Villosa iris* (Bivalvia: Unionidae) and adult Asian clams (*Corbicula fluminea*). Pp. 253-259 *in*: P.D. Johnson and R.S. Butler, eds. Freshwater Mollusk Symposium Proceedings--Part II: Proceedings of the First Symposium of the Freshwater Mollusk Conservation Society, March 1999, Chattanooga, Tennessee. Ohio Biological Survey, Columbus.

Yoder, C.O., R.J. Miltner & D. White. 1999. Assessing the status of aquatic life designated uses in urban and suburban watersheds. Proceedings of National Conference on Retrofit Opportunities for Water Resource Protection in Urban Environments, pp. 16-28. EPA/625/R-99/002.

Zigler, S.J., T.J. Newton, J.J. Steuer, M.R. Bartsch & J.S. Sauer. 2008. Importance of physical and hydraulic characteristics to unionid mussels: a retrospective analysis in a reach of large river. Hydrobiologia (2008) 598:343–360.

Appendices I – V

Appendix I-A. Current condition landscape values and percent change since 2011 for Western Fanshell and “Ouachita” Fanshell MUs (source: National Land Cover Dataset).

Species	Management Unit	MU Area (km^2)	Overall Unpaved Road Density in MU (km/km^2)	# Unpaved Stream Crossings in MU	Overall Unpaved Road Stream Crossing Density in MU (Crossings/km)	Unpaved Road Kilometers in 108m Stream Buffer (Road km/Stream km)	% Forest within 108m Stream Buffer (2016)	% Change in Forest within 108m Stream Buffer (2011-2016)	% Forest Cover in MU (2016)	% Urban in MU (2016)	% Change in Urban in MU (2011-2016)	Mean % Impervious Cover in MU (2016)	% Agriculture in MU (2016)	% Change in Agriculture in MU (2011-2016)
“Ouachita” Fanshell	Saline	8,372	0.63	498	0.11	0.06	86.60	-0.50	75.97	6.12	0.91	1.19	5.74	-0.45
“Ouachita” Fanshell	Caddo	1,117	0.79	97	0.18	0.16	77.23	-0.66	73.41	4.72	0.49	0.48	12.61	-1.79
“Ouachita” Fanshell	Upper Ouachita	8,854	0.72	753	0.16	0.10	79.51	1.08	70.34	4.81	0.24	0.79	11.71	-0.45
“Ouachita” Fanshell	Ouachita Headwaters	4,007	0.84	427	0.22	0.20	75.05	0.48	76.10	6.97	0.68	1.19	11.34	-0.81
Western Fanshell	Middle Verdigris	3,930	0.70	322	0.22	0.09	47.36	-0.92	18.18	4.96	0.42	0.86	67.89	-0.13
Western Fanshell	Middle White	3,822	0.68	315	0.15	0.12	71.13	0.85	68.71	5.40	0.77	0.93	22.63	-0.25
Western Fanshell	Black	7,105	0.95	887	0.31	0.27	60.29	0.30	60.90	4.30	0.96	0.51	32.76	-0.12
Western Fanshell	Buffalo	3,471	0.86	303	0.18	0.15	80.94	0.62	79.03	3.90	0.02	0.24	14.18	-0.56
Western Fanshell	Spring	3,147	1.10	488	0.32	0.18	51.51	-12.19	60.34	5.17	0.47	0.68	31.23	-0.08
Western Fanshell	Strawberry	1,970	0.85	176	0.18	0.10	61.30	0.56	58.40	5.31	15.58	0.53	32.80	-0.06
Western Fanshell	Little Red	4,666	0.60	216	0.10	0.09	79.53	0.83	67.74	5.60	1.24	1.02	21.41	-0.31
Western Fanshell	Lower St. Francis	1,221	1.35	87	0.30	0.18	49.99	0.24	28.68	4.84	-5.21	0.73	63.22	-1.19
Western Fanshell	Fall	2,227	0.63	158	0.20	0.09	38.02	-0.61	11.60	3.33	0.41	0.60	27.07	0.90
Western Fanshell	Spring	6,708	1.58	1,142	0.56	0.21	44.10	0.33	19.52	8.36	0.80	1.93	71.09	-0.09
Western Fanshell	Upper St. Francis	3,362	0.81	468	0.31	0.29	68.09	0.89	76.87	4.14	1.11	0.58	16.85	-0.17

Appendix I-B. . Current condition flow values for Western Fanshell MUs (EPA PHWA, 2016; U.S. Drought Monitoring Data)

Western Fanshell Management Units	**State**	**Flow**			
		Water Use Vulnerability	**Known Flow Issues**	**Drought**	**Flow Score**
Fall	Kansas	0.23	Yes, but effects unknown	10 days, no multiyear D2-D4	High
Middle Verdigris	Kansas, Oklahoma	0.16	No	40 days, no multiyear D2-D4	High
Spring	Kansas, Missouri	0.19	Yes, but effects unknown	89 days, no multiyear D2-D4	Medium
Lower St. Francis	Arkansas, Missouri	0.16	Yes, but effects unknown	NA, no multiyear D2-D4	Medium
Upper St. Francis	Missouri	0.10	No	52 days, no multiyear D2-D4	Medium
Buffalo	Arkansas	0.09	No	74 days, no multiyear D2-D4	Medium
Little Red	Arkansas	0.13	No	17 days, no multiyear D2-D4	High
Middle White	Arkansas	0.13	No	9 days, no multiyear D2-D4	High
Spring	Arkansas	0.19	No	10 days, no multiyear D2-D4	High
Strawberry	Arkansas	0.13	No	27 days, no multiyear D2-D4	High

Western Fanshell Management Units	State	Flow			
		Water Use Vulnerability	Known Flow Issues	Drought	Flow Score
Black	Arkansas, Missouri	0.15	Yes, but effects unknown	30 days, no multiyear D2-D4	Medium

Appendix I-C. . Current condition flow values for "Ouachita" Fanshell MUs (EPA PHWA, 2016; U.S. Drought Monitoring Data).

"Ouachita" Fanshell Management Units	State	Flow			
		Water Use Vulnerability	Known Flow Issues	Drought	Flow Score
Caddo	Arkansas	0.11	No	32 days	High
Ouachita Headwaters	Arkansas	0.13	No	30 days	High
Saline	Arkansas	0.24	Yes, but effects unknown	42days	Medium
Upper Ouachita	Arkansas	0.21	Yes, with effects to mussel community	23 days	Medium

Appendix I-D Water quality for Western Fanshell populations under Future Scenario 1.

Management Unit	TAN (mg/L)	$NO_3 + NO_2$ (mg/L)	Cadmium (mg/L)	Copper (mg/L)	Zinc (mg/L)	Lead (µg/L)	Air Temperature RCP4.5 2025-2049	Air Temperature RCP4.5 2050-2074	Overall WQ Trend
Fall	Declining; 0.03 mg/L increase every 25 yrs. results in no samples exceeding acute toxicity by 2068	Declining; 0.04 mg/L increase every 25 yrs. results in no samples exceeding acute toxicity by 2068	Improving	Improving, but 8% of samples exceed acute toxicity by 2068	Declining; 0.03 mg/L increase every 25 yrs. results <2% samples exceeding acute toxicity by 2068	Improving	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Middle Verdigris	Improving	Improving	Stable	Improving, but 27% of samples still above acute toxicity in 25 yrs., 18% in 50 years	Improving	Improving	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Spring	Improving	Declining; 0.119 mg/L increase every 25 yrs. results in 64% of samples exceeding acute toxicity by 2043 and 68% by 2068	Improving	Improving, but 8% of samples exceed acute toxicity by 2068	Improving	Improving	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Black	Improving	Improving	Improving	Improving	Improving	Improving	0.9 – 2.2ºC increase	>2.2ºC increase	Medium
Buffalo	Improving	Improving	Improving	Improving	Declining; 0.0085 mg/L; no samples exceed acute by 2068	Improving	<0.9ºC increase	>2.2ºC increase	Medium
Little Red	Improving	Beech Fk - Declining; 0.0347 mg/L increase every 25 yrs. results in no samples exceeding acute toxicity by 2068; Mdl Fk - Declining; 0.0034 mg/L every 25 years; no samples exceed acute by 2068	Improving	Improving	Improving	Improving	<0.9ºC increase	>2.2ºC increase	Medium
Middle White	Improving	Stable	Improving	Stable (CC is Moderate)	Stable (CC is Moderate)	Improving	<0.9ºC increase	>2.2ºC increase	Medium
Spring	Improving	Improving	Stable	S. Fk - Improving; Spring - Stable	S. Fk Declining; 0.0011 mg/L; < 2% of samples exceeding acute toxicity. Spring - stable	Improving	0.9 – 2.2ºC increase	>2.2ºC increase	Medium
Strawberry	Improving	Improving	Improving	Improving	Improving	Improving	<0.9ºC increase	>2.2ºC increase	Medium
Lower St. Francis	Improving	Stable (CC M)	Improving	Stable (CC M)	Improving	Declining; 0.0085 mg/L; no samples exceed acute by 2068	<0.9ºC increase	>2.2ºC increase	Low
Upper St. Francis	Improving	Declining slightly; <2% of samples exceed acute toxicity	Improving	Declining; 0.0052 mg/L increase every 25 yrs. results in <2% of samples exceeding acute toxicity by 2043 and 2068	Improving	Stable	0.9 – 2.2ºC increase	>2.2ºC increase	Low

Appendix I-E Water quality for “Ouachita” Fanshell populations under Future Scenario 1.

Management Unit	**TAN (mg/L)**	**$NO_3 + NO_2$ (mg/L)**	**Cadmium (mg/L)**	**Copper (mg/L)**	**Zinc (mg/L)**	**Lead (µg/L)**	**Air Temperature RCP4.5 2025-2049**	**Air Temperature RCP4.5 2050-2074**	**Overall Water Quality**
Saline River	Improving	Declining; 0.1 mg/L increase every 25 yrs. results <2% samples exceeding acute toxicity by 2068	Stable	Declining; all 6 monitoring stations increase 0.002-0.003 in 50 years results in a mean 16% of samples exceeding acute toxicity by 2068	Improving at 50% of monitoring stations	Improving at upper 3 monitoring stations, declining at Rison & Warren, improving at lowermost station; no samples exceeding acute toxicity by 2068	<0.9ºC increase	0.9 – 2.2ºC increase	Low
Ouachita Headwaters	Improving	Declining; 0.1 mg/L increase every 25 yrs. results in no samples exceeding acute toxicity by 2068	Improving	Declining; 0.0016 mg/L increase every 25 yrs. results in ~2% of samples exceeding acute toxicity by 2043 and ~6% by 2068	Stable	Improving	<0.9ºC increase	0.9 – 2.2ºC increase	Moderate
Upper Ouachita	Improving	Stable; 2 stations improving, 1 slightly declining (0.2 mg/L), 2 stations stable	Stable to Improving	Ouachita River stable at upper site with 8 & 12% of samples exceeding acute criteria by 2068; Antoine River trend leads to all values exceeding acute criteria by 2068; Little Missouri River stable.	Declining; 3 of 4 stations on main stem Ouachita River declining; < 2% of samples exceeding acute toxicity.	Improving at 4 of 6 stations, stable at other 2 stations, <2% of samples exceeding acute toxicity.	<0.9ºC increase	0.9 – 2.2ºC increase	Moderate
Caddo	Improving	Stable	Improving	Improving	Improving	Stable	<0.9ºC increase	0.9 – 2.2ºC increase	High

Appendix I-F Water quality for Western Fanshell populations under Future Scenario 2.

Management Unit	TAN (mg/L)	$NO_3 + NO_2$ (mg/L)	Cadmium (mg/L)	Copper (mg/L)	Zinc (mg/L)	Lead (µg/L)	Air Temperature RCP8.5 2025-2049	Air Temperature RCP8.5 2050-2074	Overall WQ Trend
Fall	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Rate of decline increases every 25 yrs., but results in no samples exceeding acute toxicity by 2068	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining; 18% of samples exceed acute toxicity by 2068.	Rate of improving trends under current conditions declines but maintains improving conditions; <2% of samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Middle Verdigris	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Rate of improving trends under current conditions declines but maintains improving conditions; <2% of samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining; 32% of samples exceed acute toxicity by 2068.	Rate of improving trends under current conditions declines but maintains improving conditions; <2% of samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Spring	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining; 73% of samples exceed acute toxicity by 2068.	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Rate of improvement declines; 9% of samples exceed acute toxicity by 2068.	Rate of improvement declines; 6% of samples exceed acute toxicity by 2068.	Rate of improvement declines; 7% of samples exceed acute toxicity by 2068.	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Black	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining slightly; <2% of samples exceed acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Medium
Buffalo	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Medium
Little Red	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Rate of decline increases every 25 yrs., but results in no samples exceeding acute toxicity by 2068	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining slightly; <2% of samples exceed acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Medium
Middle White	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining; 5% of samples exceed acute toxicity by 2068.	Declining slightly; <2% of samples exceed acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Spring	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining slightly; <1% of samples exceed acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining slightly; <2% of samples exceed acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Strawberry	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining slightly; <2% of samples exceed acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Medium
Lower St. Francis	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining slightly; <2% of samples exceed acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Rate of improvement declines; 9% of samples exceed acute toxicity by 2068.	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Upper St. Francis	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Rate of improvement declines; 14% of samples exceed acute toxicity by 2068.	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining; 32% of samples exceed acute toxicity by 2068.	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Low

Appendix I-G Water quality for “Ouachita” Fanshell populations under Future Scenario 2.

Management Unit	**TAN (mg/L)**	**$NO_3 + NO_2$ (mg/L)**	**Cadmium (mg/L)**	**Copper (mg/L)**	**Zinc (mg/L)**	**Lead (µg/L)**	**Air Temperature RCP8.5 2025-2049**	**Air Temperature RCP8.5 2050-2074**	**Overall WQ Trend**
Saline River	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity; improving current conditions stabilize	Declining slightly; <2% of samples exceed acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining; mean 32% of samples among 6 monitoring stations exceed acute toxicity by 2068.	Slight improvements from current conditions stabilize by 2068 results in <2% of samples exceeding acute toxicity	Improving current conditions stabilize; stable current conditions decline slightly results in zero samples exceeding acute toxicity by 2068	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Ouachita Headwaters	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Declining; 3% of samples exceed acute toxicity by 2016; annual mean increases to 0.002 mg/L.	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Moderate
Upper Ouachita	Improving sites under current conditions stabilize; stable sites decline by 20% resulting in zero samples exceeding acute toxicity	Improving sites under current conditions stabilize; stable sites decline by 20% resulting in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Ouachita River stable at upper site with 2 & 31% of samples exceeding acute criteria by 2068; Antoine River trend leads to all values exceeding acute criteria by 2068; Little Missouri River stable.	Declining; 3 of 4 stations on main stem Ouachita River declining; < 2% of samples exceeding acute toxicity.	Stable at 4 of 6 stations, declining at other 2 stations, <2% of samples exceeding acute toxicity.	0.9 – 2.2ºC increase	>2.2ºC increase	Low
Caddo	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	20% Decline in WQ by 2068 results in zero samples exceeding acute toxicity	Rate of improving trends under current conditions declines but maintains improving conditions; <2% of samples exceeding acute toxicity	Slight declines from current conditions worsen by 2068 but results in zero samples exceeding acute toxicity	Slight improving conditions stabilize or worsen slightly by 2060 results in zero samples exceeding acute toxicity	0.9 – 2.2ºC increase	>2.2ºC increase	Moderate

Appendix II-A. Projected future condition (2060) of landscape based on 5-year trend observed for 2011 – 2016 applied to each 5-year period 2016 - 2060 for Western Fanshell and "Ouachita" Fanshell MUs with a moderate increase in stressors (source: National Land Cover Dataset).

Species	Management Unit	MU Area (km^2)	% Forest within 108m Stream Buffer (2016)	% Change in Forest within 108m Stream Buffer (2011-2016)	% Forest within 108m Stream Buffer (2060)	% Urban in MU (2016)	% Change in Urban in MU (2011-2016)	%Urban (2060)	% Agriculture in MU (2016)	% Change in Agriculture in MU (2011-2016)	% Agriculture (2060)	Mean % Impervious Cover in MU (2011)	Mean % Impervious Cover in MU (2016)	Mean % Impervious Cover in MU
"Ouachita" Fanshell	Saline	8,372	86.6	-0.5	82.81	6.12	0.91	6.64	5.74	-0.45	5.51	1.16	1.19	1.50
"Ouachita" Fanshell	Caddo	1,117	77.23	-0.66	72.78	4.72	0.49	4.93	12.61	-1.79	10.72	0.47	0.48	0.58
"Ouachita" Fanshell	Upper Ouachita	8,854	79.51	1.08	87.56	4.81	0.24	4.91	11.71	-0.45	11.24	0.79	0.79	0.88
"Ouachita" Fanshell	Ouachita Headwaters	4,007	75.05	0.48	78.37	6.97	0.68	7.41	11.34	-0.81	10.54	1.16	1.19	1.46
Western Fanshell	Middle Verdigris	3,930	47.36	-0.92	43.59	4.96	0.42	5.15	67.89	-0.13	67.08	0.85	0.86	0.98
Western Fanshell	Middle White	3,822	71.13	0.85	76.74	5.40	0.77	5.79	22.63	-0.25	22.12	0.91	0.93	1.15
Western Fanshell	Black	7,105	60.29	0.30	61.97	4.30	0.96	4.68	32.76	-0.12	32.41	0.48	0.51	0.70
Western Fanshell	Buffalo	3,471	80.94	0.62	85.53	3.90	0.02	3.9	14.18	-0.56	13.48	0.24	0.24	0.25
Western Fanshell	Spring	3,147	51.51	-12.19	15.99	5.17	0.47	5.39	31.23	-0.08	31	0.67	0.68	0.80
Western Fanshell	Strawberry	1,970	61.3	0.56	64.48	5.31	15.58	19.55	32.8	-0.06	32.61	0.53	0.53	0.61
Western Fanshell	Little Red	4,666	79.53	0.83	85.67	5.60	1.24	6.25	21.41	-0.31	20.82	0.98	1.02	1.35
Western Fanshell	Lower St. Francis	1,221	49.99	0.24	51.08	4.84	-5.21	2.99	63.22	-1.19	56.76	0.71	0.73	0.91
Western Fanshell	Fall	2,227	38.02	-0.61	35.97	3.33	0.41	3.45	27.07	0.9	29.35	0.60	0.60	0.69
Western Fanshell	Spring	6,708	44.1	0.33	45.4	8.36	0.8	8.98	71.09	-0.09	70.55	0.89	1.93	3.34
Western Fanshell	Upper St. Francis	3,362	68.09	0.89	73.72	4.14	1.11	4.58	16.85	-0.17	16.6	0.56	0.58	0.71

Appendix II-B. Modeled future condition (2060) of landscape and percent change since 2016 for Western Fanshell and “Ouachita” Fanshell MUs with a severe increase in stressors (Scenario A2) (source: FORE-SCE, September 2018, ICLUS).

Species	Management Unit	MU Area (km^2)	Forest Square km within 108m Steam Buffer	% Change in Forest within 108m Stream Buffer	Urban Square km in MU	% Change Urban in MU	Mean % Impervious Cover in MU	Mean % Impervious Cover in MU	Agriculture (km^2) in MU	% Change in Agriculture
"Ouachita" Fanshell	Saline	8372	696.63	-3.25	119.56	74.86	1.19	0.98	649.25	8.56
"Ouachita" Fanshell	Caddo	1117	66.56	-13.13	4.75	0.00	0.48	0.66	178.38	22.65
"Ouachita" Fanshell	Upper Ouachita	8854	690.38	-4.09	73.81	34.51	0.79	0.62	1558.31	12.01
"Ouachita" Fanshell	Ouachita Headwaters	4007	247.50	-10.02	216.06	137.43	1.19	1.55	532.00	14.50
Western Fanshell	Middle Verdigris	3930	76.38	-2.24	133.44	85.98	0.86	0.92	2043.88	1.43
Western Fanshell	Middle White	3822	267.56	-7.58	65.94	71.27	0.93	0.96	1042.75	21.17
Western Fanshell	Black	7105	328.88	-4.77	111.94	100.32	0.50	0.84	2630.69	16.42
Western Fanshell	Buffalo	3471	265.31	-4.35	4.56	2.82	0.24	0.51	681.38	25.04
Western Fanshell	Spring	3147	182.25	-7.31	50.50	103.02	0.68	1.02	1033.94	18.92
Western Fanshell	Strawberry	1970	120.75	-5.34	8.13	39.78	0.53	0.72	655.81	12.49
Western Fanshell	Little Red	4666	278.00	-11.18	73.94	69.73	1.02	1.13	1447.63	30.70
Western Fanshell	Lower St. Francis	1221	22.38	-8.44	30.25	106.84	0.73	1.09	809.63	-1.17
Western Fanshell	Fall	2227	24.63	-8.37	36.50	113.14	0.60	0.62	766.19	15.26
Western Fanshell	Spring	6708	101.81	-22.54	412.19	43.56	1.93	2.01	5325.50	5.29
Western Fanshell	Upper St. Francis	3362	192.00	-4.21	68.56	45.30	0.58	1.04	680.25	18.25

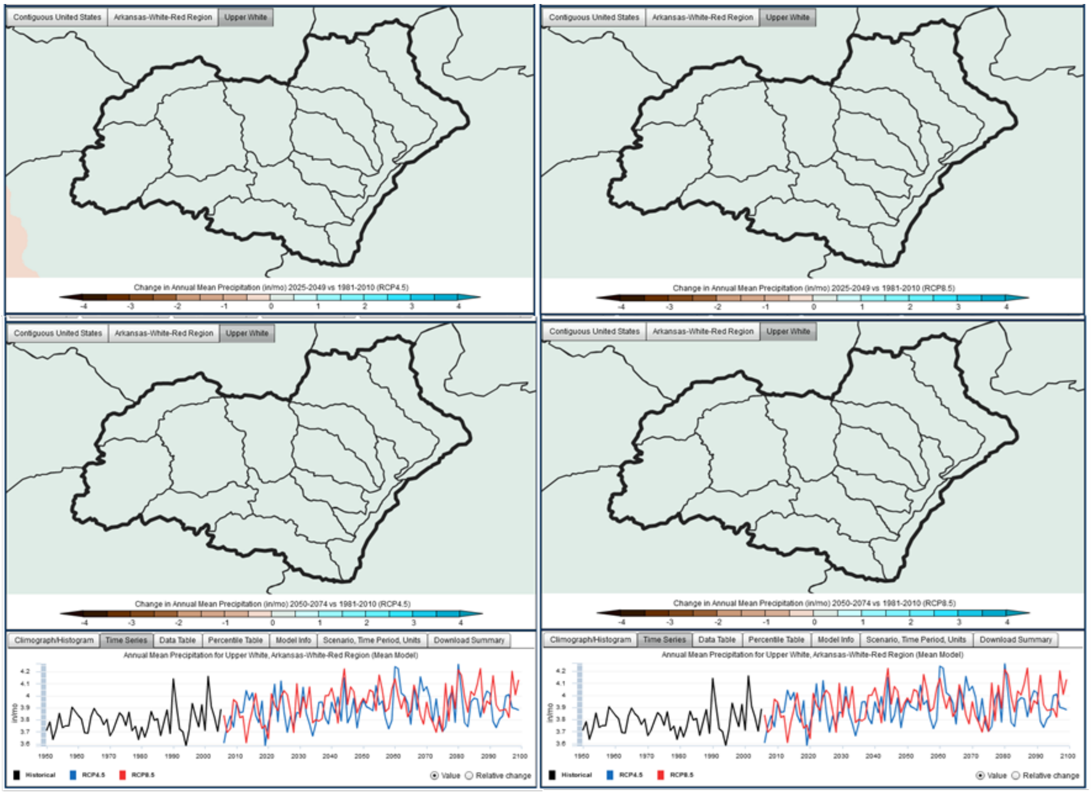
Appendix II-C. Projected future condition (2016 – 2060) of unpaved road density and unpaved road stream crossing density for Western Fanshell and "Ouachita" Fanshell MUs with a moderate increase in stressors based on the mean of Scenarios SSP1 – SSP5 for the U.S. (Meijer 2018).

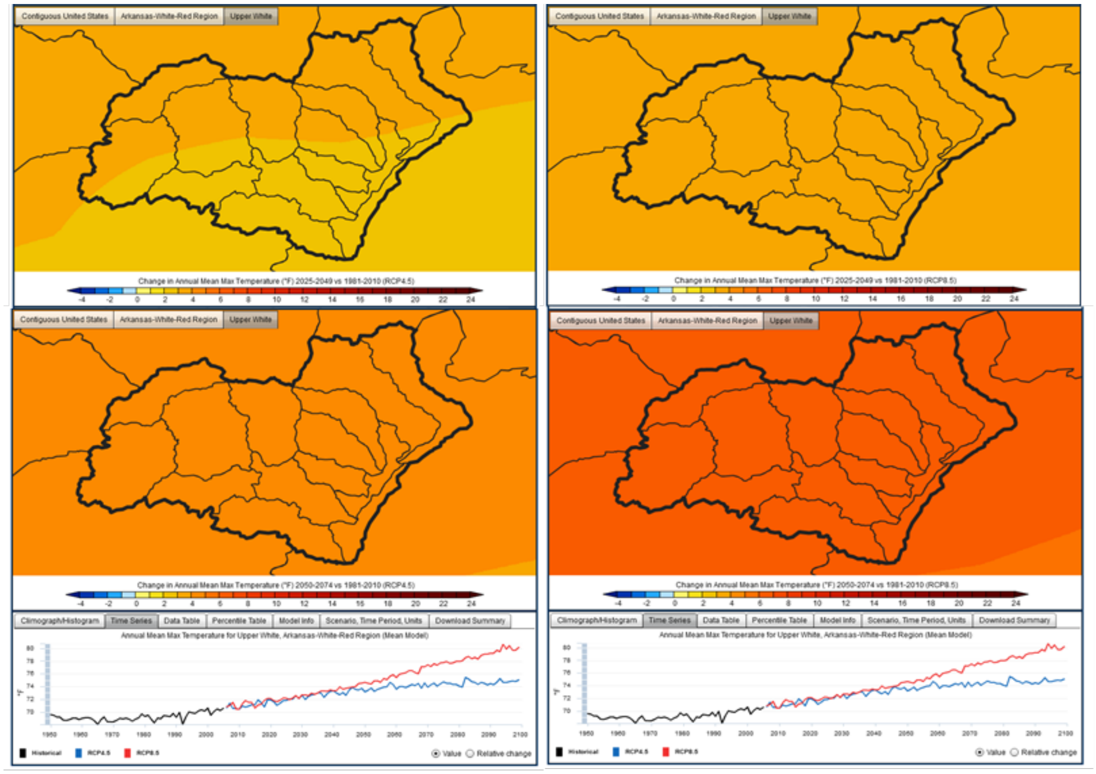
MU Name	MU Area	Overall Unpaved Road Density in MU (km/km^2)	%change through 2050	Overall Unpaved Road Density in MU (km/km^2) in 2050	%change 2051 - 2060	Overall Unpaved Road Density in MU (km/km^2) in 2060	Overall Unpaved Road Stream* Crossing Density in MU (Crossings/km2)	%change through 2050	Overall Unpaved Road Stream* Crossing Density in MU (Crossings/km^2) in 2050	%change 2051 - 2060	Overall Unpaved Road Stream* Crossing Density in MU (Crossings/km^2) in 2060
Saline	8,372	0.63	15.00%	0.72	5.00%	0.76	0.11	15.00%	0.13	5.00%	0.14
Caddo	1,117	0.79	15.00%	0.91	5.00%	0.95	0.18	15.00%	0.21	5.00%	0.22
Upper Ouachita	8,854	0.72	15.00%	0.83	5.00%	0.87	0.16	15.00%	0.18	5.00%	0.19
Ouachita Headwaters	4,007	0.84	15.00%	0.97	5.00%	1.01	0.22	15.00%	0.25	5.00%	0.26
Middle Verdigris	3,930	0.70	15.00%	0.80	5.00%	0.84	0.22	15.00%	0.25	5.00%	0.26
Middle White	3,822	0.68	15.00%	0.78	5.00%	0.82	0.15	15.00%	0.18	5.00%	0.19
Black	7,105	0.95	15.00%	1.09	5.00%	1.15	0.31	15.00%	0.36	5.00%	0.36
Buffalo	3,471	0.86	15.00%	0.99	5.00%	1.04	0.18	15.00%	0.21	5.00%	0.22
Spring	3,147	1.10	15.00%	1.26	5.00%	1.32	0.32	15.00%	0.36	5.00%	0.38
Strawberry	1,970	0.85	15.00%	0.98	5.00%	1.02	0.18	15.00%	0.21	5.00%	0.22
Little Red	4,666	0.60	15.00%	0.69	5.00%	0.73	0.10	15.00%	0.11	5.00%	0.12
Lower St. Francis	1,221	1.35	15.00%	1.55	5.00%	1.63	0.30	15.00%	0.35	5.00%	0.36
Fall	2,227	0.63	15.00%	0.73	5.00%	0.76	0.20	15.00%	0.23	5.00%	0.24
Spring	6,708	1.58	15.00%	1.81	5.00%	1.91	0.56	15.00%	0.64	5.00%	0.67
Upper St. Francis	3,362	0.81	15.00%	0.93	5.00%	0.98	0.31	15.00%	0.36	5.00%	0.38

Appendix II-D. Future condition (2016 – 2060) of unpaved road density and unpaved road stream crossing density for Western Fanshell and "Ouachita" Fanshell MUs with a severe increase in stressors based on Scenario SSP5 for the U.S. (Meijer 2018).

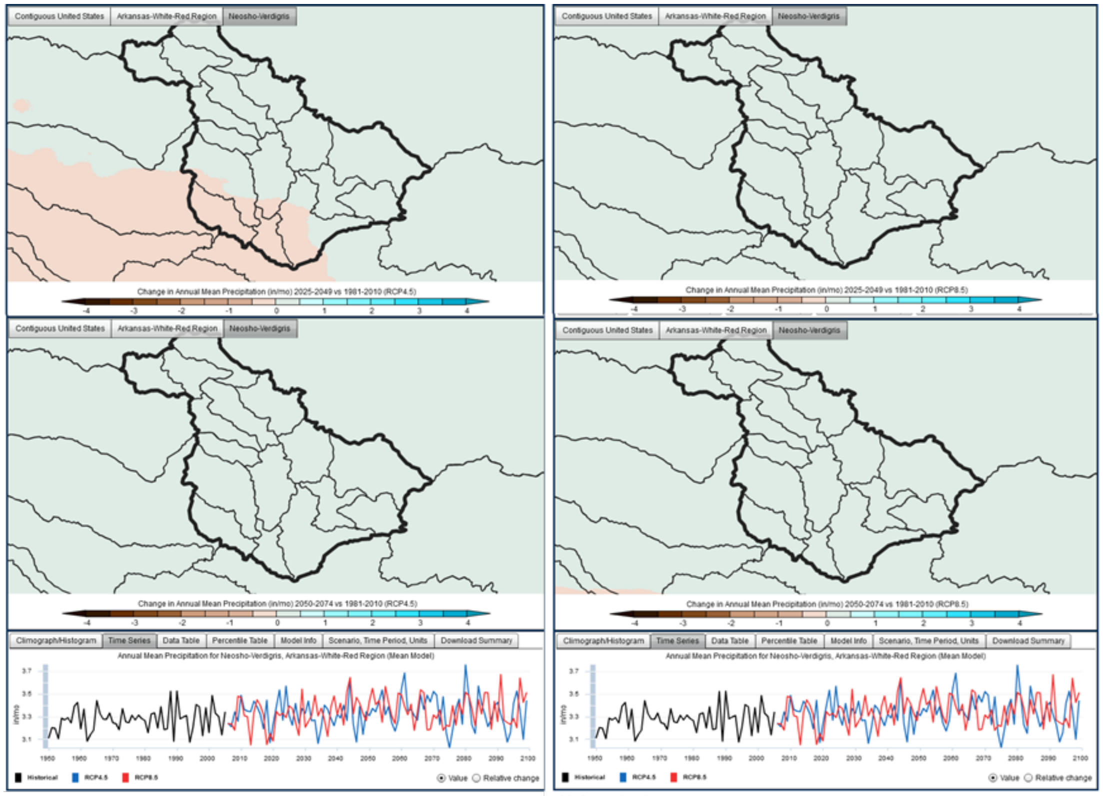
MU Name	MU Area	Overall Unpaved Road Density in MU (km/km2)	% Change	Unpaved Road Density in MU (2050)	Unpaved Road Density in MU (2060)	Overall Unpaved Road Density in MU (km/km^2)	% Change	Unpaved Road Stream Crossing (2050)	Unpaved Road Stream Crossings (2060)
Saline	8,372	0.63	27.35%	0.80	0.87	0.11	27.35%	0.14	0.16
Caddo	1,117	0.79	27.35%	1.01	1.10	0.18	27.35%	0.23	0.25
Upper Ouachita	8,854	0.72	27.35%	0.92	1.00	0.16	27.35%	0.20	0.22
Ouachita Headwaters	4,007	0.84	27.35%	1.07	1.17	0.22	27.35%	0.28	0.30
Middle Verdigris	3,930	0.70	27.35%	0.89	0.97	0.22	27.35%	0.28	0.30
Middle White	3,822	0.68	27.35%	0.86	0.94	0.15	27.35%	0.20	0.21
Black	7,105	0.95	27.35%	1.21	1.32	0.31	27.35%	0.40	0.43
Buffalo	3,471	0.86	27.35%	1.09	1.19	0.18	27.35%	0.23	0.25
Spring	3,147	1.10	27.35%	1.40	1.52	0.32	27.35%	0.40	0.44
Strawberry	1,970	0.85	27.35%	1.08	1.18	0.18	27.35%	0.23	0.25
Little Red	4,666	0.60	27.35%	0.77	0.83	0.10	27.35%	0.13	0.14
Lower St. Francis	1,221	1.35	27.35%	1.72	1.87	0.18	27.35%	0.23	0.25
Fall	2,227	0.63	27.35%	0.80	0.88	0.20	27.35%	0.26	0.28
Spring	6,708	1.58	27.35%	2.01	2.19	0.56	27.35%	0.71	0.78
Upper St. Francis	3,362	0.81	27.35%	1.03	1.13	0.31	27.35%	0.40	0.43

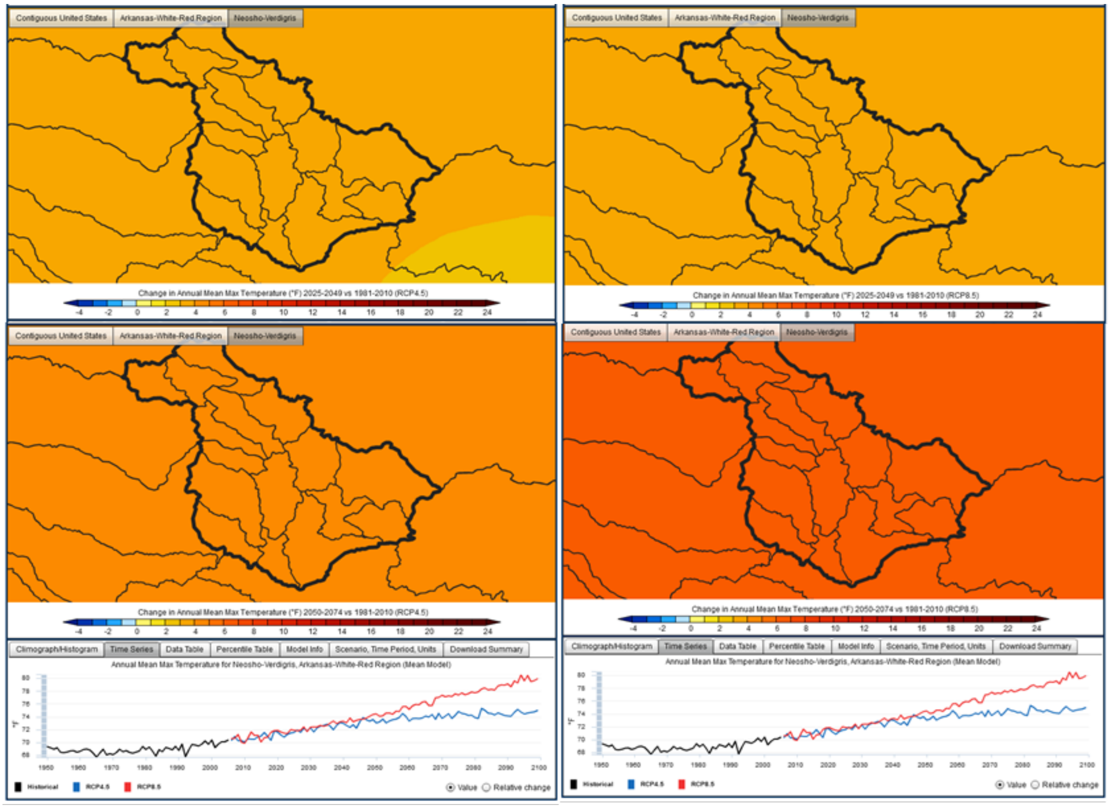
Appendix III. Modeled future changes in annual mean precipitation and annual maximum air temperature (RCP 4.5 & 8.5), 2025 – 2049 and 2050 – 2074, for Western Fanshell and "Ouachita" Fanshell MUs (National Climate Change Viewer 2016).



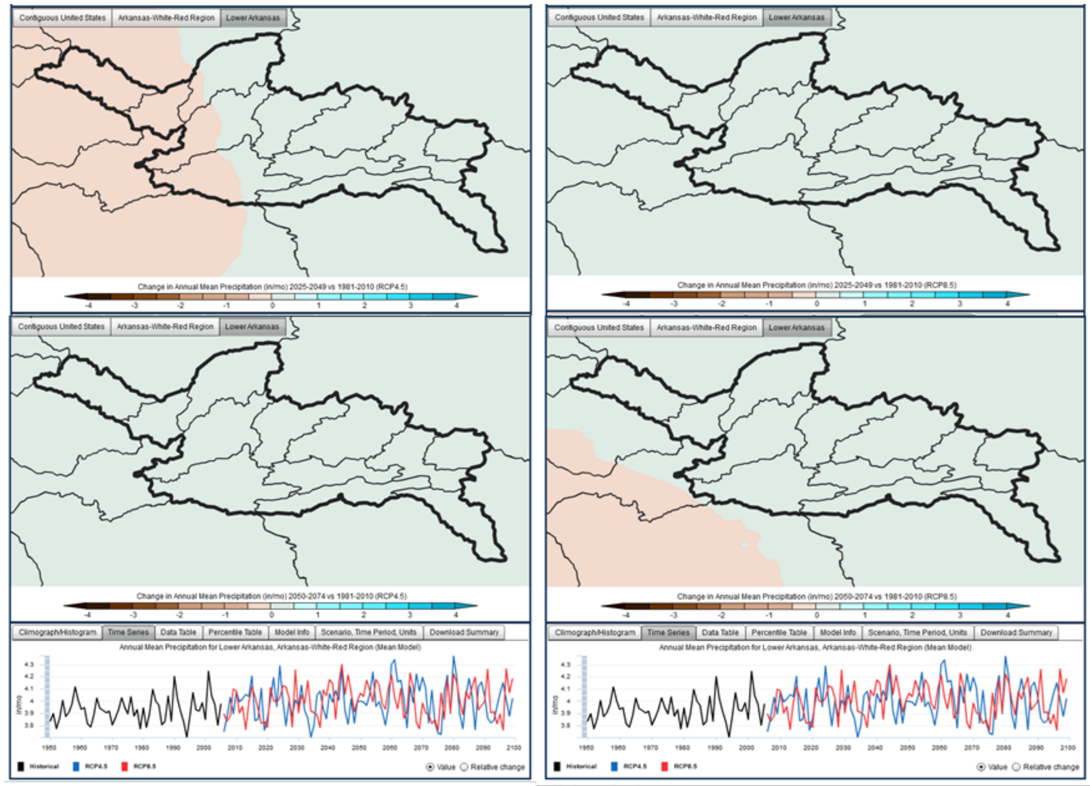


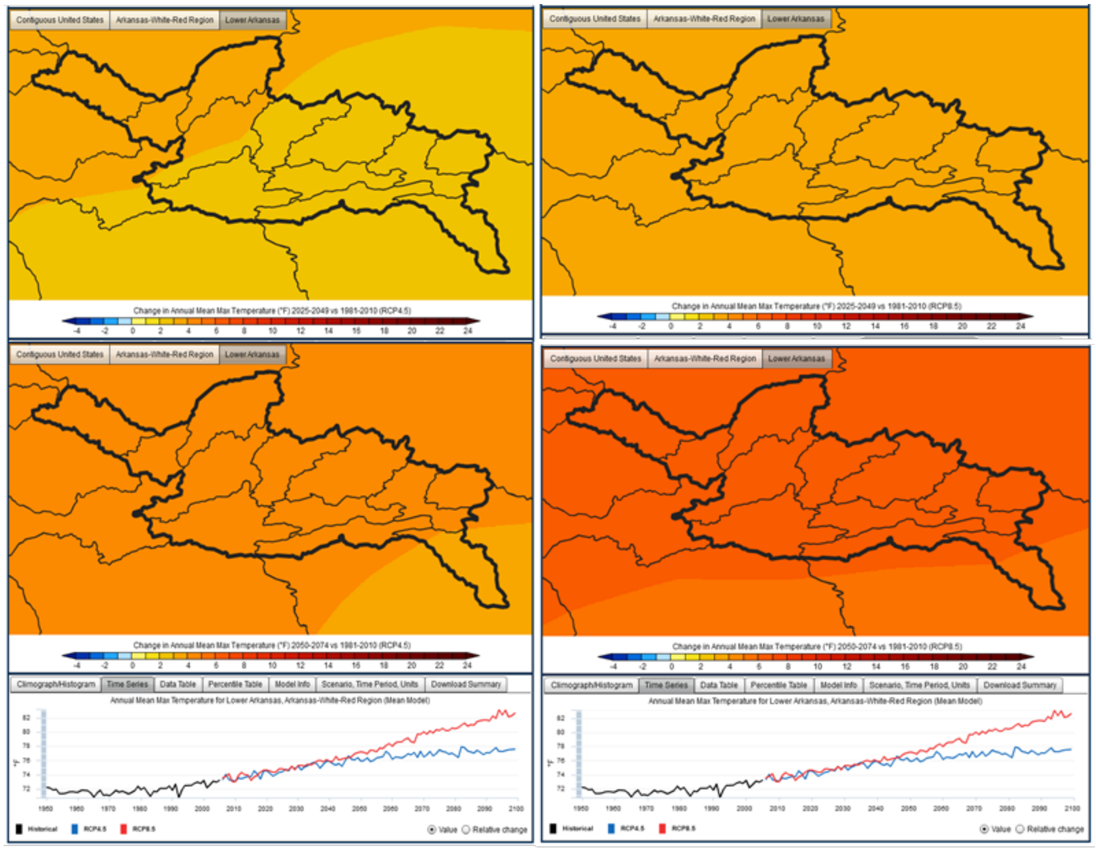
Appendix III. Continued.



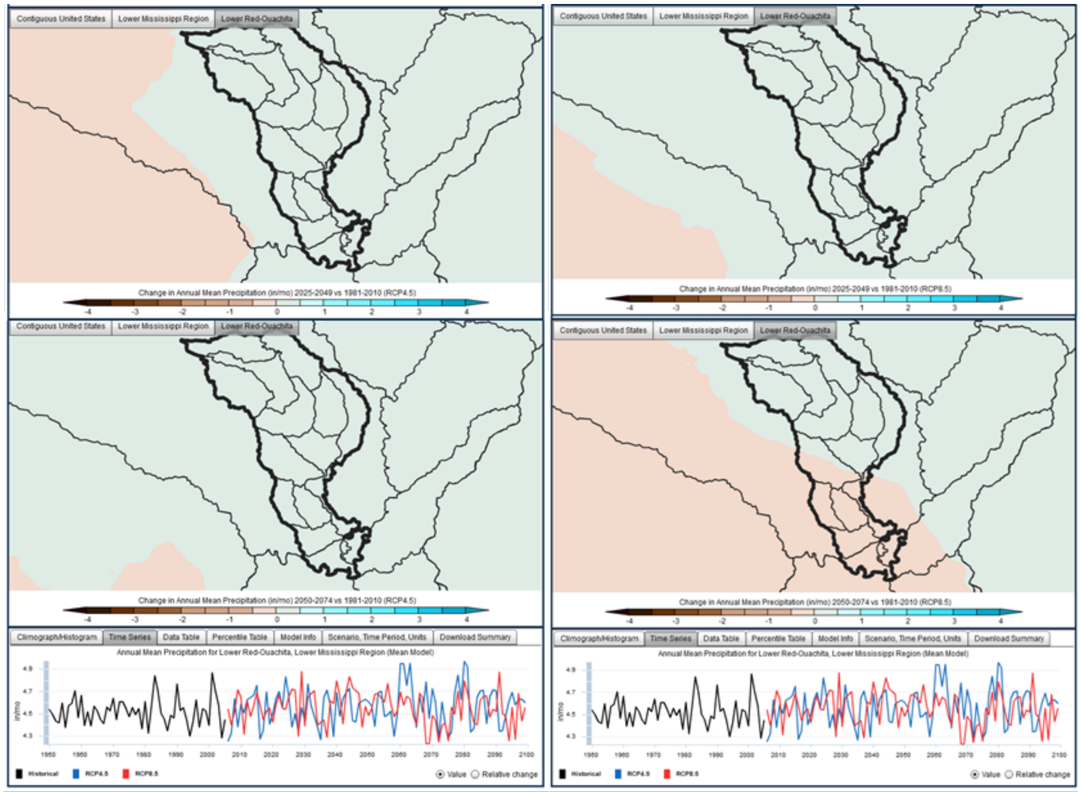


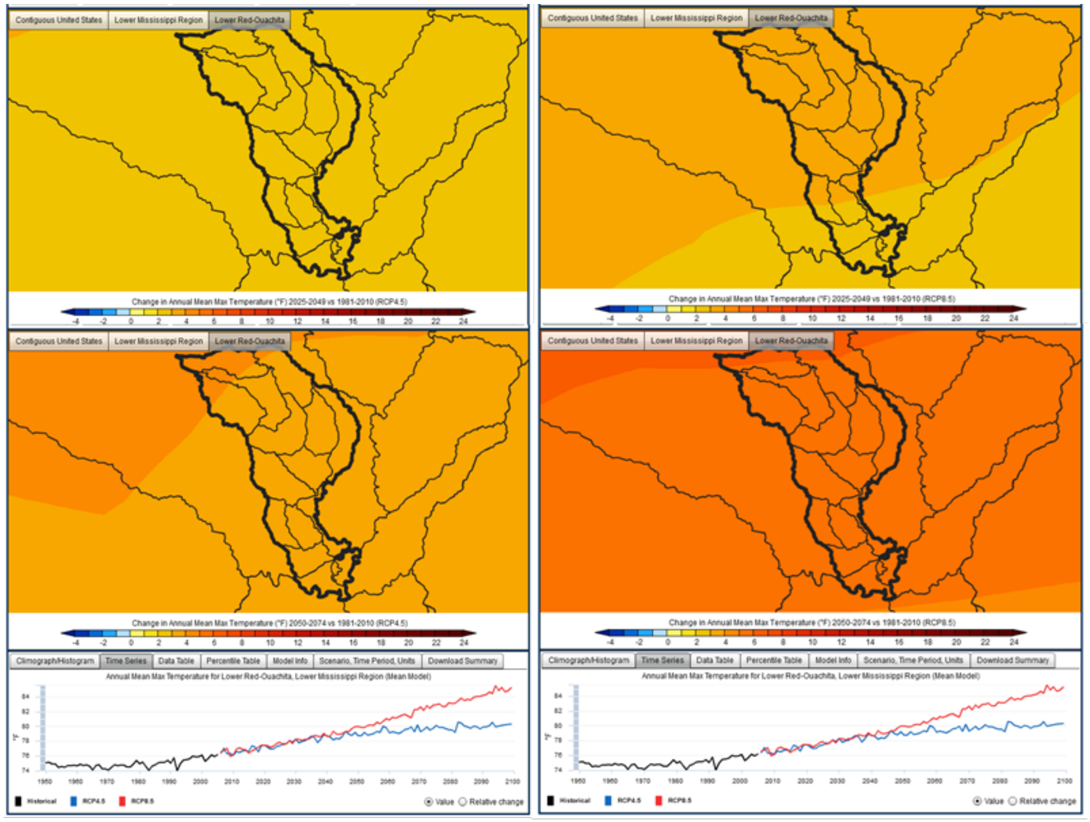
Appendix III. Continued.





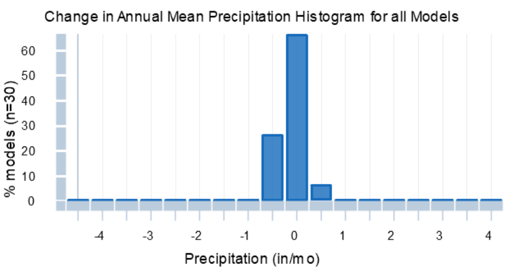
Appendix III. Continued.

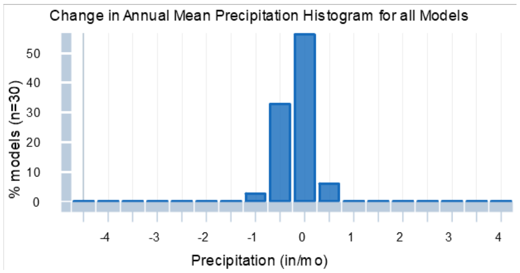


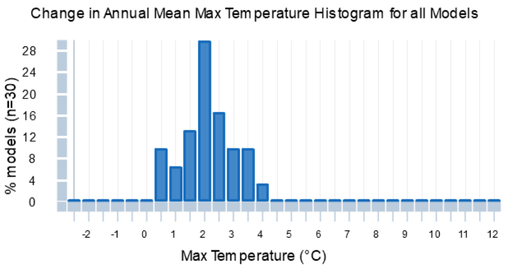


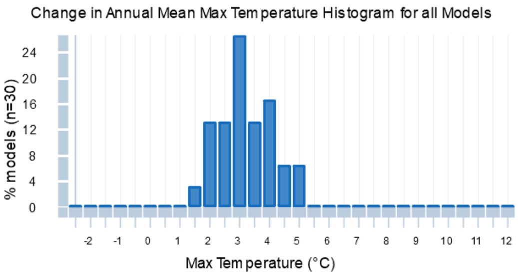
Appendix III-A. Annual mean precipitation and annual maximum air temperature for all (30) National Climate Change Viewer models for emission scenarios RCP 4.5 and 8.5, 2050 – 2074, for Western Fanshell and “Ouachita” Fanshell MUs (National Climate Change Viewer 2016).

Upper White (Left column RCP 4.5, right column RCP 8.5)

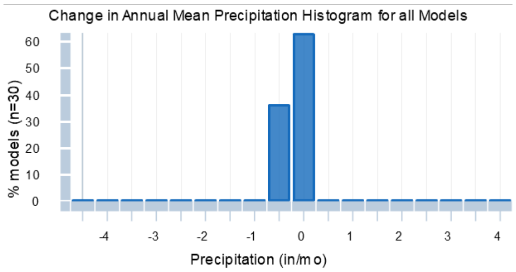


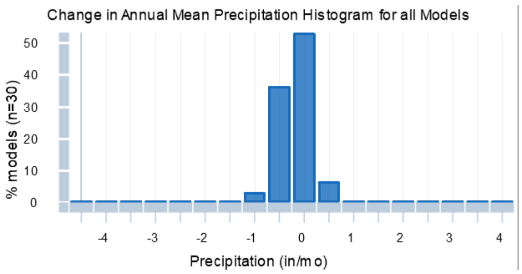


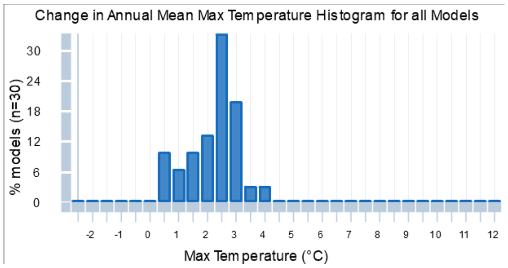


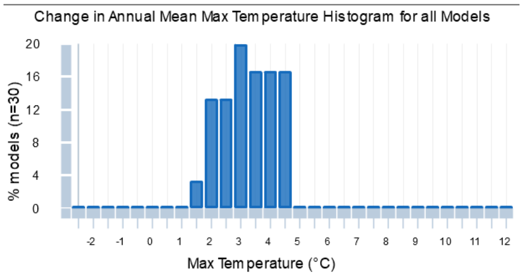


Neosho-Verdigris (Left column RCP 4.5, right column RCP 8.5)



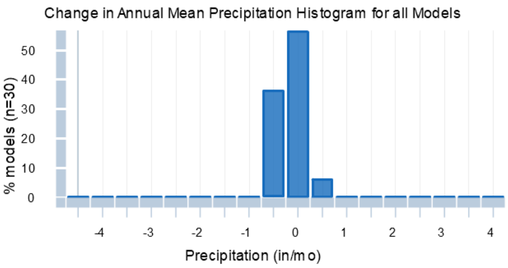


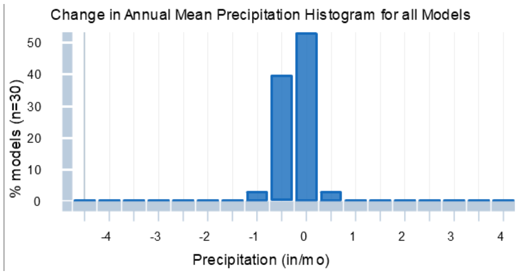


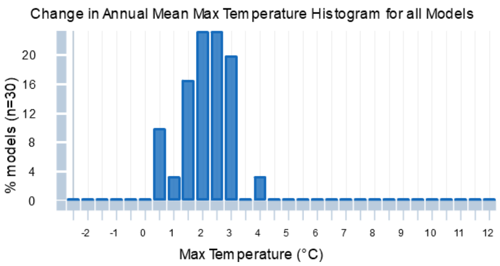


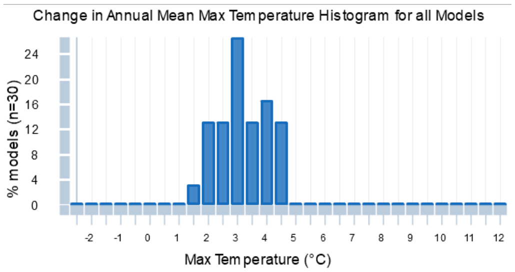
Appendix III-A. Continued

Lower Arkansas (Left column RCP 4.5, right column RCP 8.5)

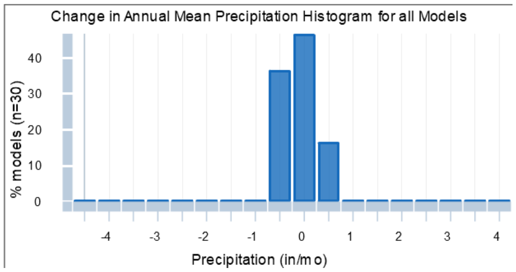

Change in Annual Mean Precipitation Histogram for all Models

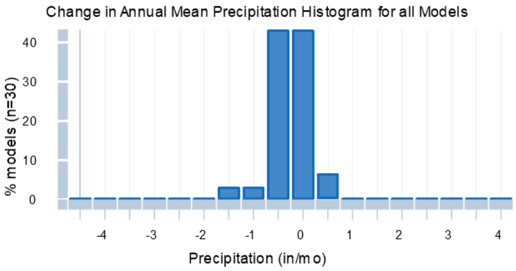

Change in Annual Mean Precipitation Histogram for all Models

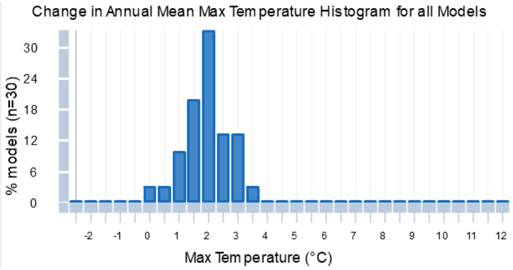

Change in Annual Mean Max Temperature Histogram for all Models

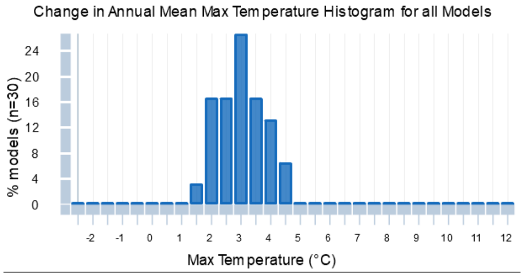

Change in Annual Mean Max Temperature Histogram for all Models

Lower Red-Ouachita (Left column RCP 4.5, right column RCP 8.5)

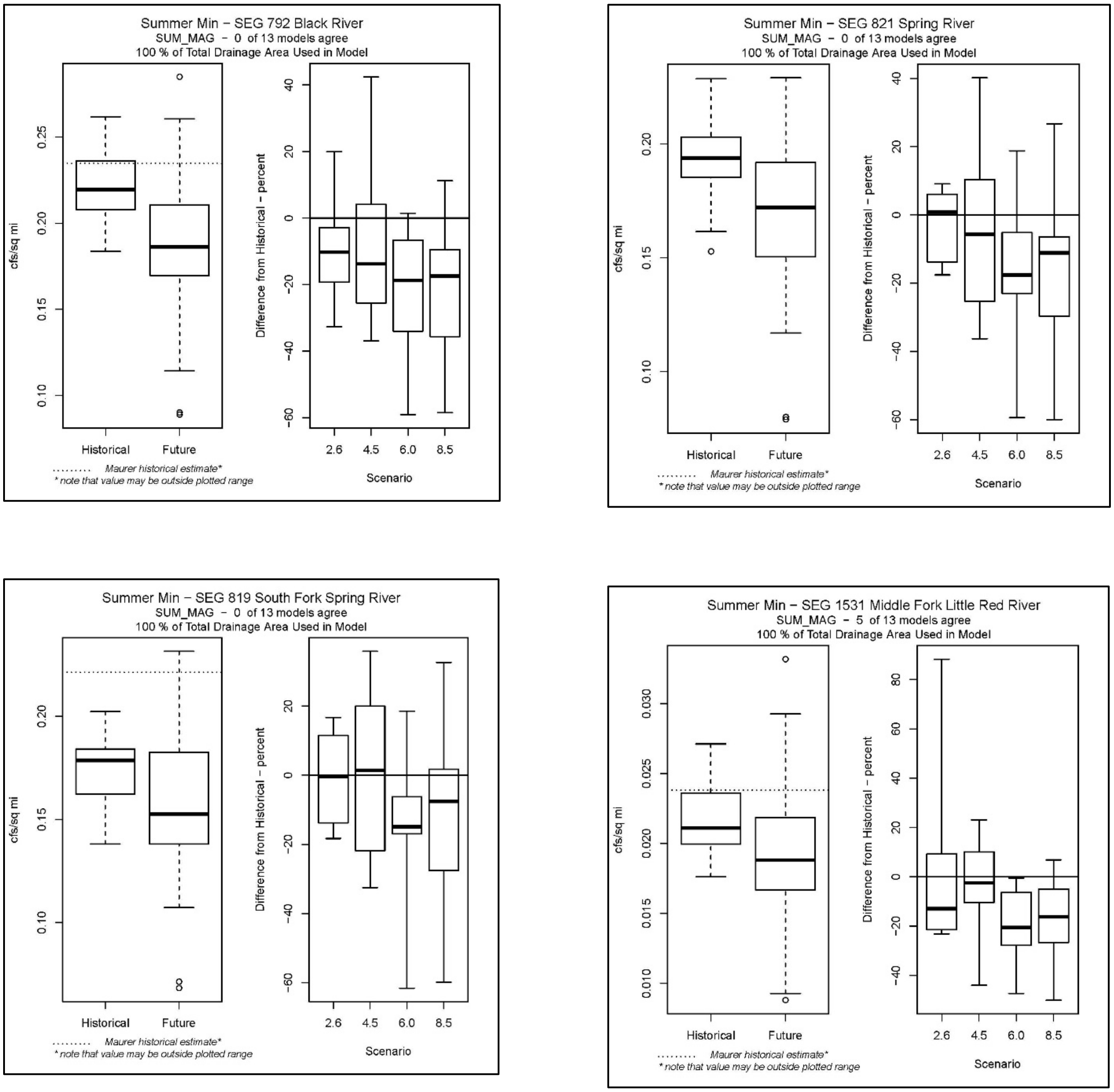

Change in Annual Mean Precipitation Histogram for all Models

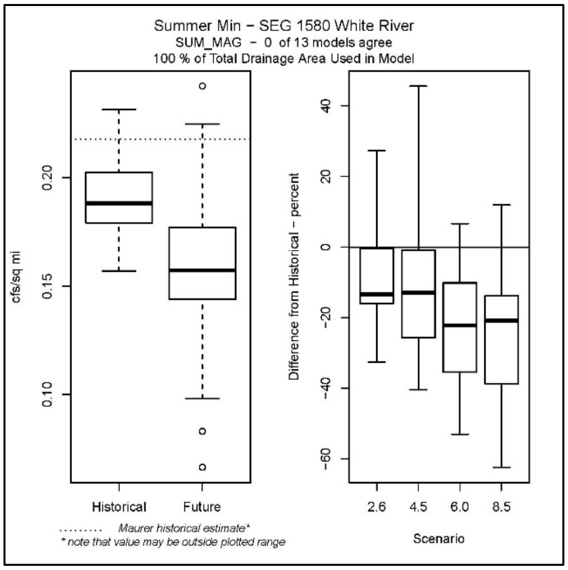

Change in Annual Mean Precipitation Histogram for all Models

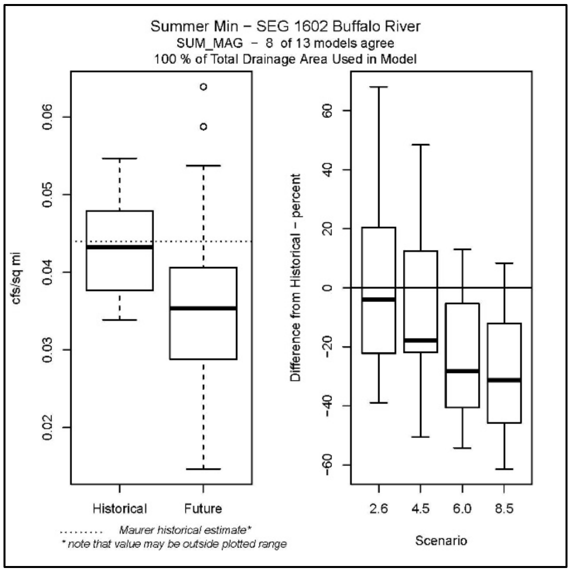

Change in Annual Mean Max Temperature Histogram for all Models

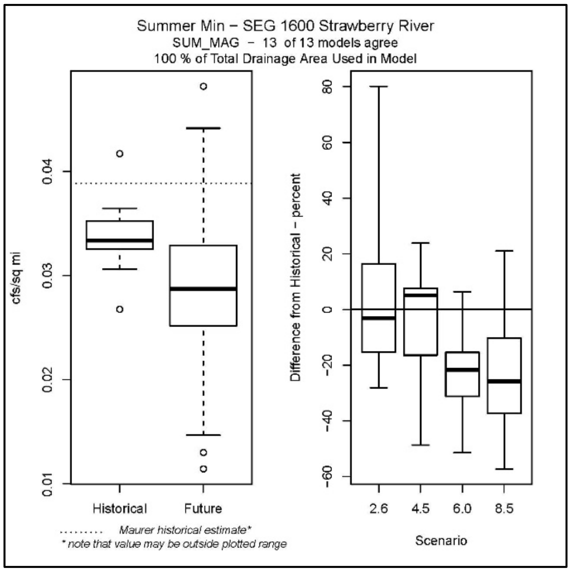

Change in Annual Mean Max Temperature Histogram for all Models

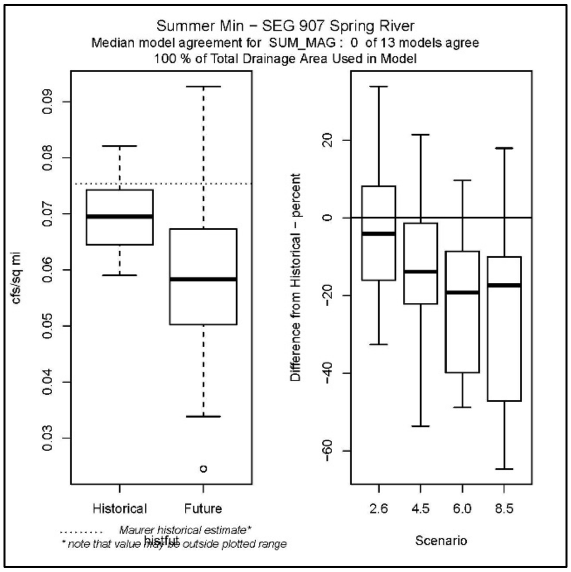
Appendix IV-A. Future percent difference from historical minimum summer (June – September) flows in Western Fanshell MUs (Source: USGS Precipitation Runoff Modeling System). Data are based on 13 models using four emission scenarios.

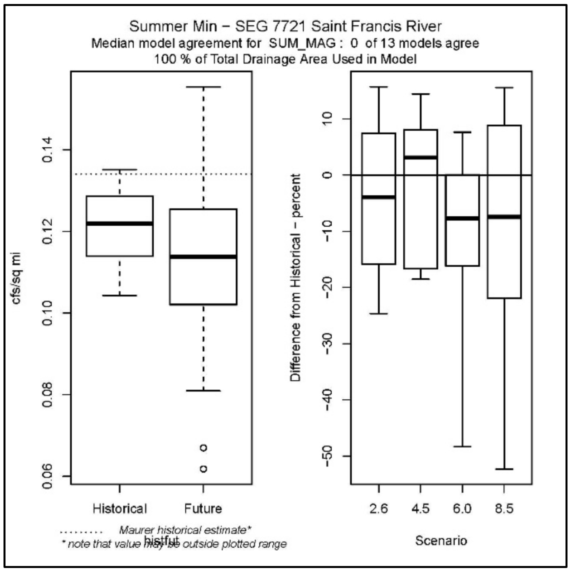


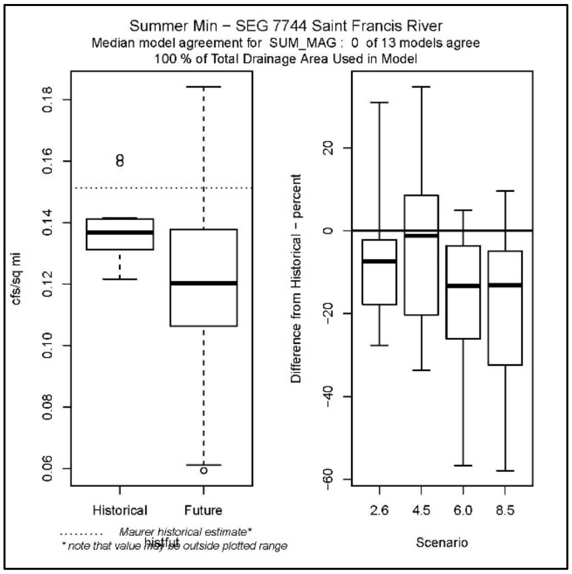

Summer Min – SEG 1580 White River
SUM_MAG – 0 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs/sq mi
0.10
0.15
0.20
Historical
Future
Difference from Historical – percent
-60
-40
-20
0
20
40
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range


Summer Min – SEG 1602 Buffalo River
SUM_MAG – 8 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs/sq mi
0.02
0.03
0.04
0.05
0.06
Historical
Future
Difference from Historical – percent
-60
-40
-20
0
20
40
60
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range

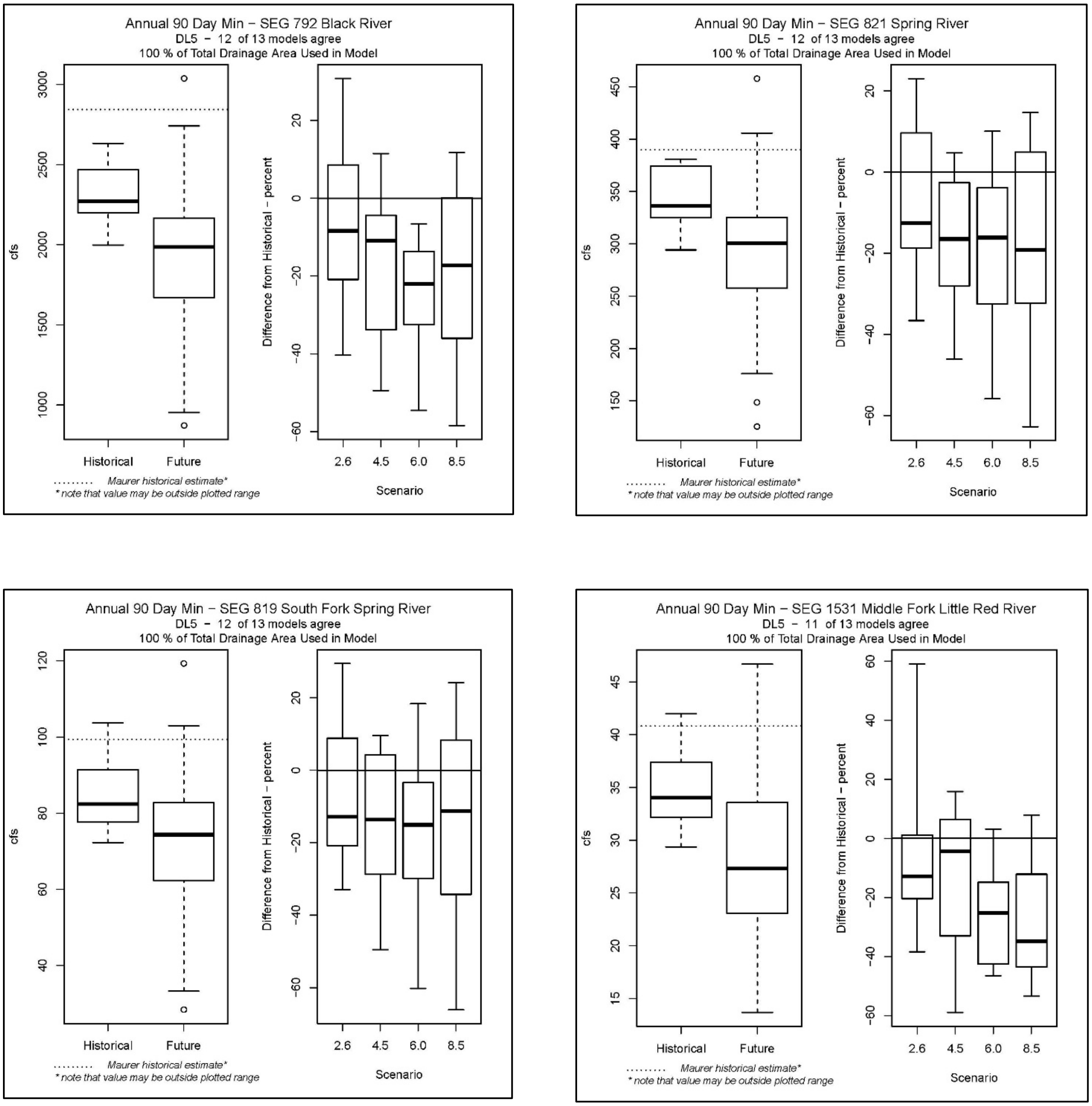

Summer Min – SEG 1600 Strawberry River
SUM_MAG – 13 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs/sq mi
0.01
0.02
0.03
0.04
Historical
Future
Difference from Historical – percent
-60
-40
-20
0
20
40
60
80
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range

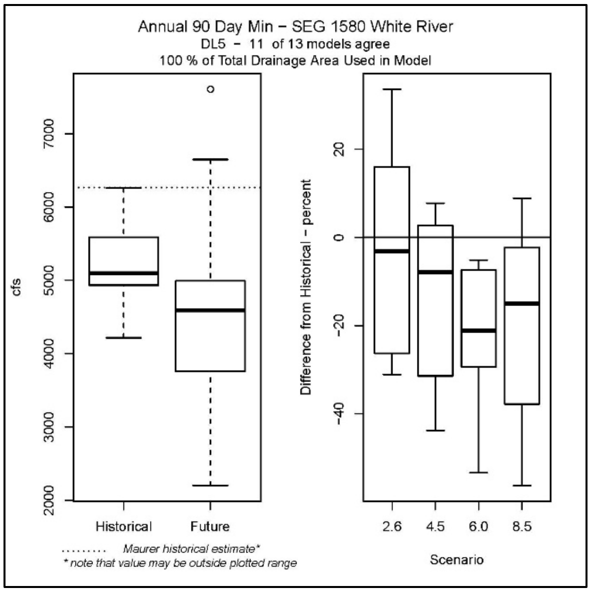

Summer Min – SEG 907 Spring River
Median model agreement for SUM_MAG : 0 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs/sq mi
0.03
0.04
0.05
0.06
0.07
0.08
0.09
Historical
Future
histfut
Difference from Historical – percent
-60
-40
-20
0
20
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range

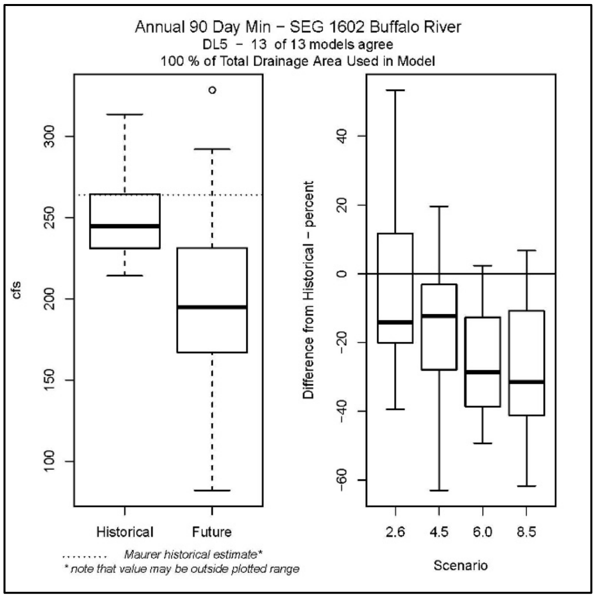

Summer Min − SEG 7721 Saint Francis River
Median model agreement for SUM_MAG : 0 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs/sq mi
0.06
0.08
0.10
0.12
0.14
Historical
Future
histfut
Difference from Historical − percent
−50
−40
−30
−20
−10
0
10
2.6
4.5
6.0
8.5
Scenario
Maurer historical estimate*
* note that value may be outside plotted range

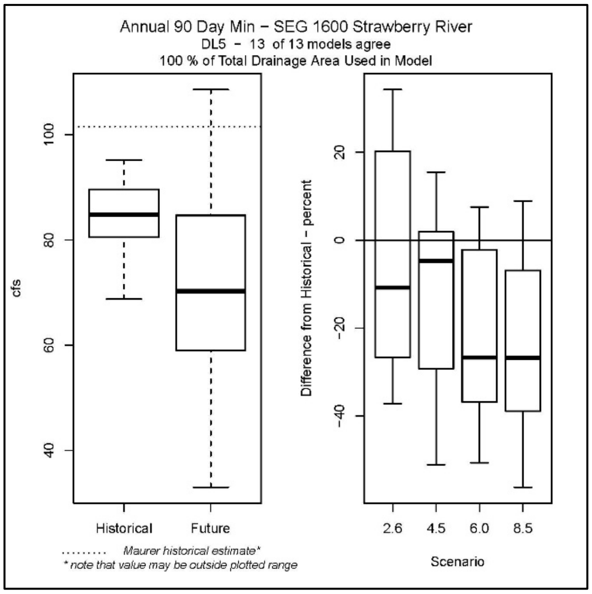

Summer Min − SEG 7744 Saint Francis River
Median model agreement for SUM_MAG : 0 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs/sq mi
0.06
0.08
0.10
0.12
0.14
0.16
0.18
Historical
Future
histfut
Difference from Historical − percent
−60
−40
−20
0
20
2.6
4.5
6.0
8.5
Scenario
Maurer historical estimate*
* note that value may be outside plotted range

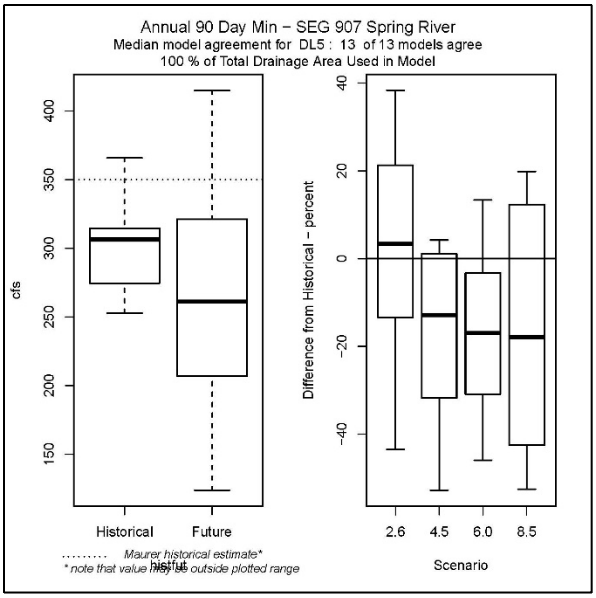
Appendix IV-B. Future percent difference from historical annual minimum 90-day moving average flow in Western Fanshell MUs (Source: USGS Precipitation Runoff Modeling System). Data are based on 13 models using four emission scenarios.

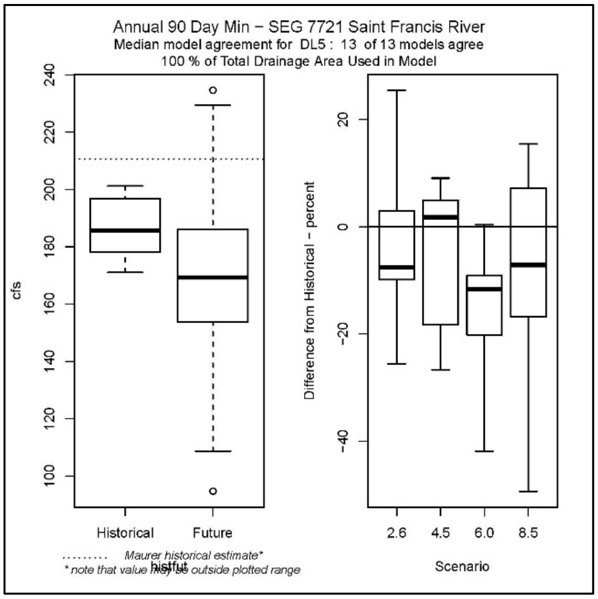


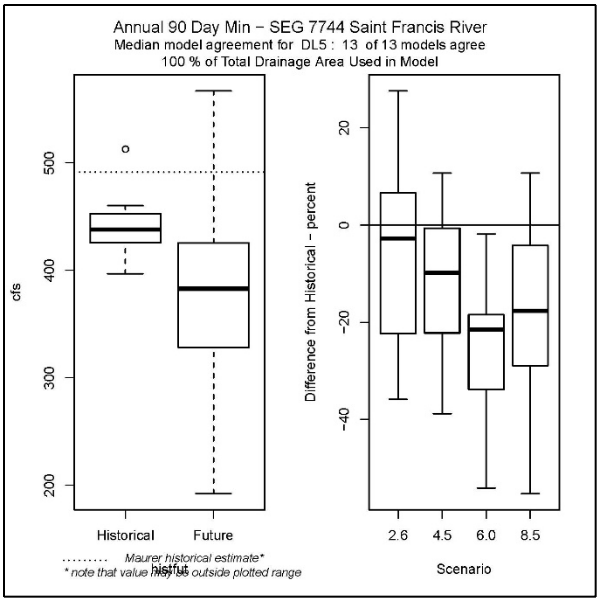

Annual 90 Day Min – SEG 1580 White River
DL5 – 11 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs
2000
3000
4000
5000
6000
7000
Historical
Future
Difference from Historical – percent
-40
-20
0
20
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range


Annual 90 Day Min – SEG 1602 Buffalo River
DL5 – 13 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs
100
150
200
250
300
Historical
Future
Difference from Historical – percent
-60
-40
-20
0
20
40
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range

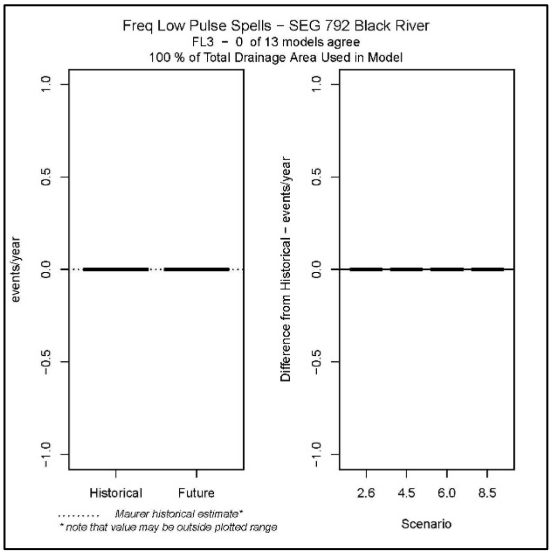

Annual 90 Day Min – SEG 1600 Strawberry River
DL5 – 13 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs
40
60
80
100
Historical
Future
Difference from Historical – percent
-40
-20
0
20
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range

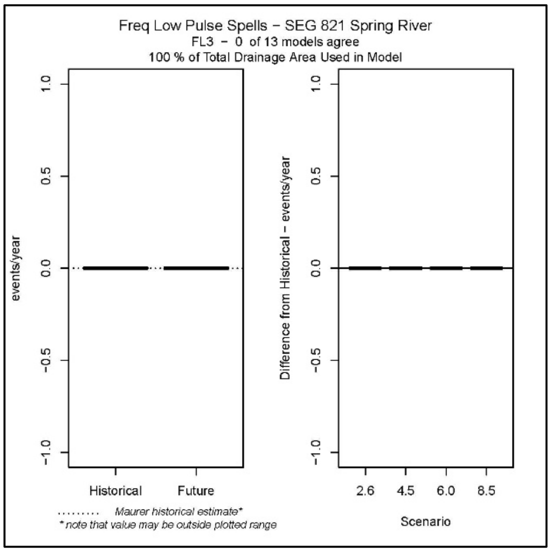

Annual 90 Day Min – SEG 907 Spring River
Median model agreement for DL5 : 13 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs
150
200
250
300
350
400
Historical
Future
histfut
Difference from Historical – percent
-40
-20
0
20
40
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range

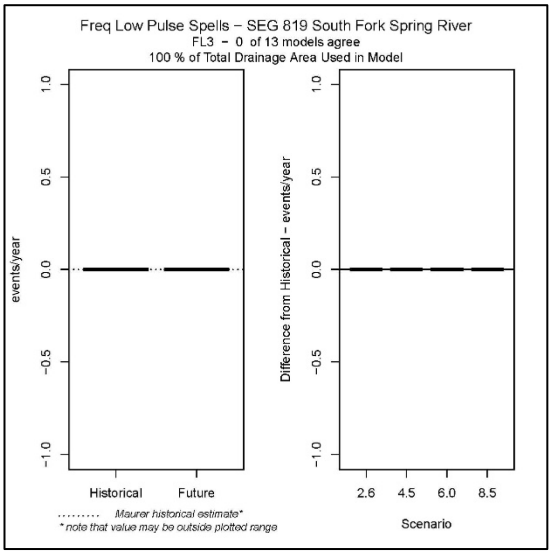

Annual 90 Day Min − SEG 7721 Saint Francis River
Median model agreement for DL5 : 13 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs
240
220
200
180
160
140
120
100
Historical
Future
histfut
Difference from Historical − percent
20
0
−20
−40
2.6
4.5
6.0
8.5
Scenario
Maurer historical estimate*
* note that value may be outside plotted range

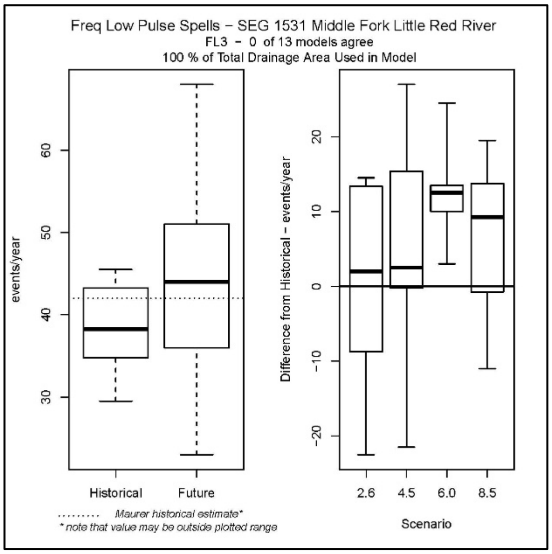

Annual 90 Day Min − SEG 7744 Saint Francis River
Median model agreement for DL5 : 13 of 13 models agree
100 % of Total Drainage Area Used in Model
cfs
500
400
300
200
Historical
Future
histfut
Difference from Historical − percent
20
0
−20
−40
2.6
4.5
6.0
8.5
Scenario
Maurer historical estimate*
* note that value may be outside plotted range

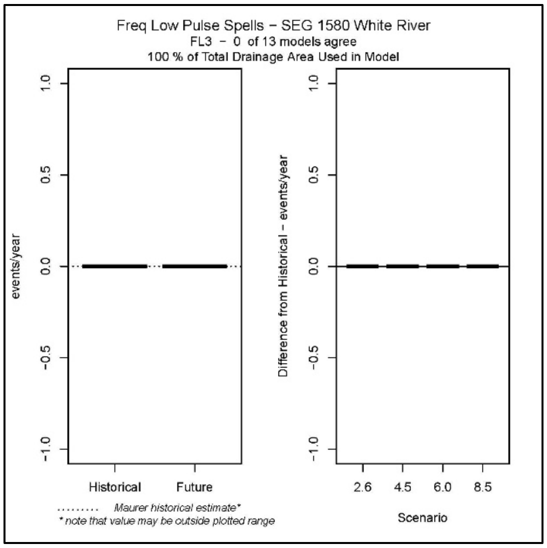
Appendix IV-C. Frequency of low pulse spells (average number of flow events with flows <5% of the mean flow for entire flow record) in Western Fanshell MUs within the Arkansas River basin (AR, KS, MO, OK) (Source: USGS Precipitation Runoff Modeling System)

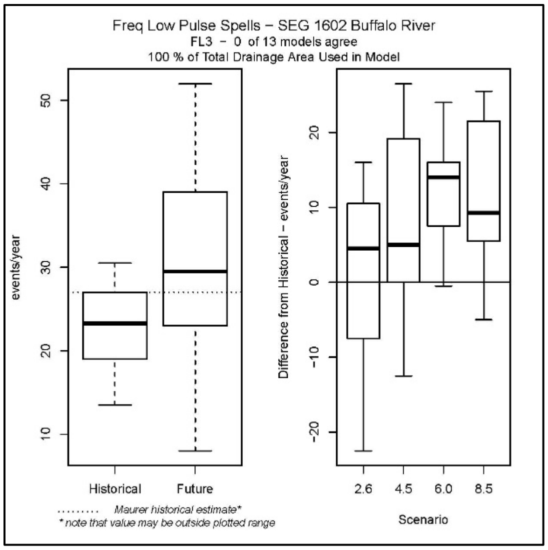


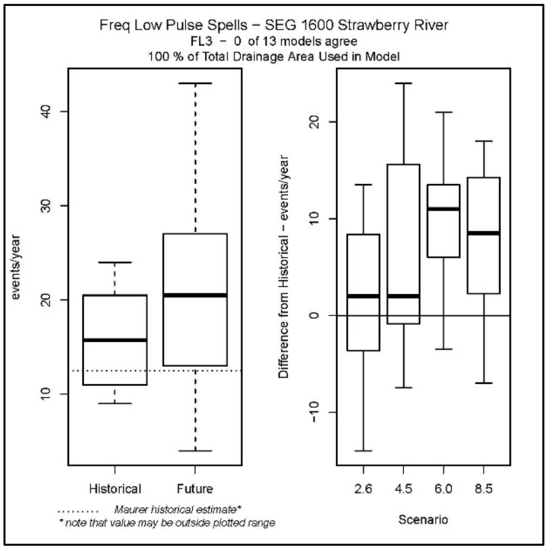


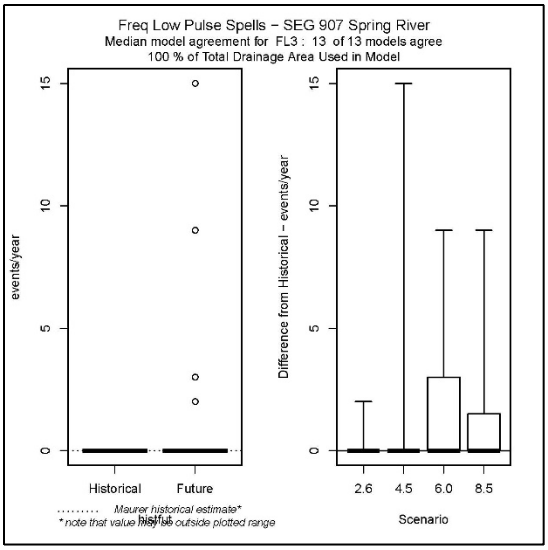


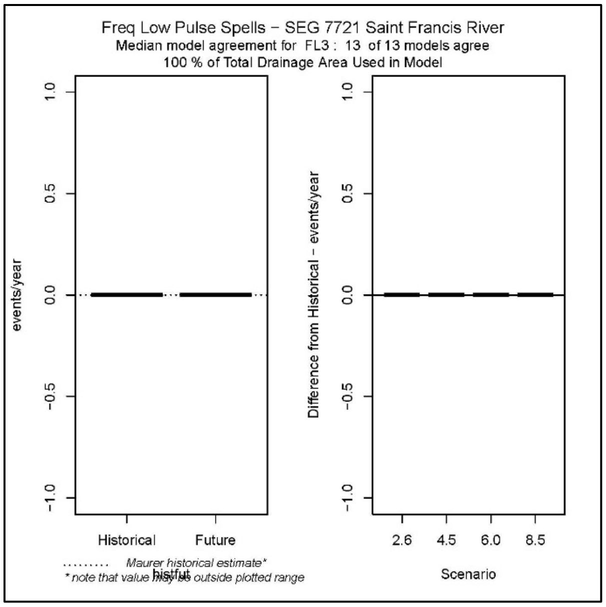


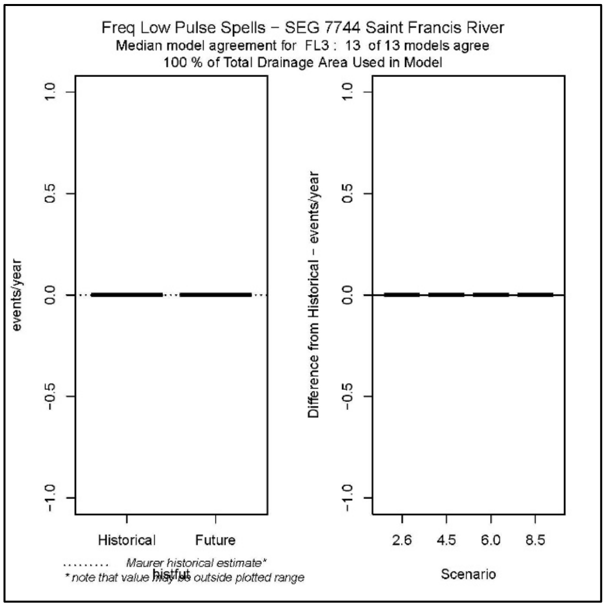

Freq Low Pulse Spells – SEG 1580 White River
FL3 – 0 of 13 models agree
100 % of Total Drainage Area Used in Model
events/year
1.0
0.5
0.0
−0.5
−1.0
Historical
Future
Difference from Historical – events/year
1.0
0.5
0.0
−0.5
−1.0
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range


Freq Low Pulse Spells – SEG 1602 Buffalo River
FL3 – 0 of 13 models agree
100 % of Total Drainage Area Used in Model
events/year
50
40
30
20
10
Historical
Future
Difference from Historical – events/year
20
10
0
−10
−20
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range

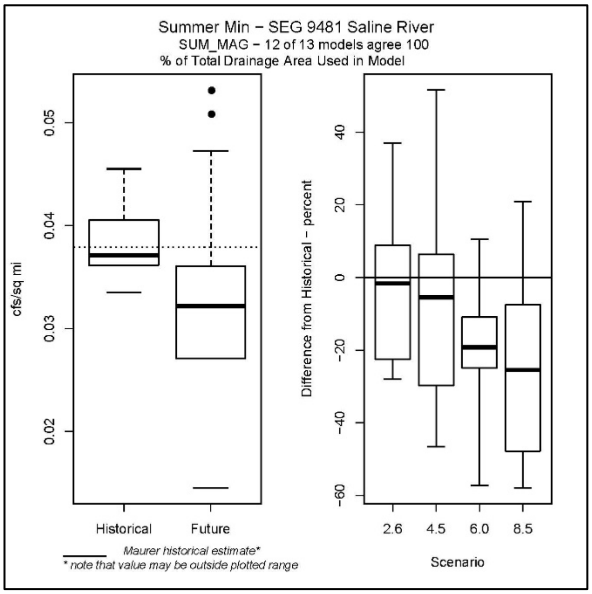

Freq Low Pulse Spells – SEG 1600 Strawberry River
FL3 – 0 of 13 models agree
100 % of Total Drainage Area Used in Model
events/year
40
30
20
10
Historical
Future
Difference from Historical – events/year
20
10
0
−10
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range

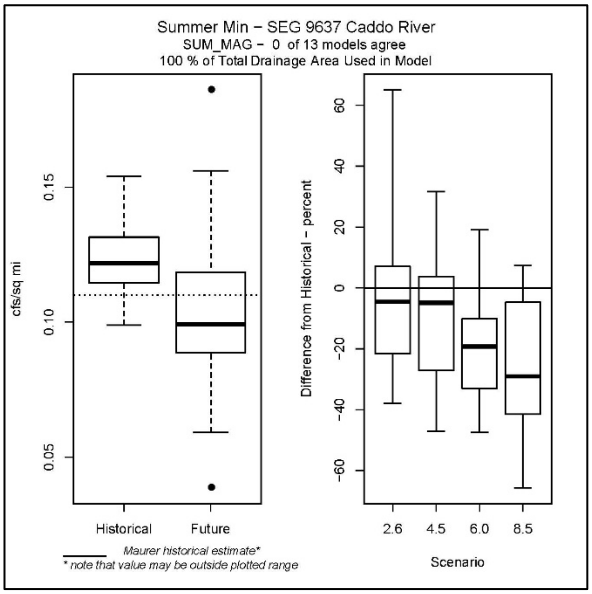

Freq Low Pulse Spells – SEG 907 Spring River
Median model agreement for FL3 : 13 of 13 models agree
100 % of Total Drainage Area Used in Model
events/year
15
10
5
0
Historical
Future
histfut
Difference from Historical – events/year
15
10
5
0
2.6
4.5
6.0
8.5
Scenario
.... Maurer historical estimate*
* note that value may be outside plotted range

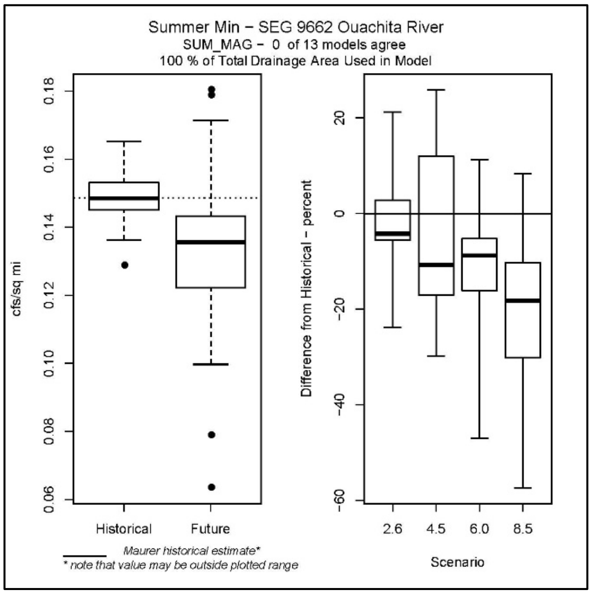

Freq Low Pulse Spells − SEG 7721 Saint Francis River
Median model agreement for FL3 : 13 of 13 models agree
100 % of Total Drainage Area Used in Model
events/year
1.0
0.5
0.0
−0.5
−1.0
Historical
Future
histfut
Difference from Historical − events/year
2.6
4.5
6.0
8.5
Scenario
Maurer historical estimate*
* note that value may be outside plotted range

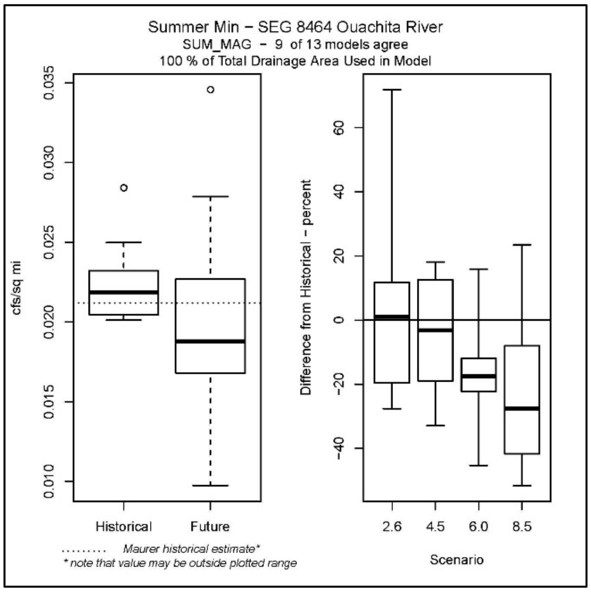

Freq Low Pulse Spells − SEG 7744 Saint Francis River
Median model agreement for FL3 : 13 of 13 models agree
100 % of Total Drainage Area Used in Model
events/year
1.0
0.5
0.0
−0.5
−1.0
Historical
Future
histfut
Difference from Historical − events/year
2.6
4.5
6.0
8.5
Scenario
Maurer historical estimate*
* note that value may be outside plotted range

Appendix IV-D. Future percent difference from historical minimum summer (June – September) flows in "Ouachita" Fanshell MUs within the Ouachita River basin (AR) (Source: USGS Precipitation Runoff Modeling System). Data are based on 13 models using four emission scenarios.

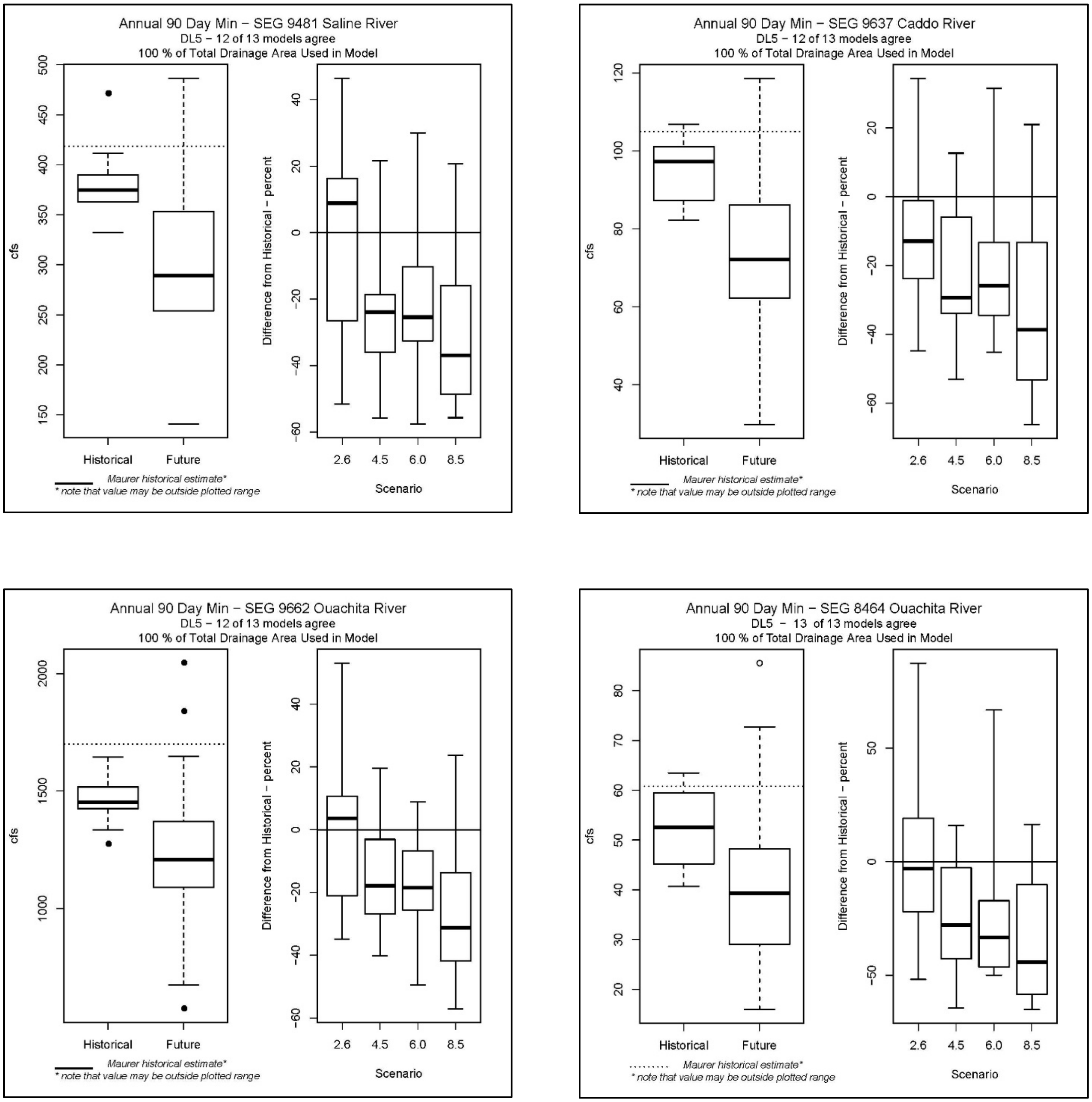








Appendix IV-E. Future percent difference from historical annual minimum 90-day moving average flow in "Ouachita" Fanshell MUs within the Ouachita River basin (AR) (Source: USGS Precipitation Runoff Modeling System). Data are based on 13 models using four emission scenarios.



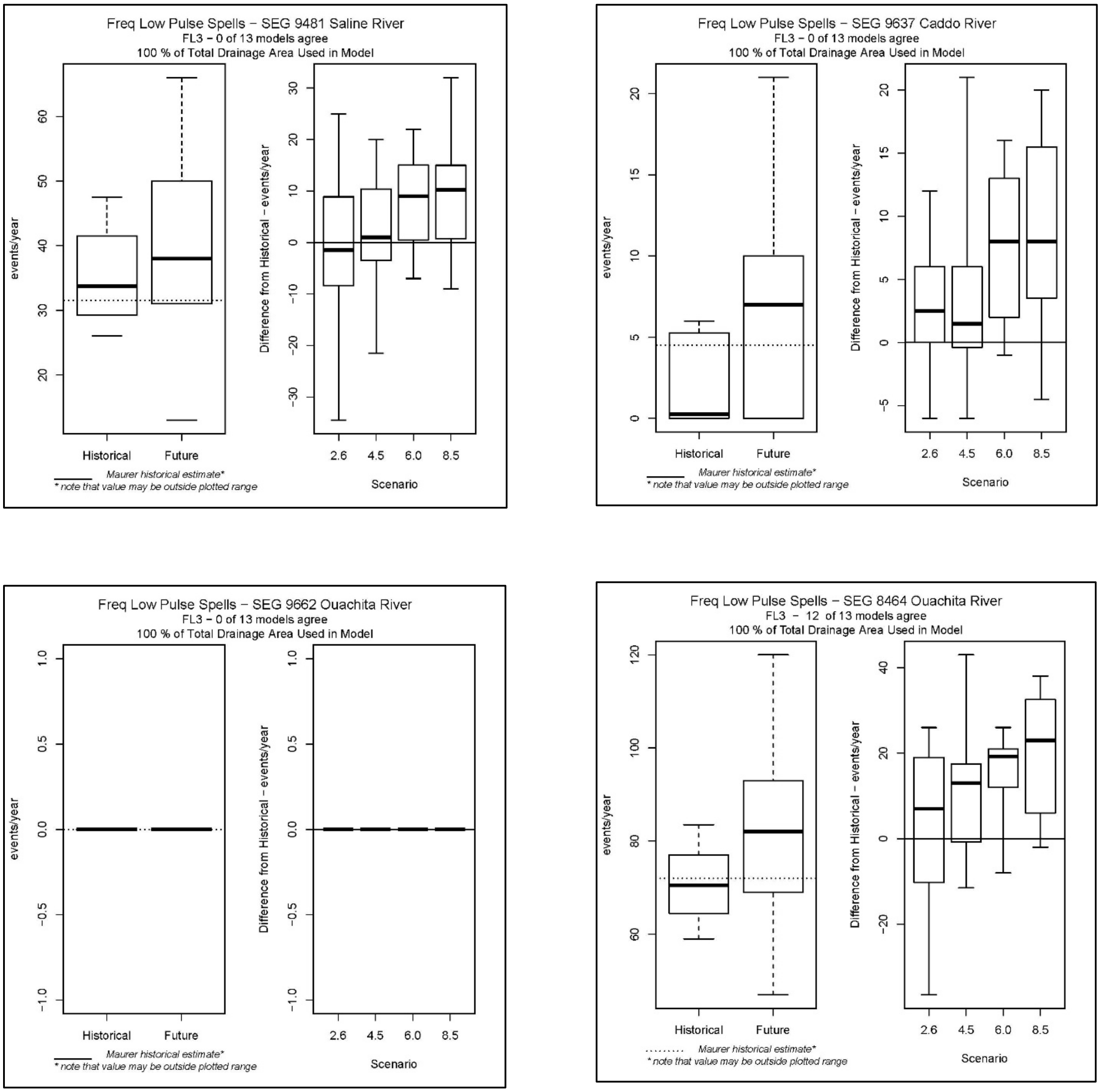
Annual 90 Day Min – SEG 9481 Saline River
DL5 – 12 of 13 models agree
100 % of Total Drainage Area Used in Model

Annual 90 Day Min – SEG 9637 Caddo River
DL5 – 12 of 13 models agree
100 % of Total Drainage Area Used in Model

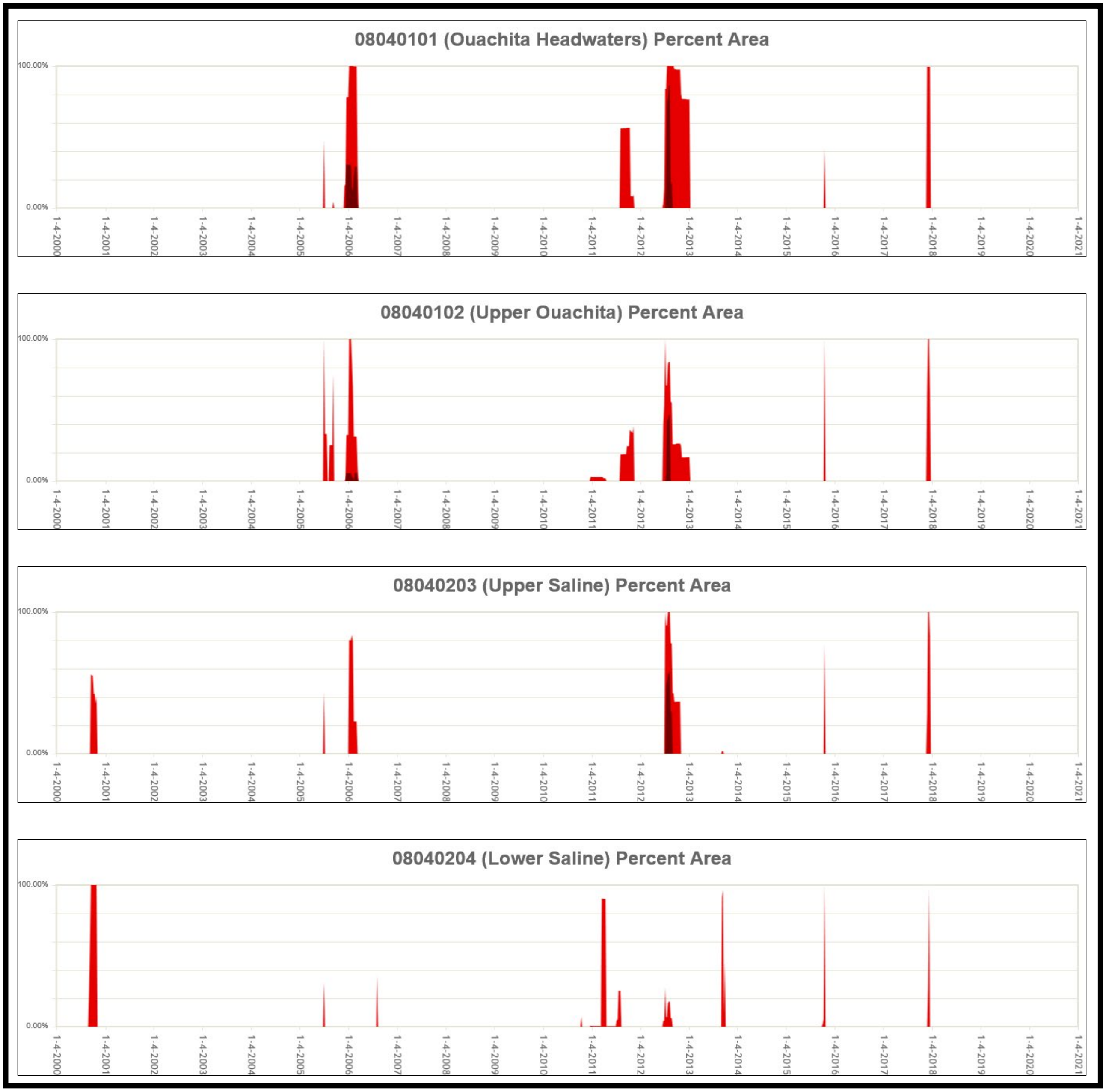
Annual 90 Day Min – SEG 9662 Ouachita River
DL5 – 12 of 13 models agree
100 % of Total Drainage Area Used in Model

Annual 90 Day Min – SEG 8464 Ouachita River
DL5 – 13 of 13 models agree
100 % of Total Drainage Area Used in Model

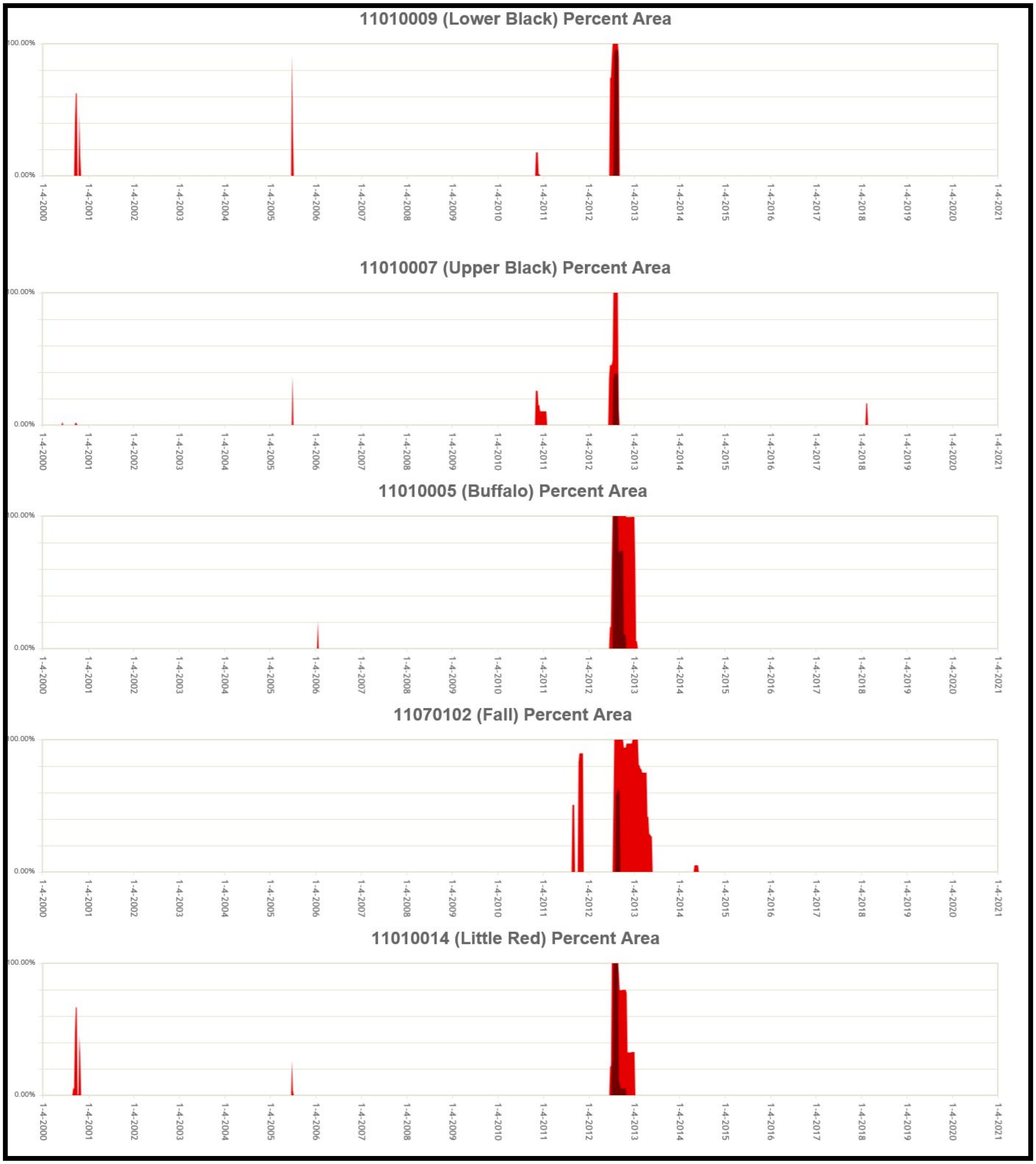
Appendix IV-F. Future percent difference from historical frequency of low pulse spells (average number of flow events with flows <5% of the mean flow for entire flow record) in "Ouachita" Fanshell MUs within the Ouachita River basin (AR) (Source: USGS Precipitation Runoff Modeling System). Data are based on 13 models using four emission scenarios.



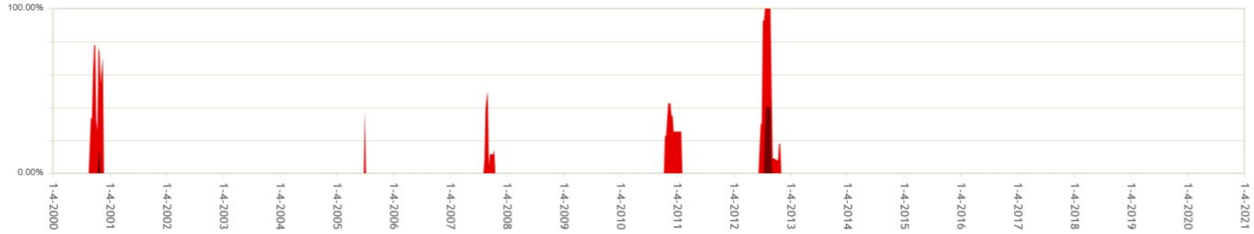
Appendix V-1. U.S. Drought Monitor data for "Ouachita" Fanshell MUs (2000 – 2019). The Caddo River MU is included within the Upper Ouachita MU. Colors correspond with category colors in Figure 3.3.



Appendix V-2. U.S. Drought Monitor data for Western Fanshell MUs (2000 – 2019). The Black River MU includes the Lower Black and Upper Black HUCs merged. Colors correspond with category colors in Figure 3.3.



08020203 (Lower St. Francis) Percent Area

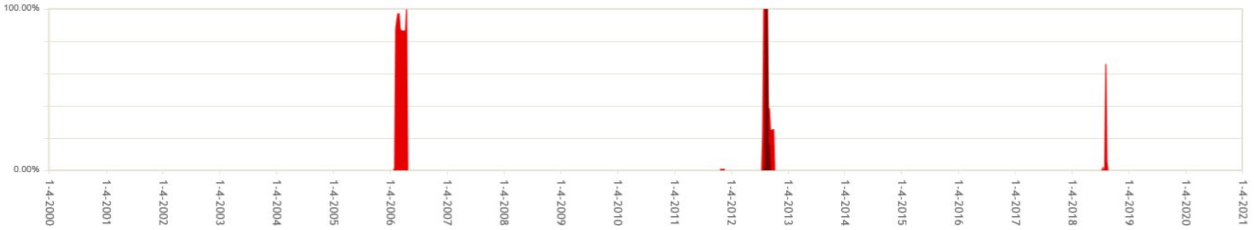


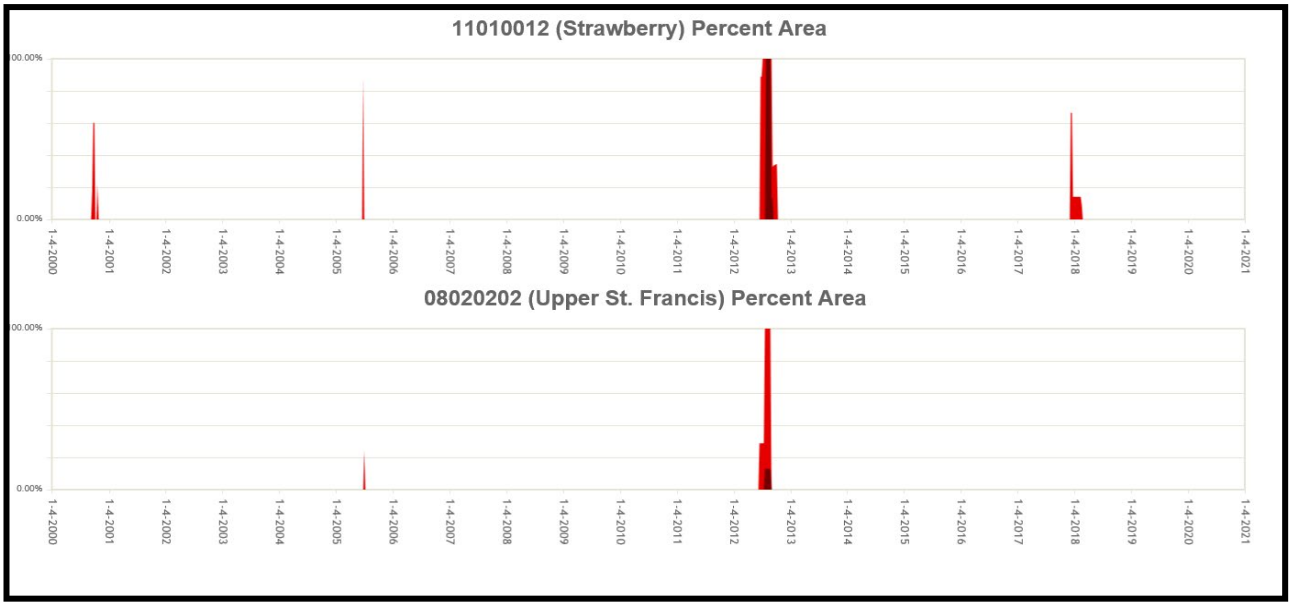
11070103 (Middle Verdigris) Percent Area

11010004 (Middle White) Percent Area

11010010 (Spring) Percent Area

11070207 (Spring) Percent Area





11010012 (Strawberry) Percent Area

08020202 (Upper St. Francis) Percent Area