Species Status Assessment Report for the Brawleys Fork Crayfish (*Cambarus williami*)

Version 1.1

Photo credit: Wesley Giddens, USFWS

February 2023
U.S. Fish and Wildlife Service
Atlanta, GA

ACKNOWLEDGEMENTS

This document was prepared by the U.S. Fish and Wildlife Service's Brawleys Fork crayfish Species Status Assessment Team: Santiago Martín (USFWS – Tennessee Ecological Services Field Office), Geoff Call (USFWS – Tennessee Ecological Services Field Office), Wesley Giddens (USFWS – Tennessee Ecological Services Field Office), Kendell Hamm (Tennessee Tech University), Hayden Mattingly (Tennessee Tech University), and Melissa Lombardi (USFWS – Species Assessment Team, Interior Regions 2 and 4). We would like to extend a special thank you to Kurt Snider (USFWS – Tennessee Ecological Services Field Office) for his invaluable efforts with the GIS analysis for the Species Status Assessment (SSA).

We would also like to recognize and thank the following individuals who provided substantive information and/or insights for our SSA: Carl Williams (Tennessee Wildlife Resources Agency), David Withers (Tennessee Department of Environment and Conservation), John Johansen (Fisk University), and Jeffrey Simmons (Tennessee Valley Authority).

Additionally, valuable input into the analysis and reviews of a draft of this document were provided by peer reviewers. We appreciate their input and comments, which resulted in a more robust status assessment and final report.

Suggested reference:

U.S. Fish and Wildlife Service. 2021. Species status assessment report for the Brawleys Fork crayfish (*Cambarus williami*), Version 1.1. February 2023. Atlanta, GA.

VERSION UPDATES

Version	Date	Author	Rationale
1.1	February 2023	SSA Core Team	Improved consistency in characterization of current representation and redundancy

EXECUTIVE SUMMARY

Background

Brawleys Fork crayfish (*Cambarus williami*) is a small, freshwater crayfish endemic to the Nashville Basin and Eastern Highland Rim ecoregions of central Tennessee. The species occurs primarily in small- to medium-sized streams (first- to third-order streams) of the Stones and Collins river systems, and in one medium sized river (fifth order). Brawleys Fork crayfish is known to occur in 20 streams in five Hydrologic Unit Code-12 (HUC 12) watersheds within its range. Brawleys Fork crayfish typically occupies runs and riffles with moderate to fast flow and layered cherty gravel substrate and cobble with ample interstitial space not consolidated by fine substrates such as silt. Individuals often burrow a short distance into the cherty substrate during times of normal and reduced stream flows. Individuals reach reproductive maturity by one year. A portion of males are in reproductive form in all months except August. Females bear eggs in the spring as typical of most crayfish species. The species' lifespan appears to be three years with two to three age classes present in healthy populations.

The primary factor influencing Brawleys Fork crayfish is sedimentation from sources including agricultural and horticultural practices, gravel dredging, stream impoundment, and urban growth. In addition to sedimentation, water quality degradation, channel modifications, and the effects of climate change influence Brawleys Fork crayfish. Excess sediment can cover the substrate and fill in the spaces the crayfish needs for feeding, breeding, sheltering, and other life-sustaining activities. Each of these threats influencing Brawleys Fork crayfish viability may be further exacerbated by the effects of climate change, urban growth, and isolated populations lacking gene flow.

Methodology

We evaluated the current condition and future condition of Brawleys Fork crayfish using the conservation biology principles of population resiliency, and species' redundancy and representation. We delineated five analysis units (AUs) for Brawleys Fork crayfish using available spatial occurrence data (1955–2019) obtained from State agency survey reports and data (Tennessee Wildlife Resources Agency, Tennessee Department of Environment and Conservation), Federally-owned corporation data (Tennessee Valley Authority), an interim research report (Tennessee Tech University), peer-reviewed literature, and other surveys. Based on Brawleys Fork crayfish individual and population needs, we developed an approach using key habitat and demographic parameters to assess population resiliency. These included three habitat condition factors: percent riparian canopy cover, percent agricultural and/or urban development, and drought, and three demographic condition factors: extent, abundance, and age class distribution. We developed a scoring framework for current resiliency that categorized each AU as either high, moderate, low, or very low.

Then, we developed plausible future scenarios with varying levels of each threat to determine the effect on the resiliency, representation, and redundancy of Brawleys Fork crayfish to project the future species' condition in 2036 (15 years from now) and 2051 (30 years from now). We chose to model these scenarios at the timesteps because of the average lifespan of the species (approximately three years), confidence in models and projections of factors influencing the species' viability, and certainty in predictions of the species' response to those factors. To assess the potential future condition of Brawleys Fork crayfish, we selected four key threats (urbanization, crop land-use change, climate change, and water withdrawal) based on the influences these factors have on Brawleys Fork crayfish viability. We quantitatively assessed expected levels of urbanization (SLEUTH model), land use change (FORE-SCE model), and climate change (USGS NCCV model) using various modeling techniques, and we qualitatively assessed the threat of water withdrawal. Three scenarios were considered when predicting future condition: (1) status quo with lower development; (2) status quo with higher development; and (3) increased impacts.

Conclusions

Current Condition – We determined Brawleys Fork crayfish current resiliency, redundancy, and representation to assess viability. Three of the five Brawleys Fork crayfish AUs exhibit moderate resiliency. However, all five Brawleys Fork crayfish AUs exhibit low habitat condition scores. Species redundancy is not reduced from a historical range and distribution with no known extirpations. We determined that the species current representation is not reduced from historical levels and is sufficient to support species' viability .

Future Condition – Our analysis of future conditions projects that by 2036 resiliency is estimated to decrease by at least one resiliency class in four of the five Brawleys Fork crayfish AUs under all future condition scenarios. One AU (Bullpen Creek) is projected to maintain low resiliency in 15 years under Scenario 1. No AUs are estimated to maintain moderate resiliency in 15 years under any future condition scenario. Redundancy is expected to decline as a function of loss of resiliency in the AUs, although no AUs are projected to be extirpated and the distribution of the species across the range is projected to remain at the current level. Representation is expected to decline slightly in the future as the demographic parameters used to assess adaptive capacity in Brawleys Fork crayfish decline.

Our analysis indicates that by 2051, resiliency is estimated to decrease by at least one resiliency class in all five Brawleys Fork crayfish AUs under all future condition scenarios. No AUs are estimated to maintain moderate resiliency. Under the high-impact scenario, three AUs are estimated to decrease by two resiliency class categories and one is projected to be extirpated. Redundancy is expected to decline as a function of loss of resiliency in the AUs and the extirpation of one AU under the high-impact scenario, although the distribution of the species across the range is projected to remain at the current level under the two lower-impact scenarios. Representation is expected to decline or remain low as demographic parameters used to assess adaptive capacity in Brawleys Fork crayfish decline, and as the predicted extirpation of the West Fork Stones River population occurs under the high-impact scenario.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 - INTRODUCTION AND ANALYTICAL FRAMEWORK

1.1 Background and Previous Federal Actions

This report summarizes the results of a Species Status Assessment (SSA) conducted for the Brawleys Fork crayfish (*Cambarus williami*). In this chapter, we discuss the previous Federal actions including petition history for the Brawleys Fork crayfish and the analytical framework used to evaluate the status of the species.

The Brawleys Fork crayfish is a small freshwater crayfish endemic to small- and medium-sized streams and rivers in central Tennessee. On April 20, 2010, the U.S. Fish and Wildlife Service (Service) was petitioned to list 404 riparian, and wetland species, including the Brawleys Fork crayfish, in the southeastern United States as endangered or threatened under the Endangered Species Act of 1973, as amended (Act) and designate critical habitat (CBD 2010, entire). On September 27, 2011, the Service published a 90-day finding, which determined that the petition contained substantial information indicating the Brawleys Fork crayfish may warrant listing (76 FR 59836). The Service now is required to make a 12-month finding on whether the species is warranted for listing, and therefore, a review of the status of the species was initiated to determine if the petitioned action is warranted. Based on the status review, the Service will issue a 12-month finding for the Brawleys Fork crayfish.

We conducted an SSA to compile the best available data regarding the species' biology and factors that influence the species' viability. The SSA report for the Brawleys Fork crayfish is a summary of the information assembled and reviewed by the Service and incorporates the best scientific and commercial data available. This SSA report documents the results of the comprehensive status review for the Brawleys Fork crayfish and will be the biological underpinning of the Service's forthcoming decision on whether the species warrants protection under the Act.

1.2 Analytical Framework

Using the SSA Framework (Service 2016, entire), this SSA report provides an in-depth review and evaluation of its biological status and an assessment of the resources and conditions needed to maintain long-term viability. The intent is for the SSA report to be 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 will be a living document that may be used to inform Endangered Species Act decision making, including listing, recovery, Section 7, Section 10, and reclassification (the latter four decision types are only relevant should the species warrant listing under the Act).

For the purpose of this assessment, we define viability as the ability of Brawleys Fork crayfish to sustain populations in stream and river ecosystems over time. To assess viability, we use the conservation biology principles of resiliency, redundancy, and representation (Shaffer and Stein 2000, pp. 308–311). To sustain populations over time, a species must have the capacity to withstand:

(1) environmental and demographic stochasticity and disturbances (Resiliency),
(2) catastrophes (Redundancy), and
(3) novel changes in its biological and physical environment (Representation).

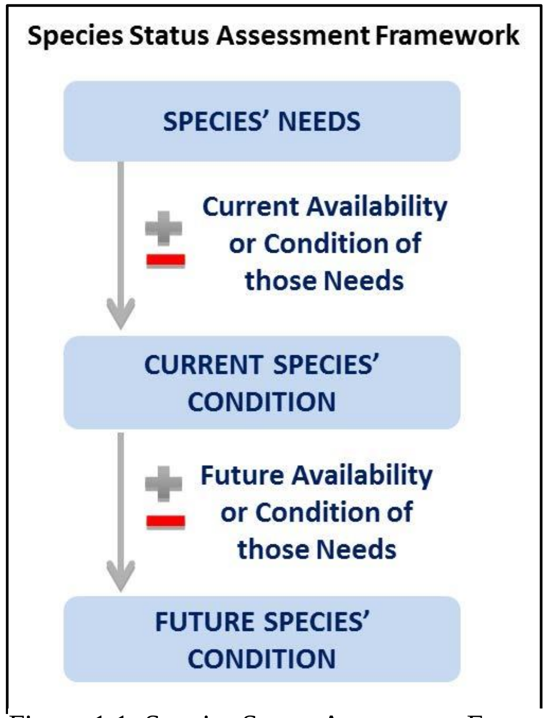


Figure 1.1: Species Status Assessment Framework.

A species with a high degree of resiliency, representation, and redundancy (the 3Rs) is better able to adapt to novel changes and to tolerate environmental stochasticity and catastrophes.

In general, species viability will increase with increases in resiliency, redundancy, and representation (Smith et al. 2018, p. 306). Using the SSA framework (Figure 1.1), we consider what the species needs to maintain viability by characterizing the status of the species in terms of its resiliency, representation, and redundancy (Service 2016, entire; Wolf et al. 2015, entire). To evaluate the viability of the Brawleys Fork crayfish, we estimated and predicted the current and future condition of the species in terms of its resiliency, representation, and redundancy.

Resiliency is the ability of a species to withstand environmental stochasticity (normal, year-to-year variations in environmental conditions such as temperature, rainfall), periodic disturbances within the normal range of variation (fire, floods, storms), and demographic stochasticity (normal variation in demographic rates such as mortality and fecundity) (Redford et al. 2011, p. 40). Simply stated, resiliency is the ability to sustain populations through the natural range of favorable and unfavorable conditions.

We can best gauge resiliency by evaluating population-level characteristics such as: demography (abundance and the components of population growth rate -- survival, reproduction, and migration), genetic health (effective population size and heterozygosity), connectivity (gene flow and population rescue), and habitat quantity, quality, configuration, and heterogeneity. Also, for species prone to spatial synchrony (regionally correlated fluctuations among populations), distance between populations and degree of spatial heterogeneity (diversity of habitat types or microclimates) are also important considerations. For Brawleys Fork crayfish, resiliency may be characterized by demographic and habitat condition parameters.

Representation is the ability of a species to adapt to both near-term and long-term changes in its physical (climate conditions, habitat conditions, habitat structure, etc.) and biological (pathogens, competitors, predators, etc.) environments. This ability to adapt to new environments (referred to as adaptive capacity) is essential for viability, as species need to continually adapt to their continuously changing environments (Nicotra et al. 2015, p. 1269). Species adapt to novel changes in their environment by either (1) moving to new, suitable environments or (2) by altering their physical or behavioral traits (phenotypes) to match the new environmental conditions through either plasticity or genetic change (Beever et al. 2016, p. 132; Nicotra et al. 2015, p. 1270). The latter (evolution) occurs via the evolutionary processes of natural selection, gene flow, mutations, and genetic drift (Crandall et al. 2000, p. 290–291; Sgro et al. 2011, p. 327; Zackay 2007, p. 1).

We can best gauge representation by examining the breadth of genetic, phenotypic, and ecological diversity found within a species and its ability to disperse and colonize new areas. In assessing the breadth of variation, it is important to consider both larger-scale variation (such as morphological, behavioral, or life history differences which might exist across the range and environmental or ecological variation across the range), and smaller-scale variation (which might include measures of interpopulation genetic diversity). In assessing the dispersal ability, it is important to evaluate the ability and likelihood of the species to track suitable habitat and climate over time. Lastly, to evaluate the evolutionary processes that contribute to and maintain adaptive capacity, it is important to assess (1) natural levels and patterns of gene flow, (2) degree of ecological diversity occupied, and (3) effective population size. In our species status assessments, we assess all three facets to the best of our ability based on available data. For Brawleys Fork crayfish, we assess representation based on the species' attributes that contribute to adaptive capacity.

Redundancy is the ability of a species to withstand catastrophes. Catastrophes are stochastic events that are expected to lead to population collapse regardless of population heath and for which adaptation is unlikely (Mangal and Tier 1993, p. 1083). We can best gauge redundancy by analyzing the number and distribution of populations relative to the scale of anticipated species-relevant catastrophic events. The analysis entails assessing the cumulative risk of catastrophes occurring over time. Redundancy can be analyzed at a population or regional scale, or for narrow-ranged species, at the species level. For Brawleys Fork crayfish, we determined the number of moderate and highly resilient analysis units and assessed the distribution of these units across the range to measure redundancy.

This SSA report provides a thorough assessment of the biology and natural history of the Brawleys Fork crayfish and assesses demographic risks, stressors, and conservation factors in the context of determining the viability and risk of extinction for the species. Importantly, the SSA report does not result in, nor predetermine, any decision by the Service under the Act. In the case of Brawleys Fork crayfish, this SSA report does not determine whether the species warrants protections of the Act, or whether it should be proposed for listing as endangered or threatened species under the Act. That decision will be made by the Service after reviewing this report, along with supporting analysis, and any other relevant scientific information, and all applicable laws, regulations, and policies. The results of a decision will be announced in the *Federal Register*.

CHAPTER 2 - SPECIES BIOLOGY, NEEDS, AND DISTRIBUTION

In this chapter, we provide biological information about the Brawleys Fork crayfish, including its taxonomic history, morphological description, historical and current distribution and range, and known life history. We then outline the resource needs of individuals, populations, and the species.

2.1 Morphology and Taxonomy

The Brawleys Fork crayfish was described as a new species within the genus *Cambarus* in 1995 (Bouchard and Bouchard 1995, p. 2; Crandall and De Grave 2017, p. 13). The species description is based on individuals collected from Brawleys Fork, a tributary of the East Fork Stones River located in Cannon County, Tennessee, within the Cumberland River basin (Bouchard and Bouchard 1995, pp. 2, 6–7). The Brawleys Fork crayfish is considered to be most closely related to the hairy crayfish (*Cambarus friaufi*) based on similar claw proportions, areola[1] featuring less punctation, and club-like end observed in the form I (reproductive form) male gonopod[2] (Bouchard and Bouchard 1995, p. 8). Diagnostic features of Brawleys Fork crayfish can be determined by close examination of the species' secondary sexual characteristics (Bouchard and Bouchard 1995, p. 8). The reduced central projection angle of the gonopod is only exhibited by three other species within the genus, the Big South Fork crayfish (*C. bouchardi*), the Obey crayfish (*C. obeyensis)*, and the pristine crayfish (*C. pristinus)*, representing three of the most primitive members of *Cambarus* (Bouchard 1975, p. 585; Bouchard and Bouchard 1995, p. 8). Female Brawleys Fork crayfish also feature a prominent two-lobed swelling, a primitive characteristic of the reproductive structure that is only expressed by Brawleys Fork crayfish within *Cambarus* (Bouchard and Bouchard 1995, p. 8). The taxonomic status of the Brawleys Fork crayfish has not changed since its original description and there is no taxonomic uncertainty around the species.

2.2 Species Description

Brawleys Fork crayfish are markedly smaller than other *Cambarus* with individuals ≤ 2 years old having an average carapace length (CL) of 13–15 millimeters (mm) (0.5–0.6 inches (in)) (Bouchard and Bouchard 1995, p. 6; Giddens and Mattingly 2020, pp. 5–6). Reproductively mature form I males as small as 9.2 mm CL and reproductively mature females as small as 10.7 mm CL have been observed (Giddens and Mattingly 2020, p. 7). The species' coloration is variable with most individuals exhibiting a green to greenish-brown color, and some individuals occasionally exhibiting a blue or yellowish-green coloration during winter months (Figure 2.1 A, C, D) (Bouchard and Bouchard 1995, p. 6; Giddens and Mattingly 2020, pp. 9–10). Recently molted individuals may exhibit a slight reddish-orange coloration (Figure 2.1 B).

---

[1] The space between the two carapace plates of the exoskeleton

[2] Male reproductive structure

Figure 2.1: Brawleys Fork crayfish color morphs. Photo credit: Wesley Giddens, USFWS.

2.3 Life History

Timing of Reproductive Events

A recent life history study provides a detailed account of the timing of Brawleys Fork crayfish reproductive events (Figure 2.2) (Giddens and Mattingly 2020, entire). Form I (reproductive form) males are present throughout the year with the exception of the month of August, when form II (nonreproductive form) males are dominant until the occurrence of a widespread molting event between September and October (Giddens and Mattingly 2020, pp. 8–9). Females are ovigerous (egg-bearing) during the spring (March to June) and hatchlings develop during the spring and summer (May to June) (Giddens and Mattingly 2020, p. 8). Females exhibit glair (a cloudy adhesive substance appearing on the ventral surface of the abdomen) during the winter (November to February) and again in early spring (January to April) (Giddens and Mattingly 2020, p. 8). Potential copulation was observed in a pair of Brawleys Fork crayfish during June 2019; however, no other pairs have been observed exhibiting potential reproductive behavior (Giddens and Mattingly 2020, p. 9). Sex ratios remained at or near 1:1 Male:Female throughout a 12-month period; however, sampled sites had slightly more males from March to June and slightly more females during August, September, and December (Giddens and Mattingly 2020, pp. 6–7).

Brawleys Fork crayfish are reproductively mature within their first year (Giddens and Mattingly 2020, p. 7). This evolutionary adaptation is attributed to the species' occupancy of headwater streams, which frequently experience fluctuations in habitat structure (Giddens and Mattingly 2020, p. 7). Rapid development into reproductive maturity may increase species viability by allowing rapid reproduction and recruitment, thus increasing the likelihood of maintaining gene flow despite the occurrence of stochastic events (including low or high stream flows).

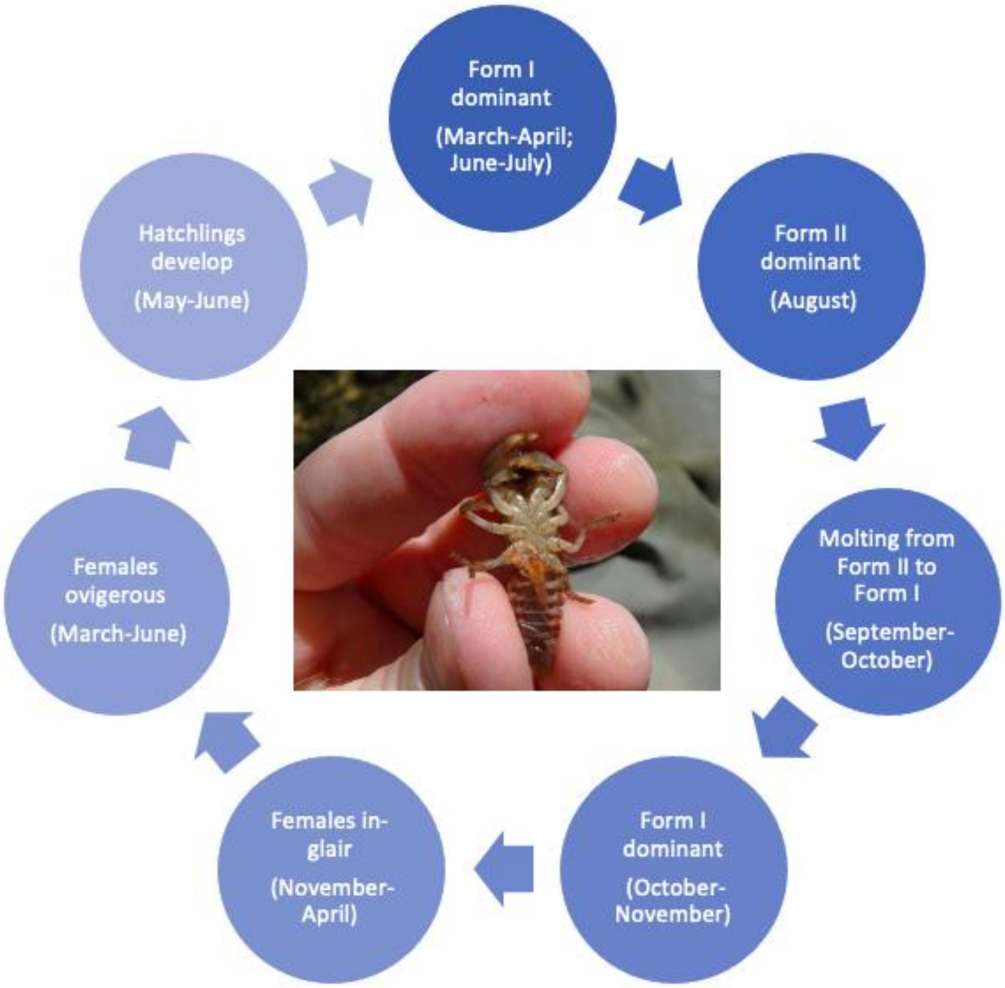


Figure 2.2: Brawleys Fork crayfish reproductive cycle. Image shows a female Brawleys Fork crayfish with a hatchling attached to abdomen. Photo credit: Wesley Giddens, USFWS.

Frequency of Molting

Molting (shedding of the exoskeleton) occurs throughout the year but peaks during October (Giddens and Mattingly 2020, p. 7), with at least 50% of individuals sampled recently molted during October (Giddens and Mattingly 2020, p. 7). Molting appeared to occur more frequently from October to April and less frequently from May to September (Giddens and Mattingly 2020, p. 7).

Age-Specific Growth Rate

Three age classes occurred in populations of Brawleys Fork crayfish sampled during a recent 12-month study in East Fork Stones River, Hollis Creek, and Mountain Creek (Appendix B; (Giddens and Mattingly 2020, p. 6). The youngest class experiences the most rapid growth rate, with little change in the oldest age class (age 2) (Table 2.1) (Giddens and Mattingly 2020, p. 6). The Brawleys Fork crayfish appears to have a lifespan of approximately three years (H. Mattingly 2021 pers. comm.).

Table 2.1: Brawleys Fork crayfish growth rates by age class.

Age Class	Lengths in November	Lengths in May
Youngest Class (age 0)	10–11 mm CL	13–14 mm CL
Intermediate Class (age 1)	16–17 mm CL	18–19 mm CL
Oldest Class (age 2)	21–22 mm CL	22–23 mm CL

2.4 Resource Needs and Habitat

Brawleys Fork crayfish primarily occurs in first- to third-order streams with fast to moderately rapid flow and frequently burrow into cherty[3] gravel substrate within the wetted stream channel (Figure 2.3; Bouchard and Bouchard 1995, p. 6; Giddens and Mattingly 2020, pp. 2–3; Williams et al. 2017, p. 51). The species also occurs in one fifth-order stream, the West Fork Stones River, in Rutherford County, Tennessee (J. Johansen 2021, pers. comm.). However, Brawleys Fork crayfish most often occupies first-, second-, and third-order streams (J. Johansen 2021, pers. comm.; H. Mattingly 2021, pers. comm.; J. Simmons 2021, pers. comm.; C. Williams 2021, pers. comm.;). Brawleys Fork crayfish occur in streams with fast to moderately rapid flow and thalweg depths ranging from 5–30 centimeters (cm) (2–12 in) (Withers and McCoy 2005, pp. 3, 27–48; Rohrbach and Withers 2006, p. 3; Williams et al. 2017, p. 51). Brawleys Fork crayfish typically occupy runs and riffles with moderate to fast flow and layered cherty gravel substrate with ample interstitial space not consolidated by finer substrates such as sand or silt (T. Khan, TTU, unpublished data). Streams with Brawleys Fork crayfish occurrence are characterized by water temperatures ranging from 10–23°Celsius (°C) (50–73 °Fahrenheit (°F) (Giddens and Mattingly 2020, pp. 4–5; J. Simmons 2021, pers. comm.). Ample riparian cover is an important habitat characteristic that creates shaded conditions and maintains a cooler water temperature required by the species. Riparian vegetation also buffers streams against pollutants carried by stormwater runoff. Brawleys Fork crayfish site occupancy is associated with a high volume of clean ground water discharged into the stream from subterranean aquifers (J. Simmons 2021, pers. comm.). The individual needs of Brawleys Fork crayfish are primarily a function of habitat condition and are summarized in Table 2.2.

[3] Fragments of small, fine-grained sedimentary rock

Figure 2.3: Example of Brawleys Fork crayfish habitat at Mountain Creek in Warren County, Tennessee. Photo credit: Wesley Giddens, USFWS.

Table 2.2: Individual level needs of Brawleys Fork crayfish.

Type of Requirement	Description
Stream Permanence	Permanent
Stream Order	First- to third-order streams
Water Temperature	10-23°C (50–73°F)
Stream Flow Velocity	Riffle and run habitats with fast to moderate flow
Stream Substrate	Cherty-gravel substrate with unconsolidated pieces of cobble and gravel
Embeddedness	Low embeddedness so that food and refugia under rocks and in crevices remain accessible
Refugia	Cavities and burrows within gravel
Diet	Likely smaller invertebrates, periphyton, and/or plant and detritus (specific diet unknown)

Population and Species Needs

At the population level, resilient Brawleys Fork crayfish populations need the same key habitat-based resources as individuals (Table 2.2), as well as a sustainable population size and connectivity within and among populations. At its most basic level, a population needs to reproduce and survive to replace lost individuals to maintain a sustainable population size. With a short-lived species such as Brawleys Fork crayfish, successful year class and recruitment of hatchlings to the adult population become increasingly important because a failed year class could quickly undermine population viability. Therefore, the population needs relatively stable conditions within the stream ecosystem each year, especially during the spring when females are ovigerous.

In general, larger, more connected populations will have increased opportunities for reproduction via emigration and immigration in order to maintain genetic diversity. To maintain gene flow, there needs to be some population connectivity to facilitate reproduction between different populations. For Brawleys Fork crayfish, maintaining gene flow within and among populations will be facilitated by maintaining suitable corridors for movement of individuals throughout the stream network, including road crossings that are designed to easily pass aquatic organisms at a range of streamflow conditions. Other potential barriers to individual movement and gene flow could be ameliorated by maintaining adequate temperatures, unembedded substrate, and good water quality conditions.

For species viability, there must be adequate redundancy (suitable number of populations, distribution of populations, and connectivity between populations allow the species to withstand catastrophic events) and representation (suitable genetic and environmental diversity to allow the species to adapt to changing environmental conditions). Redundancy improves with increasing numbers of populations at moderate and high resiliency conditions and connectivity among those populations to allow populations to “rescue” each other after catastrophic events. Representation improves with increased genetic diversity and environmental conditions within and among populations.

2.5 Range and Distribution

To determine the historical and current range of the Brawleys Fork crayfish, we reviewed all available occurrence data (1955–2020) associated with peer-reviewed research (Bouchard and Bouchard 1995), an interim research report (Giddens and Mattingly 2020), and State agency (TWRA, TDEC-Division of Natural Heritage) survey reports and data (Withers and McCoy 2005; Rohrbach and Withers 2006).

2.5.1 Historical Range and Distribution

Brawleys Fork crayfish was first collected from Brawleys Fork Creek, a tributary of the East Fork Stones River in Cannon County, Tennessee (Bouchard and Bouchard 1995, pp. 2, 7). The species’ historical range and distribution were considered to be restricted to the East Fork Stones River watershed (HUC 10) within the Eastern Highland Rim physiographic region (Figure 2.4) (Bouchard and Bouchard 1995, pp. 1–2, 6–7). The Highland Rim physiographic region is located in central Tennessee and surrounds the crater-like Nashville Basin physiographic region, extending north into Kentucky as well as south into Alabama (Etnier and Starnes 1993, p. 7). The region is primarily composed of limestone, chert, and shale and is characterized by a rich network of cave and spring systems that provide cold, clean groundwater input to various streams in the region (Etnier and Starnes 1993, p. 7). Streams within the Eastern Highland Rim physiographic region are characterized by coarse cherty-gravel and sand substrates with interspersed bedrock and moderate gradient (Etnier and Starnes 1993, p. 7).

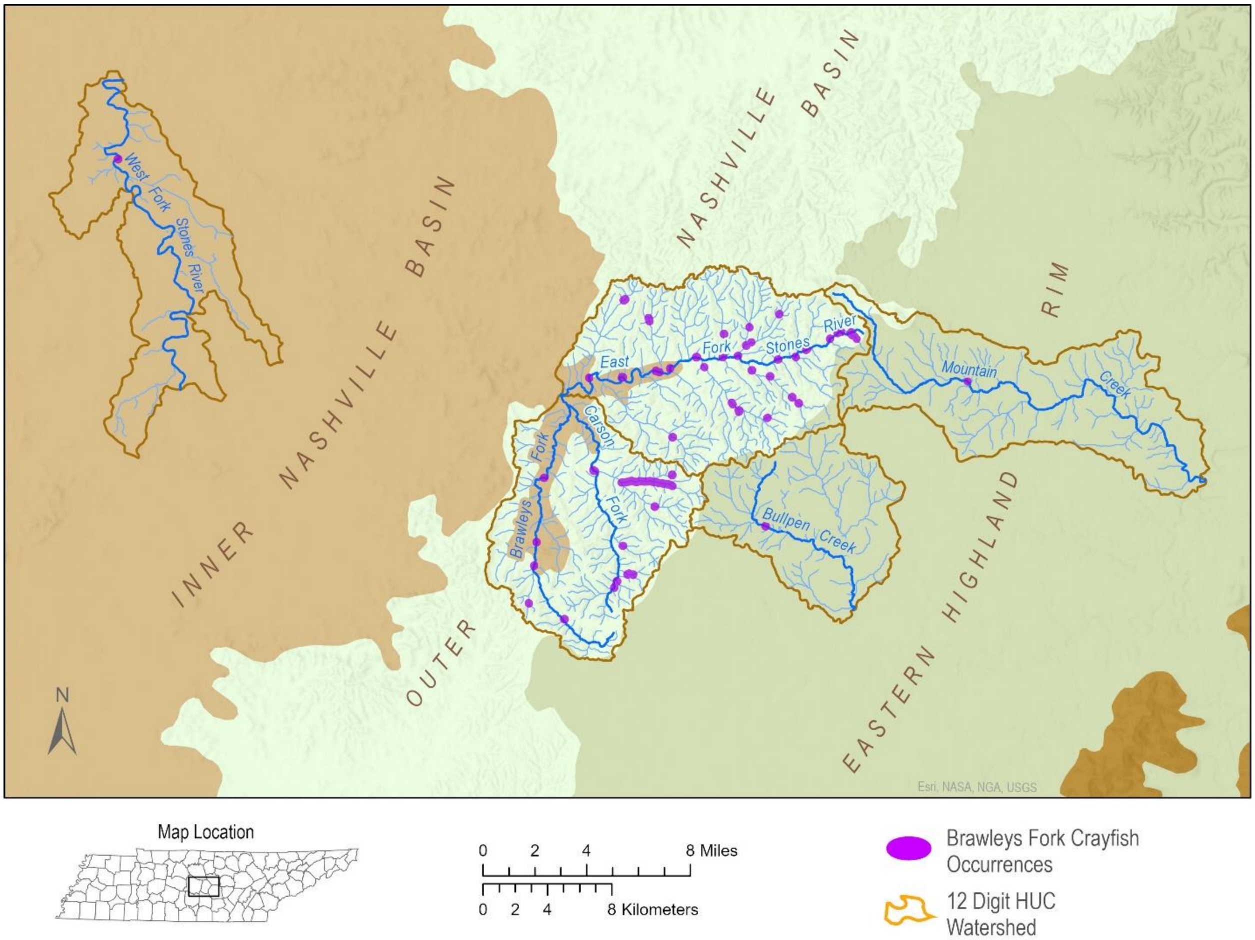


Figure 2.4: Brawleys Fork crayfish occurrences in HUC 12 watershed and EPA level IV ecoregions.

2.5.2 Current Range and Distribution

The Brawleys Fork crayfish's current known range has been expanded from the historical range to include the West Fork Stones River, Barren Fork, and Charles Creek-Collins watersheds (HUC 10) in Warren and Rutherford counties, Tennessee (Figure 2.5; Table 2.3) (Withers and McCoy 2005, pp. 26–48; Rohrbach and Withers 2006, p. 18; Williams et al. 2017, p. 51; Giddens and Mattingly 2020, pp. 2–3). Therefore, the species' current range now includes two river systems: the Stones (East Fork Stones River and West Fork Stones River) and Collins (Barren Fork and Charles Creek-Collins) river systems (HUC 8). Both the Stones and Collins rivers watersheds are partially located in the Eastern Highland Rim and Nashville Basin physiographic regions (Figure 2.4) (TDEC 2003a, p. 23; TDEC 2003b, p. 24).

In Mountain Creek in the Collins River watershed, first-order headwater reaches are primarily occupied by the hairy crayfish, a close congener, with a gradual increase in occupancy of Brawleys Fork crayfish moving into second- and third-order reaches downstream (J. Simmons 2021, pers. comm.). However, it is currently not well understood if niche differentiation between these two species is influenced by habitat preference, competition, or some other environmental or physiographic factor. Studies of this transitional relationship of occupancy may provide an estimation of the time required for species' divergence to occur, potential factors influencing

Brawleys Fork crayfish's limited distribution, as well as ecological relationships among other members of the genus.

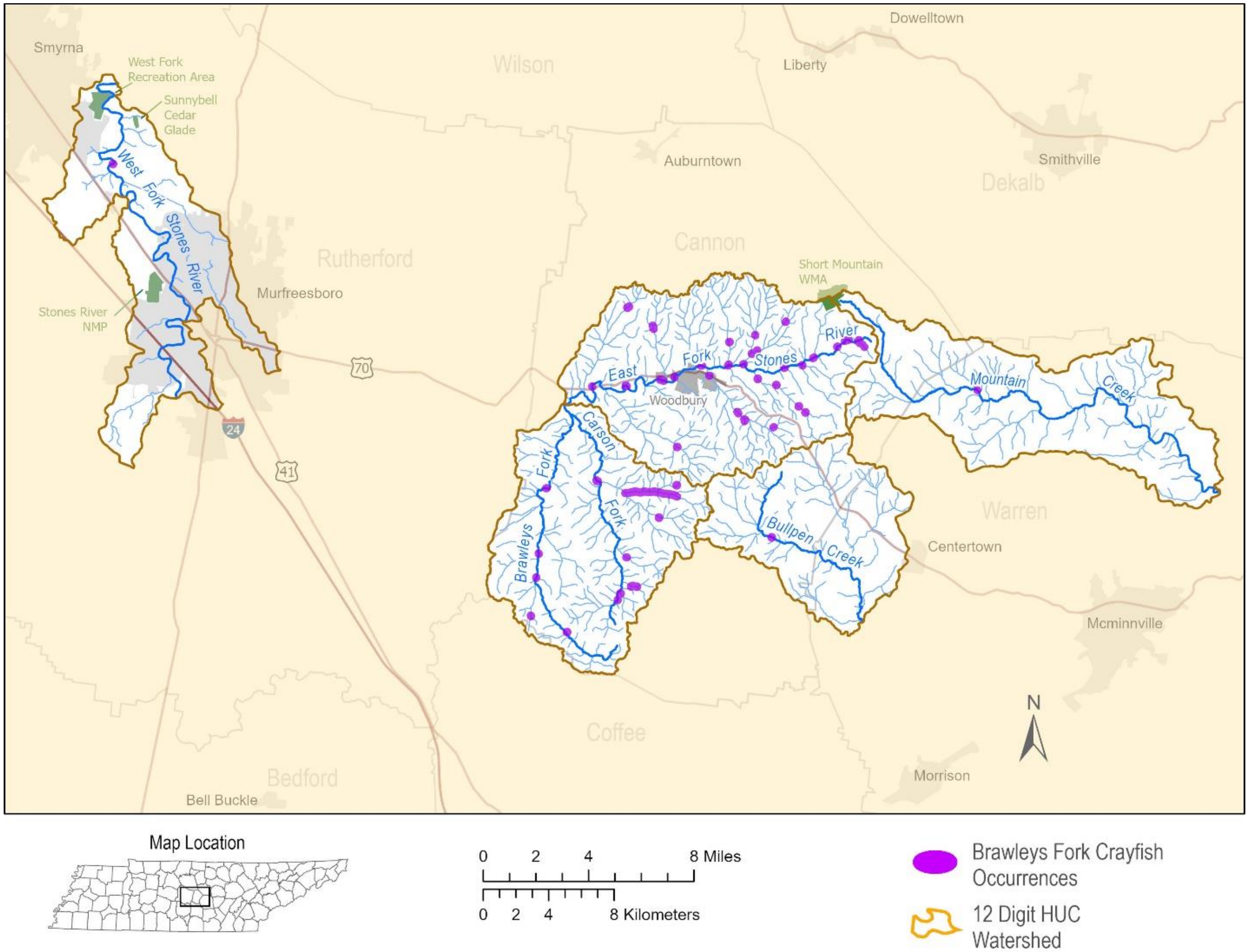


Figure 2.5: Range and distribution of Brawleys Fork crayfish occurrences in five HUC 12 watersheds.

Table 2.3: Brawleys Fork crayfish current range and distribution in occupied river systems (Hydrological Unit Code (HUC) 8), watershed (HUC 10), subwatershed (HUC 12), and streams.

River System (Hydrological Unit Code 8)	Watershed (Hydrological Unit Code 10)	Subwatershed (Hydrological Unit Code 12)	Stream
Stones River	East Fork Stones River	Hollis Creek – East Fork Stones River	East Fork Stones River
			Locke Creek
			Rush Creek
			Doolittle Branch
			Cavender Branch
			Rockhouse Creek
			Seal Hollow Branch
			Shanborne Branch
			Parchcorn Hollow Branch
			Hill Creek
			Hollis Creek
		Brawleys Fork	Brawleys Fork
			Carson Branch
			Duck Branch
			Smith Branch
			Shelton Branch
			Haws Spring Fork
	West Fork Stones River	Lower West Fork Stones River	West Fork Stones River
Collins River	Barren Fork	Bullpen Creek	Bullpen Creek
	Charles Creek - Collins	Mountain Creek	Mountain Creek

CHAPTER 3 - FACTORS INFLUENCING VIABILITY

The following discussion provides a summary of the factors that are affecting or may be affecting the current and future condition of the Brawleys Fork crayfish throughout some or all its range.

3.1 Sedimentation

Sedimentation of substrate and filling of interstitial spaces is considered to be the primary influence on Brawleys Fork crayfish viability. Crayfish are benthic (bottom-dwelling) macroinvertebrates that occupy the bottom of their associated stream or riverine habitat. The availability of unembedded rocks, crevices, and woody debris are essential to crayfish viability as they rely on these microhabitats for access to prey, refuge from predation and competition, as well as cover during vulnerable periods such as molting or egg extrusion. Brawleys Fork crayfish occurs primarily in lower-order headwater streams. Under base flow conditions, headwater streams typically do not have adequate velocity to dislodge and transport excess sediment further downstream. This results in sediment deposition that embeds resources (e.g., food, shelter, refugia) necessary to Brawleys Fork crayfish (Withers and McCoy 2005, p. 5; Rohrbach and Withers 2006, p. 8). Therefore, additional sediment input from a variety of sources overwhelms the system’s capacity to remove it (except during heavy rainfall events) and therefore negatively affects Brawleys Fork crayfish.

The specific diet of the Brawleys Fork crayfish is unknown, but crayfish are generally omnivores that feed on a variety of dietary resources such as smaller invertebrates, aquatic vegetation, as well as decaying plant and animal matter. When sedimentation occurs, these benthic food resources are buried under a layer of silt which blocks exposure to sunlight essentially suffocating these benthic organisms. This, in turn, leaves the crayfish with limited food resources and restricts the number of individuals that a given habitat can support.

The following sections describe the sources of sedimentation on the Brawleys Fork crayfish and its habitat as a result of current and historical surrounding land uses such as agriculture and horticulture, and as a result of small stream impoundment. Sedimentation is also related to water quality as sediment may carry pollutants into the stream and also cause the water to become cloudy with suspended solids, reducing light availability and causing aquatic plants to die. However, sedimentation has a direct effect on the physical availability of benthic resources (e.g., food, shelter, refugia, etc.), and we address the influence of sedimentation on Brawleys Fork crayfish viability separate from water quality.

3.1.1 Surrounding Land Use

Agriculture and Horticulture

The relatively flat terrain of the Eastern Highland Rim and Nashville Basin regions provide suitable land for agriculture and horticulture, particularly row crop, pasture, livestock grazing, and plant nurseries. Brawleys Fork crayfish density is strongly and positively correlated with the relative abundance of unconsolidated cobble and gravel substrates (Withers and McCoy 2005, p. 3; Rohrbach and Withers 2006, p. 3). Agricultural and horticultural practices influence Brawleys Fork crayfish viability by contributing to sedimentation within nearby streams. Practices that contribute to sedimentation include the exposure of loose soil following crop harvest and the use of heavy machinery that disturbs soil composition and breaks down sediments into fine particles (Burskey and Simon 2009, p. 207). Heavy machinery entering the stream channel via the stream bank contributes sediment and modifies the channel structure (Schmidt 1982, p. 39). Sedimentation from nearby agricultural and horticultural practices embeds preferred cover habitat and cobble substrate, reducing Brawleys Fork crayfish access to required resources (e.g., food, shelter, refugia, etc.), in turn decreasing the species' likelihood of withstanding future stochastic events.

3.1.2 Stream Impoundment

Sedimentation is considered to be the most significant influence on freshwater habitat quality in relation to small stream impoundment (Arnwine et al. 2006, p. 3). Eighty percent of small streams in headwater areas surveyed by the Tennessee Department of Environment and Conservation - Division of Water Pollution Control failed to meet regional habitat quality expectations as a result of sediment deposition below small dams (Arnwine et al. 2006, p. 3). Decreased flow velocity associated with stream impoundment has been shown to result in fine sediment accumulation leading to subsequent substrate embeddedness, decreased woody debris availability, and more severely entrenched stream channels, and increased water temperature, potentially eliminating the majority of Brawleys Fork crayfish required resources (Adams 2013, p. 1328; Arnwine et al. 2006, p. 3; Barnett and Adams 2021, p. 3; C. Williams, TWRA, pers. comm. 2021). Additionally, surveys of impounded and unimpounded streams within the Eastern Highland Rim and Outer Nashville Basin ecoregions (EPA Level IV) demonstrated a lower percentage of dominant cobble substrate in impounded streams compared to unimpounded streams (Arnwine et al. 2006, p. 62). The percentage of small impoundments (<250 acres) within Brawleys Fork crayfish distribution is relatively low in comparison to other watersheds within the state of Tennessee with 0.6% of the state's small impoundments located in the Stones watershed and 1.7% located in the Collins watershed (Arnwine et al. 2006, p. 9-14). However, future residential development within the East Fork and West Fork Stones river watersheds may be associated with construction of new small impoundments and may influence Brawleys Fork crayfish's ability to withstand future stochastic events as a result of increased sedimentation associated with stream impoundment (Withers and McCoy 2005, p. 5; Rohrbach and Withers 2006, p. 8).

3.2 Water Quality

Suitable water quality is a requirement for most freshwater species, including the Brawleys Fork crayfish. Although little is known regarding the Brawleys Fork crayfish's specific water quality requirements, water quality parameters such as water temperature, nutrient load, pH, and conductivity (the ability of water to pass an electrical current in relation to the concentration of inorganic ions in the water) are significant factors influencing several biological processes of crayfish including osmoregulation, immunology, acid/base regulation, gas exchange, reproduction, molting, growth rate, and behavior (Schorr et al. 2013, p. 340; Romano and Zeng 2013, p. 17). In the sections that follow, we will describe the influence of water quality alteration on the Brawleys Fork crayfish as a result of historical and current surrounding land uses.

3.2.1 Surrounding Land Use

Agriculture and Horticulture

Agricultural and horticultural practices influence water quality by means of stormwater runoff that transports pesticides, herbicides, fertilizers, and livestock waste into nearby streams. Stormwater runoff from agricultural fields during planting season (spring and early summer) is the most significant source of water quality contamination and causes deleterious effects on crayfish behavior (Sohn et al. 2018, pp. 900, 905). For example, one common grub control product contains imidacloprid, clothianidin, and thiamethoxam. Crayfish in the genus *Orconectes* become less responsive to threat stimuli after exposure to the pesticide imidacloprid at low concentrations (1 $\mu g{\cdot}L^{-1}$) and individuals exposed to the highest concentration (100 $\mu g{\cdot}L^{-1}$) become fully unresponsive, with stiff body posture and unable to right themselves (Sohn et al. 2018, p. 905). In other studies, *Orconectes* crayfish became less responsive to threat stimuli after exposure to clothianidin at concentrations greater than 50 $\mu g{\cdot}L^{-1}$, and *Procambarus* crayfish showed increased aggression after exposure to concentrations of thiamethoxam above 500 $\mu g{\cdot}L^{-1}$ (Sohn et al. 2018, p. 905). Though the effects of sublethal pesticide exposure specific to the Brawleys Fork crayfish are unknown, the potential exists for pesticide contamination to have similar influences on the species. Brawleys Fork crayfish that exhibit a similar response to *Orconectes* crayfish would have a greater risk of predation under a state of decreased reactivity. However, it is important to consider that the severity of behavioral changes observed may vary between crayfish species, type of pesticide, as well as pesticide concentration (Sohn et al. 2018, p. 905). We are unable to estimate the amount and diversity of pesticide use within the Brawleys Fork crayfish's range or the level of pesticide in streams with Brawleys Fork crayfish occurrence. However, certain locations within the species' range are exposed to pesticides on an ongoing basis. For example, the life history study site at Mountain Creek (Giddens and Mattingly 2021, entire) regularly receives pesticide applications to the surrounding horticultural lands and some of these chemicals presumably enter the stream itself (H. Mattingly, TTU, pers. comm. 2021).

Stormwater runoff from agricultural and horticultural practices also contributes to increased nutrient loads within nearby streams as a result of fertilizers and livestock waste transported into the streams. Nitrogen loading has several deleterious effects on crustaceans: inhibition of growth rate, reduced osmoregulation, reduced immunological capacity, altered acid/base regulation, and reduced gas exchange (Romano and Zeng 2013, p. 17). In addition, suitable habitat may become stagnant and eutrophied[4] (oxygen depleted) as a result of livestock having direct access to the stream (Rorhbach and Withers 2006, p. 8; Withers and McCoy 2005, p. 5). Brawleys Fork crayfish affected by stunted, inefficient biological processes would experience an overall decrease in fitness and would be less likely to successfully mature and reproduce, leading to decreased population abundance.

3.2.2 Sewage Treatment Outfall

Historically, the Woodbury municipal sewage treatment plant has contributed to increased nutrient loads in the East Fork Stones River (Schmidt 1982, pp. 26, 50). The occurrence of several fish kills in the East Fork Stones River has been attributed to effluent released from the facility with one recorded event impacting nearly four miles of river (Schmidt 1982, pp. 26, 30, 33). However, other manufacturing and processing facilities in Woodbury were also potential contributors to the influx of organic waste entering the river (Schmidt 1982, p. 33). Benthic macroinvertebrate survey results showed communities immediately downstream of the Woodbury sewage treatment plant were under much greater stress than communities located upstream, as well as those located farther downstream (Schmidt 1982, pp. 49–50).

Additionally, pharmaceuticals have been recently been detected in the surface water of the East Fork Stones River (Kaur et al. 2020, entire). Sewage treatment plants are the primary pathway for the entry of pharmaceuticals into bodies of water as sewage treatment plants are not engineered to remove non-biodegradable contaminants from sewage and lack the infrastructure to detect the presence of such contaminants in treated water (Kaur et al. 2020, pp. 241– 242). Although the specific effects of pharmaceutical contamination on the Brawleys Fork crayfish is unknown, contamination often influences the feminization or masculinization of exposed aquatic organisms (Kaur et al. 2020. p. 241). Therefore, pharmaceutical contamination could influence reproductive behavior or reproductive success exhibited by the Brawleys Fork crayfish.

The effects of excessive nutrients and nutrient loading on crayfish molting and growth rate is described in *3.2.1 Surrounding Land Use* and eutrophication as a result of excess nutrients may influence Brawleys Fork crayfish viability through effects to molting, respiration, disease resistance, and also disruption of reproductive behaviors (Schorr et al. 2013, p. 340; Romano and Zeng 2013, p. 17).

---

[4] Eutrophication occurs as a result of excess nutrients entering the stream, causing dense algal growth that depletes oxygen in the water and leads to mortality of other aquatic organisms

3.3 Stream Modification

Brawleys Fork crayfish occurs in shallow runs, riffles, and pools in first- to fifth-order streams with thalweg depths of 5–30 cm (3–11.8 in) and fast to moderately rapid flow (Bouchard and Bouchard 1995, p. 6; Rohrbach and Withers 2006, p. 3; Williams et al. 2017, p. 51; Withers and McCoy 2005, p. 3; Giddens and Mattingly 2020, p. 2–3). Stream modification or stream impoundment may significantly influence Brawleys Fork crayfish site occupancy through altered stream depth and flow. For example, Mountain Creek, East Fork Stones River, and Hollis Creek study sites (Giddens and Mattingly 2021, entire) have experienced significant disturbance and modification including heavy machinery directly entering the stream channel to dredge gravel, modify stream banks, and alter the stream channel (Figure 3.1) (H. Mattingly, TTU, pers. comm. 2021).

In addition to the effects of sedimentation associated with stream impoundment described in *3.1.2 Stream Impoundment*, changes to stream depth, flow, and water temperature associated with stream impoundments and barriers may influence Brawleys Fork crayfish resiliency. Altered stream depth and subsequent habitat change due to impoundment (e.g., increased temperature and decreased flow) may significantly alter the structure of crayfish assemblage downstream of the impoundment (Adams 2013, p. 1325; Hartfield 2010, pp. 25, 43). Stream impoundment also influences downstream water temperature, with elevated water temperature in below-dam reaches (Adams 2013, p. 1328; Arnwine et al. 2006, p. 152; Barnett and Adams 2021, pp. 2, 4). The average upper temperature tolerance of freshwater crayfish is 33.4°C (92.1°F) with variability in species-specific temperature tolerance among genera (Westhoff and Rosenberger 2016, pp. 339, 341). Therefore, changes to stream depth, flow, and temperature caused by stream impoundment may negatively influence Brawleys Fork crayfish site occupancy and impair the ability of affected populations to withstand future stochastic events. At Mountain Creek, for example, recreational visitors built rock dams by hand that resulted in local alteration of flows, depths, and siltation of substrate particles that could negatively impact Brawleys Fork crayfish (H. Mattingly, TTU, pers. comm. 2021).

Figure 3.1: Altered stream channel structure due to gravel dredging at Mountain Creek in Warren County, TN. Photo credit: Wesley Giddens, USFWS

3.4 Climate Change

Climate change refers to the various changes in global and regional climate patterns, typically spanning over several decades, as a result of natural climate change processes, human activity (such as the burning of fossil fuels), or a combination of both. The influence of human activity on climate change has become increasingly evident since the beginning of the 20th century as global temperatures continue to rise and stochastic events such as storms, floods, drought, and wildfires become more frequent and severe. From 1880 to 2012, global surface temperatures increased by more than 0.85°C (1.53°F) and are expected to continue to increase by 1.5–5.8°C (2.7–10.44°F) by 2100 (Nissenbaum 2016, pp. 4–5; Poff et al. 2002, p. 2). This projected increase in global surface temperatures will likely alter precipitation patterns, subsequently altering hydrologic regimes as well. However, the specific patterns that may manifest are less certain and more difficult to predict, with uncertainty increasing as we project further in the future. The frequency, duration, and severity of precipitation may vary on both a spatial and temporal scale as some regions may experience more or less precipitation than other regions, and some calendar years may experience more or less precipitation that other calendar years. Because of this, it is important to consider a range of circumstances in which the average amount of precipitation in the southeastern United States may increase or decrease, and how each circumstance could influence the viability of the Brawleys Fork crayfish.

Increased precipitation scenario

Average global precipitation has been projected to increase up to 7% by the end of the 21st century (Nissenbaum 2016, p. 6). This projection, combined with the prediction that existing wet regions will experience the greatest increase in precipitation, is relevant to the southeastern United States' wet and humid subtropical climate (Nissenbaum 2016, pp. 6–7). Within the range of Brawleys Fork crayfish, Cannon, Rutherford, and Warren counties, Tennessee, commonly experienced above-average annual rainfall from 2010–2020 with Warren County receiving more than 20 inches of precipitation above the annual average in 2020 (Figures 3.2–3.4) (Climate Explorer 2021). An increase in the frequency, duration, and severity of rain events may influence the Brawleys Fork crayfish through increased sedimentation and degraded water quality as a result of heavier stormwater runoff transporting a heavier load of sediment, pollutants, and nutrients into streams (Poff et al. 2002, p. 12). Additionally, more frequent and heavier rain events would also likely result in more frequent and intense flooding (Lockaby et al. 2013, p. 310). Flooding has the potential to modify the stream channel as higher volumes of water with increased velocity scour the streambed and stream banks, altering the depth, width, and substrate composition of the stream (Poff et al. 2002, p. 12). As described in *3.3 Stream Modification*, changes in depth and velocity influence Brawleys Fork crayfish habitat and site occupancy by changing the structure of shallow streams where Brawleys Fork crayfish occurs (Bouchard and Bouchard 1995, p. 6; Rohrbach and Withers 2006, p. 3; Williams et al. 2017, p. 51; Withers and McCoy 2005, p. 3; Giddens and Mattingly 2020, p. 2–3). Displacement of preferred substrate by higher water flows negatively influences Brawleys Fork crayfish site occupancy as the species typically inhabits streams with cherty gravel substrate that could be displaced downstream. Furthermore, individual crayfish could also be displaced downstream in the event of a flood resulting in altered crayfish assemblages in terms of both species composition and abundance. If members of upstream Brawleys Fork crayfish populations are moved and establish downstream populations in suitable habitat, gene flow would be facilitated. However, if flooding also transports sediment and pollutants downstream, the negative influences of habitat degradation could offset the potential positive influence of increased gene flow from individuals transported downstream. Severe flooding events could also result in direct mortality, with increased mortality expected as severe flooding becomes more frequent as a result of heavier and more frequent rain events due to climate change.

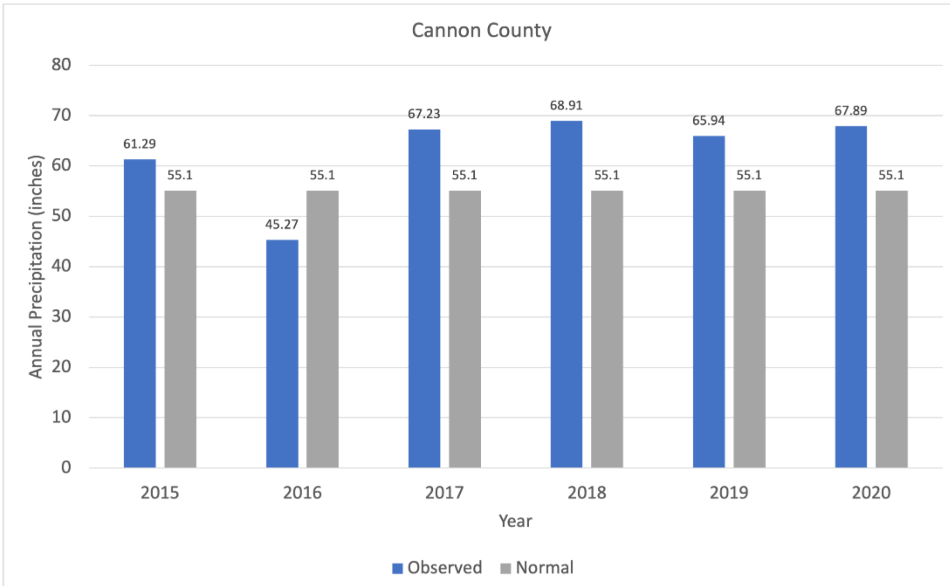


Figure 3.2: Observed and normal annual precipitation (inches) in Cannon County, Tennessee from 2015–2020.

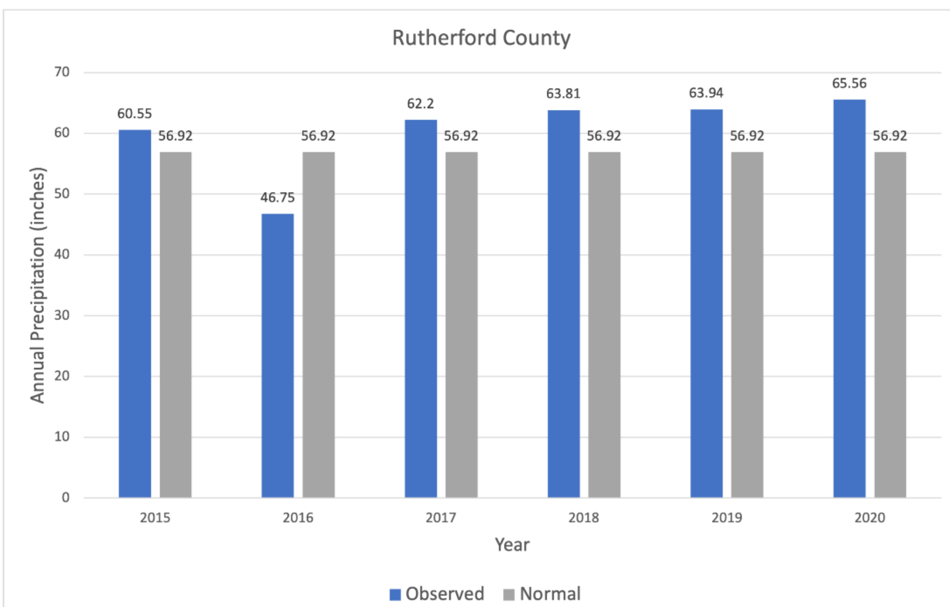


Figure 3.3: Observed and normal annual precipitation (inches) in Rutherford County, Tennessee from 2015–2020.

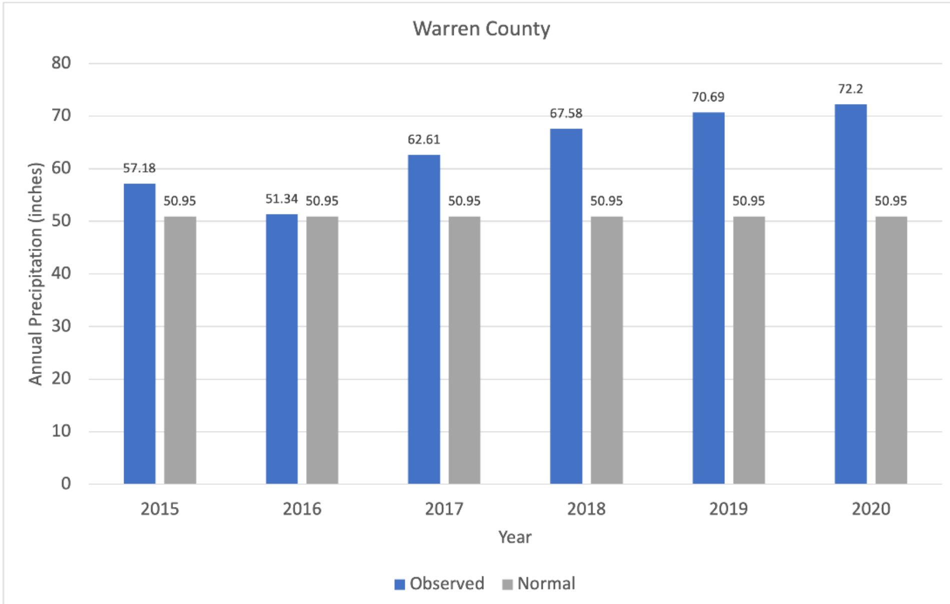


Figure 3.4: Observed and normal annual precipitation (inches) in Warren County, Tennessee from 2015–2020.

Decreased precipitation scenario

Changes in global precipitation patterns as a result of climate change may decrease the amount of precipitation in various regions of the southeastern United States. A study that modeled the effects of climate change on summertime precipitation in the Southeast reported that precipitation decreased over the majority of the Ohio Valley, which is in the general geographic range of Brawleys Fork crayfish (Nissenbaum 2016, p. 33). Precipitation may decrease or become more inconsistent within the Brawleys Fork crayfish's range. The combination of higher temperatures and decreased precipitation could ultimately result in more frequent and prolonged drought. Since the 1970s, moderate to severe droughts in the Southeast have increased by 12% during spring months and by 14% during summer months (Jones et al. 2015, p. 126). An increase in the frequency and severity of droughts could result in streams becoming shallower or eventually dry due to increased evapotranspiration if not counteracted by rainfall and groundwater recharge (Lockaby et al. 2013, p. 310). Lower-order (typically shallower) streams are particularly vulnerable to low flow and subsequent drying which could influence the Brawleys Fork crayfish by decreasing the amount of available habitat, in turn increasing predation and competition and reducing prey items and shelter and refugia sites. These factors, along with the possibility of desiccation, could ultimately result in increased mortality and subsequent local extirpation. However, it is important to consider adaptive strategies exhibited by the Brawleys Fork crayfish during periods of prolonged drought. During dry periods, the species burrows deeper into the streambed, thereby accessing subterranean water (J. Simmons, TVA, pers. comm. 2021; C. Williams, TWRA, pers. comm. 2021). This behavior is advantageous for the Brawleys Fork crayfish as other species that are not as well adapted for burrowing could have a greater risk of mortality in dry periods.

Higher temperatures and lower flow due to decreased precipitation could also result in warmer water temperatures, particularly in lower order streams, which may influence the Brawleys Fork crayfish growth and reproduction. Temperature tolerances of the Brawleys Fork crayfish are unknown. Life stage development of several aquatic organisms, including crayfish, is temperature-dependent and an in increase in water temperature could result in changes to growth rates, reproduction, as well as overall survival (Poff et al. 2002, p. 7). A higher rate of microbial activity is associated with warmer water temperatures, leading to an increased rate of organic material decomposition and nutrient loading within streams (Poff et al. 2002, p. 7). Other crayfish species occupying downstream reaches may migrate upstream to cooler headwater habitats in response to warmer water temperatures if suitable habitat is available (Poff et al. 2002, p. 8). The Brawleys Fork crayfish is a headwater-adapted species, and the potential invasion of downstream species into headwater reaches occupied by Brawleys Fork crayfish could result in increased competition and in some circumstances local extirpation of Brawleys Fork crayfish.

3.5 Urbanization and Development

Urbanization and development refer to all forms of commercial and residential development such as the expansion of metropolitan areas, urban and rural residential community development, as well as associated road construction and commercial development within those communities. Over the past 60 years the southeastern United States has experienced urban growth nearly 40% greater than that of the rest of the country (Terando et al. 2014, p. 2). Within the range of Brawleys Fork crayfish, Rutherford County, Tennessee, experienced a 122% increase in population size from 1990 to 2010 and an additional 32% increase from 2010 to 2020 (World Population Review 2021). Similar growth patterns have been observed for Cannon and Warren counties, though less extreme (World Population Review 2021). In the future, urbanization in the Southeast is projected to increase by up to 192% by 2060. Furthermore, the greatest change in land use is expected to be the conversion of agricultural land into urban land use with up to 20% of agricultural land lost to urbanization (Terando et al. 2014, p. 5). Streams in the Southeast experience significant impacts to water quality when urban land use reaches 10–14% of the area (Suttles et al. 2018, p. 813). Because Brawleys Fork crayfish occurs in a region of heavy agricultural land use, the species is especially vulnerable to future urban growth. Therefore, if urbanization and development within the Brawley Forks crayfish's range increase as projected, the subsequent ecological impacts of urbanization will influence the Brawleys Fork crayfish's ability to persist into the future.

Urban development can alter atmospheric and hydrologic patterns in a number of ways. The reduction of green space and consolidation of human activity emitting CO_2 into the atmosphere can result in the development of "urban heat islands" that have higher air and water temperatures than surrounding areas. These differences in temperatures can alter wind, rain, and hydrologic patterns which could in turn impact aquatic ecosystems as described in *3.4 Climate Change* (Martin et al. 2017, p. 2). An increase in impervious surfaces associated with urban land use directly results in a higher volume of stormwater runoff with higher velocity discharged into streams. Hydrological alterations due to increased high-velocity runoff can result in the scouring of streambeds and stream banks of lower-order streams similar to the effects of flooding (Lockaby et al. 2013, p. 333). Receiving streams could also experience spikes in water temperature as stormwater runoff flowing over warm impervious surfaces is warmed and may negatively influencing the Brawleys Fork crayfish as described in *3.4 Climate Change*. Furthermore, an increase in the volume and velocity of stormwater runoff due to urbanization can in turn result in an increased amount of sediment and pollutants discharged into receiving streams. Under such circumstances, Brawleys Fork crayfish viability may be negatively influenced due to degradation of habitat quality and availability, and subsequent changes to biological processes such as the frequency of competition and predation.

3.6 Fragmentation and Population Isolation

The Brawleys Fork crayfish's limited range and fragmented distribution, coupled with small population sizes in certain streams such as Bullpen Creek, are factors influencing population resiliency. Small population size along with population isolation often leads to reduced genetic diversity as a result of inbreeding, in turn resulting in increased susceptibility to disease and parasites, reduced reproductive fitness, reduced evolutionary potential, and reduction in the overall ability to withstand stochastic events (Frankham 1995, p. 309; Frankham 2005, pp. 132–135; Grubb 2019, p. 29; Johansen 2018, p. 38). These deleterious effects associated with small population size can exacerbate the negative influences of habitat degradation caused by other sources as described in sections 3.1–3.5. However, there is no genetic information available to suggest that small population is currently influencing Brawleys Fork crayfish viability. Genetic analyses of isolated populations including West Fork Stones River, Mountain Creek, and Bullpen Creek are recommended to determine genetic variability and the potential for inbreeding depression.

3.7 Conservation Actions

3.7.1 *State Protections*

Brawleys Fork crayfish is globally ranked as a G2 species (imperiled globally; 6–20 occurrences worldwide) and state ranked as an S2 species (imperiled within state; 6–20 occurrences statewide) (TN-SWAP 2015, p. 26). The species is protected under State regulations with endangered status by the State of Tennessee under the provisions of the state's wildlife code. As noted by TWRA, "The Tennessee Nongame and Endangered or Threatened Wildlife Species Conservation Act of 1974 (Tennessee Code Annotated, Section 70-8-101-112) states that it is unlawful for any person to take, attempt to take, possess, transport, export, process, sell or offer for sale, or ship nongame wildlife, or for any common or contract carrier knowingly to transport or receive for shipment nongame wildlife. Violation constitutes a Class B misdemeanor and incurs warrantless searches and seizure of the wildlife taken and the instrumentalities used in the taking. A list of Tennessee's Threatened and Endangered Species and Species Deemed in Need of Management appear in Rule 1660-01-32.01-.03." (TWRA 2018, pp. 3–4).

In addition to State protections by regulations, Brawleys Fork crayfish is considered a Tier 1 Species of Greatest Conservation Need (SGCN) in Tennessee's State Wildlife Action Plan (TN-SWAP 2015, Appendix C, p. 255). Tier 1 species are defined as "wildlife under Tennessee Code Annotated 70-8-101, (i.e., amphibians, birds, fish, mammals, reptiles, crustaceans & mollusks), excluding federally listed and game species" (TN-SWAP 2015, p. 29). Key goals of TN-SWAP are to develop and implement conservation strategies and prioritize funding for conservation projects to protect SGCN species and their habitats.

3.7.2 The Clean Water Act

The Clean Water Act of 1972 (33 U.S.C. §1251) provides some protections to the habitat where Brawleys Fork crayfish occurs. Section 404 of the Clean Water Act requires a Department of the Army permit to discharge dredge or fill material in "waters of the United States" including areas below the ordinary high-water mark in navigable waters and tributaries to those waters. Streams and rivers where Brawleys Fork crayfish occur are likely to be considered jurisdictional under the current Environmental Protection Agency and Department of the Army definition of waters of the United States. The U.S. District Court for the District of Arizona's August 30, 2021, order vacated and remanded the Navigable Waters Protection Rule of June 20, 2020 (85 FR 22250). Federal agencies (Environmental Protection Agency and Corps of Engineers are interpreting "waters of the United States" consistent with the pre-2015 regulatory regime until further notice. Applicants for a section 404 permit must show that steps have been taken to avoid and minimize impacts to wetlands, streams, and other aquatic resources, and that compensation will be provided for all remaining unavoidable impacts. Specific surveys for Brawleys Fork crayfish are not required and compensation may not occur in suitable Brawleys Fork crayfish habitat. State-level regulation of water quality occurs through the Tennessee Department of Environment and Conservation (TDEC), whereby laws such as Tennessee's Water Quality Control Act 0f 1977 (T.C.A. 69–3–101) are enforced. TDEC personnel also monitor water quality in surface waters throughout the state, including watersheds within the Brawleys Fork crayfish's range.

3.8 Synergistic Effects

Due to the complexity of freshwater ecosystems, any single factor influencing Brawleys Fork crayfish viability often impacts the species in a variety of ways (Figure 3.5). The interconnectedness of these influences and their ecological impacts create complex cumulative effects on Brawleys Fork crayfish viability. For example, agriculture is often associated with subsequent stream impoundment that creates reservoirs for livestock or crop irrigation. Similarly, urban growth may also lead to subsequent stream impoundment to establish drinking water or wastewater treatment infrastructure. Therefore, we expect an increase in agriculture or urban growth to be associated with an increase in stream impoundment. Furthermore, warmer temperatures and more frequent and/or severe drought associated with climate change could lead to decreased water availability. As a result, water withdrawal from nearby streams would likely increase in order to support crop irrigation and/or drinking water demands. Additionally, urbanization can also exacerbate drought conditions by channeling stormwater runoff from impervious surfaces into ditches and drains that directly flow into sewer lines and/or larger-order streams, thereby decreasing the amount of water available for groundwater recharge to headwater streams. Without adequate groundwater recharge, lower-order streams such as those occupied by the Brawleys Fork crayfish are especially susceptible to going dry in the event of severe drought. Reduced groundwater recharge would also adversely affect Brawleys Fork crayfish by decreasing the availability of subterranean water which the species may use as refuge during periods of drought. Lastly, small, isolated populations are most vulnerable to the effects of human activity and climate change as they often are not large enough to withstand stochastic events and maintain reproductive success and gene flow. The Brawleys Fork crayfish's small population size in certain streams such as Bullpen Creek exacerbates the effects of other threats to the species. Therefore, we consider the cumulative impact of all the potential influences on Brawleys Fork crayfish viability when assessing the future condition of the species.

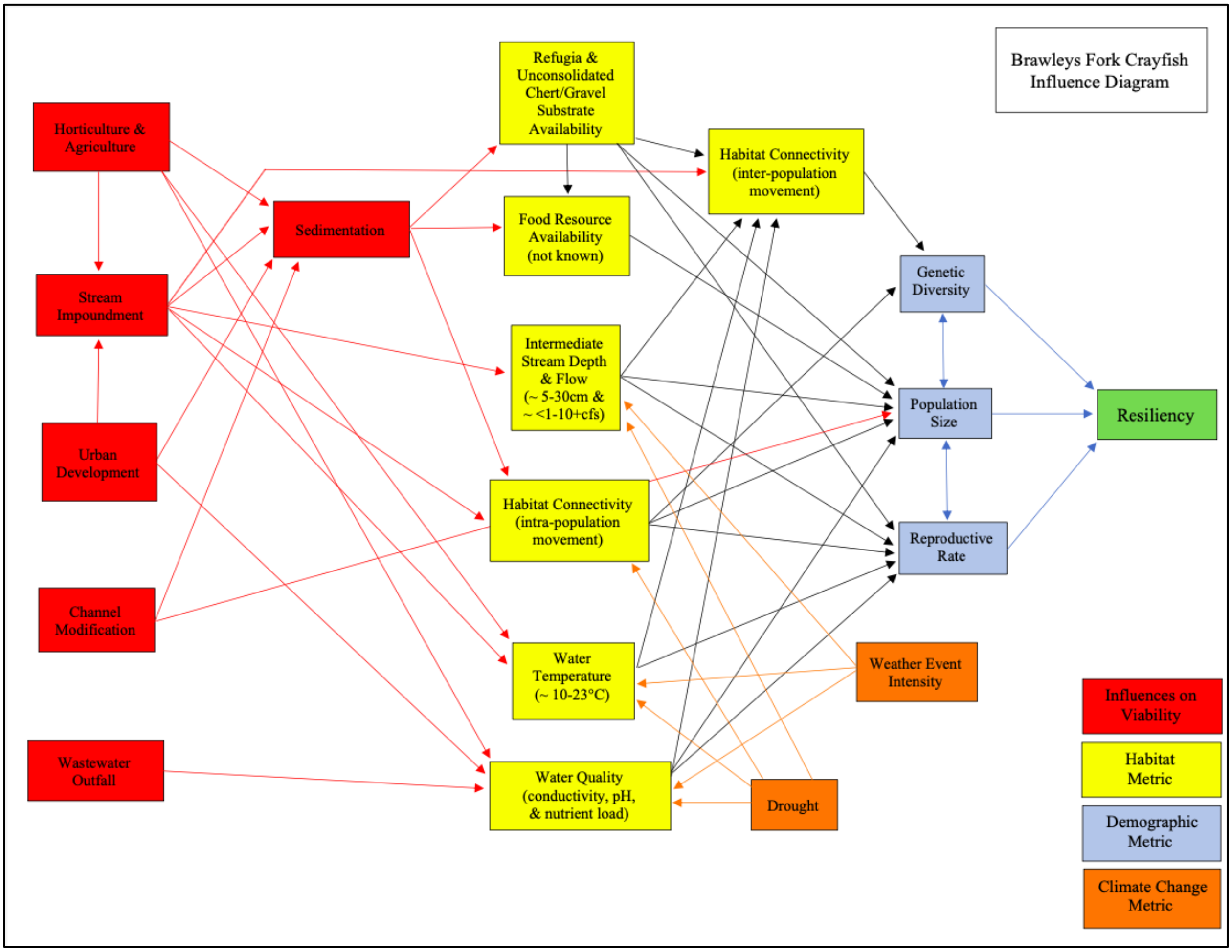


Figure 3.5: Influence diagram for Brawleys Fork crayfish.

3.9 Summary of Factors Influencing Viability

The primary factor influencing viability of the Brawleys Fork crayfish is sedimentation. Sedimentation leads to benthic resources, such as refugia and food, becoming embedded and inaccessible to the Brawleys Fork crayfish resulting in decreased reproductive success, increased competition and predation, and increased mortality. There are several potential sources contributing to sedimentation including agricultural and horticultural practices, gravel dredging, channel alteration, stream impoundment, and urban growth. In addition to sedimentation, each of these sources also contributes to habitat degradation as a result degraded water quality or channel modification. Each factor influencing Brawleys Fork crayfish viability may be further exacerbated by the effects of climate change and urban growth. Therefore, our assessment of current and future conditions will consider each influence individually and the cumulative impact of these influences on Brawleys Fork crayfish resiliency as it relates to species' viability.

CHAPTER 4 - CURRENT CONDITION

In this chapter, we assess and describe the current condition and viability of the Brawleys Fork crayfish. We first define analysis units for the species. Next, we characterize the needs of the species in terms of population resiliency and species' representation and redundancy (the 3Rs). Finally, we estimate the current condition of Brawleys Fork crayfish using population and habitat metrics to characterize the 3Rs.

4.1 Delineating Populations

We delineated populations using spatial occurrence data (1955–2020) from peer-reviewed research (Bouchard and Bouchard 1995), an interim research report (Giddens and Mattingly 2020), and State agency (TDEC) survey reports (Withers and McCoy 2005; Rohrbach and Withers 2006). We determined analysis units (AUs) at a scale useful for assessing the species condition. We proposed these divisions based on our knowledge of the species' current and historical distribution in the Stones and Collins rivers systems, and the level of current geographic isolation observed among tributary systems. We determined AUs based on subwatershed (HUC 12) assessment of the occurrences and threats to the species at a biologically meaningful level. Therefore, we have delineated five Brawleys Fork crayfish AUs across the range of the species including 20 streams with records of Brawleys Fork crayfish occurrence (Figure 2.5, Table 2.3).

4.2 Methods for Estimating Current Condition

Using the SSA framework, we used resiliency, representation, and redundancy (the 3Rs) to qualitatively assess the viability of Brawleys Fork crayfish. We described species-specific viability as the ability of the species to sustain populations in occupied streams and rivers in relation to habitat needs such as the availability of unembedded cherty gravel and cobble substrate with ample interstitial space free of finer substrates (sand or silt) within areas of fast to moderate flow. For this assessment, we described the current condition of the species and predicted a range of plausible future scenarios and future conditions (Chapter 5) using the 3Rs.

4.2.1 Population Resiliency

Resilient populations of Brawleys Fork crayfish should be robust to normal stochastic events or disturbances. However, influences contributing to habitat quality and water quality degradation described in *Chapter 3 Factors Influencing Viability* may exacerbate the impacts of stochastic events and affect population resiliency. With these factors in consideration, we assessed the resilience of each Brawleys Fork crayfish AU by synthesizing the best available information about habitat condition and population demographics from survey data as well as studies pertaining to Brawleys Fork crayfish life history (Withers and McCoy 2005, entire; Rohrbach and Withers 2006, entire; Giddens and Mattingly 2020, entire).

We considered Brawleys Fork crayfish individual and population needs, such as the availability of unembedded cherty gravel and cobble substrate within areas of fast to moderate flow, adequate water quality, as well as appropriate population size and connectivity to support reproduction and recruitment within an AU. We developed an approach using key habitat and demographic parameters to assess population resiliency. These included three habitat factors: riparian canopy cover, percent agriculture and/or urban development within a catchment, and drought, and three demographic factors: extent, abundance, and population age class distribution. The individual factors assessed and the scoring process for each are described below.

Current Condition Scoring Framework

We categorized the current resiliency for each AU from High to Very Low based on the total number of points scored out of 24 possible points (Table 4.1). We calculated the total number of points possible by summing the scores of three habitat parameters (12 points) and three demographic parameters (12 points). For each parameter, we assigned a score from 1 to 4 (4 = High, 3 = Moderate, 2 = Low, 1 = Very Low) based on parameter condition categories that we developed in coordination with species experts. The following sections describe our reasoning for each parameter, the parameter condition categories, and the methodology we used to derive an overall score for each parameter.

Table 4.1: Scale used to determine overall current resiliency condition class for Brawleys Fork crayfish populations. Overall scores were summed from demographic and habitat factor scores (as adjusted).

Overall Resiliency Condition Class	Extirpated	Very Low	Low	Moderate	High
Overall Resiliency Score	≤0	1–6	6.1 - 12	12.1 - 18	>18

Habitat Factors

Riparian Canopy Cover –Riparian canopy cover has a critical role in regulating stream temperature, reducing sedimentation, as well as sequestration of stormwater runoff and associated pollutants. Therefore, we selected riparian canopy cover as a habitat parameter to assess the influence of local land use/land cover on Brawleys Fork crayfish resiliency. We developed four categories for mean percent canopy cover score within 30 m of the stream edge: high (>75% mean percent canopy cover), moderate (50–75% mean percent canopy cover), low (25–50% mean percent canopy cover), and very low (<25% mean percent canopy cover) (Table 4.2). To score this parameter, we gathered data from flowlines (i.e., streams) and medium resolution catchments from the National Hydrography Dataset Plus (NHDPlus; EPA 2014) as well as the National Land Cover Database (NLCD) 2016 Tree Canopy Cover for the continental United States (Coulston et al. 2012). We used ArcGIS Pro (Esri Inc. 2021) to create 30-meter buffers around all flowlines (i.e., streams) within each AU. Then, we extracted tree canopy raster cells within the stream buffers. Finally, we used the zonal statistics to table tool in ArcGIS Pro to calculate the mean value of percent tree canopy cover with each medium-resolution catchment. We calculated the overall riparian canopy cover score for each AU by averaging the scores of the catchments with Brawleys Fork crayfish occurrences within each AU.

Table 4.2: Habitat parameters and parameter condition categories used in determining Brawleys Fork crayfish resiliency. Parameters were assessed at the catchment level and averaged over the analysis unit, except drought which was assessed at the analysis unit level.

Habitat Parameters	**High (4)**	**Moderate (3)**	**Low (2)**	**Very Low (1)**
Mean % canopy cover within 30 m from stream	>75%	50–75%	25–50%	<25%
% Agriculture and urban development	<10%	10–30%	30–50%	>50%
Drought (D3 or D4 in the last 20 years)	D3 or D4 drought never exceeds 4 consecutive weeks in any	D3 or D4 drought exceeds 4 consecutive weeks in any non-	D3 or D4 drought exceeds 4 consecutive weeks during	D3 or D4 drought exceeds 4 consecutive weeks during

	season in a calendar year	reproductive season in a calendar year	reproductive season in one calendar year	reproductive season in two or more calendar years

Percent Agriculture and/or Urban Development – Agricultural practices and urban development may influence Brawleys Fork crayfish resiliency as a result of sedimentation and water quality degradation described in *Chapter 3 Factors Influencing Viability*. Therefore, percent agriculture and/or urban development within each medium resolution catchment was selected as a habitat parameter for scoring Brawleys Fork crayfish resiliency. We developed four resiliency categories for percent agriculture and/or urban development: high resiliency (<10% agricultural and urban land use), moderate resiliency (10–30% agricultural and urban land use), low resiliency (30–50% agricultural and urban land use), and very low resiliency (≥50% agricultural and urban land use) (Table 4.2). To score this parameter, we gathered medium-resolution catchments from the NHDPlus (EPA 2014) and the NLCD 2016 Land Cover raster for the continental United States (Homer et al. 2020). We then used ArcGIS Pro (Esri Inc. 2021) to select all medium-resolution catchments with Brawleys Fork crayfish occurrences. Then, we divided the number of agricultural and urbanized acres (number of cells in the agricultural and urban land cover categories multiplied by 0.00741316-acre) from the total number of acres within a catchment (number of cells of any land cover category multiplied by 0.00741316-acre) to estimate the percent agriculture and urbanized land cover within the medium resolution catchments. Finally, we assigned each medium-resolution catchment a score based on the parameter categories. We calculated the overall percent agricultural and urbanized land cover score by averaging the scores of the medium-resolution catchments with Brawleys Fork crayfish occurrences within each AU.

Drought – We selected drought as a habitat parameter for scoring Brawleys Fork crayfish resiliency based on the species' need for access to perennial stream flow. Disruption of stream connectivity during dry periods limits reproduction and recruitment by restricting individuals that would occupy an otherwise continuous stream segment to now-isolated "refuge" habitats, such as pools, disconnected by dry stream segments. Additionally, the reduction of available habitat during periods of drought limits resources such as food and refuge from predation and/or competition, potentially increasing Brawleys Fork crayfish mortality. While Brawleys Fork crayfish have some ability to burrow deeper into the hyporheic zone of the streambed to access subterranean water during times of drought, prolonged and severe drought would likely still negatively impact the species as a result of the aforementioned consequences of limited resources.

We used the U.S. Drought Monitor dataset to assess the severity and duration of drought within the state of Tennessee from 2000 to the present (U.S. Drought Monitor 2021). We selected drought categories D3 and D4 to assess the influence of drought on Brawleys Fork crayfish because water shortages of that magnitude are expected to influence the water quantity need of Brawleys Fork crayfish. Drought category D3 is described as Extreme Drought with impacts of major crop/pasture losses and widespread water shortages or restrictions. Drought category D4 is described as Exceptional Drought with impacts of exception and widespread crop/pasture loss and shortages of water in reservoirs, streams, and wells creating water emergencies (U.S. Drought Monitor 2021). Historically, D3 drought conditions have resulted in inadequate water supply for wildlife in Tennessee (U.S. Drought Monitor 2021). We categorized drought experienced by Brawleys Fork crayfish AUs based on the duration of D3 or D4 category drought conditions that occurred during reproductive (March – June) as well as non-reproductive seasons (July – February) within the past 20 years (Table 4.3). We define "reproductive season" as the period from March to June during the annual reproductive cycle in which females are ovigerous and hatchlings are undergoing development considering that this period of the reproductive cycle is expected to be the most sensitive to environmental stressors. Category D3 and/or D4 drought occurred in Brawleys Fork crayfish AUs were the years 2007 and 2008 (U.S. Drought Monitor 2021). We developed drought parameter condition categories to reflect the effect on Brawleys Fork crayfish: high (D3 or D4 drought never exceeds 4 consecutive weeks in any season in a calendar year), moderate resiliency (D3 or D4 drought exceeds 4 consecutive weeks in any non-reproductive season on a calendar year), low resiliency (D3 or D4 drought exceeds 4 consecutive weeks during reproductive season in one calendar year), and very low resiliency (D3 or D4 drought exceeds 4 consecutive weeks during reproductive season on two or more calendar years) (Table 4.3).

Table 4.3: Monthly D3 and/or D4 drought conditions within Brawleys Fork crayfish analysis units exceeding 4 consecutive weeks during 2007 (A) and 2008 (B). * indicates months during reproductive season.

(A) 2007

Analysis unit (HUC 12)	Jan	Feb	*Mar	*Apr	*May	*June	July	Aug	Sep	Oct	Nov	Dec
Hollis Creek – East Fork Stones River							D3	D3/D4	D4	D4	D3	D3
Brawleys Fork						D3	D3	D3/D4	D4	D4	D3	D3
Lower West Fork Stones River						D3	D3	D3/D4	D4	D4	D3/D4	D3
Bullpen Creek						D3	D3	D3/D4	D4	D4	D3/D4	D3
Mountain Creek						D3	D3	D3/D4	D4	D4	D3/D4	D3

(B) 2008

Analysis unit (HUC 12)	Jan	Feb	*Mar	*Apr	*May	*June	July	Aug	Sep	Oct	Nov	Dec
Hollis Creek – East Fork Stones River	D3/D4	D4	D3/D4									
Brawleys Fork	D3/D4	D4	D3/D4									
Lower West Fork Stones River	D3/D4	D4	D3/D4									
Bullpen Creek	D3/D4	D4	D3/D4									
Mountain Creek	D3/D4	D4	D3/D4									

Score Adjustments – Each medium-resolution catchment with known Brawleys Fork crayfish occupancy received a score for three parameters (i.e., riparian canopy cover, percent agriculture and/or urban development, and drought). Catchments with no Brawleys Fork crayfish occurrences were not scored. We calculated the total habitat score for each AU by summing the overall habitat scores for each parameter. The habitat parameter scores for catchments that contained first-, second-, and third-order streams were adjusted by -0.5 to account for the more profound impact influences such as water pollution and habitat modification have on smaller order streams (Kaplan et al. 2008, pp. 2, 3, 9; J. Johansen, Fisk University, pers. comm. 2021; J. Simmons, TVA, pers. comm. 2021; C. Williams, TWRA, pers. comm. 2021). In other words, the scores for riparian canopy cover and percent agriculture and/or urbanization were reduced by 0.5 for first-, second-, and third-order streams. The drought parameter score was not reduced because the resolution of the data was such that most, or all, catchments within a particular AU experience the same drought levels, as categorized by the U.S. Drought Monitor. For example, if a medium-resolution catchment containing first-, second-, and third-order streams received a total habitat score of 12, the adjusted parameter score (-0.5 for two parameters) would shift the total score to 11 to account for the greater influence these factors on lower-order (smaller) streams.

Demographic Factors

Connectivity of Brawleys Fork crayfish populations within and among occupied streams is essential to prevent inbreeding and associated negative impacts such as genetic drift and inbreeding depression. Populations with adequate connectivity have a higher probability of maintaining genetic flow that supports more genetically diverse populations with higher adaptive potential, making larger populations more resilient to environmental stochasticity. Evidence of reproduction is an indicator of population fitness and ability to sustain a population over time. Therefore, we selected the number of individuals per population and the evidence of reproduction (multiple age classes) within a population as demographic factors for assessing the resiliency of Brawleys Fork crayfish AUs. We developed four resiliency condition categories for extent, abundance, and age class distribution as key demographic parameters essential for assessing connectivity, population size, and reproduction and recruitment (Table 4.4).

Table 4.4: Demographic parameters for scoring Brawleys Fork crayfish resiliency. See text for description of categories for “Extent”.

Demographic Parameters	**High (4)**	**Moderate (3)**	**Low (2)**	**Very Low (1)**
Extent	50%	30% - 50%	10% - 30%	<10%

Abundance	Quantitative density estimates averaging >20 individuals per 100 m^2; or qualitative abundance averaging >10 individuals counted per person hour or per site visit	Quantitative density estimates averaging between 10 and 20 individuals per 100 m^2; or qualitative abundance averaging between 5 and 10 individuals counted per person hour or per site visit	Quantitative density estimates averaging between 1 and 9 individuals per 100 m^2; or qualitative abundance averaging between 1 and 4 individuals counted per person hour or site visit	Quantitative density estimates averaging <1 individuals per 100 m^2; or qualitative abundance averaging <1 individual counted per person hour or per site visit
Age Class Distribution	Presence of 3 distinct age classes including hatchlings or juveniles	Presence of 2 distinct age classes including hatchlings or juveniles	Presence of 2 distinct age classes, but no hatchlings or juveniles	Presence of only 1 age class of any type

Extent – We used the proportion of catchments occupied by Brawleys Fork crayfish within an AU to estimate the species' distribution extent using ArcGIS Pro (Esri Inc. 2021). Extent was scored based on the proportion of stream catchments occupied by Brawleys Fork crayfish out of the total catchments within an AU. We developed four categories for extent: high resiliency (≥50% of catchment in an AU have Brawleys Fork crayfish occurrences), moderate (30–50% of catchments), low resiliency (10–30% of catchments), and very low resiliency (<10% of catchments) (Table 4.4)

Because there is no available genetic information pertaining to Brawleys Fork crayfish to indicate the level of connectivity within and among AUs, resiliency scores for extent were adjusted by dendritic network complexity. Increasing fragmentation within branching stream systems results in more severe genetic consequences (Fagan 2002, pp. 3243–3249). If the extant occurrences within an AU were located in the mainstem stream or river and in more than two tributaries, then the score was not adjusted. If occurrences were within the mainstem and two named tributaries, then the score was adjusted by -1. If occurrences were in the mainstem and one named tributary, then the score was adjusted by -2. All other less complex networks were adjusted by -3.

Abundance – We used abundance estimates to assess population size, an essential demographic factor influencing Brawleys Fork crayfish resiliency. If available, abundance estimates (reported as crayfish/100 m) for each stream occupied by Brawleys Fork crayfish were obtained through quantitative estimation of abundance based on quadrat sampling results (T. Khan, TTU, unpublished data). If quantitative abundance data were not available, qualitative estimation of abundance was obtained based on average catch per unit effort (CPUE reported as number of individuals/person hours) or average catch per site visit (number of individuals/number of site visits) (Withers and McCoy 2005, pp. 20–48; Rohrbach and Withers 2006, p. 18). A qualitative abundance estimate was assessed either by average catch per unit effort (individuals/person hours) or average catch per site visit (individuals/number of site visits), but never both. Similarly, each stream was scored either by a quantitative estimate of abundance or a qualitative estimate of abundance, but never both; if both types of abundance estimates were available, then we used the quantitative estimates for our analysis. We developed four quantitative and four qualitative abundance estimate categories (Table 4.4 and 4.5). Abundance scores for each stream catchment within an analysis unit were then averaged to obtain a abundance score for each analysis unit.

Table 4.5: Four condition category parameters for quantitative and qualitative abundance estimates for Brawleys Fork crayfish.

Abundance Data Type	**Condition Category**			
	High (4)	**Moderate (3)**	**Low (2)**	**Very Low (1)**
Quantitative	>20 individuals/100 m	10–20 individuals/100 m	1–9 individuals/100 m	<1 individuals/100 m
Qualitative	>10 individuals/person hours or site visit	5–10 individuals/person hours or site visit	1–4 individuals/person hours or site visit	averaged <1 individual/person hours or site visit

Age Class Distribution – We used population age class distribution to assess reproduction and recruitment. Population age class distribution was assessed using length frequency histograms for populations with available demographic data collected during previous study (Giddens and Mattingly 2020, pp. 14-16). We developed four age class distribution categories: high (3 distinct age classes including hatchlings or juveniles), moderate (2 distinct age classes including hatchlings or juveniles), low (2 distinct age classes but no hatchlings or juveniles), and very low (1 age class of any type) (Table 4.4). We considered individuals ≤10 mm CL to be juveniles based on a 10.7 mm CL Brawleys Fork crayfish being the smallest female in glare collected during a recent study (Giddens and Mattingly 2020, p. 7).

If demographic data were not available, we assigned each stream with abundance data a default population age class distribution score of 1 (Very Low) under the assumption that at least one age class must be present if abundance is measurable. We recognize that this assignment of a very low age class distribution to populations with unknown age class distribution may underestimate the condition and resiliency of an AU. We next averaged the population age class distribution scores for each stream within an AU to calculate the overall score for a particular AU. We then summed the extent, abundance, and population age class distribution scores for each AU to obtain a total demographic score for each AU.

Finally, we summed the habitat and demographic parameter scores to obtain an overall AU condition score. Each AU was assigned an overall resiliency condition class from High to Very Low using the scale in Table 4.1. An AU may not exhibit each characteristic of the category as defined, but most parameters known for the population fall into the resilience category. For example, a population that is described as highly resilient may have a high degree of riparian canopy cover and a low percentage of agriculture or urban land use, and multiple age classes, but extent and abundance may be limited.

An AU that exhibits high resiliency is able to withstand stochastic events, has a stable or increasing population trend with evidence of reproduction and recruitment and occurs in habitat that meets or exceeds the individual-, population- and species-level needs (Table 4.6). An AU that exhibits moderate resiliency is less robust with lower abundance and extent and has limited recruitment or reproduction and occurs in habitat in good condition that meets species' needs, but does not exceed those resource needs. An AU in low resiliency is expected to have low abundance, limited extent, very low or no recruitment and reproduction with habitat in marginally suitable condition (contains most, but not all resources necessary for Brawleys Fork crayfish viability). An AU in very low resiliency has low abundance, no recruitment or reproduction, with limited extent in poor habitat conditions and, thus, is extremely vulnerable to stochastic events and extirpation.

Table 4.6: Summary of resiliency categories for Brawleys Fork crayfish based on habitat and demographic parameters.

High	Moderate	Low	Very Low
• Most of the riparian area has canopy cover (>75%) • Very limited agriculture and/or urban land cover (<10%) • Drought does not occur • Species occurs in over half of catchments • Abundance is high • Multiple age classes including juveniles indicate reproduction and recruitment are such that the population remains stable or increases • Reproduction and/or recruitment is occurring in most streams	• Much of riparian area has canopy cover (50–75%) • Low levels of agricultural and/or urban land cover (10–30%) • Drought occurs, but is outside reproductive season • Species occurs in 30–50% of catchments • Abundance is moderate • Recruitment and mortality are equal such that the population does not grow • Reproduction and/or recruitment in occurring in some streams	• Part of riparian area has canopy cover (25–50%) • Moderate levels of agricultural and/or urban land cover (30–50%) • Drought occurs during reproductive period • Species occurs in 10–30% of catchments in the AU • Abundance is low • Mortality exceeds recruitment such that the population declines slowly • Reproduction and/or recruitment is occurring in a few streams	• Riparian canopy cover is limited (<25%) • High levels of agricultural and/or urban land cover (>50%) • Drought occurs multiple years during reproductive period • Species occurs in few catchments (<10%) • Abundance is very low • Mortality exceeds recruitment such that the population declines • Reproduction and/or recruitment are not occurring

4.2.2 Species Representation and Redundancy

Redundancy within the SSA framework describes a species' ability to withstand catastrophic events based on the existence of multiple resilient populations distributed across the species' range (Service 2016, p. 13). Species that are widely distributed across their historical range are considered less susceptible to extinction and more likely to have higher viability than species confined to a small portion of their range (Carroll et al. 2009, entire; Redford et al. 2011, entire). For Brawleys Fork crayfish, we assessed redundancy by mapping the number and distribution of resilient populations (defined as high or moderate resiliency) across the species' geographic range.

Representation within the SSA framework describes the species' ability to adapt to changing environmental conditions over time whether those changes may be the result of natural environmental change, anthropogenic influence, and/or climate change (Service 2016, p. 12). Adaptive capacity reflects a suite of ecological and evolutionary factors that allow a species to either persist in place or shift in space to withstand changing conditions (Thurman et al. 2020, p. 521). Assessment of a species' representation may be based on many attributes including those related to demographics, distribution, movement, life history, niche, ecological role, and evolutionary potential within and among populations (Thurman et al. 2020, p. 522). A high degree of diversity and subsequent adaptability significantly reduces the probability of a species going extinct due to environmental changes over time (USFWS 2016, pp. 12-13). Genetic information pertaining to Brawleys Fork crayfish is currently unavailable. Therefore, our assessment of species representation includes core attributes related to distribution as expressed by the extent (area of occupancy) and evolutionary potential as expressed through abundance (population size). We also consider the attribute of demographics evidenced by the age class distribution parameter (reproduction/recruitment). Adequate population size, higher area of occupancy, and reproduction/recruitment facilitate gene flow within and among populations through emigration (individuals leaving a population) as well as immigration (individuals entering a population). The movement of individuals and their respective genes to and from populations increases genetic diversity within and among populations, thereby increasing adaptive potential within and among populations as well. In our resiliency analysis, the total demographic score for each AU includes the area of occupancy (extent), population size (abundance), and age structure as attributes that indicate a species' adaptive capacity potential. We qualitatively describe pristine crayfish representation based on the total demographic score condition categories and consider species-level attributes. We consider the current level of these attributes compared to expected historical levels.

4.3 Current Condition Results

4.3.1 Current Population Resiliency

Of the five delineated Brawleys Fork crayfish AUs, two are in moderate condition (Hollis Creek – East Fork Stones River and Brawleys Fork) and three are in low condition (Lower West Fork Stones River, Bullpen Creek, and Mountain Creek) (Table 4.7) (Figure 4.1).

Table 4.7: Current population condition scores for Brawleys Fork crayfish analysis units.

Subwatershed (HUC 12)	Total Habitat Score Adjusted (out of 12 points)	Total Demographic Score (out of 12 points)	Population Condition Score Adjusted (out of 24 points)
Hollis Creek – East Fork Stones River	Low	Moderate	Moderate
Brawleys Fork	Low	Moderate	Moderate
Lower West Fork Stones River	Low	Moderate	Low
Bullpen Creek	Low	Low	Low
Mountain Creek	Low	Moderate	Low

The current habitat condition score in all AUs was determined to be low (Table 4.7). This suggests that Brawleys Fork crayfish AU resiliency may be limited by habitat conditions and may not be able to support highly resilient populations currently. We determined Brawleys Fork crayfish demographic condition to be moderate for all analysis units with the exception of Bullpen Creek (Table 4.7). This suggests that most Brawleys Fork crayfish populations have adequate demographic condition to support resilient populations. However, we determined three analysis units (Lower West Fork Stones River, Bullpen Creek, and Mountain Creek) to have very low extent (area of occupancy), suggesting that although Brawleys Fork crayfish currently have moderate demographic condition, a lack of connectivity and gene flow may be a limiting factor in Brawleys Fork crayfish demographic condition.

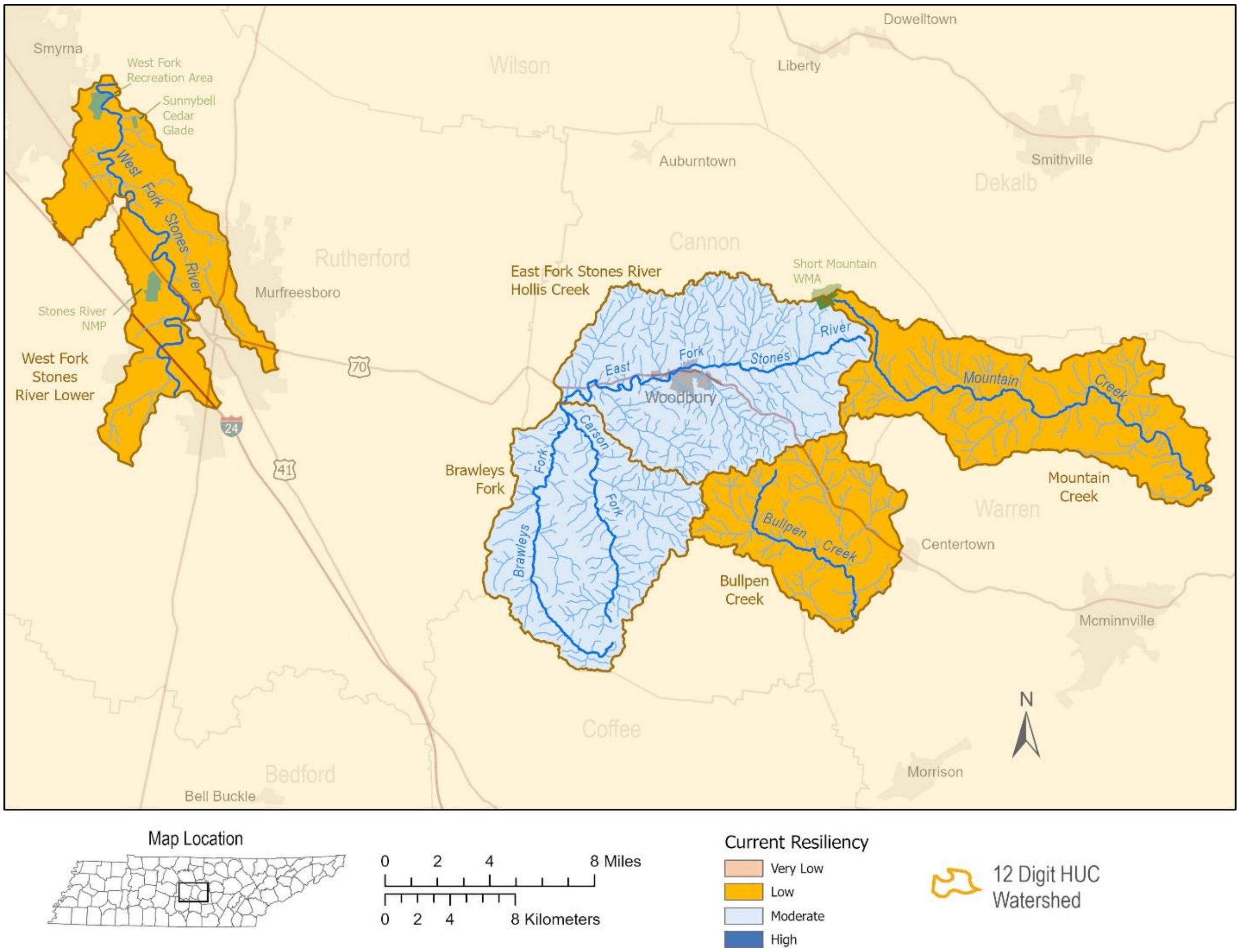


Figure 4.1: Brawleys Fork crayfish current resiliency score.

4.3.2 Current Species Redundancy

We consider the Brawleys Fork crayfish to have redundancy that has not declined from historical levels. As an endemic species with a limited range, Brawleys Fork crayfish may have naturally lower redundancy than a more broadly distributed species. Within the known range, Brawleys Fork crayfish typically occurs in low or very low abundance at most sites with 8 of 15 streams with species abundance data. Available information indicates no loss of populations or analysis units over time and the current known range of the species is wider than the historical range (no range reduction).

4.3.3 Current Species Representation

Brawleys Fork crayfish has a known distribution encompassing five AUs that occur in different EPA level IV ecoregions that possess correspondingly different stream habitat conditions. The best available information indicates that the species' current representation is not reduced from historical representation (i.e., through range contraction or extirpation of populations). As part of our resiliency assessment, we calculated a total demographic score that includes parameters expected to indicate adaptive capacity of the species including extent, abundance, and age class distribution influencing gene flow and subsequent genetic diversity. Four of five AUs exhibit moderate levels of the assessed attributes that are expected to contribute to adaptive capacity (Table 4.7). Bullpen Creek, with a single known occurrence and low extent, does not express high levels of attributes that represent adaptive capacity. Overall, we have determined that the Brawleys Fork crayfish species-level representation is not reduced from historical levels and is sufficient to support current species viability.

4.4 Current Condition Summary

We determined Brawleys Fork crayfish currently exhibits low resiliency in three of five AUs, and species' redundancy and representation that have not declined from historical levels with no known extirpations or range contraction (Table 4.7; Figure 4.1). All AUs scored low in the habitat parameters analyzed, suggesting habitat may be a limiting factor for resiliency. Four of the five Brawleys Fork crayfish AUs exhibit moderate demographic condition suggesting that Brawleys Fork crayfish has sufficient levels of adaptive capacity to withstand environmental change (Table 4.7). However, isolation and a lack of connectivity in four of the five AUs suggests that Brawleys Fork crayfish could be susceptible to the deleterious effects of inbreeding, although we have no information that indicates the effects of limited gene flow are currently affecting the species.

CHAPTER 5 - FUTURE CONDITIONS AND VIABILITY

We have considered what the Brawleys Fork crayfish needs for viability and the current condition of those needs (Chapters 2 and 4), and we reviewed the factors that are driving the current and future conditions of the species (Chapter 3). We now consider what the species' future condition is likely to be. We apply our future forecasts to the concepts of resiliency, representation, and redundancy to describe the future viability of the Brawleys Fork crayfish.

5.1 Models and Scenarios

5.1.1 Future Condition Parameters Used to Estimate Future Condition

To assess the potential future condition of the Brawleys Fork crayfish, we selected four key parameters (i.e., urbanization, land use change, climate change, and water withdrawal) based on the influences these factors have on Brawleys Fork crayfish viability. Parameters such as urbanization, land use change, and climate change were assessed and scored quantitatively using various modeling techniques, whereas water withdrawal was assessed and scored qualitatively due to the inability to accurately predict in what streams future water withdrawal will likely occur and at what rate water withdrawal is likely to increase or decrease in the future. We assessed future projections of each parameter and their associated influence on Brawleys Fork crayfish future condition out to the year 2036 (15 years) and 2051 (30 years). We chose these timesteps based on Brawleys Fork crayfish's short lifespan (approximately 3 years) as well as populations having increased vulnerability to future environmental change due to small population size in some streams and low connectivity in some AUs. The following subsections will describe how each parameter was assessed.

Urbanization

Future urbanization was assessed quantitatively based on SLEUTH model projections of urban growth likely to occur within each Brawleys Fork crayfish AU in 15 years (2036) and 30 years (2051) (Jantz et al. 2010; Belyea 2013; Chaudhuri and Clarke 2013). Because SLEUTH model projections are estimated in 10-year increments, our assessment of urbanization likely to occur in 2036 was estimated by taking the average growth expected to occur between the years 2030 and 2040. We used SLEUTH projections for the year 2050 to assess the probability of urban growth in 2051

Stream flow in the Southeast has been shown to become impacted when the amount of urban land use reaches 10% of the watershed (Suttles et al. 2018, p. 813). Therefore, we based our assessment of the impact of urbanization on 10% or more of the land within each analysis unit having a ≥50% probability of becoming urbanized within the years 2036 and 2051. The three scenarios under which future urbanization was evaluated to assess and score Brawleys Fork crayfish future condition are described below in *5.1.2 Future Scenarios and Resiliency Calculations*.

Climate Change

Future climate change was assessed quantitatively based on USGS National Climate Change Viewer (NCCV 2021) model projections of future annual air temperatures and precipitation likely to occur within the Stones River watershed and the Collins River watershed in 15 years (2036) and 30 years (2051) under two climate scenarios: RCP 4.5 and RCP 8.5. Representative concentration pathways (RCPs) are potential future climate scenarios based on various levels of CO_2 concentrations in the atmosphere expected to rise by the year 2100 as a result of varying levels of action that could potentially be taken in the future to address climate change. Under the RCP 4.5 scenario, concentrations of CO_2 stabilize at ~850 parts per million (ppm) after 2100 (Van Vuuren et al. 2011, p. 12). Under the RCP 8.5 scenario, concentrations of CO_2 increase to ~1370 ppm by 2100 (Van Vuuren et al. 2011, p. 12).

Fluctuations in average annual air temperature can be expected to vary from year to year with some years experiencing cooler average annual air temperature than the previous year, rather than a continual linear increase in average annual air temperature through time. To account for among-year variability, we assessed future change in average annual air temperature using projections for average change three years before and three years after each timestep (i.e., we used seven years of data from 2033–2039 for the 2036 timestep and seven years of data from 2048–2054 for the 2051 timestep). We also evaluated projected average change in annual precipitation, runoff, and evaporation for the Stones River watershed and the Collins River watershed at both timesteps under both climate change scenarios. However, average annual change for these three parameters did not exceed 0.25 inches/month at either timestep or under RCP 4.5 or 8.5 climate change scenario. This level of change is not expected to affect the Brawleys Fork crayfish or its habitat conditions in a biologically meaningful way. Therefore, we did not consider precipitation, runoff, or evaporation to be viable parameters for assessing and scoring the influence of future climate change on Brawleys Fork crayfish resiliency.

Change in future average annual air temperature was considered to be a viable predictor of Brawleys Fork crayfish future condition based on the relationship between air temperature and stream temperature, as well as the presumption that Brawleys Fork crayfish site occupancy is associated with groundwater input influencing cooler stream water temperatures during summer months. Previous study has shown that a linear relationship exists between air temperature and stream temperature with each degree increase in air temperature resulting in a similar increase in stream temperature up until ~20°C (68°F) (Mohseni et al. 1999, pp. 3723– 3725). It is at this point that stream temperature remains at ~20°C despite air temperature exceeding this value as a result of evaporative cooling removing the warm top layer of water (Mohseni et al. 1999, pp. 3723– 3724). However, if future stream temperatures were to consistently remain ~20°C as a result of rising air temperature, chronic exposure to elevated stream temperatures could potentially influence Brawleys Fork crayfish resiliency considering that the Brawleys Fork crayfish has previously been collected from streams ranging from 10– 23°C (Giddens and Mattingly 2020, pp. 4– 5). It should be noted that the influence of groundwater within headwater streams occupied by Brawleys Fork crayfish could potentially guard the species from exposure to consistently elevated stream temperatures in the future. Although Brawleys Fork crayfish have been collected from streams with temperatures ~20°C, other factors such as drought and water withdrawal could potentially increase in the future as a result of climate change and limited water supply, which could subsequently decrease groundwater recharge. Under these circumstances, the influence of groundwater may become insufficient for regulating stream temperature.

Therefore, we assessed the influence of future climate change based on the degree at which average annual air temperature is projected to increase within each Brawleys Fork crayfish AU in 15 years (2036) and 30 years (2051). The various scenarios under which future climate change were evaluated to assess Brawleys Fork crayfish future condition are described in *5.1.2 Future Scenarios and Resiliency Calculations*.

Land Use Change

Future land use change was assessed quantitatively based on USGS Earth Resources Observation and Science Center FOREcasting SCEnarios (FORE-SCE) to model projections of land use change likely to occur within each Brawleys Fork crayfish AU in 15 years (2036) and 30 years (2051). Land use change was assessed within the model under two different Special Report on Emission Scenarios (SRES) for both timesteps: SRES B1 and SRES A2. SRES B1 assumes a future with low population growth, development, and emissions similar to what is assumed under RCP 4.5 (Nakicenovic et al. 2000, entire; Sohl et al. 2014, entire). SRES A2 assumes a future with high population growth, development, and emissions similar to what is assumed under RCP 8.5 (Nakicenovic et al. 2000, entire; Sohl et al. 2014, entire). For the purpose of this assessment, our definition of land use change is the percent change in cropland within each Brawleys Fork crayfish AU.

FORE-SCE cropland projections were used as a proxy for estimating the potential influence of future changes in agricultural and horticultural land cover considering that sedimentation and water quality degradation derived from these practices can potentially influence Brawleys Fork crayfish resiliency as described in Chapters 2 and 3. Previous study has found that the Barrens darter (*Etheostoma forbesi*), a species currently listed as endangered by the Tennessee Wildlife Resources Agency that is endemic to the Barrens Region of the Eastern Highland Rim, was not detected at sites with greater than 5% nursery land cover (Zuber 2014, pp. 2–3, 79). In fact, sites where Barrens darter were detected only had 1% nursery land cover (Zuber 2014, p. 79). Furthermore, a 5% change in land use during a 30-year period (1976 to 2006) was determined to be the greatest percent change in land use within the Barrens Region (Zuber 2014, pp. 68–92). Therefore, considering that Brawleys Fork crayfish also inhabits streams of the Barrens Region on the Eastern Highland Rim and are vulnerable to many of the same influences derived from horticultural practices as the Barrens darter, we based our assessment of the impact of land use change on an increase in cropland by 5% or more within each analysis unit in 15 years (2036) and 30 years (2051). The various scenarios under which future land use change were evaluated to assess and score Brawleys Fork crayfish future condition are described below in *5.1.2 Future Scenarios and Resiliency Calculations*.

Water Withdrawal

Because the likelihood of water withdrawal increasing in the future cannot be estimated with quantitative modeling programs, we qualitatively assessed the influence of future water withdrawal on the assumption that as an increase in average annual air temperature and drought can be expected to result in limited water supply, water withdrawal can also be expected to increase to some degree. For example, periods of decreased precipitation and prolonged drought would likely result in more intense irrigation related to horticultural practices, particularly in regions such as the Eastern Highland Rim that have a higher concentration of plant nurseries. Furthermore, under the TDEC Division of Water Resources Rule 0400-40-13, inter-basin transfer of up to 500,000 gallons of water per day is permitted for the benefit of (or to supply) the receiving basin's public water system (TDEC 2021). Under this rule, permission has been granted to transfer water from the Stones River watershed to the Duck River watershed to meet water supply demands as development within the Duck River watershed increases. We expect water supply demand to continue to increase within the Duck River watershed due to development resulting in increased water usage and decreased groundwater recharge, which will likely require water withdrawal from the Stones River watershed to continue. Water withdrawals for municipal purposes are typically in higher order mainstream rivers and may not include headwater tributaries. However, smaller, unpermitted agricultural withdrawals are expected in the Brawleys Fork range and are expected to increase with increasing water demand. Continuation of water withdrawal from the Stones River watershed in the future could potentially exacerbate the influence of drought on Brawleys Fork crayfish resiliency by contributing to decreased water availability. Therefore, we qualitatively assessed the influence of water withdrawal on Brawleys Fork crayfish within each AU in 15 years (2036) and 30 years (2051). The various scenarios under which future water withdrawal were evaluated to assess Brawleys Fork crayfish future condition are described below in *subsection 5.1.2 Future Scenarios and Resiliency Calculations*.

5.1.2 Future Scenarios and Resiliency Calculations

To assess Brawleys Fork crayfish future condition, we developed three plausible future scenarios related to four habitat influences from (1) urbanization, (2) land use change (change in cropland), (3) effect of climate change (air temperature), and (4) water withdrawal. The scenarios: (1) status quo and lower development, (2) status quo and higher development, and (3) increased impacts are summarized below and in Table 5.1.

We estimated a future resiliency score for each analysis unit by adjusting each analysis unit's current condition score based on impacts from projected changes in the four habitat influences. In the following sections, we describe the plausible future condition parameters that may influence Brawleys Fork crayfish future condition under three future condition scenarios and the adjustments to current condition associated with each.

Table 5.1: Data sources for Brawleys Fork crayfish future condition under each future scenario.

Scenario	Parameters			
	Urbanization	Land Use Change	Climate Change	Water Withdrawal
Scenario 1	SLEUTH	FORE-SCE SRES B1	USGS NCCV RCP 4.5	Reduced Rate
Scenario 2	SLEUTH	FORE-SCE SRES B1	USGS NCCV RCP 4.5	Current Rate
Scenario 3	SLEUTH	FORE-SCE SRES A2	USGS NCCV RCP 8.5	Increased Rate

Scenario 1: Status Quo/Lower Development

Scenario 1 is characterized by a "status quo/lower development" future in which influences such as water withdrawal continues to increase at less than the current rate, urbanization is assessed with a ≥50% probability, land use change (change in cropland land cover) is assessed under SRES B1, and climate change is assessed at the RCP 4.5 level. In other words, under this scenario each future condition parameter was assessed at a low impact level. The following sections describe how each future condition parameter was assessed and scored under Scenario 1. The cumulative adjustments associated with the score of each parameter (i.e., urbanization, land use change, climate change, and water withdrawal) were then applied to each Brawleys Fork crayfish AU's current condition score to estimate the future condition score of each Brawleys Fork crayfish analytical at 15 years (2036) and 30 years (2051) under Scenario 1.

Urbanization

Under Scenario 1, urbanization was assessed and scored using a quantitative approach based on SLEUTH model projections (Table 5.1). We used ArcGIS Pro (Esri, Inc. 2021) to calculate the proportion of cells within and AU with a ≥50% probability of urbanization. If 5-10% of the area within an AU is projected to have a ≥50% probability of urbanization, the current condition score of that analysis unit was adjusted by -1. If 10-20% of the area within an analysis unit is projected to have a ≥50% probability of urbanization, the current condition score of that analysis unit was adjusted by -2. If >20% of the area within an analysis unit is projected to have a ≥50% probability of urbanization, the current condition score of that analysis unit was adjusted by –3 (Table 5.2).

Land Use Change

Under Scenario 1, land use change was assessed and scored using a quantitative approach based on FORE-SCE (SRES B1) model projections (Table 5.1). We used ArcGIS Pro (Esri, Inc. 2021) to assess the proportion of each AU that is predicted to be in cropland or If there was no projected change or a projected reduction in cropland within an analysis unit, no adjustment was made. If cropland was projected to increase by 0.1–5%, the current condition score was adjusted by -0.5. If cropland was projected to increase by >5%, the current condition score was adjusted by -1 (Table 5.2).

Climate Change

Under Scenario 1, climate change was assessed and scored using a quantitative approach based on USGS NCCV projections at the RCP 4.5 level (Table 5.1). If average annual air temperature was projected to increase by <1°C (1.8°F), the current condition score was adjusted by -1 (Table 5.2). If average annual air temperature was projected to increase by 1–2°C (1.8–3.6°F), the current condition score was adjusted by -3 (Table 5.2). If average annual air temperature was projected to increase by >2°C (3.6°F), the current condition score was adjusted by -5 (Table 5.2). We chose higher adjustment values for climate change effects to account for the multiple influences of the parameter including increased stream temperature, increased drought, and increased water withdrawal, all expected to negatively affect Brawleys Fork crayfish resiliency.

Water withdrawal

Under Scenario 1, water withdrawal was assessed and scored using a qualitative approach which assumed water withdrawal to increase at less than the current rate (Table 5.1). Under this scenario, no adjustment was made to the current condition score (Table 5.2).

Scenario 2: Status Quo/Higher Development

Scenario 2 was assessed by assuming a "status quo/higher development" future in which influences such as water withdrawal continue to increase at the current rate, urbanization is assessed with a ≥50% probability, land use change (change in cropland land cover) is assessed under SRES B1, and climate change is assessed at the RCP 4.5 level. In other words, under this scenario each future condition parameter was assessed at a moderate impact level. The following sections describe how each future condition parameter was assessed and scored under Scenario 2. The cumulative adjustments associated with the score of each parameter (i.e., urbanization, land use change, climate change, and water withdrawal) were then applied to each Brawleys Fork crayfish AU's current condition score to estimate the future condition score of each Brawleys Fork crayfish analytical at 15 years (2036) and 30 years (2051) under Scenario 2.

Urbanization, Land Use Change, and Climate Change

Under Scenario 2, urbanization, land use change, and climate change were assessed and scored using the same quantitative approaches as was used under Scenario 1 (Table 5.1; Table 5.2).

Water withdrawal

Under Scenario 2, water withdrawal was assessed and scored using a qualitative approach which assumed water withdrawal to continue to increase at the current rate (Table 5.1). Under this scenario, the current condition score was adjusted by -1 across all analysis units (Table 5.2).

Scenario 3: Increased Impacts

Scenario 3 was assessed by assuming an "increased impacts" future in which influences such as water withdrawal continues to increase above the current rate, urbanization is assessed with a ≥50% probability, land use change (change in cropland land cover) is assessed under SRES A2, and climate change is assessed at the RCP 8.5 level. In other words, under this scenario each future condition parameter was assessed at a high impact level. The following sections describe how each future condition parameter was assessed and scored under Scenario 3. The cumulative adjustments associated with the score of each parameter (i.e., urbanization, land use change, climate change, and water withdrawal) were then applied to each Brawleys Fork crayfish AU's current condition score to estimate the future condition score of each Brawleys Fork crayfish analytical at 15 years (2036) and 30 years (2051) under Scenario 3.

Urbanization, Land Use Change, and Climate Change

Under Scenario 3, urbanization and land use change were assessed and scored using the same quantitative approaches as was used under Scenarios 1 and 2 with the exception of land use change being assessed under FORE-SCE (SRES A2) rather than FORE-SCE (SRES B1) (Table 5.1; Table 5.2). Climate change was assessed and scored using the same quantitative approach used under Scenarios 1 and 2 with the exception of being assessed at the RCP 8.5 level rather than the RCP 4.5 level (Table 5.1; Table 5.2).

Water withdrawal

Under Scenario 3, water withdrawal was assessed and scored using a qualitative approach which assumed water withdrawal to increase above the current rate (Table 5.1). Under this scenario, the current condition score was adjusted by -2 across all AUs (Table 5.2).

Table 5.2: Parameter rubric used to score Brawleys Fork crayfish future condition in 15 years (2036) and 30 years (2051) under each future scenario.

Impact Level	Parameter Rubric			
	Urbanization	Land Use Change	Climate Change	Water Withdrawal
Low	5-10% of the area within an analysis unit has a ≥50% probability of urbanization (adjustment = -1)	Reduction or no change in cropland (adjustment = 0)	Average annual air temperature increases by <1°C (adjustment = -1)	Water withdrawal increases at less than the current rate (adjustment = 0)
Moderate	10-20% of the area within an analysis unit has a ≥50% probability of urbanization (adjustment = -2)	0.1–5% increase in cropland (adjustment = -0.5)	Average annual air temperature increases by 1–2°C (adjustment = -3)	Water withdrawal continues to increase at the current rate (adjustment = -1)
High	>20% of the area within an analysis unit has a ≥50% probability of urbanization (adjustment = -3)	>5% increase in cropland (adjustment = -1)	Average annual air temperature increases by >2°C (adjustment = -5)	Water withdrawal increases above the current rate (adjustment = -2)

5.2 Future Condition Results

5.2.1 Future Population Resiliency

Scenario 1-Future Condition

In the first timestep (2036) under Scenario 1 (status quo/lower development), three of the five Brawleys Fork crayfish AUs are reduced from moderate to low resiliency and one is reduced from low to very low resiliency. The Bullpen Creek AU is projected to maintain low resiliency (Table 5.3). No Brawleys Fork crayfish populations are estimated to be extirpated in 15 years under Scenario 1 (Table 5.3) (Figures 5.1 and 5.4).

In 2051, under Scenario 1 (status quo/lower development), all Brawleys Fork crayfish AUs are projected to reduce by one resiliency class, except Bullpen Creek which is projected to maintain low resiliency. Three of the five Brawleys Fork crayfish AUs are reduced from moderate to low resiliency and one is projected to reduce from low to very low (Table 5.3). No Brawleys Fork crayfish populations are estimated to be extirpated in 30 years under Scenario 1 (Table 5.3) (Figure 5.1 and 5.4).

Table 5.3: Brawleys Fork crayfish future condition summary by analysis unit, scenario, and timestep.

		Scenario 1		Scenario 2		Scenario 3	
Analysis unit (HUC 12)	Current Resiliency Class	2036	2051	2036	2051	2036	2051
Hollis Creek – East Fork Stones River	Moderate	Low	Low	Low	Low	Low	Very Low
Brawleys Fork	Moderate	Low	Low	Low	Low	Low	Very Low
Lower West Fork Stones River	Low	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low
Bullpen Creek	Low	Low	Low	Low	Very Low	Very Low	Very Low
Mountain Creek	Low	Low	Low	Low	Low	Low	Very Low

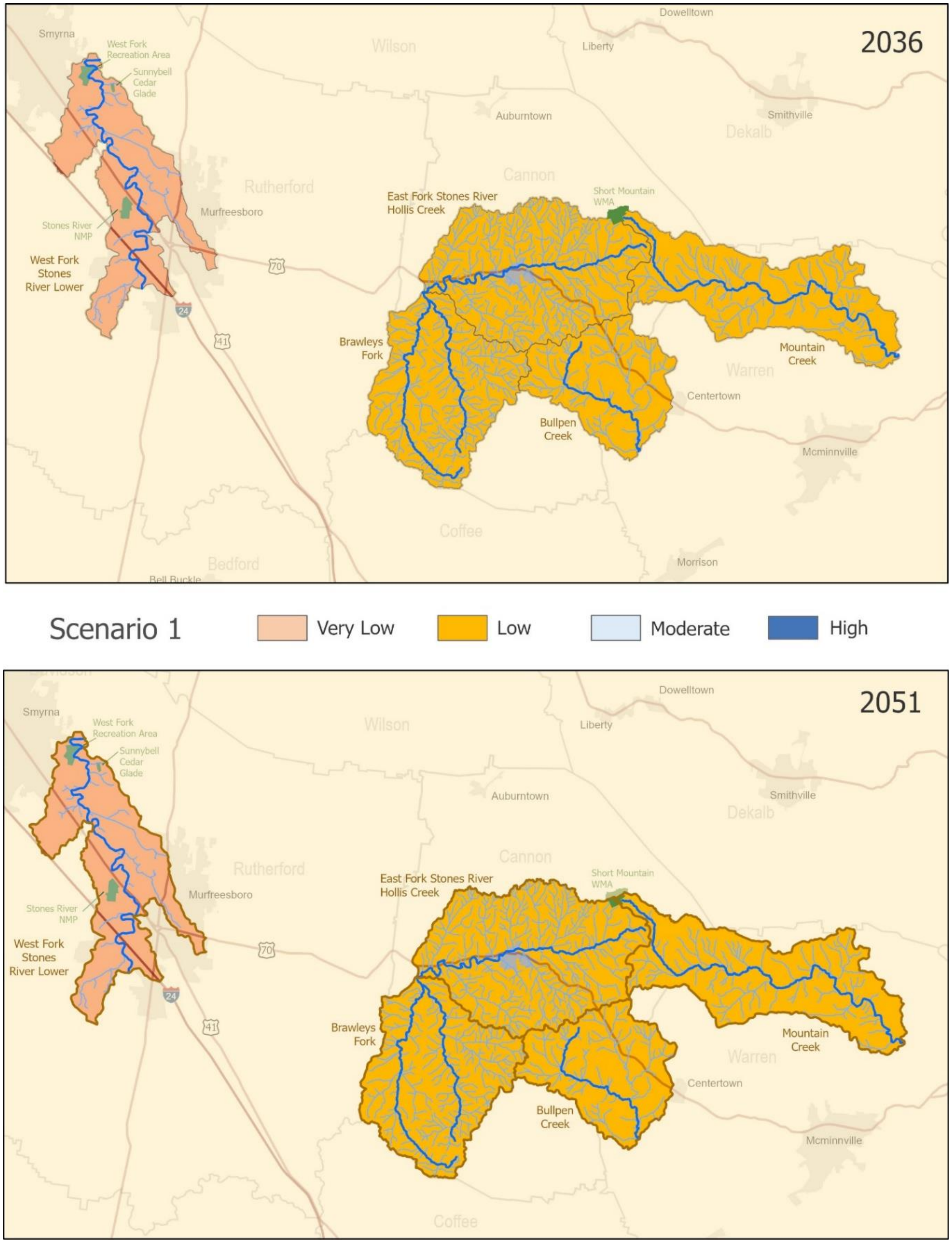


Figure 5.1: Future resiliency class for Brawleys Fork crayfish analysis units in 2036 and 2051 under Scenario 1.

Scenario 2-Future Condition

In the first timestep (2036) under Scenario 2 (status quo/higher development), all Brawleys Fork crayfish AUs are projected to reduce by one resiliency class, except Bullpen Creek which is projected to maintain low resiliency. Three of the AUs are reduced from moderate to low resiliency and one is projected to decrease from low to very low resiliency (Table 5.3). No Brawleys Fork crayfish populations are estimated to be extirpated in 30 years under Scenario 1 (Table 5.3) (Figure 5.2 and 5.4).

In 2051, under Scenario 2 (status quo/higher development), all Brawleys Fork crayfish AUs are projected to decrease by one resiliency class.Three of the AUs are reduced from moderate to low resiliency and two are project to decrease from low to very low resiliency (Table 5.3) (Figure 5.2 and 5.4).

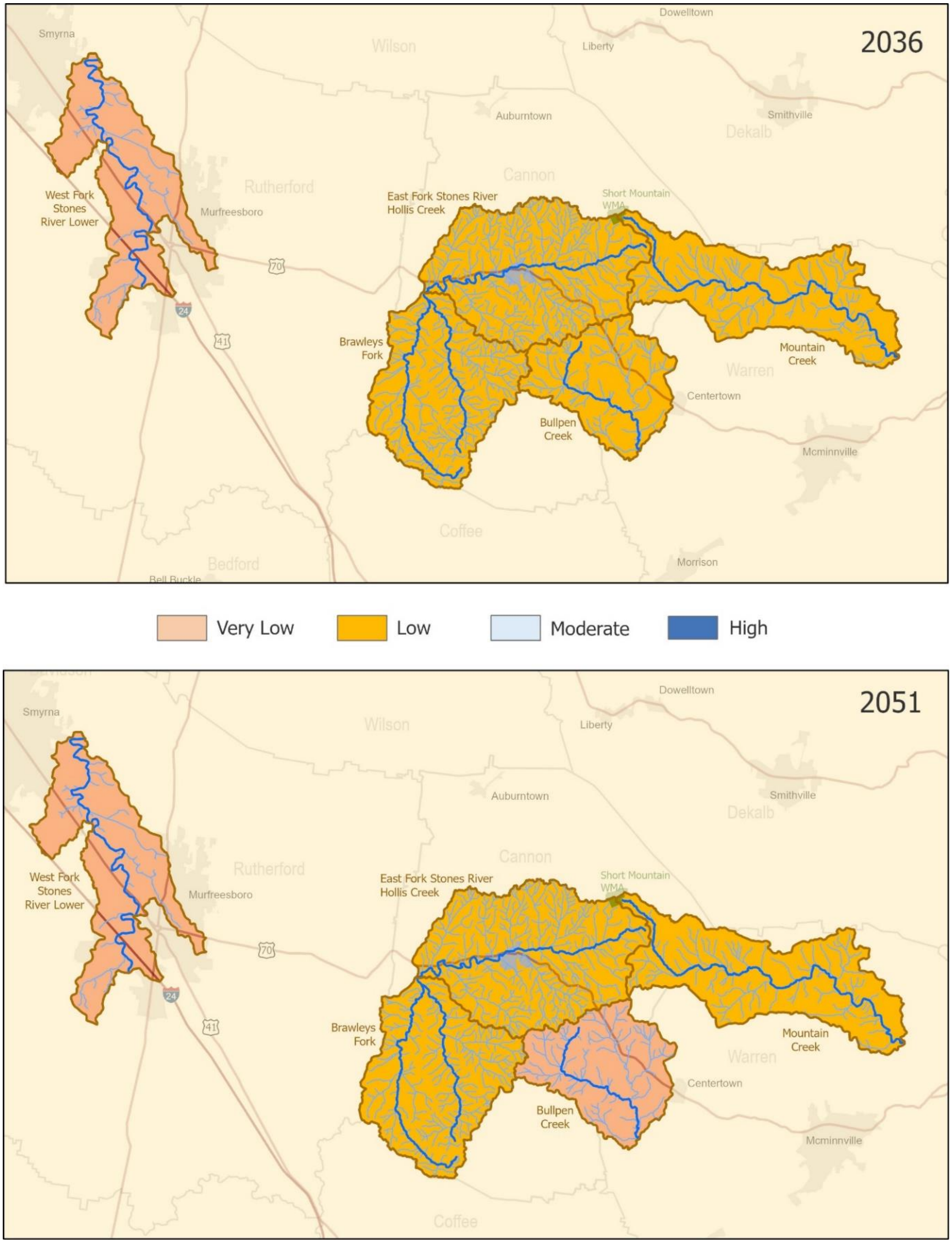


Figure 5.2: Future resiliency class for Brawleys Fork crayfish analysis units in 2036 and 2051 under Scenario 2.

Scenario 3-Future Condition

In the first timestep (2036) under Scenario 3 (increased impacts), all Brawleys Fork crayfish AUs are projected to reduce by one resiliency class. Three of the five AUs are reduced from moderate to low resiliency and two are projected to decrease from low to very low resiliency (Table 5.3). No Brawleys Fork crayfish populations are estimated to be extirpated in 15 years under Scenario 3 (Table 5.3) (Figure 5.3 and 5.4).

In 2051, under Scenario 3 (increased impacts), the projections decline further from the 2036 projection. The threats and species responses to the threats increase in severity between 15 and 30 years under Scenario 3, primarily in the effects of urbanization and climate change (temperature increase). Under this scenario, all Brawleys Fork crayfish AUs are in very low resiliency (Table 5.3) (Figure 5.3 and 5.4).

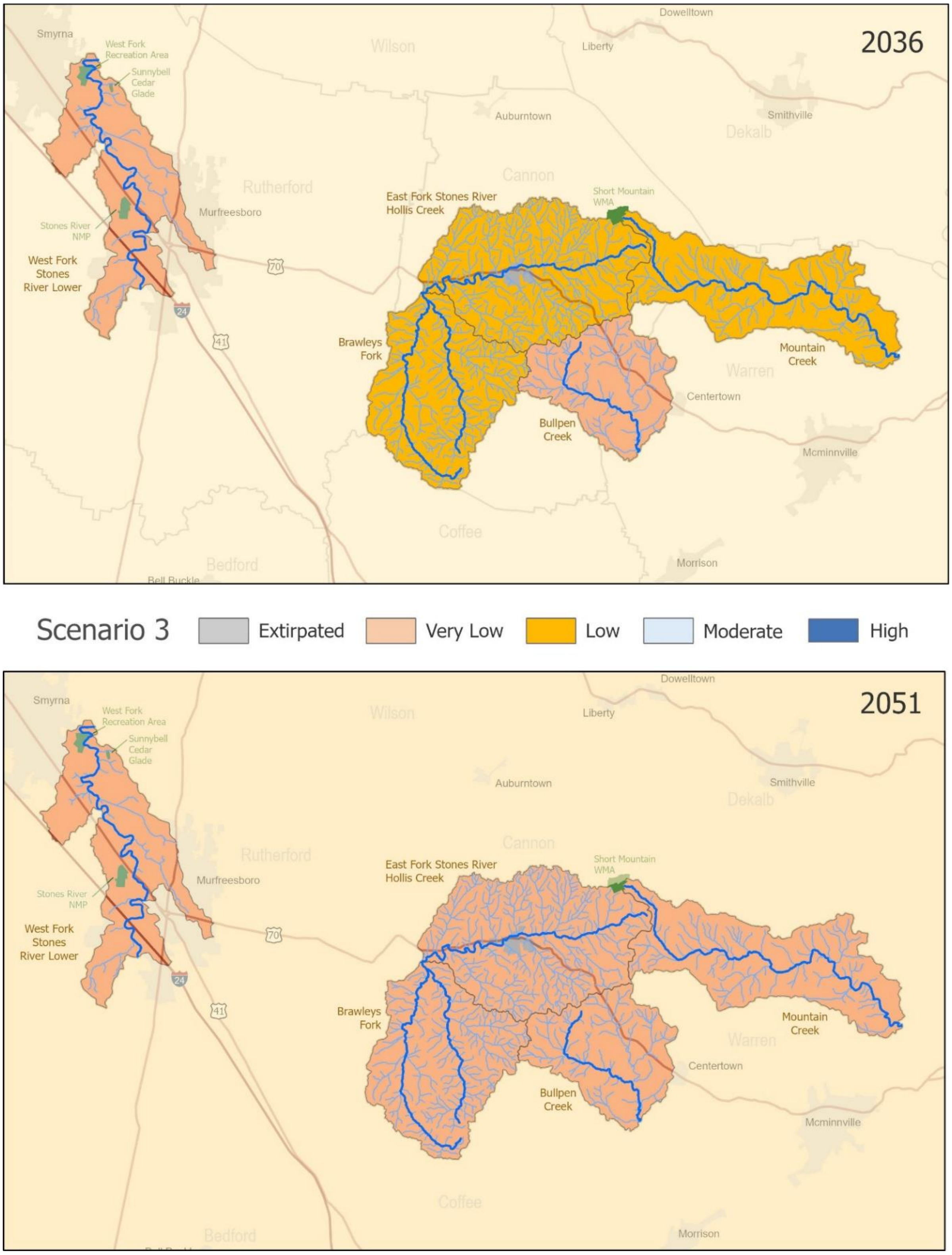
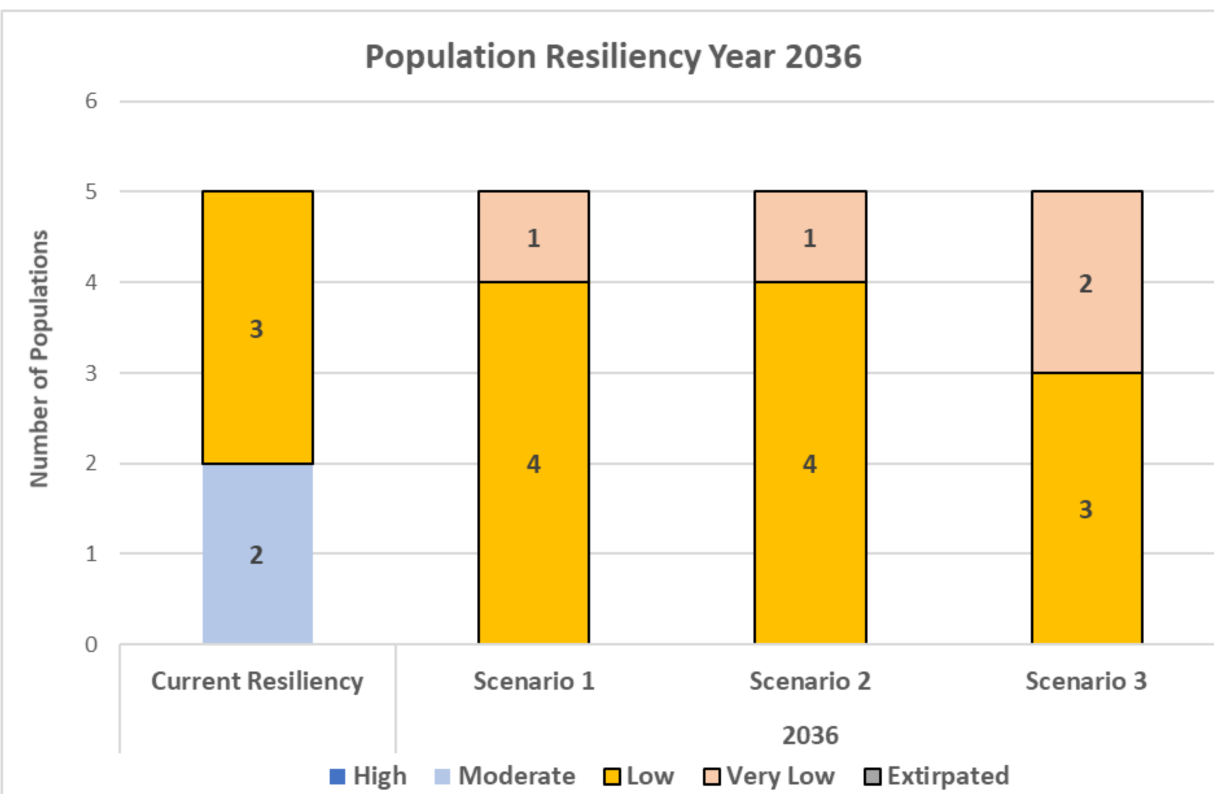


Figure 5.3: Future resiliency class for Brawleys Fork crayfish analysis units in 2036 and 2051 under Scenario 3.

Table 5.4: Number of Brawleys Fork crayfish analysis units within each resiliency condition class by scenario and timestep.

Brawleys Fork crayfish		Resiliency Condition Category					Total Extant Populations
		High	Moderate	Low	Very Low	Extirpated	
	Current Resiliency	0	2	3	0	0	5
2036	Scenario 1	0	0	4	1	0	5
	Scenario 2	0	0	4	1	0	5
	Scenario 3	0	0	3	2	0	5
2051	Scenario 1	0	0	4	1	0	5
	Scenario 2	0	0	3	2	0	5
	Scenario 3	0	0	0	5	0	5



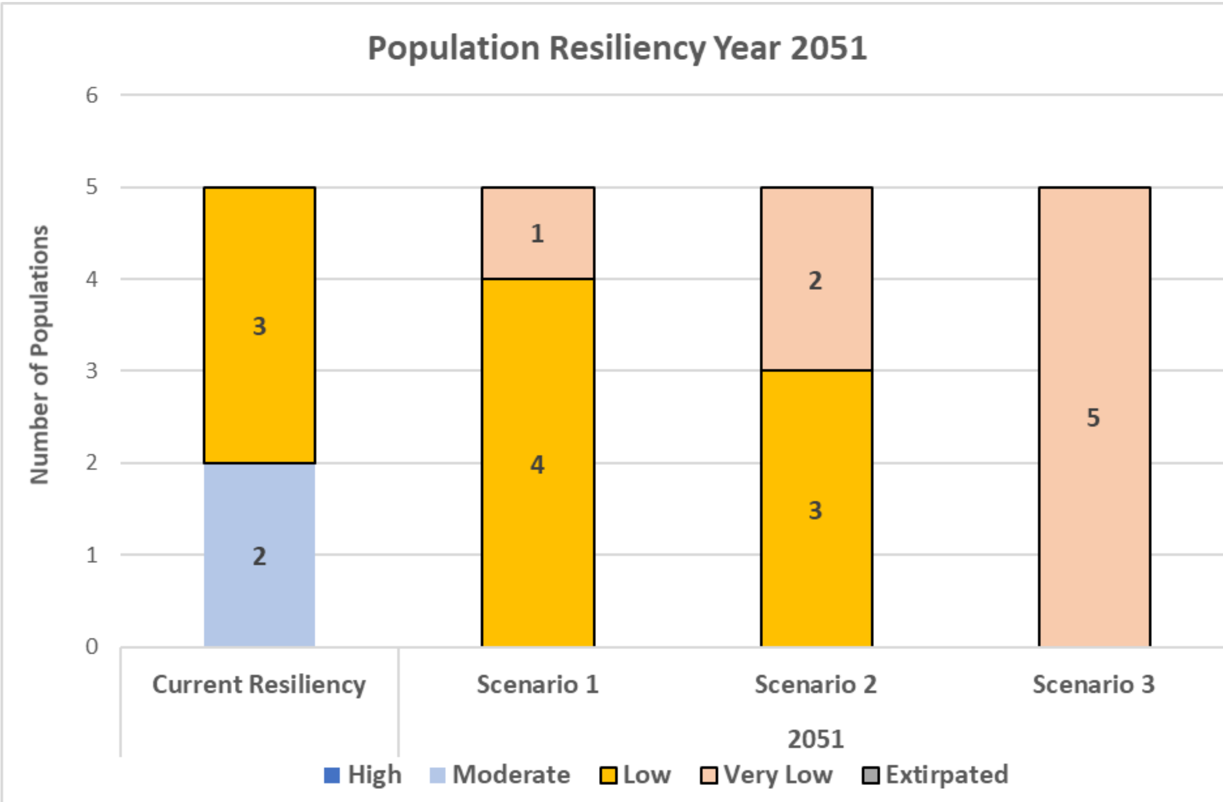


Figure 5.4: Number of Brawleys Fork crayfish analysis units within each resiliency condition class by scenario and timestep.

5.2.2 Future Species Redundancy

Brawleys Fork crayfish redundancy is projected to decline under all future scenarios. We define a resilient population as one with high or moderate resiliency. The number of AUs exhibiting moderate resiliency declines under all scenarios. As Brawleys Fork crayfish resiliency decreases as projected in the future, we expect redundancy for the species to also decrease under all future scenarios in 15 years and 30 years (Table 5.3 and 5.4) due to reductions in resiliency in all AUs. In both timesteps under Scenario 1 and in 2036 under Scenario 2, at least four of the five AUs are projected to decline in resiliency. In the 2051 timestep under Scenario 2 and in 2036 under Scenario 3, all AUs decline in resiliency class. In 2051 under Scenario 3, all AUs are projected to decline to very low resiliency. Therefore, the distribution of Brawleys Fork crayfish is projected to remain the same at the AU level in most future scenarios, although specific occurrences are expected to blink out or shift in location.

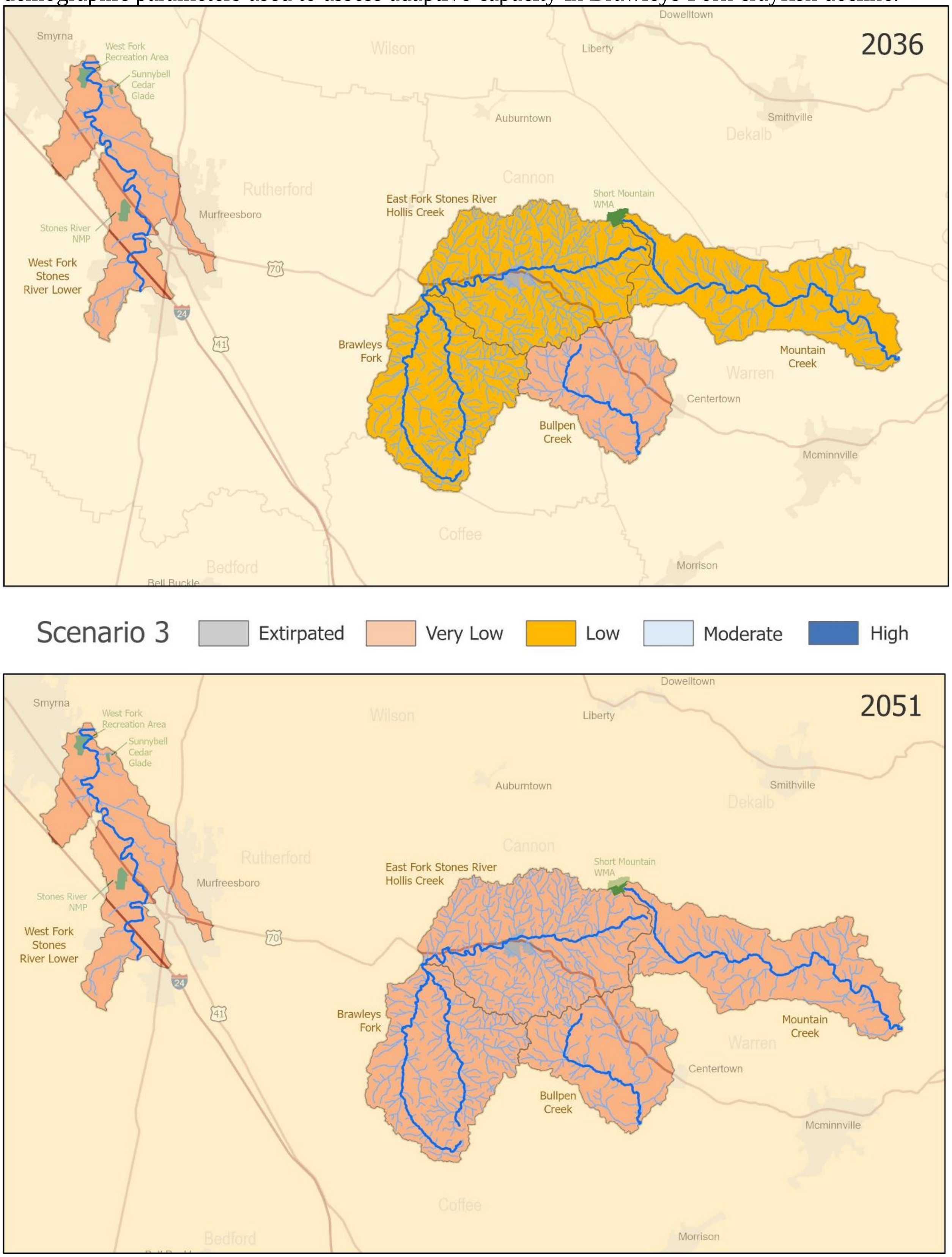
5.2.3 Future Species Representation

As Brawleys Fork crayfish AU resiliency declines, the parameters we use to measure representation are expected to decline as well. Abundance, extent and age class distribution are expected to be reduced in the future under all scenarios. Brawleys Fork crayfish representation is expected to decline at the species level in the projected future scenarios.

5.3 Summary of Future Conditions and Viability

In 2036, resiliency is estimated to decrease by at least one resiliency class in three of the five Brawleys Fork crayfish AUs under all future condition scenarios (Table 5.3). Two AUs (Bullpen Creek and Mountain Creek) are projected to maintain low resiliency under Scenario 1 and Scenario 2. However, the Bullpen Creek AU is projected to exhibit very low resiliency under Scenario 3 (Table 5.3). The Mountain Creek unit maintains low resiliency under Scenario 3. No AUs are estimated to maintain moderate resiliency in 15 years under any future condition scenario (Table 5.3). Redundancy is expected to decline as a function of loss of resiliency in the AUs, although no AUs are projected to be extirpated and the distribution of the species across the range is projected to remain at the current level. Representation is expected to be reduced as the demographic parameters used to assess adaptive capacity in Brawleys Fork crayfish decline.

In 30 years, resiliency is estimated to generally decrease in all five Brawleys Fork crayfish AUs under all future condition scenarios (Table 5.3). No AUs are estimated to maintain moderate resiliency (Table 5.3). Under Scenario 1, three AUs decrease by one resiliency class and two AUs maintain the current level of low resiliency. Under Scenario 2, four AUs decrease by a resiliency class and only Mountain Creek maintains its current low resiliency. Under Scenario 3, all AUs are in very low resiliency; however, no extirpations are projected. Redundancy is expected to decline as a function of loss of resiliency in the AUs, although no AUs are projected to be extirpated and the distribution of the species across the range is projected to remain at the current level. Representation is expected to be reducedas the demographic parameters used to assess adaptive capacity in Brawleys Fork crayfish decline.



LITERATURE CITED

Adams, S. B. 2013. Effects of small impoundments on downstream crayfish assemblages. Freshwater Science 32(4):1318-1332.

Arnwine, D. H., K. J. Sparks, and R. R. James. 2006. Probabilistic monitoring of streams below small impoundments in Tennessee. Tennessee Department of Environmental and Conservation Division of Water Pollution Control. Nashville, TN.

Barnett, Z. C., S. B. Adams. 2021. Review of dam effects on native and invasive crayfishes illustrates complex choices for conservation planning. Frontiers in Ecology and Evolution 8:621-723.

Beever, E. A., J. O'Leary, C. Mengelt, J. M. West, S. Julius, N. Green, D. Magness, L. Petes, B. Stein, A. B. Nicotra, and J. J. Hellmann. 2016. Improving conservation outcomes with a new paradigm for understanding species' fundamental and realized adaptive capacity. Conservation Letters 9:131-137.

Belyea, C. M and A. J. Terrando. 2013. Urban growth modeling for the SAMBI Designing Sustainable Landscapes Project. North Carolina State University. http://www.basic.ncsu.edu/dsl/urb.html. <Accessed 15 May 2021>

Bouchard, R. W. 1975. Geography and ecology of crayfishes of the Cumberland Plateau and Cumberland Mountains, Kentucky, Virginia, Tennessee, Georgia, and Alabama. Natioanl Museum of Natural History. Washington, D.C. 585-595.

Bouchard, R. W. and J. W. Bouchard. 1995. Two new species and subgenera (*Cambarus* and *Orconectes*) of crayfishes (Decapoda: Cambaridae) from the eastern United States. Notulae Naturae 471:1-20.

Burskey, J. L. and T. P. Simon. 2009. Reach- and watershed-scale associations of crayfish within an area of varying agricultural impact in west-central Indiana. Conservation, Biology, and Natural History of North American Crayfishes Southeastern Naturalist 8 (Special Issue 3): 193-210.

Carroll, R., C. Augspurger, A. Dobson, J. Franklin, G. Orians, W. Reid, R. Tracy, D. Wilcove, and J. Wilson. Strengthening the use of science in achieving the goals of the endangered species act: An assessment by the Ecological Society of America. Ecological Applications 1996 (6):1–11.

Center for Biological Diversity (CBD). 2010. Petition to list 404 aquatic, riparian and wetland species from the Southeastern United States as threatened or endangered under the Endangered Species Act. April 20, 2010. 1145p.

Chaudhuri, G., and K. C. Clarke 2013. The SLEUTH land use change model: a review. The International Journal of Environmental Resources Research 1:88–104.

Climate Explorer. 2021. https://crt-climate-explorer.nemac.org/. Accessed July 2, 2021.

Coulston, J. W., G. G. Moisen, B. T. Wilson, M. V Finco, W. B. Cohen, and C. K. Brewer. 2012. Modeling percent tree canopy cover—A pilot study: Photogrammetric Engineering and Remote Sensing, v. 78, no. 7, p. 715–727.

Crandall, K. A., O. R. Bininda-Emonds, G. M. Mace, R. and K. Wayne. 2000. Considering evolutionary processes in conservation biology. Trends in Ecology & Evolution 15:290-295.

Crandall, K. A. and S. DeGrave. 2017. An updated classification of the freshwater crayfishes (Decapoda: Astacidae) of the world, with a complete species list. Journal of Crustacean Biology 1-39.

Etnier, D. A. and W. C. Starnes. 1993. The Fishes of Tennessee. The University of Tennessee Press/ Knoxville 1-689.

Esri Inc. 2021. ArcGIS Pro (Version 2.8.2). Redlands, CA. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.

Fagan, W. F. 2002. Connectivity, Fragmentation, and Extinction Risk in Dendritic Metapopulations. Ecology 83(12):3243-3249.

Frankham, R. 1995. Conservation genetics. Annual Review of Genetics 29:305-327.

Frankham, R. 2005. Genetics and extinction. Biological Conservation 126:131-327.

Giddens, D. W. and H. T. Mattingly. 2020. Life history and habitat requirements of Brawleys Fork crayfish, *Cambarus williami*. Interim Report submitted to Tennessee Wildlife Resources Agency, Nashville, TN.

Grubb, B. 2019. Phylogeography and population genetics of a headwater-stream adapted crayfish, *Cambarus prisitnus* (Decapoda: Cambaridae), from the Cumberland Plateau in Tennessee. (No. 27672344). Master's thesis, Austin Peay State University, Clarksville, TN. ProQuest Dissertations Publishing.

Hartfield, E. E. 2010. Consequences of Low-head Dams on Crayfish Distribution and Gene Flow in Alabama Streams. Master's thesis, Auburn University, Auburn, AL. Retrieved from Auburn University Electronic Theses and Dissertations. (http://etd.auburn.edu/handle/10415/2274).

Homer, C., J. Dewitz, S. Jin, G. Xian, C. Costello, P. Danielson, L. Gass, M. Funk, J. Wickham, S. Stehman, R. Auch, and K. Riitters. 2020. Conterminous United States land cover change patterns 2001–2016 from the 2016 National Land Cover Database: ISPRS Journal of Photogrammetry and Remote Sensing, v. 162, p. 184–199.

Jantz, C. A., S. J. Goetz, D. Donato, and P. Claggett. 2010. Designing and implementing a regional urban modeling system using the SLEUTH cellular urban model. Computers, Environment, and Urban Systems 34:1-16.

Johansen, J. W. 2018. Using multiscale rarity patterns to inform conservation actions in a diverse and understudied taxonomic group. (No. 10980046). Doctoral dissertation, Tennessee Technological University, Cookeville, TN. ProQuest Dissertation Publishing.

Johansen, J.W. 2021. Fisk University, formerly with Austin Peay University. Expert elicitation meeting held virtually April 5, 2021.

Jones, J. R., J. S. Schwartz, K. N. Ellis, J. M. Hathaway, C. M. Jawdy. 2015. Temporal variability of precipitation in the Upper Tennessee Valley. Journal of Hydrology 3:125-138.

Kaplan, L. A., T. L. Bott, J. K. Jackson, J. D. Newbold, B. W. Sweeney. 2008. Protecting Headwaters: The Scientific Basis for Safeguarding Stream and River Ecosystems. Research synthesis from Stroud Water Research Center, Avondale, PA.

Kaur, R., A. Akuley-Amenyenu, K. G. Garner, and S. O. Dennis. 2020. Detection of human pharmaceuticals in the surface water of East Fork Stones River. Journal of Water Resource and Protection 12:240-259.

Lockaby, G., C. Nagy, J. Vose, C. Ford, G. Sun, S. G. Mcnulty, P. V. Caldwell, E. Cohen, J. M. Moore. 2013. Forests and water. In: Wear DN, Greis JG, eds. 2013. The southern forest futures project: technical report. General Technical Report SRS-GTR-178. Asheville, North Carolina: USDA-Forest Service, Southern Research Station. 178:309-339.

Mangal, M. and C. Tier. 1993. A simple direct method for finding persistence times of populations and application to conservation problems. Proceedings of the National Academy of Sciences of the USA 90:1083-1086.

Martin, K. L., T. Hwang, J. M. Vose, J. W. Coulston, D. N. Wear, B. Miles, L. E. Band. 2017. Watershed impacts of climate and land use changes depend on magnitude and land use context. Ecohydrology 10: e1870. (https://doi.org/10.1002/eco.1870.)

Mattingly, H. 2021. Tennessee Tech University. Expert elicitation meeting held virtually April 5, 2021.

Mohseni, O., T. R. Erickson, and H. G. Stefan. 1999. Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario. Water Resources Research 35(12):3723-3733.

National Climate Change Viewer (NCCV). 2021. https://www2.usgs.gov/landresources/lcs/nccv.asp. Accessed August 23, 2021.

Nakicenovic, N., J. Alcamo, G. Davis, B. Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T. Y. Jung, T. Kram, E. L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H.

Pitcher, L. Price, K. Riahi, A. Roehrl, H. H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. Van Rooijen, N. Victor, Z. Dadi. 2000. Special Report of Emissions Scenarios. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Nicotra, A.B., E. A. Beever, A. L. Robertson, G. E. Hofmann, and J. O'Leary. 2015. Assessing the components of adaptive capacity to improve conservation and management efforts under global change. Conservation Biology 29:1268-1278.

Nissenbaum, M. 2016. Climate change effects on precipitation organization: a summertime case study in the southeast United States. Master's thesis, East Carolina University, Greenville, NC. Retrieved from The Scholarship. (http://hdl.handle.net/10342/6030.)

Poff, L. and M. Brinson, J. Day. 2002. Aquatic ecosystems and global climate change: Potential impacts on inland freshwater and coastal wetland ecosystems in the United States. Pew Center on Global Climate Change: 1-44.

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

Rohrbach, G. M. and D. I. Withers. 2006. A status survey of the Caney Fork Crayfish (*Cambarus pristinus*) and Hardin County crayfish (*Orconectes wrighti*) with notes on the Brawley's Fork crayfish (*Cambarus williami*). Tennessee Natural Heritage Program. Final Report Contract No. ID-06-08125-00.

Romano, N. and C. Zeng. 2013. Toxic effects of ammonia, nitrite, and nitrate to decapod crustaceans: A review on factors influencing their toxicity, physiological consequences, and coping mechanisms. Reviews in Fisheries Science 21(1):1-21.

Schmidt, J. E. 1982. The freshwater mussels of the Stones River above J. Percy Priest Reservoir. Master's thesis, Tennessee Technological University, Cookeville, TN.

Schorr, M. S., M.C. Dyson, C. H Nelson, G. S. Van Horn, D. E. Collins, S. M. Richards. 2013. Effects of streams acidification on lotic salamander assemblages in a coal-mined watershed in the Cumberland Plateau. Journal of Freshwater Ecology 28(3):339–353.

Sgro, C. M., A. J. Lowe, and A.A. Hoffmann. 2011. Building evolutionary resilience for conserving biodiversity under climate change. Evolutionary Applications 4:326-337.

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

Simmons, J. 2021. Tennessee Valley Authority. Expert elicitation meeting held virtually April 5, 2021.

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

Sohl, T. L., K. L. Sayler, M. A. Bouchard, R. R. Reker, A. M. Freisz, S. L. Bennett, B. M. Sleeter, R. R. Sleeter, T. Wilson, C. Soulard, M. Knuppe, and T. Van Hofwegen. 2014. Spatially explicit modeling of 1992 to 2100 land cover and forest stand age for the conterminous United States. Ecological Applications 24(5):1115-1136. https://doi.org/10.1890/13-1245.1

Sohn, L., R. J. Brodie, G. Couldwell, E. Demmons, and J. Sturve. 2018. Exposure to a nicotinoid pesticide reduces defensive behaviors in a non-target organisms, the rusty crayfish *Orconectes rusticus*. Ecotoxicology 27:900-907.

Suttles, K. M., N. K. Singh, J. M. Vose, K. L. Martin, R. E. Emanuel, J. W. Coulston, S. M. Saia, and M. T. Crump. 2018. Assessment of hydrologic vulnerability to urbanization and climate change in a rapidly changing watershed n the Southeast U.S. Science of the Total Environment 645:806-816.

Tennessee Department of Environment and Conservation (TDEC) Division of Water Pollution Control Watershed Management Section. 2003a. Collins River Watershed (05130107) of the Cumberland River Basin Watershed Water Quality Management Plan.

Tennessee Department of Environment and Conservation (TDEC) Division of Water Pollution Control Watershed Management Section. 2003b. Stones River Watershed (05130203) of the Cumberland River Basin Water Quality Management Plan.

Tennessee Department of Environment and Conservation (TDEC). 2021. https://www.tn.gov/environment/permit-permits/water-permits1/inter-basin-transfer-permit.html. Accessed September 12, 2021.

Tennessee State Wildlife Action Plan Team (TN-SWAP). 2015. Tennessee State Wildlife Action Plan 2015. Tennessee Wildlife Resources Agency. Nashville, TN. http://twraonline.org/2015swap.pdf. October 3, 2021.

Tennessee Wildlife Resources Agency (TWRA). 2018. Northern Cumberlands Resources Habitat Conservation Plan. Tennessee Wildlife Resources Agency, Nashville, TN. 184 pp.

Thurman, L., B. Stein, Es. Beever, W. Foden, S. Geange, N. Green, J. Gross, D. Lawrence, O. LeDee, J. O'Leary, J. Olden, L. Thompson, and B. Young. 2020. Persist in place or shift in space? Evaluating the adaptive capacity of species to climate change. Frontiers in Ecology & the Environment 18(9):520-528. https://doi.org/10.1002/fee.2253

Terando, A. J., J. Costanza, C. Belyea, R. R. Dunn, A. McKerrow, and J. A. Collazo. 2014. The southern megalopolis: Using the past to predict the future of urban sprawl in the Southeast U.S. PLoS ONE 9(7): e102261. doi:10.1371/journal.pone.0102261.

U.S. Drought Monitor. 2021. https://droughtmonitor.unl.edu/. Accessed April 14, 2021.

U.S. Environmental Protection Agency (EPA). 2014. NHDPlus (Version 2). https://www.epa.gov/waterdata/ nhdplus-national-hydrography-dataset-plus

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

Van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J. F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. T. Smith, and S. K. Rose. 2011. The representative concentration pathways: an overview. Climate Change 109:5-31.

Westhoff, J. T., and A. E. Rosenberger. 2016. A global review of freshwater crayfish temperature tolerance, preference, and optimal growth. Reviews in Fish Biology and Fisheries 26:329–349.

Williams, C. 2021. Tennessee Wildlife Resources Agency. Expert elicitation meeting held virtually April 5, 2021.

Williams, C. E., R. D. Bivens, B. D. Carter. 2017. Key to the crayfishes of Tennessee, abstracted from H.H. Hobbs Jr. 1972, H.H. Hobbs Jr. 1981, and Bouchard 1978 and annotated list of crayfishes of Tennessee. Tennessee Wildlife Resources Agency.

Withers, D. I., R. A. McCoy. 2005. Distributional surveys for *Cambarus pristinus* and *Cambarus williami*, two endangered crayfish in Tennessee. Tennessee Division of Natural Heritage. Final Report Contract No. ID-05-0828-00.

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 65:200–207.

World Population Review. 2021. https://worldpopulationreview.com/us-counties. Accessed May 2021.

Zackay, A. 2007. Random genetic drift and gene fixation. [online] https://www.metabolic-economics.de/pages/seminar_theoretische_biologie_2007/ausarbeitungen/zackay.pdf [Accessed 21 June 2018]

Zuber, B. C. 2014. Post-Spawning Distribution, Abundance, and Species-Habitat Associations of the Barrens Darter (*Etheostoma forbesi*). Doctoral dissertation, Tennessee Technological University, Cookeville, TN.

APPENDIX A

Table A1: Demographic parameter scores for Brawleys Fork crayfish analysis units. ** denotes assumed population age class distribution score of Very Low based on the available abundance date (i.e., if there is abundance data, then there must be at least one age class).

Analysis Unit/ Subwatershed (HUC 12)	Stream	Extent	Demographic Parameter Scores			Total Resiliency Score (Habitat+Demographic)
			Abundance	Population Age Class Distribution	Total Demographic Score (Out of 12)	
Hollis Creek – East Fork Stones River (051302030102; 115 mid-level catchments)	*AU average*	3	2.44	1.56	7.00	5.10 + 7.00 = **12.10 Moderate**
	East Fork Stones River	Moderate (3) (34%; no adjustment)	High (4)	Moderate (3)		
	Locke Creek		Low (2)	Very Low** (1)		
	Rush Creek		Low (2)	Very Low** (1)		
	Doolittle Branch		Very Low (1)	Very Low** (1)		
	Cavender Branch		No Data	No Data		
	Rockhouse Creek		Low (2)	Very Low** (1)		
	Seal Hollow Branch		Moderate (2)	Very Low** (1)		
	Shanborne Branch		Low (2)	Very Low** (1)		
	Parchorn Hollow Branch		No Data	No Data		
	Hill Creek		Low (2)	Very Low** (1)		

	Hollis Creek		High (4)	High (4)		
Brawleys Fork (051302030101; 73 mid-level catchments)	*AU Average*	2	2.67	2.00	6.67	5.94 + 6.67 = **12.61 Moderate**
	Brawleys Fork	Low (2) (24.7%; no adjustment)	High (4)	High (4)		
	Carson Fork		No Data	No Data		
	Duck Branch		No Data	No Data		
	Smith Branch		No Data	No Data		
	Shelton Branch		Very Low (1)	Very Low** (1)		
	Haws Spring Fork		Moderate (3)	Very Low** (1)		
Lower West Fork Stones River (051302030206; 23 mid-level catchments)	*AU Average*	1	3	3	7.00	4.00 + 7.00 = **11.00 Low**
	West Fork Stones River	Very Low (1) (4.3%; no adjustment b/c it's already very low)	Moderate (3)	Moderate (3)		
Bullpen Creek (051301070201; 73 mid-level catchments)	*AU Average*	1	2	2	5.00	6.00 + 5.00 = **11.00 Low**
	Bullpen Creek	Very Low (1) (1.4%; no adjustment b/c it's already very low)	Low (2)	Low (2)		
	AU Average	1	3	4	8.00	4.00 + 8.00 = **12.00 Moderate**

Mountain Creek (051301070402; 52 mid-level catchments)	Mountain Creek	Very Low (1) (3.8%; no adjustment b/c it's already very low)	Moderate (3)	High (4)		

Table A2: Habitat parameter scores for each Brawleys Fork crayfish analysis unit.

Analysis Unit/Subwatershed (HUC 12)	Average Riparian Canopy Cover (adjusted score)	Average Percent Urban and Agricultural Land Cover (adjusted score)	Drought Score	Total Adjusted Habitat Score (Out of 12)
Hollis Creek – East Fork Stones River	1.62	1.49	2	5.10
Brawleys Fork	2.06	1.89	2	5.94
Lower West Fork Stones River	1.00	1.00	2	4.00
Bullpen Creek	3.00	1.00	2	6.00
Mountain Creek	1.00	1.00	2	4.00

APPENDIX B

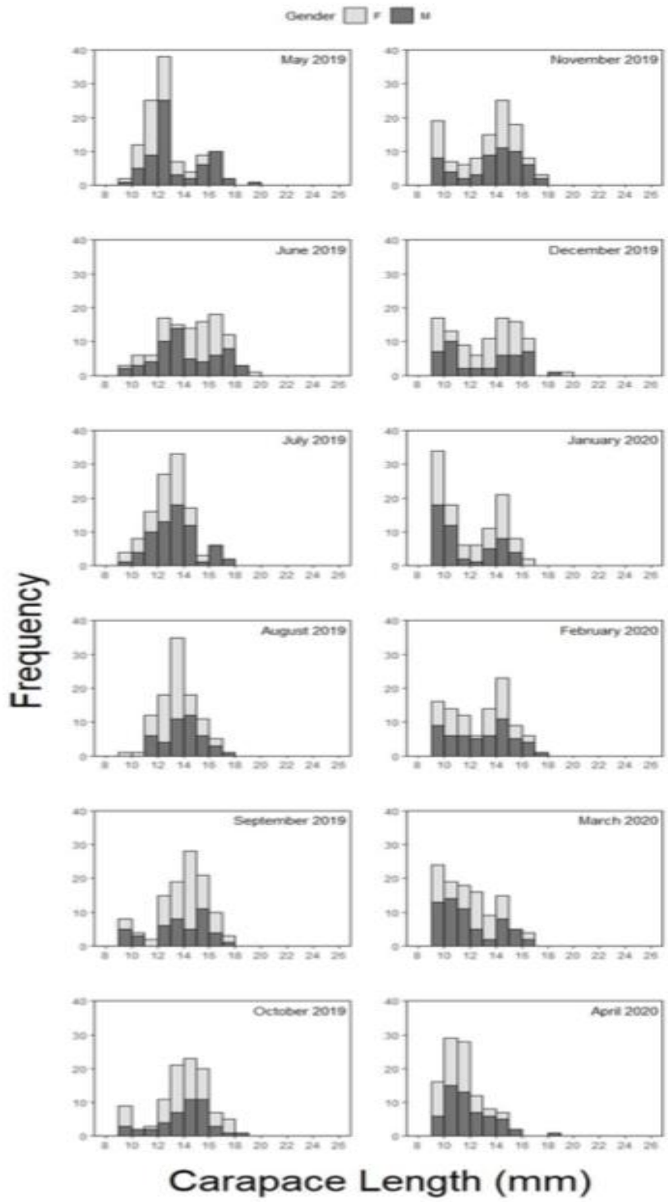


Figure B1: Length frequency histograms of Brawleys Fork crayfish individuals collected from East Fork Stones River (Giddens and Mattingly 2020, p. 14).

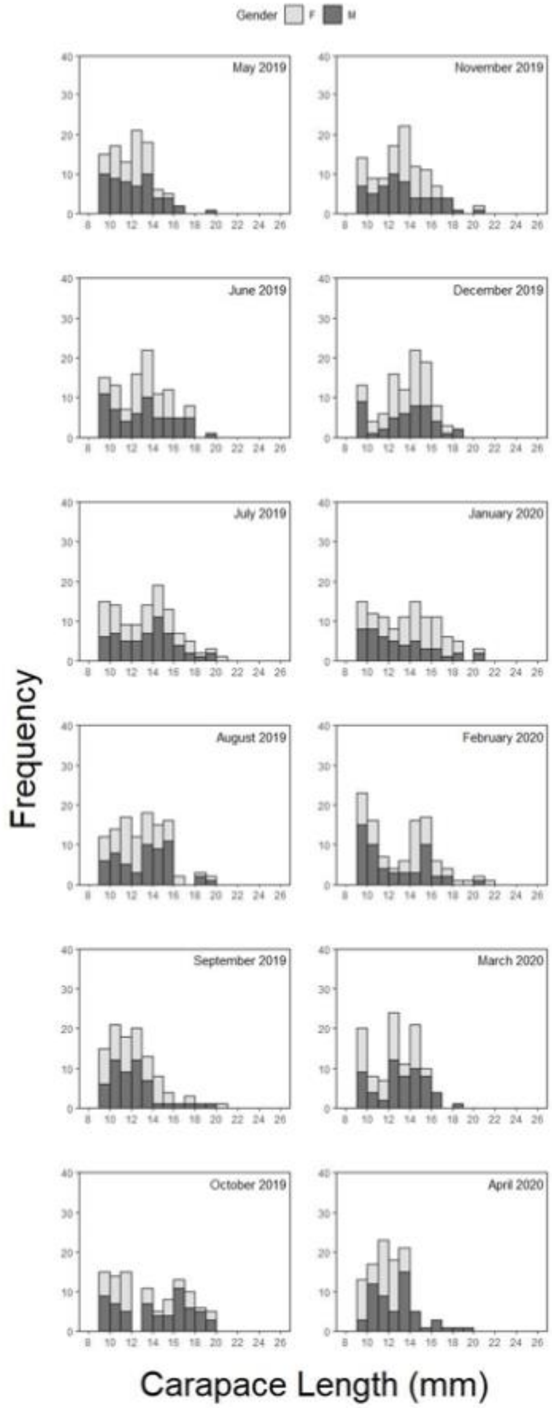


Figure B2: Length frequency histograms of Brawleys Fork crayfish individuals collected from Hollis Creek (Giddens and Mattingly 2020, p. 15).

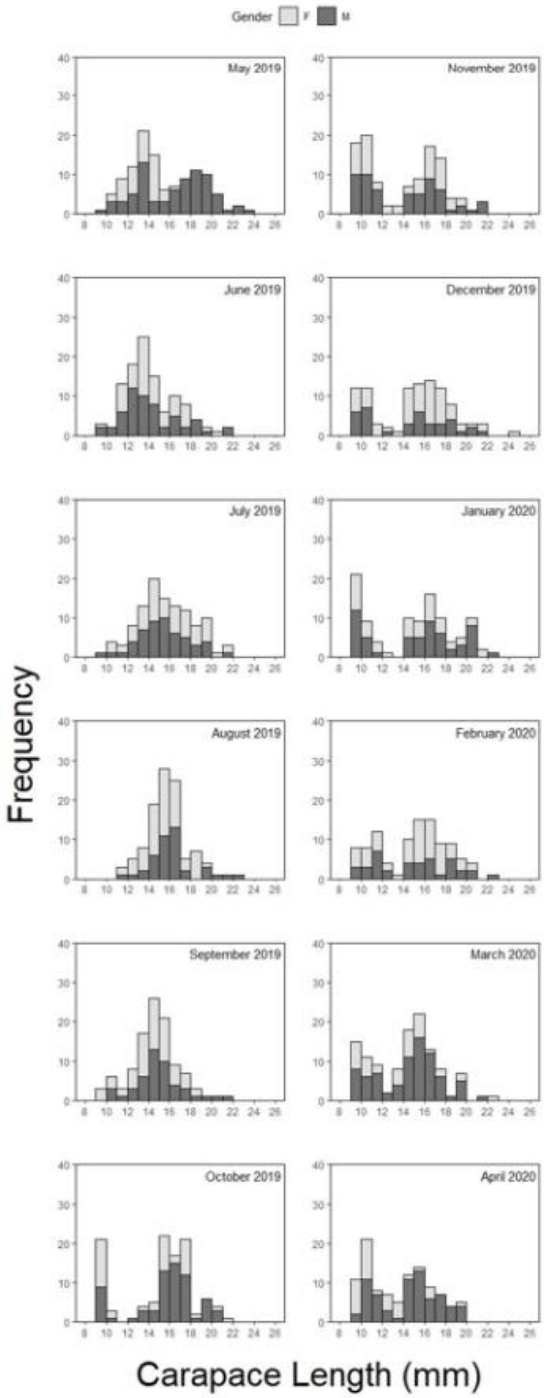


Figure B3: Length frequency histograms of Brawleys Fork crayfish individuals collected from Mountain Creek (Giddens and Mattingly 2020, p. 16).