Species Status Assessment Report for the Pyramid Pigtoe Mussel (*Pleurobema rubrum*)

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ACRONYMS USED

Act	Endangered Species Act
ADCNR	Alabama Department of Conservation and Natural Resources
AGFC	Arkansas Game and Fish Commission
AMD	acid mine drainage
ANSP	Academy of Natural Sciences of Philadelphia
ANS	aquatic nuisance species
ARA	active river area
BMP	Best management practices
CAFO	Concentrated Animal Feeding Operations
CBD	Center for Biological Diversity
CM	Carnegie Museum
CWA	Clean Water Act
CWP	Center for Watershed Protection
DMNH	Delaware Museum of Natural History
DNR	Department of Natural Resources
EPA	U.S. Environmental Protection Agency
EKU	Eastern Kentucky University
ESI	Ecological Specialists, Inc.
FMNH	Florida Museum of Natural History
FPG	forest practices guidelines
FR	Federal Register
HUC	Hydrologic unit codes
INHS	Illinois Natural History Survey
KDEP	Kentucky Department for Environmental Protection
KSNPC	Kentucky State Nature Preserves Commission
KYDOW	Kentucky Division of Water
KDFW	Kentucky Department of Fish & Wildlife Resources
LEC	Lewis Environmental Consulting
MCZ	Museum of Comparative Zoology
MFM	Museum of Fluviatile Mollusks
MU	Management Unit
MSMNS	Mississippi Museum of Natural Sciences
NCASI	National Council for Air and Stream Improvement
NCMNS	North Carolina Museum of Natural Sciences
NGO	non-governmental organization
NHP	Natural Heritage Program
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NPS	National Park Service
NWR	National Wildlife Refuge
ODNR	Ohio Department of Natural Resources
OSUM	Ohio State University Museum
OWC	organic wastewater contaminants
PPM	parts per million
RM	river mile
ROW	right-of-way
RRI	Reservoir Release Improvement
Service	U.S. Fish and Wildlife Service
SMCRA	Surface and Mining Control and Reclamation Act of 1977
SSA	Species Status Assessment
SWAP	State Wildlife Action Plan
TAN	total ammonia-nitrogen
TDEC	Tennessee Department of Environment and Conservation
TNC	The Nature Conservancy
TSS	total suspended solids
TVA	Tennessee Valley Authority
TWRA	Tennessee Wildlife Resources Agency
UMMZ	University of Michigan Museum of Zoology
UTMM	University of Tennessee McClung Museum
Corps	U.S. Army Corps of Engineers
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
USNM	U.S. National Museum
VDWR	Virginia Department of Wildlife Resources

EXECUTIVE SUMMARY

In 1820, Constantine Rafinesque described the Pyramid Pigtoe, a medium-sized mussel, up to 3.6 inches (91 millimeters (mm)) in size, which can be long-lived, likely 20-30 years, but potentially up to 50 years or more. It is found in medium to large rivers, and prefers a mixture of sand, gravel, and cobble substrates. The Pyramid Pigtoe was previously a candidate for listing by the Service, but was withdrawn in 1991 due to taxonomic uncertainty. Subsequent taxonomic treatments have considered the species valid and recent genetic analyses also confirmed the Pyramid Pigtoe to be a valid species.

The Pyramid Pigtoe is historically known from 18 states, but considered extirpated from 9 states (Pennsylvania, West Virginia, Indiana, Illinois, Wisconsin, Minnesota, Iowa, Kansas, Missouri). The species has been recorded live during surveys since 2000 from the states of Kentucky, Tennessee, Virginia, Ohio, Alabama, Oklahoma, Arkansas, Mississippi, and Louisiana.

The Clinch River population spans the Tennessee and Virginia border but the species has experienced a documented decline and is considered very rare and potentially on the verge of extirpation from Virginia. Similarly, the species is known to currently occur in Oklahoma only in the Little River, which spans the border of Oklahoma and Arkansas, and is very rare in Oklahoma, having experienced decline from historical conditions. There is also only one population remaining in Ohio, in the Muskingum River, where the species has suffered a dramatic decline in abundance and extent.

For representation analyses, the basin level (HUC 2) was used. The Pyramid Pigtoe formerly occurred in 6 major river basins, but now occurs in 4. The Pyramid Pigtoe is considered extirpated from the Upper Mississippi and Missouri basins, indicating a significant reduction in basin representation from its historical distribution. Despite substantial documentation in museums and literature, a lack of genetic material from these basins, combined with very similar morphology to closely-related species, results in difficulties assessing the historical distributional limits of the Pyramid Pigtoe, so we relied on the best available information from publications, state rankings, and museum databases.

A rangewide genetic study is underway but incomplete. Populations within the Upper Mississippi and Missouri (now extirpated), and Arkansas-White-Red, and Lower Mississippi basins have been a source of taxonomic and systematic challenges for mussel biologists for decades. To be as inclusive as possible and illustrate the entire documented range of these species these populations are included within the text and listed in appendices B and C with supporting information. Threats facing the Pyramid Pigtoe in the Arkansas-White-Red and Lower Mississippi basins are similar to those in the Ohio and Tennessee basins, and these are listed in Appendix E.

The HUC 8 level in this assessment is referred to as a Management Unit (MU), and represents one or more populations. The Pyramid Pigtoe is a medium to large river species, and there are only a few examples of its occurrence in smaller tributary streams within a Management Unit. As a result, populations are predominantly linear in orientation and vulnerable to stochastic events. The MU-level, when used in conjunction with populations, has been used as a visual

basis for other wide-ranging aquatic species, and was considered most appropriate to assess and display resiliency and redundancy under both current and future conditions. The Pyramid Pigtoe potentially formerly occupied as many as 136 MUs rangewide, but currently occurs in only 28 MUs. Known populations have declined in number from 151 historically to 35 today.

The Pyramid Pigtoe has suffered impacts from negative influences to aquatic species commonly found in the central and eastern U.S., including habitat fragmentation from dams and other barriers; habitat loss; degraded water quality from chemical contamination and erosion from poorly managed development, agriculture, mining, and timber operations; direct mortality from dredging and harvest; and the proliferation of invasive species, such as the Zebra Mussel, Asian Clam, and Black Carp. Projections 20 to 30 years into the future indicate that the number of MUs could remain at 28 or drop to as low as 15, and be reduced from 4 legacy FWS regions (2, 3, 4, & 5) to 1 (4), depending on the variety of considerations built into the scenarios we evaluated.

Given current and possible future conditions, it is possible that the Pyramid Pigtoe could disappear entirely from the Arkansas-White-Red basin, where as many as 17 MUs were historically occupied, but only 3 remain. Projections also indicate the species may be lost from the Muskingum and Cumberland River systems in 20-30 years. These major river systems within the Ohio basin formerly harbored populations large in extent and abundance, with multiple tributaries occupied (Appendix C). There is currently only one remaining population and MU within the Cumberland and Muskingum River MUs and both are currently in low condition. The states of Ohio, Oklahoma, and Virginia have only one linear population each, restricted to small reaches of the Muskingum, Little, and Clinch Rivers, respectively, and given future projections, persistence of the Pyramid Pigtoe within those state boundaries is tenuous.

Cumulative totals of historical and current basins, MUs, and populations are summarized in Table ES-1, below. In projecting the future viability of the Pyramid Pigtoe, two scenarios were considered: one in which current influences remain constant 20-30 years into the future; and one in which negative influences increase in number, frequency and/or severity over the 20-30 years. Due to the current presence of populations within the four extant basin, Table ES-1 also contains current and future basin, MU, and population projection summaries, which form the basis of this SSA. The table articulates the number of populations and MUs (redundancy), the distribution of the populations across major river basins (representation), and the potential capability of the populations and MUs to withstand stochastic events (resiliency).

Table ES-1. Overall summary of historical, current, and future conditions for Pyramid Pigtoe MUs across its range.

- **High**—MUs with sizable populations generally distributed over a significant and more or less contiguous length of stream (greater than or equal to 30 river miles [RM]), with evidence of recent recruitment. Water quality and habitat conditions remain optimal for recruitment and multiple age classes are represented. Populations are not linearly distributed, or are distributed in a way that the population is buffered against a stochastic event (i.e., occur in tributary streams within the river system). *(Thriving; capable of expanding range.)*
- **Medium**— MUs with small, generally restricted populations, with some level of age class structure, but vulnerable to existing threats. Appropriate substrates are generally maintained with instream flows that mimic natural conditions. Water quality and habitat degradation may occur but not at a level that negatively affects both the density and extent of a population. *(Stable, not necessarily thriving or expanding its range.)*

- **Low**— MUs with very small and highly restricted populations, with little to no evidence of age class structure. Loss of mussel habitat or water quality degradation within the formerly occupied river/stream reach has been measured or observed and imminent threats are documented. Not likely to withstand stochastic events. Population is linearly distributed and geographically restricted within a management unit. *(Surviving, still observable but as older individuals only; population likely declining.)*

(FUTURE CONDITION ONLY)

- **Very Low**— MUs with populations expected to no longer occur in the future (20 to 30 years). A population may be below detectable levels despite consistent survey effort within its formerly occupied range. *(No survival or survival uncertain; no longer observable, or only detected as weathered dead or relic shells.)*

	Historical	Current Condition	Future Scenario 1	Future Scenario 2
Upper Mississippi Basin				
# total populations	19	--	--	--
# Management units	18	--	--	--
# states	5	--	--	--
Missouri Basin				
# total populations	4	--	--	--
# Management units	4	--	--	--
# states	2	--	--	--
Arkansas-White-Red Basin				
# populations	19	3	3	0
# Management units	17	3	3	0
# very low MUs	--	--	0	3
# low MUs	--	3	3	0
# medium MUs	--	0	0	0
# high MUs	--	0	0	0
# states	4	2	2	0
Lower Mississippi Basin				
# populations	28	17	16	8
# Management units	20	12	11	8
# very low MUs	--	--	1	3
# low MUs	--	4	4	5
# medium MUs	--	5	4	3
# high MUs	--	3	3	0
# states	3	3	3	2
Ohio Basin				
# populations	64	6	4	3
# Management Units	61	6	4	3
# very low MUs	--	--	2	3
# low MUs	--	4	1	2
# medium MUs	--	3	3	1
# high MUs	--	1	0	0
# states	7	3	1	1

Tennessee Basin				
# populations	17	8	7	4
# Management Units	15	7	6	4
# very low MUs	--	--	1	3
# low MUs	--	4	4	4
# medium MUs	--	3	1	0
# high MUs	--	0	0	0
# states	3	3	2	2
TOTAL	**Historical**	**Current Condition**	**Future Scenario 1**	**Future Scenario 2**
# basins	6	4	4	3
# very low MUs	--	--	4	13
# low MUs	--	14	13	11
# medium MUs	--	10	8	4
# high MUs	--	14	3	0
# populations	151	35	30	15
# Management Units	136	28	24	15
# states	18	9	6	3

This SSA Report for the Pyramid Pigtoe includes:

(1) An Introduction, including taxonomy (Chapter 1);
(2) A description of the SSA Framework, including Resiliency, Redundancy, and Representation (Chapter 2);
(3) A description of Pyramid Pigtoe's ecology (Chapter 3);
(4) The resource needs of the Pyramid Pigtoe as examined at the individual, and population, and rangewide scales (Chapter 4);
(5) Characterization of the historical and current distribution, abundance, and demographic conditions of the Pyramid Pigtoe across its range (Chapter 5);
(6) An assessment of the current factors that negatively and positively influence the Pyramid Pigtoe and the degree to which the various factors influence its viability (Chapter 6);
(7) Descriptions of future scenarios, including an evaluation of those factors that may influence the species in the future at the population or rangewide scale and a synopsis of resiliency, redundancy, and representation given the potential future condition scenarios (Chapter 7);
(8) An overall synthesis of this report (Chapter 8).

CHAPTER 1 - INTRODUCTION

1.1 Purpose of SSA

The Species Status Assessment (SSA) framework (Service 2016a, entire) is an in-depth review of a species' biology and threats, an evaluation of its biological status, and an assessment of the resources and conditions needed to maintain long-term viability. The SSA report is easily updated as new information becomes available and to support all functions of the Endangered Species Program from Candidate Assessment to Listing to Consultations to Recovery. As such, the SSA report is a living document that may be used to inform decision making under the Endangered Species Act (Act).

Importantly, the SSA report is not a decisional document; rather, it provides a review of available information strictly related to the biological status of the Pyramid Pigtoe mussel (also referred to herein as "the Pyramid Pigtoe"). Any decisions regarding the legal classification of a species are made after reviewing this document and all relevant laws, regulations, and policies, and the results of a proposed decision will be announced in the *Federal Register*, with appropriate opportunities for public input.

1.2 Species Basics - Taxonomy and Evolution

The Pyramid Pigtoe belongs to a complex of four morphologically similar-looking species, which includes the Ohio Pigtoe (*Pleurobema cordatum*), Rough Pigtoe (*P. plenum*) and Round Pigtoe (*P. sintoxia*) (Figure 1-1). The Pyramid Pigtoe (*Pleurobema rubrum*; Figure 1-2) is a freshwater mussel currently found within the states of Virginia, Kentucky, Tennessee, Ohio, Arkansas, Oklahoma, Mississippi, Louisiana, and Alabama (Figure 1-3). *Pleurobema rubrum* is part of a genus that includes 23 mussel species (Williams *et al.* 2017, p. 49).

It is considered extirpated from Pennsylvania, West Virginia, Indiana, Illinois, Wisconsin, Minnesota, Iowa, Kansas, and Missouri; including the entirety of the Upper Mississippi and Missouri basins (Figure 1-3). Despite hypothesized historical occurrence in Nebraska, there is no documentation of the species from that state (Hoke, 2011, entire). For this SSA, we used information about the species historical and current range to partition Pyramid Pigtoe into geographical units (HUC 2 basins; Figure 1-4). Then, we further categorized occurrence information into management units (HUC 8, Figure 1-5).

Early molecular studies have hypothesized two distinct taxonomic units residing within current species concepts of Pyramid Pigtoe. Campbell *et al*. (2005, p. 143) included two individuals in a large phylogenetic study and showed that the Pyramid Pigtoe from the Duck River (Tennessee basin) was genetically distinct from the St. Francis River (Lower Mississippi basin). At least two additional unpublished sources have reported phylogeographic structuring between Pyramid Pigtoe from the Ouachita and St. Francis Rivers (both Lower Mississippi basin) that may represent species-level variation (Christian *et al*. 2008, p.12; Harris *et al*. 2009, p. 74).

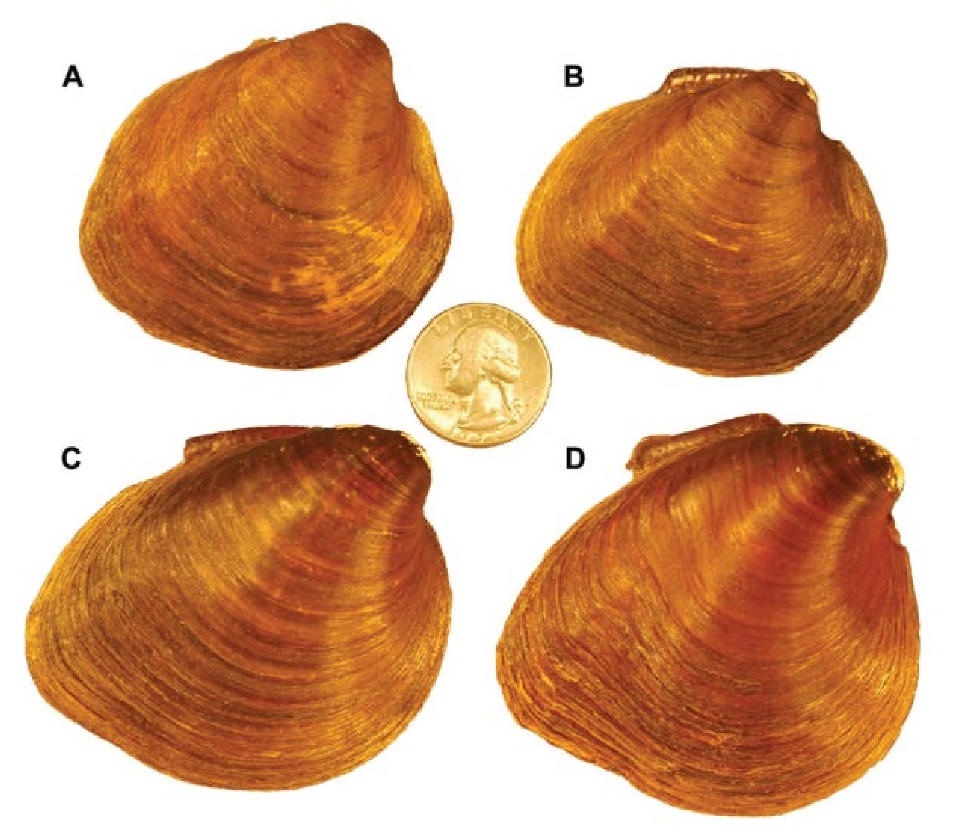

Figure 1-1. Shells (right valve shown) of the four species belonging to the Ohio Pigtoe complex: (A) Rough Pigtoe (B) Ohio Pigtoe (C) Round Pigtoe and (D) Pyramid Pigtoe. Shells and locality data are at The Ohio State University Museum and were photographed by J.W. Jones in 2006. From Jones *et al.* 2015, p. 340.

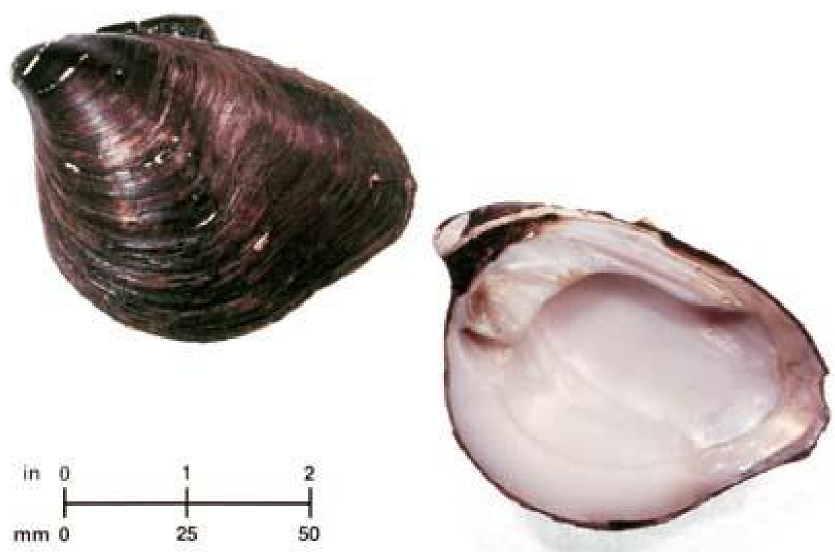

Figure 1-2. Pyramid Pigtoe, left valve upper, right valve lower. From Ostby and Beaty 2016, p. 176.

Figure 1.3. Pyramid Pigtoe range map indicating the entire Pyramid Pigtoe historical distribution, which includes the Upper Mississippi, Missouri, Lower Mississippi, Arkansas-White-Red, Ohio, and Tennessee basins (HUC 2; Service 2020b, unpublished data).

The Pyramid Pigtoe is a valid species, but there is some uncertainty regarding the phylogenetic status of populations across the basins of occurrence, specifically the populations in the western portion of its range (See additional genetics discussion in Section 3.2, below). Historical and archaeological records exist from the upper Mississippi and Missouri basins, but the phylogenetic status of those populations is unknown (Haag and Cicerello 2016, p. 199). Arkansas-White-Red and Lower Mississippi basin populations in Oklahoma, Arkansas, Louisiana, and Mississippi may represent a different or undescribed species (Campbell *et al*. 2005; Harris *et al*. 2009).

Figure 1-4. Pyramid Pigtoe range map indicating the current Pyramid Pigtoe distribution, which includes the Lower Mississippi, Arkansas-White-Red, Ohio, Cumberland, and Tennessee River basins. The species is considered extirpated from the Upper Mississippi and Missouri basins (Source: Service 2020b, unpublished data).

1.2.1 Taxonomy

The Pyramid Pigtoe mussel belongs to the family Unionidae, also known as the naiads and freshwater pearly mussels. This group of bivalves has existed for over 400 million years, and includes over 600 species worldwide and over 250 species in North America (Strayer *et al.* 2004, p. 429; Lopes-Lima *et al.* 2018, p. 3). This report follows the accepted taxonomic treatment of North American freshwater mussels as provided by Williams *et al.* (2017, entire). The Pyramid Pigtoe (*Pleurobema rubrum*) was originally described from the Kentucky River in 1820 by Constantine Rafinesque as *Obliquaria rubra* Rafinesque 1820 (p. 314).

The currently accepted classification is (Integrated Taxonomic Information System, 2017):

- Phylum: Mollusca
- Class: Bivalvia
- Order: Unionoida
- Family: Unionidae
- Subfamily: Ambleminae
- Tribe: Pleurobemini
- Genus: *Pleurobema*
- Species: *rubrum*

Due to a widespread distribution, variability in shell shape and size throughout its range, and similarity in morphological characters to other closely-related species (Figure 1.1), *Pleurobema rubrum* has undergone several scientific name changes since its original description in 1820. The synonomy is also complicated due to misidentifications (Roe, 2002, p. 4; Watters *et al*. 2009, p. 233). Additionally, based on shell characters alone, it has been periodically considered a subspecies of the Ohio Pigtoe (*P. cordatum*) (Ortmann 1911, p. 331). The previously accepted scientific name was *Pleurobema pyramidatum*, which is referenced in many older scientific publications, reports, and museum collections (Stansbery 1970, p. 13; Williams *et al*. 1993, p. 13). However, *Pleurobema rubrum* is currently the accepted scientific name used to recognize the Pyramid Pigtoe (Williams *et al.* 2017, p. 42), and should be the only scientific name used by the U.S. Fish and Wildlife Service (Service).

1.3 Petition History

We, the Service, were petitioned by the Center for Biological Diversity (CBD), Alabama Rivers Alliance, Clinch Coalition, Dogwood Alliance, Gulf Restoration Network, Tennessee Forests Council, and West Virginia Highlands Conservancy, to list the Pyramid Pigtoe as an endangered or threatened species under the Endangered Species Act of 1973, as amended (Act). This petition was part of a 2010 petition to list 404 aquatic, riparian, and wetland species in the southeastern United States (CBD 2010, pp. 538–540). On September 27, 2011, we found that the petition presented substantial scientific or commercial information indicating that listing the Pyramid Pigtoe may be warranted (76 FR 59836 59862); substantial findings were made for the other species in this same *Federal Register* notice, although analyses and findings for those other species are addressed separately.

While the Service was petitioned to list the Pyramid Pigtoe, at some point the use of the name Pink Pigtoe was incorporated into workplans and internal documents instead. The Pink Pigtoe was used by the Service in 1989 to refer to the species as a candidate for federal listing, but it was withdrawn due to taxonomic uncertainty (Service, 1989, 50 CFR 17 (4)). The species was previously referred to as the Pink Pigtoe likely due to the pink shell nacre observed in some specimens, it also typically displays a reddish-brown periostracum (Watters *et al*. 2009, p. 233). However, nacre or periostracum color alone are not a reliable characters for species level identification, and use of Pink Pigtoe as a common name is currently invalid.

Since the Pink Pigtoe is not a valid or officially recognized common name it will not be used in this document and should not be used in Service publications associated with this species. Both the Pink and Pyramid common names refer to *Pleurobema rubrum*, but the published and currently accepted common name is the Pyramid Pigtoe (Williams *et al*. 2017, p. 42), which will be used exclusively in this SSA.

1.4 State Listing Status

Of the states where the Pyramid Pigtoe is known to currently occur, it is state-listed as of conservation concern all states (Table 1-1). While some state listings provides state statutory language against taking or possession of the species, many are mandates through the state wildlife agencies and lack regulatory protection. Permits may be obtained for taking or possession of Pyramid Pigtoe for zoological, educational, or scientific purposes, or for propagation in captivity to preserve the species. All states have wildlife management agency protective regulatory measures for freshwater mussels prohibiting the take or possession of freshwater mussels without a scientific collector's permit.

The states of Arkansas, Alabama, Tennessee, and Kentucky have mussel harvest sanctuaries, or designated reaches of rivers where it is unlawful to take, catch, or kill freshwater mussels, and the degradation of aquatic habitat is prohibited. These sanctuaries provide some indirect protection to the Pyramid Pigtoe in these states, but since commercial harvest is no longer considered a primary threat to the species, in part due to its rarity, the actual protection is limited. The Pyramid Pigtoe is a species of conservation concern in these states, making it unlawful for anyone to take, possess, transport, export, process, sell or offer for sale or ship, and for any contract carrier to knowingly transport or receive for shipment Pyramid Pigtoe mussels.

Table 1-1. State and NatureServe conservation status of Pyramid Pigtoe mussel throughout its entire documented range.

State Status	AL	IL	IN	KY	MO	MN	WI	OH	PA	TN	VA	WV	AR	OK	MS	IA	LA	KS
State Rank (Wildlife Action Plans) 2015	P1	X	E	S1	X	NR	NR	E	X	T	Tier 2	NR	S2	S2	E	SNR	S2	NR
NatureServe (as of 2009)	S1	SX	SX	S1	SNR	NR	NR	S1	SH	S1 S2	SH	NR	S2	SNR	S2	SX	S2	SNR

KEY: E = endangered; P1 = highest conservation concern; NR = not recognized; T = threatened; X = extirpated; Tier 2 = Very High Conservation Need; SX = Presumed Extirpated; SH = Possibly Extirpated; S1 = Critically Imperiled; S2 = Imperiled; S3 = Vulnerable; SNR = Not Ranked/Under Review

CHAPTER 2 - METHODOLOGY AND DATA

2.1 SSA Framework

This report is a summary of the SSA analysis, which entails three iterative assessment stages: species (resource) needs, current species condition, and future species condition (Figure 2-1).

2.1.1 Species Needs

The SSA includes a compilation of the best available biological information on the species and its ecological needs at the individual, population, and rangewide levels based on how environmental factors are understood to act on the species and its habitat.

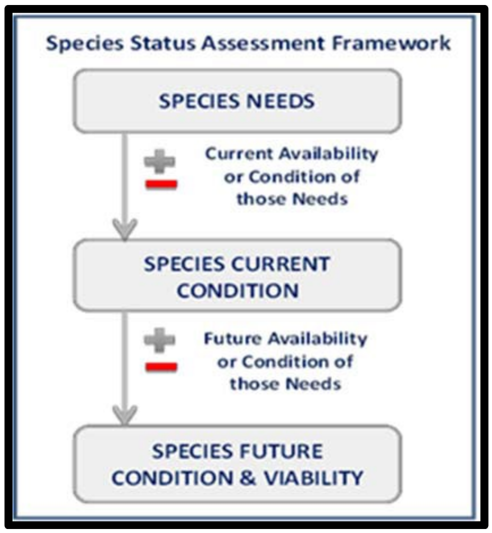

Figure 2-1. The three analysis steps in a Species Status Assessment.

- Individual level: These resource needs are those life history characteristics that influence the successful completion of each life stage. In other words, these are survival and reproduction needs that make the species sensitive or resilient to particular natural or anthropogenic influences.

- Population level: These components of the Pyramid Pigtoe's life history profile describe the resources, circumstances, and demographics that most influence **resiliency** of the populations.

- Rangewide level: This is an exploration of what influences **redundancy** and **representation** for the Pyramid Pigtoe. This requires an examination of the mussel's evolutionary history and historical distribution to understand how the species functions across its range.

To assess the biological status of the Pyramid Pigtoe across its range, we used the best available information, including peer-reviewed scientific literature, academic reports, museum data, and survey data provided by state and Federal agencies. State malacologists were an invaluable source of information. Additionally, we consulted with several species experts who provided important information and comments on Pyramid Pigtoe distribution, life history, and habitat. We researched and evaluated the best available scientific and commercial information on the Pyramid Pigtoe's life history. To identify population-level needs, we used published literature, unpublished reports, information from consultants, and data from current agency survey and taxonomic research projects.

To date, no specific life history study has been conducted on the Pyramid Pigtoe. Arnold E. Ortmann published some information on Pyramid Pigtoe internal anatomy and timing of reproduction as part of comprehensive studies of regional mussel faunas in the early 1900s (Ortmann 1909a; 1912; 1913; 1919; 1921). Some life history information, such as host fish suitability, on the species was reported recently in Culp *et al*. (2009, p. 20). Where applicable, such maximum age estimates, surrogate life history information was also used from the closely related Ohio Pigtoe (*Pleurobema cordatum*) and Round Pigtoe (*P. sintoxia*). The Ohio Pigtoe and Round Pigtoe are sympatric (i.e., joint occurrence of species) with the Pyramid Pigtoe in rivers throughout its range.

2.1.2 Current Species Condition

The SSA describes the current known condition of the Pyramid Pigtoe's habitat and demographics, and the probable explanations for past and ongoing changes in abundance and distribution within areas representative of the geographic, genetic, or life history variation across the species range. Due to substantial range reduction through the loss of so many populations across 9 states, and the similar appearance of closely related species, it is difficult to fully understand the historical distribution of the species. Only museum specimens are available for currently extirpated populations, and field identifications without voucher or museum specimens are questionable because of overlapping distributions of morphologically similar species with the Pyramid Pigtoe (see Figure 1.1).

We considered the Pyramid Pigtoe's distribution, abundance, and factors currently influencing the viability of the species. We identified known historical and current distribution and abundance, and examined factors that negatively and positively influence the species. Scale, intensity, and duration of threats were considered for their impacts on the populations, MUs, basins, and habitat across all life history stages. The magnitude and scale of potential impacts to the Pyramid Pigtoe or its habitat by a given threat are qualitatively described using a High/Moderate/Low category scale.

How Populations Were Evaluated For Current Conditions

For the current condition analyses, the Pyramid Pigtoe was considered extant if a live individual or fresh dead specimen was collected since 2000[1]. Given the longevity of the genus

[1] We used the year 2000 in this analysis for consistency, due to the longevity of the species, highly variable recent survey information across the range of the Pyramid Pigtoe, and available state heritage databases and information support for the likelihood of the species continued presence within this timeframe.

Pleurobema, and the timing and frequency of mussel surveys conducted throughout the species' range, collections or observations of live individuals or fresh dead specimens since 2000 likely indicates the continued presence of the species within a river or stream (Stodola *et al.* 2014, p. 1). For large water bodies such as the Tennessee River, or for rivers that have not received consistent survey effort, it is difficult to determine whether a recent lack of occurrence reflects a lack of sampling or a decline in abundance or distribution (Haag and Cicerello 2016, pp. 65–66). Given the rarity and low detection rates of the Pyramid Pigtoe in most populations, trends are difficult to ascertain.

Presumed extirpation was determined by documentation in literature, reports, or from communications with state malacologists and aquatic biologists. General reference texts on regional freshwater mussel faunas such as Haag and Cicerello (2016), Harris *et al*. (2009), Jones *et al*. (2019), Williams *et al.* (2008), Watters *et al.* (2009), Parmalee and Bogan (1998), and Gordon and Layzer (1989) provided substantial information on species distribution.

There is no systematic sampling regime to monitor the Pyramid Pigtoe's distribution and status across its range. We gathered information from a large body of published and unpublished survey work rangewide since the early 1900s (Appendix C). More recent published and unpublished distribution and status information was provided by biologists from Department of Natural Resources (DNR) and State Natural Heritage Programs (NHP), other state and Federal agencies, academia, and museums; all information was compiled into an excel database for reference. Occurrence data were grouped by named river, county, and state, then organized by 8-digit hydrologic unit code watershed (HUC 8)[2]. All records were also added to a Geographic Information System (GIS) database to facilitate spatial analyses. Additional detail on the current condition analysis methodology is presented in Chapter 5.

Defining Management Units

The smallest measure of the Pyramid Pigtoe occurrence is at the river reach, which varies in length and width. Occasional or regular interaction among individuals in different reaches not interrupted by a barrier likely occurs. Unfortunately, all rivers of current occurrence are either fragmented by a barrier and/or affected in some way by impoundments. In general, species occurrence is strongly influenced by habitat fragmentation and distance between occupied river or stream reaches or mussel beds (appropriate habitat patches containing concentrations of one or more species of mussels).

Once released from their fish host, freshwater mussels are benthic, generally sedentary aquatic organisms and closely associated with appropriate habitat patches within a river. Available data

[2] Hydrologic unit codes (HUC) are two to twelve-digit codes based on the four levels of classification in a hydrologic unit system, as described in Seaber *et al.* 1987 and USGS (2018). In summary, the United States is divided into successively smaller hydrologic units arranged or nested within each other. Each successively smaller hydrologic unit/code contains successively smaller drainage areas, river reaches, tributaries, etc. HUC 8 is the fourth-level (cataloguing unit) that maps the subbasin level, which is analogous to medium-sized river systems across the U.S.

were organized by named river that was subsequently used as the unit to delineate an individual population. All populations of documented occurrence of the Pyramid Pigtoe, past and present, are located in Appendices A, B, & C.

The HUC 8 watershed is termed a Management Unit (MU) in this report. The Pyramid Pigtoe current range includes 28 MUs, all of which are fragmented by large or small dams within or adjacent to their respective MUs. For example, in the Green and Tennessee Rivers, there are occurrence records in three different MUs each, and all have the presence of dams, which fragment mussel beds and the habitats that support them.
Management units (MU) were defined as a HUC 8, which were identified as most appropriate for assessing population-level resiliency. Range-wide species occurrence data were used to create maps indicating the historical and current distribution of Pyramid Pigtoe among management units for each of 35 populations and 28 MUs currently known to be extant. Given the large historical range of the species, using management units at this HUC 8 scale allowed rivers such as the Ouachita, Saline, Green, Duck, and Tennessee to be summarized into smaller, more manageable areas for analysis and discussion. The HUC 8 - management unit approach has also been used for other wide-ranging aquatic species for the purposes of an SSA (e.g., the Longsolid, Round Hickorynut, and Purple Lilliput (Service 2018, 2019, 2020a, entire).

All rivers of current occurrence all have been comparatively well surveyed for freshwater mussels, in part, due to the presence of other federally listed species and historical abundances of mussels. The Muskingum, Green, Barren, Cumberland, Holston, White, Ouachita, and Clinch Rivers formerly supported large mussel beds with abundances dense enough for commercial harvest activities, but all commercial harvest is currently restricted in these rivers. The Tennessee River, specifically Wheeler, Pickwick, and Kentucky reservoirs, allow commercial mussel harvest. Additionally, Wheeler Reservoir (Wheeler Lake MU) on the Tennessee River was subject to intensive mussel harvest from 1947-1992 that has since subsided (Ahlstedt and McDonough 1992, p. 21; see section 5.1).

2.1.3 Future Species Condition

The SSA forecasts a species' response to probable future scenarios of environmental conditions and conservation efforts. As a result, the SSA characterizes the species' ability to sustain populations in the wild over time (viability) based on the best scientific understanding of current and future abundance and distribution within the species habitat.

To examine the potential future condition of the Pyramid Pigtoe, we developed two future scenarios that focus on a range of conditions based on projections for habitat degradation or loss, invasive or non-native species, harvest and overutilization, and small population size; beneficial conservation actions, such as dam removals, were also considered. The range of what may happen in each scenario is described based on the current condition and how resilience, representation, and redundancy may change.

We chose a time frame of 20 to 30 years for our analysis based on the estimated maximum age of the species, availability of trend information, planning documents, and climate modeling that helps inform future conditions, as well as the estimated maximum age of the species. The scenarios consider the most probable threats with the potential to influence the species at the population or rangewide scales, based on our understanding of the adaptive capacity of the Pyramid Pigtoe, including potential cumulative impacts if applicable.

For this assessment, we define viability as the ability of the Pyramid Pigtoe to sustain resilient populations in the wild over time. Adaptive potential and population genomic data rangewide are lacking for the Pyramid Pigtoe, but given the estimated maximum age (30 years), we can make estimates of the predicted response to known environmental stressors within timeframes relevant to extinction risk for the species (Funk *et al*. 2019, p. 117). Using the SSA framework (Figure 2-1, above), we consider what the species needs to maintain viability by characterizing the status of the species in terms of its resiliency, redundancy, and representation (Service 2016, entire; Wolf *et al.* 2015, entire).

- ***Resiliency*** is assessed at the level of populations (and MUs) and reflects a species' ability to withstand stochastic events (events arising from random factors). Demographic measures that reflect population health, such as fecundity, survival, and population size, are the metrics used to evaluate resiliency. Resilient populations are better able to withstand disturbances such as random fluctuations in reproductive rates and fecundity (demographic stochasticity), variations in rainfall (environmental stochasticity), and the effects of anthropogenic activities.

- ***Representation*** is assessed at the species level and characterizes the ability of a species to adapt to changing environmental conditions. Metrics that speak to a species' adaptive potential, such as genetic and ecological variability, can be used to assess representation. Representation is directly correlated to a species' ability to adapt to changes (natural or human-caused) in its environment.

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

To evaluate the current and future viability of the Pyramid Pigtoe, we assessed a range of conditions to characterize the species' resiliency, representation, and redundancy. Throughout this analysis, when data were lacking for the Pyramid Pigtoe, we used information from closely related mussel species, such as the Ohio Pigtoe (*Pleurobema cordatum*), and Round Pigtoe (*P. sintoxia*). The Ohio Pigtoe and Round Pigtoe are sympatric with the Pyramid Pigtoe in large portions of its range.

CHAPTER 3 - SPECIES BACKGROUND AND ECOLOGY

3.1 Physical Description

Mollusks are mostly aquatic, and are named from the Latin *molluscus*, meaning "soft." Their soft bodies are often enclosed in a hard shell made of calcium carbonate ($CaCO_3$), which functions as an exoskeleton. This shell is secreted by a thin sheet of tissue called mantle, which encloses the internal organs within the mantle cavity (Figure 3-1). Some soft anatomy information on Pyramid Pigtoe is available from Ortmann (1911, p. 330), who stated that only the outer gills are utilized for brooding eggs.

Pyramid Pigtoe adult mussels are reddish to chestnut brown in color with a smooth periostracum, but darken with age (Watters *et al*. 2009, p. 233). Juveniles may have green rays that typically disappear with age. The shell is thick, triangular, and medium-sized (up to 3.6 inches (in) (91 millimeters (mm)) (Williams *et al.* 2009, p. 564). It has a shallow sulcus and high anteriorly directed umbo, with a beak that is elevated above the hinge line (Stansbery 1967, p. 3). The beak cavity of the Pyramid Pigtoe is deep, the hinge teeth are heavy, and the pseudocardinal teeth are thick and low, and near the umbo (Williams *et al*. 2008, p. 564). The species is not considered to be sexually dimorphic.

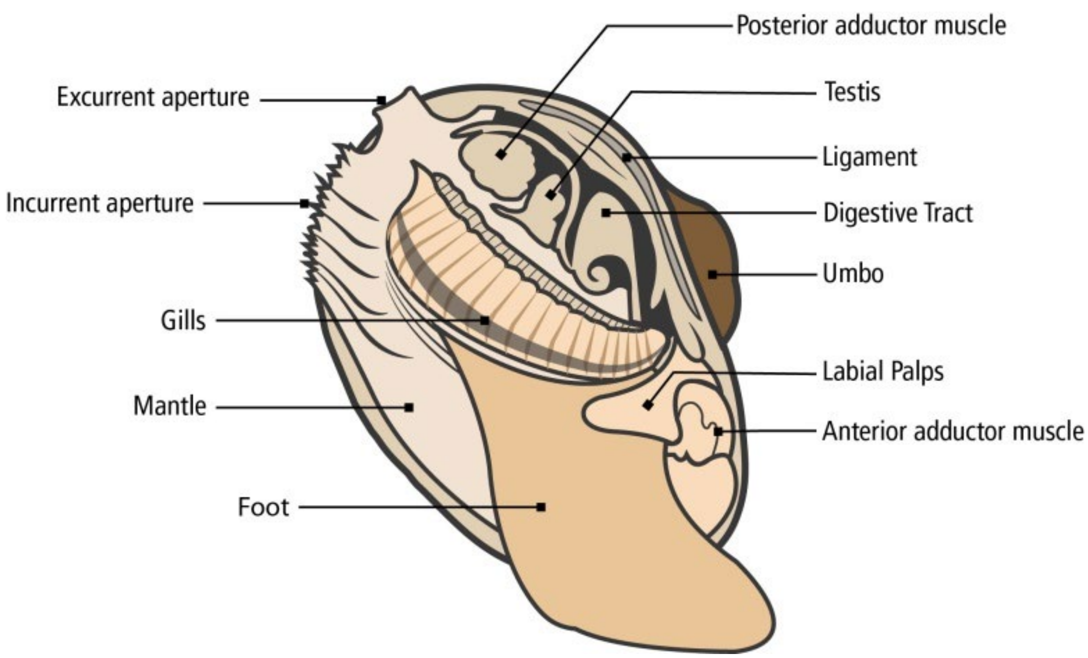

Figure 3-1. Generalized internal anatomy of a freshwater mussel (Image courtesy of Matthew Patterson, Service).

3.2 Genetics

Species identification of members of the tribe Pleurobemini is among the most challenging in freshwater mussels due to morphological convergence and phenotypic plasticity, particularly when similar species are sympatric or syntopic (Ortmann 1920, p. 272; Shea *et al*. 2011, p. 448; Inoue *et al*. 2018, p. 689). Recent molecular studies have been integral in resolving taxonomic uncertainty in *Pleurobema* yet questions remain regarding the validity and entire distribution of Pyramid Pigtoe. Early molecular studies hypothesized two distinct taxonomic units residing within current concepts of Pyramid Pigtoe.

Only two Pyramid Pigtoe individuals were included in a study investigating phylogenetic relationships using mtDNA, and analyses showed that Pyramid Pigtoe sampled from the Duck River, Tennessee, was genetically distinct from the St. Francis River, Arkansas (Campbell *et al*. 2005, p. 143). These same data were included in subsequent phylogenetic studies focused on *Fusconaia* (Burdick and White 2007, p. 372) and *Pleurobema* (Campbell *et al*. 2008, p. 714; Campbell and Lydeard 2012b, p. 27) with similar results.

At least two studies have reported phylogeographic structuring between Pyramid Pigtoe from the Ouachita and St. Francis drainages in Arkansas that may represent species-level variation (Christian *et al*. 2008, p. 9; Harris *et al*. 2009, p. 74). A recently published molecular study, however, which included all previously published and newly generated data representing a broad sampling across Pleurobemini, revealed that Pyramid Pigtoe and Round Pigtoe may represent a single species (Inoue *et al*. 2018, p. 694). The Inoue *et al.* (2018) study is the most comprehensive published study to date on the Round and Pyramid Pigtoe and in that study, 2 out of 3 species delineation models indicated one lineage present in specimens identified as Round Pigtoe and Pyramid Pigtoe. One model indicated there might be two lineages present, but no data was presented that would suggest those lineages correspond to shell morphology.

Support for recognition of the Pyramid Pigtoe as a singular species is maintained by the scientific community at large (Williams *et al.* 2017, p. 39; Graf and Cummings, 2021). To our knowledge, there are no comprehensive studies that thoroughly address intraspecific divergence in genetic diversity throughout the range of Pyramid Pigtoe. A molecular systematics study was recently initiated by Dr. Nathan Johnson (USGS) to resolve taxonomic uncertainty for Pyramid Pigtoe. The collection of specimens throughout the geographic range of both Pyramid Pigtoe and Round Pigtoe, as well as the Ohio Pigtoe, was coordinated with state agencies and regional experts to ensure individuals representing the range of morphological variation across both species were included for evaluation.

This study methods include DNA extractions and initial identifications using mitochondrial loci before utilizing next-generation sequencing methods. DNA quality for a subset of specimens, specifically those from museum collections, is poor and may ultimately be insufficient for molecular analyses. Examining genetic relationships using specimens from locations where both the Round and Pyramid Pigtoe are sympatric, or in our case, syntopic, is ideal for testing species boundaries. However, the study is incomplete, and results are not available for inclusion in this SSA.

3.3 Life History

Little information is known or available on the life history of the Pyramid Pigtoe across its range. Some internal anatomy information is available in Ortmann (1911 and 1912, entire).
Additionally, some information was gathered as part of a fish host study conducted by Culp *et al*

(2006 & 2009, entire) with specimens from the Green River, KY (see section 3.4, below). An age and growth study using shell material from the Holston River, TN was later conducted by Slater (2018, entire). For other aspects of life history, we rely on the best available scientific and commercial information for other closely related species to help summarize life history characteristics of the Pyramid Pigtoe.

Using relic shell material (n = 29) from two sites (McBee Island, lower site [1], Surgeonsville, upper site [2]) on the Holston River, Tennessee, the estimated the yearly growth rate of Pyramid Pigtoe was 0.1 to 2.3 mm, with the most growth in the warmer months of the year (Slater 2018, p. 35). Also, the Pyramid Pigtoe relic shells collected appeared to be overall younger in age compared to other mussel species studied (Slater 2018, p. 50).

Slater (2018, p. 101) developed log-averaged growth curves for Pyramid Pigtoe using shell material at these two sites, which indicates an obvious decrease in growth at Surgeonsville, the upper site (2), before age five (Figure 3-2). The difference between the upper and lower sites was unexplained, but the decrease growth from the upper Surgeonsville site (2) is potentially due to its' closer proximity to Cherokee Dam, a hydropower dam operated by TVA at Holston RM 52.3. Suppressed mussel growth and reproduction as the result of persistent cold, hypolimnetic discharges and large fluctuations in flows and river depth has devastated the Holston River mussel fauna, and likely contributed to decline of the Pyramid Pigtoe (Parmalee and Faust 2006, p. 74; see Sections 4.1.2 & 6.1.5).

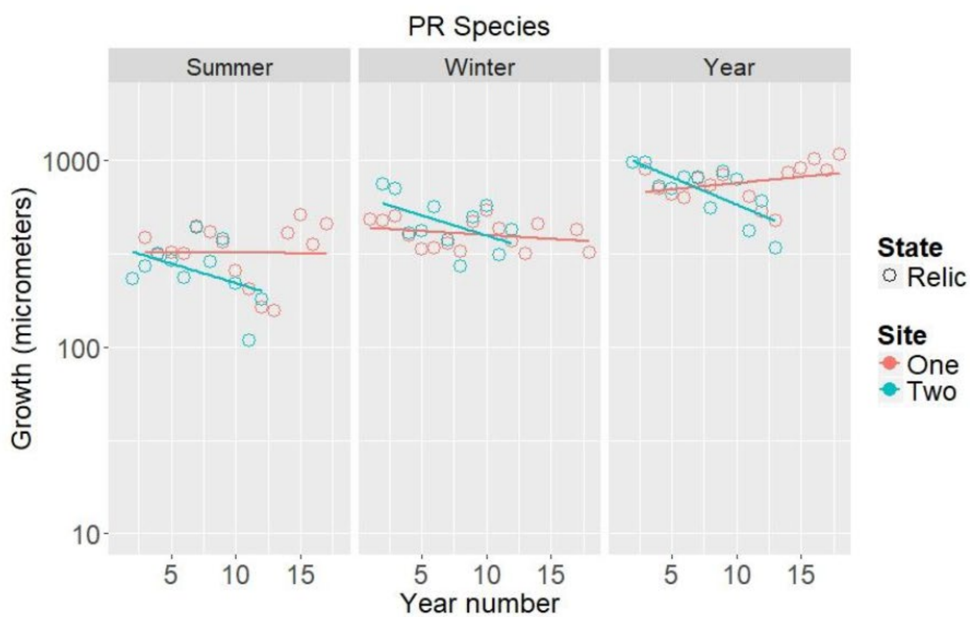

Figure 3-2. Pyramid Pigtoe growth regression from two sites on the Holston River, TN.

There are no studies on the average life expectancy of the Pyramid Pigtoe. Based on aging shells, the closely related Ohio Pigtoe was found to live at least 18 years (Yokley 1972, p. 351). Maximum age estimates for the closely related Round Pigtoe based on thin-sectioning of shells are 30 years, with some species of *Pleurobema* living up to 45 years (Haag and Rypel 2011, p. 230). At this time, the best available information suggests that the Pyramid Pigtoe is a relatively long-lived species averaging 20 to 30 years (Slater 2018, p. 35; Watters *et al*. 2009, p. 299). Given the longevity of closely related species, it possibly lives up to 40-45 years in some locations (Ostby 2016, p. 117).

Variation in mussel longevity and growth is likely related to site-specific factors and response to changes in environmental conditions such as water quality and habitat conditions present at a given location (Haag and Rypel 2011, p. 243). As expected, the growth rate slows as individuals age. Depending on water quality and other environmental conditions, negative growth is possible, or could even be expected as the individuals age and their shells erode. Annual growth of the Pyramid Pigtoe is likely similar to growth rates of other freshwater mussels (Haag and Rypel 2011, p. 248).

The Pyramid Pigtoe exhibits a preference for sand and gravel in rivers, but also may be found in coarse sand in larger rivers (Gordon and Layzer 1989, p. 31). They can be found at depths less than 3 ft (1 m), but in large rivers can be commonly found at depths of 13 to 20 ft or greater (4 to 6+ m) (Parmalee and Bogan 1998, p. 193; Williams *et al*. 2009, p. 566). Adult freshwater mussels within the genus *Pleurobema* are suspension-feeders that filter water and nutrients to eat. Mussels may shift to deposit feeding, though reasons for this are poorly known and may depend on flow conditions or temperature. Ciliary tracks on the adult foot apparently facilitate this feeding behavior. Their diet consists of a mixture of algae, bacteria, detritus, and microscopic animals (Gatenby *et al.* 1996, p. 606; Strayer *et al.* 2004, p. 430). It has also been surmised that dissolved organic matter may be significant source of nutrition (Strayer *et al.* 2004, p. 431).

Such an array of foods, containing essential long-chain fatty acids, sterols, amino acids, and other biochemical compounds, may be necessary to supply total nutritional needs (Strayer *et al.* 2004, p. 431). For their first several months, juvenile mussels ingest food through their foot and are thus deposit feeders, although they may also filter interstitial pore water and soft sediments (Yeager *et al.* 1994, p. 221; Haag 2012, p. 26). Due to the mechanism by which food and nutrients are taken in, freshwater mussels collect and absorb toxins (see section 6.1.2, below). Additionally, there is evidence that emphasizes the importance to riverine mussels of the uptake and assimilation of detritus and bacteria over that of algae (Nichols and Garling 2000, p. 881).

3.4 Reproduction

The Pyramid Pigtoe has a complex life cycle (see Figure 3-2) that relies on fish hosts for successful reproduction, similar to other mussels. In general, mussels are either male or female, but differences between sexes in shell shape are subtle (Haag 2012, p. 54). Males release sperm into the water column, which is taken in by the female through the incurrent aperture, where water enters the mantle cavity. The sperm fertilize eggs in the suprabranchial chamber (located above the gills) as ova are passed from the gonad to the marsupia (Yokley 1972, p. 357). The developing larvae remain in the gill chamber until they mature (called glochidia) and are ready for release.

The Pyramid Pigtoe is a short-term brooder, typically gravid from May-July (Gordon and Layzer 1989, p. 50). Host fish species are minnows of the family Cyprinidae and genera *Cyprinella,* *Erimystax, Lythrurus, and Notropis* (Culp *et al*. 2009, p. 19). Similar to other species in the Pleurobemini, the Pyramid Pigtoe targets drift-feeding minnow species by releasing glochidia contained in packets called conglutinates (Haag 2012, p. 163). Following release from the female mussel, the semi-buoyant conglutinates drift in the water column where they are targeted by sight-feeding minnows (Culp *et al*, 2009, p. 21).

In a life history study of the Ohio Pigtoe, Yokley (1972, p. 359) describe glochidia in this group as small and hookless. The glochidia snap shut in contact with fish and attach to the gills, head, or fins (Vaughn and Taylor 1999, p. 913). For most mussels, the glochidia will die if they do not attach to a fish within a short period. Once on the fish, the glochidia are engulfed by tissue from the host fish that forms a cyst. The cyst protects the glochidia and aids in their maturation. The larvae draw nutrients from the fish and develop into juvenile mussels, weeks to months after initial attachment.

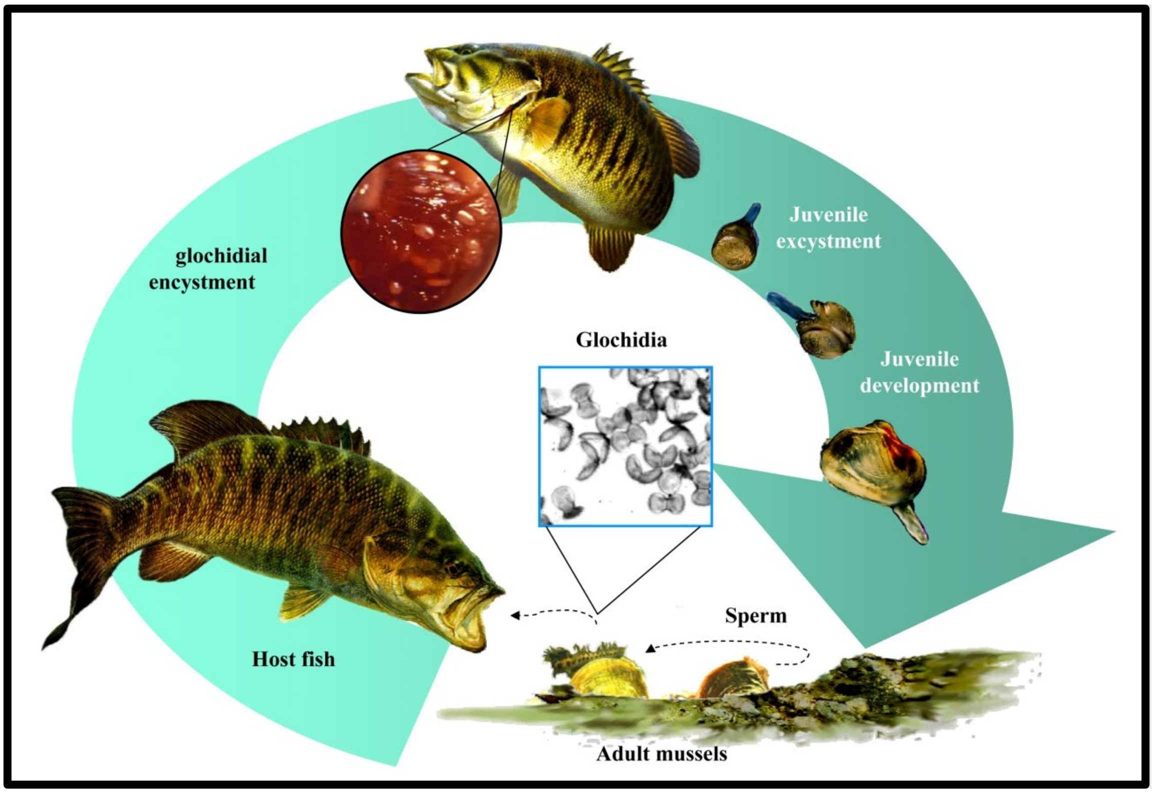

Figure 3-3. Generalized freshwater mussel life cycle. Freshwater mussels such as the Pyramid Pigtoe have a complex life history involving an obligate parasitic larval life stage, called glochidia, which are wholly dependent on host fish. (Image courtesy Shane Hanlon, Service).

Age and size affect fecundity, and length is positively related to fecundity in other mussels (Haag and Staton 2003, p. 2,118). Localized habitat and environmental conditions are also a factor in fecundity of individuals (Moles and Layzer 2008, p. 220). Only a few glochidia reach the free-living juvenile stage, and mortality rates for the glochidial stage have been estimated at 99 percent, making this a critical phase in the life history of freshwater mussels (Jansen *et al.* 2001, p. 211).

The best available life history information specifically on the Pyramid Pigtoe is from Culp *et al*. (2009, entire), who conducted host fish studies in captivity using specimens collected from the Green River, Kentucky. A single female, 79 mm in length, was observed releasing conglutinates in June when water temperature was 22.5 C. This female released approximately 50 white conglutinates (15–20 mm long and about 5 mm wide), which contained few glochidia (10 were measured: mean length = 162 µm, mean height = 173 µm), and consisted mostly of unfertilized eggs. All conglutinates released combined totaled an estimated 2500 glochidia. After 12–15 days, transformation of glochidia to juveniles occurred on four fish species from the family Cyprinidae: Spotfin Shiner (*Cyprinella spiloptera*), Streamline Chub (*Erimystax dissimilis*), Scarlet Shiner (*Lythrurus fasciolaris*), and Silver Shiner (*Notropis photogenis*) (Culp *et al*. 2009, p. 19).

CHAPTER 4 - RESOURCE NEEDS

As discussed in Chapter 3, the Pyramid Pigtoe has a multi-staged life cycle: fertilized eggs to glochidia to juveniles to adults. The life cycle represents several stages that have specific requirements (resource needs) that must be met (Table 4-1) for the mussel to progress to the next stage.

Table 4-1. Requirements for each life stage of the Pyramid Pigtoe mussel.

Life stage	Resource Needs – Habitat Requirements[3]	Source

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).
	1. Natural, unaltered ambient water temperature generally < 27ºC
	2. D.O. > 3 mg/L
	3. Low salinity/total dissolved solids
	4. Low nutrient concentrations
	  1. TAN < 0.3 – 1.0 at pH 8.0 & 25ºC
	  2. NO_3 < 2.0 mg/L
	  3. NO_2 < 55.8 mg/L
	5. Low concentrations of metals
	  1. Cd < 0.014 mg/L at 50 mg/L $CaCO_3$ hardness
	  2. Zn < 0.120 mg/L at 50 mg/L $CaCO_3$ hardness
	  3. Pb < 0.205 mg/L at 50 mg/L $CaCO_3$ hardness
	  4. Cu < 0.005 mg/L in moderately hard water
		Allen *et al*. 2007, pp. 80 – 85;
		Augspurger *et al*. 2003, p. 2569;
		Bringolf *et al* 2007a, p. 2094;
		Bringolf *et al* 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.

All Life Stages	**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**	1. Sexually mature males and females with appropriate water temperatures for spawning, fertilization, and brooding. 2. Presence of fish hosts (of appropriate species) with sufficient flow to allow attachment, encystment, relocation, excystment, and dispersal of glochidia. 3. 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)	1. Stable substrate comprised of mixed sand, gravel and cobble, and appropriate for burrowing, pedal feeding, and survival. 2. Appropriate food sources (phytoplankton, zooplankton, protozoans, detritus, dissolved organic matter) in adequate supply 3. Presence and abundance of fish hosts available for recruitment 4. 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. 8-19, 33.

[3] These resource needs are common among North American freshwater mussels; however, due to lack of species-specific research, parameters specific to Pyramid Pigtoe are unavailable.

4.1 Individual-level Resource Needs

In the following subsections, we outline the resource needs of individuals including physical habitat and diet.

4.1.1 Clean, Flowing Water

Pyramid Pigtoe habitat is in rivers with natural flow regimes. While mussels can survive seasonally low flows and (random) short-term, periodic drying events, intermittent stream habitats generally cannot support mussel populations. Because a lotic (i.e., flowing water) environment is a critical need, perturbations that disrupt natural flow patterns (e.g., dams) have a negative influence on Pyramid Pigtoe and host fish resilience. Pyramid Pigtoe habitat must have adequate flow to deliver oxygen, enable passive reproduction, and deliver food to filter-feeding mussels (see Table 4-1, above).

Further, flowing water removes contaminants and fine sediments from interstitial spaces preventing mussel suffocation. Mussels may also shift to deposit feeding, underlying the importance of clean-swept substrates and interstitial spaces. Stream velocity is not static over time, and variations may be attributed to seasonal changes (with higher flows in winter/spring and lower flows in summer/fall), extreme weather events (e.g., drought or floods), or anthropogenic influence (e.g., flow regulation via impoundments). The Pyramid Pigtoe relies on sight-feeding fishes as part of its life cycle; therefore, turbidity during critical reproductive periods may impact glochidial attachment and ultimately decrease recruitment in any given population (McLeod *et al*. 2017, p. 348).

While mussels have evolved in habitats that experience seasonal fluctuations in discharge, global weather patterns can have an impact on the normal regimes (e.g., El Niño or La Niña). Even during naturally occurring low flow events, mussels can become stressed because either they exert significant energy to move to deeper waters or vertically in the substrate, if not, they may succumb to desiccation (Haag 2012, p. 109). Localized droughts during the late summer and early fall may be especially stress-inducing because rivers are already at their naturally occurring lowest flow rate during this time, and the post spawning season is when juvenile development is imperative. Conversely, prolonged or sustained flooding can result in dislocation of mussels that are unable to burrow completely and isolation when water levels recede (Hastie *et al*. 2001, p. 111). Areas of high shear stress and scour do not support stable substrates and affect juvenile and adult mussel settlement and occupation (Layzer and Madison 1995, p. 329).

4.1.2 Appropriate Water Quality and Temperatures

Freshwater mussels, as a group, are particularly sensitive to changes in water quality, including (but not limited to): dissolved oxygen (generally below 2-3 parts per million (ppm)), salinity (generally above 2-4 ppm), ammonia (generally above 0.5 ppm total ammonia-nitrogen (TAN)), elevated temperature (generally above 86 °Fahrenheit (°F) (30 °Celsius (°C)), excessive total suspended solids (TSS), and other pollutants (see discussion in Chapter 6). Habitats with appropriate levels of these parameters are considered suitable, while those habitats with levels outside of the appropriate ranges are considered less than suitable.

Appropriate water temperature thresholds for the Pyramid Pigtoe are unknown; thus, we must rely on the best available information for other mussel species, which primarily focuses on temperatures necessary for reproduction. A fish host study of the Pyramid Pigtoe from the Green River suggests that glochidia are released at 22-23 °C (Culp *et al*. 2009, p. 19). These temperature ranges are reasonable estimates of required thermal regimes for this species during their reproductive cycle. These temperature ranges are also similar to those reported for another member of the Pleurobemini, the Atlantic Pigtoe (*Fusconaia masoni*) (Service 2017, p. 7).

Cold water discharges from hydropower dams alter temperature regimes downstream, and result in water temperatures that are consistently below 20 °C throughout the year (Heinricher and Layzer 1999, p. 141). Thus, populations of Pyramid Pigtoe surviving under these circumstances (e.g. Cumberland River, Holston River) are potentially unable to complete spawning due to the effects of these thermal regimes (resulting in gonad emaciation) and persist only as older non-reproducing individuals (Heinricher and Layzer 1999, p. 143).

4.1.3 In-Stream Sedimentation

Optimal substrate for the Pyramid Pigtoe is predominantly stable sand, gravel, and cobble without excessive accumulation of silt and detritus. Riparian condition strongly influences the composition and stability of substrates that mussels inhabit (Allan *et al.* 1997, p. 149). Rivers and streams with urbanized or agriculturally-dominated riparian corridors are subject to increased sediment-loading as soil erodes from banks that do not have a dense network of roots holding soil in place, or from the landscape in general in areas without sufficient ground cover. Streams in urban areas may be subject to excessive runoff from impervious surfaces, which can overwhelm a stream channel's capacity to carry the water, resulting in increased stream bed and bank erosion (see discussion in section 6.1.3, below). Excess sediment in streams settles to the stream bottom, filling spaces needed by juvenile mussels and host fish eggs. The result is a less suitable in-stream habitat for mussels compared to habitat with forested corridors (Allan *et al.* 1997, p. 156).

4.1.4 Food and Nutrients

Adult freshwater mussels, including the Pyramid Pigtoe, are filter-feeders, drawing in suspended phytoplankton, zooplankton, rotifers, protozoans, detritus, and dissolved organic matter from the water column or from sediment (Strayer *et al.* 2004, p. 430). Juvenile mussels are capable of pedal and deposit feeding to collect food items from sediments (Vaughn *et al.* 2008, pp. 409-411). Glochidia can derive what nutrition they need from their obligate fish hosts (Barnhart *et al.* 2008, p. 372). Freshwater mussels must keep their shells open, or gaped, to obtain food and facilitate gas exchange, but they often respond to water quality impairments by closing their shells (Bonner *et al.* 2018, p. 141).

Food supply is not generally considered limiting in environments inhabited by Pyramid Pigtoe. However, food limitation may be important during times of elevated water temperature, as both metabolic demand and incidence of valve closure increases concomitantly, resulting in reduced growth and reproduction (Bonner *et al.* 2018, p. 6). In addition, in areas where nonnative species (e.g., Zebra Mussel and Asian Clam) attain high densities, competition for food resources may affect overall food availability for the Pyramid Pigtoe (Strayer 1999b, p. 90).

4.2 Population- and Species-level Needs

In order to assess the viability of a species, the needs of individuals are only one aspect. This section examines the larger-scale population and species-level needs of Pyramid Pigtoe.

4.2.1 Connectivity of Aquatic Habitat

River systems are a hierarchical network of aquatic habitats, and lotic, or flowing, landscapes are naturally dynamic and heterogeneous. Dendritic, or branched, orientation can enhance metapopulation persistence compared to linear or two-dimensional systems (Fagan 2002, p. 3,243). Tributary connection to river mainstems allows movement of fishes, and helps facilitate dispersal and colonization of appropriate habitat patches by mussels. A high degree of connection between habitat patches and occupied reaches is necessary for mussel populations to persist, because mussels are heavily dependent on gene exchange and host fish movement and dispersal within river corridors to maintain viable populations (Newton *et al.* 2008, p. 425). Connectivity to a larger ‘parent’ water body can also have positive effects in that it may combine with other local factors to discourage the settlement and survival of nonnative species, such as Zebra Mussel (Zanatta *et al*. 2002, p. 487).

Latitudinal shifts in distributions may occur in response to a warming climate, underscoring the importance of longitudinal and dendritic connectivity (Evans 2010, p. 18; Inoue and Berg 2016, p. 2). Fragmentation can reduce the potential for recolonization, increasing the likelihood, and compounding the significance of, local extirpation events (Fagan 2002, p. 3,248). In the case of mussels, fragmentation results in barriers to host fish movement, which in turn, influences mussel distributions. Mussels that use small host fishes, such as minnows and shiners (family Cyprinidae), are more susceptible to impacts from habitat fragmentation. This is due to increasing distance between suitable habitat patches and low likelihood of small host fish swimming over that distance as compared to large host fishes (Vaughn 2012, p. 7). Barriers to movement can cause isolated or patchy distributions of mussels, which may limit both genetic exchange and recolonization (Jones *et al.* 2006, p. 528).

The fragmentation of river habitat by dams and other aquatic barriers (e.g., perched or undersized culverts) is one of the primary threats to aquatic species in the U.S. (Martin and Apse 2014, p. 7). Dams (whether man-made or nature-made (e.g., from beavers (*Castor canadensis*) or large woody debris)) have a profound impact on in-stream habitat as they can change lotic systems (flowing water) to lentic systems (stationary or relatively still water). Moreover, fragmentation by dams or culverts generally involves loss of access to quality habitat for one or more life stages of freshwater species.

In the case of mussels, fragmentation can result in barriers to host fish movement, which in turn, may influence mussel distributions. Mussels that use small host fishes such as minnows and shiners are more susceptible to impacts from habitat fragmentation due to increasing distance between suitable habitat patches and low likelihood of small host fish swimming over that distance as compared to larger host fishes (Vaughn 2012, p. 7). Barriers to movement can cause isolated or patchy distributions of mussels, which may limit both genetic exchange and recolonization potential (e.g., after a high flow, scouring event).

4.2.2 Dispersal-Adult Abundance and Distribution

Mussel abundance in a given river reach is a product of the number of mussel beds (aggregations of freshwater mussels) and the density of mussels within those beds. For populations of Pyramid Pigtoe to be healthy, individuals must be numerous, with multiple age classes, and display evidence of recruitment. For Pyramid Pigtoe populations to be resilient, there must be multiple mussel beds of sufficient density such that local stochastic events do not eliminate the bed(s), allowing the mussel bed and the overall local population within a river reach to recover from any one event. A dendritic (non-linear) distribution over a large area (occurrence in tributaries, in addition to the mainstem) also helps buffer against stochastic events that may impact populations. Mussel abundance also facilitates reproduction; mussels do not actively seek mates, rather males release sperm into the water column, where it drifts until a female takes it in (Moles and Layzer 2008, p. 212). Therefore, successful individual reproduction, and population viability, requires sufficient numbers of female mussels downstream of sufficient numbers of male mussels.

Mussel abundance is indicated by the number of individuals found during a sampling event. Mussel surveys are not a complete census of the population, and detectability can be affected by various factors such as visibility, experience level of the surveyor, and changing environmental conditions. Mussel density is estimated by the number found in a given area, or over a time period, during a survey event, using various statistical techniques. Because we do not have population estimates for most populations of Pyramid Pigtoe, nor are the techniques directly comparable (i.e., same area size searched, similar search time), we use the number of individuals captured as an index over time. While we cannot precisely determine population abundances at these sites using these numbers, we are able to determine if the species is abundant, common, or rare at the site, and examine these generalized estimates over time.

4.2.3 Host Fishes

Host fish species for Pyramid Pigtoe are minnows of the family Cyprinidae. Known hosts are: *Cyprinella spiloptera, Erimystax dissimilis, Lythrurus fasciolaris,* and *Notropis photogenis* (Culp *et al*. 2009, p 19). There are potentially other hosts capable of transforming juvenile Pyramid Pigtoe which have not been studied, or other species which may become infested but transformation and survival to juvenile stage does not occur (Culp *et al*. 2009, p 20).

4.3 Uncertainties

Life history uncertainties include the age at maturity, age structure within populations (number within each age class or cohort in any population), and sex ratios (the species is not considered sexually dimorphic). Population estimates are lacking, due to inconsistent survey efforts and methodologies, and because it is challenging to detect and accurately quantify the individuals of a species that occurs at low densities or composes a small fraction of a total mussel assemblage. Information on fecundity, the time period to complete metamorphosis, including ranges of water temperatures at which transformation occurs, is limited to one female, gathered during host fish studies. Species-specific diet studies have not been conducted, and growth curves have not been developed.

Dispersal occurs via glochidia attached to host fish species, several which have been identified, but dispersal distances are unknown. Additionally, numeric water quality criteria specific for Pyramid Pigtoe threshold tolerances are unknown. Due to challenges associated with propagating short term brooders such as Pyramid Pigtoe in captive environments, information regarding their restoration potential through production is extremely limited, which potentially limits the species' recovery potential. Abundance and precise locality information for most populations currently considered extirpated is lacking, therefore it is difficult to specifically attribute localized extirpation to a specific stressor or species need. The species relies on a consistent, low-level of reproductive success to maintain populations, but the actual environmental events that cue variations (increases or decreases) in reproductive success is not documented.

4.4 Summary of Resource Needs

As discussed in Chapter 1, for the purpose of this assessment, we define viability as the ability of the Pyramid Pigtoe to sustain populations in the wild over time (in this case, 40 to 50 years). The availability and quality of those resources, as well as the level of negative and beneficial influences acting upon those resources, will determine whether populations are resilient over time. Based upon the best available scientific and commercial information (summarized in Sections 4.1 and 4.2, above), and acknowledging existing ecological uncertainties (Section 4.3, above), the Pyramid Pigtoe's resource and demographic needs (see Figure 4-1, below) are characterized as follows:

- Clean flowing water with appropriate water quality and temperate conditions, such as (but not limited to) dissolved oxygen above 2-3 ppm, ammonia generally below 0.5 ppm

TAN, temperatures generally below 86 °F (30 °C), and (ideally) an absence of or lack of excessive TSS and other pollutants.

- Natural flow regimes that vary with respect to the timing, magnitude, duration, and frequency of river discharge events.
- Predominantly silt-free, stable sand, gravel and cobble substrates.
- Suspended food and nutrients in the water column including (but not limited to) phytoplankton, zooplankton, protozoans, detritus, and dissolved organic matter.
- Availability of sufficient host fish numbers to provide for glochidia infestation and dispersal. Host fish species include (but may not be limited to): minnows and shiners of the family Cyprinidae and genera *Cyprinella*, *Erimystax, Lythrurus*, and *Notropis*.
- Connectivity among populations. Although the species' capability to disperse is evident through historical occurrence of a wide range of rivers, the fragmentation of populations by small and large impoundments has resulted in isolation and only patches of what once was contiguous river occupation. Genetic exchange occurs between and among mussel beds via sperm drift, host fish movement, and movement of mussels during high flow events. For genetic exchange to occur, connectivity must be maintained.
- Most freshwater mussels, including the Pyramid Pigtoe, are found in mussel beds that vary in size and are often separated by stream reaches in which mussels are absent or rare (Vaughn 2012, p. 983). The species is often a component of a large healthy mussel assemblage within optimal mussel habitats; therefore, mussel beds, containing an assemblage of native mussel species are needed for Pyramid Pigtoe viability.

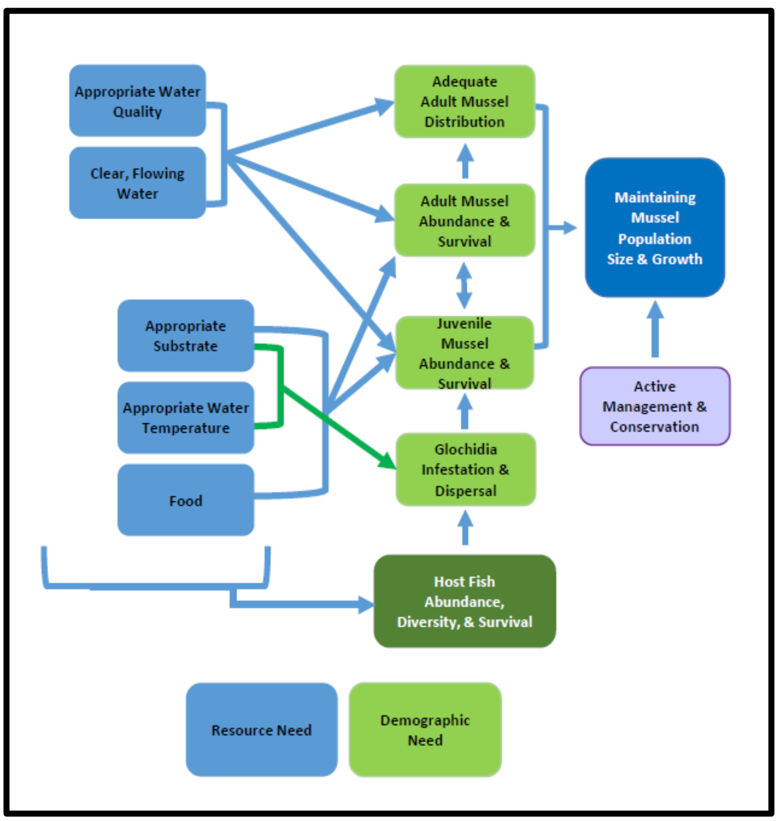

Figure 4-1. Resource and demographic needs of the Pyramid Pigtoe.

CHAPTER 5 - CURRENT CONDITIONS, ABUNDANCE AND DISTRIBUTION

Fundamental to our analysis of the Pyramid Pigtoe was the determination of scientifically sound, analytical units, at a scale useful for assessing the species (see Section 2.1.2, above). Specific Pyramid Pigtoe demographic and genetic data with which to support this construct are sparse; therefore we used the best available information, which includes occurrence location records and levels of river connectivity (amount and scale (porosity) of barriers to dispersal) to define Pyramid Pigtoe basins, MUs, and populations.

After identifying the factors (i.e., stressors) likely to affect the Pyramid Pigtoe, we estimated the condition of each Pyramid Pigtoe management unit. The population size and extent metrics used were selected because the supporting data were relatively consistent across the range of the species and at a resolution suitable for assessing the species at the management unit level. The output was a condition score for each Pyramid Pigtoe population that was then used to assess the Pyramid Pigtoe across its range under the concepts of resiliency, redundancy, and representation.

The Pyramid Pigtoe is wide-ranging, historically known from the Upper Mississippi, Ohio, Missouri, Tennessee, Arkansas-White-Red, and Lower Mississippi basins. It is considered extirpated from the Upper Mississippi and Missouri basins. The species is considered extirpated from Pennsylvania, West Virginia, Indiana, Illinois, Minnesota, Wisconsin, Iowa, Kansas, and Missouri. The results of surveys conducted since 2000 indicate the currently occupied range of the Pyramid Pigtoe includes 4 basins, 35 populations, 28 MUs and 27 rivers, all of which are fragmented to some extent by impoundments. A summary of all known extant populations, grouped by MU, and their generalized estimated size and extent is found in Table 7-1.

5.1 Historical Conditions For Context

To summarize the overall current conditions, Pyramid Pigtoe MUs were considered extant if a live individual or fresh dead specimen was collected since 2000. Populations from the Arkanasas-White-Red and Lower Mississippi basin are summarized with the date of most recent live or fresh dead specimens collected (Appendix B); more detailed population descriptions are available for the Ohio and Tennessee basins in Appendix A. Populations were considered extirpated based on documentation in literature, reports, or from communications with state malacologists and aquatic biologists. Museum collections and general reference texts on regional freshwater mussel fauna such as Haag and Cicerello (2016), Williams *et al.* (2008), Watters *et al.* (2009), Parmalee and Bogan (1998), Harris *et al* (2009), Jones *et al* (2019), and Gordon and Layzer (1989) provided substantial information on species distribution, both past and present.

The Pyramid Pigtoe is documented from 151 populations, 136 MUs, and 6 basins across 18 states. The species has suffered a drastic range reduction from historical occurrence to current condition as documented from museum records, literature, and reports (Figure 5-1). Populations of the Pyramid Pigtoe have been lost from entire watersheds in which the species once occupied multiple MUs, such as the Scioto, Wabash, Kentucky, and Ohio Rivers in the Ohio basin (Appendix C). The Pyramid Pigtoe formerly occurred throughout the Ohio River mainstem in 14 MUs, but no live or fresh dead individuals have been collected in over 50 years (Haag and

Cicerello, 2016, p. 199), likely a direct result of conversion of the river to a series of locks and dams. It is also extirpated from the type locality, the Kentucky River, where it once occurred throughout the river (Haag and Cicerello, 2016, p. 199).

Another illustrative example is in the Muskingum River system, which drains a large portion of eastern Ohio. Based on large collection lots at OSUM, the species was once abundant and comprised a sizeable portion of the mussel assemblage in the Tuscarawas River, and also occurred in the Mohican and Walhonding Rivers, all upstream tributaries to the Muskingum River (Appendix C). It currently survives in only a two mile river reach in the lowermost Muskingum River, below Devola Dam. A table of all populations and MUs considered extirpated along with the authority, and the year of the record, is in Appendix C.

Precipitous declines and loss of Pyramid Pigtoe populations are most pronounced in the Ohio basin. Examples of entire river systems where it is considered extirpated within the Ohio basin include: Allegheny, Monongahela, and Beaver Rivers, Pennsylvania (Ortmann 1909, p. 199); Licking, Salt, and Beech Fork Rivers, Kentucky (Haag and Cicerello 2016, p. 199); Tippecanoe, Wabash, and White Rivers, Indiana (Cummings & Berlocher 1990, p. 94; Fisher 2006, p. 105); Big South Fork Cumberland, Obey, and Stones Rivers, Kentucky/Tennessee (Ahlstedt *et al* 2004, p. 64, Schmidt *et al* 1989, p. 58).

In many instances, the specific cause for extirpation is unknown, and is likely attributable to a variety of compounded threats. Due to its thick shell, widespread distribution, and abundance in some locations, the Pyramid Pigtoe was among the most desired mussel species of the button and pearl industries of the early 20th century, and the cultured pearl industries of the later 20th century. The Pyramid Pigtoe was heavily exploited in the first half of the 20th century for mother of pearl buttons (Anthony and Downing 2001, p. 2,078). Populations large enough to be heavily exploited indicates that the species once occurred in much larger numbers across its range than are observed today. There is no doubt that freshwater mussel commercial exploitation contributed to Pyramid Pigtoe decline and permanently altered population recovery potential (Anthony and Downing 2001, p. 2,087).

The pearl culture industry renewed commercial interest in freshwater mussels in the latter half of the 20th century. Ahlstedt (1980, p. 61; and 1991, p. 103) reported fresh dead Pyramid Pigtoe shells from commercial shell piles along the Tennessee and Cumberland Rivers. The Ohio Pigtoe and Pyramid Pigtoe can be difficult to distinguish where they co-occur and were often lumped together by commercial shellers and even in assessments of the commercial mussel fishery (Scruggs 1960, entire; Isom 1969, entire). In the Tennessee River, over a hundred thousand tons of mussels were harvested by commercial shellers from 1945-1967, with 10,000 tons annually for several years (Isom, 1969, p. 401). Bowen *et al*. 1994 (p. 313), estimated 570 metric tons of live mussels were harvested from Wheeler Reservoir alone on the Tennessee River between July 1991 and June 1992.

Although the Pyramid Pigtoe is considered rare in all locations where it persists, incidental commercial harvest of the Pyramid Pigtoe is still possible due to its co-occurrence with the morphologically similar Ohio Pigtoe. The Ohio Pigtoe was once of the most commercially valuable mussel species (Yokley 1972, p. 351). Due to a dramatically lowered value for shells, the commercial mussel fishery and associated industry has been drastically reduced from its heyday (Anthony and Downing, 2001, p. 2,085).

Commercial harvest of mussels, as well as commercial sand and gravel dredging, still occurs in some areas of Kentucky Reservoir on the Tennessee River within the Lower Tennessee – Beech MU (Hubbs 2012, p. 2). As a result, commercial harvest is considered an ongoing secondary threat to the Pyramid Pigtoe, however, it is currently only considered a threat for the species in the mainstem Tennessee River. Mussel harvest sanctuaries have been established in some locations within the Tennessee River and in other rivers occupied by the Pyramid Pigtoe. This threat is substantially reduced from past conditions, and will possibly see further reduction in the future due to species rarity and diminished value of shells.

Other causes of Pyramid Pigtoe declines include habitat loss, fragmentation, and degradation due to impoundment and navigational impacts, and impaired water quality due to pollution and land use changes, as well as the introduction of nonnative species (Watters and Flaute 2010, p. 6; Watters 2000, p. 269). As early as 1909, pollution caused by coal mining and oil refineries and habitat loss due to impoundment were identified as contributors to the decline of the freshwater mussel fauna in Pennsylvania (Ortmann 1909b, p. 97). The Pyramid Pigtoe is extirpated from Pennsylvania; it formerly occurred multiple river systems, and was even abundant in the Monongahela River in some locations (Ortmann 1909a, p. 199).

These threats to mussels identified as early as 1909 continue into the present. In particular, mining and resource extraction impacts have been specifically identified as contributing to declines of freshwater mussel diversity and abundance in some of the rivers that harbor remaining Pyramid Pigtoe populations, such as the Clinch River in Tennessee and Virginia (Van Hassel 2007, p. 328). All extant populations of Pyramid Pigtoe are affected by impoundments, which persist as one of the most pervasive threats to the species. Dams isolate populations and restrict host fish movement, altering dispersal capability, and their operations can limit fitness, reproduction potential, and growth (Heinricher and Layzer 1999, p. 143).

5.2 Current Population Abundance, Trends, and Distribution

To assess the distribution, abundance, and (if data are available) trends of Pyramid Pigtoe populations, we first assigned a status category of extant or extirpated to each population (Figure 5-1). Second, for extant populations with genetic confirmation, we estimated the occupied extent of each river and size of each population so each could be evaluated relative to one another (Table 5-1). Due to lack of consistency of survey efforts, population size (Table 5-2) was based on count numbers of the species summarized from inventory data. Third, we developed threat condition categories (Table 5-3) based on our qualitative assessment of the magnitude and immediacy of a potential threat within each population. Lastly, we assigned a low/moderate/high overall condition category to each population based on the combined consideration of the aforementioned population extent, size, and threat information (Table 5-4). This approach is consistent with other wide-ranging mussel SSAs (Service 2018, 2019, 2020a).

Population extent for each river was based on available inventory data. Estimates of occupied river kilometers were derived from polygons generated by the NHP, DNR datasets, and through mapping of point occurrence data, and evaluated by examining available appropriate habitat and its connectivity relative to natural or constructed barriers such as dams. Population extent was ranked as small, medium, and large, as described in Table 5-1, below.

Population extent was mapped in ArcGIS v. 10.5. Data sources for population extent include NatureServe species' occurrence information sourced from states, primary literature, and gray literature; and reports and personal communications with state malacologists and aquatic biologists familiar with the extent of suitable mussel habitat within the drainage. We also used aerial imagery and topographic maps to delineate the maximum extent of the species potential occurrence. Additionally, when available, negative data (surveys that did not detect Pyramid Pigtoe) from mussel inventories conducted within the known drainages of Pyramid Pigtoe occurrence were used to inform extent for each population.

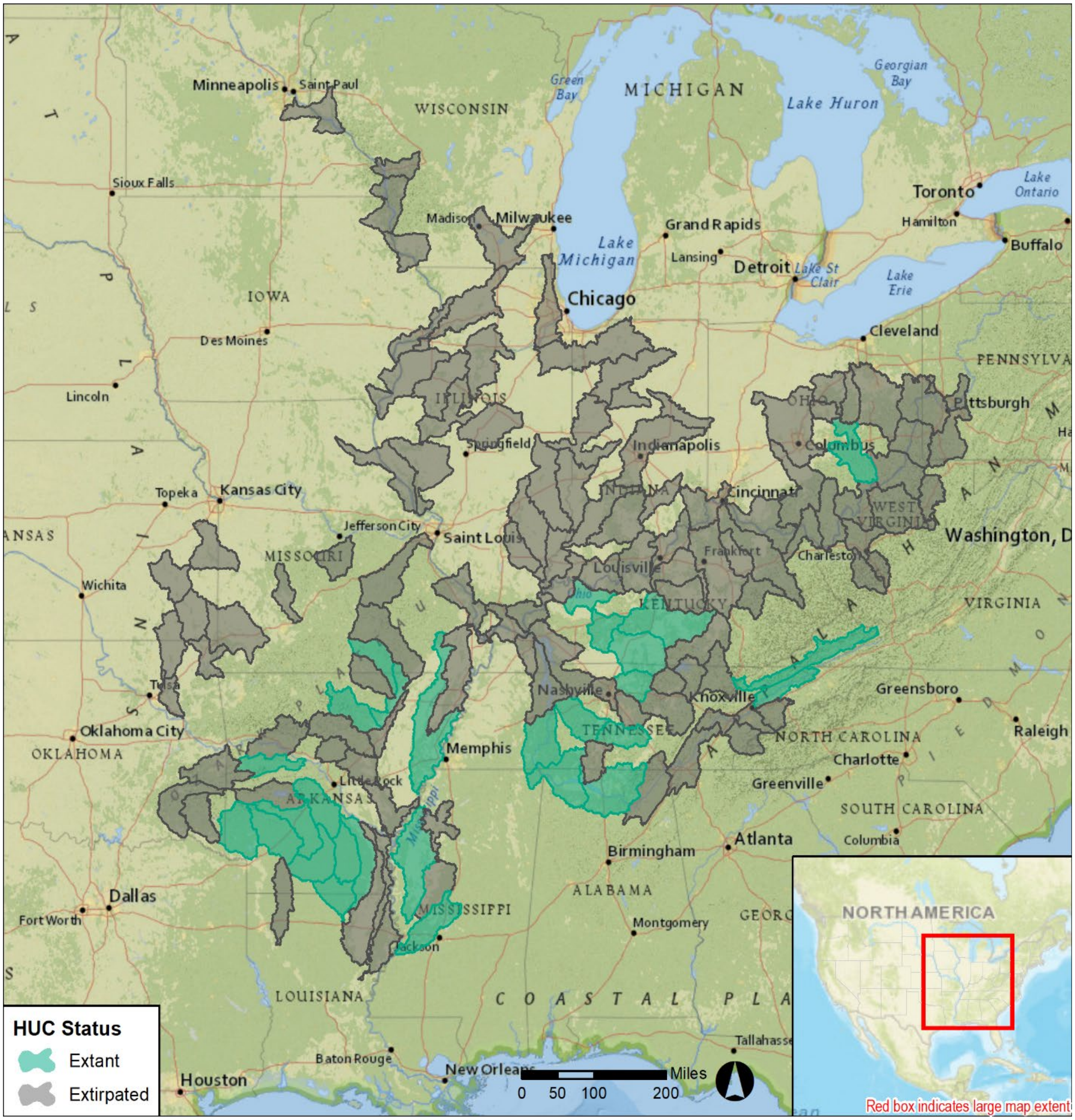

Figure 5-1. Extant and Extirpated MUs (HUC 8) of Pyramid Pigtoe across its entire historical and current range.

Table 5-1. Population extent categories to describe Pyramid Pigtoe's distribution within rivers throughout its range.

Category	Description
Small	Species is estimated to continuously occur in less than 6.2 mi (10 km) of rivers/streams based on available survey information and data on the lack of detection of the species in surveys.
Medium	Species is estimated to continuously occur in more than 6.2 mi (10 km) but less than 31 mi (50 km) of rivers/streams based on available survey information and data on the lack of detection of the species in surveys.
Large	Species is estimated to continuously occur in more than 31 mi (50 km) of rivers/streams based on available survey information and data on the lack of detection of the species in surveys.

Population size for each river was based on inventory data collected for freshwater mussels since 2000. Various state and Federal agencies as well as 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 Table 5-2). Our estimates of the size of each population are detailed in Appendix A; these categories were reviewed by state malacologists and mussel biologists, and are consistent with SSAs for other wide ranging mussel species (Service 2019). Available negative mussel data (mussel surveys in the river or stream that failed to detect Pyramid Pigtoe) and information on threats to the aquatic fauna in these watersheds was also used to inform analyses.

Table 5-2. Population size categories to help describe the Pyramid Pigtoe's abundance within rivers throughout its range.

Category	Description*
Small (very rare to uncommon in collections or surveys)	Less than 10 individuals (live or fresh dead) reported cumulatively or in any sampling event since 2000; qualitative collections of varying effort; surveys within known occupied reaches did not detect species, not enough information available to generate population estimate; or population potentially represented by larger older individuals not reproducing.
Medium (occasional to common in collections or surveys)	10–50 individuals (live, fresh dead) reported since 2000; and/or some quantitative information available for a population estimate at sampling locations within occupied river reach (with large confidence intervals); potentially multiple size classes represented; or species is frequently observed or detected when preferred habitat is targeted in sampling efforts.
Large (abundant in collections or surveys)	More than 50 individuals (live) reported since 2000; or a population estimate for the river or a site within the river may already be available or possible due to the availability of quantitative data at sampling locations within occupied river reach; or potentially some evidence of recent recruitment.

* (A population may meet one or more criteria but does not have to meet all)

Potential threats to the Pyramid Pigtoe or its habitat were categorized in terms of magnitude and immediacy based on the best available information in the literature or other sources such as State Wildlife Action Plans (SWAP), watershed planning documents, or Clean Water Act 303d lists. We ranked threat levels based on their apparent or likely magnitude of presence in the drainage (Table 5-3). Pyramid Pigtoe population characteristics (extent and size) were considered relative to current threats.

Table 5-3. Categories to describe the magnitude and immediacy of potential threats influencing Pyramid Pigtoe.

Category	Description
Low	Threats to freshwater mussels or aquatic fauna have been identified in this HUC and are in the literature or are available in State Wildlife Action Plans - threats are minimal (potential threats identified but direct tie to loss of mussels possibly lacking) compared to other occupied rivers and streams or MUs that harbor the species. Public land holdings within the river where the Pyramid Pigtoe occurs were incorporated into this threat level.
Moderate	Threats to freshwater mussels or aquatic fauna have been identified or evaluated in this HUC and are in the literature or are available in State Wildlife Action Plans - threats are moderate (multiple threats identified but may not be imminent, or the status of the threat is unknown) compared to other occupied rivers that harbor the species.
High	Threats to freshwater mussels or aquatic fauna have been identified and evaluated in this HUC and are in the literature or are available in State Wildlife Action Plans - threats are substantial (multiple threats identified and one or more imminent) and synergistic, compared to other occupied rivers that harbor the species.

Mussel declines in the range of the Pyramid Pigtoe are primarily the result of habitat and water quality loss and degradation (Neves 1993, p. 4). The chief causes of lost populations or declining populations are impoundments, channelization, chemical contaminants, mining, non-native species, and sedimentation (Neves 1993, p. 4; Williams *et al.* 1993, p. 5; Watters 2000, p. 261).

Expanding human populations within the range of the species (e.g., Lawler *et al.* 2014, p. 55; Terando *et al.* 2014, p. 3) will invariably increase the likelihood current factors will continue to impact Pyramid Pigtoe populations into the future. The level of threat that climate change exerts on the species rangewide is unknown; however, due to the species occurrence in medium and large rivers, climate change is not considered a primary threat. Regardless, the highly fragmented remaining populations rangewide, affected by the threats listed above, are likely affected by secondary impacts through climate change such as drought or prolonged flooding.

5.3 Estimated Viability of Pyramid Pigtoe Mussel Based on Current Conditions

We define viability as the ability of the species to sustain healthy populations (and MUs) in natural river systems within a biologically meaningful timeframe. Using the SSA framework, we describe the species' current viability in terms of resiliency, redundancy, and representation.

5.3.1 Resiliency

Resiliency describes the ability of populations to withstand stochastic events (arising from random factors). We can measure resiliency based on metrics of population health, for example, birth versus death rates and population size. Highly resilient populations are better able to withstand disturbances such as random fluctuations in birth rates (demographic stochasticity), variations in rainfall (environmental stochasticity), or the effects of anthropogenic activities. For the purpose of this SSA, with a lack of broad demographic data, each population's estimated size and extent helps provide a measure of resiliency given that larger mussel populations distributed over a larger area would be better able to rebound from stochastic events than smaller populations with limited distribution.

Populations within MUs were cumulatively ranked according to the following overall condition categories: high, medium, low (Table 5-4). As discussed above under section 5.2, these categories were informed by each population's extent, size, and probable threat level, with population size and extent weighted more heavily than threat level because of more limited information on current threats specific to the Pyramid Pigtoe. Overall condition categories for each of the currently extant Pyramid Pigtoe populations are presented in Table 5-5, below. These categories have been used in SSAs for other wide ranging freshwater mussels (Service 2018; 2019; 2020a).

Table 5-4. Categories for estimating the overall current condition of Pyramid Pigtoe mussel populations and MUs.

High (Stronghold)	Medium	Low
Populations generally distributed over a significant and more or less contiguous length of stream (≥ 30 RMs), with evidence of recent recruitment, and currently considered resilient.	Small, generally restricted populations, with lowered resiliency. Some age class structure documented but limited recruitment. Likely stable, but with greater possibility for decline than High condition populations due to known threats.	Very small and highly restricted populations, with no evidence of recruitment or age class structure. Population lacks resiliency and declines from historical conditions documented.

Condition category tables are a structured way to assess the current and future state of populations based on specific variables related to the resiliency of each population. Condition category tables are a transparent way to illustrate to the public which variables we are assessing and how these variable contribute to the overall status of populations. The tables allow us to weigh the different variables differently depending on the importance of that variable to the species ecology.

Using condition category tables is a common FWS practice in Species Status Assessments when further quantitative methods to assess population risk on a continuous scale may be inappropriate due to the lack of data to do so. Assigning condition or health based on multiple criteria, which is what the condition table does, is common in a variety of applications - such as, Element Occurrence rank, risk level in IUCN Red List criteria, and indices of biological integrity.

Table 5-5. Extant populations of Pyramid Pigtoe by major river basin, MU (8 digit HUC), and their current condition. Current condition colors correspond with Figure 5-2.

Major River Basin	Management Unit	State	Contiguous Population (occupied river)	Overall MU Current Condition
Ohio	Muskingum	OH	Muskingum River	Low
Ohio	Upper Green	KY	Upper Green River	High
Ohio	Middle Green	KY	Middle Green River	Med
Ohio	Lower Green	KY	Lower Green River	Low
Ohio	Barren	KY	Barren River	Med
Ohio	Lower Cumberland – Old Hickory	TN	Cumberland River (below Cordell Hull Dam)	Low
Tennessee	Upper Clinch	TN VA	Clinch River	Med
Tennessee	Holston	TN	Holston River	Low
Tennessee	Wheeler Lake	AL	Tennessee River (below Guntersville Dam) Paint Rock River	Low
Tennessee	Pickwick Lake	AL/TN	Tennessee River (below Wilson Dam)	Low
Tennessee	Lower Tennessee - Beech	TN	Tennessee River (below Pickwick Dam)	Low
Tennessee	Upper Duck	TN	Upper Duck River	Med
Tennessee	Lower Duck	TN	Lower Duck River	Med
Arkansas-White-Red	Petit Jean	AR	Petit Jean River	Low
Arkansas-White-Red	Eleven Point	AR	Eleven Point River	Low
Arkansas-White-Red	Lower Little	OK AR	Little River	Low
Lower Mississippi	Lower Black	AR	Black River	Low
Lower Mississippi	Lower St. Francis	AR	St. Francis River Tyronza River	Med.
Lower Mississippi	Middle White	AR	White River	Low
Lower Mississippi	Upper Ouachita	AR	Upper Ouachita River	High

Major River Basin	Management Unit	State	Contiguous Population (occupied river)	Overall MU Current Condition
Lower Mississippi	Little Missouri	AR	Little Missouri River	Med
Lower Mississippi	Lower Ouachita-Smackover	AR	Lower Ouachita River (Smackover)	Med
Lower Mississippi	Upper Saline	AR	Upper Saline River	High
Lower Mississippi	Lower Saline	AR	Lower Saline River	High
Lower Mississippi	Bayou Bartholomew	AR	Bayou Bartholomew	Med
		LA		
Lower Mississippi	Lower Ouachita-Bayou De Loutre	AR	Lower Ouachita River (Bayou De Loutre)	Low
		LA		
Lower Mississippi	Big Sunflower	MS	Hushpuckna River	Med
			Bogue Phalia	
			Little Sunflower River	
			Sunflower River	
			Sandy Bayou	
			Big Sunflower River	
Lower Mississippi	Lower Big Black	MS	Big Black River	Low

The overall current condition of the Pyramid Pigtoe indicates the species has low resiliency: 14 of the 28 MUs (50 percent) are in low condition compared to 10 MUs (36 percent) in moderate condition, and 4 MUs (14 percent) in high condition. Although 50 percent of the populations are considered low condition, the remainder of the populations (and MUs) that are considered moderate or high condition are spread across 8 states.

Of the 6 MUs in the Ohio basin, the Upper Green is currently high condition, the Middle Green and Barren are in medium condition, and the Muskingum, Lower Green, and Lower Cumberland-Old Hickory MUs are in low condition. These low condition populations are small in extent and have a high magnitude of threats. There is currently only one population remaining in the entire Cumberland River system, a large tributary within the Ohio basin, and it is in low condition. The Pyramid Pigtoe once occupied the entire Cumberland and Muskingum Rivers and multiple tributaries (Appendix C).

The Pyramid Pigtoe in the Green River is distributed across 3 different MUs, the Upper, Middle, and Lower. The Upper Green has the highest resiliency of all MUs in the Ohio and Tennessee basins. Densities of Pyramid Pigtoe decrease proceeding downstream in the Green, and the population in the river is fragmented by multiple dams. However, the Barren River enters the Green within the Middle Green MU. The Barren is also occupied and currently in medium condition. This non-linear distribution with a stronghold in the upper reaches and a medium condition tributary population makes the Green River watershed in central Kentucky the most viable and important for Pyramid Pigtoe persistence in the eastern portion of its range.

The Pyramid Pigtoe has a single remaining MU in the Cumberland River, and the best available information indicates that the species has been extirpated in all but one reach of the Cumberland River, with its extent reduced from historical conditions by approximately 1,087 KM (Schuster 1988, p. 769; Haag and Cicerello 2016, p. 199). Wolf Creek Dam, completed in 1951 by the US Army Corps of Engineers (Corps), and continued operation of the impoundment, has completely transformed the middle Cumberland River drainage. This transformation has resulted in a loss of approximately 50 percent of the mainstem riverine mussel fauna and recruitment failure of any species that are able to remain (Miller *et al*. 1984, p. 109; Haag and Cicerello 2016, pp. 14, 52).

The remaining Pyramid Pigtoe population is restricted to a 12.4-mi (20-km) reach of the Cumberland River main stem below Cordell Hull Dam. This reduction in resiliency within the Ohio basin is a good example of rangewide population extent declines. Although this population is located within the Tennessee Wildlife Resources Agency (TWRA) Rome Mussel Sanctuary, and is protected from mussel harvest activities, the population is threatened by hypolimnetic discharges (i.e., the perpetually cold and non-circulated water layer that lies below the thermocline) from upstream impoundments (specifically Wolf Creek Dam, Cumberland River Dam, Center Hill Dam, and Caney Fork Dam) (Heinricher and Layzer 1999, p. 140). As sedentary organisms, mussels are incapable of migrating to more desirable environmental conditions (see Chapter 3, above).

Of the 7 MUs in the Tennessee basin, the Upper Clinch, Wheeler Lake, and Upper Duck MUs are currently medium condition, and the Holston, Pickwick Lake, Lower Tennessee-Beech, and Middle Duck HUCs are in low condition. All low condition populations have moderate or high levels of threats. For example, the Pyramid Pigtoe distribution in the Tennessee River is fragmented by large dams (Wheeler, Wilson, Pickwick), and limited to tailwater reaches, directly affected by dam discharges. The Wheeler Lake MU actually contains 2 occupied river reaches, the lower Paint Rock River, and upper Wheeler Reservoir below Guntersville Dam. Despite this non-linear distribution, only one live individual has ever been collected in the Paint Rock River, and in Wheeler Reservoir, only older, non-reproducing individuals have been collected live since 2000 (Appendix A).

The low condition populations have a moderate level of threats, primarily related to impoundment, agriculture, and resource extraction issues associated with sand and gravel dredging (Ahlstedt *et al.* 2004, p. 2). Commercial sand and gravel dredging, conducted on the Lower Tennessee River since at least the 1920’s, and currently permitted on approximately 48 of the 95 river miles (RM), has degraded a significant portion of the available aquatic habitat. Significantly lower mussel abundance and diversity values have been observed at dredge sites, indicating bottom substrates altered by dredging and resource extraction operations do not provide suitable habitat to support mussel populations similar to those found inhabiting non-dredged reaches (Hubbs *et al.* 2006, p. 169).

The Duck River in Tennessee harbors incredible aquatic diversity, and although it has a medium condition MU of Pyramid Pigtoe, it is under substantial threats associated with rapid urban development, land use changes, incompatible agricultural practices, wastewater management, water supply practices, and resource extraction activities (Corps, 2018, p. 2). Further, many developed communities in the watershed are experiencing periodic flooding which is only expected to worsen as development continues, and water quality and water supply are significant long-term resource management issues. The watershed's aquatic and terrestrial life is experiencing stress from increased development, hydraulic regime changes, and declining suitable habitats. Forty-six of the 64 watersheds within the Duck River system were experiencing major to severe ecological disturbance compared to 15 watersheds experiencing minimal to minor ecological disturbance (Corps 2018, p. 2).

Although improvements in discharge and dissolved oxygen at Normandy Dam on the Duck River have improved water quality, aquatic habitats are fragmented by several low head mill dams and flows are altered through agricultural activities such as irrigation (Ahlstedt *et al.* 2017, p. 4). Water quality problems in the Duck River stem from predominantly from agriculture; including riparian buffer alteration, bank erosion, sedimentation, nutrient loading, low dissolved oxygen, and land management. Water supply problems are controversial because a high quality and quantity water flow is essential for both supporting rare aquatic species and meeting the basin's growing municipal water demands (Corps 2018, p. 2). Agricultural activities, impoundment, and human development are the greatest threats to this population and the Upper and Lower Duck MUs.

Threats that are acting upon the low condition MUs in the Tennessee basin include the introduction of contaminants resulting from agriculture, fragmentation due to impoundment, human development pressures such as wastewater treatment discharges, irrigation, and mining. Oil and gas exploration are contributors to these threats (Tennessee Wildlife Resources Agency [TWRA] 2016, p. 18; Buchanan *et al*. 2017, p. 37). Dams are the most prevalent threat to the species throughout its range, their presence and continued operation limiting available habitat and contributing to small population size. Other primary threats that are acting upon the medium condition MUs include habitat and water quality degradation and the introduction of contaminants resulting from wastewater treatment discharges and mining activities. Additionally, agriculture and human development (urbanization) act cumulatively with these stressors on Pyramid Pigtoe populations throughout its range (Ahlstedt *et al.* 2016a, p. 10; Cicerello 1999, p. 6; TWRA 2015).

Despite the presence of Pyramid Pigtoe in the Clinch MU in Tennessee, the species is considered extremely rare in the Virginia portion of the river. The mussel fauna in the Virginia portion of the Clinch River has declined, specifically at sites such as Pendleton Island where the Pyramid Pigtoe was once common but is now rare (Ahlstedt *et al.* 2016a, p. 11; Jones *et al*. 2018, p. 43). Additionally, downstream impoundments on both the Clinch and Tennessee Rivers fragment this population from others within the Tennessee River basin, and the resulting fragmentation and lack of connectivity decreases dispersal capability, limits population extent, and increases the potential for genetic isolation.

Stressors exerted on the species affect the stronghold MUs in the Ohio and Lower Mississippi basins. Pervasive stressors include impoundments, which separate these high condition populations from others within the Ohio and Lower Mississippi basins. The resulting isolation and lack of connectivity decreases dispersal capability and increases vulnerability, and the potential for genetic isolation. Nonnative species, such as the Zebra Mussel, are an imminent threat to portions of the Ohio and Lower Mississippi basin populations in particular, and water quality and habitat degradation resulting from agriculture, resource extraction, and human development (urbanization) act cumulatively as stressors on Pyramid Pigtoe populations throughout its range.

5.3.2 Representation

Representation refers to the breadth of genetic or environmental diversity within a species and reflects the ability of a species to adapt to changing environmental conditions. The greater the diversity, the more successfully a species should be able to respond to changing environmental conditions. In the absence of genetic data for the Pyramid Pigtoe, we considered environmental diversity across the species' range. The best available data indicate four representative units (i.e., four major river basins) where Pyramid Pigtoe is currently found: the Ohio, Tennessee, Arkansas-White-Red, and Lower Mississippi basins.

Since there is very little rangewide genetic information available for the Pyramid Pigtoe, we considered geographic range as surrogates for geographic variation and proxies for potential local adaptation and adaptive capacity. We used hydrographic (management) units (at the HUC 2 level; see additional discussion in Chapter 2) to 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*. 2019, p. 14).

Museum records indicate that there were at least 23 populations in the Upper Mississippi and Missouri basins where the species is now extirpated (Appendix C). The Pyramid Pigtoe has suffered population and MU losses in all basins of historical occurrence due to systemic threats such as impoundments (Appendices B & D). The species has been reduced from six to four major basins (~33%) compared to historical information. Threats in the Arkansas-White-Red and Lower Mississippi basins are under similar threats as the Ohio and Tennessee (Christian *et al*. 2007, entire; Davidson *et al*. 2000, p. 22; Jones *et al*. 2005, p. 84).

As evaluated by major river basin, using genetic information, the current distribution of the Pyramid Pigtoe across its range reflects a 33 percent loss from historical representation. Additionally, there are only 3 populations and MUs in the Arkansas-White-Red basin currently, and those are all in low condition. So the species is at immediate risk of losing another 17 percent of its representation. The species currently ranges across four major river basins as small populations geographically restricted from one another in most situations. The variety of trend information available across its range (i.e., loss of populations and entire MUs in river systems, loss of populations and MUs throughout the Upper Mississippi and Missouri River basins, declines in population extent and size in portions of the species' current range) indicate that the Pyramid Pigtoe's overall ability to adapt to changing environmental conditions (representation) is minimal.

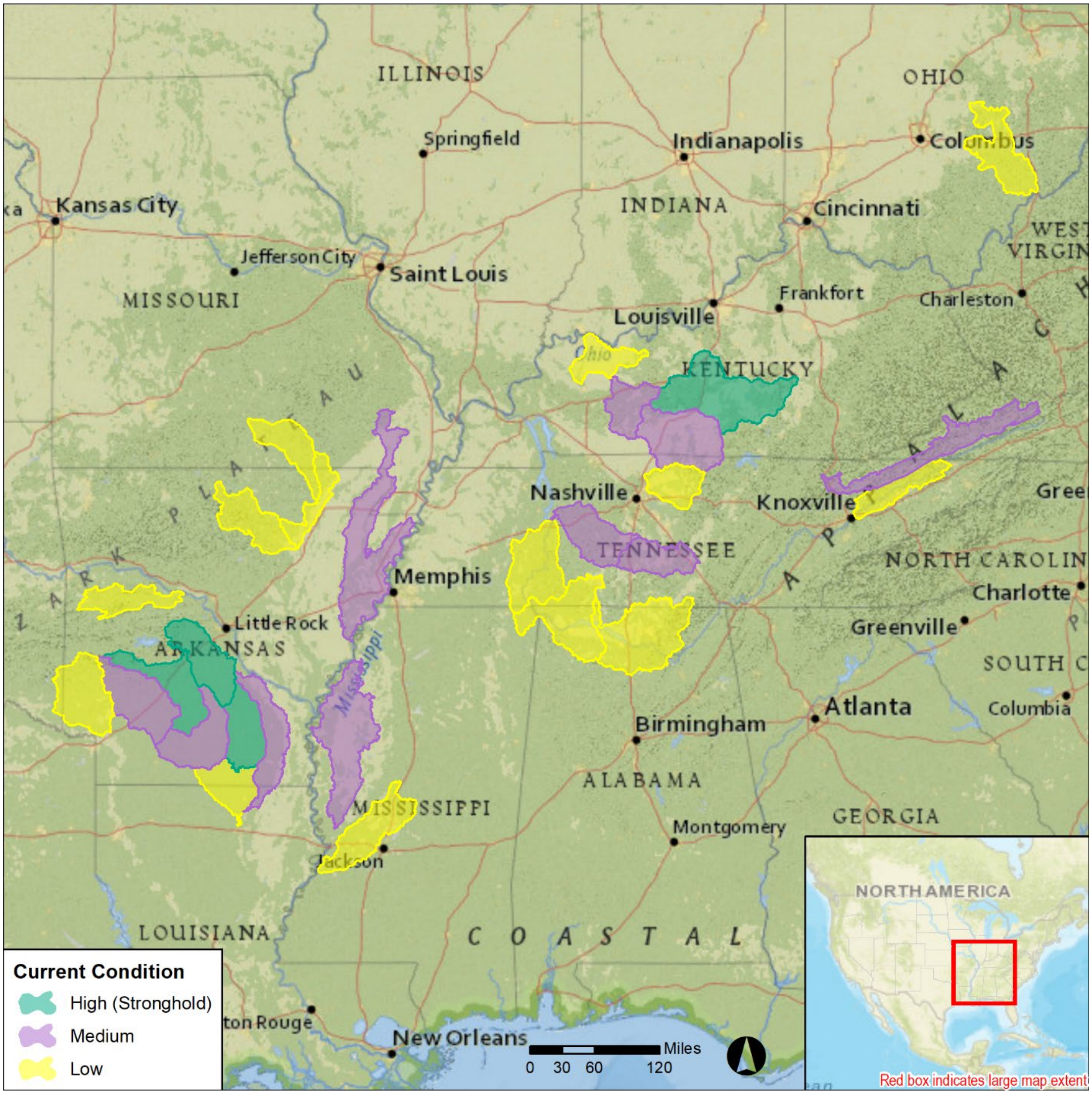

Figure 5-2. Distribution of the currently occupied Management Units (MUs; a.k.a. HUC 8s) of Pyramid Pigtoe. Currently occupied MUs are represented with low, medium, and high condition categories (as described in Chapters 2 and 5; Service 2020b, unpublished data).

5.3.3 Redundancy

Redundancy refers to number of populations (or MUs) of a species and their distribution across the landscape, reflecting the ability of a species to survive catastrophic events. The greater the number of populations, and the more widely they are distributed, the lower the likelihood a single catastrophic event will cause a species to become extinct. For a wide-ranging species such as the Pyramid Pigtoe, a single catastrophic event that affects the species throughout its range is unlikely, and therefore the redundancy metric is less informative for conservation efforts than resiliency and representation metrics.

Pyramid Pigtoe populations are distributed over nine states, with very rare status in Ohio, Oklahoma, and Virginia. The redundancy metric we use in this SSA is number of MUs, based on population status (Table 5-5, Appendix A). The Ohio River basin currently contains 6 MUs, including the only stronghold (Upper Green), and the Tennessee River basin contains 7 MUs, but none currently in high condition. The Arkansas-White-Red contains only 3 MUs which are all in low condition, and the Lower Mississippi basin contains 12 MUs, with 3 in high condition (Upper Ouachita, Upper Saline, Lower Saline), 5 in medium condition, and 4 in low condition.

The total number of extirpated populations and MUs by river basin are:

- 18 populations (16 MUs) in the Upper Mississippi
- 4 populations (4 MUs) in the Missouri,
- 58 populations (57 MUs) in the Ohio,
- 11 populations (8 MUs) in the Tennessee;
- 14 populations (9 MUs) in the Lower Mississippi, and
- 14 populations (14 MUs) in the Arkansas-White-Red

Given the current status encompasses 28 MUs across at least 9 states in 4 basins, the species currently retains redundancy for withstanding and surviving potential catastrophic events. However, it is important to note that 14 of 28 MUs (50 %) are currently in low condition, the species is at immediate risk of being lost from Ohio, Oklahoma, and Virginia, and resiliency overall is limited; which, in turn, reduces redundancy.

Also, based on our understanding of the historical distribution, given the large geographic range the species initially occupied, it is perhaps more likely to undergo range-thinning through local population diminishment than large fractional reductions (Strayer 2004, p. 16). Overall, the Pyramid Pigtoe has decreased redundancy across its range due to the loss of at least 108 MUs (69 percent), and 2 basins (33 percent) compared to historical levels. Illustrative examples of large reductions in population abundance and extent are those within the Cumberland and Muskingum River systems, as discussed in sections 5.2 and 5.3.1.

5.4 Uncertainties of Current Condition

For wide-ranging species with variable data availability across MUs, there are many uncertainties. Some uncertainties of our current condition analysis include the following:

- Some gene flow potentially occurs within and across the Ohio and Tennessee basins, and likely between the Barren and Middle Green MUs and within the Wheeler Lake MU, although the timing and frequency of gene flow is not known and may be inadequate to maintain genetic diversity.

- Population genetic structure and its variation at differing spatial scales is completely unknown. We assume that the Pyramid Pigtoe populations exhibit relatively large amounts of within-population genetic variation (Berg *et al*. 2007, p. 1,437), but this area in particular needs further study, ideally before recovery criteria are developed.

- Specific Pyramid Pigtoe demographic and genetic data with which to delineate MUs and populations, and estimate the condition of each, are sparse. However, our approach for assessing the species' condition has been used for other aquatic species in the eastern U.S. and is based on the best available science.

- Some populations/MUs have very little information available; for example, despite museum material from locations within the current occupied range, the Muskingum and Lower Tennessee – Beech MUs have had only one documented live collection of the species since 2000, with no additional survey data on the Pyramid Pigtoe in the past 5 years, despite survey efforts for other freshwater mussels in these rivers.

- Information on threats came from a wide variety of sources such as published literature and mussel survey reports. There is a paucity of information available on threats specific to the Pyramid Pigtoe. In most instances threats were reported to the entire mussel fauna or aquatic fauna in general.

- The level at which climate change is currently affecting the Pyramid Pigtoe is poorly understood. Population discontinuity and isolation is possible due to the dynamics in range shifts of the Pyramid Pigtoe and its host fishes (primarily minnows) as a result of warming climates, based on life history traits (Archambault *et al*. 2018, p. 880). However, the mechanisms behind these shifts and how they alter population connectivity and gene flow are uncertain, and unlikely to be a greater threat than better-studied impacts on water quality and the habitat needs of the species (such as dams).

CHAPTER 6 - FACTORS INFLUENCING VIABILITY

In this chapter, we evaluate past, current, and future factors affecting what the Pyramid Pigtoe needs for long-term viability. Aquatic systems face myriad natural and anthropogenic factors that influence species viability (Neves *et al.* 1997, p. 44; Strayer 2006, p. 272). Generally, these factors can be categorized as either environmental stressors (e.g., development, agriculture practices, forest management, dam operation, regulatory frameworks) or systematic changes (e.g., invasive species, barriers, changing climate conditions, conservation management practices). Current and potential future effects, along with current distribution and abundance, help inform viability, and therefore vulnerability to extinction.

Negative factors influencing the viability of Pyramid Pigtoe are presented below. While examples are primarily from the Ohio and Tennessee basins, these factors are representative of influences the species is exposed to in the Arkansas-White-Red and Lower Mississippi basins as well (see Appendix E for information on primary threats to each population). In addition to describing the potential impacts and sources of each influence (Figure 6-1, below), we present examples from within the species' range in an attempt to illustrate the scope and magnitude of the impacts based on the best available scientific and commercial information. Additionally, we present a summary of the beneficial conservation measures (regulatory and voluntary) occurring to reduce the impacts, and if those conservation measures are considered effective.

6.1 Habitat Alteration, Degradation, and Loss

6.1.1 Development & Urbanization

We use the term "development" to refer to urbanization of the landscape, including (but not limited to) land conversion for residential, commercial, and industrial uses and the accompanying infrastructure. The effects of urbanization may include alterations to water quality, water quantity, and habitat (both in-stream and streamside) (Ren *et al.* 2003, p. 649; Wilson 2015, p. 424).

Urban development can lead to increased variability in streamflow, typically increasing the extent and volume of water entering a stream after a storm and decreasing the time it takes for the water to travel over the land before entering the stream (Giddings *et al.* 2009, p. 1). An "impervious surface" refers to all hard surfaces like paved roads, parking lots, roofs, and even highly compacted soils like sports fields. Impervious surfaces prevent the natural soaking of rainwater into the ground and ultimately and gradually seeping into streams (Brabec *et al.* 2002, p. 499). Instead, rainwater accumulates and often flows rapidly into storm drains, which rapidly drain to local streams. This results in deleterious effects on streams in three important ways (USGS 2014, pp. 2–5):

(1) *Water Quantity*: Storm drains deliver large volumes of water to streams much faster than would naturally occur, often resulting in flooding and bank erosion that reshapes the channel, and causes substrate instability, resulting in destabilization of bottom sediments. Increased, high velocity discharges can cause species living in streams (including mussels) to become stressed, displaced, or killed by fast moving water and the debris and

sediment carried in it.

(2) *Water Quality*: Pollutants (e.g., gasoline, oil drips, fertilizers) that accumulate on impervious surfaces may be washed directly into streams during storm events.

(3) *Water Temperature*: During warm weather, rain that falls on impervious surfaces becomes superheated and can stress or kill freshwater species when it enters streams.

Urbanization increases the amount of impervious surfaces (Center for Watershed Protection (CWP) 2003, p. 1). The resulting storm water runoff affects water quality parameters such as temperature, pH, dissolved oxygen, and salinity, which in turn alters the water chemistry potentially making it inhospitable for aquatic biota. The rapid runoff also reduces the amount of infiltration into the soil to recharge aquifers, resulting in lower sustained streamflow, especially during low flow periods (Giddings *et al.* 2009, p. 1).

Water infrastructure development, including water supply, reclamation, and wastewater treatment, results in pollution point discharges to streams. Concentrations of contaminants (including nitrogen, phosphorus, chloride, insecticides, polycyclic aromatic hydrocarbons, and personal care products) increase with urban development (Giddings *et al.* 2009, p. 2; Bringolf *et al.* 2010, p. 1,311).

Utility crossings and right-of-way (ROW) maintenance are additional aspects of development that affect stream habitats. Direct impacts from utility crossings include direct exposure or crushing of individuals, sedimentation, and flow disturbance. The most significant cumulative impact involves cleared ROWs that result in direct runoff and increased stream temperature at the crossing location, and potentially allow access of maintenance utility and all-terrain vehicles from the ROW (which destroy banks and instream habitat, leading to increased erosion). Maintenance of these utility crossings and ROWs are additional aspects of development that can influence stream habitats. Herbicides mixed with their surfactants which are used to clear ROWs also have deleterious effects to aquatic organisms (See Contaminants, Section 6.1.3, below).

The Upper and Lower Duck MUs of Pyramid Pigtoe are threatened by development encroaching from the city of Nashville and nearby smaller urban areas such as Columbia, TN (TWRA 2016, p. 15). In terms of abundance, the population in the Duck River in Tennessee is second only to the Green, Saline, and Ouachita Rivers (TWRA 2016, p. 33). The extent of the Pyramid Pigtoe in the Duck River is limited to a reach downstream of Lillard's Mill Dam to Columbia, and the species is rare in the Duck River (Ahlstedt *et al*. 2017, p. 69). Despite the presence of the species in a high quality reach of the Duck River, where it co-occurs with other state and federally protected mussels, the population is linear in orientation, fragmented by mill dams, and affected by agriculture and human residential development, which continues to degrade habitat and water quality in the Upper and Lower Duck MUs.

The Tuscarawas River has been severely degraded by industrial development, which continues to affect water quality in the basin (Hoggarth 1994, p. 3; Haefner and Simonson 2018, p. 1). Population centers along the Ohio, Cumberland, and Tennessee River main stems have a long history of human settlement and associated construction within their floodplains, and are experiencing accelerated development activities within the Pyramid Pigtoe's former range in riparian areas along these rivers (ORSANCO 2016, p. 10). This human population expansion may limit reintroduction potential of the species in the Tuscarawas and Ohio Rivers, which, based on museum collections, were large in abundance and extent prior to extirpation.

There are several locations where the Pyramid Pigtoe occurs in water bodies located on or immediately adjacent to Federal lands. These include the National Wildlife Refuges (Refuge) managed by the Service, and a National Park managed by the National Park Service (NPS). While the Pyramid Pigtoe is not a species currently receiving any active management strategies, it likely receives some indirect benefits from occurrence on these lands (such as lack of urbanization/developmental pressure).

The Pond Creek Refuge in Arkansas (Arkansas-White-Red basin) as well as Upper Ouachita, Felsenthal, and White River Refuges (Lower Mississippi basin), and Wheeler Refuge (Tennessee Basin) are important public land holdings adjacent to large rivers where the Pyramid Pigtoe occurs. The location of Mammoth Cave National Park also provides a level of localized protection against development pressures for the Pyramid Pigtoe population in the upper Green River, Kentucky (Ohio Basin).

A programmatic Safe Harbor Agreement (SHA) and Candidate Conservation Agreement with Assurances (CCAA) with private landowners in Arkansas focuses on those non-Federal lands adjacent to streams and upland areas that may contribute sediment and pollutant runoff; these conservation tools are intended to provide benefits to a suite of protected and at-risk aquatic species. This agreement resulted from a partnership between the Arkansas Game & Fish Commission (AGFC), the Nature Conservancy's (TNC) Arkansas Field Office, Natural Resources Conservation Service (NRCS), and the Service. The Saline-Caddo-Ouachita Programmatic Safe Harbor Agreement covers large tracts of land in the upper Saline and Ouachita river systems, but are primarily in headwaters where the Pyramid Pigtoe does not occur (Service 2015, p. 6). Regardless, this protection of upstream tributaries and portions of river systems where the species occurs is likely to have a positive indirect long term benefit to the species.

The Nature Conservancy (TNC) has targeted areas for conservation within MUs occupied by the Pyramid Pigtoe: the upper Green River in Kentucky, the upper Clinch/Powell River, Tennessee and Virginia, the Saline River in Arkansas, and the Paint Rock River in Alabama. Although TNC has few riparian inholdings in these watersheds, they have carried out community-based and partner-oriented projects that are intended to address aquatic species and instream habitat conservation. TNC has worked with riparian landowners to help them restore and protect streambanks and riparian zones, and they collaborate with various other stakeholders in conserving aquatic resources. The location of Mammoth Cave National Park also provides a significant level of localized watershed protection against development pressures for the Pyramid Pigtoe population in the upper Green River, Kentucky. Continued collaborative conservation efforts with TNC, as well as the National Park Service (NPS) is imperative for the conservation of the Pyramid Pigtoe.

There are various small, isolated, parcels of public land (e.g., state parks, state forests, wildlife management areas) along MUs where Pyramid Pigtoe occurs. However, vast tracts of riparian lands where Pyramid Pigtoe occur are privately owned, and the prevalence of privately owned lands along rivers is comparatively much larger than the species' occurrence on public lands. This will necessitate substantial additional voluntary conservation or maintenance of riparian vegetation for overall protection of stream health. Limited overlap of the species' range with public lands diminishes the level of importance to conservation afforded by these lands that may implement various protective land use restrictions. In other words, activities in riparian lands that occurs outside or upstream of public lands may be pervasive and have a profound impact on the downstream mussel populations. Habitat protection benefits on public lands may therefore easily be negated by detrimental activities upstream or immediately downstream in a watershed.

Increased human population growth projections indicate urban sprawl will affect Pyramid Pigtoe populations in the Tennessee and Ohio basins (Terando *et al.* 2014, p. 7; Tayyebi *et al.* 2015, p. 110). A frequently cited threat to mussels is poor wastewater discharge treatments, which are generally more common in rural areas, but regardless are an indicator of anthropogenic disturbance (ESI 2009, p. 14; see section 6.1.3, Contaminants, below). The effects of commercial and residential urbanization and development on aquatic communities at large spatial scales are poorly studied (Wheeler *et al.* 2005, p. 162).

Extant populations of Pyramid Pigtoe are not concentrated in urban areas with large human occupation on the landscape; therefore, it is the potential rapid expansion of urban and suburban growth into rural and undeveloped areas that is most likely to affect the species' populations. It is currently unknown whether the anthropogenic effects of development and urbanization are likely to impact Pyramid Pigtoe at the individual or population level; however, secondary impacts such as the increased contaminant introduction, stream disturbance caused by impervious surfaces, barrier construction, and forest conversion to other land use types such as agriculture or urban uses are likely to act cumulatively on Pyramid Pigtoe populations.

6.1.2 Transportation

A major aspect of urbanization is the resultant road development. By its nature, road development increases impervious surfaces as well as land clearing and habitat fragmentation. Roads are generally associated with negative effects on the biotic integrity of aquatic ecosystems, including changes in surface water temperatures and patterns of runoff, sedimentation, adding heavy metals (especially lead), salts, organics, and nutrients to stream systems (Trombulak and Frissell 2000, p. 18). The adding of salts through road-deicing results in high salinity runoff, which is toxic to freshwater mussels. In addition, a major impact of road development is improperly constructed culverts at stream crossings. These culverts act as barriers if flow through the culvert varies significantly from the rest of the stream, or if the culvert ends up being perched, and aquatic organisms, specifically mussel host fishes, cannot pass through them. Improperly installed culverts alter in-stream habitat, and can cause changes in stream depth, resulting in pools upstream and a destabilized channel downstream of the culvert.

Transportation also includes river commerce and river navigation impacts. Dredging and channelization activities as a means of maintaining waterways have profoundly altered riverine habitats nationwide (Ebert 1993, p. 157). Channelization affects many physical characteristics of streams through accelerated erosion, increased bedload, reduced depth, decreased habitat diversity, geomorphic instability, and riparian canopy loss (Hartfield 1993, p. 139). All of these impacts contribute to loss of habitat for the Pyramid Pigtoe, and alter habitats for host fish. Changes in the water velocity, and changes in deposition of sediments not only alters physical habitat but the associated increases in turbulence, suspended sediments, and turbidity affect mussel feeding and respiration (Aldridge *et al.* 1987, p. 25). Levels of high suspended solids also result in mussel reproductive failure or low fertilization rates of long-term brooders, such as species of the genus *Pleurobema* (Gascho-Landis and Stoeckel 2015, p. 229).

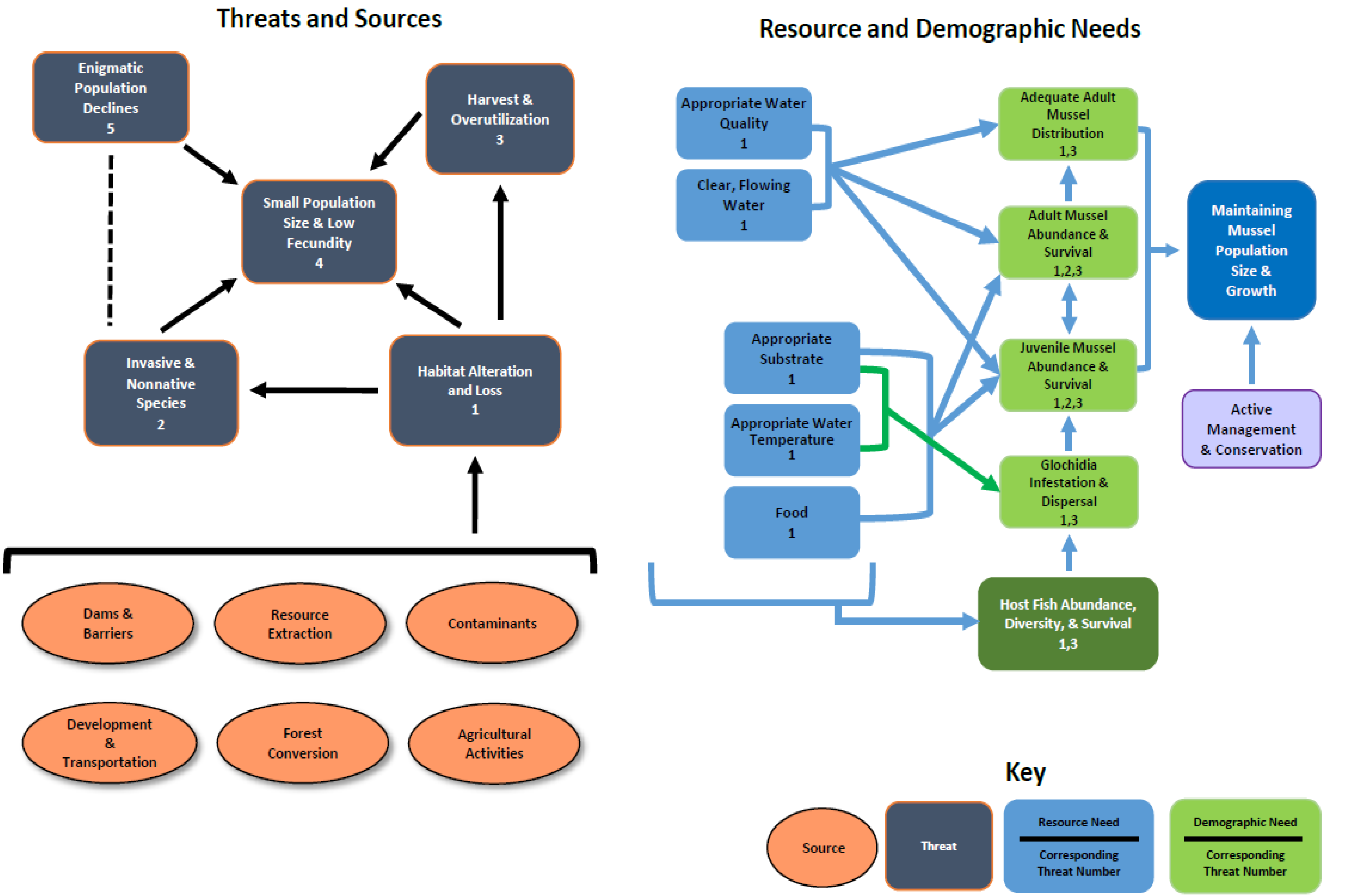

Figure 6-1. Influence diagram for Pyramid Pigtoe, depicting threats, sources of threats, and resource and demographic needs

Channel construction and modification for navigation is known to increase flood heights, and is partially attributed to a decrease in stream length and increase in gradient (Hubbard *et al.* 1993, p. 135). As a result, flood events may be exacerbated, conveying into downstream reaches large quantities of sediment, potentially with adsorbed contaminants (see section 6.1.3, below), which covers suitable mussel habitat and affects water quality. Channel maintenance, such as hydraulic (suction) dredging, may result in profound impacts downstream, including increased turbidity that may impede sight-feeding host fishes and sedimentation that smothers juvenile mussels (Ellis 1936, p. 39).

Channelization activities, which include channel enlargement, channel realignment, clearing and snagging, and manipulation of banks, were widespread in lowland areas and in the lower reaches of rivers and streams occupied by the Pyramid Pigtoe in the 1900s in the Ohio and Tennessee River basins (Haag and Cicerello 2016, p. 60). Extensive stream channelization and snag removal is also documented to result in severe impacts to the freshwater mussel fauna and habitat in the Paint Rock River system, including the lower reaches of Estill Fork and Hurricane Creek (Ahlstedt 1995-96, p. 65). Studies indicate that even if active channelization activities are not currently occurring in rivers and streams occupied by the Pyramid Pigtoe, impacts of these actions can have permanent effects such as habitat destabilization, which result in altered habitat that may be more suitable for nonnative species, or in some situations elimination of the mussel fauna (Haag and Cicerello 2016, p. 60; Hubbard *et al.* 1993, p. 142; Watters 2000, p. 274).

The Rivers and Harbors Act of 1946 authorized the U.S. Army Corps of Engineers (Corps) to maintain a navigable channel in rivers such as the Ohio, Muskingum, Ouachita, White, Mississippi, Cumberland, and Tennessee to promote and facilitate river commerce. Open channel maintenance may require hydraulic or clamshell (scoop) dredging of the navigation channel and placement of the dredged material (spoil). Dredging and spoil disposal continues to affect habitat for the Pyramid Pigtoe in these rivers. These impacts include the reduction of suitable substrates for mussel settlement and growth, and increasing suspended sediments and siltation, which affects mussel feeding and respiration (Ebert 1993, p. 157).

In addition to dredging and channel maintenance, impacts associated with barge traffic, which includes construction of fleeting areas, mooring cells, docking facilities, and propeller wash, also destroy and disrupt mussel habitat. Repeated dredging and navigation activities in concentrated areas, such as below dams, affected mussel beds in the mainstem Ohio, Mississippi, Ouachita, White, Tennessee, and Cumberland Rivers. While direct impacts of navigation such as barge traffic are more likely to affect individuals, the scope of channel maintenance activities over extensive areas alters physical habitat and degrades water quality, which affects the species at the population and MU levels.

Although most prevalent on the mainstem Ohio and Tennessee rivers, commerce and commercial navigation activities currently affect Pyramid Pigtoe populations in the Muskingum, Cumberland, Ouachita, White, and Tennessee Rivers. Commercial navigation also previously took place in the lower Green and Barren Rivers where navigation dams remain, but are not in operation. The impacts of past dredging and navigation affected mussel beds in the mainstem Cumberland River, which has the last remaining population of Pyramid Pigtoe in the Cumberland River system (Hubbs 2012, p. 9). While direct impacts of navigation such as barge traffic are more likely to affect individuals, the scope of channel maintenance activities over extensive areas alters physical habitat and degrades water quality, which affects the species at the population level.

Channel maintenance and navigation was undoubtedly a major disturbance to 14 formerly occupied MUs in the mainstem Ohio River, all of which are now considered extirpated. Currently, all of the Tennessee River mainstem Pyramid Pigtoe MUs (3) are likely affected to some extent by channel maintenance and navigation operations, due to their clustered distribution and proximity to locks and dams. The current status of these populations is difficult to accurately assess, due to challenges associated with surveying large river habitats.

6.1.3 Contaminants

Contaminants contained in point and non-point discharges can degrade water and substrate quality and adversely impact mussel populations. Although chemical spills and other point sources of contaminants may directly result in mussel mortality, widespread decreases in density and diversity may result in part from the subtle, pervasive effects of chronic, low-level contamination (Naimo 1995, p. 354). The effects of heavy metals, ammonia, and other contaminants on freshwater mussels were reviewed by Mellinger (1972); Fuller (1974); Havlik and Marking (1987); Naimo (1995); Keller and Lydy (1997); and Newton *et al.* (2003) (entire).

The effects of contaminants such as metals, chlorine, and ammonia are profound on juvenile mussels (Bartsch *et al.* 2003, p. 2,566; Augspurger *et al.* 2003, p. 2,571). Juvenile mussels may readily ingest contaminants adsorbed to sediment particles while pedal feeding (Newton and Cope 2007, p. 276). These contaminants also affect mussel glochidia, which are very sensitive to some toxicants; as has been displayed in Upper Clinch MU, which contains the Pyramid Pigtoe (Goudreau *et al.* 1993, p. 221; Jacobson *et al.* 1997, p. 2,386; Valenti *et al.* 2005, p. 1,243).

Mussels are noticeably intolerant of heavy metals (Havlik and Marking 1987, p. 4). Even at low levels, certain heavy metals may inhibit glochidial attachment to fish hosts. Cadmium appears to be the heavy metal most toxic to mussels (Havlik and Marking 1987, pp. 4–9), although chromium, copper, mercury, and zinc also negatively affect biological processes (Naimo 1995, p. 355; Jacobson *et al.* 1997, p. 2,389; Valenti *et al.* 2005, p. 1,243).

Recent improvements to remove trace metals have been made at the Appalachian Power Company's Clinch River coal-fired steam plant wastewater treatment facility, in Carbo, Virginia, which has likely resulted in improved water quality immediately downstream of the plant (Ahlstedt *et al.* 2017a, p. 221). However, the long-term declines and extirpation of mussels from the Upper Clinch MU in Virginia have been attributed to copper and zinc contamination originating from wastewater discharges at electric power plants, which emphasizes that despite localized improvements, these metals can stay bound in sediments, affecting recruitment and densities of the mussel fauna for decades (Price *et al.* 2014, p. 12; Zipper *et al.* 2014, p. 9).

Heavy metals and their toxicity to mussels have been documented in the Muskingum, Upper Clinch, and all Tennessee River MUs (Havlik and Marking 1987, pp. 4-9), which are currently occupied by the Pyramid Pigtoe. Shell concentrations of manganese, a contaminant from coal mine wastes that is negatively correlated with freshwater mussel survival and biomass (Archambault *et al.* 2017, p. 402), and potentially assimilated by mussels as a replacement of calcium during growth, was documented at high levels in the Muskingum River, Ohio (Havlik and Marking 1987, p. 8). TVA Coal plants are located within the Lower Green and Cumberland-Old Hickory MUs, and the effects of these facilities on water quality and the freshwater mussel fauna, including the Pyramid Pigtoe, are likely similar.

Among pollutants, ammonia warrants priority attention for its effects on mussels. It has been shown to be lethal to juveniles at concentrations as low as 0.7 parts per million (ppm) total ammonia nitrogen, normalized to pH 8 (range = 0.7–19.7 ppm) and lethal to glochidia at concentrations as low as 2.4 ppm total ammonia nitrogen, normalized to pH 8 (range = 2.4–10.4 ppm) (Augspurger *et al.* 2003, p. 2,574). The un-ionized form of ammonia (NH_3) is usually identified as the most toxic to aquatic organisms, although the ammonium ion form (NH_4+) may contribute to toxicity under certain conditions (Newton 2003, p. 2,554).

Documented toxic effects of ammonia on freshwater bivalves include reduced survival, reduced growth, and reduced reproduction (Augspurger *et al.* 2003, p. 2,575; Mummert *et al.* 2003, p. 2,522). Ammonia has also been shown to cause a shift in glucose metabolism and to alter the metabolic utilization of total lipids, phospholipids, and cholesterol (Chetty and Indira 1994, p. 693). Toxic effects of ammonia are more pronounced at higher pH and water temperature because the level of the un-ionized form increases as a percentage of total ammonia (Mummert *et al*. 2003, p. 2,545; Newton 2003, p. 2,554). Therefore, this contaminant may become more problematic for juvenile mussels during low flow, high temperature periods (Cherry *et al*. 2005, p. 378).

Sources of ammonia are agricultural (e.g., animal feedlots and nitrogenous fertilizers), municipal (e.g., outdated water treatment plants and industrial waste products), and from natural processes (e.g., precipitation and decomposition of organic nitrogen) (Goudreau *et al.* 1993, p. 222; Augspurger *et al.* 2003, p. 2,575; Newton 2003, p. 2,554). In stream systems, ammonia frequently is at its highest concentrations in interstitial spaces where juvenile mussels live and feed, and may occur at levels that exceed water quality standards (Cooper *et al.* 2005, p. 392; Frazier *et al.* 1996, p. 97). U.S. Environmental Protection Agency (EPA) established ammonia water quality criteria (WQC) (USEPA 1985, entire) that may not be protective of mussels (Augspurger *et al.* 2003, p. 2,571). Ammonia is considered a limiting factor for survival and recovery of some mussel populations due to its high level of toxicity and because the highest concentrations occur in their microhabitats (Augspurger *et al.* 2003, p. 2,569).

Other common contaminants associated with households and urban areas, particularly those from industrial and municipal effluents, may include heavy metals, chlorine, phosphorus, and numerous other toxic compounds. Pharmaceuticals, hormones, and other organic wastewater contaminants (OWCs) were detected downstream from urban areas and livestock production (Kolpin *et al.* 2002, p. 1,208). These OWCs (82 of the 95 tested for) originated from a wide range of residential, industrial, and agricultural sources, and some are known to have deleterious effects on aquatic organisms (Kolpin *et al.* 2002, p. 1,210). Wastewater is discharged through NPDES-permitted (and some non-permitted) sites throughout the country. In Virginia, high counts of coliform bacteria originating from wastewater treatment plants have been documented in the Upper Clinch MU, and degradation of water quality is a primary threat to aquatic fauna in these systems (Neves and Angermeier 1990, p. 50).

The toxic effects of high salinity wastewater from oil and natural gas drilling on juvenile and adult freshwater mussels were observed in the Allegheny River, Pennsylvania (Patnode *et al.* 2015, p. 55), where the Pyramid Pigtoe is extirpated (Patnode *et al.* 2015, p. 55). Extraction of mineral resources produces water with high chlorine concentrations, to which all stages of freshwater mussels are highly sensitive (Patnode *et al.* 2015, p. 56). The degradation of water quality as a result of land-based oil and gas drilling activities is a significant adverse effect on freshwater mussels, and specifically Pyramid Pigtoe in the Green River MUs.

Chemical spills occur often and are devastating for isolated populations of rare, relatively immobile species with limited potential for recolonization, such as mussels (Wheeler *et al.* 2005, p. 155). Rivers within the range of the Pyramid Pigtoe have experienced mussel and fish kills from toxic chemical spills, especially in the upper Tennessee River system in Virginia (Ahlstedt *et al.* 2016b, p. 8; Neves 1987, p. 254; Jones *et al.* 2001, p. 20; Schmerfeld 2006, p. 12).

Catastrophic pollution events, coupled with pervasive sources of contaminants from municipal and industrial pollution and coal-processing wastes have likely contributed to the decline of the Pyramid Pigtoe and other species in the Clinch River (Neves 1991, p. 260). An alkaline fly ash pond spill in 1967 and a sulfuric acid spill in 1970 on the Clinch River at Carbo, Virginia, caused massive mussel kills for up to 12 RMs downstream from a power plant (Ahlstedt *et al*. 2016b, p. 8). Sediment from the upper Clinch River was found to be toxic to juvenile mussels, which has contributed to the decline and lack of recruitment of mussels in the Virginia portion of the river (Ahlstedt and Tuberville 1997, p. 74; Price *et al.* 2014, p. 855).

In 1998, a major spill of rubber accelerant in the upper Clinch River, Virginia, eliminated approximately 18,000 individuals of several mussel species (Jones *et al.* 2001, p. 20; Schmerfeld 2006, p. 12). The death toll also included approximately 750 individuals of three federally listed species (Schmerfeld 2006, p. 12). A catastrophic chemical spill in 1999 of sodium dimethyl dithiocarbamate, a chemical used to reduce and precipitate hexachrome, affected approximately 10 RMs of the Ohio River and resulted in the loss of an estimated one million mussels, including two federally listed species (Butler 2005 p. 24). Chemical spills will invariably continue to occur and have the potential to reduce or eliminate Pyramid Pigtoe populations.

Spills of hazardous or toxic materials are an ongoing problem associated with commercial navigation and river-oriented industry, and a threat to freshwater mussels. Activities and areas of particular concern include vessel fueling operations (including midstream), barge loading/off-loading operations, queuing areas, and river reaches with heavy debris (Miller *et al.* 1989, p. 15). Spills also may damage or contaminate nearshore and depth-transitional areas where mussel beds are common (Miller and Payne 1998, p. 184).

State and Federal Water Quality Programs

Section 401 of the Federal Clean Water Act (CWA) requires that an applicant for a Federal license or permit provide a certification that any discharges from the facility will not degrade water quality or violate water-quality standards, including those established by states. Section 404 of the CWA establishes a program to regulate the discharge of dredged and fill material into waters of the United States.

Permits to fill wetlands and fill, culvert, bridge, or re-align streams or water features are issued by the Corps under Nationwide Permits, Regional General Permits, or Individual Permits.

- *Nationwide Permits* are for "minor" impacts to streams and wetlands, and do not require an intense review process. These impacts usually include stream impacts under 150 ft (45.7 m), and wetland fill projects up to 0.50 ac (0.2 ha). Mitigation is usually provided for the same type of wetland or stream affected, and is usually at a 2:1 ratio to offset losses and make the "no net loss" closer to reality.
- *Regional General Permits* are for various specific types of impacts that are common to a particular region; these permits will vary based on location in a certain region/state.
- *Individual Permit*s are for the larger, higher impact and more complex projects. These require a complex permit process with multi-agency input and involvement. Impacts in these types of permits are reviewed individually and the compensatory mitigation chosen may vary depending on project and types of impacts.

Current State regulations regarding pollutants are designed to be protective of aquatic organisms; however, unionids may be more susceptible to some pollutants than the test organisms commonly used in bioassays. Additionally, water quality criteria may not incorporate data available for freshwater mussels (March *et al.* 2007, pp. 2,066–2,067). A multitude of bioassays conducted on 16 mussel species (summarized by Augspurger *et al.* 2007, pp. 2,025–2,028) show that freshwater mollusks are more sensitive than previously known to some chemical pollutants, including chlorine, ammonia, copper, fungicides, and herbicide surfactants.

Another study found that nickel and chloride were toxic to a federally threatened mussel species at levels below the current criteria (Gibson 2015, p. 80). The study also found mussels are sensitive to sodium dodecyl sulfate (SDS), a surfactant commonly used in household detergents, for which water quality criteria do not currently exist (Gibson 2015, p. 90). Several studies have demonstrated that the criteria for ammonia developed by EPA in 1999 were not protective of freshwater mussels (Augspurger *et al.* 2003, p. 2,571; Newton *et al.* 2003, pp. 2,559–2,560; Mummert *et al.* 2003, pp. 2,548–2,552). However, in 2013 EPA revised its recommended criteria for ammonia after having considered newer toxicity data on sensitive freshwater mollusks (August 22, 2013, 78 FR 52192). Few states in the range of the Pyramid Pigtoe have adopted the new ammonia criteria. NPDES permits are valid for 5 years; thus, even after the new criteria are adopted, it could take several years before facilities must comply with the new limits.

Despite existing authorities such as the Clean Water Act, pollutants continue to impair the water quality in portions of the Pyramid Pigtoe. State and Federal regulatory mechanisms have helped reduce the negative effects of point source discharges since the 1970s, yet these regulations are difficult to implement and regulate. Although new water quality criteria are under development that will take into account more sensitive aquatic species, most current criteria do not. It is expected that several years will be needed to implement new water quality criteria throughout the range.

6.1.4 Agricultural Activities

6.1.4.1 Nutrient Pollution

Farming operations, including Concentrated Animal Feeding Operations (CAFOs), can contribute to nutrient pollution when not properly managed (EPA 2016, entire). Fertilizers and animal manure, which are both rich in nitrogen and phosphorus, are the primary sources of nutrient pollution from agricultural sources. If fertilizers are not applied properly, at the right time of the year and with the right application method, water quality in the stream systems can be affected. Excess nutrients affect water quality when it rains or when water and soil containing nitrogen and phosphorus wash into nearby waters or leach into groundwater. Excess nitrogen and phosphorus may cause algal blooms in surface waters (Carpenter *et al.* 1998, entire).

Fertilized soils and livestock can be significant sources of nitrogen-based compounds like ammonia and nitrogen oxides (Carpenter *et al.* 1998, entire). Ammonia can be harmful to aquatic life if large amounts are deposited to surface waters (see section 6.1.3, Contaminants, above). The lack of stable stream bank slopes from agricultural clearing or the lack of stable cover crops between rotations on farmed lands can increase the amount of nutrients that enter nearby streams by way of increased soil erosion (cover crops and other vegetation will use excess nutrients and increase soil stability) (Barling and Moore 1994, p. 543). Livestock often use streams or artificial in-line ponds as a water source, this degrades water quality and stream bank stability and reduces water quantity available for aquatic fauna, like the Pyramid Pigtoe, that may occur downstream from these agricultural activities.

6.1.4.2 Pumping for Irrigation

Irrigation is the controlled application of water for agricultural purposes through manmade systems to supply water requirements not satisfied by rainfall. It is common practice to pump water for irrigation from adjacent streams or rivers into a reservoir pond, or spray it directly onto crops. If the water withdrawal is excessive, this may cause impacts to the amount of water available to downstream sensitive areas during low flow months, resulting in dewatering of channels and stranding of mussels. Some water withdrawal is done illegally (without permit if needed, or during dry time of year, or in areas where sensitive aquatic species occur without consultation).

Some water withdrawals are done illegally (without permit if needed, or during dry time of year, or in areas where sensitive aquatic species occur without consultation). Currently, water withdrawals for irrigation are a threat to Pyramid Pigtoe populations in all basins in which it occurs, and are particularly detrimental to the medium condition Upper Duck MU (Corps 2012, p. 34). Water withdrawals for irrigation for agricultural uses increase during the most dry times of year, and when combined with drought, reduce surface and groundwater levels which affect resource needs for the Pyramid Pigtoe such as clean, flowing water (see Chapter 4).

6.1.4.3 Agriculture Exemptions from Permit Requirements

Normal farming (practices consistent with proper, acceptable customs and standards), silviculture, and ranching activities are exempt from the section 404 permitting process under the CWA. This includes activities such as construction and maintenance of farm ponds, irrigation ditches, and farm roads. If the activity might affect rare aquatic species, the Corps does require farmers to ensure that any "discharge shall not take, or jeopardize the continued existence of, a threatened or endangered species, or adversely modify or destroy the critical habitat of such species," and to ensure that "adverse impacts to the aquatic environment are minimized." However, the Corps does not require the farmer to consult with appropriate State or Federal Agencies regarding these sensitive species.

Channelization associated with the draining of agricultural fields is a concern for the species. For example, significant permanent negative impacts on river and stream habitats have been documented in Indiana, including in the Mississinewa River drainage (Lau *et al.* 2006, p. 324), where the Pyramid Pigtoe is extirpated. Specifically, the loss of riffle and pool habitats as a result of modification causes a lack of variable stream width, depth, flow, substrates and vegetative cover, and creates homogeneous habitats that do not support diverse fish assemblages (Lau *et al.* 2006, p. 327). The loss of river habitats as a result of channelization affects the Pyramid Pigtoe directly and indirectly, as it also relies on mixed substrates, habitat heterogeneity, and microhabitats supporting benthic fish species (Gordon and Layzer 1989, p. 28).

Agricultural impacts have been documented in streams where Pyramid Pigtoe occurs. Agricultural erosion is listed among the factors affecting the Clinch River (Ahlstedt *et al.* 2016a, p. 8), and is identified as a threat to Clinch River health (Zipper *et al.* 2014, p. 810). The medium condition Upper and Lower Duck MUs in Tennessee have significant agricultural activity in their headwaters and tributaries and are a suspected cause for mussel community declines (Ahlstedt *et al*. 2017b, p. 100). Conversion of agricultural land for suburban development is increasing at rapid rates in the Duck River system (TWRA 2011, p. 13; Irwin and Alford 2018, p. 40). Agricultural Best Management Practices (BMP) generally are not required unless the applicant is receiving federal grant funds, therefore compliance is sporadic.

The decline of mussel diversity has been tied to increases of density and scale of maize agriculture and prehistoric land use patterns, particularly in the Lower Mississippi basin (Peacock *et al.* 2005, p. 549). Conversion of forest to row crop and pasture agricultural practices have been identified as a primary factor in freshwater mussel declines. The specific impacts identified include loss of riparian vegetation, reduced water quality and erosion problems, siltation, introduction of pathogens related to poor agricultural and silvicultural practices, and presence of potentially high levels of nitrogenous wastes (Hanlon *et al.* 2009, p. 12).

6.1.4.4 Agricultural Activities Summary

The advent of intensive row crop agricultural practices has been cited as a potential factor in freshwater mussel decline, and species extirpation, in the eastern United States (Peacock *et al.* 2005, p. 550). Nutrient enrichment and water withdrawals, threats commonly associated with agricultural activities, may be localized and limited in scope, and have the potential to affect individual Pyramid Pigtoe mussels. However, chemical control using pesticides; including herbicides, fungicides, and insecticides as well as their surfactants and adjuvants, are highly toxic to juvenile and adult freshwater mussels (Bringolf *et al.* 2007, p. 2,092). Waste from confined animal feeding and commercial livestock operations is another potential source of contaminants that come from agricultural runoff. The concentrations of these contaminants from fields or pastures may be at levels that can affect an entire population, especially given the highly fragmented distribution of the Pyramid Pigtoe (also see section 6.1.3).

Agencies such as the Natural Resources Conservation Service (NRCS), and the Soil and Water Conservation Districts, provide technical and financial assistance to farmers and private landowners. Additionally, county resource development councils and university agricultural extension services disseminate information on the importance of minimizing land use impacts, specifically agriculture, on aquatic resources. These programs help identify opportunities for conservation through projects such as exclusion fencing and alternate water supply sources, which help decrease nutrient inputs and water withdrawals and help keep livestock off of stream banks and shorelines, reducing erosion. However, the overall effectiveness of these programs over a large scale with varying agricultural intensities is unknown.

Impacts from agricultural runoff and cultivation activities are a threat to the Pyramid Pigtoe populations and MUs in the Ohio and Tennessee basins. Given the large extent of private land and agricultural activities within the range of the Pyramid Pigtoe, the effects of agricultural activities that degrade water quality and result in habitat deterioration are not frequently detected until after the event(s) occur. In summary, agricultural activities are pervasive across the range of the Pyramid Pigtoe. Populations are located in areas across nine states that have varying levels of agricultural activity. The effects of agricultural activities on the Pyramid Pigtoe are widespread and a contributing factor in its decline.

6.1.5 Dams and Barriers

The effects of impoundments and barriers on aquatic habitats and freshwater mussels are relatively well-documented (Watters 2000, p. 261). This section is intended to be summary of the effects, as opposed to a comprehensive overview, dams and other barriers have on the Pyramid Pigtoe.

Extinction/extirpation of North American freshwater mussels can be traced to impoundment and inundation of riffle habitats in all major river basins of the central and eastern U.S. (Haag 2009, p. 107). Humans have constructed dams for a variety of reasons: flood prevention, water storage, electricity generation, irrigation, recreation, and navigation (Eissa and Zaki 2011, p. 253). Dams, either natural (by beavers or by aggregations of woody debris) or man-made, have many impacts on stream ecosystems. Reductions in the diversity and abundance of mussels are primarily attributed to habitat shifts caused by impoundments (Neves *et al.* 1997, p. 63). The survival of mussels and their overall reproductive success are influenced:

● *Upstream of dams* – the change from flowing to impounded waters, increased depths, increased buildup of sediments, decreased dissolved oxygen, and the drastic alteration in resident fish populations.

● *Downstream of dams* – fluctuations in flow regimes, minimal releases and scouring flows, seasonal dissolved oxygen depletion, reduced or increased water temperatures, and changes in fish assemblages.

As mentioned above in section 6.1.2, improperly constructed culverts at stream crossings may act as significant barriers, and have some similar effects as dams on stream systems. Fluctuating flows through the culvert can vary significantly from the rest of the stream, preventing fish passage and scouring downstream habitats. For example, if a culvert sits above the streambed, aquatic organisms cannot pass through them. These barriers not only fragment habitats along a stream course, they also contribute to genetic isolation of the aquatic species inhabiting the streams.

All of the rivers currently occupied by the Pyramid Pigtoe in the Ohio and Tennessee River basins are directly affected by dams, thus directly influencing the species' distribution rangewide, perhaps more so than any other factors influencing the species. It is not only the existence of these structures but how they are operated which influences mussel populations. Impacts of these dams to the Pyramid Pigtoe include population isolation, hydrological instability, high shear stress, scour, and cold water releases, which suppress mussel recruitment (Hardison and Layzer 2001, p. 79; Hubbs 2012, p. 8).

Hypolimnetic discharges from hydropower dams, associated with peaking hydropower production, especially during peak spawning season, are a continual threat to the Pyramid Pigtoe in the Ohio and Tennessee basins, and undoubtedly contributed to species decline in the Cumberland River system (Layzer *et al*. 1993, p. 69). The correlation of these cold water discharge "spikes" and the abortion of embryos and glochidia, result in mussel recruitment failure (McMurray *et al.* 1999, p. 61). A list of some of the dams currently directly influencing populations, MUs, and the overall distribution of the Pyramid Pigtoe in the Ohio and Tennessee basins include:

- Green River Dam and 4 Locks and Dams - Green River (Kentucky)
- Barren River Dam and Lock and Dam 1 - Barren River (Kentucky)
- Wolf Creek, Old Hickory, and Cordell Hull Dams - Cumberland River (Tennessee and Kentucky)
- Cherokee Dam - Holston River (Tennessee)
- Norris Dam - Clinch River (Tennessee and Virginia)
- Normandy and Shelbyville, Lillards Mill, and Columbia Dams - Duck River (Tennessee)
- Kentucky, Pickwick, Wilson, Wheeler, and Guntersville Dams - Tennessee River (Alabama and Tennessee)

Additionally, there are 11 Locks & Dams on the Muskingum River in Ohio from Zanesville downstream to the Ohio River. Operational changes to incorporate hydropower in addition to flood control and navigation at existing dams are underway (Boyer 2020, pers. comm.). These changes increase the potential for negative impacts to the Pyramid Pigtoe and other rare mussels in the Muskingum River through changes in shear velocity, potentially affecting the substrate and unionid communities through alteration of habitat (ESI 2012, p. 26).

The construction and continued operation of dams have historically resulted in extirpations of the Pyramid Pigtoe. In the Caney Fork River, Tennessee, many adverse effects of impoundments are contributing to habitat loss for mussels, including altered temperature regimes, silt deposition, unstable substrates, sedimentation, oxygen depletion, altered river morphology, dewatering, and reservoir fluctuation (Layzer *et al.* 1993, p. 68). A low condition population currently persists in the lower main stem Holston MU in Tennessee, where construction of Cherokee Dam in 1941 has resulted in extirpation of approximately 75 percent of the native mussel fauna downstream of the dam (Parmalee and Faust 2006, pp. 74-77). Large fluctuation in flow rates, water temperatures, and water depth hinder colonization potential (Parmalee and Faust 2006, p. 73).

Another dramatic example of dam impacts within Pyramid Pigtoe's historical range is on the Ohio River, where there are 19 Locks & Dams on the mainstem between Pennsylvania and Illinois (Watters and Flaute 2010, p. 2). Though it once occurred throughout the river, the Pyramid Pigtoe is now extirpated from the entire Ohio River mainstem, with dam construction cited as a primary contributor (Watters and Flaute, 2010, p. 1). A net loss of 18.6 linear mi (30 km) of mussel beds occurred between RM 317 and RM 981 since 1967 (Williams and Schuster 1989, p. 3; whose studies geographically overlap ESI 2000, p. 9).

The most drastic change was the complete absence of mussel beds in 51.8 mi (83 km) of the Ohio River above McAlpine Lock & Dam (Williams and Schuster 1989, p. 10). In the interval between 1967 and 1982, within the same study area above the McAlpine Lock & Dam, four high-lift dams (Cannelton, Newburgh, John T. Myers, and Smithland) replaced wicket dams (non-modern dams that helped regulate the river for boat passage); subsequently, between 1982 and 1994, eight mussel beds were lost entirely in tailwaters between RM 438 and RM 981 (Clarke 1995, p. 13).

Green River Lock and Dam 6 in the Ohio basin in central Kentucky was removed in 2017 through a collaborative effort between state and federal agencies and non-governmental partners. This dam removal expanded free flowing hydrological conditions of the Green River approximately 9.9 RM (16 km) downstream, as well as provided river habitat connectivity with the Nolin River. The anticipated future removal of Lock and Dam 5 downstream will continue to open up riverine habitats for freshwater mussels in the middle and lower Green River, which harbors the best remaining Pyramid Pigtoe population.

The Reservoir Release Improvement (RRI) Program, initiated by TVA in 1988, focuses on improvements in dissolved oxygen concentrations below dams, including initiating minimum flows at dams in the Tennessee River drainage (Higgins and Brock 1999, p. 4). The RRI program has resulted in improved oxygen, stable water temperatures, decreased bank erosion, and stabilization of habitat in several river systems (Scott *et al.* 1996, p. 5). However, impacts to mussels continue to limit distribution, specifically affecting the remaining riverine habitat for the Pyramid Pigtoe or its host fishes below other dams in the Tennessee basin, including lack of seasonal variability in flow releases, thermal regimes that are unsuitable for mussels, and significant bank erosion and riverbed scour (Parmalee and Faust 2006, p. 73; Layzer and Scott 2006, p. 488).

Whether constructed for purposes such as flood control, navigation, hydropower, water supply, recreation, or multi-purpose uses, the construction and continued operation of dams is a pervasive negative influence on the Pyramid Pigtoe and its habitat throughout the range of the species. Although there have been recent efforts to remove older, failing dams such as Lock and Dam 6 on the Green River, and future removal of smaller mill dams on the Duck River is possible, dam removals on larger rivers such as the Tennessee and Cumberland are not foreseeable.

Dams on rivers occupied by the Pyramid Pigtoe; on the Ouachita, White, Green, Barren, Cumberland, Clinch, Holston, Tennessee, and Duck Rivers, are owned by the federal government (Corps and TVA). Operations are authorized through congressional mandates, and as such, not only are they unlikely to be removed, but alterations from current operational regimes require opportunities that do not occur frequently, such as water control manual updates or reservoir operation system studies. Updates and re-assessments of how these dams are operated may occur only once every 10-20 years, and are the primary opportunities to implement changes in how these dams are operated. Dams and their effects on Pyramid Pigtoe population distribution have had perhaps the greatest documented negative influence on the species (Hardison and Layzer 2001, p. 79; Layzer *et al.* 1993, p. 68; Hubbs 2012, p. 8; Watters and Flaute 2010, p. 2).

Dams destroy habitat, alter and disrupt connectivity, and alter water quality, all of which affect Pyramid Pigtoe species needs at the individual and population levels. The five genetically verified MUs containing Pyramid Pigtoe are located either below (Normandy Dam, Duck River, Tennessee), above (Norris Dam, Clinch River, Tennessee and Virginia) or below and above (Lock & Dam 4, Green River Dam, Green River, Kentucky) dams. While few new dams are likely to be constructed in the 21st century, Federal mandates issued to the Corps and TVA for the maintenance and continued operation of dams (such as Normandy, Norris, and Green River Dam), as well as dams on the Muskingum, Cumberland and Tennessee Rivers, make this a persistent population, basin, and rangewide threat to the Pyramid Pigtoe.

6.1.6 Resource Extraction

6.1.6.1 Coal Mining

Across the Pyramid Pigtoe's range, the most significant resource extraction impacts come from coal mining and oil and gas exploration activities. Activities associated with coal mining and oil and gas drilling can contribute chemical pollutants to streams. Acid mine and saline drainage (AMD) is created from the the oxidation of iron-sulfide minerals such as pyrite, forming sulfuric acid (Sams and Beer 2000, pp. 3). This AMD may be associated high concentrations of aluminum, manganese, zinc, and other constituents (TDEC 2014, p. 72). These metals, and the high acidity typically associated with AMD, can be acutely and chronically toxic to aquatic life (Jones 1964, pp. 96). Implementation of the Surface Mining Control and Reclamation Act of 1977 (SMCRA) has significantly reduced AMD from new coal mines; however, un-reclaimed areas mined prior to SMCRA continue to generate AMD in portions of the Pyramid Pigtoe's range.

Surface mining has been identified as a source of impairment for approximately 775 mi (1,247 km) of streams in Kentucky (KDEP 2014, p. 66). Mining continues to impair water quality in streams in the Cumberland Plateau and Central Appalachian regions of Tennessee and Kentucky (TDEC 2014, p. 62), and is the primary source of low pH impairment of 376 mi (605 km) of rivers in Tennessee (TDEC 2014, p. 53). According to Ahlstedt *et al.* (2016b, p. 8), coal mining has resulted in discharges of industrial and mine wastes, black water release events, and fly-ash spills in the Clinch and Powell Rivers.

High concentrations of zinc and copper were found in sediments below a coal processing plant in the Clinch River, Virginia, resulting in reduced survival of juvenile mussels (Ahlstedt and Tuberville 1997, p. 75). The negative influence of mined land on mussels in the Clinch River has also been demonstrated through elevated levels of tissue zinc concentrations and dissolved manganese, indicating chronic mussel exposure to contaminated runoff (Van Hassel 2007, p. 323). The concentrations of toxic metals as a result of coal processing and mining activities, in addition to water quality degradation from abandoned mines, is a population-level threat to the Pyramid Pigtoe in the Upper Clinch MU.

6.1.6.2 Natural Gas Extraction

Natural gas extraction in the Marcellus Shale (the largest natural gas field in the U.S. that runs through northern Appalachia) region has negatively affected water quality through accidental spills and discharges, as well as increased sedimentation due to increases in impervious surface and tree removal for drill pads and pipelines (Vidic *et al*. 2013, p. 6). Disposal of insufficiently treated brine wastewater, more saline than seawater, has specifically been found to adversely affect freshwater mussels (Patnode *et al*. 2015, p. 62). Contaminant spills are also a concern.

Sediment appears to be the largest impact to mussel streams from gas extraction activities (Clayton, 2018, pers. comm.). Excessive suspended sediments can impair feeding processes, leading to acute short-term or chronic long-term stress. Both excessive sedimentation and excessive suspended sediments can lead to reduced mussel populations (Ellis 1936, p. 29; Anderson and Kreeger 2010, p. 2). This sediment is generated by construction of the well pads, access roads, and pipelines (for both gas and water). The impact of pipelines crossing mussel streams through open-trenching, the preferred industry method, increases sediment load and contributes to a loss of mussel habitat through sedimentation, and the covering of appropriate substrates.

The release of drilling mud through fracturing is an additional potential impact to rivers and streams, as well as spill of frack fluids used in the well drilling process, which are high in chlorides and other chemicals (Patnode *et al* 2015, p. 63). Other significant sediment impacts originate from bank slippage and mudslides due to pipeline construction, access road construction and well pad construction in mountainous terrain (Clayton 2018, pers. comm.).

6.1.6.3 Gravel Mining & Dredging

Instream sand and alluvial gravel mining has been implicated in the destruction of mussel populations (Hartfield 1993, p. 138). Negative impacts associated with gravel mining include stream channel modifications such as altered habitat, disrupted flow patterns, and sediment transport (Hubbs *et al* 2006, p. 170). Additionally, water quality modifications including increased turbidity, reduced light penetration, increased temperature, and increased sedimentation result from gravel mining. These habitat and water quality degradations result in reductions in macroinvertebrate population and fish populations, which suffer impacts to spawning and nursery habitat, and food web disruptions (Brown *et al.* 1998, p. 988; Kondolf 1997, p. 541).

The Corps and state water quality agencies retain regulatory oversight for sand and gravel mining, but most sand, gravel, and rock mining in rivers is unmonitored. Detection of destructive instream and riparian gravel mining is sometimes only observed through organismal inventory and river monitoring efforts. The extensive mining of gravel in riparian zones reduces vegetative buffers and causes channel instability, and has been implicated in mussel declines in the Walhonding River, Ohio, where the Pyramid Pigtoe is considered extirpated (Hoggarth 1995–96, p. 150).

6.1.6.4 Resource Extraction Summary

Coal mining, AMD, and the legacy effects of abandoned mine runoff are currently affecting Pyramid Pigtoe populations in the Ohio and Tennessee basins. The presence of a large number of mine waste ponds in the Ohio and Tennessee basins increase the risk of dam and levee failure, and blowouts, resulting in mining waste covering the substrate, which could be catastrophic to remaining Pyramid Pigtoe populations. Resource extraction and acid mine drainage are associated with the loss of mussel species in the Cumberland River system (Haag and Cicerello 2016, p. 15). This is specifically true in the Big South Fork Cumberland River, where the Pyramid Pigtoe no longer occurs, and which may limit recovery opportunities (Ahlstedt *et al.* 2003-2004, p. 39).

Abandoned AMD is cited as an imminent threat to the medium condition Pyramid Pigtoe in the Upper Clinch MU (Ahlstedt *et al.* 2016a, p. 11). Additionally, direct and indirect effects of water quality degradation, pollution, and chemical toxicity as a result of active or past mining activities have been cited as affecting freshwater mussel populations throughout much of the historical and current range of the Pyramid Pigtoe (Haag and Cicerello 2016, pp. 9-16). The Pyramid Pigtoe is extirpated from the Caney Fork & Big South Fork, as well as the upper Cumberland River. These rivers have experienced water quality degradation resulting from acid mine drainage and intensive surface mining activity, and mussel population declines have been well documented (Ahlstedt *et al*. 2004, p. 33; Anderson *et al.* 1991, p. 6; Layzer and Anderson 1992, p. 97; Layzer *et al*. 1993, entire; Warren and Haag 2005, p. 1,383).

Commercial sand and gravel mining and dredging directly affects the Pyramid Pigtoe in the Tennessee River, specifically within the Lower Tennessee – Beech MU (Hubbs *et al.* 2006, p. 170). The Pyramid Pigtoe in the Tennessee River (Wheeler Lake, Pickwick, and Lower Tennessee-Beech MUs) is restricted primarily to tailwater reaches below locks and dams that have periodic dredging to the lock approaches and to maintain the navigation channel. The Lower Cumberland Old Hickory MU has also been affected by gravel mining and dredging in the past (Sickel 1982, p. 4), which results in permanent alteration of substrates and hydraulic patterns, contributing to habitat loss for freshwater mussels. Additionally, although aggregate extraction activities no longer occur in the Allegheny River, the long-lasting impacts of these activities remain, which limits restoration potential particularly in the lower reaches, where the Pyramid Pigtoe is considered extirpated (Ortmann 1919, p. 223; Smith and Meyer 2010, p. 542).

6.1.7 Conversion and Loss of Forests

A forested landscape provides many ideal conditions for aquatic ecosystems. Depending on the structure and function of the forest, and particularly if native, natural mixed hardwood-conifer forests comprise the active river area (ARA), rain is allowed to slowly infiltrate and percolate (as opposed to rapid surface runoff), a variety of food resources enter the stream and river via leaf litter and woody debris, banks are stabilized by tree roots, habitat is created by occasional wind throw, and riparian trees shade the stream or river and maintain thermal climate.

Small and large-scale conversion of forested habitats to other land uses have been shown to have a significant impact depending on the physical, chemical, and biological characteristics of adjacent streams (Allan and Castillio 2004, p. 107). The conversion of large areas of forested wetlands and riparian systems to agricultural or urban uses eliminates shade once provided by the tree canopies, exposing streams to more sunlight and increasing the in-stream water temperature (Wenger 1999, p. 35). The increase in stream temperature and light after deforestation has been found to alter the macroinvertebrate and other aquatic species richness and abundance composition in streams to various degrees depending a species tolerance to temperature change and increased light in the aquatic system (Kishi *et al.* 2004, p. 283; Couceiro *et al.* 2007, p. 272; Caldwell *et al.* 2014, p. 2196).

Sediment runoff from cleared areas is a known stressor to aquatic systems (e.g., Webster *et al.* 1992, p. 232; Jones III *et al.* 1999, p. 1,455; Broadmeadow and Nisbet 2004, p. 286; Aust *et al.* 2011, p. 123). The physical characteristics of stream channels are affected when large quantities of sediment are added or removed (Watters 2000, p. 263). Mussels and fish are potentially affected by changes in suspended and bed material load, bed sediment composition associated with increased sediment production and runoff in the watershed, channel changes in form, stream crossings, and inadequately buffered clear-cut areas, all of which can be significant sources of sediment entering streams (Taylor *et al.* 1999, p. 13).

Around the turn of the 21st century, biologists, foresters, and managers recognized the need for wholesale implementation of BMPs and FPGs to address many of the aforementioned issues related to forest conversion and silvicultural practices. Currently, forestry BMP and FPG manuals suggest planning road systems and harvest operations to minimize the number of stream crossings. Proper construction and maintenance of crossings reduces soil erosion and sedimentation with the added benefit of increasing harvest operation efficiency.

6.2 Invasive and Non-native Species

Approximately 42 percent of Federally Threatened or Endangered species are estimated to be significantly affected by nonnative, nuisance species across the nation, and nuisance species are significantly impeding recovery efforts for them in some way (National Invasive Species Council Management Plan 2016, p. 2). When a nonnative species is introduced into an ecosystem, it may have many advantages over native species, such as easy adaptation to varying environments and a high tolerance of living conditions that allow it to thrive in its new habitat.

There may not be natural predators to keep the nonnative species in check; therefore, it can potentially live longer and reproduce more often, further reducing the biodiversity in the system. The native species may become an easy food source for invasive species, or the invasive species may carry diseases that extirpate populations of native species. Examples of non-native species that affect freshwater mussels such as the Pyramid Pigtoe are the Asian Clam (*Corbicula fluminea*), Zebra Mussel (*Dreissena polymorpha*), Quagga Mussel (*Dreissena bugenis*), Black Carp (*Mylopharyngodon piceus*), Didymo (a.k.a. rock snot; *Didymosphenia geminata*), and Hydrilla (a.k.a. water-thyme; *Hydrilla verticillata*).

The Asian Clam alters benthic substrates, may filter mussel sperm or glochidia, competes with native species for limited resources, and causes ammonia spikes in surrounding water when they die off en masse (Scheller 1997, p. 2). The Asian clam is hermaphroditic, enabling fast colonization and is believed to practice self-fertilization, enabling rapid colony regeneration when populations are low (Cherry *et al.* 2005, p. 378). Reproduction and larval release occur biannually in the spring and in the late summer. A typical settlement of the Asian clam occurs with a population density ranging from 100 to 200 clams per square meter, which may not be detrimental to native unionids; however, populations can grow as large as 3,000 clams per square meter, which would influence both food resources and competition for space for the Pyramid Pigtoe. Asian clams are prone to have die-offs that reduce available dissolved oxygen and increase ammonia, which can cause stress and mortality to the Pyramid Pigtoe (Cherry *et al.* 2005, p. 377).

Dreissenid mollusks, such as the Zebra Mussel and Quagga Mussel, are a threat to native freshwater mussels. These nonnative mollusks are known to occur in the Great Lakes, Ohio, Tennessee, and the St. Lawrence River basins. Mussels, such as the Pyramid Pigtoe, are adversely affected by Dreissenids through direct colonization, reduction of available habitat, changes in the biotic environment, or a reduction in food sources (MacIsaac 1996, p. 292). Zebra mussels are listed by Congress by statute as Injurious Wildlife under the Lacey Act (*https://www.fws.gov/injuriouswildlife/pdf_files/Current_Listed_IW.pdf)*. Zebra mussels are also known to alter the nutrient cycle in aquatic habitats, affecting other mollusks and fish species (Strayer *et al.* 1999, p. 22).

Since its introduction in the Great Lakes in 1986, zebra mussel colonization has resulted in the decline and regional extirpation of freshwater mussel populations in lakes and river systems across North America (Schloesser *et al.* 1996, p. 303; Schloesser *et al.* 1998, p. 300). One of the direct consequences of the invasion of zebra and quagga mussels is the local extirpation of native freshwater mussel populations from: (1) attachment to the shells of native mussels, which can kill them (dreissenid mussels are sessile, and cling to hard surfaces); (2) affecting vertical and lateral movements of mussels, due to heavy infestations which can prevent valve closure; and (3) outcompeting native mussels and other filter feeding invertebrates for food. This problem has been particularly acute in some areas of the U.S. that have a very rich diversity of native freshwater mussel species, such as the Ohio and Tennessee River systems. Densities of Zebra mussels attained 17,000 per square meter in the Tennessee River below Wilson Dam in 2017, although recent survey efforts indicate a decline from that population explosion (Garner 2018, pers. comm.).

The two nonnative plant species that are most problematic for the Pyramid Pigtoe are hydrilla and didymo, but golden alga, (*Prymnesium parvum*), a marine algae, has spread into the upper Ohio River basin and is a potential threat to mussel populations, particularly during low-flow years and if coupled with brine discharges (Anderson and Kreeger 2010, p. 9). Hydrilla is an aquatic plant that alters stream habitat, decreases flows, and contributes to sediment buildup in streams (Balciunas *et al*. 2002, p. 2). High sedimentation can cause suffocation, reduce stream flow, and make it difficult for mussels' interactions with host fish necessary for development.

Hydrilla can quickly dominate native vegetation, forming dense mats at the surface of the water and dramatically altering the balance of the aquatic ecosystem. Hydrilla covers spawning areas for native fish and can cause significant reductions in stream oxygen levels (Colle *et al.* 1987, p. 410). Hydrilla is widespread in the Ohio, Cumberland, and Tennessee River systems. Second, didymo or "rock snot" is a nonnative alga (diatom) that can alter the habitat and change the flow dynamics of a site (Jackson 2016, p. 970). Invasive plants grow uncontrolled and can cause the habitat to fill in, they can affect flow dynamics, and cause the water to become warmer, and can even dry out completely, especially in drought situations (Colle *et al.* 1987, p. 416).

Black Carp, a molluscivore, has been reported in Arkansas, Illinois, Mississippi, and Missouri (Nico *et al.* 2005, p. 155), has been established in Louisiana since the early 1990s, and was observed most recently in 2018 in Tennessee and Kentucky (Nico and Neilson 2018, USGS Nonindigenous Aquatic Species Database). The Black Carp is listed as Injurious Wildlife under the Lacey Act. The species is present in the Ohio, Tennessee, Lower Mississippi and Arkansas-White-Red basins where it co-occurs with populations of the Pyramid Pigtoe. There is high potential that the Black Carp will negatively impact native aquatic communities by direct predation, and thus reducing, populations of native mussels and snails, many of which are considered endangered or threatened (Nico *et al.* 2005, p. 193).

Given their size and diet preferences, Black Carp have the potential to restructure benthic communities by direct predation and removal of algae-grazing snails. Mussel beds consisting of smaller individuals and juvenile recruits are probably most vulnerable to being consumed by black carp (Nico *et al.* 2005, p. 192). Furthermore, because Black Carp attain a large size (well over 3.28 ft (1 m) long), and their life span is reportedly over 15 years, they are be expected to persist many years and therefore have the potential to cause significant harm to native molluscs by way of predation to multiple age classes (Nico *et al.* 2005, p. 77).

The Aquatic Nuisance Species (ANS) Task Force, co-chaired by the Service and the National Oceanic and Atmospheric Administration (NOAA), encourages state and interstate planning entities to develop management plans describing detection and monitoring efforts of aquatic nuisance and nonnative species, prevention efforts to stop their introduction and spread, and control efforts to reduce their impacts. Management plan approval by the ANS Task Force is required to obtain funding under Section 1204 of the ANS Prevention and Control Act. Regardless of financial incentives, plans are a valuable and effective tool for identifying and addressing ANS problems and concerns in a climate of many jurisdictions and other interested entities. Each state within the range of the Pyramid Pigtoe has either a plan approved by or submitted to the ANS Task Force, or a plan under development. These plans have been effective in terms of raising awareness at the state level of the severity of ecological damage that non-native and nuisance species are capable of, but many are in early stages of implementation.

Asian clams are present throughout the range of the Pyramid Pigtoe, and the competitive interactions and effects of their massive die-offs have been documented, but the complete impacts of these non-native bivalves on native unionids is not completely understood. The arrival and proliferation of the zebra mussel in the Ohio River in the early 1990s corresponded with a significant decline in native freshwater mussel populations, including all Ohio River MUs formerly occupied by the Pyramid Pigtoe (Watters and Flaute 2010, p. 1). Zebra and quagga mussel densities are highly variable annually, and may depend on discharge rates, water temperatures, and settlement location, as well as predator presence (Cope *et al.* 2006, p. 185).

Although there are non-native species present throughout the range of the Pyramid Pigtoe in the Ohio and Tennessee River basins, the greatest concentration of non-native species that has the potential to affect mussels is in the Tennessee River MUs (Lower Tennessee – Beech, Pickwick Lake, Wheeler Lake). These non-native species discussed above affect Pyramid Pigtoe individuals through competitive interactions, water quality degradation, predation, and habitat alteration. In summary, the presence of non-native species is a substantial threat to the Pyramid Pigtoe throughout its range, but the concentration of non-native species in the Tennessee River is most problematic.

6.3 Harvest and Overutilization

Although not currently considered an imminent threat, harvest of Pyramid Pigtoe, and references to the commercial value of the species, or the Ohio Pigtoe group, are mentioned in Böpple and Coker (1912, p. 5), Coker (1919, p. 22), Danglade (1922, p. 5), Isom (1969, p. 402), Dennis (1985, p. 86), Cochran and Layzer (1993, p. 63), Cummings *et al.* (1992, p. 46), Watters and Dunn (1993-94, p. 252), and Williams *et al.* (2008, p. 54). Commercial harvest associated with the button and pearl industries of the 19th and 20th centuries, as well as the search for native pearls, likely contributed to the decline of freshwater mussels in eastern US (Anthony and Downing 2001, p. 2,072).

Native Americans harvested mussels for food. There is no documentation regarding harvest of the Pyramid Pigtoe in particular, but it was likely included among their catch. The species was collected by pearlers circa 1900 and other commercial interests in later times due to the extensive harvest that occurred within the species range (Anthony and Downing 2001, p. 2,073). Although not one of the most actively sought species for pearls, the Ohio Pigtoe group was sacrificed for this purpose (Böpple and Coker 1912, p. 5-6). Additionally, Wilson and Clark (1914, p. 9-13) documented many portions of the Cumberland River where large piles with tons of shells were left on streambanks by pearlers hoping to get rich quick.

Single beds were sometimes harvested for pearls a decade or more. In shallow Clinch River shoals harvesting mussels buried in the substrate with "a plow drawn by a strong team" was particularly disruptive to habitat (Böpple and Coker 1912, p. 10). Considering that perhaps only 1 in 15,000 mussels may produce a commercially valuable pearl, it is likely that hundreds of thousands, if not millions, of mussels were needlessly sacrificed by harvesters over several decades (Anthony and Downing 2001, p. 2,073).

Despite the alarm generated over exploitation events in historical times, the collective impact from human harvest of mussels is significantly less than the impacts realized from habitat alteration. It is unlikely that exploitation activities have eliminated Pyramid Pigtoe populations, but rather, they have potentially contributed to the species' decline. The Pyramid Pigtoe is not currently a commercially valuable species, but it may be inadvertently harvested as "by-catch" or by inexperienced mussel collectors unfamiliar with commercial species identification. In Kentucky, mussels may legally be harvested only by brail (i.e., dragging poles with hooks drug along the bottom of a river). Most states that allow commercial harvest, such as Alabama, Kentucky, and Tennessee, have established mussel sanctuaries where harvest is prohibited. Sanctuaries are generally associated with beds that have state or federally listed mussels present.

Watters and Dunn (1993-94, p. 252) attribute significant decline of mussels from previous surveys to potential over-harvest in the lowermost mussel beds in the Muskingum MU, which previously harbored a much greater extent of the species occupied than today (OSUM records; Appendix A & C). A recent survey of the lower Muskingum River reported collection of only two live Pyramid Pigtoe at 1 of 10 sites, which were estimated to be aged 16 to 25 years (ESI 2012, p. 136). A potential explanation of the increasing rarity of the Pyramid Pigtoe and other riverine mussels in the Muskingum MU and Wheeler Lake MU may be a result of years of intensive commercial activity.

Although illegal harvest of protected off-limits mussel beds occurs rangewide, commercial harvest is not thought to currently have a significant impact on the Pyramid Pigtoe. The Muskingum MU may at least in part serve as an example of the impacts of threats such as habitat fragmentation and loss combined with previous intensive collection activities on freshwater mussels. In most of the remaining MUs occupied by the Pyramid Pigtoe, harvest of mussels is restricted, and its populations are relatively small in density (see Appendix A).

Overall, the future potential direct and indirect threat of harvest and overutilization is minimal, and a small fraction of what it was 20 years ago. The Pyramid Pigtoe is morphologically similar to the Ohio Pigtoe, which was among the most commercially valuable mussel species until 2000, when it was recommended to be removed from the list of species allowed to be harvested in Tennessee (Hubbs 2000). Mussels continue to be commercially harvested from the Lower Tennessee – Beech MU, and is also permitted in the Pickwick and Wheeler Lake MUs, but direct and indirect mortality of the Pyramid Pigtoe from bycatch is unlikely to be a primary threat in the future.

6.4 Small Population Size and Low Fecundity

Pyramid Pigtoe exhibit several inherent traits that influence population viability, including relatively small population size and low fecundity at many locations compared to other mussels (see Appendix A). Pyramid Pigtoe prefer sites with clean, flowing water and stable substrates (see sections 4.1.1-4.1.3) and are not often abundant within their occupied habitats. Smaller population size puts the species at greater risk of extirpation from stochastic events (e.g., drought) or anthropomorphic changes and management activities that affect habitat. In addition, smaller populations may have reduced genetic diversity, be less genetically fit, and more susceptible to disease during extreme environmental conditions (Frankham 1996, p. 1,505).

Genetic drift occurs in all species, but disruption of genetic drift is more likely to negatively affect populations that have a smaller effective population size (number of breeding individuals) and populations that are geographically spread out and isolated from one another. Relatively low fecundity, commonly observed in species of *Pleurobema*, is another inherent factor that could influence population viability (Geist 2010, p. 91). Survival of juveniles in the wild is already low and females produce fewer offspring than other mussel species (Haag and Staton 2003, p. 2,125).

Factors such as low effective population size, genetic isolation, relatively low levels of fecundity and recruitment, and limited juvenile survival could all affect the ability of this species to maintain current population levels and to rebound if a reduction in population occurs (e.g., predation, toxic releases or spills, poor environmental conditions that inhibit successful reproduction). Additionally, hosts of the Pyramid Pigtoe are small-bodied fishes (minnows and shiners) that have comparatively limited movement (Vaughn 2012, p. 6); therefore, natural expansion of Pyramid Pigtoe populations is limited.

Fragmentation and isolation contribute to the extinction risk that mussel populations face from stochastic events (see Haag 2012, pp. 336-338). Rivers are naturally dynamic, frequently creating or shifting areas of quality habitat over a particular period. A number of factors, most of which interact to create stable patches of suitable and unsuitable mussel habitat, bring about habitat fragmentation (natural and human-induced) in stream systems. The definition of fragmentation is the breaking apart of habitat segments, independent of habitat loss (Fahrig 2003, p. 499). Some causes, like barriers, directly and permanently fragment habitat. Other sources, like drought, water quality, host fish movement, substrate stability, adjacent land use, etc., lead to increasing stream fragmentation in more subtle and interdependent ways.

In dendritic landscapes, such as streams and rivers, barriers can lead to multiple fragments of variable size (Fagan 2002, p. 3,247). In contrast to landscapes where multiple routes of movement among patches are possible, pollution or other habitat degradation at specific points in dendritic landscapes can completely isolate portions of the system (Fagan 2002, p. 3,246). Connectivity between patches (mussel beds or occupied habitat) is important in landscapes where these patches of suitable habitat are created or destroyed frequently. Where populations are small, local extinction caused by demographic stochasticity (e.g., changes in the proportion of males and females, the reproductive potential of females, survival of individuals) happens often, and populations must be re-established by colonization from other patches. Given that these conditions may apply to many lotic mussel populations, connectivity of mussel populations and their required resources is an important factor to consider for Pyramid Pigtoe persistence (Newton *et al.* 2008, p. 428).

Impoundments result in the genetic isolation of fishes, which act as hosts, and mussel populations (Vaughn 2012, p. 6; also see section 6.1.5, above). Perched or improperly maintained culverts at stream crossings can also act as significant barriers (see section 6.1.2 and 6.1.5, above), and have similar effects as dams on stream systems. Fluctuating flows through a culvert can differ significantly from the rest of the stream, preventing fish passage and scouring downstream habitats. The likelihood is high that some Pyramid Pigtoe populations are below the effective population size required to maintain long-term genetic and population viability (see Chapter 5, above and Appendices A, B, C). Recruitment reduction or failure is a potential problem for many small Pyramid Pigtoe populations rangewide, a potential condition exacerbated by its reduced range and increasingly isolated populations.

A once extensive, largely contiguous, Pyramid Pigtoe population occurred through much of the eastern US. On a geological scale, there were limited barriers preventing genetic interchange among river systems. With the completion of hundreds of dams in the 1900s, many large river Pyramid Pigtoe populations were lost, resulting in isolation of tributary populations. The population size of a long-lived species, such as the Pyramid Pigtoe, may take decades to become extirpated post-impoundment, even if recruitment failure had been complete since dam construction. At best, limited post-impoundment recruitment may be occurring in many isolated Pyramid Pigtoe populations, indicating that these small populations are probably not viable long-term.

Without the level of genetic interchange the species experienced historically (i.e., without barriers such as reservoirs), small isolated populations that may now be comprised predominantly of adult individuals could be slowly dying out. Even given the very improbable absence of other anthropogenic threats, these disjunct populations could be lost simply due to the consequences of below-threshold effective population sizes. However, the best available information suggests that general degradation of many isolated stream reaches is continuing to result in ever decreasing patches of suitable habitat. Thus, these threats appear to be acting insidiously to contribute to the decline of mussel populations over time (Butler 2005, p. 114).

Only 28 MUs among at least 136 historically occupied continue to harbor populations of the Pyramid Pigtoe, which is likely partial testimony to the principle of effective population size and its role in population loss. The rarity displayed by most Pyramid Pigtoe populations creates challenges for resource managers to incorporate conservation measures that address many of the issues associated with maintaining a high level of genetic diversity associated with small populations.

6.5 Enigmatic Population Declines

Mussel populations occasionally experience declines in the absence of obvious severe point or non-point source pollution or severe habitat loss and destruction. These recent declines are termed enigmatic population declines due to their mysterious and puzzling nature (Haag 2012, p.

341). The cause of these die-offs is unknown, but competition with non-native species, such as Asian Clam, is a potential culprit, as well as water quality limitations and disease or pathogens (Haag *et al* 2019, p. 17).

Contaminants that are not easily observable, such as metals bound in sediments, a result of past land use, could also be a contributor to mussel population declines with unidentified causes (Price *et al.* 2014, p. 855; see also section 6.1.3, above). Such declines have occurred within rivers occupied by the Pyramid Pigtoe (Haag 2019, p. 49-50; Neves 1987, p. 9). Fish and aquatic insect communities in locations where these mussel die-offs have been documented sometimes remain relatively intact; however, juvenile mussels are sensitive to the unknown factors causing the declines, and the Pyramid Pigtoe may be affected (Haag 2012, p. 342).

Mussel die-offs of unknown origin have been observed since at least the 1980s and continue to occur, particularly in the eastern U.S. (Neves 1987, p. 9; Freshwater Mollusk Conservation Society 2018). They have been observed in the Ohio and Tennessee basins in past decades (Haag 2019, p. 49-50; Ahlstedt *et al.* 2016, p. 9), and as recently as 2016–present in the medium condition Upper Clinch MU in Tennessee (Richard 2018, p. 2). These die-offs in the Clinch River were observed along at least a 50-mi (80-km) stretch, and sick and dead mussels have been reported, as well as fresh dead shells of the Pyramid Pigtoe collected (Henderson 2018, personal observation). Mussel die-offs are thought to be a combination of many environmental factors and are an imminent threat to linear Pyramid Pigtoe MUs and those in low condition. The mussel die-off in the medium condition Upper Clinch MU is directly affecting the Pyramid Pigtoe.

6.6 Other Factors Affecting Pyramid Pigtoe Populations

At this time, our analysis of the best available scientific and commercial information suggest that impacts due to host fish, disease, parasites, predation, and climate change are not likely resulting in basin or rangewide-level impacts to the Pyramid Pigtoe. However our understanding of these factors is limited, especially disease and climate change. Some of these impacts may be influencing Pyramid Pigtoe populations in specific locations, and examples are given below.

6.6.1 Host Fishes

The overall distribution of mussels is, in part, a function of the dispersal of their host fish. There is limited potential for immigration between populations other than through the attached glochidia being transported to a new area or to another population (see section 4.2.3, above). The Pyramid Pigtoe depends on host fish for dispersal, therefore, barriers such as dams limit recolonization potential (see section 6.1.5, above). Small populations are more affected by this limited immigration potential because they are susceptible to genetic drift, resulting from random loss of genetic diversity, and inbreeding depression (Geist 2010, p. 78). Populations that are eliminated due to stochastic events cannot be recolonized naturally, leading to reduced overall redundancy and representation.

The primary host fish species for the Pyramid Pigtoe are known to be common, widespread riverine minnow species (Culp et al 2006, p. 6). Families of host fishes known for the genus

Pleurobema require clean flowing water over mixed substrates and are intolerant of impoundment (Haag 2012, p. 347). Factors that contribute to habitat loss and water quality degradation of Pyramid Pigtoe such as dams, fragmentation, resource extraction, contaminants, and nonnative species are considered to act simultaneously on its host fish.

Prior to initiation of modified pulsing discharge regimes at hydropower dams in the Tennessee River basin, such as in the French Broad River, Tennessee, where the Pyramid Pigtoe is now considered extirpated, operation of Douglas Dam was limited to peaking hydroelectric power. Hydropeaking reduced habitat available for mussel colonization through aerial exposure of shoals when not generating, destabilized substrates, and increased water temperatures (Layzer and Scott 2006, p. 475). While restoration potential of other mussel species that use minnows and shiners has improved, the prognosis for restoring the Pyramid Pigtoe below Douglas Dam is poor (Layzer and Scott 2006, p. 481).

The continued operation of Douglas Dam limits the occurrence and abundance of mid-water column cyprinids, through reduced habitat under hydropeaking flows, limiting the restoration potential of the Pyramid Pigtoe below Douglas Dam (Layzer and Scott 2006, p. 489). Similar conditions likely limit host fish abundance and distribution in the Holston MU, which is in low condition and downstream of Cherokee Dam (Parmalee and Faust 2006, p. 74). The threat of limited host fish availability under these conditions is influenced by impoundment and dam operations, in addition to cyprinid distributional limitations.

Therefore, the best available scientific and commercial information suggests that the availability and distribution of host fish is not a limiting factor in Pyramid Pigtoe distribution throughout its entire range, but rather in specific locations in the Tennessee River basin such as the Holston MU. However, hydropeaking operations at other dams within the current range of the species are prevalent, and this may be a greater threat than is currently documented. Populations of mussels and their host fish have become isolated over time following the construction of major dams and reservoirs throughout the range of the Pyramid Pigtoe.

6.6.2 Parasites and Disease

Disease is likely a factor in some freshwater mussel population declines, but to date has been poorly studied (Grizzle and Brunner 2009, p. 454). Coordinated mussel health assessments are a high priority in the research community, but lack of continuous dedicated funding has hampered advancement in this area. Waller and Cope (2019, p. 26) propose a strategy to identify potential agents of disease, define clinical signs of declining condition, refine stress-specific biomarkers for health assessment, and develop protocols specific for mussels. This type of approach is crucial to better understand mussel microbiota and pathogens, and their potential effects on the Pyramid Pigtoe and other freshwater mussel species.

Sampling of obviously sick and moribund mussels from the Clinch River by the Service from 2016-2019 revealed five undescribed viruses that may contribute in development of a previously undocumented mussel disease, but the precise identity of the virus, disease, and causative agent(s) remains unknown. Recent research suggests that mussels involved in an ongoing mussel die-off are strongly associated with infection and high viral load of densovirus, which is known to be the cause of lethal epidemics in other invertebrate groups, indicating that some freshwater mussel declines could be the result of viral epidemics (Richard et al. 2020).

We have no data or information which indicates diseases are a factor in Pyramid Pigtoe decline, but no disease studies have been conducted specifically on the species, and few overall have been focused on freshwater mussels. Future studies could identify mussel disease as a primary or secondary factor influencing the species, especially in places like the Clinch River, where mussel die-off events have been observed frequently (Ahlstedt *et al* 2016, p. 8).

Mussel parasites include water mites, trematodes, leeches, bacteria, and some protozoa (Grizzle and Brunner 2009, p. 433). Although these organisms are generally not suspected to be a major limiting factor for mussel populations in general, reproductive output can be negatively correlated with mite abundance, and physiological condition is negatively correlated with trematode abundance Gangloff *et al.* (2008, p. 28). Trematodes live directly in mussel gonads and may negatively affect gametogenesis. It is possible mussels are more susceptible to parasites after anthropogenic factors reduce their fitness (Henley 2018, pers. comm.).

6.6.3 Predation

Native Americans extensively harvested freshwater mussels for food (Morrison 1942, p. 348; Bogan 1990, p. 112), but unlike their saltwater counterparts, freshwater mussels are not a component of the human diet in North America currently. Among mussel predators, the Muskrat (*Ondatra zibethicus*) is probably cited most often (Tyrrell and Hornbach 1998, p. 301), but the North American River Otter (*Lontra canadensis)* is also a lesser-studied substantial predator. Based on a study of muskrat predation on imperiled mussels in the upper North Fork Holston River in Virginia, Neves and Odom (1989, p. 939) concluded that this activity could limit the recovery potential of endangered mussel species or contribute to the local extirpation of already depleted mussel populations.

Predation by Muskrat may represent a seasonal and localized threat to the Pyramid Pigtoe but not a significant one unless the population is at a critically low number of individuals. Since Muskrat predation is size-selective, this threat is considered to be more likely to affect random individuals rather than at a population or MU level. Although other mammals such as raccoon, mink, otter, hogs, rats, turtles, and aquatic birds occasionally feed on mussels, the threat from these species is not currently deemed significant (Tyrrell and Hornbach 1998, p. 301).

Some species of native fish, such as Freshwater Drum (*Aplodinotus grunniens*), Redear Sunfish (*Lepomis microlophus*), River Redhorse (*Moxostoma carinatum*), and Blue Catfish (*Ictalurus furcatus*) feed on mussels, and potentially upon young of this species; however, predation by Black Carp (*Mylopharyngodon piceus*) is considered a greater threat since they attain a greater size and live comparatively longer and have not co-evolved with Pyramid Pigtoe populations (see Section 6.2, above).

According to Zimmerman *et al.* (2003, p. 28), flatworms are voracious predators on newly metamorphosed juvenile mussels in culture facilities. Young juveniles may also fall prey to various other invertebrates such as *Hydra*, non-biting midge larvae (Chironomidae), dragonfly larvae (Odonata), and crayfish (*Cambarus* spp.). Based on the current available information, we determined the overall threat posed by vertebrate and invertebrate predators of the Pyramid Pigtoe in most instances is less significant than other threats that are currently influencing population status rangewide.

6.6.4 Changing Climate Conditions

Changing conditions that can influence freshwater mussels include changing water temperature and changes in precipitation patterns that increase flooding, prolong droughts, or reduce stream flows, as well as changes in salinity levels (Nobles and Zhang 2011 pp. 147–148). An increase in the number of days with heavy precipitation over the next 25-35 years over the range of the Pyramid Pigtoe is expected (https://science2017.globalchange.gov/chapter/7/). Although the effects of climate change have potentially affected the Pyramid Pigtoe, the timing, frequency, and extent of these effects is currently unknown. The effects of hypolimnetic discharges on freshwater mussels as a result of hydropower generation is better documented.

Several potential climate change impacts to aquatic ecosystems (Poff *et al.* (2002, pp. ii-v) may influence the Pyramid Pigtoe and its habitat:

- Increases in water temperatures that may alter fundamental ecological processes, thermal suitability of aquatic habitats for resident species, and their geographic distribution, thus increasing the likelihood of species extinction and loss of biodiversity.
- Changes and shifts in seasonal patterns of precipitation and runoff which can alter the hydrology of stream systems, affecting species composition and ecosystem productivity. Aquatic organisms are sensitive to changes in frequency, duration, and timing of extreme precipitation events such as floods or droughts, potentially resulting in interference of reproduction. Further, increased water temperatures and seasonally reduced streamflow can alter many ecosystem processes, including increases in nuisance algal blooms.
- Cumulative or synergistic impacts that can occur when considering how climate change may be an additional stressor to sensitive freshwater systems, which are already adversely affected by a variety of other human impacts, such as altered flow regimes and deterioration of water quality.
- Adapting to climate change may be limited for some aquatic species depending on their life history characteristics and resource needs.
- Changes in presence or combinations of native and nonnative, invasive species could result in specific ecological responses to changing climate conditions that cannot be easily predicted at this time. These types of changes (e.g., increased temperatures that are more favorable to a non-native, invasive species compared to a native species) can result in novel interactions or situations that may necessitate adaptive management strategies.
- Shifts in mussel community structure which can stem from climate-induced changes in water temperatures since sedentary freshwater mussels have limited refugia from disturbances such as droughts and floods, and since they are thermo-conformers whose physiological processes are constrained by water temperature within species-specific thermal preferences (Galbraith *et al.* 2010, p. 1,176).

Small mussel populations are already at an increased risk for extinction given the biological restrictions associated with small populations and reduced distribution (Furedi 2013, p. 3). Additionally, although climate change may further magnify the factors contributing to the decline of the species (e.g., barriers and associated fragmentation), the precise locations and extent of these magnifications that may be influenced specifically by changing climate conditions are difficult to predict.

Within the range of the species, shifts in the Pyramid Pigtoe's species-specific physiological thresholds in response to altered precipitation patterns and resulting thermal regimes are possible. Additionally, nonnative, invasive species expansion because of climatic changes have the potential for long-term detriment to the Pyramid Pigtoe and its habitat. The influences of these changes on the Pyramid Pigtoe are possible under future conditions (see scenario 2, section 7.5, below). However, the effects of landscape-level changes on long-lived sedentary species such as freshwater mussels may be difficult to observe and quantify, requiring systematic collection of data over an extended time period (Ahlstedt *et al.* 2016a, p. 4).

Available life history data on the Pyramid Pigtoe and its host fishes suggest that negative responses to alterations in thermal regimes could result in longitudinal shifts in distribution, underlying the importance of river and stream connectivity (Archambault *et al*. 2018, p. 889). At the basin and population scales, increases in greenhouse gas concentrations have the potential to decrease genetic diversity through reductions in stream connectivity for wide-ranging mussel species in the eastern U.S. (Inoue and Berg 2016, p. 10).

Other potential impacts are associated with changes in food web dynamics and the genetic bottleneck that can occur with low effective population sizes (Nobles and Zhang 2011, p. 148; Inoue and Berg 2016, p. 12). At some point in the future, with dramatic alterations of the natural flow regime, changes in habitat connectivity, and other water quality impacts, the Pyramid Pigtoe may be affected by climate change.

Linkages between climate and river connectivity highlight not only the importance of maintaining current suitable habitats but also the linkages between these habitats and populations. Therefore, climate change is considered a secondary factor currently influencing the viability of the Pyramid Pigtoe and is not currently thought to be a primary factor in its occurrence and distribution throughout its range. Climate change could have a greater influence in the distribution of the species beyond the 20- to 30-year timeframe analyzed in this report due to potential loss of populations specifically in the Ohio basin, and could limit restoration and recovery potential in the Tennessee basin.

Reducing the likelihood of significant climate change impacts would largely depend on human activities that reduce other sources of ecosystem stress to ultimately enhance adaptive capacity, which could include, but not be limited to: maintaining riparian forests, reducing nutrient loading, restoring damaged ecosystems, minimizing groundwater and stream withdrawal, and strategically locating any new reservoirs to minimize adverse effects.

Changing climate conditions within the range of the Pyramid Pigtoe are less likely to have significant adverse effects at the population, MU, basin, or rangewide scales, as compared to other mussel species that reside in the southwestern U.S. where increasing temperatures and decreasing precipitation levels are predicted to be more severe. Therefore, climate change is occurring, but do to our limited understanding of its effects on the Pyramid Pigtoe, it is considered a secondary factor influencing the viability of the species and is not likely a primary factor in the species' current occurrence and distribution.

In summary, changing climate conditions are an increasing concern across the U.S. The most significant concerns for the Pyramid Pigtoe and its aquatic habitat include the potential for alteration of the natural flow regime and thermal changes which can contribute to reduced connectivity between populations, and increased risk of stress to individuals. This effect has been documented through hydropower dam hypolimnetic discharges, which are currently a greater threat to the species. Pollutants, specifically ammonia compounds, may be exacerbated by higher temperatures, which are predicted to increase.

6.7 Overall Summary of Factors Affecting the Species

Factors discussed in this chapter which are currently affecting the Pyramid Pigtoe include those that are systemic and contribute to the greatest threats to the species throughout its range: habitat loss and alteration, impoundment, water quality impairment, and more site-specific threats, such as harvest or invasive species. The topics discussed in this chapter are reflective of the best available information as it pertains to the Pyramid Pigtoe; there may be other factors we are unaware of, or for which data are currently lacking.

Impacts to freshwater mussels, and benthic riverine aquatic organisms in general, often involve multiple interrelated actions and compounded stressors, and rarely lack a single causative agent. Due to the dynamic nature of river systems, negative effects are not usually easy to observe real-time, and may be difficult to quantify after they occur. While factors such as climate change, host fish availability, disease, or predation may affect the species currently or in the future, we do not have sufficient data or information to suggest that these are currently contributing to Pyramid Pigtoe decline. Commercial harvest was likely a significant threat which previously contributed to species decline, but it is less likely to be a future threat based on the rarity of the species.

The current resiliency, redundancy, and representation of the Pyramid Pigtoe is directly tied to population and habitat fragmentation by the construction of impoundments throughout the species' range. Hypolimnetic discharges downstream from dams continue to impact populations and MUs specifically in the Tennessee basin, and in the Lower Cumberland – Old Hickory MU in the Ohio basin. Impoundments fragment and isolate populations from one another, prevent dispersal which reduces gene flow, and compounds stressors such as the introduction of contaminants and pollution; whether the result of mining, oil and gas exploration, agricultural runoff, or untreated or poorly treated wastewater discharges.

Across the Ohio and Tennessee basins, there are one or more threats to the species, which results in effects to individuals and populations at a more rapid rate. The combined impacts of dams and barriers, resource extraction, agricultural activities, and nonnative species have led to a cumulative loss of 65-70 percent of Pyramid Pigtoe populations and MUs compared to its historical distribution. Overall, the greatest threats currently to the Pyramid Pigtoe are habitat alteration and loss, water quality degradation, nonnative species, and small population size, which affect resource and demographic needs for the species.

A variety of stressors contribute to these threats, which may vary in intensity and duration based on temporal and spatial considerations, but similar prevalent impacts have been observed on Pyramid Pigtoe resiliency, redundancy, and representation throughout its range. In the Ohio and Tennessee basins, the primary stressors presenting consistent threats are impoundments, non-native species, resource extraction, and agricultural activities, as well as small population size and isolation of populations. Throughout the species' range, contaminants and mussel die-offs are difficult to measure and almost impossible to predict, but have been documented in the Upper Clinch MU in the Tennessee basin. The magnitude of effects from secondary factors such as disease, predation, and climate change will potentially increase as small populations become even more isolated.

CHAPTER 7 - FUTURE CONDITIONS

This chapter summarizes our projections of the species' likely future conditions in terms of resiliency, representation, and redundancy to describe future Pyramid Pigtoe viability.

7.1 Future Scenario Considerations

Four primary factors currently influencing the viability of Pyramid Pigtoe are: (1) habitat alteration or loss, (2) water quality degradation, (3) invasive and non-native species (4) small population size and low fecundity. These factors are expected to continue into the future at varying degrees, depending on the populations and locations across the landscape (e.g., some sources of habitat degradation or loss are likely to be more significant in some populations than others). Commercial harvest of freshwater mussels, although a likely contributor declines of Pyramid Pigtoe populations, has declined dramatically since the 1990s and is less likely to occur in the future due to strict regulation of harvest and the depressed global demand for shells; thus, the harvest factor is not carried forward in our analysis of potential future conditions.

We attempted to discern variance in future projections by using the best available information on proposed projects and modeling efforts (e.g., climate change/Resource Concentration Pathway [RCP] models). RCP refers to a greenhouse gas concentration (not emissions) trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC) in its 5th Assessment Report (IPCC, 2014, entire) Four pathways were selected by the IPCC for climate modeling and research, all describing potential future climate outcomes, and all considered possible depending on the amount of greenhouse gases that are emitted in the future.

7.2 Future Scenarios

We forecast the Pyramid Pigtoe's future conditions, in terms of resiliency, representation, and redundancy, under two plausible future scenarios. These scenarios forecast the Pyramid Pigtoe's viability over approximately 20 to 30 years. We selected this duration because: (1) the species is slow growing and long-lived and has relatively low fecundity (see section 3.3, above); (2) long-term trend information on Pyramid Pigtoe abundance and threats is not available across the species' range to contribute to meaningful alternative timeframes; and, (3) the decade 2050-2060, approximately 30 years from the completion of this SSA, has been used as a cut-off timeframe for predictions by the International Panel on Climate Change (IPCC) (Furedi 2013, p. 2).

Given the 28 MUs under consideration, we describe the threats that may occur at the scale of each within the Ohio, Tennessee, Arkansas-White-Red, and Lower Mississippi basins, the four major basins the species currently inhabits. Threats either remain constant from current conditions (scenario 1) or become worse (scenario 2). Additionally we provide specific population, MU, or river system examples where possible to demonstrate potential impacts.

Resiliency of Pyramid Pigtoe populations depends on future water quality, availability of flowing water, substrate suitability, abundance and distribution of host fish species, and habitat connectivity. We expect Pyramid Pigtoe populations to experience changes to these resource needs in different ways under the different scenarios. We project the expected future resiliency of each population based on events likely to occur under each scenario. We did not include an assessment of reproduction for the future scenarios; rather, the abundance of the populations in the future reflects whether reproduction, and more importantly, recruitment, are occurring. We also project an overall condition for each MU as either High, Medium, Low, or Very Low (see Table 7-1 for definitions). We also describe future condition habitat conditions in table 7-1.

Table 7-1. Descriptions of projected future condition of Pyramid Pigtoe population and MU categories based on estimated likelihood (See Table 7-2).

Future Condition Category	Description
High condition populations and MUs	Resilient populations generally distributed over a significant and more or less contiguous length of river (greater than or equal to 30 river miles), with evidence of recruitment and multiple age classes represented. Likely to maintain viability and connectivity among populations. Populations are not linearly distributed (i.e., occur in tributary rivers within or adjacent to an occupied management unit). These populations are expected to be mainatined, persist in 20 to 30 years and beyond, and withstand stochastic events. (*Thriving; capable of expanding range*.)
High Condition Habitats	Water quality meets designated uses and contiguous reaches with clean, mixed sand, gravel, and cobble substrates without excessive silt are predominant. Stable habitats available for all life stages.
Medium condition populations and MUs	Spatially restricted populations with limited levels of recruitment or age class structure. Populations may be linearly distributed, but occurrence is consistently detectable and spread across a contiguous reach of river. Resiliency is less than under high conditions, but populations are expected to persist in 20 to 30 years. Populations are smaller in extent and less dense than the high condition category (*Stable, not necessarily thriving or expanding its range*).
Medium condition habitats	Mixed sand, gravel, & cobble substrates free of excessive silt are maintained in stable shoals, and natural flow regimes persist in currently occupied rivers. Lowered water quality and habitat degradation from current conditions are possible, but not at a level that negatively affects both the density and extent of distribution simultaneously.
Low condition populations and MUs	Small and highly restricted populations, with no evidence of recent recruitment or age class structure, and limited detectability. Potentially observable but without age class structure, or only represented by older, potentially non-reproducing individuals. No evidence of recruitment, indicating reproduction is no longer occurring. Populations are only linearly distributed, have low resiliency, and not likely to withstand stochastic events. These populations are are the least likely to persist in 20 to 30 years (*Surviving, barely observable; populations clearly declining from past abundance and extent*).
Low condition habitats	Loss of mussel habitat or water quality degradation within the formerly occupied river or stream reach has been measured and indicates limited potential for restoration. Altered thermal and flow regimes potentially limit reproduction and colonization.

(Future Condition Only)	Description
Very Low Condition Populations and MUs	Likely extirpated, below detectable levels despite consistent survey effort within formerly occupied range. Evidence of population limited to relic or weathered dead shells (*No longer observable as live or fresh dead individuals*).
Very Low Condition Habitats	Contiguous mussel habitat with clean, silt-free substrates and interstitial spaces have been lost or are covered in sediment within destabilized channels. Water quantity and quality possibly limits colonization as well as restoration and reintroduction potential.

For each scenario, we qualitatively ranked each population and MU using best judgement based on the best available scientific and commercial information to estimate the likelihood that a particular condition would apply in 20 to 30 years. We consulted species experts and state and regional malacologists familiar with Pyramid Pigtoe distribution for feedback on preliminary future condition rankings. We also reviewed literature for possible explanations of Pyramid Pigtoe population losses rangewide. Due to limitations in available staff and time constraints, more sophisticated modeling techniques were not possible, so we used consistent methodology with our current condition rankings and approaches for other wide-ranging mussel species (Service 2018, 2019, 2020a). For example, we used development planning documents, peer-reviewed literature projections, mussel expert advice and input, and our best professional judgement. We used the scale in Table 7-2, below, to estimate these likelihoods.

Table 7-2. Explanation of confidence terminologies used to estimate the likelihood of a particular future condition category.

Confidence Terminology	Explanation
Highly likely	We are more than approximately 90 percent certain this condition category will occur.
Moderately likely	We are approximately 50 to 90 percent certain this condition category will occur.
Somewhat likely	We are less than approximately 50 percent certain this condition category will occur.

7.3 Scenario 1

Under this scenario, factors influencing current Pyramid Pigtoe populations are assumed to remain constant into the future.

Factors influencing Pyramid Pigtoe populations are assumed to remain constant into the future for the next 20 to 30 years, including existing habitat degradation and beneficial conservation actions, and climate and hydrological conditions. This scenario assumes the current levels of translocation and monitoring capacity (i.e., population augmentation is not currently taking place, and the species has limited production and reintroduction potential).

Scenario 1 assumes that existing patterns and rates of land use change continue across the species' range (Lawler *et al.* 2014, p. 56), including urban growth and changes in agricultural practices (Lasier *et al.* 2016, p. 672; Newton *et al.* 2008, p. 434; Terando *et al.* 2014, p. 4). This scenario also assumes that existing regulatory mechanisms and voluntary conservation measures indirectly benefiting the species remain in place and limited or no new additional conservation measures are added. See Table 7-1, above, for designated condition categories into the future for Scenario 1.

Ohio Basin

There is discharge reduction due to periodic drought conditions, and negative changes in physical habitat features due to agricultural practices, human population growth, and resource extraction activities. Diminishment of seasonally low flows, which makes individuals more susceptible to drought (which can expose aquatic habitat, isolate mussels during sperm and juvenile mussel dispersal, increase predation, and concentrate contaminants), more susceptible to temperature increases, and, in extreme situations, can impede delivery of sufficient dissolved oxygen.

Water quality declines are evident due to untreated or poorly treated wastewater discharges, development, resource extraction, and high risk of contaminant spills in the Muskingum, Lower Green, and Lower Cumberland – Old Hickory MUs. The pervasive impacts of water quality degradation can affect the entire populations with these MUs, which are already vulnerable to habitat loss due to impoundment and hypolimnetic discharges. Habitat degradation continues due to development and extensive agriculture in riparian areas. Riparian development and agriculture stressors cause sedimentation that fills in the interstitial spaces needed by juvenile mussels and host fish eggs. This habitat degradation has the potential to affect individuals initially, but over time, results in impacts to populations.

Nonnative species, such as Asian Clam, Zebra Mussel, Quagga Mussel, Black Carp, continue to negatively influence populations basin-wide. Asian Clam abundance and distribution is widespread within the range of the species and competes for food and nutrients needed for mussel growth and development. Black Carp are predators on mussels, and competition for space and resources from Zebra and Quagga mussels result in reduced fitness of Pyramid Pigtoe.

Water quality degradation continues in the Lower Cumberland – Old Hickory MU, which can affect growth and result in direct mortality of mussels. The small population size and increased distance between sexually mature individuals makes it subsequently harder for females to intake sperm, affecting reproduction and recruitment. Mussel recruitment in the upper reach of Old Hickory Reservoir continues to be suppressed by cold water during the reproductive period resulting from hypolimnetic releases from upstream Corps reservoirs (e.g., Wolf Creek, Dale Hollow, and Center Hill).

Tennessee Basin

Small to moderate discharge reductions occur due to drought, and agricultural and resource extraction activities in the Upper Clinch and Lower Duck MUs, resulting in habitat loss through increased sedimentation and siltation, which covers substrates used for settlement. Wastewater and runoff from land use activities also have increased concentrations of contaminants such as ammonia and chlorine. Water extraction activities also result in periodic loss of connectivity between mussel beds. Impacts from periodic loss of connectivity can be exacerbated if it occurs during reproductively active periods of sperm distribution (limiting the ability of sperm to fertilize eggs) or juvenile mussel dispersal (limiting the distribution of the mussel in the stream).

Water quality declines are evident in rivers with medium condition populations such as the Upper Duck, Holston, and Upper Clinch MUs due to untreated or poorly treated wastewater discharges, resource extraction, hypolimnetic releases from dams, and high risk of contaminant spills, affecting entire populations due to predominantly linear distributions. Habitat degradation continues in due to development, and extensive agriculture in riparian areas. This degradation results in direct habitat loss, increased sediment which fills substrate spaces required for juvenile mussel development and host fish eggs, and excessive storm water flows which erodes substrate habitat. Our current understanding of die-offs in the Upper Clinch MU is limited, and without diagnosis protocols for understanding sick and dying mussels, and prioritizing health assessments, further decline through future die-offs is inevitable.

Habitat degradation continues in the Tennessee River mainstem MUs (Wheeler Lake, Pickwick, and Lower Tennessee – Beech) due to development, navigational impacts such as dredging and increases in river commerce traffic, and extensive agriculture in riparian areas. Kentucky Reservoir in the Lower Tennessee-Beech MU is subject to sand and gravel dredging and commercial mussel harvest. This degradation results in direct habitat loss, increased sediment which fills substrate spaces required for juvenile mussel development and host fish eggs, and excessive storm water flows which erodes substrate habitat.

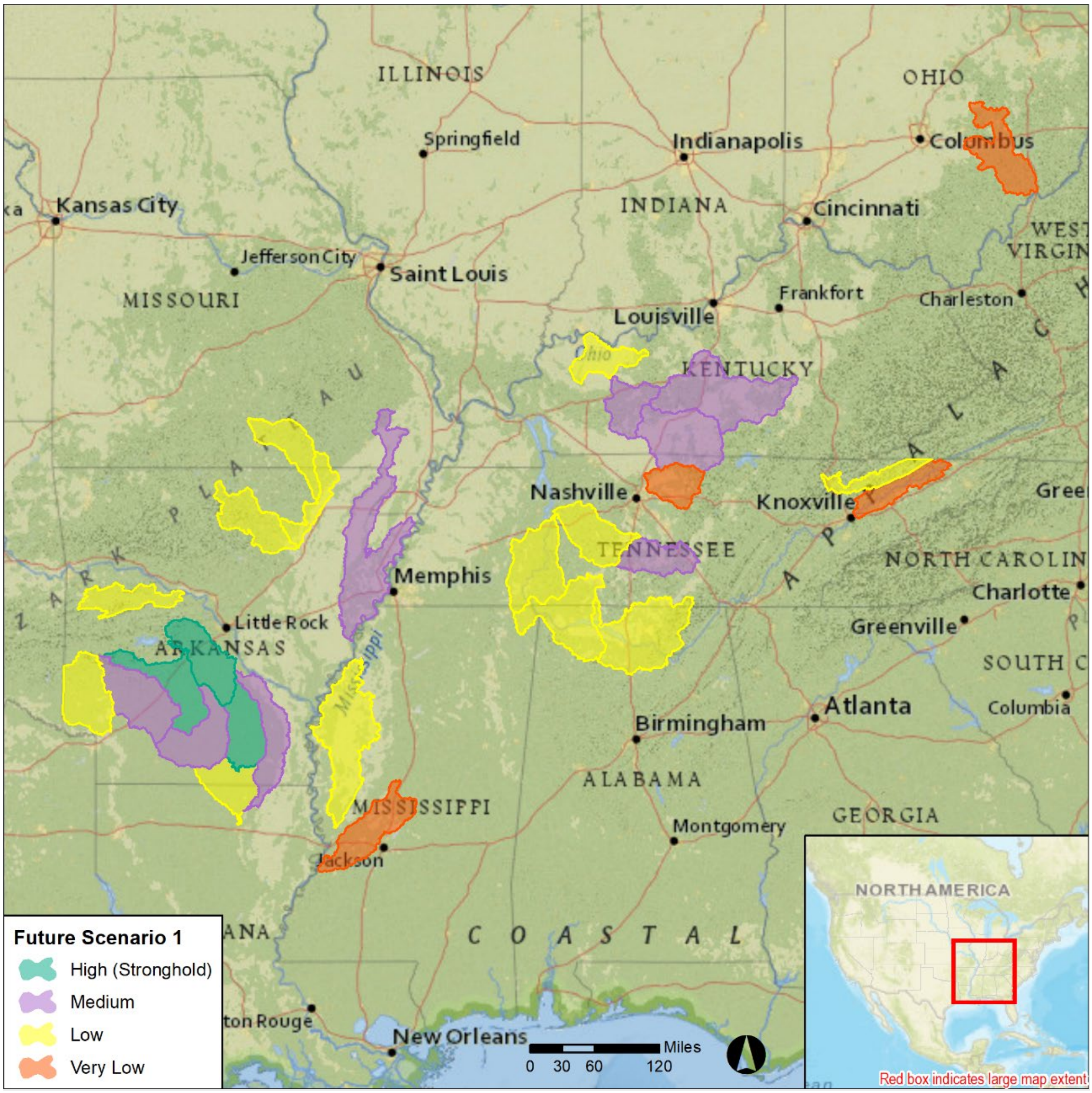

Figure 7-1. Distribution of the currently occupied Management Units (MUs; a.k.a. HUC8s) of Pyramid Pigtoe under Future Condition Scenario 1. Currently occupied MUs are represented with very low, low, medium, and high condition categories (as described in Chapter 7; Service 2020b, unpublished data).

Nonnative species such as Asian Clam continue to impact MUs basin-wide through competitive interactions for food and nutrients. Zebra Mussel, Quagga Mussel, and Black Carp continue to impact individuals in the Tennessee River MUs through competition, suffocation, and predation. Habitat fragmentation within the Tennessee basin is detrimental; large impoundments on the Clinch, Holston, Tennessee, and Duck Rivers, and MUs within, where there are dams both upstream and downstream of Pyramid Pigtoe populations, continue to limit the mussel's access to suitable habitat and isolate populations, which in turn reduces the amount of genetic exchange between populations and contributes to small population sizes.

Arkansas-White-Red basin

Water quality declines are evident in MUs currently identified as medium condition due to untreated or poorly treated wastewater discharges, development, resource extraction, and high risk of contaminant spills (e.g., Eleven Point, Petit Jean MUs). The pervasive impacts of water quality degradation can affect these entire MUs.

Habitat degradation continues due to development, navigational impacts such as dredging and increases in river commerce traffic, and extensive agriculture in riparian areas. In the Little River, streamside development and agriculture causes sedimentation that fills in the interstitial spaces needed by juvenile mussels and host fish eggs. This habitat degradation has the potential to affect individuals initially, but over time, results in impacts to MUs.

Nonnative species, such as Asian Clam and Zebra Mussel, continue to negatively influence MUs basin-wide. Asian Clam abundance and distribution is widespread within the range of the species and competes for food and nutrients needed for mussel growth and development. Competition for space and resources from Zebra and Quagga Mussels result in reduced fitness of Pyramid Pigtoe.

Habitat fragmentation is a common issue for many of the populations in the Arkansas-White-Red River basin. Large impoundments on the Little River and tributaries, where there are dams both upstream and downstream of Pyramid Pigtoe MUs, limit the mussel's access to suitable habitat and contributes to isolation, which in turn limits the amount of genetic exchange. Under this scenario the species persists in the Arkansas portion of the Little River MU, but is lost from the Oklahoma portion, resulting in extirpation from the state of Oklahoma.

Lower Mississippi River basin

Habitat alteration occurs in this basin through channelization, bank erosion, widened channels, uniform flows, unstable sediments, and meander cutoffs; this threat continues as the greatest threat to the Pyramid Pigtoe in this basin. Agricultural impacts and human development have led to high levels of suspended solids, ammonia, and other contaminants degrading water quality and habitat. However, due to presence of the Saline and Upper Ouachita populations, which are less affected by impoundment than other portions of the basin, the species maintains high condition populations due to dense mussel beds, connectivity, and high quality habitats.

Nonnative species, such as Asian Clam and Black Carp, continue to negatively influence MUs basin-wide. Asian Clam abundance and distribution is widespread within the range of the species and competes for food and nutrients needed for mussel growth and development. Black Carp are predators on mussels and recent collections of juveniles have been collected in many tributaries to the Mississippi River.

Habitat fragmentation is a common issue for many of the Pyramid Pigtoe MUs in the Lower Mississippi River basin. Impoundments on the Ouachita and St. Francis, where there are dams both upstream and downstream of Pyramid Pigtoe MUs, may limit the mussel's access to suitable habitat contributes to isolation, which in turn limits the amount of genetic exchange.

7.3.1 Resiliency

Under Scenario 1, factors currently influencing Pyramid Pigtoe populations remain constant into the future. In total, 8 Pyramid Pigtoe MUs (29 percent) deteriorate in resiliency in 20-30 years. In contrast, 20 MUs (71 percent) maintain some resiliency over time as some existing regulatory and voluntary conservation measures continue to be implemented to counteract existing threats. This takes into account habitat preservation and restoration partnerships with agencies and landowners and the presence of the species on National Wildlife Refuge lands and in Mammoth Cave National Park boundaries. Also, the recent removal of Lock and Dam 6 and the potential for additional dam removals on the Green River aids MU resiliency (Figure 7-1).

However, the effect of current levels of basin, MU, and population fragmentation by dams, sedimentation, dredging, and resource extraction remain. Increases in numbers of competing non-native species continue to result in habitat loss, water quality degradation, and competition for food resources and suitable substrates, which contributes to reduced recruitment and low Pyramid Pigtoe abundance and survival. Small population size, a contributor to genetic isolation, caused by habitat fragmentation and distance between populations, becomes a more influential factor with the loss of MUs within basins. Low dissolved oxygen and hypolimnetic flow releases from hydropower dams remain insufficient for the Little, Holston, and Lower Cumberland – Old Hickory MUs without major changes in dam operations by TVA and the Corps.

While reductions in resiliency are primarily in the Ohio and Tennessee basins, we estimate that 3 of the 28 (11 percent) currently occupied MUs would be in high condition, 8 MUs (29 percent) in medium condition, and 13 MUs (46 percent) in low condition. As many as 4 MUs (14 percent) are in very low condition, indicating they are no longer detectable and likely extirpated. Of the 25 current MUs projected to persist (high, medium, or low condition), the 3 MUs (33 percent) represented as high condition are confined to the Lower Mississippi basin in the western portion of the species range. There are no high condition populations remaining in the Ohio, Tennessee, or Arkansas-White-Red basins, and only low condition populations in the Arkansas-White-Red basin (Figure 7-1; Appendix C). The greatest loss in the Arkansas-White-Red basin is the extirpation of the species from the Oklahoma portion of the Little River, resulting in the loss of the Pyramid Pigtoe from the state of Oklahoma.

The Ohio River basin has 2 MUs likely extirpated under Scenario 1, including the Muskingum MU, which results in the loss of the species from the state of Ohio, and the Lower Cumberland – Old Hickory MU, which is the last remaining in the entire Cumberland River system. The Tennessee basin has 1 MU likely extirpated, the Holston. The Pyramid Pigtoe was once a sizeable component of the Holston River mussel assemblage, but impoundment and hypolimnetic discharges have contributed to its documented decline there (Parmalee and Faust 2006, entire).

Additionally, it is projected that the species extent is further reduced in the Clinch River due to imminent threats such as die-off events and emerging diseases, and is extirpated from Virginia, persisting only in Tennessee in the Clinch River. In the Arkansas-White-Red basin, no MU extirpation is projected, but populations remain small, isolated from one another, and in low condition. In the Lower Mississippi basin, only the Big Black MU is projected to be extirpated, but this reduces the species in Mississippi to one remaining MU, the Big Sunflower.

7.3.2 Representation

The Pyramid Pigtoe retains some representation in 20-30 years, but with 13 of 28 MUs (46 percent) in low condition, the species is at an increased risk of extirpation, or falling into very low condition, in all but the medium and high condition MUs (11 total). The watersheds with high and medium condition populations under this scenario would maintain representation in the Ohio, Tennessee, and Lower Mississippi basins (Figure 7-1, above).

However, the loss of the Muskingum MU under this scenario, due to hydropower implementation at Devola Dam, results in extirpation from the state of Ohio, where the species formerly occupied multiple river systems (Watters *et al*. 2009, p. 235). The loss of the Lower Cumberland – Old Hickory MU results in extirpation from the entire Cumberland River system within the Ohio basin, where the species once occupied multiple tributaries (Haag and Cicerello 2016, p. 100).

Additionally, the species is in decline and very rare already in the Virginia portion of the Upper Clinch MU, occurring in Scott County only (Ostby 2016, p. 181). While the Pyramid Pigtoe is projected to persist under Scenario 1 in the Tennessee portion of the Upper Clinch MU, a reduction in upstream extent results in loss of the species from the state of Virginia Further, the Pyramid Pigtoe is lost from the Oklahoma portion of Little River, where it is currently very rare and has long been documented in decline (Vaughn 2017, p. 5).

7.3.3 Redundancy

Under Scenario 1, redundancy for the Pyramid Pigtoe in all basins is reduced from current conditions (see Figure 7-1, above, and Appendix C). The loss of the population in Lower Cumberland – Old Hickory MU results in extirpation from the entire Cumberland River drainage. The best available information suggests that 4 of 28 MUs (14 percent) are likely in very low condition and potentially lost. The 13 low condition MUs (46 percent), almost all of which are linear in extent, increases the species vulnerability to additional river extirpation within basins (i.e., range thinning; Strayer 2004, p. 16). Additionally, the species is lost entirely from the states of Ohio, Virginia, and Oklahoma, concentrating its range to legacy Service Region 4 states.

7.4 Scenario 2

Under this scenario, factors that influence the current extant populations of Pyramid Pigtoe are likely to become worse from the implementation of known existing and projected development, resource extraction, hydroelectric projects, etc.; as well as additional risks to the species and its habitat are more challenging to predict with accuracy at this time, such as climate change.

In general, this scenario assumes that all four primary threats and associated stressors are worse in the future, leading to reductions in water quality in those areas that are already marginal and increased habitat degradation of areas that are not fully supporting resource needs (i.e., appropriate food, nutrients, and water quality condition) for aquatic life. The abundance and distribution of host fishes decline. Changing climate conditions, and variations from the natural flow regime, with periodic drought and flooding, may result in desiccation, scour, and increased sedimentation and deposition in quality mussel habitats.

This scenario assumes that existing regulatory mechanisms and voluntary conservation measures that are benefiting the species would remain in place, although funding and staffing constraints prohibit significant additional protections. See Table 7-1, for designated condition categories into the future for for the Pyramid Pigtoe MU condition under Scenario 2.

Under Scenario 2, the Pyramid Pigtoe's response to multiple impacts acting synergistically on the landscape result in significant declines coupled with limited capacity for rescue efforts, reintroductions, and/or augmentations. Monitoring capabilities, especially in the mainstem Tennessee River MUs (3 total) also decrease due to reductions in staff, cost, and time. In general, this scenario considers a future where conditions are worse for the species across its entire range compared to Current Conditions (Chapter 5). In this scenario, there is some reduction or negative effects to all of the species' resource and demographic needs (flow reduction, decline in water quality, reduced connectivity between populations, etc.).

Ohio Basin

Under Scenario 2, discharge reductions in small tributaries to occupied MUs lead to alterations in the natural flow regime and changes to physical habitat downstream. Reduced frequency of flow events that help keep clean-swept substrates, a species requirement, leads to reduced extent and connectivity. These changes affect Pyramid Pigtoe recruitment in the Upper, Middle and Lower Green, and Barren MUs, where the species previously had the largest cumulative extent occupied. The Upper Green MU is the only with detectable age class structure in the species.

The Pyramid Pigtoe is unable to withstand impacts from prolonged drought or periodic flooding, which results in desiccation, scour, and increased sedimentation and deposition in shoal habitats occupied by the Pyramid Pigtoe. Habitat fragmentation increases, reducing connectivity more than what would occur under Scenario 1, further reducing opportunities for Pyramid Pigtoe expansion. If MUs persist, they become extremely restricted and genetically isolated from other populations. Population restoration through augmentation is not possible due to lack of sufficient available brood stock.

Water quality deteriorates due to lack of appropriate treatment of wastewater discharges, especially in rural areas; however, the degree of water quality decline is substantially worse than that experienced under Scenario 1. There is little to no water quality improvement through BMPs concerning agricultural practices and development. Impacts from resource extraction activities (water withdrawal, stream contamination, deposition of fine sediment, etc.) are exacerbated by increased localized concentrations of abandoned mines and oil and gas exploration, increasing long-term water contamination issues that have significant influence on the survival of the Pyramid Pigtoe. Risks of population losses due to the increased possibility of contaminant spills are greater than Scenario 1.

Habitat degradation continues due to human population growth and associated land-use changes in and around the City of Bowling Green, KY. There is an increase in the extent of habitat degradation in riparian areas due to increased agricultural activities without adequate BMPs. The costs of mussel population monitoring increases substantially, reducing the capabilities of gathering annual estimates of species abundance and distribution. Nonnative species such as Asian Clam, Zebra Mussel, Quagga Mussel, and Black Carp spread significantly across the basin due to changing air and water temperature patterns. The potential for introduction of new non-native species becomes greater than in Scenario 1, increasing competition for Pyramid Pigtoe resource needs and water quality requirements, and potentially predation on the species.

Tennessee Basin

Significant decreases river discharge variability occurs in the Upper Clinch, Upper Duck and Wheeler Lake MUs, leading to substantial alterations in the natural flow regime and changes in physical habitat, resulting in reduced connectivity of aquatic habitat and, in turn, Pyramid Pigtoe recruitment. Due to very small population sizes, the species is unable to withstand minor impacts from drought or periodic flooding in all but the Pickwick and Lower Tennessee-Beech MUs.

This additional reduction habitat conditions combined with low adaptive capacity results in desiccation, scour, and increased sedimentation and deposition in shoal habitats occupied by the Pyramid Pigtoe. Habitat fragmentation increases significantly compared to current conditions and Scenario 1, reducing connectivity more than status quo, further reducing opportunities for Pyramid Pigtoe expansion. Only 4 populations and MUs are projected to persist, and they become more restricted in extent and genetically isolated from other populations. Population restoration/augmentation is not possible due to only older non-reproducing individuals within populations and a lack of sufficient available reproductively viable broodstock.

Water quality deteriorates due to untreated wastewater discharges, especially in rural areas. There are no initiatives or funding resources to improve water quality through BMPs concerning agricultural practices and human population growth and development. Impacts from resource extraction activities (water withdrawal, stream contamination, deposition of fine sediment, etc.) are exacerbated by greater localized concentrations of abandoned mines. This increases long-term water contamination issues that have a significant influence on the survival of the Pyramid Pigtoe especially in the Upper Clinch MU.

Water temperature effects below hydropower dams are exacerbated by climatic changes in rainfall. The lack of consistent seasonal rainfall, which results in prolonged droughts reduces river flow into upstream reservoirs, altering seasonal dam release schedules by TVA, which no longer provides minimum flows and dissolved oxygen addition. Risks of contaminant spills remain high and elevate the likelihood of water quality contamination and direct effects to mussels due to the presence of only very small, linear populations.

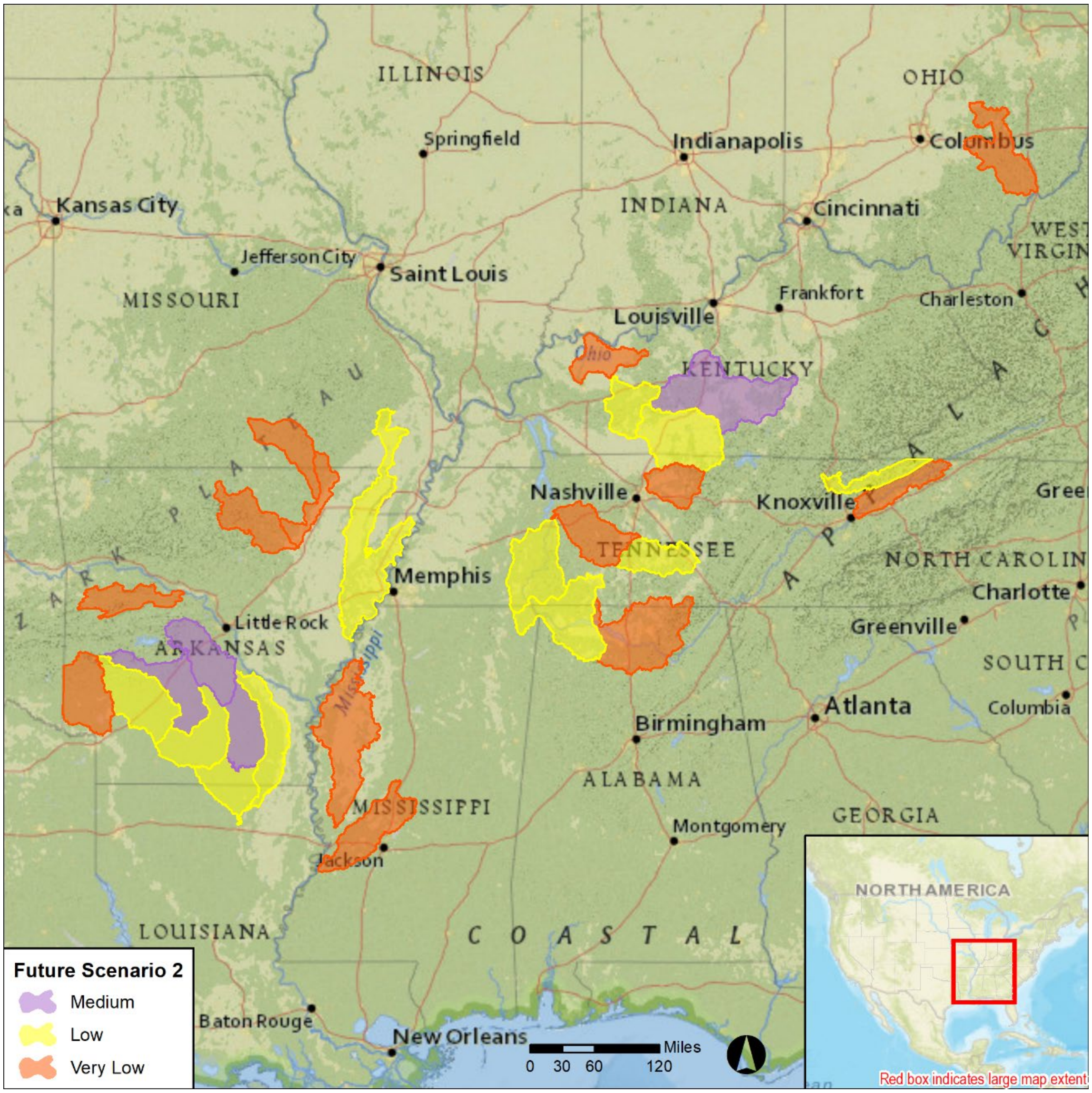

Figure 7-2. Distribution of the current and formerly occupied Management Units (MUs; a.k.a. HUC8s) of Pyramid Pigtoe under Future Condition Scenario 2. Currently occupied MUs are represented with very low, low, and medium condition categories (as described in Chapter 7; Service 2018, unpublished data).

Water temperature effects below hydropower dams are exacerbated by severe changes in rainfall. The lack of consistent seasonal rainfall, which results in prolonged droughts reduces river flow into upstream reservoirs, altering seasonal dam release schedules by TVA, which no longer provides minimum flows and dissolved oxygen addition. Risks of contaminant spills remain high and elevate the likelihood of water quality contamination and direct effects to mussels due to the presence of only very small, linear populations.

Habitat degradation continues and becomes worse in the Pickwick and Lower Tennessee-Beech MUs due to human population growth in and around the City of Florence, AL. Sedimentation and navigational impacts such as dredging and barge mooring, with increases in river commerce traffic, affect transitional habitats in riverbends where mussels commonly occur. Activities that formerly only affected individuals, such as barge traffic and fleeting, now have greater effects due to increasing rarity of the species. There is an increase in the magnitude of agricultural activities in riparian areas to accommodate population growth. This results in loss of appropriate habitat patches and habitat heterogeneity, increasing the likelihood of Pyramid Pigtoe isolation. The costs of monitoring large river mussel populations increase due to reductions in staffing of agency partners and reliance on private industry for data and survey information, reducing the capabilities of gathering annual estimates of species abundance and distribution.

Nonnative species such as Asian Clam, Zebra Mussel, Quagga Mussel, and Black Carp spread significantly across the basin due to changing air and water temperature patterns. The potential for introduction of new non-native species becomes greater than in Scenario 1, increasing competition for Pyramid Pigtoe resource needs and water quality requirements, and potentially predation on the species

Arkansas-White-Red

Water quality deteriorates due to untreated wastewater discharges, especially in rural areas. There is no initiative to improve water quality through BMPs concerning agricultural practices and human population growth and development. Impacts from resource extraction activities (water withdrawal, stream contamination, deposition of fine sediment, etc.) are exacerbated by greater localized concentrations of abandoned mines, increasing long-term water contamination issues that have an influence on the survival of the Pyramid Pigtoe (e.g., Petit Jean MU).

Habitat fragmentation is a common issue for the Arkansas-White-Red River basin MUs and it continues to worsen due to human development and agricultural stressors. Habitat degradation continues due to development and extensive agriculture in riparian areas. In the Eleven Point MU in Arkansas, streamside development and agriculture causes sedimentation that fills in the interstitial spaces needed by juvenile mussels and host fish eggs. This habitat degradation negatively impacts entire MUs.

Nonnative species (such as Asian Clam, Zebra Mussel, and Quagga Mussel) continue to negatively influence populations basin-wide. Asian Clam abundances and distribution increases and results in increased competition for food and nutrients needed for Pyramid Pigtoe growth and development. Black Carp expand and increase the potential for concentration of predators in large river MUs (e.g., Eleven Point MU).

Lower Mississippi

Habitat alteration occurs in this basin through channelization, bank erosion, widened channels, unstable sediments, and meander cutoffs; this threat continues as the greatest threat to the species and remaining populations in this basin. These impacts are exacerbated and occur at a much more rapid rate than under Scenario 1, with no opportunity for education, outreach, or restoration initiatives. Water quality degradation through high levels of suspended solids continues, which affects respiration and smothers invertebrates, and resulting in direct mortality of Pyramid Pigtoe in this basin.

Habitat fragmentation is a common issue for many of the MUs in the Lower Mississippi River basin and it continues to worsen under this scenario. More impoundments, constructed predominantly for agricultural uses, can limit water availability and the mussel's access to suitable habitat and isolate more populations, which in turn limits the amount of genetic exchange between MUs. There is an increase in the magnitude of agricultural activities in riparian areas to accommodate human population growth. This results in loss of appropriate habitat patches and habitat heterogeneity, which increases the likelihood of Pyramid Pigtoe isolation from large rivers.

Nonnative species (such as Asian Clam, Zebra Mussel, Quagga Mussel, and Black Carp) continue to negatively influence MUs across the basin. Asian Clam abundances and distribution increases and results in increased competition for food and nutrients needed for Purple Lilliput growth and development. Black Carp spread from currently occupied large river MUs into tributaries throughout the basin, increasing predation on the Pyramid Pigtoe (e.g., Upper Saline, Lower Saline MUs).

7.5.1 Resiliency

Under Scenario 2, where conditions become worse, 19 of 28 Pyramid Pigtoe MUs (68 percent) deteriorate in resiliency (negative change in condition category from current condition). Only 12 of 28 MUs remain in 20-30 years, and 11 (38 percent) of these are estimated to have low resiliency. Current threats continue along with elevated (compared to Scenario 1) impacts to populations and MUs (Table 7-4, below). Significant changes may not be observed at first due to continued implementation of existing regulatory and voluntary conservation measures that help reduce (but not eliminate) threats (see Table 7-4).

Increased levels of population and MU fragmentation further exacerbate the effects of small population size, and gene flow between basins, MUs, and populations is affected. Detectability during surveys becomes difficult, affecting the understanding of population status. The deposition of fine sediments into suitable substrates is prevalent, and habitat patches supporting mussel beds are lost.

The magnitude and scale of wastewater discharges and oil and gas exploration result in a substantial reduction of non-point source water treatment, which affects species needs through increased contaminants levels. Human energy and water supply needs result in changes in operations at existing dams, affecting flow rates, thermal regimes, and seasonal discharges.

Additional hydropower development at dams, such as Normandy Dam on the Duck River, currently only used for flood control and water supply, results in substrate scouring in existing downstream Pyramid Pigtoe habitat (Upper Duck MU). These cumulative impacts lead to recruitment failure and decreased mussel abundance and survival throughout the Pyramid Pigtoe's remaining range.

Targeted programs to improve water quality through BMPs concerning agricultural practices and anthropogenic land uses are not developed or lack implementation due to lack of funding. There is an increase of impacts from resource extraction activities, such as resource extraction in the Ohio and Tennessee basins, which contributes to long-term water contamination issues. Decreases in dissolved oxygen and changes to thermal regimes such as the increased potential of hypolimnetic flow releases from hydropower dams suppress population viability.

Regardless of ongoing regulatory and voluntary conservation measures, 13 of 28 populations that deteriorate in resiliency (46 percent) are likely to become extirpated (very low condition). Small population size coupled with potential genetic isolation is a significant concern, decreasing resilience to stochastic events. We estimate that none of the 28 MUs would be in high condition, and 4 (14 percent) in medium condition, persisting only in the Ohio and Lower Mississippi basins. Further, the remaining 11 (39 percent) would be in low condition.

The 15 MUs that continue to be represented across the species' range are largely dependent on public lands such as Mammoth Cave National Park and Felsenthal, Pond Creek, and Upper Ouachita National Wildlife Refuges. Connectivity between the Barren and Green Rivers, and Ouachita and Saline Rivers is critical for species persistence. Maintaining some level of consistent dam operation and monitoring below Wilson and Pickwick Dams on the Tennessee River is also vital.

Watersheds with aquatic species conservation incorporated into long-term planning strategies with active landowner involvement continue to aid the Upper Clinch and Upper Duck MUs, but these decline in resiliency to low condition due to linear orientation and reductions in extent. The Green, Saline, Clinch, and Duck Rivers are biodiversity hotspots and have some level of resource planning measures such as conservation easements, but riparian lands are predominantly privately owned and in 20-30 years may only offer limited refugia and conservation opportunities.

7.5.2 Representation

The Pyramid Pigtoe loses representation over time, with no high condition MUs in any basins (Figure 7-3 and Table 7-4). Largely due to the species' very large distribution initially; and owing to the Saline, Green, Clinch, and Duck Rivers which are aquatic biodiversity hotspots, the species maintains populations and MUs in the Ohio, Tennessee, and Lower Mississippi basins under Scenario 2. However, the species is extirpated from the Arkansas-White-Red basin and the Tennessee basin only persists as low condition MUs, no medium condition MUs remain.

Populations within MUs are geographically restricted and linearly distributed due to reductions in population and habitat connectivity, thus resulting in substantial fragmentation and a high likelihood of very small population sizes and increased vulnerability to stochastic and catastrophic events. It is predicted that the species is lost from the states of Mississippi, Virginia, Ohio, and Oklahoma. With 11 MUs (46 percent) in low condition and the potential extirpation (very low condition) of 13 MUs (46 percent), the species is in significant decline in the majority of its range; all but 4 populations and MUs (Upper Green, Upper Saline, Upper Ouachita, Lower Saline) are in low or very low condition. Additionally, the loss of almost half of the populations from current conditions substantially increases the extinction risk of Pyramid Pigtoe (Table 7-4).

7.5.3 Redundancy

The Pyramid Pigtoe loses redundancy compared to current conditions (see Table 7-4, above). The best available information suggests that up to 13 populations (46 percent) would become extirpated. Loss of populations and MUs in all portions of its currently occupied range occurs in all four basins, extirpation from one basin (Arkansas-White-Red), and there are no longer any high condition populations which could be used for brood stock for translocation or captive propagation efforts. Options for recovery opportunities are extremely limited and reliant on public lands or their proximity.

CHAPTER 8 - OVERALL SYNTHESIS

The goal of this assessment is to describe the viability of the Pyramid Pigtoe in terms of resiliency, representation, and redundancy by using the best available commercial and scientific information at the time of the analysis. We described both current and potential future conditions regarding the Pyramid Pigtoe's viability within the context of these three parameters. To capture the uncertainty associated with the degree and extent of potential future risks and their impacts on the species' needs, we assessed potential future conditions using two plausible scenarios. These scenarios were based on a variety of negative and positive influences on the species across its current 9-state range, allowing us to predict potential changes in habitat used by the Pyramid Pigtoe. The results of our analysis described a range of possible conditions in terms of the number and distribution of Pyramid Pigtoe populations and MUs (Table ES-1).

Historical Range and Abundance - The Pyramid Pigtoe has been documented from 18 states: Pennsylvania, West Virginia, Indiana, Illinois, Ohio, Wisconsin, Minnesota, Iowa, Kansas, Missouri, Oklahoma, Arkansas, Kentucky, Virginia, Tennessee, Alabama, Mississippi, and Louisiana. This range included six major basins: the Upper Mississippi, Missouri, Arkansas-White-Red, Lower Mississippi, Ohio, and Tennessee. The best available information suggests that there were at least 151 populations and 136 MUs within this range; however, it is also likely that more populations were undetected, prior to the use of more intensive contemporary survey methods. There is taxonomic uncertainty regarding populations within the Arkansas-White-Red and Lower Mississippi basins.

Current Viability Summary - The species is now considered extirpated from Pennsylvania, West Virginia, Indiana, Illinois, Wisconsin, Minnesota, Iowa, Kansas, and Missouri. The species is but limited to one population and MU in Ohio, Oklahoma, and Virginia each. The current range, which includes 4 basins, the Ohio, Tennessee, Arkansas-White-Red, and Lower Mississippi extends over 9 states: Ohio, Kentucky, Tennessee, Virginia, and Alabama. The species is considered extirpated from the Upper Mississippi and Missouri basins, a loss of 23 populations and 22 MUs across 7 states. Only 3 low conditions and MUs remain in the Arkansas-White-Red basin, where as many as 17 populations existed and 17 MUs were historically occupied.

In addition, its representation in the Cumberland River system within the Ohio basin is currently a single population & MU (loss of 8 populations and MUs). Overall, the Pyramid Pigtoe is presumed extirpated from 69 percent of its historically occupied populations (104 of 151 populations); including 19 populations (the entirety) of the Upper Mississippi basin, 4 populations in the Missouri basin (the entirety), 58 populations in the Ohio basin, ten populations in the Tennessee basin, 14 populations in the Arkansas-White-Red basin, and 11 populatons in the Lower Mississippi basin (Appendix A & B).

Of the current populations and MUs, 4 (14 percent) are estimated to be in highly resilient, 10 (36 percent) are moderately resilient, and 14 (50 percent) have low resiliency. To date, declines in the species have been dramatic. The Pyramid Pigtoe was once a common, occasionally abundant, and widespread component of the mussel assemblage in rivers where it is now considered extirpated. Examples include the Monongahela and Ohio Rivers, Pennsylvania

(Ortmann 1909, p. 199); Ohio River; Ohio/Kentucky (Watters *et al* 2009, p. 235; Haag and Cicerello 2016, p. 199); Illinois River, Illinois (Warren 1995, p. 5); Wabash and White Rivers; Indiana/Illinois (Cummings *et al.* 1992, p. 46); and Cumberland River, Kentucky/Tennessee (Haag and Cicerello 2016, p. 199; Peres et al 2016, p. 44; Wilson and Clark 1914, p. 15).

Significant declines and loss of the Pyramid Pigtoe from river reaches have been documented in the Ohio, Illinois, Neosho, White, Cumberland, Mississippi, and Tennessee Rivers (Appendix C). An illustrative example of abundance and extent reductions is in the Muskingum River system, where the species once occurred in the Mohican, Walhonding, and Tuscarawas tributaries, all of which are now extirpated, and the last remaining population in the state of Ohio has been reduced to a small reach of the lower Muskingum River below Devola Dam (Watters *et al.* 2009, p. 235; ESI 2012, p. 23).

Future Condition Scenarios - An important assumption of the predictive analysis is that future population resiliency is largely dependent on water quality, water flow, instream habitat conditions, and condition of riparian habitats (see Resource Needs, Chapter 4). It is also an important assumption that our understanding of extant populations and current habitat conditions is correct. Our assessment predicts that if conditions remain the same or become worse in the future, all 28 MUs would experience negative changes to important habitat requisites, potentially resulting in no highly resilient populations (Scenarios 1 and 2). Predicted viability varied among scenarios and is summarized below (see also Table 8-1 and Table ES-1).

Given Scenario 1, loss of resiliency and redundancy is expected, and representation within basin is affected. Under this scenario, we predict that 3 MUs (11 percent) would remain in high condition, 8 MUs (29 percent) would be in medium condition, and 12 MUs (43 percent) in low condition. Redundancy would be reduced with projected extirpation of 3 out of 28 currently extant MUs (11 percent). The Pyramid Pigtoe would continue to be represented in the Ohio, Tennessee, Arkansas-White-Red, and Lower Mississippi basins, but reduced to six states (as compared to the current nine states) occupied by the species, and only low condition MUs remaining in the Arkansas-White-Red basin. Predictions of species or even population level improvement, as a result of conservation actions, can be difficult to predict for a long lived freshwater mussel such as the Pyramid Pigtoe. For example, it will take many years (potentially beyond the 20- to 30-year time frame analyzed in this report) for full evaluation of species response to any current beneficial actions, such as removal of Lock and Dam 6 on the Green River, or the SHAs and CCAAs in the Upper Ouachita and Upper Saline Rivers.

Given Scenario 2, we predicted a significant decrease in resiliency and redundancy across the species range, and representation is reduced to only three basins. Redundancy would be reduced with no high condition MUs remaining, and the likely loss of 13 (46 percent) MUs. The resiliency of the remaining 15 MUs is expected to be reduced to four (14 percent) in medium condition and 11 (39 percent) in low condition. Thirteen (46 percent) of MUs are predicted to be in very low condition. Representation would be reduced to 15 MUs, with no high condition MUs in any basin, and the loss of the species from the Arkansas-White-Red basin, thus substantially increasing the risk of extirpation. This scenario results in the potential extirpation of the species from the states of Virginia, Ohio, Oklahoma, and Mississippi.

Overall Summary - Estimates of current and future resiliency for the Pyramid Pigtoe (Table 8-1, below) are low given that only four (14 percent) of the populations are estimated to be highly resilient and eight (29 percent) are moderately resilient. The Pyramid Pigtoe faces a variety of threats including habitat degradation or loss (i.e., declines in water quality, loss of stream flow, riparian and instream fragmentation, and small population size from development, urbanization, contaminants, agricultural activities, impoundments, changing climate conditions, resource extraction, and forest conversion), as well as impacts associated with invasive and non-native species and legacy impacts from past commercial harvest and overutilization.

These negative influences, which are expected to be exacerbated by continued growing human populations that demand associated development, energy, infrastructure, and water needs, as well as potentially climate change, were important factors in our assessment of the future viability of the Pyramid Pigtoe. Given current and future decreases in resiliency, populations and MUs become more vulnerable to extirpation from stochastic events (particularly the small populations that are linearly distributed), in turn, resulting in concurrent losses in representation and redundancy. Predictions of the Pyramid Pigtoe's habitat conditions and population factors in the future suggest possible extirpation of between 4 (14 percent) and 13 (46 percent) currently extant populations unless additional conservation is implemented and effective.

Table 8-1. Summary of Pyramid Pigtoe mussel population size, extent, threat level, current conditions, and potential future conditions. Only overall condition is listed for future scenarios.

Management Unit	Contiguous Population (occupied river)	Population Size	Population Extent	Threat Level	Current Condition	Future Condition	
						Scenario 1	Scenario 2
OHIO BASIN							
Muskingum	Muskingum River	Small	Small	High	Low	Very Low	Very Low
Upper Green	Upper Green River	Large	Large	Low	High	Medium	Medium
Barren	Barren River	Small	Small	Moderate	Medium	Medium	Low
Middle Green	Middle Green River	Medium	Medium	Moderate	Medium	Medium	Low
Lower Green	Lower Green River	Small	Small	Moderate	Low	Low	Very Low
Lower Cumberland-Old Hickory Lake	Cumberland River (Old Hickory Reservoir) Cordell Hull Tailwater	Medium	Small	High	Low	Very Low	Very Low
TENNESSEE BASIN							
Holston	Holston River	Small	Small	High	Low	Very Low	Very Low
Upper Clinch	Clinch River	Medium	Medium	Medium	Medium	Low	Low
Wheeler Lake	Paint Rock River	Small	Small	Medium	Low	Low	Very Low
	Tennessee River (Wheeler Reservoir) Guntersville Tailwater	Medium	Small	High	Low	Low	Very Low
Pickwick Lake	Tennessee River (Pickwick Reservoir) Wilson Tailwater	Medium	Medium	High	Low	Low	Low
Lower Tennessee-Beech	Tennessee River (Kentucky Reservoir) Pickwick Tailwater	Small	Small	High	Low	Low	Low
Upper Duck	Upper Duck River	Large	Medium	Moderate	Medium	Medium	Low
Lower Duck	Lower Duck River	Large	Small	Moderate	Medium	Low	Very Low
ARKANSAS-WHITE-RED BASIN							
Petit Jean	Petit Jean River	Small	Small	Moderate	Low	Low	Very Low
Eleven Point	Eleven Point River	Small	Small	Low	Low	Low	Very Low
Lower Little	Little River	Medium	Small	Moderate	Low	Low	Very Low
LOWER MISSISSIPPI BASIN							
Lower Black	Lower Black River	Small	Small	Moderate	Low	Low	Very Low
Lower St. Francis	St. Francis River	Medium	Small	High	Medium	Medium	Low
	Tyronza River	Medium	Large	High	Medium	Medium	Low

Management Unit	Contiguous Population (occupied river)	Population Size	Population Extent	Threat Level	Current Condition	Future Condition	
						Scenario 1	Scenario 2
Middle White	Middle White River	Small	Small	Moderate	Low	Low	Very Low
Upper Ouachita	Upper Ouachita River	Large	Large	Moderate	High	High	Medium
Little Missouri	Little Missouri River	Large	Medium	Moderate	Medium	Medium	Low
Lower Ouachita - Smackover	Lower Ouachita River (Smackover)	Medium	Medium	Moderate	Medium	Medium	Low
Upper Saline	Upper Saline River	Large	Large	Moderate	High	High	Medium
Lower Saline	Lower Saline River	Large	Large	High	High	High	Medium
Bayou Bartholomew	Bayou Bartholomew	Large	Large	High	Medium	Medium	Low
Lower Ouachita-Bayou De Loutre	Lower Ouachita River (Bayou De Loutre)	Medium	Medium	High	Low	Low	Low
Big Sunflower	Hushpuckna River	Small	Small	High	Medium	Low	Very Low
	Bogue Phalia	Small	Small	High	Medium	Low	Very Low
	Little Sunflower River	Small	Small	High	Medium	Low	Very Low
	Sunflower River	Medium	Large	High	Medium	Low	Very Low
	Sandy Bayou	Small	Small	High	Medium	Low	Very Low
	Big Sunflower River	Medium	Large	High	Medium	Low	Very Low
Lower Big Black	Big Black River	Small	Small	High	Low	Very Low	Very Low

LITERATURE CITED

NOTE: SOME OF THE WORKS CITED ARE NOT WITHIN THE DOCUMENT BUT ARE IN THE APPENDICES.

Ahlstedt, S.A. 1989. Update of the Watts Bar Nuclear Plant preoperational monitoring of the mussel fauna in upper Chickamauga Reservoir. Tennessee Valley Authority Water Resources Report. 32 pp.

Ahlstedt, S.A. 1991a. Twentieth century changes in the freshwater mussel fauna of the Clinch River (Tennessee and Virginia). Walkerana 5(13):73–122.

Ahlstedt, S.A. 1991b. Cumberlandian Mollusk Conservation Program: mussel surveys in six Tennessee Valley streams. Walkerana 5(13):123–160.

Ahlstedt, S.A. and T.A. McDonough. 1993. Quantitative evaluation of commercial mussel populations in the Tennessee River portion of Wheeler Reservoir, Alabama. pp. 38-49 *In* Conservation and management of freshwater mussels. Proceedings of a UMRCC symposium.

Ahlstedt, S.A. 1995–96. Status survey for federally listed endangered freshwater mussel species in the Paint Rock River system, northeastern Alabama, U.S.A. Walkerana 8(19):63–80.

Ahlstedt, S.A., and 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.

Ahlstedt, S.A., and T.A. McDonough. 1995–96. Summary of pre-operational monitoring of the mussel fauna in the upper Chickamauga Reservoir (Tennessee River) in the vicinity of TVA's Watts Bar Nuclear Plant, 1983–1993. Walkerana 8(19):107–126.

Ahlstedt, S.A., S. Bakaletz, M.T. Fagg, D. Hubbs, M.W. Treece, and R.S. Butler. 2003-2004. Current status of freshwater mussels (Bivalvia: Unionidae) in the Big South Fork National River and Recreation Area of the Cumberland River, Tennessee and Kentucky (1999-2002): Evidence of faunal recovery. Walkerana 12(31):33-77.

Ahlstedt, S.A., J.R. Powell, R.S. Butler, M.T. Fagg, D.W. Hubbs, S.F. Novak, S.R. Palmer, and P.D. Johnson. 2004. Historical and current examination of freshwater mussels (Bivalvia: Margaritiferidae, Unionidae) in the Duck River basin Tennessee. Final Report: Tennessee Wildlife Resource Agency contract FA-02-14725-00.

Ahlstedt, S.A., M.T. Fagg, R.S. Butler, and J.F. Connell. 2005. Long-term trend information for freshwater mussel populations at twelve fixed-station monitoring sites in the Clinch and Powell rivers of eastern Tennessee and southwestern Virginia. Report prepared for US Fish & Wildlife Service, Cookeville, Tennessee. 38 pp.

Ahlstedt, S.A., M.T. Fagg, R.S. Butler, J.F. Connell, and J.W. Jones. 2016. Quantitative Monitoring of Freshwater Mussel Populations from 1979-2004 in the Clinch and Powell Rivers of Tennessee and Virginia, with Miscellaneous Notes on the Fauna. Freshwater Mollusk Biology and Conservation 19:1–18.

Ahlstedt, S.A., J.W. Jones, and C. Walker. 2017a. Current status of freshwater mussel populations in the Clinch River at the Appalachia Power Company's Clinch River Steam Plant, Russell County, Virginia. Malacological Review 45/46:213–225.

Ahlstedt, S.A., J.R. Powell, R.S. Butler, M.T. Fagg, D.W. Hubbs, S.F. Novak, S.R. Palmer, and P.D. Johnson. 2017b. Historical and current examination of freshwater mussels (Bivalvia: Margaritiferidae: Unionidae) in the Duck River basin, Tennessee, U.S.A. Malacological Review 45:1–163.

Akers, P.E. 2000. The freshwater mussels (Bivalvia: Unionidae) of the Rolling Fork River drainage of Kentucky. M.S. thesis, Eastern Kentucky University. 36 pp.

Alig, R. S. Stewart, D. Wear, S. Stein, and D. Nowak. 2010. Conversions of Forest Land: Trends, Determinants, Projections, and Policy Considerations. Chapter in Advances in Threat Assessment and Their Application to Forest and Rangeland Management. U.S. Forest Service General Technical Report PNW-GTR-802.

Aldridge, D. W., Payne, B. S., and A.C. Miller. 1987. The effects of intermittent exposure to suspended solids and turbulence on three species of freshwater mussels. Environmental Pollution 45(1):17–28.

Allan, J.D., D.L. Erikson, and J.Fay. 1997. The influence of catchment land use on stream integrity across multiple spatial scales. Freshwater Biology 37:149–161.

Allan, J.D., and M.M. Castillo. 2007. Stream Ecology: Structure and Function of Running Waters. 2nd edition. Springer, Netherlands.

Allen, A.W., Y.K. Bernal, and R.J. Moulton. 1996. Pine Plantations and Wildlife in the Southeastern United States: An Assessment of Impacts and Opportunities. Information and Technology Report 3, U.S. Department of Interior, Washington, D.C. 40 pp.

Anderson, R.M., and D.A. Kreeger. 2010. Potential for impairment of freshwater mussel populations in Delaware River Basin Commision special protection waters as a consequence of natural gas exploratory well development. 14 pp.

Anthony, J.L., and J.A. Downing. 2001. Exploitation trajectory of a declining fauna: a century of freshwater mussel fisheries in North America. Canadian Journal of Fisheries and Aquatic Sciences 58:2,071–2,090.

Athearn, H. 1957. Mollusks of the tentative Tellico Dam inundation area. 2 pp.

Archambault, J.M., C.M. Bergeron, W.G. Cope, P.R. Lazaro, J.A. Leonard, and D. Shea. 2017. Assessing toxicity of contaminants in riverine suspended sediments to freshwater mussels. Environmental Toxicology and Chemistry 36(2):395–407.

Archambault, J.M., W.G. Cope, and T.J. Kwak. 2018. Chasing a changing climate: Reproductive and dispersal traits predict how sessile species respond to global warming. Diversity and Distributions 24:880–891.

Augspurger, T., A.E. Keller, M.C. Black, W.G. Cope, and F.J. Dwyer. 2003. Water quality guidance for protection of freshwater mussels (Unionidae) from ammonia exposure. Environmental Toxicology and Chemistry 22(11):2,569–2,575.

Augspurger, T., F. J. Dwyer, C. G. Ingersoll, and C. M. Kane. 2007. Advances and opportunities in assessing contaminant sensitivity of freshwater mussel (Unionidae) early life stages. Environmental Toxicology and Chemistry 26:2,025–2,028.

Aust, W.M., Carroll, M.B., Bolding, M.C., and C.A. Dolloff. 2011. Operational forest stream crossings effects on water quality in the Virginia Piedmont. Southern Journal of Applied Forestry 35:123–130.

Balciunas, J.K, M.J. Grodowitz, A.F. Cofranesco, and J.F. Shearer. Hydrilla. *in*: Van Driesche, R., 2002, Biological Control of Invasive Plants in the Eastern United States, USDA Forest Service Publication Forest Health Technology Enterprise Team, 2002–04, 413 pp.

Barling, R.D., and I.D. Moore. 1994. Role of buffer strips in management of waterway pollution: A review. Environmental Management 18(4)543–558.

Barnhart, M.C., W.R. Haag, and W.N. Roston. 2008. Adaptations to host infection and larval parasitism in Unionoida. Journal of the North American Benthological Society 27(2):370–394.

Barr, W.C., S.A. Ahlstedt, G.D. Hickman, and D.M. Hill. 1993-94. Cumberlandian Mollusk Conservation Program. Activity 8: analysis of macrofauna factors. Walkerana 7(17-18):159–224.

Bartsch, M.R., T.J. Newton, J.W. Allran, J.A. O'Donnell, and W.B. Richardson. 2003. Effects of pore-water ammonia on situ survival and growth of juvenile mussels (*Lampsilis cardium*) in the St. Croix riverway, Wisconsin, USA. Environmental Toxicology and Chemistry. 22(11):2,561–2,568.

Berg, D.J., A.D. Christian, and S.I. Guttman. 2007. Population genetic structure of three freshwater mussel (Unionidae) species within a small stream system: significant variation at local spatial scales. Freshwater Biology 52:1,427–1,439.

Berg, D.J., T.D. Levine, J.A. Stoeckel, and B.K. Lang. 2008. A conceptual model linking demography and population genetics of freshwater mussels. Journal of the North American Benthological Society 27(2):395–408.

Berkman, H.E, and C.F. Rabeni. 1987. Effect of siltation on stream fish communities. Environmental Biology of Fishes. 18(4):285–294.

Blalock, H.N., and J.B. Sickel. 1996. Changes in mussel (Bivalvia: Unionidae) fauna within the Kentucky portion of Lake Barkley since impoundment of the lower Cumberland River. American Malacological Bulletin. 13(1/2):111-116.

Bogan, A.E. 1990. Stability of recent unionid (Mollusca: Bivalvia) communities over the past 6000 years. Pp. 112–136 in: W. Miller, III, ed. Paleocommunity temporal dynamics: the long-term development of multispecies assemblies. The Paleontological Society Special Publication No. 5.

Bogan, A.E., and G.W. Davis. 1990a. Report #3. The Unionidae of Pennsylvania: rare, endangered, extinct. Allegheny River survey: river miles 31.5–45.5, navigation pools 5 and 6, September 18-20, 1990. Academy of Natural Sciences of Philadelphia, Pennsylvania. 8 pp.

Bogan, A.E., and G.W. Davis. 1990b. Report #2. The Unionidae of Pennsylvania: rare, endangered, extinct. Allegheny River survey: river miles 98.4–120.2, August 20–23, 1990. Academy of Natural Sciences of Philadelphia, Pennsylvania. 8 pp.

Böpple, J.F., and R.E. Coker. 1912. Mussel resources of the Holston and Clinch River, Tennessee and Virginia. U.S. Bureau of Fisheries Document No. 765:3–13.

Bonner, T.H., E.L. Oborny, B.M. Littrell, J.A. Stoeckel, B.S. Helms, K.G. Ostrand, P.L. Duncan, and 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.

Boyer, A. 2020. Personal communication on July, 10, 2020, between U.S. Fish and Wildlife Service personnel. Angela Boyer (Ohio Field Office, Columbus, Ohio, State) and Andrew Henderson, regarding dams on the Muskingum River, Ohio.

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

Bringolf, R.B., W.G. Cope, C.B. Eads, P.R. Lazaro, M.C. Barnhart, and D. Shea. 2007. Acute and chronic toxicity of technical-grade pesticides to glochidia and juveniles of freshwater mussels (Unionidae). Environmental Toxicology and Chemistry. 26(10):2,086–2,093.

Bringolf, R.B., R.M. Heltsley, T.J. Newton, C.B. Eads, S.J. Fraley, D. Shea, and W.G. Cope. 2010. Environmental occurrence and reproductive effect of the pharmaceutical fluoxetine in native freshwater mussels. Environmental Toxicology and Chemistry 29(6):1,311–1,318.

Broadmeadow, S. and T.R. Nisbet. 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practices. Hydrology and Earth System Sciences 8(3):286–305.

Brown, A.V., M.M. Lyttle, and K.B. Brown. Impacts of gravel mining on gravel bed streams. Transactions of the American Fisheries Society. 127(1998):979–994.

Brown, M.E., M. Kowalewski, R.J. Neves, D.S. Cherry, and 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. Environmental Science and Technology. 39(2005):1,455–1,462.

Buchanan, B.P., D.A. Auerbach, R.A. McManamay, J.M. Taylor, A.S. Flecker, J.A. Archibald, D.R. Fuka, and M.T. Walter. 2017. Environmental flows in the context of unconventional natural gas development in the Marcellus Shale. Ecological Applications 27(1):37–55.

Burdick, R. C. and M. M. White. 2007. Phylogeography of the Wabash pigtoe, Fusconaia flava (Rafinesque, 1820) (Bivalvia: Unionidae). Journal of Molluscan Studies 73(4): 367-375.

Butler, R.S. 2005. Status Assessment Report for the Rabbitsfoot, *Quadrula cylindrica cylindrica*, a freshwater mussel occurring in the Mississippi River and Great Lakes Basins. Report Prepared by the Ohio River Valley Ecosystem Team Mollusk Subgroup. 208 pp.

Cairns, J., Jr., J.S. Crossman, K.L. Dickman, and E.E. Herrick. 1971. Chemical plants leave unexpected legacy in two Virginia rivers. Science 198:1,015–1,020.

Caldwell, P. C .Segura, S.G. Laird, G. Sun, S.G. McNulty, M. Sandercock, J. Boggs, and J.M. Vose. 2014. Short-term stream water temperature observations permit rapid assessment of potential climate change impacts. Hydrological Processes 29(9):2,196–2,211.

Call, R.E. 1900. A descriptive illustrated catalogue of the Mollusca of Indiana. 24th Annual Report of the Indiana Department of Geology and Natural Resources for 1899:335–535, 1013-1017.

Call, S.M., and K. Robinson. 1983. Mollusks from an archaeological site in Woodford County, Kentucky. American Malacological Bulletin 1: 31–34.

Campbell, D., J. Serb, J. Buhay, K. Roe, R. Minton and C. Lydeard. 2005. Phylogeny of North American amblemines (Bivalvia, Unionoida): prodigious polyphyly proves pervasive across genera. Invertebrate Biology 124(2): 131-164.

Campbell, D. C., P. D. Johnson, J. D. Williams, A. K. Rindsberg, J. M. Serb, K. K. Small and C. Lydeard. 2008. Identification of 'extinct' freshwater mussel species using DNA barcoding. Molecular Ecology Resources 8(4): 711-724.

Campbell, D.C., and C. Lydeard. 2012a. Molecular systematics of *Fusconaia* (Bivalvia: Unionidae: Ambleminae). American Malacological Bulletin 30(1):1–17.

Campbell, D.C., and C. Lydeard. 2012b. The genera of Pleurobemini (Bivalvia: Unionidae: Ambleminae). American Malacological Bulletin 30(1):19–38.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Shartley, V.H. Smith. 1998. Non point Pollution of Surface Waters with Phosphorus and Nitrogen. Ecological Applications 8(3):559–568.

Casey, J.L., 1986. The prehistoric exploitation of unionacean bivalve molluscs in the Lower Tennessee-Cumberland-Ohio River valleys in western Kentucky. Simon Fraser University, unpublished Master's Thesis. 196 pp.

[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. 538–540.

Chen, L.-Y., A.G. Heath, and R.J. Neves. 2001. Comparison of oxygen consumption of freshwater mussels (Unionidae) from different habitats during declining dissolved oxygen concentration. Hydrobiologia 450:209–215.

Cherry, D.S., J.L. Scheller, N.L. Cooper, and 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(2):369–380.

Chetty, A.N., and K. Indira. 1994. Alterations in the tissue lipid profiles of Lamellidens marginalis under ambient ammonia stress. Bulletin of Environmental Contamination and Toxicology 53:693–698.

Christian, A. D., J. L. Harris, J. M. Serb, D. M. Hayes and K. Inoue. 2008. Preliminary Analysis for Identification, Distribution, and Conservation Status of Species of Fusconaia and Pleurobema in Arkansas. Unpublished report. Arkansas Game and Fish Commission. 41 pp.

Cicerello, R.R. 1999. A survey of the freshwater mussels (Mollusca: Unionoidea) of the Green River, Green River Lake Dam to Mammoth Cave National Park, Kentucky. Kentucky State Nature Preserves Commission, Frankfort. 42 pp.

Cicerello, R.R., and R.R. Hannan. 1990. Survey of the freshwater unionids (mussels) (Bivalvia: Margaritiferidae and Unionidae) in the Green River in Mammoth Cave National Park, Kentucky. Report prepared for Mammoth Cave National Park. 49 pp.

Cicerello, R.R., M.L. Warren, Jr., and G.A. Schuster. 1991. A distributional checklist of the freshwater unionids (Bivalvia: Unionoidea) of Kentucky. American Malacological Bulletin 8(2):113–129.

Clarke, A.H. 1995. Survey of mussel beds in the lower Ohio River (ORM 438.1 to 981.0). Unpublished report, ECOSEARCH, Inc., Port Arthur, Texas, for U.S. Army Corps of Engineers, Louisville, Kentucky. 123 pp + appendices.

Clayton, J.L. 2018. Personal email communications with Janet Clayton, West Virginia Division of Natural Resources (WVDNR), regarding threats associated with oil and gas development.

Cochran, T.G., Jr., and J.B. Layzer. 1993. Effects of commercial harvest on unionid habitat use in the Green and Barren Rivers, Kentucky. Pp. 61–65 *in:* K.S. Cummings, A.C. Buchanan, and L.M. Koch (eds). Conservation and management of freshwater mussels. Proceedings of a UMRCC symposium, October 1992, St. Louis, Missouri. Upper Mississippi River Conservation Committee, Rock Island, Illinois.

Coker, R.E. 1919. Fresh-water mussels and mussel industries of the United States. US Bureau of Fisheries Document 865. Washington, DC. 89 pp.

Colle, D.E., J.V. Shireman, W.T. Haller, J.C. Joyce, and D.E. Canfield. 1987. Influence of *Hydrilla* on harvestable sport-fish populations, angler use, and angler expenditures at Orange Lake, Florida. North American Journal of Fisheries Management 7:410–417.

Compton, M.C., B.D. Yahn, L.T. Phelps. 2017. Preliminary ecological assessment of the Green and Nolin rivers in Mammoth Cave National Park, Kentucky, following the removal of lock and dam #6. Kentucky State Nature Preserves Commission Report to the US Fish & Wildlife Service, Frankfort, Kentucky.

Cooper, N.L., J.R. Bidwell, and D.S. Cherry, D.S. 2005. Potential effects of Asian clam (Corbicula fluminea) die-offs on native freshwater mussels (Unionidae) II: porewater ammonia. Journal of the North American Benthological Society 24(2):381–394.

Cope, W.G., M.R. Bartsch, and J.E. Hightower. 2006. Population dynamics of Zebra mussels Dreissena polymorpha (Pallas, 1771) during the initial invasion of the upper Mississippi River, USA. Journal of Molluscan Studies 72:179–188.

[Corps] U.S. Army Corps of Engineers. 2006. Ohio River Mainstem System Study Integrated Main Report. System Investment Plan/Programmatic Environmental Impact Statement. 453 pp.

[Corps] U.S. Army Corps of Engineers. 2012. Duck River Watershed Tennessee. Initial Watershed Assessment. 57 pp.

[Corps] U.S. Army Corps of Engineers. 2018. Duck River Watershed Tennessee. Final Watershed Assessment. 318 pp.

Couceiro, S., Hamada, N., Luz, S., Forsberg, B., and Pimentel, T. 2007. Deforestation and sewage effects on aquatic macroinvertebrates in urban streams in Manaus, Amazonas, Brazil. Hydrobiologia. 575:271–284.

Culp, J.J., A.C. Shepard, and M.A. McGregor. 2006. New host fish identifications for the Pyramid Pigtoe, *Pleurobema rubrum*. Ellipsaria 8(3):5-6.

Culp, J.J., A.C. Shepard, and M.A. McGregor. 2009. Fish hosts and conglutinates of the pyramid pigtoe (*Pleurobema rubrum*). Southeastern Naturalist 8(1):19–22.

Cummings, K.S., and J.M.K. Berlocher. 1990. The naiads or freshwater mussels (Bivalvia: Unionidae) of the Tippecanoe River, Indiana. Malacological Review 23:83–98.

Cummings, K.S., and C.A. Mayer. 1992. Field guide to freshwater mussels of the Midwest. Illinois Natural History Survey Manual 5. Champaign, Illinois.

Cummings, K.S., C.A. Mayer, L.M. Page, and J.M.K. Berlocher. 1987. Survey of the freshwater mussels (Mollusca: Unionidae) of the Wabash River drainage. Phase I: lower Wabash and Tippecanoe Rivers. Illinois Natural History Survey Technical Report No. 1987(5). 149 pp.

Cummings, K.S., L. Suloway, and L.M. Page. 1988a. The freshwater mussels (Mollusca: Bivalvia: Unionidae) of the Embarras River in Illinois: Thirty years of stream change. Illinois Natural History Survey Technical Report No. 1988(2). 63 pp.

Cummings, K.S., C.A. Mayer, and L.M. Page. 1988b. Survey of the freshwater mussels (Mollusca: Unionidae) of the Wabash River drainage. Phase II: upper and middle Wabash River. Illinois Natural History Survey Technical Report 1988(8). 47 pp.

Cummings, K.S., C.A. Mayer, and L.M. Page. 1991. Survey of the freshwater mussels (Mollusca: Unionidae) of the Wabash River drainage. Phase III: White River and selected tributaries. Illinois Natural History Survey Technical Report 1991(3). 80 pp.

Cummings, K.S., C.A. Mayer, and L.M. Page. 1992. Survey of the freshwater mussels (Mollusca: Unionidae) of the Wabash River drainage. Final Report. Illinois Natural History Survey Technical Report 1992. 201 pp.

Center for Watershed Protection. 2003. Impacts of Impervious Cover on Aquatic Systems. Watershed Protection Research Monograph No. 1. Ellicott City, Maryland. 158 pp.

Danglade, E. 1922. The Kentucky River and its mussel resources. Monograph. U.S. Department of Commerce, Bureau of Fisheries Document 934.

Davis, G.W., and A.E. Bogan. 1990a. The Unionidae of Pennsylvania: rare, endangered, extinct. Academy of Natural Sciences of Philadelphia, Pennsylvania. 86 pp.

Davis, G.W., and A.E. Bogan. 1990b. Report No. 2. The Unionidae of Pennsylvania: rare, endangered, extinct. Allegheny River survey: river miles 98.4-120.2, August 20-23, 1990. Academy of Natural Sciences of Philadelphia, Pennsylvania. 10 pp.

Dennis, S.D. 1985. Distributional analysis of the freshwater mussel fauna of the Tennessee River system, with special reference to possible limiting effects of siltation. Tennessee Wildlife Resources Agency Report No. 85-2, Nashville. 171 pp.

Diamond, J.M., D.W. Bressler, and V.B. Serveiss. 2002. Assessing relationships between human land uses and the decline of native mussels, fish, and macroinvertebrates in the Clinch and Powell River watershed, USA. Environmental Toxicology and Chemistry 21(6): 1147–1155.

Dimmock, R.V. and A.H. Wright. 1993. Sensitivity of Juvenile Freshwater Mussels to hypoxic, thermal and acid stress. The Journal of the Elisha Mitchell Scientific Society 109(4):183–192.

Dunn, H.L., B.E. Sietman, and D.E. Kelner. 2000. Evaluation of recent unionid (Bivalvia) relocations and suggestions for future relocations and reintroductions. Pp. 169–183 in: P.D. Johnson and R.S. Butler, eds. Freshwater Mollusk Symposium Proceedings—Part II: musseling in on…biodiversity. Proceedings of the 1st symposium of the Freshwater Mollusk Conservation Society, March 1999, Chattanooga, Tennessee. Ohio Biological Survey, Columbus.

Ebert, D.J. 1993. Dredging. Pp. 157-164. in: C.F. Bryan, and D.A. Rutherford, eds. Impacts on warmwater streams: Guidelines for evaluation. Southern Division, American Fisheries Society, Little Rock, Arkansas.

Eissa, A.E. and M.M. Zaki. 2011. The impact of global climatic changes on the aquatic environment. Procedia Environmental Sciences 4:251–259.

Edleman, A.J., J. Moran, T.J. Garrabrant, and K.C. Vorreiter. 2015. Muskrat predation of native freshwater mussels in Shoal Creek, Alabama. Southeastern Naturalist 14(3):473-483.

[EPA] U.S. Environmental Protection Agency. 1985. Ambient water quality criteria for ammonia. Office of Water Regulations and Standards, Criteria and Standards Division, EPA 440/5-85-001, Washington, DC.

[EPA] U.S. Environmental Protection Agency. 2013. 78 FR 52192, Rec. Criteria for ammonia

[EPA] U.S. Environmental Protection Agency. 2016. Nutrient Pollution – The Sources and Solutions: Agriculture. *https://www.epa.gov/nutrientpollution/sources-and-solutions-agriculture* (Accessed: October 1, 2018).

[EPA] U.S. Environmental Protection Agency. 2018. Section 404 of the Clean Water Act. *https://www.epa.gov/cwa-404/exemptions-permit-requirements* (Accessed: October 1, 2018).

[ESI] Ecological Specialists, Inc. 1993. Mussel habitat suitability and impact analysis of the Tippecanoe River. Indiana Department of Natural Resources, Indianapolis, and U.S. Fish and Wildlife Service, Bloomington, Indiana. 102 pp.

[ESI] Ecological Specialists, Inc. 2000. Freshwater mussels (Bivalvia: Unionidae) of the upper Ohio River. Report for the Mussel Mitigation Trust Fund Committee, Cincinnati, Ohio, and U.S. Fish and Wildlife Service, Cookeville, Tennessee. 99 pp.

[ESI] Ecological Specialists, Inc. 2009. Amended report: Analysis of threats to the distribution of unionid mussels in the Elk River, West Virginia, Clay, Braxton, and Kanawha counties. Unpublished report prepared for the U.S. Fish & Wildlife Service, Elkins, West Virginia Field Office. 110 pp.

[ESI] Ecological Specialists, Inc. 2012. Unionid mussel communities near proposed hydropower facilities in the Muskingum River, 2011. Unpublished report prepared for Free Flow Power. 136 pp.

Eissa, A.E. and M.M. Zaki. 2011. The impact of global climatic changes on the aquatic environment. Procedia Environmental Sciences 4:251–259.

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

EnviroScience, Inc. 2007. Freshwater mussel survey for Dover Dam safety assurance program. Unpublished survey report for Burgess and Niple, Ltd. and the US Army Corps of Engineers, Huntington District. 29 pp.

EnviroScience, Inc. 2009. 2008 Freshwater mussel translocation and monitoring of the American Electric Power Dresden Plant on the Muskingum River (River Mile ~90). Unpublished survey report to American Electric Power. 62 pp.

Fagan, W.F. 2002. Connectivity, fragmentation, and extinction risk in dendrictic metapopulations. Ecology. 83(12):3,243–3,249.

Fahrig, L. 2003. Effects of habitat fragmentation on biodiversity. Annual Reviews of Ecology, Evolution, and Systematics. 34(2003):487–515.

Fetchner, F.R. 1963. Checklist of east central Illinois Unionidae. Nautilus. 76(3):99–101.

Fisher, B.E. 2006. Current status of freshwater mussels (Order Unionoida) in the Wabash River drainage of Indiana. Proceedings of the Indiana Academy of Science. 115(2):103–109.

Fleece, C. 2012. Ohio River freshwater mussel survey for the proposed Rolling Hills Generating, LLC conversion and pipeline project, Gallia, Meigs, and Vinton counties, Ohio. Unpublished report prepared by Stantec for Rolling Hills Generating, LLC. 88 pp.

Fobian, T.B., M.L. Buntin, J.T. Holifield, T.A. Tarpley, J.T. Garner, and P.D. Johnson. 2014. Freshwater mussels (Unionidae) in the Paint Rock River (Jackson, Madison, and Marshall counties), Alabama. Southeastern Naturalist 13(2):347-366.

Freshwater Mollusk Conservation Society. 2018. Mollusk health & disease workshop program. 11th biennial workshop. LaCrosse, Wisconsin. 47 pp.

Frankham, R. 1996. Relationship of genetic variation to population size in wildlife. Conservation Biology. 10(6):1,500–1,508.

Frazier B.E., Naimo T.H., and M.B. Sandheinrich. 1996. Temporal and vertical distribution of total ammonia nitrogen and un-ionized ammonia nitrogen in sediment pore water from the upper Mississippi River. Environmental Toxicology Chemistry 15:92–99.

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. Forster, S.J. Converse, C. Dartst, S. Morey. 2019. 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 (*https://doi.org/10.1007/s10592-018-1096-1*)

Furedi, M. 2013. An examination of the effects of climate change on species in Pennsylvania. Pennsylvania Natural Heritage Program, Western Pennsylvania Conservancy, Pittsburgh, Pennsylvania. 83 pp.

Galbraith, H.S., D.E. Spooner, and C.C. Vaughn. 2010. Synergistic effects of regional climate patterns and local water management on freshwater mussel communities. Biological Conservation 143:1,175–1,183.

Gangloff, M.M., K.K. Lenertz, and J.W. Feminella. 2008. Parasitic mite and trematode abundance are associated with reduced reproductive output and physiological condition of freshwater mussels. Hydrobiologia 610:25–31.

Garner, J. 2019. Email communication between J. Garner, Alabama Department of Conservation and Natural Resources, with Andrew Henderson, Service, on November 25, 2018, regarding threats to mussel populations.

Garner, J.T., and S.W. McGregor. 2001. Current status of freshwater mussels (Unionidae, Margaritiferidae) in the Muscle Shoals area of Tennessee River in Alabama (Muscle Shoals revisited again). American Malacological Bulletin 16(1/2):155–170.

Gascho-Landis, A.M., and J.A. Stoeckel. 2015. Multi-stage disruption of freshwater mussel reproduction by high suspended solids in short and long-term brooders. Freshwater Biology 61(2):229–238.

Gatenby, C.M., R.J. Neves, and B.C. Parker. 1996. Influence of sediment and algal food on cultured juvenile freshwater mussels. Journal of the North American Benthological Society 15(4):597–609.

Gibson, K.J. 2015. Acute Toxicity Testing on Freshwater Mussels (Bivalvia: Unionidae) and Freshwater Snails (Gastropoda: Caenogastropoda). Unpublished Master's Thesis, Troy University, Troy, Alabama. 129 pp.

Giddings, E.M.P., Bell, A.H., Beaulieu, K.M., Cuffney, T.F., Coles, J.F., Brown, L.R., Fitzpatrick, F.A., Falcone, James, Sprague, L.A., Bryant, W.L., Peppler, M.C., Stephens, Cory, and McMahon, Gerard. 2009. Selected physical, chemical, and biological data used to study urbanizing streams in nine metropolitan areas of the United States, 1999–2004: U.S. Geological Survey Data Series 423, 11 pp. + data tables.

Geist, J. 2010. Strategies for the conservation of endangered freshwater pearl mussels (*Margaritifera margaritifera* L.): A synthesis of conservation genetics and ecology. Hydrobiologia 644:69–88.

Godwin, J.C. 2002. Monitoring of federally listed and rare mussels in the Paint Rock River. Report prepared by the Alabama Natural Heritage Program for the Alabama Department of Conservation and Natural Resources, Montgomery. 80 pp.

Gooch, C.H., W.J. Pardue, and D.C. Wade. 1979. Recent mollusk investigations on the Tennessee River: 1978. Tennessee Valley Authority, Muscle Shoals, Alabama, and Chattanooga, Tennessee. 126 pp.

Goodrich, C., and H. van der Schalie. 1944. A revision of the Mollusca of Indiana. American Midland Naturalist 32(2):257–326.

Gordon, M.E., and J.B. Layzer. 1989. Mussels (Bivalvia: Unionidea) of the Cumberland River: Review of life histories and ecological relationships. US Fish & Wildlife Service Biological Report 89(15). 99 pp.

Gordon, M.E., and G. Sherman. 1995. Survey of endangered mussels in the Barren and Green Rivers. Unpublished report, Tennessee Technological University, Cookeville, for the Kentucky Department of Fish and Wildlife Resources, Frankfort, Kentucky. 44 pp.

Goudreau, S., R.J. Neves, and R.J. Sheehan. 1993. Effects of wastewater treatment plant effluents on freshwater mollusks in the upper Clinch River, Virginia, U.S.A. Hydrobiologia 252(3):211–230.

Grizzle, J.M., and C.J. Brunner. 2009. Infectious diseases of freshwater mussels and other freshwater bivalve mollusks. Reviews in Fisheries Science 17(4):425–467.

Haag, W. 2009. Past and future patterns of freshwater mussel extinctions in North America during the Holocene. Holocene extinctions (2009):107–128

Haag, W. 2012. North American Freshwater Mussels: Natural History, Ecology, and Conservation. Cambridge University Press, Cambridge, New York.

Haag, W.R., and J.L. Staton. 2003. Variation in fecundity and other reproductive traits in freshwater mussels. Freshwater Biology 48:2,118–2,130.

Haag, W.R., and M.L. Warren. 2003. Host fishes and infection strategies of freshwater mussels in large Mobile Basin streams, USA. Journal of the North American Benthological Society 22(1):78–91.

Haag W.R. and A.L. Rypel 2010. Growth and longevity in freshwater mussels: evolutionary and conservation implications. Biological Reviews 86(1):225–247.

Haag, W.R., and R.R. Cicerello. 2016. A distributional atlas of the freshwater mussels of Kentucky. Scientific and Technical Series Number 8. Kentucky State Nature Preserves Commission, Frankfort, Kentucky.

Haag, W., J.J. Culp, M.A. McGregor, R. Bringolf, and J.A. Stoeckel. 2019. Growth and survival of juvenile freshwater mussels in streams: Implications for understanding enigmatic mussel declines. Freshwater Science 38(4):753-770.

Haefner, R.J., and L.A. Simonson. 2018. Summary of hydrologic data for the Tuscarawas River basin, Ohio, with an annotated bibliography. USGS Scientific Investigations Report 2010–5010. 115 pp.

Hanlon, S.D., M.A. Petty, and R.J. Neves. 2009. Status of native freshwater mussels in Copper Creek, Virginia. Southeastern Naturalist 8(1):1–18.

Hartfield, P.W. 1993. Headcuts and their effect on freshwater mussels. Pp. 131–141 *in:* K.S. Cummings, A.C. Buchanan, and L.M. Koch (eds). Conservation and management of freshwater mussels. Proceedings of a UMRCC symposium, October 1992, St. Louis, Missouri. Upper Mississippi River Conservation Committee, Rock Island, Illinois.

Hartfield, P.D., and D. Ebert. 1986. The mussels of southwest Mississippi streams. American Malacological Bulletin 4(1) (1986):21-23.

Hartfield, P.D., and R.G. Rummel. 1985. Freshwater mussels (Unionidae) of the Big Black River, Mississippi. The Nautilus 99(4):116–119.

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

Harris, J.L., W.R. Posey, C.L Davidson, J.L. Farris, S.R. Oetker, J.N. Stoeckel, B.G. Crump, M.S. Barnett, H.C. Martin, J.H. Seagraves, M.W. Matthews, R. Winterringer, C. Osborne, A.D. Christian, and N.J. Wentz. 2009. Unionoida (Mollusca: Margaritiferidae, Unionidae) in Arkansas, Third Status Review. Journal of the Arkansas Academy of Science 63(1): 50-84.

Havlik, M.E., and L.L. Marking. 1987. Effects of contaminants on naiad mollusks (Unionidae): a review. Unpublished report, U.S. Fish and Wildlife Service Resource Publication 164. 20 pp.

Heinricher, J.R., and J.B. Layzer. Reproduction by individuals of a nonreproducing population of *Megalonaias nervosa* (Mollusca: Unionidae) following translocation. American Midland Naturalist 141(1):140-148.

Henderson, A.R. 2018. Personal observation of fresh dead Pyramid Pigtoe in the Clinch River, at Kyles Ford, TN, within the affected area of mussel die-off. U.S. Fish and Wildlife Service, Asheville Ecological Services Office.

Henley, W.F. 2018. Email communications with Bill Henley, Virginia Polytechnic Institute and State University (VPI) regarding mussel histology, June 12, 2018.

Hersey, K.A., J.D. Clark and J.B. Layzer. Consumption of freshwater bivalves by muskrats in the Green River, Kentucky. American Midland Naturalist 170(2):248–259.

Higgins, J.M., and W.G. Brock. 1999. Overview of reservoir release improvements at 20 TVA dams. Journal of energy engineering 125(1):1–17.

Hoggarth, M.A. 1994. The unionidae (Mollusca:Bivalvia) of the Walhonding River, Coshocton County, Ohio. Unpublished report to the Ohio Department of Natural Resources and the US Fish & Wildlife Service Region 3 office. 37 pp.

Hoggarth, M.A. 1995–96. The Unionidae (Mollusca: Bivalvia) of the Walhonding River, Coshocton County, Ohio, including the federally endangered catspaw (Epioblasma obliquata obliquata), fanshell (Cyprogenia stegaria), and clubshell (Pleurobema clava) mussels. Walkerana 8(20):149–176.

Hoos, A.B., J.A. Robinson, R.A. Aycock, R.R. Knight, and M.D. Woodside. 2000. Sources, instream transport, and trends of nitrogen, phosphorus, and sediment in the lower Tennessee River Basin, 1980-96: U.S. Geological Survey Water-Resources Investigations Report 99–4139, 96 p.

Howells, R.G, R.W. Neck, and H.D. Murray. 1996. Freshwater Mussels of Texas. Texas Parks and Wildlife Press. 224 pp.

Hubbard, W.D., D.C. Jackson, and D.J. Ebert. 1993. Channelization. Pp. 135-–55 *in:* E.F. Bryan and D.A. Rutherford (eds). Impacts on warm-water streams: guidelines for evaluation. Warm-water Stream Committee, Southern Division, American Fisheries Society, Little Rock, Arkansas.

Hubbs, D.W. 2012. Orangefoot Pimpleback and Catspaw survey, Tennessee and Cumberland rivers, Tennessee. Report prepared for Kentucky Waterways by Tennessee Wildlife Resources Agency, Project 7367. 52 pp.

Hubbs, D.W. 2015. 2014–2015 Orangefoot Pimpleback, Tennessee River, Tennessee. Report prepared for Kentucky Waterways by Tennessee Wildlife Resources Agency, Project 7367. 32 pp.

Hubbs, D., D. McKinney, D. Sims, S. Lanier, and P. Black. 2006. Aggregate extraction impacts on unionid mussel species richness and density. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies (2006):169–173.

Hughes, M.H., and P.W. Parmalee. 1999. Prehistoric and modern freshwater mussel (Mollusca: Bivalvia: Unionoidea) faunas of the Tennessee River: Alabama, Kentucky, and Tennessee. Regulated Rivers: Research & Management 15:25–42.

Inoue, K., D.M. Hayes, J.L. Harris, N.A. Johnson, C.L. Morrison, M.S. Eakles, T.L. King, J.W. Jones, E.M. Hallerman, A.D. Christian, and C.R. Randklev. 2018. The Pleurobemini (Bivalvia: Unionida) revisited: Molecular species delineation using a mitochondrial DNA gene reveals multiple conspecifics and undescribed species. Invertebrate Systematics 32:689–702.

[INHS] Illinois Natural History Survey. 2018. Mollusk collection Pyramid Pigtoe record database query. Champaign, Illinois.

Integrated Taxonomic Information System. 2017. (https://www.itis.gov/servlet/SingleRpt/SingleRpt?search_topic=TSN&search_value=80051#null). Accessed October 1, 2018.

Irwin, K.L., and J.B. Alford. 2018. Survey of native mussels in the upper Duck and Harpeth River drainages, Tennessee. University of Tennessee Report submitted to the Tennessee Wildlife Resources Agency. 134 pp.

Isom, B.G. 1969. The mussel resource of the Tennessee River. Malacologia 7(2-3):397–425.

Isom, B.G. 1974. Mussels of the Green River, Kentucky. Transactions of the Kentucky Academy of Science 35(1-2):55-57.

Isom, B.G., and P. Yokley, Jr. 1968. The mussel fauna of Duck River in Tennessee, 1965. American Midland Naturalist 80(1):34–42.

Isom, B.G., and P. Yokley, Jr. 1973. The mussels of the Flint and Paint Rock River systems of the southwest slope of the Cumberland Plateau in north Alabama - 1965 and 1967. American Midland Naturalist 89(2):442–446.

Jackson, L.J., L. Corbett, and G. Scrimgeour. 2016. Environmental constraints on *Didymosphenia geminata* occurrence and bloom formation in Canadian Rocky Mountain lotic systems. Canadian Journal of Fisheries and Aquatic Sciences 73:964–972.

Jacobson, P.J., R.J. Neves, D.S. Cherry, and J.L. Farris. 1997. Sensitivity of glochidial stages of freshwater mussels (Bivalvia: Unionidae) to copper. Environmental Toxicology and Chemistry 16:2,384–2,392.

Jansen, W., Bauer, G., & E. Zahner-Meike. 2001. Glochidial mortality in freshwater mussels. *In* Ecology and evolution of the freshwater mussels Unionoida (pp. 185-211). Springer, Berlin, Heidelberg.

Jenkinson, J. J. 1988. Resurvey of freshwater mussel stocks in the Duck River, Tennessee. Tennessee Valley Authority, River Basin Operations, Water Resources Report, Knoxville, Tennessee. 28 pp.

Johnson, R.I. 1980. Zoogeography of North American Unionacea (Mollusca: Bivalvia) north of the maximum Pleistocene glaciation. Bulletin of the Museum of Comparative Zoology 149(2):77–189.

Johnson, R.I., and H.B. Baker. 1973. The Types of Unionacea (Mollusca: Bivalvia) in the Academy of Natural Sciences of Philadelphia. Proceedings of the Academy of Natural Sciences of Philadelphia. 125(9):145–186.

Jones, J.R.E. 1964. Fish and river pollution. Elsevier. 212 pp.

Jones, J.W., R.J. Neves, M.A. Patterson, C.R. Good, and A. DiVittorio. 2001. A status survey of freshwater mussel populations in the upper Clinch River, Tazewell County, Virginia. Banisteria 17:20–30.

Jones, J.W., E.M. Hallerman, and R.J. Neves. 2006. Genetic management guidelines for captive propagation of freshwater mussels (Unionoidea). Journal of Shellfish Research 25(2):527-535.

Jones, J.W., S.A. Ahlstedt, B.J.K. Ostby, B. Beaty, M. Pinder, N. Eckert, R.S. Butler, D. Hubbs, C. Walker, S. Hanlon, J. Schmerfeld, and R.J. Neves. 2014. Clinch River freshwater mussels upstream of Norris Reservoir, Tennessee and Virginia: A quantitative assessment from 2004–2014. Journal of the American Water Resources Association 50:820–836.

Jones, J.W, N. Johnson, D. Schilling, R.J. Neves, E.M. Hallerman, and P. Grobler. 2015. Endangered Rough Pigtoe Pearlymussel: Assessment of phylogenetic status and genetic differentiation of two disjunct populations. Journal of Fish and Wildlife Management 6(2):338-349.

Jones, J., T. Lane, B. Ostby, B. Beaty, S. Ahlstedt, R. Butler, D. Hubbs, and C. Walker. 2018. Collapse of the Pendleton Island mussel fauna in the Clinch River, Virginia: Setting baseline conditions to guide recovery and restoration. Freshwater Mollusk Biology and Conservation 21:36–56.

Jones, R.L., W.T. Slack, and P.D. Hartfield. 2005. The freshwater mussels (Mollusca: Bivalvia: Unionidae) of Mississippi. Southeastern Naturalist 4(1):77–92.

Jones, R.L., M.D. Wagner, W.T. Slack, S. Peyton and P.D. Hartfield. 2019. Guide to the identification and distribution of freshwater mussels (Bivalvia: Unionidae) in Mississippi. Jackson, MS, Mississippi Department of Wildlife, Fisheries, and Parks. 340 pp.

Jones III, E.B.D., G.S. Helfman, J.O. Harper, and P.V. Bolstad. 1999. Effects of Riparian Forest Removal on Fish Assemblages in Southern Appalachian Streams. Conservation Biology 13(6):1,454–1,465.

[KDEP] Kentucky Department for Environmental Protection. 2014. Integrated Report to Congress on the condition of water resources in Kentucky, 2014, volume 1. Division of Water, Frankfort, Kentucky, 104 pp. + appendices.

Keller, A.E., and M. Lydy. 1997. Biomonitoring and the hazards of contaminants to freshwater mollusks. Unpublished report in: Freshwater mollusks as indicators of water quality: a workshop. US Geological Survey Biological Resources Division and National Water Quality Assessment Program.

Kishi, D., Murakami, M., Nakano, S., & Taniguchi, Y. 2004. Effects of forestry on the thermal habitat of Dolly Varden (Salvelinus malma). Ecological Research 19:283–290.

Kolpin, D.W., E.T. Furlong, M.T. Meyer, E.M. Thurman, S.D. Zaugg, L.B. Barber, and 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(6):1,202–1,211.

Kondolf, G.M. 1997. Hungry water: Effects of dams and gravel mining on river channels. Environmental Management 21(4):533–551.

Lasier, P.J., M.L. Urich, S.M Hassan, W.N. Jacobs, R.B. Bringolf, K.M. Owens. 2016. Changing agricultural practices: Potential consequences to aquatic organisms. Environmental Monitoring and Assessment 2016 (12):188–672.

Lau, J.K., T.E. Lauer, and M.L. Weinman. 2006. Impacts of channelization on stream habitats and associated fish assemblages in east central Indiana. American Midland Naturalist. 156:319–330.

Laudermilk, E.L. 1993. A survey of the unionids (Bivalvia: Unionidae) of the mainstream Licking River and selected tributaries below Cave Run Reservoir, Kentucky. M.S. thesis, Eastern Kentucky University, Richmond. 75 pp.

Lawler, J.J., D.J. Lewis, E. Nelson, A.J. Plantinga, S. Polasky, J.C. Withey, D.P. Helmers, S. Martinuzzi, D. Pennington, and V.C. Radeloff. 2014. Projected land-use change impacts on ecosystem services in the United States. Proceedings of the National Academy of Sciences 2014: 55–57.

Layzer, J.B., and R.M. Anderson. 1992. Impacts of the coal industry on rare and endangered aquatic organisms of the upper Cumberland River basin. Kentucky Department of Fish and Wildlife Resources, Frankfort, and Tennessee Wildlife Resources Agency, Nashville. 118 pp.

Layzer, J.B., M.E. Gordon, and R.M. Anderson. 1993. Mussels: the forgotten fauna of regulated rivers. A case study of the Caney Fork River. Regulated Rivers: Research and Management 8:63–71.

Layzer, J.B., and L.M. Madison. 1995. Microhabitat use by freshwater mussels and recommendations for determining their instream flow needs. Regulated Rivers: Research & Management 10:329-345.

Layzer, J.B., and E.M. Scott, Jr. 2006. Restoration and colonization of freshwater mussels and fish in a southeastern United States tailwater. River Research and Applications 22:475–491.

Lea, I. 1831. Observations on the Naiads, and Descriptions of New Species of That and Other Families. Transactions of the American Philosophical Society 4(1834):63–121.

Lefevre, G. and W.C. Curtis. 1912. Studies on the reproduction and artificial propagation of fresh-water mussels (Vol. 30). US Government Printing Office.

[LEC] Lewis Environmental Consulting. 2008. Mussel surveys at Barren River miles 7.7, 9.7, 12, and 14 in Warren County, Kentucky to assess pipeline crossing impacts to mussel beds. Report prepared for Gulfstar Energy, LLC. Morgantown, Kentucky. 85 pp.

[LEC] Lewis Environmental Consulting. 2011. 2010 Mussel survey of Green River pools 2, 3, and 4. Report prepared for US Army Corps of Engineers Louisville District. 202 pp.

[LEC] Lewis Environmental Consulting. 2013. 2012 Mussel survey of Green River pool 4. Butler and Warren counties, Kentucky. Report prepared for US Fish and Wildlife Service – Kentucky Field Office. 46 pp.

[LEC] Lewis Environmental Consulting. 2019. Mussel survey of the Green River downstream of Lock and Dam 5, Butler and Warren counties, Kentucky, 2019. Report prepared for US Fish and Wildlife Service – Kentucky Field Office. 65 pp.

Lopes-Lima, M., L.E. Burlakova, A.Y. Karateyev, K. Mehler, M. Seddon, and R. Sousa. 2018. Conservation of freshwater bivalves at the global scale: diversity, threats, and research needs. Hydrobiologia 810 (1):1–14.

MacIsaac, H.G. 1996. Potential abiotic and biotic impacts of Zebra mussels on the inland waters of North America. American Zoologist. 36:287-299.

Maestas, A. 2013. Study: Rising Demand of Southeast Trees Puts Wildlife, Biodiversity at Risk; Landmark study examines rapidly expanding forest biomass energy development in Southeastern U.S. National Wildlife Federation.

March, F.A., F.J. Dwyer, T. Augspurger, C.G. Ingersoll, N. Wang, and C.A. Mebane. 2007. An evaluation of freshwater mussel toxicity data in the derivation of water quality guidance and standards for copper. Environmental Toxicology Chemistry 10:2,066–2,074.

Martin, E. and C. Apse. 2014. Northeast Aquatic Connectivity: An Assessment of Dams on Northeastern Rivers. The Nature Conservancy & Northeast Association of Fish and Wildlife Agencies. Brunswick, Maine. 102 pp.

McCann, M.T., and R.J. Neves. 1992. Toxicity of coal-related contaminants to early life stages of freshwater mussels in the Powell River, Virginia. Unpublished report to US Fish and Wildlife Service, Asheville, North Carolina. 92 pp.

McGregor, M.A., A.C. Shepard, C. Owen, T. Bailey, A. McDonald, F. Vorisek, and D. Cravens. 2015. Community changes in a freshwater mussel bed from 2004 to 2014 in the Green River, Kentucky. Annual Research Highlights of the Kentucky Department of Fish and Wildlife Resources. 3 pp.

McLeod, J.M, H.L. Jelks, S. Pursifull, and N.A. Johnson. 2017. Characterizing the early life history of an imperiled freshwater mussel (*Ptychobranchus jonesi*) with host-fish determination and fecundity estimation. Freshwater Science 36(2):338–350.

McMurray, S.E., G.A. Schuster, and B.A. Ramey. 1999. Recruitment in a freshwater unionid (Mollusca: Bivalvia) community downstream of Cave Run Lake in the Licking River, Kentucky. American Malacological Bulletin 15(1):57–63.

Mellinger, P.J. 1972. The comparative metabolism of cadmium, mercury, and zinc as environmental contaminants in the freshwater mussel, Margaritifera margaritifera. Ph.D. dissertation, Oregon State University, Corvallis. 129 pp.

Miller, A.C., and B.S. Payne. 1993. Survey for freshwater mussels (Unionidae) in the Lower Green and Barren Rivers, Kentucky, 1992. U.S. Army Corps of Engineers Vicksburg Experiment Station Report. 62 pp.

Miller, A.C., and B.S. Payne. 1998. Effects of disturbances on large-river mussel assemblages. Regulated Rivers: Research and Management 14:179–190.

Miller, A.C., L. Rhodes, and R. Tippit. 1984. Changes in the naiad fauna of the Cumberland River below Lake Cumberland in Central Kentucky. The Nautilus 98(3):107–110.

Miller, A.C., B.S. Payne, and C.M. Way. 1989. Phase I studies: Impacts of commercial navigation traffic on freshwater mussels - A review. U.S. Army Corps of Engineers Vicksburg Experiment Station Report prepared for the Mussel Mitigation Trust, Columbus, Ohio. 57 pp.

Miller, A.C., B.S. Payne, and L.T. Neill. 1994. A recent re-evaluation of the bivalve fauna of the lower Green River, Kentucky. Transactions of the Kentucky Academy of Science 55:46–54.

Miller, A.C., and B.S. Payne. 1998. Effects of disturbances on large-river mussel assemblages. Regulated Rivers: Research and Management 14:179–190.

Moles, K.R., and J.B. Layzer. 2008. Reproductive ecology of *Actinonaias ligamentina* (Bivalvia: Unionidae) in a regulated river. Journal of the North American Benthological Society 27(1):212–222.

Morey, D.F., and G.M. Crothers. 1998. Clearing Up Clouded Waters: Palaeoenvironmental analysis of freshwater mussel assemblages from the Green River shell middens, western Kentucky. Journal of Archaeological Science 25:907–926.

Morrison, J.P.E. 1942. Preliminary report on mollusks found in the shell mounds of the Pickwick Landing basin in the Tennessee River Valley. Pp. 337–392 in: W.S. Webb and D.L. DeJarnette, eds. An archeological survey of Pickwick Basin in the adjacent portions of the states of Alabama, Mississippi, and Tennessee. Bureau of American Ethnology Bulletin No. 129.

Mummert, A.K., R.J. Neves, T.J. Newcombe, and D.S. Cherry. 2003. Sensitivity of juvenile freshwater mussels (Lampsilis fasciola, Villosa iris) to total and un-ionized ammonia. Environmental Toxicology and Chemistry 22(11):2,545–2,553.

Naimo, T.J. 1995. A review of the effects of heavy metals on freshwater mussels. Ecotoxicology 4:341–362.

National Invasive Species Council Management Plan. 2018. *https://www.doi.gov/sites/doi.gov/files/uploads/2016-2018-nisc-management-plan.pdf*

[NCASI] National Council for Air and Stream Improvement, Inc. 2015, p. 2.

Neel, J.K., and W.R. Allen. 1964. The mussel fauna of the upper Cumberland Basin before its impoundment. Malacologia 1(3):427–459.

Newton, T.J., J.W. Allran, J.A. O'Donnell, M.R. Bartsch, and W.B. Richardson. 2003. Effects of ammonia on juvenile unionid mussels (*Lampsilis cardium*) in laboratory sediment toxicity tests. Environmental Toxicology and Chemistry. 22(11):2,554–2,560.

Newton, T.J., D.A. Woolnough, and D.L. Strayer. 2008. Using landscape ecology to understand and manage freshwater mussel populations. Journal of the North American Benthological Society 27(2):424–439.

Neves, R.J. 1987. Recent die-offs of freshwater mussels in the United States: an overview. Pp. 7–18 *in:* R.J. Neves (ed). Proceedings of the workshop on die-offs of freshwater mussels in the United States, June 1986, Davenport, Iowa. Virginia Polytechnic Institute and State University, Blacksburg.

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. 1993. A state-of-the unionid address. Pp. 1–10 in: K.S. Cummings, A.C. Buchanan, and L.M. Koch, eds. Conservation and management of freshwater mussels. Proceedings of a UMRCC symposium, October 1992, St. Louis, Missouri. Upper Mississippi River Conservation Committee, Rock Island, Illinois.

Neves, R.J., and M.C. Odom. 1989. Muskrat predation on endangered freshwater mussels in Virginia. Journal of Wildlife Management 53(4):934–941.

Neves, R. J., and P. L. Angermeier. 1990. Habitat alteration and its effects on native fishes in the upper Tennessee River system, east-central USA. Journal of Fish Biology 37:45–52.

Neves, R.J., A.E. Bogan, J.D. Williams, S.A. Ahlstedt, and P.W. Hartfield. 1997. Status of Aquatic Mollusks in the Southeastern United States: A Downward Spiral of Diversity; Chapter 3 (pp.44-86) in Aquatic Fauna in Peril: The Southeastern Perspective, edited by G.W. Benz and D.E. Collins (1997), Special Publication 1. Southeast Aquatic Research Institute. Lenz Design and Communications, Decatur, Georgia. 554 pp.

Newton, T.J. and W.G. Cope. 2007. Biomarker responses of unionid mussels to environmental contaminants. Pp. 257-284 in: J.L. Farris and J.H. Van Hassel, eds. Freshwater Bivalve Ecotoxicology. CRC Press, Boca Raton, Florida.

Newton, T.J., D.A. Woolnough, and D.L. Strayer. 2008. Using landscape ecology to understand and manage freshwater mussel populations. Journal of the North American Benthological Society 27(2):424–439.

Newton, T.J., J.W. Allran, J.A. O'Donnell, M.R. Bartsch, and W.B. Richardson. 2003. Effects of ammonia on juvenile unionid mussels (*Lampsilis cardium*) in laboratory sediment toxicity tests. Environmental Toxicology and Chemistry 22:2,554–2,560.

Nichols, S.J., and D. Garling. 2000. Food-web dynamics and trophic-level interactions in a multispecies community of freshwater unionids. Canadian Journal of Zoology 78:871–882.

Nico, L.G., J.D. Williams, and H.L. Jelks. 2005. Black carp: biological synopsis and risk assessment of an introduced fish. American Fisheries Society Special Publication No. 32. 337 pp.

Nico, L.G., and M.E. Neilson. 2018. *Mylopharyngodon piceus* (Richardson, 1846): U.S. Geological Survey, Nonindigenous Aquatic Species Database, Gainesville, Florida, *https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=573*. Revision Date: August 6, 2018, Peer Review Date: April 1, 2016, Access Date: August 26, 2018.

Nobles, T. and Zhang, Yixin. 2011. Biodiversity Loss in Freshwater Mussels: Importance, Threats, and Solutions. Chapter 6 (pp. 137–162) in Biodiversity Loss in a Changing Planet, edited by O. Grillo and G. Venora (2011). InTech, Rijeka, Croatia. 328 pp.

[ODNR] Ohio Department of Natural Resources; Ohio Division of Wildlife. 2015. Ohio's State Wildlife Action Plan. Columbus, Ohio, USA.

Ohio Mussel Survey Protocol. 2018. Ohio Department of Natural Resources (ODNR), Division of Wildlife and U.S. Fish and Wildlife Service (USFWS), Ohio Ecological Services Field Office. https://wildlife.ohiodnr.gov/portals/wildlife/pdfs/licenses%20&%20permits/OH%20Mussel%20Survey%20Protocol.pdf (Accessed 10/1/18).

[ORSANCO] Ohio River Valley Water Sanitation Commission. 2016. Assessment of Ohio River water quality conditions 2010-2014. Cincinnati, Ohio. 74 pp.

Ortmann, A.E. 1909a. A preliminary list of the Unionidae of western Pennsylvania, with new localities for species from eastern Pennsylvania. Annals of the Carnegie Museum 5(2-3):178–210.

Ortmann, A.E. 1909b. The destruction of the fresh-water fauna in western Pennsylvania. Proceedings of the American Philosophical Society 48(191):90–110.

Ortmann, A.E. 1911. Monograph of the naiads of Pennsylvania. Part I. Anatomical investigations; Part II. The system of the North American Naiads. Memoirs of the Carnegie Museum 4(6):279–348.

Ortmann, A.E. 1912. Notes upon the families and genera of the najades.

Ortmann, A.E. 1913. The Alleghenian Divide, and its influence upon the freshwater fauna. Proceedings of the American Philosophical Society 52(210):287–390.

Ortmann, A.E. 1919. A monograph of the naiades of Pennsylvania. Part III: systematic account of the genera and species. Memoirs of the Carnegie Museum 8(1):1–384.

Ortmann, A.E. 1920. Correlation of shape and station in freshwater mussels. Proceedings of the American Philosophical Society 59(4):268–312.

Ortmann, A.E. 1921. The anatomy of certain mussels from the upper Tennessee. The Nautilus 34(3):81–91.

Ortmann, A.E. 1924. The naiad-fauna of Duck River in Tennessee. American Midland Naturalist 9(1):18–62.

Ortmann, A.E. 1925. The naiad fauna of the Tennessee River system below Walden Gorge. American Midland Naturalist 9(8):321–372.

Ortmann, A.E. 1926. The naiades of the Green River drainage in Kentucky. Annals of the Carnegie Museum 17(1):167-188.

Ostby, J.K., and B.B. Beaty 2016. Conservation plan for the State-listed freshwater mussels of the Upper Tennessee River Basin in Virginia. Report to Virginia Department of Game and Inland Fisheries. Contract number 2014-14593. 214 pp.

[OSUM] Ohio State University Museum Mollusk Collection. 2018. Museum Database Query by Andrew Henderson.

Pardue, W.J. 1981. A survey of the mussels (Unionidae) of the upper Tennessee River--1978. Sterkiana 71:41–51.

Parmalee, P.W. 1960. Mussels from the Angel site, Indiana. The Nautilus 74(2):70–75.

Parmalee, P.W. 1967. The freshwater mussels of Illinois. Illinois State Museum Popular Science Series Vol. VIII. 136 pp.

Parmalee, P.W. 1988. A comparative study- of late prehistoric and modern molluscan faunas of the Little Pigeon River system, Tennessee. American Malacological Bulletin 6(2):165–178.

Parmalee, P.W., and A.E. Bogan. 1986. Molluscan remains from aboriginal middens at the Clinch River Breeder Reactor Plant site, Roane County, Tennessee. American Malacological Bulletin 4(1):25–37.

Parmalee, P.W., and A.E. Bogan. 1998. The freshwater mussels of Tennessee. The University of Tennessee Press, Knoxville, Tennessee. 328 pp.

Parmalee, P.W., and H.D. Faust. 2006. Diversity and relative abundance of preimpoundment freshwater mussel (Bivalvia: Unionidae) populations in the lower Holston River, Tennessee. Journal of the Tennessee Academy of Science 81(3-4):73–78.

Parmalee, P.W., and R.R. Polhemus. 2004. Prehistoric and pre-impoundment populations of freshwater mussels (Bivalvia: Unionidae) in the South Fork Holston River, Tennessee. Southeastern Naturalist 3(2):231 –240.

Parmalee, P.W., and W.E. Klippel. 1974. Freshwater mussels as a prehistoric food resource. American Antiquity 39(3):421–434.

Parmalee, P.W., W.E. Klippel, and A.E. Bogan. 1980. Notes on the prehistoric and present status of the naiad fauna on the middle Cumberland River, Smith County, Tennessee. The Nautilus 94(3):93–105.

Parmalee, P.W., W.E. Klippel, and A.E. Bogan. 1982. Aboriginal and modern freshwater mussel assemblages (Pelecypoda: Unionidae) from the Chickamauga Reservoir, Tennessee. Brimleyana 8:75–90.

Patnode, K.A., R.M. Anderson, L. Zimmermann, E. Hittle, and J.W. Fulton. 2015. Effects of high salinity wastewater discharges on unionid mussels in the Allegheny River, Pennsylvania. Journal of Fish and Wildlife Management 6(1):55–70.

Peacock, E., and 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., W.R. Haag, and M.L. Warren, Jr. 2005. Prehistoric decline in freshwater mussels coincident with the advent of maize agriculture. Conservation Biology 19(2):547–551.

Peacock, E., J. Mitchell, and 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.

Pilsbry, H.A., and S.N. Rhoads. 1896. Contributions to the zoology of Tennessee. No. 4, Mollusks. Proceedings of the Academy of Natural Sciences of Philadelphia 48:487–506.

Poff, N.L., M.M. Brinson, and J.W. Day, Jr. 2002. Aquatic ecosystems & Global climate change: Potential Impacts on Inland Freshwater and Coastal Wetlands Ecosystems in the United States. Pew Center on Global Climate Change. 56 pp.

Price, J. E., C.E. Zipper, J.W. Jones, and C.T. Franck. 2014. Water and Sediment Quality in the Clinch River, Virginia and Tennessee, USA, over Nearly Five Decades. Journal of the American Water Resources Association 50(4):837–858.

Reed, M.P. 2014. Freshwater mussels (Bivavia: Margaritiferidae and Unionidae) of the Buffalo River drainage, Tennessee. University of Tennessee, unpublished Master's Thesis. 98 pp.

Ren, W., Y. Zhong, J. Meligrana, B. Anderson, W.E. Watt, J. Chen, H. Leung. 2003. Urbanization, land use, and water quality in Shanghai: 1947–1996. Environment International 29(5):649–659.

Ricciardi, A., R.J. Neves, and J.R. Rasmussen. 1998. Impending extinctions of North American freshwater mussels (Unionoida) following the zebra mussel (Dreissena polymorpha) invasion. Journal of Animal Ecology 67:613–619.

Richard, J. 2018. Freshwater mussel die-offs: Insights from a Compilation of Known Cases. Presentation at the Freshwater Mollusk Conservation Society Mollusk Health and Disease Workshop, La Crosse Wisconsin. 23 pp.

Sams, J.I., and K.M. Beer. 2000. Effects of coal-mine drainage on stream water quality in the Allegheny and Monongahela river basins – sulfate transport and trends. Water-Resources Investigations Report 99-4208. U.S. Geological Survey, National Water-Quality Assessment Program, Lemoyne, Pennsylvania. 17 pp.

Scheller, J.L. 1997. The effects of dieoffs of Asian Clams (*Corbidula fluminea*) on Native Freshwater Mussels (Unionidae). MS thesis. Virginia Polytechnic Institute and State University. 100 pp.

Schloesser, D.W., T.F. Nalepa, and G.L. Mackie. 1996. Zebra Mussel Infestation of Unionid Bivalves (Unionidae) in North America. American Zoologist 36:300–310.

Schloesser, D.W., W.P. Kovalak, G.D. Longdon, K.L. Ohnesorg, and R.D. Smithee. 1998. Impact of zebra and quagga mussels (*Dreissena* spp.) on freshwater unionids (Bivalvia: Unionidae) in the Detroit River of the Great Lakes. American Midland Naturalist 140(2):299–313.

Schloesser, D.W., J.L. Metcalfe-Smith, W.P. Kovalak, G.D. Longton, and R.D. Smithee. 2006. Extirpation of freshwater mussels (Bivalvia: Unionidae) following the invasion of dressenied mussels in an interconnecting river of the Laurentian Great Lakes. American Midland Naturalist 155(2):307-320.

Schmidt, J.E., R.D. Estes, and M.E. Gordon. 1989. Historical changes in the mussel fauna (Bivalvia: Unionoidea) of the Stones River, Tennessee. Malacological Review. 22:55–60.

Schmerfeld, J. 2006. Reversing a textbook tragedy. Endangered Species Bulletin 31(1):12–13.

Schuster, G.A. 1988. The distribution of unionids (Mollusca: Unionidae) in Kentucky. Kentucky Department of Fish and Wildlife Resources, Frankfort. 1,099 pp.

Scott, E.M., Jr., K.D. Gardner, D.S. Baxter, and B.L. Yeager. 1996. Biological and water quality responses in tributary tailwaters to dissolved oxygen and minimum flow improvements. Tennessee Valley Authority, Norris, Tennessee. 211 pp.

Seaber, P.R., F.P. Kapinos, G.L. Knapp. 1987. Hydrologic Unit Map, USGS Water-Supply Paper 2294. 63 pp.

[Service] 1989. U.S. Fish and Wildlife Service. Candidate Notice of Review 50 CFR 17 Vol. 4

[Service] U.S. Fish and Wildlife Service. 2011. Endangered and Threatened Wildlife and Plants; Partial 90-Day Finding on a Petition to List 404 Species in the Southeastern United States as Endangered or Threatened With Critical Habitat. 76 FR 59836–59862.

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

[Service] U.S. Fish and Wildlife Service. 2017. Species status assessment report for the Atlantic Pigtoe (Fusconaia masoni). Version 1.2. March 2017. Atlanta, Georgia.

[Service] U.S. Fish and Wildlife Service. 2018. Longsolid (Fusconaia subrotunda) Species Status Assessment, Asheville, North Carolina.

[Service] U.S. Fish and Wildlife Service. 2019. Round Hickorynut (Obovaria subrotunda) Species Status Assessment, Asheville, North Carolina.

[Service] U.S. Fish and Wildlife Service. 2020a. Purple Lilliput (Toxolasma lividum) Species Status Assessment, Asheville, North Carolina.

[Service] U.S. Fish and Wildlife Service. 2020b. Unpublished data prepared and analyzed for management units and Pyramid Pigtoe populations, Asheville, North Carolina.

Shoup, C.S., J.H. Peyton, and G. Gentry. 1941. A limited biological survey of the Obey River and adjacent streams in Tennessee. Journal of the Tennessee Academy of Science 16(1):48–76.

Sickel, J.B. 1982. A survey of the freshwater mussel of the lower Cumberland River from Barkley Dam tailwater downstream to the Ohio River. Report to the US Army Corps of Engineers, Nashville District. 24 pp.

Sickel, J.B., and C.C. Chandler. 1996. Unionid fauna of the lower Cumberland River from Barkley Dam to the Ohio River, Kentucky (Mollusca: Bivalvia: Unionidae). Transactions of the Kentucky Academy of Science 57(1):33–46.

Sickel, J.B., and M.D. Burnett. 2005. Historical mussel and aquatic snail database for the Tennessee River between Kentucky lock and dam on the Ohio River. Report to the US Army Corps of Engineers, Nashville District. 45 pp.

Sickel, J.B., M.D. Burnett, C.C. Chandler, C.E. Lewis, H.N. Blalock-Herod, and J.J. Herod. 2007. Changes in the freshwater mussel community in the Kentucky portion of Kentucky Lake, Tennessee River, since impoundment by Kentucky Dam. Journal of the Kentucky Academy of Science 68(1):68–80.

Simpson, C.T. 1914. A descriptive catalogue of the naiades or pearly fresh-water mussels. Parts I-III. Bryant Walker, Detroit, MI, xii + 1540 pp.

Slater, A.G. 2018. Freshwater mussel growth in the Holston River: water quality and inferences from sclerochronology, racemization and low precision C14 dating. The University of Tennessee, unpublished Master's Thesis. 103 pp.

Smith, D.R., R.F. Villella, and D.P. Lemarie. 2001. Survey protocol for assessment of endangered freshwater mussels in the Allegheny River, Pennsylvania. Journal of the North American Benthological Society 20(1):118–132.

Smith, T.A., and E.S. Meyer. 2010. Freshwater mussel (Bivalvia: Unionidae) distributions of the Habitat Relationships in the navigational pools of the Allegheny River, Pennsylvania. Northeastern Naturalist 17(4):541–564.

Spaeth, J., C. Swecker, and K. McGill. 2015. Freshwater mussel (Unionidae) surveys on the Ohio River (Markland pool) in Clermont and Hamilton counties, Ohio. Final Report prepared by Environmental Solutions and Innovations, Inc. for Duke Energy. 277 p.

Sparks, B.L., and D.L. Strayer. 1998. Effects of low dissolved oxygen on juvenile Elliptio complanata (Bivalvia: Unionidae). Journal of the North American Benthological Society 17(1):129–134.

Spooner, D. and 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.

Stansbery, D.H. 1965. The naiad fauna of the Green River at Munfordville, Kentucky. Bulletin of the American Malacological Union Annual Reports for 1964 (1965):13-14.

Stansbery, D.H. 1967. T*he Pleurobema cordatum* (Rafinesque, 1920) complex in the Ohio River drainage system (Molluca: Pelecypoda: Unionacea). Abstract of papers presented at the 15th annual meeting of the midwest benthological society. 3 pp.

Stansbery, D.H. 1970. Eastern Freshwater Mollusks, the Mississippi and St. Lawrence River systems. Malacologia 10(1):9-22.

Stansbery, D.H. 1972. A preliminary list of the naiad shells recovered from the Buffalo Site. In: Broyles, Bettye, J. (ed.): A late 17th century Indian village site in Putnam County, West Virginia. Report of Archaeological Investigations Number 6, West Virginia Geological and Economic Survey, Morgantown, West Virginia.

Stansbery, D.H. 1983. Some sources of nomenclatorial and systematic problems in unionid mollusks.

Sterki, V. 1892. A few observations concerning death of freshwater Mollusca. The Nautilus 5:135–136.

Strayer, D.L. 1999a. Use of flow refuges by unionid mussels in rivers. Journal of the North American Benthological Society 18(4):468–476.

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

Strayer, D.L. 2006. Challenges for freshwater invertebrate conservation. Journal of the North American Benthological Society 25(2):271–287.

Strayer, D.L. 2008. Freshwater mussel ecology: a multifactor approach to distribution and abundance. University of California Press. 216 pp.

Strayer, D.L., J.A. Downing, W.R. Haag, T.L. King, J.B. Layzer, T.J. Newton, and S.J. Nichols. 2004. Changing perspectives on pearly mussels, North America's most imperiled animals. BioScience 54(5):429–439.

Strayer, D.L., and H.M. Malcom. 2012. Causes of recruitment failure in freshwater mussel populations in southeastern New York. Ecological Applications 22: 1,780–1,790.

Stodola, A.P., S.A. Douglass, and D.K. Shasteen. 2014. Historical and current distributions of freshwater mussels in Illinois. Illinois Natural History Survey Technical Report 2014 (37). 83 pp.

Swank, W.T. and J.E. Douglass. 1974. Streamflow Greatly Reduced by Converting Deciduous Hardwood Stands to Pine. Science 185(4154):857–859. DOI:10.1126/science.185.4154.857

Swank, W. T., and N. H. Miner. 1968. Conversion of Hardwood-Covered Watersheds to White Pine Reduces Water Yield. Water Resources Research 4(5):947–954.

Taylor, R.W. 1980. A survey of the freshwater mussels of the Ohio River from Greenup Locks and Dam to Pittsburg, Pennsylvania. Report submitted to the U.S. Army Corps of Engineers, Huntington District. 79 pp.

Taylor, R.W. 1983. A survey of the freshwater mussels of the Kanawha River from river head (Gauley Bridge, WV) to river mouth (Point Pleasant, WV). U.S. Army Corps of Engineers, Huntington District. 62 pp.

Taylor, S.E., R. Rummer, K.H. Yoo, R.A. Welch, and J.D. Thompson. 1999. What we know and don't know about water quality at stream crossings. Journal of Forestry 97(8):12–17.

Tayyebi, A., B.C. Pijanowski, and B.K. Pekin. 2015. Land use legacies of the Ohio River Basin: Using a spatially explicit land use change model to assess past and future impacts on aquatic resources. Applied Geography. 57: 100–111

[TDEC] Tennessee Department of Environment and Conservation. 2014. 2014 305(b) report: the status of water quality in Tennessee. Division of Water Pollution Control, Nashville, Tennessee. 114 pp.

Terando, A.J., J. Costanza, C. Belyea, R.R. Dunn, A. McKerrow, J.A. Collazo. 2014. The southern megalopolis: Using the past to predict the future of urban sprawl in the southeast US. PLOS ONE 9(7):1-8.

Trombulak, S.C. and C.A. Frissell. 2000. Review of Ecological Effects of Roads on Terrestrial and Aquatic Communities. Conservation Biology 14(1):18–33.

[TWRA] Tennessee Wildlife Resources Agency. 2011. 2010 Duck River Quantitative Mussel Survey. Aquatic Habitat Protection Program Report 11–04. 48 pp.

[TWRA] Tennessee Wildlife Resources Agency. 2016. 2015 Duck River Quantitative Mussel Survey 16–06. 60 pp.

[TWRA] Tennessee Wildlife Resources Agency. 2020. 2020 Duck River Quantitative Mussel Survey 16–06. 39 pp.

Tyrrell, M., and D.J. Hornbach. 1998. Selective predation by muskrats on freshwater mussels in 2 Minnesota rivers. Journal of the North American Benthological Society 17(3):301–310.

[USEPA] U.S. Environmental Protection Agency. 1985. Ambient water quality criteria for ammonia. Office of Water Regulations and Standards, Criteria and Standards Division, EPA 440/5-85-001, Washington, DC.

[USEPA] U.S. Environmental Protection Agency. 2013. 78 FR 52192, Rec. Criteria for ammonia

[USEPA] U.S. Environmental Protection Agency. 2016. Nutrient Pollution – The Sources and Solutions: Agriculture. https://www.epa.gov/nutrientpollution/sources-and-solutions-agriculture (Accessed: October 1, 2018).

[USEPA] U.S. Environmental Protection Agency. 2018. Section 404 of the Clean Water Act. https://www.epa.gov/cwa-404/exemptions-permit-requirements (Accessed: October 1, 2018).

[USGS] U.S. Geological Survey. 2018. Effects of Urbanization on Stream Ecosystems. http://water.usgs.gov/nawqa/urban/ (Accessed: October 1, 2018).

[USGS] U.S. Geological Survey. 2018. https://water.usgs.gov/GIS/huc.html. Accessed: October 1, 2018).

Valenti, T.W., D.S. Cherry, R.J. Neves, and 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(5):1,242–1,246.

van der Schalie, H. 1939. Additional notes on the naiades (freshwater mussels) of the lower Tennessee River. American Midland Naturalist 22(2):452–457.

Van Hassel, J.H. 2007. Case Study: Discrimination of Factors Affecting Unionid Mussel Distribution in the Clinch River, Virginia, USA. Pp. 311-333. *in:* J.L. Farris and J.H. Van Hassel, eds. Freshwater Bivalve Ecotoxicology. CRC Press, Boca Raton, Florida.

Vaughn, C.C. 2012. Life history traits and abundance can predict local colonisation and extinction rates of freshwater mussels. Freshwater Biology 57(5):982–992.

Vaughn, C.C., and 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. 2003. The mussel fauna of the Glover River, Oklahoma. Proceedings of the Oklahoma Academy of Science 83:1–6.

Vidic, R.D., S.L. Brantley, J.M. Vandenbossche, D. Yoxtheimer, and J.D. Abad. 2013. Impact of shale gas development on regional water quality. Science 340(1235009):1–9.

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. 2007. Chronic toxicity of copper and ammonia to juvenile freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10):2,048–2,056.

Warrington, B.M., W.M. Aust, S.M. Barrett, W.M. Ford, C.A. Dolloff, E.B. Schilling, T.B. Wigley, and M.C. Bolding. 2018. Forestry best management practices relationships with aquatic and riparian fauna: A review. Forests 8(331):1–16.

Watters, G.T. 1992. Unionids, fishes, and the species-area curve. Journal of Biogeography 19:481–490.

Watters, G.T. 2000. Freshwater mollusks and water quality: effects of hydrologic and instream habitat alterations. Pp. 261–274 in: P.D. Johnson and R.S. Butler, eds. Freshwater Mollusk Symposium Proceedings—Part II: musseling in on…biodiversity. Proceedings of the 1st symposium of the Freshwater Mollusk Conservation Society, March 1999, Chattanooga, Tennessee. Ohio Biological Survey, Columbus.

Watters, G.T., and H.L. Dunn. 1993-94. The Unionidae of the lower Muskingum River (RM 34.1-0), Ohio, U.S.A. Walkerana 7(17/18):225–263.

Watters, G.T., M.A. Hoggarth, and D.H. Stansbery. 2009. The Freshwater Mussels of Ohio. The Ohio State University Press, Columbus, Ohio. 421 pp.

Watters, G.T., and C.J.M. Flaute. 2010. Dams, zebras, and settlements: The historical loss of freshwater mussels in the Ohio River mainstem. American Malacological Bulletin 28:1–12.

Weilbaker, C., C.D. Baker, B.J. Forsyth, C.M. Christenson, and R.W. Taylor. 1985. The freshwater naiads, Bivalvia, Unionidae, of the Blue River, a southern Indiana tributary of the Ohio River. Proceedings of the Indiana Academy of Science 94:687–691.

Wear, D.N. and J.G. Greis. 2012. The Southern Forest Futures Project: summary report. General Technical Report SRS-GTR-168. Asheville, North Carolina: USDA-Forest Service, Southern Research Station. 54 pp.

Webster, J.R., S.W. Golladay, E.F. Benfield, J.L. Meyer, W.T. Swank, and J.B. Wallace. 1992. Catchment disturbance and stream response: An overview of stream research at Coweeta Hydrologic Laboratory. In River conservation and management, ed. P.J. Boon, P. Calow and G.E. Petts, 231–253. Chichester, England: John Wiley & Sons Ltd.

Weiss, J.L. 1993. Factors influencing the distribution and abundance of freshwater mussels in the Barren River, Kentucky, with emphasis on the role of host fishes. Unpublished Master's Thesis, Tennessee Technological University. Cookeville, Tennessee. 71 pp.

Wenger, S. 1999. A Review of the Scientific Literature on Riparian Buffer Width, Extent, and Vegetation. University of Georgia, Institute of Ecology, Athens, Georgia. 59 pp.

[WVDEP] West Virginia Department of Environmental Protection. 2014. West Virginia integrated water quality monitoring and assessment report 2014. Charleston, West Virginia. 291 pp.

Wheeler, A.P., P.L. Angermeier, and A.E. Rosenberger. 2005. Impacts of new highways and subsequent landscape urbanization on stream habitat and biota. Reviews in Fishery Science 13:141–164.

Wilson, C.B., and H.W. Clark. 1914. The mussels of the Cumberland River and its tributaries. Report to the U.S. Commission of Fisheries for 1912, Special Papers. 63 pp.

Wilson, C.O. 2015. Land use/land cover water quality nexus: quantifying anthropogenic influences on surface water quality. Environmental Monitoring and Assessment 187(7):424.

Williams, J.C., and G.A. Schuster. 1989. Freshwater mussel investigations of the Ohio River: mile 317.0 to mile 981.0. Unpublished report, Kentucky Department of Fish and Wildlife Resources, Frankfort. 57 pp.

Williams, J.D., M.L. Warren, Jr., K.S. Cummings, J.L. Harris, and R.J. Neves. 1993. Conservation status of freshwater mussels of the United States and Canada. Fisheries 18(9):6-22.

Williams, J.D., A.E. Bogan, and J.T. Garner. 2008. Freshwater mussels of Alabama and the Mobile Basin of Georgia, Mississippi, and Tennessee. University of Alabama Press, Tuscaloosa.

Williams, J.D., A.E. Bogan, R.S. Butler, K.S. Cummings, J.T. Garner, J.L. Harris, N.A. Johnson, and 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.

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.

Woodside, M.D., Hoos, A.B., Kingsbury, J.A., Powell, J.R., Knight, R.R., Garrett, J.W., Mitchell, III, Reavis L., and Robinson, J.A. 2004. Water quality in the Lower Tennessee River Basin, Tennessee, Alabama, Kentucky, Mississippi, and Georgia, 1999–2001: Reston, Virginia, U.S. Geological Survey Circular 1233. 38 pp.

Yeager, M.M., D.S. Cherry, and R.J. Neves. 1994. Feeding and burrowing behaviors of juvenile rainbow mussels, Villosa iris (Bivalvia: Unionidae). Journal of the North American Benthological Society 13(2):217–222.

Yokley, P. 1972a. Freshwater mussel ecology, Kentucky Lake, Tennessee: May 1, 1969 - June 15, 1972. Unpublished report, Tennessee Game and Fish Commission, Nashville. 133 pp.

Yokley, P. 1972b. The life history of Pleurobema cordatum. Malacologia 11(2): 351-364.

Yokley, P. 2004. Summary report of freshwater mussel relocation at U.S. 231 bridge, Madison-Morgan counties, Alabama 2002 and 2004. Unpublished report to Alabama Department of Transportation. 24 pp.

Zanatta, D.T., G.L. Mackie, J.L. Metcalfe-Smith, and D.A. Woolnough. 2002. A refuge for native freshwater mussels (Bivalvia: Unionidae) from impacts of the exotic Zebra Mussel (*Dreissena polymorpha*) in Lake St. Clair. Journal of Great Lakes Research 28(3):479–489.

Zimmerman, L.L., R.J. Neves, and D.G. Smith. 2003. Control of predaceous flatworms Macrostomum sp. in culturing juvenile freshwater mussels. North American Journal of Aquaculture 65:28–32.

Zipper, C.E., B. Beaty, G.C. Johnson, J.W. Jones, J.L. Krstolic, B.J.K. Ostby, W.J.Wolfe, and P. Donovan. 2014. Freshwater mussel population status and habitat quality in the Clinch River, Virginia and Tennessee, USA: A featured collection. Journal of the American Water Resources Association 50 (4):807–819.

APPENDIX A - SUMMARY OF EXTANT POPULATIONS WITHIN OHIO & TENNESSEE BASINS AND THEIR ESTIMATED SIZE & EXTENT.

Within this appendix, the collector of each record is presented, the year of the record, and cited reference. Museum records and bibliography used to inform this report are also presented. This information has been gathered from a large body of published and unpublished survey work rangewide since the 1800s. More current, unpublished distribution and status information has been obtained from biologists with State Heritage Programs, Department of Natural Resources programs, other state and federal agencies, academia, and museums.

When referring to shell condition, fresh dead shells still have flesh attached to the shell, or at least retain a luster to their nacre, and may have a hinge intact and pliable, indicating relatively recent death. Relic shells may have been reported as either weathered or subfossil. Weathered dead or relic shells often have a loss of or peeling periostracum and faded or dull nacre (Ohio Mussel Survey Protocol, 2018, p. 47). Fresh dead shells probably indicate the continued presence of the species at a site, while weathered relic shells only probably indicate that the population in question is extirpated (Butler 2007, p. 17). QLTOT = qualitative total of all mussels all species, encountered live, QNTOT = quantitative total of all mussels, all species encountered live, RA = relative abundance of Pyramid Pigtoe in survey.

OHIO RIVER BASIN

Management Unit: Muskingum
State: Ohio
(1) Contiguous population: Muskingum River
Extant County: Washington (formerly Muskingum, Morgan, Coshocton Co.)

Year of last live or fresh dead observation: 2011, ESI, 2012 (Heidi Dunn)

Estimated occupied length: Approx. 1.6 KM based on ESI data, OSUM records span RM 5 - 109, Devola Dam is at RM 5.8; ESI 2012 p. 23 report the species from below Devola, the lowermost dam only

Notes: Only 2 individuals reported live since 2000; considered a relict, non-reproducing population by Watters and Dunn 1993-94, p. 254. Additionally, ESI (2012) did extensive surveys related to proposed hydropower development at existing dams, and cite changes in shear velocity as potentially affecting substrate and unionid communities. ESI 2012 p. 23 report live Pyramid Pigtoe below Devola dam only, consistent with Watters *et al*. 2009; Stansbery and King 1983 reported 1 L from lowermost bed.

Museum Specimens: OSUM 44835, 16418, 40084, 44049, 49482, 49611, 49707, 50012, 50116, 50930, 44124, 45161, 47619, 49152, 17080, 17530, 46942, 51875, 47206; ANSP 377195

Literature/Reports: Stansbery 1970; Stansbery and King 1983; Watters and Dunn 1993-1994; Watters *et al* 2009 and references therein; Hoggarth 1995-1996; Kelly and Watters 2010; ESI 2012

Management Unit: Upper Green
State: Kentucky
(2) Contiguous population: Green River
Extant County: Hart, Edmonson, Butler/Warren, Green

Year of last live or fresh dead observation: 2019, LEC (Chad Lewis)

Estimated occupied length: Approximately 311 mi (500 km). Likely extends the length of the Green River within this HUC below Green River Dam.

Notes: 20 Live or Fresh dead reported from the Green River since 2000 (KYNPC data). Culp *et al*. 2009, p. 19 report 14 live collected from the upper Green River. LEC 2019 report 9 live collected from RM 167-168 below Lock and Dam 5. LEC 2013 report 7 live from Green River Pool 4 RM 153.8-168.4. Cicerello (1999), reported on collections made at 25 quantitative and 15 supplemental sites from 1996-1998 1 L, 1 R at 2 of 36 sites. Cicerello and Hannan 1990 p. 24 indicated that 11 specimens were collected during qualitative surveys between 1987-1989 within MCNP boundaries, 2 L/FD at 1 of 4 sites, R at 2nd site (Hart Co.), 9 L/FD at 5 of 38 sites, R only at 5 others (Edmonson Co.). McGregor et al 2015 report the species collected only once in 3 separate sampling events 2004-2014 at Munfordville, KY (1000 m2 area sampled with 1 m2 quadrats). The Pyramid Pigtoe was 0.005 m2 and made up 0.1 % of catch in 2014. The populations in the Green and Barren rivers are among the largest in existence, but despite their occurrence throughout long reaches of these rivers, the species is rare and there is little information about the viability or age structure of these populations (Haag and Cicerello 2016, p. 199).

Museum Specimens: OSUM 26836, 27166, 33769, 39180, 42958, 44611, 54700, 75262, 83933, 85021, 50531, 11819, 12595, 12701, 13469, 16529, 16588, 17472, 17490, 27327, 33276, 44906, 83704, 84821, 34972, 68547, 68618, 82742; INHS 12984, 15678, 15807, 15862, 4811, 7448, 13828, 13834; MFM 14667, 11712, 11714; NCMNS 88120, 88129; UTMM 9236, 1023; FMNH 347066; CM 82133, 61.11188, 61.11413, 92914, 76111; DMNH 1506288, 1506708, 1509449; UMMZ 80975, 44726, 80940; USNM 677267, 677488, ANSP 72755

Literature/Reports: Cicerello 1999; Cicerello and Hannan 1990; Cicerello *et al* 1991; Classen 2011; Cochran and Layzer 1993; Gordon and Sherman 1995; Isom 1974; LEC 2008; LEC 2013; LEC 2019; Miller and Payne 1993; Miller *et al* 1994; Ortmann 1926; Stansbery 1965; Haag and Cicerello 2016 and references therein; Culp *et al* 2009; Schuster 1988; Clench and van der Schalie 1944

Management Unit: Barren
State: Kentucky
(3) Contiguous population: Barren River
Extant County: Warren (formerly Allen / Barren)

Year of last live or fresh dead observation: 2016, KYDFW (Monte McGregor)

Estimated occupied length: Unknown, potentially less than 25 KM based on recent collections. Records from RM 0.0 up to RM 72.2, but since 2000, only reported from RM 0.0 to RM 15 (KYNPC data)

Notes: Haag and Cicerello (2016, pp. 138, 139) indicate collections in the drainage since 1990, but that the population in the Barren River drainage (lower Green) is small. All collections since 2000 limited to Warren Co. Generally distributed to occasional in the lower Barren River. Weiss and Layzer 1995 p. 155, reported 2 live at 1 of 5 sites surveyed using timed diving and quantitative quadrat searches. Gordon and Sherman 1995: 1 L at 1 site during 1.3 h effort, R at 1 site, FD at 10 of 38 sites (2 sites with relics); LEC 2008. Weiss and Layzer 1993, p. 155 2 L, RA = 0.4; Cochran and Layzer (1995, p. 63) report collection of one individual in 1990 and 4 individuals in 1991 from the Barren River using quantitative sampling, from two sites below Lock and Dam No. 1 near Richardsville, KY. Although fragmented by dams, potentially some dispersal of host fishes between the lower Barren and Green Rivers. There are multiple dams on the Barren River mainstem.

Museum Specimens: OSUM 68037; NCMNS 87980, 88123, 102086; USNM 677637; INHS 12811, 13610, 16074, 26819; MFM 20107

Literature/Reports: Cochran and Layzer 1993; Gordon and Sherman 1995; LEC 2008; Miller and Payne 1993; Miller *et al* 1994; Ortmann 1926; Weiss and Layzer 1993; Cicerello *et al* 1991; Haag and Cicerello 2016 and references therein; Schuster 1988; Clench and van der Schalie 1944;

Management Unit: Middle Green
State: Kentucky
(4) Contiguous population: Green River
Extant County: Butler, McLean, Muhlenberg/Ohio Co.

Year of last live or fresh dead observation: 2018, KYDFW (Monte McGregor)
Estimated occupied length: Unknown. Potentially as much as 40.4 mi (65 km) extending the entire reach within this MU, based on recent collections and Haag and Cicerello (2016).

Notes: Gordon and Sherman 1995: 5 of 22 sites (1 site with relic) Green River; Morey and Crothers (1998, p. 913) report the species was once a dominant component of the pre-impoundment mussel fauna at the Hayes Site, an Archeological Site on the Green River in Butler County. It was represented in material excavated from the site which is located between Green River RMs 102 and 155. Although there are multiple dams on the Green River mainstem, there is a large amount of riverine habitat available in numerous reaches.

Museum Specimens: OSUM 69637, 82900, 82828, 21701, 25504, 26042, 44096, 82879, 82875, 82931, 82875, 82931; CM 81966; MFM 13334; NCMNS 102079; CM 76110, 82121, 89307, 90352, 69218, 69221, 95651; USNM 677326, 677670; ANSP 385961

Literature/Reports: Cochran and Layzer 1993; Gordon and Sherman 1995; LEC 2012; LEC 2008; Miller and Payne 1993; Ortmann 1926; Weiss and Layzer 1993; Cicerello *et al* 1991; Haag and Cicerello 2016 and references therein; Schuster 1988; Clench and van der Schalie 1944; Morey and Crothers 1998

Management Unit: Lower Green
State: Kentucky
(5) Contiguous population: Green River
Extant County: Ohio, McLean

Year of last live or fresh dead observation: 2010, LEC (Chad Lewis)
Estimated occupied length: Unknown, up to 10 KM based on KYFW & LEC records, from Lock and Dam 2 tailwater upstream to Middle Green HUC boundary

Notes: Haag and Cicerello (2016, p. 139) indicate populations in the lower Green River drainage are small. The lower Green is under surveyed but only collections reported since 2000 are from LEC, who collected it in beds below L&D 2, 3, 4; 9 live collected from 2 sites in 2010. Miller *et al*. (1994) 4 L downstream of L&D # 3 (diving). There are multiple dams on the Green River mainstem, and there is the least amount of riverine habitat available in the lowermost reaches. This reach of the river was more heavily impacted by towboats before reduced commercial traffic (Miller *et al.* 1994, p. 53) also cite hypolimnetic discharges as an impact to the lower Green River mussel fauna.

Museum Specimens: OSUM 82828

Literature/Reports: Cochran and Layzer 1993; Gordon and Sherman 1995; Isom 1974; LEC 2008; Miller and Payne 1993; Miller *et al* 1994; Ortmann 1926; Stansbery 1965; Haag and Cicerello 2016 and references therein; Schuster 1988; Morey *et al* 2002; Clench and van der Schalie 1944

Management Unit: Lower Cumberland-Old Hickory Lake
State: Tennessee
(6) Contiguous population: Cumberland River (Old Hickory Reservoir)
Extant County: Smith, Wilson, Trousdale

Year of last live or fresh dead observation: 2011, TWRA 2012 (Don Hubbs)
Estimated occupied length: Approximately 19 mi (30 km). Cumberland River RM 281-300 (Rome Landing to Lock 7; and Hartsell to Rome Island)

Notes: Collected live during TWRA dive survey work within the TWRA Rome Landing Mussel Sanctuary in 2011 (TWRA 2012): 18 collected by TWRA from Rome Landing to Lock 7 in 2011-12, 0.2-0.3 CPUE (p. 35). Reduced in extent and undoubtedly abundance. This represents the last remaining population in the Cumberland River drainage (Haag and Cicerello 2016, p. 139). Parmalee *et al* 1980, p. 101 found 66 valves at 2 prehistoric rock shelter deposits along the Cumberland River in Smith County, Tennessee.

Museum Specimens: OSUM 54079, 83919; UTMM 1026, 3809, 1239, 3337; MFM 9909; NCMNS 35311, 41041; ANSP 353159

Literature/Reports: Hubbs 2012; Parmalee *et al* 1980; Starnes and Bogan 1988; Parmalee and Bogan 1998 and references therein; Wilson and Clark 1914

TENNESSEE RIVER BASIN

Management Unit: Holston
State: Tennessee
(7) Contiguous population: Holston River
Extant County: Grainger (formerly Hamblen, Hawkins, Knox, Jefferson)

Year of last live or fresh dead observation: 2020, UT (Gerry Dinkins, pers. comm.)
Estimated occupied length: 20 KM; reach below Cherokee Dam to Tennessee River (Ft. Loudon Reservoir) is approximately 25 mi (40 km), however currently known from only a couple areas in lower reaches with islands where it is very rare.

Notes: Was once a dominant component of the mussel fauna of the Holston River (Ortmann 1919, p. 614-617). Parmalee and Faust (2006, p. 74) reported from two archaeological sites and four muskrat deposits along the lower Holston River. Probably decreasing population trend.

Museum Specimens: OSUM 35013, 68690, 68444; UTMM 994, 995, 3495, 5207, 10233; MFM 10519; INHS 4353; CM 61.657, 61.7105, 61.7106, 61.7464, 61.7107, 61.6571, 61.7467, 76108, 109202; DMNH 172904, 173220, 173223; UMMZ 80933, 80935, 80994; USNM 25401, 26193, 473231, 473236; FMNH 68193, 269946; NCMNS 100890, 7225; ANSP 127662, 68364

Literature/Reports: Parmalee and Faust 2006; Ortmann 1918; Slater 2018

Management Unit: Upper Clinch
State: Tennessee, Virginia
(8) Contiguous population: Clinch River
Extant County: Scott (VA) (formerly Russell); Claiborne, Hancock, Grainger (TN) (formerly Roane; Knox, Anderson, Union)

Year of last live or fresh dead observation: 2018 (personal observation, UTMM)
Estimated occupied length: Approximately 50 mi (80 km). From Tennessee State Highway 32 upstream to Russell Co. VA line; Ahlstedt (1991a) reported the species as extremely rare in surveys from 1979-1980.

Notes: Jones *et al*. (2014) 1 L from 18 sites in 2746 ¼ MSQ; MD <<0.01; QNTOT = 11,505; Ahlstedt *et al*. (2005) 2 L at 1 of 3 sites, Mean Length = 68.0 mm; Hubbs (2019) 1 L at 1 of 9 sites, CRM 173.9 = CPUE 0.05, Rank 31 of 31; Ostby 2016, p. 181, gives a complete breakdown of specimens of P. rubrum from Virginia section of the Clinch since 1979, considered extremely rare in Virginia portion of river, last collected live in 1998. From Ahlstedt 1991b: *Pleurobema rubrum* is an extremely rare species in the upper Clinch in Tennessee and Virginia, and the lower Clinch. It was reported from three sites between sites 87 and 137 in the upper Clinch and from five sites between sites 1 and 57 in the lower Clinch. Ortmann (1918) reported it from 10 sites in the lower Clinch and mentioned that it was abundant. The population in the Clinch River is small in abundance but has the most consistent level of survey effort over the past 30 years and some trend data is available due to the river's importance for global mussel diversity. However, it no longer occurs below Norris Dam. It has experienced a reduction in range See Jones *et al*. 2018, formerly occurred all the way up to at least Pendleton Island at CRM 226, the upstream extent in Virginia has been reduced.

Museum Specimens: Scott Co., (VA) OSUM 11509, 16639, 16675, 53881, 54975; Claiborne, Hancock, Grainger Co., (TN) 18535, 19290, 20355, 23264, 26599, 28114, 28547, 33486, 50363, 50370, 35111; UTMM 6293, 6283, 5256, 1020, 1018, 3280, 4443, 1036, 3448; NCMNS 62906, 6315, 6658, 7222, 7223, 7226, 29318, 29364, 40996, 41008, 41018, 44204, 46479; USNM 894752, 126952; MFM 6111, 1005; INHS 32470; DMNH 172906; UMMZ 66394, 134650, 80962, 80960, 80936, 35137, 80957, 80959, 32848; CM 61.8057, 61.6566, 61.7454, 61.7459, 61.7463, 61.8672, 61.5785; FMNH 376698, 66592; ANSP 127645, 48147, 376986, 69207; MCZ 51799, 55779

Literature/Reports: Ahlstedt 1980; Stansbery 1973; Ostby 2017; Jones 2015; Ahlstedt 1991a; Ahlstedt 1991b; Ahlstedt and Tuberville 1997; Ahlstedt *et al* 2016; Ortmann 1918; Cahn 1936; Hubbs 1991; Jones *et al* 2018; Jones *et al* 2014; Hubbs 2019; Barr *et al*. 1994; Parmalee and Bogan 1986 and references therein; Stansbery *et al*. 1986; Parmalee and Bogan 1998; Starnes and Bogan 1988

Management Unit: Wheeler Lake
State: Alabama
(9) Contiguous population: Paint Rock River
Extant County: Madison, Marshall
Year of last live or fresh dead observation: 2018, ADCNR (Todd Fobian)
Estimated occupied length: Approximately 20 mi (32 km), Based on Fobian *et al*. 2014. Not known from Jackson Co., limited to lower reaches

Notes: Fobian *et al*. 2014: 1 L at 1 of 7 sites, R at 2 other sites. Only live collection of the species since 2000.

Museum Specimens: MFM 17527

Literature/Reports: Fobian *et al* 2014; Williams *et al*. 2008

Management Unit: Wheeler Lake
State: Alabama
(10) Contiguous population: Tennessee River (Wheeler Reservoir) Guntersville Dam Tailwater
Extant County: Madison, Morgan (Formerly Limestone)

Year of last live or fresh dead observation: 2009, ADCNR (Jeff Garner); also Williams *et al.* (2008).
Estimated occupied length: Approximately 15.5 mi (25 km). Guntersville Dam tailwater downstream to US 231 bridge (Yokley 2004).

Notes: Found live at mouth of Flint River (TRM 339.1), 1 individual in 2009. Yokley (2004) collected 11 L at US 231 bridge site; QLTOT = 65,840; RA = T 23rd of 33 spp. L, during a relocation survey. Yokley reported 4 live collected from the same site in 1998. Williams *et al.* (2008, p. 324) state that it is extant in Alabama only in the tailwaters of Wilson and possibly Guntersville dams on the Tennessee river, and that it is rare in all extant populations. Gooch *et al*. (1979) 1 L at 1 of 16 sites from RM 334.3–348.4; From Garner and McGregor 2001, p. 166: Ortmann (1925) described Pleurobema rubrum as rare at Muscle Shoals, though both he and van der Schalie (1939) reported it to be widespread in the lower Tennessee River. Gooch *et al*. (1979) reported it from both Pickwick and Wheeler reservoirs, where it was described as " relatively uncommon." During recent surveys it was uncommon in Wilson and Guntersville tailwaters. No evidence of recent recruitment (i.e. specimens younger than ten years of age) was encountered in either area.

Museum Specimens: OSUM 66088, 64281; CM 66-78; UMMZ 129695, 300281; INHS 14376; NCMNS 46988, 46994, 46474, 46476, 46478, 46972; DMNH 1506250; FMNH 267572, 22711; ANSP 129490

Literature/Reports: Ahlstedt and McDonough 1992; Bogan 1990; Garner and McGregor 2004; Yokley 1998; Yokley 2004; Hughes and Parmalee 1999; Isom 1969; Williams *et al*. 2008; van der Schalie 1939; Gooch *et al*. 1979

Management Unit: Pickwick Lake
State: Alabama
(11) Contiguous population: Tennessee River (Pickwick Reservoir) Wilson Dam Tailwater
Extant County: Lauderdale, Colbert

Year of last live or fresh dead observation: 2014, ADCNR (Jeff Garner)
Estimated occupied length: Approximately 15.5 mi (25 km); only found live in past 20 years around Sevenmile Island and Buck Island. Williams *et al.* (2008, p. 324) state that it is extant only in the tailwaters of Wilson and possibly Guntersville dams on the Tennessee river, and that it is rare in all extant populations. Isom (1969, p. 410) reported the species from the Seven mile Island Area Muscle Shoals, Wilson Dam tailwater (TRM 247-253). From Garner and McGregor 2001, p. 166: Ortmann (1925) described Pleurobema rubrum as rare at Muscle Shoals, though both he and van der Schalie (1939) reported it to be widespread in the lower Tennessee River. Gooch *et al*. (1979) reported it from both Pickwick and Wheeler reservoirs, where it was described as " relatively uncommon." During recent surveys it was uncommon in Wilson and Guntersville tailwaters. No evidence of recent recruitment (i.e. specimens younger than ten years of age) was encountered in either area.

Notes: Highest density reported by J. Garner is 5 live in 100 minutes bottom survey time = 1 live individual collected per 20 minutes in 2001 at Buck Island Chute mid channel Tennessee River TRM 249.7. Gooch *et al*. 1979 reported ≥5 L at 4 of 16 sites from RM 234.2–258.9. Morrison 1942; Garner and

McGregor (2001, p. 166) report it as rare in the Wilson Dam tailwater with no evidence of recent recruitment.

Museum Specimens: USNM 30434, 84682; UTMM 1037; NCMNS 46596, 33570, 46477, 35371, 43426; FMNH 269457; INHS 14377, 14378, 24427; CM 61.1183; DMNH 1504813

Literature/Reports: Bogan 1990; Garner and McGregor 2004; Morrison 1942; Williams *et al*. 2008; Ortmann 1925; van der Schalie 1939; Gooch *et al*. 1979;

Management Unit: Lower Tennessee-Beech
State: Tennessee
(12) Contiguous population: Tennessee River (Kentucky Reservoir) Pickwick Dam Tailwater
Extant County: Hardin, Humphreys

Year of last live or fresh dead observation: 2012, TWRA (Don Hubbs)
Estimated occupied length: Less than 0.6 mi (1 km). Museum records extend approx. 100 KM, but recently found at islands; TRM 164 to 197; TWRA reports historically at least TRM 206-111.

Notes: Repeated sampling of freshwater mussels at sites in Kentucky Reservoir, TN have yielded only a few live individuals in over 20 years of annual survey efforts, in at least 191 hours total dive time (Hubbs 2015, p. 29). TWRA 1999, p. 13 report 2 live from 13 dive sites at RM 157; Gooch *et al* 1979.

Museum Specimens: UTMM 1035, 9631; OSUM 64903; UMMZ 129657, 129735, 129600

Literature/Reports: Parmalee and Bogan 1998; TWRA 1999; Bates 1962; Hughes and Parmalee 1999; Ortmann 1925; van der Schalie 1939; Gooch *et al*. 1979; Starnes and Bogan 1988

Management Unit: Upper Duck
State: Tennessee
(13) Contiguous population: Duck River
Extant County: Marshall

Year of last live or fresh dead observation: 2020, TWRA (2020, p. 21).
Estimated occupied length: Approx. 75 km; From Bedford Co. Line downstream to Maury Co. line; In Duck River. Limited to reach between Lillards Mill and Columbia Dams.

Notes: TWRA (2020) 6 L at Venable Spring; TWRA (2011) 4 L at 2 sites in 160 ¼ MSQ; MD = 0.10; POP = 618; QNTOT = 1003 (Lillard's Mill & Venable Spring) in 2010; TWRA (2015) 1 site only (Venable Spring), 5 L at 2 sites in 160 ¼ MSQ; MD = 0.13; POP = 750; QNTOT = 888; Jenkinson (1988) 2 L at 1 of 8 sites QUAL; 1 L at 6 sites in 146 ¼ MSQ; MD = 0.03 QUANT; QNDOT = 487; Ortmann 1925 ≥ 2 L at 2 of 2 sites. From Ahlstedt *et al*. 2017, p. 69: During our survey, it was generally distributed but rare in the upper Duck from Lillard Mill Dam downstream nearly to the old Columbia Dam. Ahlstedt *et al*. (2004) 14 L at 5 of 6 sites QUAL, QLTOT = 2171; 1 L at 2 sites in 50 ¼ MSQ; MD = 0.08 QUANT, QNDOT = 334 (Lillards Mill & Venable Spring only).

Museum Specimens: UTMM 1494, 3585, 1011, 3470, 3494, 5995, 3585; NCMNS 27053, 29248, 83047, 88139; USNM 150459, 508571, 512472, 540303; INHS 14537; UMMZ 80976, 52770, 58482, 52737, 79671, 58345; CM 61.11187, 61.11412, 61.11597, 61.11598, 61.11599; FMNH 66621, 269489, 66319; ANSP 468372; MCZ 98556, 69818; OSUM 66621, 66319

Literature/Reports: Ahlstedt *et al* 2017; Ahlstedt *et al* 2004; TWRA 2015; TWRA 2011; Isom and Yokley 1968; Ortmann 1924; Jenkinson 1988; van der Schalie 1973; Starnes and Bogan 1988; Parmalee and Bogan 1998 and references therein; Hubbs *et al* 1991

Management Unit: Lower Duck
State: Tennessee
(14) Contiguous population: Duck River
Extant County: Maury (formerly Humphreys & Hickman)
Year of last live or fresh dead observation: 2020, TWRA (2020, p. 21).
Estimated occupied length: Approx. 5 km, from Maury Co. line downstream to Columbia.

Notes: TWRA (2020) 5 L at 1 site (Hooper's Island). TWRA (2015) 8 L at 1 site in 160 ¼ MSQ; MD = 0.20; POP = 1120; QNTOT = 550 (All Hooper Island); TWRA (2011) 17 L at Hooper Island in 160 ¼ MSQ; MD = 0.43; POP = 2329; QNTOT = 654. Ahlstedt *et al*. 2017, p. 69: During our survey, it was generally distributed but rare in the upper Duck from Lillard Mill Dam downstream nearly to the old Columbia Dam. Ahlstedt *et al*. (2004) 44 L from Hooper Island only, R only at 4 of 29 sites QUAL; QLTOT = 6583, QUANT 2 L in 20 ¼ MSQ; MD = 0.40; QNTOT = 122.

Museum Specimens: UTMM 5096, 3486, 1012; NCMNS 29260, 29290; UMMZ 30127, 52770; MCZ 5911; OSUM 269489

Literature/Reports: Ahlstedt *et al* 2017; Ahlstedt *et al* 2004; TWRA 2015; TWRA 2011; Isom and Yokley 1968; Ortmann 1924; Jenkinson 1988; van der Schalie 1973; Starnes and Bogan 1988; Parmalee and Bogan 1998 and references therein; Hubbs *et al* 1991

APPENDIX B - SUMMARY OF EXTANT POPULATIONS (LIVE OR FRESH DEAD REPORTED SINCE 2000), WITHIN ARKANSAS-WHITE-RED & LOWER MISSISSIPPI BASINS.

Management Unit	Record State	Contiguous Population	Last Reported	Additional Information
(1) Petit Jean	AR	Petit Jean River	2001	Harris 2001
(2) Eleven Point	AR	Eleven Point River	2003	AGFC record
(3) Lower Little	OK	Little River	2015-2016	Vaughn 2017
	AR	Little River	2016	Davidson *et al*. 2014; Davidson *et al*. 2017
(4) Lower Black	AR	Black River	2005	UMMZ 80971
(5) Lower St. Francis	AR	St. Francis River	2002	NCMNS 41037, 41040; UTMM 975; CM 61.11186; UMMZ 130099, 129751; OSUM 12810, 75265, 75267; ANSP 100413
		Tyronza River	2007	Wentz *et al*. 2009
(6) Middle White	AR	White River	2002	AGFC record
(7) Upper Ouachita	AR	Ouachita River	2004	Harris 2017; NCMNS 88122; FLMNH 22712; CM 76109, 61.503, 61.513, 61.5314, 61.5316, 61.5586, 61.6031, 61.616, 61.6469, 61.9821; DMNH 172697; UMMZ 80942, 113497, 80970; ANSP 114069
(8) Little Missouri	AR	Little Missouri River	2004	OSUM 54440; Christian and Harris 2004

Management Unit	Record State	Contiguous Population	Last Reported	Additional Information
(9) Lower Ouachita - Smackover	AR	Ouachita River	2013	ANSP 98343, 98387
(10) Upper Saline	AR	Saline River	2020	MFM 21928; INHS 14547, 14574, 14581, 14591, 14611; UMMZ 80952, 80997, 80953; OSUM 18770, 82464, 84347, 82464, 84347, 21485, 84334, 84228
(11) Lower Saline	AR	Saline River	2012	Davidson and Clem 2004; ANSP 462280, 68019; UTMM 6064, 1013; FLMNH 475908, 402976
(12) Bayou Bartholomew	AR	Bayou Bartholomew	2004	Brooks *et al* 2008
	LA		2016 (relic)	George and Vidrine 1993, p. 364; Vidrine 1995, p. 40; Vidrine 2001, p. 234

MANAGEMENT UNIT	RECORD STATE	CONTIGUOUS POPULATION	LAST REPORTED	ADDITIONAL INFORMATION
(13) Lower Ouachita - Bayou De Loutre	AR LA	Ouachita River	2016-2017	Harris 2017; UMMZ 80945, UMMZ 54833; FMNH 22843; ANSP 97581, 98349, 98371, 98387, 98343; Vidrine 2001, Plate VII, p. 234; Vanatta 1910, p. 103; Saunders *et al*. 2005, p. 660
(14) Big Sunflower	MS	Hushpuckna River	2002	MSMNS 7114
		Bogue Phalia	2003	MSMNS 7175, 7932
		Little Sunflower	2011	MSMNS 7674, 9120, 11311
		Sunflower River	2003	MSMNS 5361, 7879, 9579, 13648, 13649, 13650, 8235, 7649, 7957, 8194, 5095, 5115, 5182, 5211, 5486, 5515, 5531, 5562, 5658, 8285, 5950
		Sandy Bayou	2003	MSMNS 7691
		Big Sunflower River	2004	CMNS 83202; MSMNS 8588, 8600, 8683, 8702, 8719, 8748, 6533, 8197, 8354, 8539, 8551; Miller and Payne 1995, p. 12; Miller and Payne 2004, p. 151; Miller *et al* 1992, p. 10; Mitchell and Peacock 2014, p. 629

MANAGEMENT UNIT	RECORD STATE	CONTIGUOUS POPULATION	LAST REPORTED	ADDITIONAL INFORMATION
(15) Lower Big Black	MS	Big Black River	2004	FLMNH 198132; OSUM 48684; MFM 22308; MSMNS 843, 958, 1343, 1362, 1954, 5340, 6426, 6613, 8786, 753, 1308, 1381, 4452, 4459, 4876; Hartfield and Rummel 1985, p. 99; Hartfield 1993, p. 132; Peacock and James 2002, p. 123

APPENDIX C - FORMER CONTIGUOUS POPULATIONS AND MANAGEMENT UNITS (MUs), NOW CONSIDERED EXTIRPATED, ACROSS THE ENTIRE PYRAMID PIGTOE HISTORICAL RANGE. TOTAL EXTIRPATED POPULATIONS = 117, TOTAL EXTIRPATED MUs = 108.

UPPER MISSISSIPPI BASIN = 19 populations, 18 MUs; MISSIOURI BASIN = 4 populations, 4 MUs; OHIO BASIN = 58 populations, 55 MUs; ARKANSAS-WHITE-RED BASIN = 15 populations, 14 MUs; TENNESSEE BASIN = 10 populations, 8 MUs; LOWER MISSISSIPPI BASIN = 11 populations, 9 MUs.

Management Unit	Record State	Former Contiguous Population	Source
UPPER MISSISSIPPI BASIN			
Rush - Vermillion	WI	Mississippi River (Lake Pepin)	Referred to as Pleurobema coccineum mississippiensis var. nov. (p. 122). From Grier, 1922, p. 22: One mile upstream from bridge at Read's Landing, 300 ft. s. w. of C. M. & St. P. R. R. at base of stone quarry, 700 ft. from Minnesota shore. July 28, 1920.
	MN	Mississippi River	INHS 80189; UMMZ 80932
La Crosse - Pine	WI	Black River (Mississippi River Pool 8)	Havlik 1983, p. 55
Coon - Yellow	WI	Mississippi River (Prairie du Chien), near McGregor, IA	ANSP 364655; (Havlik & Stansberry 1977, p. 9) cite Shimek 1921 collections as the only records for the Prairie du Chien
Grant - Little Maquoketa	WI	Mississippi River	INHS 44117, 83176
Des Plaines	IL	Saganashkee Slough	FMNH 372228; Stodola *et al* 2014, p. 55
Middle Rock	WI	Rock River	USNM 25170
Kankakee	IL	Kankakee River	MCZ 85439; Stodola *et al* 2014, p. 55
Lower Illinois - Senachwine Lake	IL	Illinois River	INHS 31304, 38714; *Pleurobema rubrum* appears to have been a subdominant species in the central reaches of the Illinois River during prehistoric and early–historic times (Warren 1995, p. 5); Stodola *et al* 2014, p. 55

Lower Illinois - Lake Chautauqua	IL	Illinois River	INHS 19161, 36685, 38843, 38931, 38966; OSUM 19230; DMNH 173219; UMMZ 80992; Stodola *et al* 2014, p. 55
Lower Illinois	IL	Illinois River	NCMNS 47032; INHS 39035, 18429; Stodola *et al* 2014, p. 55
Spoon	IL	Spoon River	CM 69958; FMNH 9137; Stodola *et al* 2014, p. 55
Lower Sangamon	IL	Sangamon River	UTMM 1016; ANSP 41727; Stodola *et al* 2014, p. 55
Salt	IL	Salt Creek	INHS 31227, 35436; Stodola *et al* 2014, p. 55
The Sny	IL	The Sny (MS River)	INHS 34436; Stodola *et al* 2014, p. 55
Copperas - Duck	IA	Mississippi River	ANSP 127665
Flint-Henderson	IA	Mississippi River	UMMZ 4286
Upper Mississippi River - Cape Girardeau	IL	Mississippi River	INHS 36655, 36677; UMMZ 4312; Stodola *et al* 2014, p. 55
OHIO RIVER BASIN			
Beaver	PA	Beaver River	Ortmann 1909, p. 199
Upper Ohio	PA	Ohio River (Dashields Pool, Elmsworth Pool, Montgomery Pool)	NCMNS 100608; CM 61.1842, 61.3896, 61.6774; quite frequent, formerly abundant (Ortmann 1909, p. 199)
	OH		UMMZ 80955; DMNH 173222, 173218; Watters *et al*. 2009, p. 235
Lower Allegheny	PA	Allegheny River	CM 61.3079, 61.3891, 61.3892, 61.4375 (Ortmann 1909, p. 199)
Lower Monongahela	PA	Monongahela River	CM 69007, 69008; Ortmann (1913, p. 294); UMMZ 80963
Tuscarawas	OH	Tuscarawas River	OSUM 17528, 34790; Dean (1890); DMNH 186550; UMMZ 22692, 80938; FMNH 9219; CM 61.1177, 42 individuals, CM 61.10189, 61.10191, 61.10192, 61.10193, 61.10194, 61.10195, 61.10196, 61.10197, 61.10198, 61.10199, 61.102, 61.10201, 61.1019; ANSP 41648; Watters *et al.*

			2009, p. 235; Large lots of OSUM records, formerly abundant at New Philadelphia
Walhonding	OH	Walhonding River	Watters *et al*. 2009, p. 235; Hoggarth 95-96, p. 159
Mohican	OH	Mohican River	Watters *et al*. 2009, p. 235; Hoggarth 95-96, p. 159
West Fork	WV	West Fork River	Taylor 1983, p. 31
Upper Kanawha	WV	Kanawha River	Taylor 1983 p. 31; UTMM 5927
Lower Kanawha	WV	Kanawha River	Stansbery (1972) Buffalo Site RA = 4.7% (tied 5th of 28 spp); Taylor 1983
Coal	WV	Little Coal River	Taylor 1983, p. 31
Little Kanawha	WV	Little Kanawha River	Taylor 1983, p. 31
Upper Ohio - Wheeling	OH	Ohio River (Hannibal Pool)	Watters and Flaute 2010, p. 11; Watters *et al*. 2009, p. 235
Lower Scioto	OH	Little Scioto River	Watters *et al*. 2009, p. 235
		Scioto River	OSUM 62796; UMMZ 43873; Watters *et al*. 2009, p. 235
Upper Scioto	OH	Scioto River	OSUM 31865, 66401; Watters *et al*. 2009, p. 235
Upper Ohio - Shade	OH	Ohio River (upper Gallapolis = Byrd Pool, Racine Pool, Belleville Pool)	CM 61.10202, 61.10459; UMMZ 80937, 80956; OSUM 52864; NCMNS 61430; Watters *et al*. 2009, p. 235
Little Muskingham - Middle Island	OH	Ohio River (Willow Island & Hannibal Pools)	CM 61.10202, 61.10458, UMMZ 80937; NCMNS 61430; Watters *et al*. 2009, p. 235
	WV		CM 61.6775, Ortmann 1919; UMMZ 80954
Raccoon-Symmes	OH	Ohio River (lower Gallapolis Pool, upper Greenup Pool)	OSUM 69363; Watters *et al*. 2009, p. 235
Little Scioto - Tygarts	OH	Ohio River (upper Meldahl Pool, lower Greenup Pool)	ESI 2000, p. 10 (Williams 1969); CM 61.6776, 61.1046; OSUM 206, 46380, 46349; Watters *et al*. 2009, p. 235

	KY		ESI 2000, p. 10 (Williams 1969); Schuster 1988, p. 768-769; Haag and Cicerello 2016, p. 199
South Fork Licking	KY	South Fork Licking River	Haag and Cicerello 2016, p. 199; KYNPC also has EO 5204, which is listed as Licking River in OSUM 21383, but likely the South Fork Licking based on locality info.
Upper Kentucky	KY	Kentucky River*	ANSP 20237; Johnson and Baker 1978, p. 163; Vanatta 1915, p. 557 (* lectotype); Haag and Cicerello 2016, p. 199
	KY	South Fork Kentucky River	CM 72031, 72046; Haag and Cicerello 2016, p. 199
Lower Kentucky	KY	Kentucky River* type locality	Call and Robinson, 1982, p. 33; Haag and Cicerello 2016, p. 199
Salt	KY	Salt River	OSUM 44752, 48018; KYNPC EO 8525, 7214, 1644; NCMNS 88131; ANSP 127666; Haag and Cicerello 2016, p. 199
Rolling Fork	KY	Beech Fork	OSUM 50950; KYNPC EO 7961, 12140; EKU 2715; Haag and Cicerello 2016, p. 199
Ohio Brush-Whiteoak	KY	Ohio River (lower Meldahl Pool, upper Markland Pool)	OSUM 68744; Haag and Cicerello 2016, p. 199
	OH		ANSP 147774; Watters *et al*. 2009, p. 235
Middle Ohio - Laughery	OH	Ohio River (lower Markland Pool, upper McAlpine Pool)	FMNH 9405, 9350, 9459, 9342, 9347, 212079, 269456, 142753; OSUM 57249, 57509, 58485, 58501, 58511, 58498, 67910, 68266, 68270, 68275, 68310, 69474, 69479, 36903; NCMNS 100643; UMMZ 80898, 80931; USNM 26192, 512463; ANSP A14659; MCZ 196956; Watters *et al*. 2009, p. 235
	KY		KYNPC EO 17, 45; CM 61.10461; USNM 620136, 620137, 620139, Schuster 1988, p. 768; Haag and Cicerello 2016, p. 199
	IN		UMMZ 80981, 80929

Blue - Sinking	KY	Ohio River (Lower Cannelton Pool)	LEC record
	IN		USNM 677508
	IN	Blue River	Weilbaker *et al*. 1985
Embarras	IL	Embarras River	INHS 41890; Stodola *et al* 2014, p. 55
Upper Wabash	IN	Little River (Wabash Tributary)	UMMZ 80993; Fisher 2006, p. 105
Middle Wabash-Busseron	IL	Wabash River	OSUM 41421; INHS 92, 6710, 8304, 18441, 18882, 28970, 38672, 41663, 4367; Stodola *et al* 2014, p. 55
	IN		DMNH 58619; UMMZ 50898; INHS 4311; Fisher 2006, p. 105; Daniels 1903 reported the species as common in the Wabash River
Middle Wabash-Little Vermillion	IN	Wabash River	MFM 1644; INHS 5046, 5312, 5990, 6052, 6216, 6230, 6407, 30783; Fisher 2006, p. 105
Middle Wabash- Deer	IN	Wabash River	UMMZ 80985, 231702; OSUM 31234, 45650, 55064; Fisher 2006, p. 105
Skillet	IL	Skillet Fork	INHS 41131; Stodola *et al* 2014, p. 55
Little Wabash	IL	Little Wabash River	INHS 3122, 3134, 4696, 20767, 23423, 27515, 30192
Tippecanoe	IN	Tippecanoe River	INHS 2179, 4074, 4708, 30189; UMMZ 80983, 80984, 80996; OSUM 56478, 56535, 56624, 57220, 57053, 56376; FMNH 296435, 50521; ANSP 341223; Cummings & Berlocher 1990, p. 94; Daniels, 1903, p. 652, lists the species as common in the Tippecanoe River in Carroll Co.
Mississinewa	IN	Mississinewa River	UMMZ 80990
Upper East Fork White	IN	East Fork White River	INHS 11604; Fisher 2006, p. 105
Lower East Fork White	IN	East Fork White River	INHS 10561, 10579, 11309, 11417, 11583, 12524; UMMZ 166244; OSUM 12084; Fisher 2006, p. 105

Upper White	IN	West Fork White River	INHS 8454, 11622, 12385, 12446, 12592; CM 61.564; UMMZ 80934; Ortmann 1919 p. 85; Fisher 2006, p. 105
Lower White	IN	White River	INHS 12415; USNM 677493, 677673, 894745; UMMZ 80999; ANSP 127663, A14730; Fisher 2006, p. 105
Lower Ohio-Little Pigeon	IN	Ohio River (Newburgh Pool)	LEC record
	KY		INHS 35195; Haag and Cicerello 2016, p. 199
Highland - Pigeon	IN	Ohio River (Myers Pool)	Parmalee 1960, p. 72; KYNPC EO ID 1406
	KY		LEC record
Lower Ohio - Bay	IL	Ohio River	OSUM 68515; Stodola *et al* 2014, p. 55
Lower Ohio	IL	Ohio River	INHS 24524, 30558, 13139; NCMNS 7291; ; Stodola *et al* 2014, p. 55
Upper Cumberland - Lake Cumberland	KY	Cumberland River	(Wilson and Clark 1914); EKU 2335, UMMZ 40690, 80943, 80989, 81000, 173692, 80944, 80946, 80947, 80948, 80949, 80950, 80951, 80966, 80967; OSUM 53515 (Schuster 1988, p. 769). UMMZ 80941; (Neel and Allen 1964, p. 453); FMNH 59247
Upper Cumberland - Cordell Hull Reservoir	TN	Cumberland River	UMMZ 134778, 58155; Shoup *et al* 1941, p. 68; Parmalee and Bogan 1998, p. 192
Lower Cumberland - Sycamore	TN	Cumberland River	UMMZ 80965, 80968, 80969; INHS 24429; Peres *et al* 2016, p. 44 report 69 shells; Parmalee and Bogan 1998, p. 192
Lower Cumberland	KY	Cumberland River	Sickel (1982, p. 20), Sickel & Chandler (1996, p. 37); Casey 1987, p. 119; KSNPC EO ID 922; Haag and Cicerello 2016, p. 199
South Fork Cumberland	TN	Big South Fork Cumberland River	FMNH 269426; Parmalee and Bogan 1998, p. 192
	KY		EKU 1260; UMMZ 80943, 81000; CM 61.1201; Wilson and Clark 1914, p. 14; Haag and Cicerello 2016, p. 199
Obey	TN	Obey River	UMMZ 134774; Shoup *et al* 1941, p. 68; Parmalee and Bogan 1998, p. 192

Caney	TN	Caney Fork	OSUM 29701; Layzer *et al* 1993 (p. 67); MFM 8777, 8778; Parmalee and Bogan 1998, p. 192
Stones	TN	Stones River	OSUM 20184; Schmidt 1984, p. 27; Schmidt *et al* 1989, p. 58; Parmalee and Bogan 1998, p. 192
MISSOURI RIVER BASIN			
Lower Marais Des Cygnes	KS	Marais des Cygnes River	INHS 28285, ANSP 79981
	MO		UMMZ 80964
Lower Osage	MO	Osage River	OSUM 52259; NCMNS 88117
Meramec	MO	Meramec River	UMMZ 80987, 80988, 80991
Pomme De Terre	MO	Pomme de Terre River	UTMM 1051
TENNESSEE RIVER BASIN			
Lower French Broad	TN	French Broad River	Parmalee and Bogan 1998, p. 192
		Little Pigeon River	Parmalee 1988; Parmalee and Bogan 1998, p. 192
		Boyd Creek	CM 61.747, (Ortmann 1919, p. 86)
Lower Little Tennessee	TN	Little Tennessee River	Parmalee and Bogan 1998, p. 192; Athearn 1965, p. 1
Watts Bar Lake	TN	Tennessee River (Ft. Loudon & Watts Bar Reservoirs)	OSUM 57319; CM 61.1185, 61.8677; DMNH 1503507; UTMM 8731; ANSP 69205; Pilsbry and Rhoads 1896; Ortmann 1919; Parmalee and Bogan 1998, p. 192
Middle Tennessee-Chickamauga	TN	Tennessee River (Chickamauga & Nickajack Reservoirs)	Ahlstedt 1989, p. 12 (RM 526.3), also report 4 total from surveys between 1983-1988 (p. 25); Ahlstedt and McDonough 1995-1996; van der Schalie 1939; OSUM 14696, 63632; NCMNS 47698; MFM 16514, 22422, 9198, 20987; UMMZ 80977, 80961, 129708; USNM 756398; Parmalee and Bogan 1998, p. 192
Guntersville Lake	AL	Tennessee River (Guntersville Reservoir)	INHS 24597; UMMZ 80958 (figured in Williams *et al*. 2008; p. 324).
Wheeler Lake	AL	Limestone Creek	Williams *et al*. 2008; p. 324

Lower Elk	TN	Elk River	UMMZ 52938; Parmalee and Bogan 1998, p. 192
Kentucky Lake	TN	Tennessee River (Kentucky Reservoir - lower & Kentucky Dam tailwater)	NCMNS 7292; UTMM 8745; UMMZ 129618; ANSP 110168; Sickel and Burnett 2005 p. 16-19; van der Schalie 1939, p. 454; Haag and Cicerello 2016, p. 199
	KY		
Lower Tennessee	KY	Tennessee River (just before OH River junction)	UMMZ 36219; 129723
ARKANSAS-WHITE-RED			
Upper Neosho	KS	Neosho River	USNM 738449; Scammon 1906, p. 366; Murray and Leonard 1962, p. 77
Middle Neosho	KS	Neosho River	USNM 738168; CM 61.10204; UMMZ 80939, 80978; Scammon 1906, p. 366; Murray and Leonard 1962, p. 77
Spring	KS	Spring River	Branson 1966, p. 282
	MO		NCMNS 88118, 88119
Middle Verdigris	KS	Verdigris River	Liechti & Huggins 1977, p. 23; Isely 1924, p. 71; Scammon 1906, p. 366
Lower Verdigris	OK	Verdigris River	CM 61.9822; UMMZ 81005; Isely 1924, Table 2; Abundant 1 site, Dominant 2 sites, Common 1 site (Isely 1924, Table 2). In some of the beds of the Verdigris as many as 50% of an entire catch belonged to this species (Isely 1924, p. 94).
		Bird Creek	Isely 1924, Table 2
Lake O' The Cherokees	OK	Neosho River	Isely 1924, Table 2; Scammon 1906, p. 366; Murray and Leonard 1962, p. 77; 5% of catch (Isely 1924, p. 94).
	KS		
Poteau	OK	Poteau River	Isely 1924, p. 77, 94, Table 2; Common at one site, 10% of catch (Isely 1924, p. 94).
Kiamichi	OK	Kiamichi River	Vaughn 1996, p. 327; Galbraith *et al* 2008, p. 46
Current	AR	Current River	ANSP 468220; Harris *et al* 2009, p. 72
Little Red	AR	Middle Fork Little Red River	Harris *et al* 2009, p. 72; AGFC records (J. Harris Collector)

Dardanelle Reservoir	AR	Big Piney Creek	Harris *et al* 2009, p. 72; AGFC records (C. Davidson Collector); Davidson *et al*. 2000
Spring	AR	Spring River	INHS 17524; ANSP 468278; UMMZ 80973; Harris *et al* 2009, p. 72
Cadron	AR	East Fork Cadron Creek	Harris *et al* 2009, p. 72; AGFC records (B. Bauer Collector)
LOWER MISSISSIPPI			
Upper White - Village	AR	White River	Harris *et al* 2009, p. 72; AGFC records (A. Miller Collector)
Lower White	AR	White River	UMMZ 80974; Harris *et al* 2009, p. 72;
Little River Ditches	AR	Left Hand Chute Little River	Harris *et al* 2009, p. 72; AGFC records (J. Bates Collector)
		Little River (St. Francis)	UMMZ 80972; Harris *et al* 2009, p. 72;
Upper Saline	AR	Alum Fork Saline River	Harris *et al* 2009, p. 72; AGFC records (J. Harris Collector)
Lower Little	AR	Cossotot River	OSUM 84330; NCMNS 88133; Harris *et al* 2009, p. 72
Big Sunflower	MS	Quiver River	Jones *et al* 2019, p. 225; Miller and Payne 1997, p. 9-12
Tallahatchie	MS	Tallahatchie River	Peacock *et al*. 2016, p. 125; 12,652 shells from 3 sites, RA = 43.6 %, #1; apparently widespread and common in the past (Peacock *et al*. 2016, p. 121); Jones *et al* 2019, p. 225
Upper Yazoo	MS	Yazoo River	MSMNS 9205; ANSP 95619; Hartfield 1993, p. 132; Jones *et al* 2019, p. 225
		Wolf Lake	MSMNS 9218; Jones *et al* 2019, p. 225
Tensas	LA	Tensas River	OSUM 80347 (WD); Vidrine 2001, Plate VII; Vidrine 1996, p. 42
Bayou Macon	LA	Bayou Macon	USFWS LA Field Office records, 2 collections in Bayou Macon, 1994-1995
Boeuf	LA	Boeuf River	Vidrine 2001, Plate VII, p. 234

Loggy Bayou	LA	Bayou Dorcheat	Vidrine 2001, Plate VII, p. 234, Vaughn 1892, p. 110-111

APPENDIX D—FUTURE CONDITION RANKINGS FOR SCENARIOS 1 & 2.

Major River Basin	Management Unit	State	Contiguous Population	Future Condition (20-30 years) Scenario 1	Future Condition (20-30 years) Scenario 2
Ohio				**Scenario 1**	**Scenario 2**
Ohio	Muskingum	OH	Muskingum River	**Very Low**	**Very Low**
Ohio	Upper Green	KY	Green River	**Med.**	**Med.**
Ohio	Middle Green	KY	Green River	**Med.**	**Low**
Ohio	Barren	KY	Barren River	**Med**	**Low**
Ohio	Lower Green	KY	Green River	**Low**	**Very Low**
Ohio	Lower Cumberland-Old Hickory Lake	TN	Cumberland River	**Very Low**	**Very Low**
Tennessee				**Scenario 1**	**Scenario 2**
Tennessee	Upper Clinch	TN	Clinch River	**Low**	**Low**
Tennessee	Holston	TN	Holston River	**Very Low**	**Very Low**
Tennessee	Wheeler Lake	AL	Paint Rock River; Tennessee River (Wheeler Reservoir) Guntersville TW	**Low**	**Very Low**
Tennessee	Pickwick Lake	AL	Tennessee River (Pickwick Reservoir) Wilson TW	**Low**	**Low**
Tennessee	Lower TN-Beech	TN	Tennessee River (Kentucky Reservoir) Pickwick TW	**Low**	**Low**
Tennessee	Upper Duck	TN	Duck River	**Med.**	**Low**
Tennessee	Lower Duck	TN	Duck River	**Low**	**Very Low**
Arkansas-White-Red				**Scenario 1**	**Scenario 2**
Arkansas-White-Red	Petit Jean	AR	Petit Jean River	**Low**	**Very Low**
Arkansas-White-Red	Eleven Point	AR	Eleven Point River	**Low**	**Very Low**
Arkansas-White-Red	Lower Little	AR	Little River	**Low**	**Very Low**
Lower Mississippi				**Scenario 1**	**Scenario 2**
Lower Mississippi	Lower Black	AR	Black River	**Low**	**Very Low**
Lower Mississippi	Lower St. Francis	AR	St. Francis River; Tyronza River	**Med.**	**Low**
Lower Mississippi	Middle White	AR	White River	**Low**	**Very Low**
Lower Mississippi	Upper Ouachita	AR	Ouachita River	**High**	**Med.**
Lower Mississippi	Little Missouri	AR	Little Missouri River	**Med.**	**Low**
Lower Mississippi	Lower Ouachita - Smackover	AR	Ouachita River	**Med.**	**Low**
Lower Mississippi	Upper Saline	AR	Saline River	**High**	**Med.**
Lower Mississippi	Lower Saline	AR	Saline River	**High**	**Med.**
Lower Mississippi	Bayou Bartholomew	AR; LA	Bayou Bartholomew	**Med.**	**Low**
Lower Mississippi	Lower Ouachita - Bayou De Loutre	AR; LA	Ouachita River	**Low**	**Low**
Lower Mississippi	Big Sunflower	MS	Hushpuckna River; Bogue Phalia; Little Sunflower River; Sunflower River; Sandy Bayou; Big Sunflower River	**Low**	**Very Low**
Lower Mississippi	Lower Big Black	MS	Big Black River	**Very Low**	**Very Low**

APPENDIX E—ESTIMATES OF MAGNITUDE AND IMMEDIACY OF POTENTIAL THREATS NEGATIVELY INFLUENCING THE VIABILITY OF PYRAMID PIGTOE POPULATIONS IN THE OHIO AND TENNESSEE BASINS.

Population	Threat Level Category	Threats	References
OHIO RIVER BASIN			
(1) Muskingum River	High	Hydropower development, impoundment, dredging, genetic isolation; past threats include commercial harvest	The occupied reach of the Muskingum River is highly fragmented by impoundments, and Watters and Dunn (1993-94, p. 258) state: It is foreseeable that a single major environmental accident upstream, such as an oil or pesticide spill, could irreparably damage or even eliminate this fauna. One such spill, although apparently minor and well contained occurred in 1992. They also cite potential dam removal and associated silt and sediment loads, dredging activities and harvesting pressure as long-term impacts on the mussel fauna in the Muskingum River. Additionally, ESI 2012, did extensive surveys related to proposed hydropower development at existing dams, and cite changes in shear velocity as potentially affecting substrate and unionid communities. Eleven L&Ds have been constructed on the Muskingum from Zanesville downstream.
(2) Upper Green River	Low	impoundment - habitat loss & water quality degradation; resource extraction; past commercial harvest threat	Although there are multiple dams on the Green River mainstem, there is a large amount of riverine habitat available in numerous reaches. The KY CWCS (2015) lists the following as threats to the species: Aquatic habitat degradation, loss of fish hosts, point and non-point source pollution, siltation and increased turbidity. Cochran and Layzer (1993, p. 64) determined that mussels in the middle Green and Lower Barren Rivers selected habitats that were less impacted by commercial harvest activities, although harvest was lighter in the Barren than the Green.
(3) Barren River	Moderate	impoundment - habitat loss & water quality degradation; resource extraction; past commercial harvest threat	There are multiple dams on the Barren River mainstem. The KY CWCS (2015) lists the following as threats to the species: Aquatic habitat degradation, loss of fish hosts, point and non-point source pollution, siltation and increased turbidity. Cochran and Layzer (1993, p. 64) determined that mussels in the middle Green and Lower Barren Rivers selected habitats that were less impacted by commercial harvest activities although harvest was lighter in the Barren than the Green.

(4) Middle Green River	Moderate	impoundment - habitat loss & water quality degradation; resource extraction; past commercial harvest threat	Although there are multiple dams on the Green River mainstem, there is a large amount of riverine habitat available in numerous reaches. Oil drilling has affected the Green watershed. The KY CWCS (2015) lists the following as threats to the species: Aquatic habitat degradation, loss of fish hosts, point and non-point source pollution, siltation and increased turbidity.
(5) Lower Green River	Moderate	impoundment - habitat loss & water quality degradation; resource extraction; past commercial harvest threat	There are multiple dams on the Green River mainstem, and there is the least amount of riverine habitat available in the lowermost reaches. The KY CWCS (2015) lists the following as threats to the species: Aquatic habitat degradation, loss of fish hosts, point and non-point source pollution, siltation and increased turbidity. This reach of the river was more heavily impacted by towboats before reduced commercial traffic. Miller *et al.* (1994, p. 53) also cite hypolimnetic discharges as an impact to the lower Green River mussel fauna.
(6) Cumberland River	High	Habitat fragmentation, hypolimnetic discharges	From Hubbs (2012, p. 3): Historically the Cumberland River contained a diverse mussel fauna with approximately 80 species reported from the drainage (Wilson and Clark 1914); however habitat alteration from impoundment and maintenance dredging of the navigation channel has substantially reduced the species richness and abundance. Mussel habitat is highly fragmented in the main channel throughout the 310 mile reach in the Tennessee portion of the Cumberland River from the KY/TN state line (mile 385) near Celina, TN downstream to the TN/KY state line near Tobaccoport (mile 75). The upper reach of Old Hickory Reservoir located between Carthage and Lebanon, runs 49 river miles and contains much of the physical habitat favorable to mussel colonization and still holds approximately 33 species including 13 state GCN and five federally endangered. Mussel recruitment in this reach of the Cumberland River has long been suppressed by cold water resulting from the hypo limnetic releases from upstream reservoirs (Wolf Creek, Dale Hollow, and Center Hill).

TENNESSEE RIVER BASIN			
(7) Holston River	High	Habitat Fragmentation, hypolimnetic discharges	Parmalee and Faust 2006, p. 77, state: Since construction of Cherokee Dam in 1941 until 2006, approximately 75% of the naiad taxa have been extirpated in the lower Holston River downstream from the Dam. Primary impacts from the dam include large fluctuations in discharges, water temperatures, and water depth.
(8) Clinch River	Moderate	logging, deep and surface coal mining, agricultural activities, dams, overharvest, 100-year floods and prolonged drought. Point and nonpoint source contaminants from coal mine activities, agricultural uses, and urban areas Non–point-source inputs of agricultural pesticides	Ahlstedt *et al.* (2016, p. 8) give a chronology of significant perturbations that have occurred in the Clinch and Powell rivers. These include: logging of the landscape, resulting in increased sedimentation, deep and surface coal mining; including discharges of industrial and mine wastes, mine blowouts, black water release events and fly-ash spills from mining activities, soil erosion from agricultural activities, construction of impoundments, overharvest, sulfuric acid spills, 100-year floods. Mussel die-offs of unknown origin continue to be a significant threat, mussel die-offs and were documented in the Clinch (1986-1988) and recently (2016) in the Clinch River, VA. Black-water release events associated with mining activity were documented in the same drainage in 2002-2003 (Ahlstedt *et al.*, 2016, p. 9). The Clinch River in Virginia and Tennessee has chronic threats including concentrated agricultural and mining activities and transportation corridors, as well as acute threats such as wastewater treatment effluents and chemical spills (Zipper *et al.* 2014, p. 810). From Diamond *et al.* (2002, p. 1,153): Point and nonpoint source contaminants from coal mine activities, agricultural uses, and urban areas are also likely to be limiting aquatic fauna distribution. Contaminant spills have been particularly detrimental and are an ongoing threat to this population. Ahlstedt *et al.* (2017a, p. 224), state that the mussel fauna of the Clinch River downstream of the Appalachia Power Company's Steam Plant at Carbo, Virginia, was severely affected by a fly ash spill in 1967 and a sulfuric acid spill in 1970. Jones *et al.* (2001, p. 20) reference a 1,400 gallon spill of rubber accelerator into the upper Clinch River just above Cedar Bluff, Virginia (Clinch River RM 323) in August 1998, which killed at least 7,000 mussels of 16 species, the species has been documented to occur within the affected reach (Jones *et al.* 2001, p. 22). High concentration levels of the toxic metals zinc and copper in sediments present below a coal processing plant resulted in reduced survival of juvenile mussels in the Clinch River, Virginia (Ahlstedt and Tuberville 1997, p. 75).

(9) Paint Rock River	Low	Habitat loss through alteration (snag removal), habitat fragmentation – population isolation due to impoundment; agriculture	The Paint Rock River drainage was severely affected in past decades by small impoundments, stream channelization, erosion, and agricultural runoff. A major detrimental impact on habitat occurred with the channelization and removal of snags and riverbank timber in the upper drainage and the lower reaches of Larkin and Estill forks and Hurricane Creek by the US Army Corps of Engineers during the 1960s (Ahlstedt 1995). This direct headwater habitat manipulation was probably a large contributor to freshwater mussel loss in the drainage. Wheeler Dam was completed by the TVA in 1936, resulting in loss of most of the mussel fauna and riverine habitat in the lower 21 km of the Paint Rock River (Ahlstedt 1995).
(10) Tennessee River (Wheeler Reservoir)	High	impoundment, habitat degradation from flow releases; past commercial harvest threat	From Ahlstedt and McDonough (1995): Beginning in the early 1950's, the Japanese discovered that freshwater mussel shells from the united States were ideal material for implantation in oysters to form the nucleus for cultured pearls. The mussel shells were cut into small blocks, which were then tumbled and polished into smooth, round beads for surgical implanting in the oysters. This development resulted in a sudden, rapid demand for shells and was a tremendous economic boost for the declining American musseling industry. The mainstream reservoirs of the Tennessee River became the nation's most important source of shell for shipment to Japan. The annual shell harvest from the Tennessee River exceeded 10,000 tons for a number of years (lsom 1969). Although a past threat, this is a considerable contributor to the decline of freshwater mussels in Wheeler Reservoir. Additional threats are the continued operation of Guntersville Dam and Browns Ferry Nuclear Plant.
(11) Tennessee River (Pickwick Reservoir)	High	impoundment, dredging, navigation impacts, past commercial harvest threat	Isom (1969, p. 410) reported the species from the Seven mile Island Area Muscle Shoals, Wilson Dam tailwater (TRM 247-253). Also, reported the species to be of some commercial importance (p. 402). The 53 RM reach of the Tennessee River in northwestern AL collectively referred to as Muscle Shoals historically harbored 69 species of mussels, making it the most diverse mussel fauna ever known from a single river reach (Garner and McGregor 2001). The construction of three dams (i.e., Wilson in 1925, Wheeler in 1930,Pickwick Landing in 1940) inundated most of the historical mussel habitat, leaving approximately 13 RMs of riverine habitat. The largest remnant habitat remaining is the Wilson Dam

			tailwaters, a several mile reach adjacent to, and downstream from, Florence, Alabama (Garner and McGregor 2001).
(12) Tennessee River (Kentucky Reservoir)	High	impoundment, dredging/navigation impacts, agriculture	From Hubbs (2015): Commercial sand and gravel dredging, conducted on the Lower Tennessee River since at least the 1920's, and currently permitted on approximately 48 of the 95 river miles in this reach has degraded a significant portion of the available aquatic habitat. Significantly lower mussel abundance and diversity values have been observed at dredge sites indicating bottom substrates altered by dredging and resource extraction operations do not provide suitable habitat to support mussel populations similar to those found inhabiting non-dredged reaches (Hubbs *et al.* 2006). During the pearl button days from the late 1800's until the mid 1950's, the river was a source of valuable shells for the button industry. With the construction of Kentucky Lock and Dam completed in 1944, major changes occurred in the aquatic habitat upstream from the dam in Kentucky Lake, with sediment accumulation in deeper areas, while the tailwater area remained riverine and retains its original gravel bottom. The entire length of the 650-mi (198-m) long Tennessee River main stem has been impounded, destroying hundreds of miles of riverine habitat for the Pyramid Pigtoe. The main stem is currently maintained as a navigational channel. Thus maintenance activities and impacts associated with barge traffic are continued threats.
(13) Upper Duck River	Moderate	Water quality degradation through agriculture and increased human development Impoundment (Normandy Dam & 3 mill dams) fragment population	Mill dams interrupt distribution. Rapidly increasing human development pressure, agricultural impacts such as water withdrawals for irrigation and cattle. Small and large impoundment. Urban development is increasing rapidly throughout the Duck River drainage, resulting in the large-scale removal of riparian vegetation. Although improvements made at Normandy Dam regarding flows and dissolved oxygen, the presence of the impoundment limits colonization potential upstream. Additional increased herbicide and pesticide use and changes to hydrology were also cited as contributors to mussel decline in the river.

(14) Lower Duck River	Moderate	Water quality degradation through increased human development	Rapidly increasing human development pressure, agricultural impacts such as water withdrawals for irrigation and cattle. Small and large impoundment. Urban development is increasing rapidly throughout the Duck River drainage, resulting in the large-scale removal of riparian vegetation. Although improvements made at Normandy Dam regarding flows and dissolved oxygen, the presence of the impoundment limits colonization potential upstream. Additional increased herbicide and pesticide use and changes to hydrology were also cited as contributors to mussel decline in the river.

ARKANSAS-WHITE-RED BASIN			
(15) Petit Jean River	Moderate	Agriculture; habitat loss & water quality degradation	River habitat degraged below confluence with Big Piney Creek, excessive silt and sediments and bank sloughing in bends clog the channel with woody debris (Harris 2001, p. 11)
(16) Eleven Point River	Low	Habitat loss & water quality degradation; agricultural effects	44 miles are National and Wild Scenic River, some lacking riparian corridor in upper river, but middle river has good riparian corridor (pHC02-HC03). high fecal coliform, nutrient loading and sedimentation and gravel deposition are most severe threats to water quality (MDC 2000, p. 2).
(17) Little River	Moderate	impoundment - habitat loss & water quality degradation	Broken Bow Reservoir releases limit downstream mussel fauna, above confluence with Mountain Fork limited good habitat reach. Very rare in Oklahoma section of river, linear population.
LOWER MISSISSIPPI BASIN			
(18) Lower Black River	Moderate	Agriculture; habitat loss & water quality degradation	The lower Black river has been channelized so headcutting could be a problem. Also, gravel loading and sedimentation is a common issue throughout most of the Ozarks (MDC 2003 p. 95-101).
(19) Lower St. Francis River	High	Agriculture; habitat loss & water quality degradation	Headcutting in the mainstem St. Francis, tributaries, and lateral ditches has caused lower stream bed elevations, wider and shallower stream channels, and steeper banks, which are experiencing severe sloughing and erosion in many locations. Poor riparian corridor, manmade drainage ditch for draining swampy areas constructed late 1800s to early 1900s (MDC. 2001, p. 1-3)

(20) Tyronza River	High	Agriculture; habitat loss & water quality degradation	Channelized and ditched late 1800s, habitat quality determined to be suboptimal (Wentz *et al*. 2011, p. 146).
(21) White River	Moderate	Impoundment, Resource extraction, habitat loss & water quality degradation	Upstream of Batesville is trout waters, thermal limitations for mussels; located within the Fayetteville Shale where oil and gas exploration is prevalent (C. Davidson, 2021, pers. comm.).
(22) Upper Ouachita River	Moderate	Impoundment, Navigation; habitat loss & water quality degradation	3 mainstem dams, maintained as waterway by Corps, 2 lock and dams, Natural gas and oil development is prevalent in the system and these fuels are transported down the river by barge, barium sulfate mining activities, sedimentation, and agricultural activities (Service 2009, p. 33)
(23) Little Missouri River	Moderate	Agriculture; habitat loss & water quality degradation	Riparian zones with cattle may result in nutrient loadings and localized streambank erosion (Service 2009, p. 33). Difficult to survey/sample due to tree blowdowns and narrow channel in some reaches.
(24) Ouachita River	Moderate	Impoundment, Navigation; habitat loss & water quality degradation	3 mainstem dams, maintained as waterway by Corps, 2 lock and dams, Natural gas and oil development is prevalent in the system and these fuels are transported down the river by barge, barium sulfate mining activities, sedimentation, and agricultural activities (Service 2009, p. 33)
(25) Upper Saline River	Moderate	Impoundment, Navigation; Agriculture; Resource extraction; habitat loss & water quality degradation	About 14% of the landuse is in agriculture. Sixteen waste water treatment plants occur in the Saline River watershed and an additional 33 facilities have NPDES permits issued by the State. Another potential threat is from open pit bauxite mines. Once thought to be the sole source of bauxite in the world, the Hurricane Creek watershed, a major tributary to the Saline River, was extensively mined for 100 years until 1990. While reclamation is ongoing to restore the areas mined, acid runoff is still impacting water quality in Hurricane Creek (Service 2009, p. 34).
(26) Lower Saline River	Moderate	Impoundment, Navigation; Agriculture; Resource extraction; habitat loss & water quality degradation	The lowermost 12 river miles of the Saline are impounded by a lock and dam on the Ouachita River. About 14% of the landuse is in agriculture. Sixteen waste water treatment plants occur in the Saline River watershed and an additional 33 facilities have NPDES permits issued by the State. Another potential threat is from open pit bauxite mines. Once thought to be the sole source of bauxite in the world, the Hurricane Creek watershed, a major tributary to the

			Saline River, was extensively mined for 100 years until 1990. While reclamation is ongoing to restore the areas mined, acid runoff is still impacting water quality in Hurricane Creek (Service 2009, p. 34).
(27) Bayou Bartholomew	High	Agriculture; pollution, habitat loss & water quality degradation	Riparian zones with cattle and row crops result in nutrient loadings and localized streambank erosion, human pollution, irrigation, sedimentation from extensive agriculture (Brooks *et al* 2008).
(28) Lower Ouachita River	High	Impoundment, Navigation; habitat loss & water quality degradation	3 mainstem dams, maintained as waterway by Corps, 2 lock and dams, Natural gas and oil development is prevalent in the system and these fuels are transported down the river by barge, barium sulfate mining activities, sedimentation, and agricultural activities (Service 2009, p. 33)
(29) Hushpuckna River (30) Bogue Phalia (31) Little Sunflower River (32) Sunflower River (33) Sandy Bayou (34) Big Sunflower River	High	Impoundment, Navigation; habitat loss & water quality degradation Agriculture; habitat loss & water quality degradation	Impoundment, dredging, channel instability, headcutting. Extensive sedimentation (Miller and Payne 2004, p. 153). Riparian zones with cattle may result in nutrient loadings and localized streambank erosion (Service 2009, p. 33). Difficult to survey/sample due to tree blowdowns and narrow channel in some reaches. From Miller and Payne 2004, p. 147: Eight counties in Mississippi border the Big Sunflower River: Bolivar, Humphreys, Issaquena, Sharkey, Sunflower, Warren, Washington, and Yazoo, which include about 12,771 km2, or approximately 10% of the land in the state. In 2002 more than 617,000 ha in those eight counties were cultivated for corn, cotton, rice, sorghum, soybeans, and wheat. The economic significance of the Delta for Mississippi should not be underestimated. In 2002 this comparatively small parcel of rich farmland was responsible for 42% of the production of those six crops in the state.

(35) Big Black River	High	Impoundment, Agriculture; habitat loss & water quality degradation	Channel instability and localized channel adjustments as severe impacts to mussels in the Big Black River (Hartfield 1993, p. 133).