Historical Assessment of Freshwater Mussel Communities in the Duck River, Tennessee: Seven Decades of Change in a Biodiversity Hotspot

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Executive Summary

The Duck River in Tennessee supports one of the most biologically diverse freshwater mussel communities in North America, historically harboring over 70 species. This comprehensive historical assessment, based on a database of over 7,000 mussel records spanning from the early 1800s to 2023, documents significant changes in mussel community structure while highlighting the continued global importance of this system for freshwater mussel conservation (Womble and Rosenberger 2025). Sixty-two mussel species remain extant in the Duck River watershed, with the core area of diversity concentrated within approximately 50 river miles between Columbia and Lillard Mill (less than 18% of the river's total length). Reported species richness has declined at 85% of surveyed sites, including at Lillard Mill and Columbia, which have decreased by 14 and 11 species, respectively. Mussel species extirpated from the Duck River are predominantly either extinct, such as the Yellow Blossom (*Epioblasma florentina)* and Turgid Blossom (*Epioblasma turgidula*), or federally endangered taxa that are naturally rare across their range, including the Cracking Pearlymussel (*Hemistena lata*), Golden Riffleshell (*Epioblasma aureola*), and Littlewing Pearlymussel (*Pegias fabula*). Several species that are common in other systems, such as the Lilliput (*Toxolasma parvum*) and Flat Floater (*Utterbackiana suborbiculata*), may persist in the Duck River at densities below detection thresholds, particularly in the lower mainstem where survey coverage has been limited. Significant data gaps identified in the lower Duck River limit our understanding of mussel community conditions across the entire watershed, and expanded survey efforts would enhance the assessment of drainage-wide trends.

Data indicate that mussel species richness declines began in the Duck River as early as the 1960s, coinciding with other enigmatic declines of freshwater mussels throughout the Southeastern United States (Haag 2019). Rebounds of mussel communities were observed in the early 2000s, and species richness was higher than in the late 1970s and late 1980s (Ahlstedt et al. 2017). While overall species richness was lower in the early 2000s than in the 1920s, site-specific declines in richness are not statistically significant (Ahlstedt et al. 2017), indicating a potential return toward historical species richness for some river reaches. This recovery has been attributed to reservoir release improvements at Normandy Dam, reduction of point source pollution, farmland acquisition and removal, and channel restoration from past destabilization events (Ahlstedt et al. 2017). Mussel community conditions in some river reaches, such as Shelbyville and above Normandy Dam, have not rebounded.

While available data provide insights into general temporal trends in mussel density and abundance in the Duck River, inconsistencies in survey methods and effort limit direct comparisons for most of the watershed. Quantitative surveys since 1979 suggest that mussel densities generally increased in the core area of mussel diversity from the late 1970s to the early 2000s (Ahlstedt et al. 2017). However, long-term monitoring by the Tennessee Wildlife Resources Agency (TWRA) from 2010 to 2020 indicates that densities in this area have declined since 2000. Despite this, some species, such as the Round Hickorynut, have experienced localized population increases (Wisniewski 2020). Trends in mussel abundance outside of the core area are mixed: while some sites (e.g., below Columbia Dam, Leftwich, Tugas Bend) show

documented increases in mussel abundance, others, like Littlelot, have experienced what may be precipitous declines.

Due to inconsistencies in the collection methods of freshwater mussel data in the Duck River, direct temporal comparisons of population metrics such as richness and abundance cannot be obtained in a statistically robust manner drainage-wide. We used the Mussel Assemblage Health Index (MAHI; Haag et a. 2024) to supplement our assessment of mussel community changes throughout the Duck River, allowing us to depict mussel community health at four long-term monitoring sites (Columbia, Venable Spring, Hooper Island, Lillard Mill). MAHI integrates fundamental aspects of mussel communities (species richness, abundance, recruitment, and population growth) to assess overall assemblage health. The tool provides an objective assessment of mussel health in the Duck River that is independent of regional context and individual perception, while still incorporating expert judgment that is often challenging to quantify in analyses. All four sites analyzed met or exceeded the minimum MAHI score for “healthy” assemblages, reflecting the robustness of Duck River mussel communities relative to overall mussel assemblage health in eastern North America. However, intermediate scores and declining densities in 3 of 4 sites highlight the importance of continued monitoring of these communities.

Given increasing anthropogenic stressors, such as water withdrawal demands, land use impacts, and drought events, the development of longer-term datasets using standardized, comparable, and validated data spanning 30 years or more would considerably improve our ability to distinguish natural population variability from anthropogenic impacts (Vaughn and Atkinson 2025). The documented susceptibility of mussel populations to dynamic lags, where environmental impacts may not manifest for several decades, underscores the importance of continued monitoring efforts and mechanistic studies to understand cause-and-effect relationships in freshwater systems (Strayer 2024). Our findings indicate that standardized, consistent monitoring approaches are critical for detecting temporal trends in mussel communities and evaluating conservation effectiveness. This analysis demonstrates the value of integrating multiple assessment frameworks, such as MAHI, with traditional monitoring datasets to provide more comprehensive evaluations of assemblage condition. The concentration of diverse mussel communities within a relatively confined geographic area (approximately 50 river miles) represents both a conservation opportunity and a vulnerability that warrants attention. Prioritizing survey methods that reduce bias and allow for the estimation of abundance will improve the accuracy and comparability of future mussel assemblage assessments. These efforts are especially urgent given the increasing threats to mussel populations in the Duck River (Ahlstedt et al. 2017; Stephenson 2024).

Introduction

Freshwater mussels offer cultural significance, economic value, and a wide variety of ecosystem services. Historically abundant throughout the freshwaters of the Southeastern United States, native mussels held importance for Indigenous cultures as a heavily exploited and supplemental food source (particularly in the winter, when other food resources were scarce; Parmalee and Klippel 1974). Archeological evidence of mussel harvesting dates back 6-10,000 years, suggesting collection and harvest were deeply imbedded in Indigenous cultural practices and ecological knowledge systems, likely impacted by both historical and contemporary declines of freshwater mussels that changed Indigenous people's usage of freshwater mussels in the region (Parmalee and Klippel 1974; Peacock et al. 2005; Noble et al. 2016). In recent history, mussels were an economic resource through the pearl button industry and the cultured pearl industry (Haag 2012). Beyond this direct human use, freshwater mussels provide vital ecosystem services. As filter feeders, mussels remove suspended particles, algae, and bacteria from the water column, with a single mussel capable of filtering up to 40 liters (about half the volume of a mini fridge) of water per day (Vaughn and Hakenkamp 2001; Vaughn et al. 2004). Their filtering and excretion support nutrient cycling by transferring nutrients to the benthos, benefiting other organisms (Atkinson et al. 2014, 2018). Mussels also serve as food for predators and offer habitat structure for algae, insects, and juvenile fish (Haag 2019; Spooner and Vaughn 2006). Mussels can also alter hydraulic and sediment dynamics and stabilize river substrates (Johnson and Brown 2000; Sansom et al. 2020). Despite these critical contributions, freshwater mussels worldwide are one of the most imperiled taxa, with an over 70% rate of imperilment in North America (Williams et al. 1993; Haag and Williams 2014).

The Duck River is a vital resource supporting human populations, various industries, recreation, and one of the world's most biologically diverse aquatic ecosystems. The river, which lies entirely within Tennessee, spans 284 miles and drains over 2,100 square miles, providing drinking water for over 250,000 people. The river originates from a spring in Coffee County and flows into the Tennessee River (Kentucky Lake) in Humphreys County, falling within two physiographic provinces: the Highland Rim and the Central Basin. The Highland Rim, characterized by broad valleys and rolling hills, includes the lower Duck and Buffalo Rivers. In contrast, the Central Basin features steeper valleys and karst topography, and the central portion of the Duck River watershed is located in this province. The upper/middle watershed is primarily composed of Ordovician limestone, gradually changing into Mississippian age formations below Columbia, with thicker chert and clay soils (Knight and Kingsbury 2007). Hydrologically, the watershed is divided into three eight-digit hydrological units: the Lower Duck (HUC 06040003), which drains 1,548 square miles; Upper Duck (HUC 06040002), which drains 1,182 square miles; and Buffalo (HUC 06040004), which drains 763 square miles (Figure 1). The Duck River's flow is influenced by both tributary contributions and groundwater, particularly in the upper Duck River watershed, where limestone and karst features—such as caves, underground streams, and sinkholes—are prevalent. While providing unique and favorable chemical qualities within its surface waters (Stueber and Criss 2005), Karst may render the river particularly vulnerable to low flows and drought (Ford and Williams 2007). Historical streamflow data indicate the section of river between Shelbyville and Columbia may lose up to 30% of aboveground water volume during extended baseflow conditions; this water returns to the river through groundwater recharge at Columbia (Knight and Kingsbury 2007; TDRDA 2011). Groundwater filtration through karst topography may provide dissolved calcium and bicarbonate ions to downstream systems, thereby buffering surface water against pH changes and supporting aquatic life (Allan et al. 2021). The calcium carbonate cycle in the Duck River may help support its distinctive ecological features (e.g., stable pH, calcium for shell-building organisms, like snails and mussels, and support for specialized algal and bacterial communities that are the food base for freshwater mussels). Downstream from where these processes dominate, Fountain Creek contributes a large portion of flow to the lower Duck River, and below Columbia, the underlying geology changes from Ordovician limestone to thicker chert and clay soils with reduced karst influence.

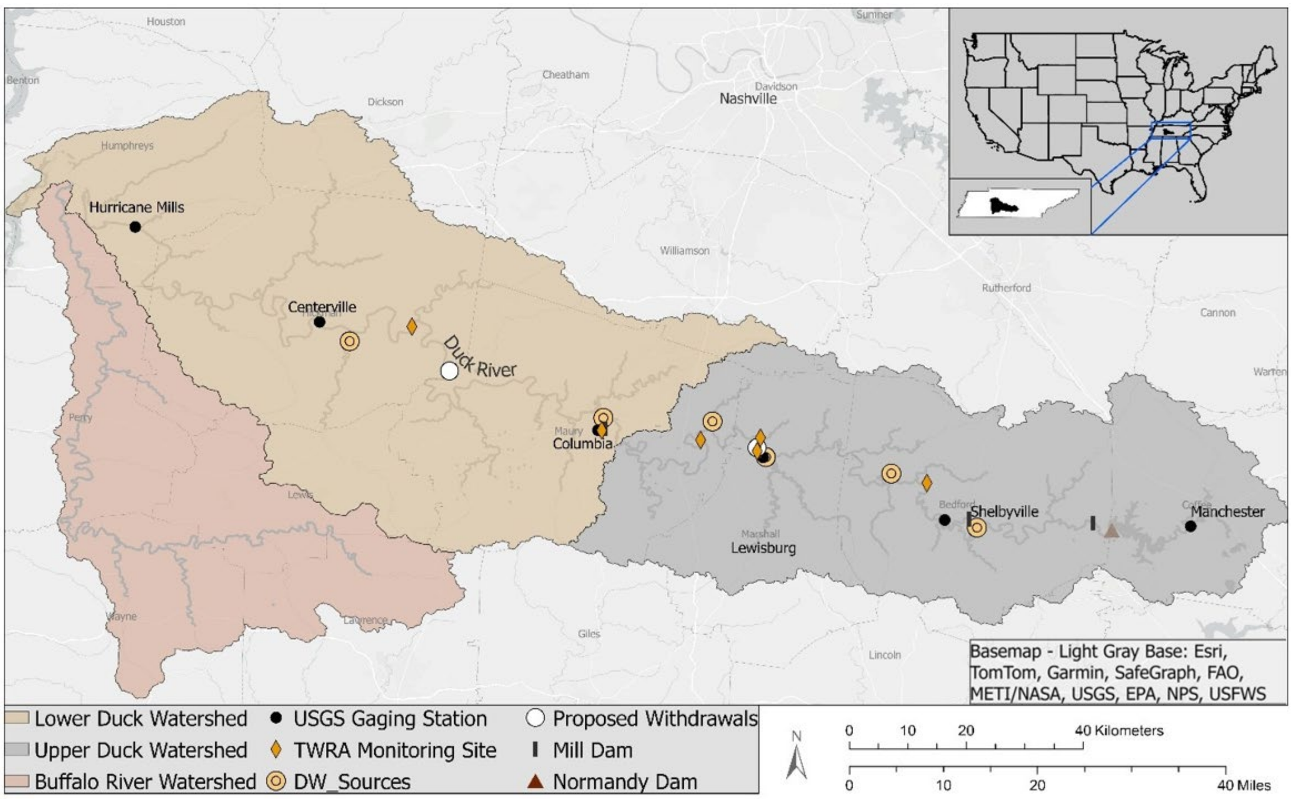


Figure 1. Map of the Duck River and its watershed, indicating location of U.S. Geological Survey (USGS) gaging stations, sites regularly monitored for freshwater mussels by the Tennessee Wildlife Resources Agency, proposed water withdrawals, and existing water withdrawals. The locations of dams, including Normandy Dam and Mill Dams, are also indicated.

The high levels of diversity and endemism in the Duck River have led wildlife, conservation, and academic entities to prioritize the river for conserving freshwater aquatic species biodiversity, including freshwater mussels. The system has high levels of endemism and harbors many federally listed species, including 15 mussel species. A substantial portion of the Duck River is designated as critical habitat for these animals (69 FR 53136, 78 FR 57076, 78 FR 59556, 85 FR 61384). At this time, over 60 miles of the river are included in the Tennessee Scenic Rivers Program, which aims to “preserve and protect the free-flowing, unpolluted and outstanding scenic, recreational, geologic, botanical, fish, wildlife, historic or cultural values of selected rivers or river segments in the state." (TDEC 2025, in reference to the Tennessee Scenic Rivers Act of 1968; Title 11, Chapter 13). This designation covers a stretch from approximately Duck River Mile (DRM) 172.5 to 136.5 (encompassing most of the core area of mussel diversity) and another downstream from DRM 128 to 98. Beyond state borders, the Duck River is recognized as a priority watershed for biodiversity and conservation by government and non-governmental organizations (NGOs) operating at national and global levels and was designated as one of the most endangered rivers by the American Rivers organization in 2024 (Smith et al. 2002; American Rivers 2024).

In a separate project funded by the U.S. Fish and Wildlife Service, the authors of this report compiled all known and reliable data for the Duck River into a single database, from which details on the spatial distributions of freshwater mussel species through time can be obtained (Womble and Rosenberger 2025). Available data and our understanding of freshwater mussel ecology suggest that the Duck River mussel fauna has fluctuated in species composition and spatial distribution throughout human history in accordance with both anthropogenic habitat alteration and natural population dynamics, although information on baseline freshwater mussel population dynamics is generally limited (Haag 2012).

Documentation of mussel communities in the Duck River began with naturalists in the early 1800s and continues into the present day with quantitative, goal-oriented surveys. Documented records of freshwater mussel collections and surveys range from incidental shell collections, casual snorkel surveys, reconnaissance sampling, qualitative timed searches, and quantitative tactile searches using quadrat sampling and scuba diving. Several Federal, State, and educational entities in Tennessee monitor and study freshwater mussel populations in the Duck River. These include, but are not limited to, the U.S. Fish and Wildlife Service, the U.S. Geological Survey, the Tennessee Wildlife Resources Agency, the Tennessee Valley Authority, the Nature Conservancy, academic institutions, and consulting firms. Each of these data sources provides unique information and is useful for a general assessment of how species richness has changed throughout the decades in the Duck River. However, these assessments are subject to incomplete information; the absence of a species from a collection event does not guarantee a verified absence. Furthermore, many historical mussel surveys and collections suffer from unmeasured sampling biases towards larger, easier-to-capture individuals, thereby limiting analysis regarding changes in population demographics (Strayer and Smith 2003; Haag 2012). Sampling methods and effort vary among sampling and survey occasions; therefore, direct comparisons are problematic and should be interpreted cautiously. Our ability to make inferences about long-term changes in mussel populations is also constrained by the characteristics of these disparate surveys that employ variable methods, intensities, and spatial coverage. Another caveat is that little is known regarding freshwater mussel population dynamics, so we do not currently know if the observed changes in density are the result of natural fluctuations in mussel population demographics or a result of true mussel declines (Haag 2012). Additionally, recruitment variation is present within species (e.g., some years are more successful) and among species (e.g., recruitment success and fecundity can vary based on life history strategy (Haag 2012). These challenges are further compounded by ongoing changes in mussel taxonomy and species misidentifications, which complicate spatiotemporal inferences for certain taxa, especially for the tribe *Pleurobemini* (Shea et al. 2011; Inoue et al. 2018; Johnson et al. 2024). Despite this, we describe what available data suggest regarding mussel community changes throughout the history of the Duck River to highlight the extent of our knowledge of this vital ecological and cultural resource. This analysis is intended to reflect available data, and conclusions are subject to change as more records are added to the database and surveys take place. The Duck River is at a pivotal time in its management and ecological history due to significant growth in the human population and economic activity, and the degree to which these watershed changes will affect freshwater mussels is not fully understood.

Our objective in this analysis is to determine distributional and population characteristics of freshwater mussels in the Duck River and detect historical and ongoing changes to mussel communities in this system. Our analysis begins with a historical species richness assessment, summarizing changes in documented species richness through time in relation to watershed activities. We then shift to describe temporal and spatial patterns of mussel abundance and density, followed by a health assessment using the recently published Mussel Assemblage Health Index (Haag et al. 2024). We end the analysis with a brief description of threats to mussels in the Duck River, followed by general findings and conclusions. While the Duck River has been more extensively surveyed for freshwater mussels compared to most drainages in Tennessee, this represents the only drainage-wide, historical assessment of mussel communities in this important system.

Relevant Information Regarding Mussel Data

We conducted this analysis using the aforementioned comprehensive Duck River mussel database. A complete list of database attributes and detailed descriptions of how those attributes were derived is publicly available (Womble and Rosenberger 2025). Several components of this list are directly relevant to this analysis. We differentiated between live mussels, fresh dead shells (tissue intact, shiny nacre), and relic shells (weathered and worn, chalky nacre) when data sources provided this information. Single valve shell records were counted as one individual. Taxonomic assignments follow the Freshwater Mollusk Conservation Society’s 2025 Checklist of Bivalve Names (FMCS 2025).

1. Historical Species Richness Assessment

We defined historical data as a documented observation of a mussel species from the early 1800s to 2023 from a locality regardless of condition (live, fresh dead, or relic). This is an estimate of the highest reported mussel species richness from a site and, therefore, represents a baseline of richness. Available data indicate that the highest mussel diversity in the Duck River was historically between the city of Columbia (46 species) and Lillard Mill (57 species) (Figure 2). Several other historically diverse sites are located between these two localities, such as Leftwich, Venable Spring, Hardison Mill, and Hooper Island (Figure 3).

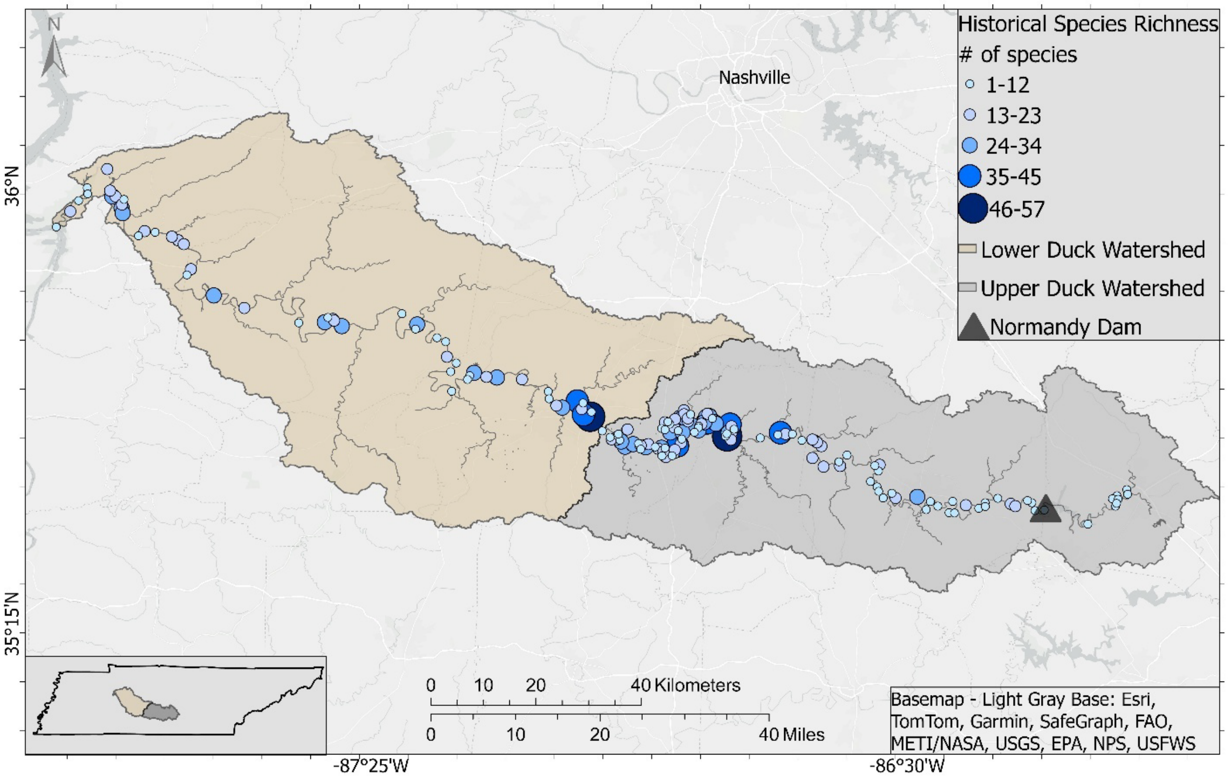


Figure 2. Historical freshwater mussel species richness documented in the Duck River (early 1800s-2023).

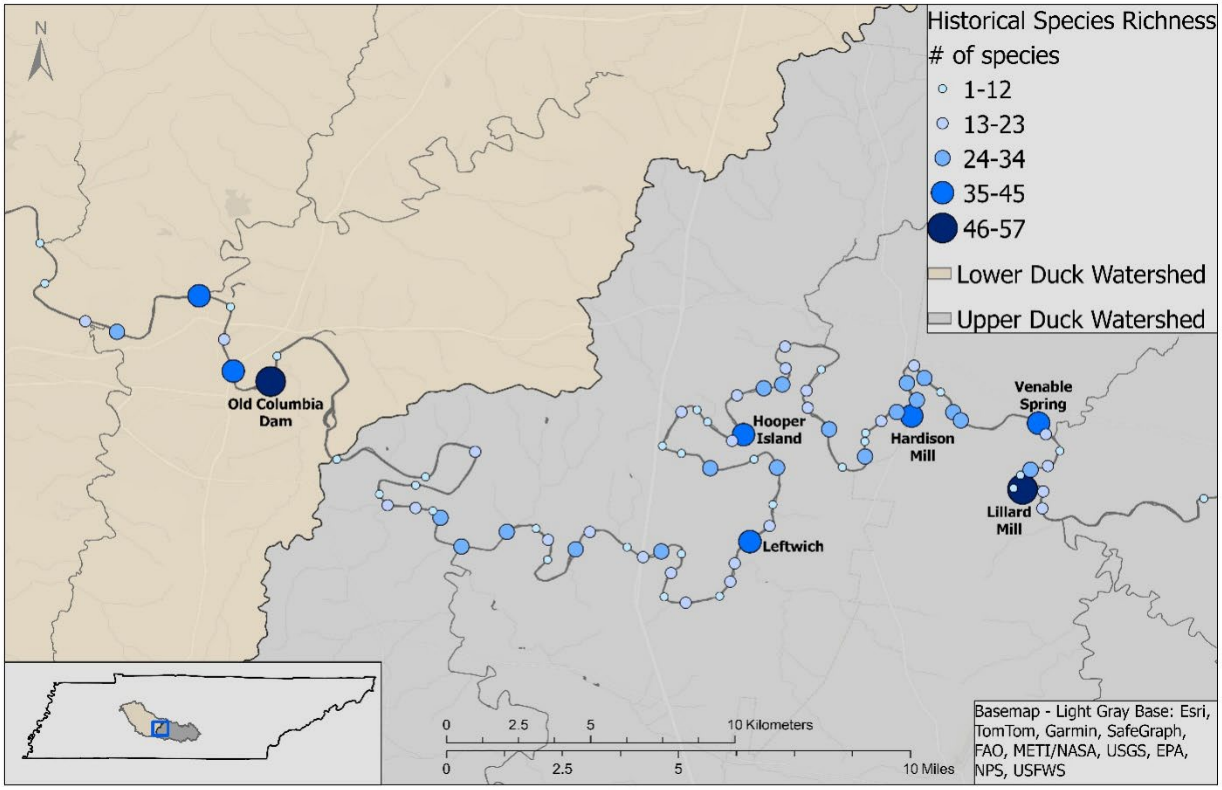


Figure 3. The core area of historical freshwater mussel species richness documented in the Duck River.

Recent mussel records indicate changes in species richness throughout the Duck River's history. Recent data are defined here as confirmed live or fresh dead individuals observed from 2000 to 2023. Both live mussels and fresh dead shell material indicate that a species persists in an area, and live and fresh dead counts are often combined in mussel survey results to represent extant species at a site (e.g., Ahlstedt et al. 2017; Reed et al. 2019). An assessment of recent freshwater mussel collections in the Duck River indicates that the core area of richness persists (Figure 4). Lillard Mill (DRM 179.2) remains the most diverse site, with a richness of 46 species. Available data indicate that overall mussel species richness has declined within this core area and throughout the drainage (Figure 5). Reported species richness has declined at 85% of surveyed sites, including at Lillard Mill and Columbia, which have decreased by 14 and 11 species, respectively.

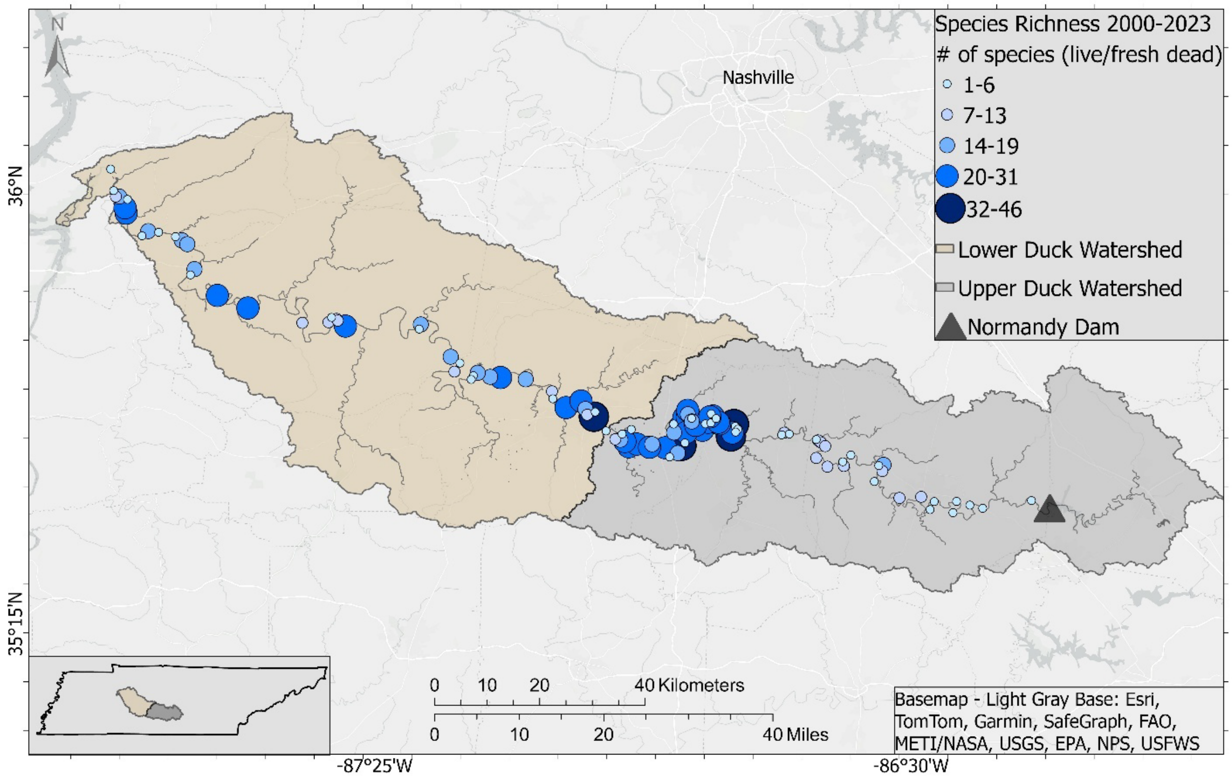


Figure 4. Recent species richness documented in the Duck River (2000-2023).

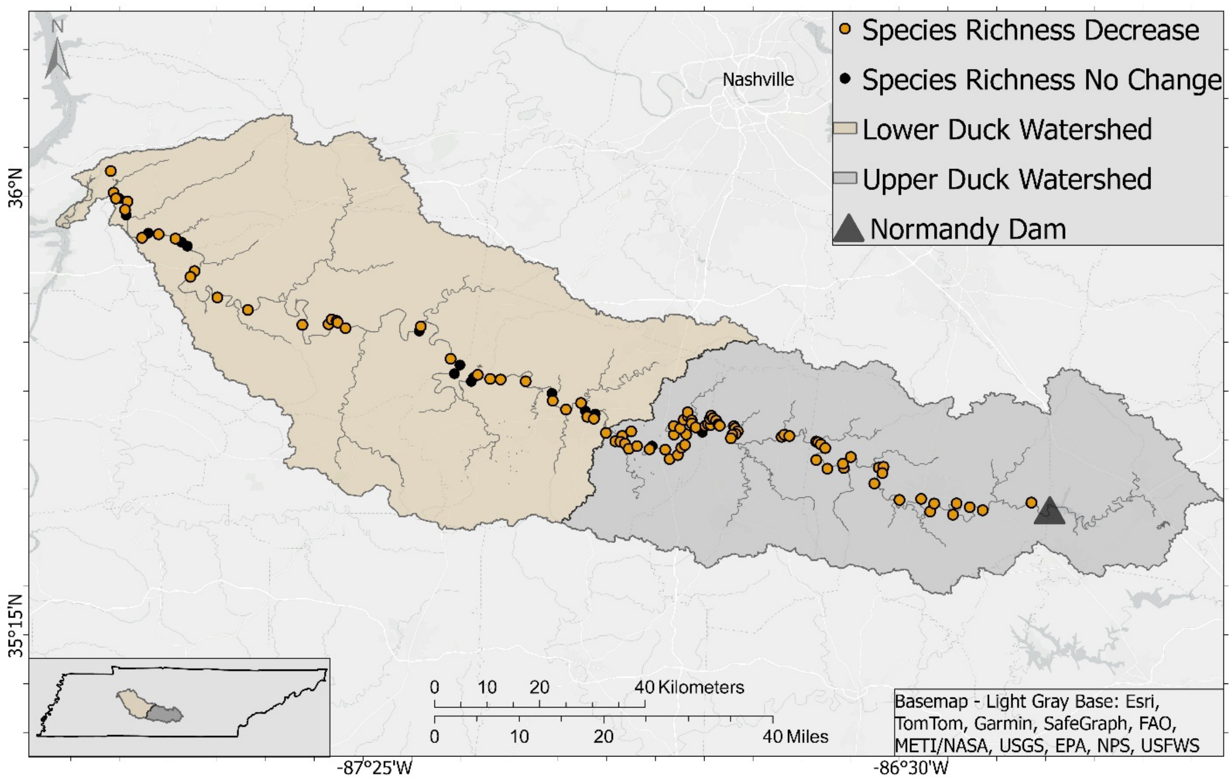


Figure 5. Changes in species richness are documented in the Duck River. Comparisons are between historical species richness (early 1800s-2023) and recent species richness (2000-2023).

Despite drainage-wide declines in mussel species richness, the Duck River remains a stronghold for freshwater mussel communities in Tennessee, with diverse mussel beds containing viable populations of endangered species such as the Duck River Dartersnapper (*Epioblasma ahlstedti*), Birdwing Pearlymussel (*Lemiox rimosus*), and the Slabside Pearlymussel (*Pleuronaia dolabelloides*) (Wisniewski 2020). While the river harbors critical aquatic resources, the portion of the river containing the most species-rich mussel beds is restricted to an approximately 50 river-mile reach in the middle of the river. The small spatial extent of the river's most diverse mussel beds is a concern due to ongoing threats in the area, such as increasing water withdrawal demand due to human development and population growth. In the following section, we assess temporal changes in documented mussel species richness in the Duck River in association with events in the watershed.

Temporal Changes in Mussel Species Richness in the Duck River

An assessment of changes in mussel species richness indicates drainage-wide loss in the Duck River. We investigated changes on a decade-by-decade basis to assess when declines occurred in relation to changes in the watershed. Due to a lack of consistent monitoring, we are inferring changes in richness based on reports of mussels of all conditions (live, fresh dead, relic) from the early 1800s to 1999 and reports of live or fresh dead mussels from 2000 to 2023. We note that our data may overestimate the richness of extant animals for early collections (e.g., higher than true richness), since we include observations of relic shells. We also note that more recent decades tend to have more collection events due to increased effort and attention in the watershed, which could lead to inconsistencies in detection between decades (i.e., improved detection of species due to greater effort). Detailed comparisons within the text are restricted to studies whose objectives were to monitor and compare mussel population demographics; however, maps include records from all available data sources (e.g., museum records, incidental collections).

1800s

Historical data on freshwater mussels from the Duck River in the 1800s are limited (Figure 6); however, Hinkley and Marsh (1885) reported 45 species near Columbia. Mussels in this community were described as particularly large, and this was attributed to abundant food resources and optimal water mineral content. Although information on specific habitat conditions throughout the Duck River during this period is limited, mill dam construction began during this decade and was widespread throughout the watershed (LaForest and Oliveira 1979). While these dams generally did not block fish passage, they impounded sections of the river and altered flows and physical habitat.

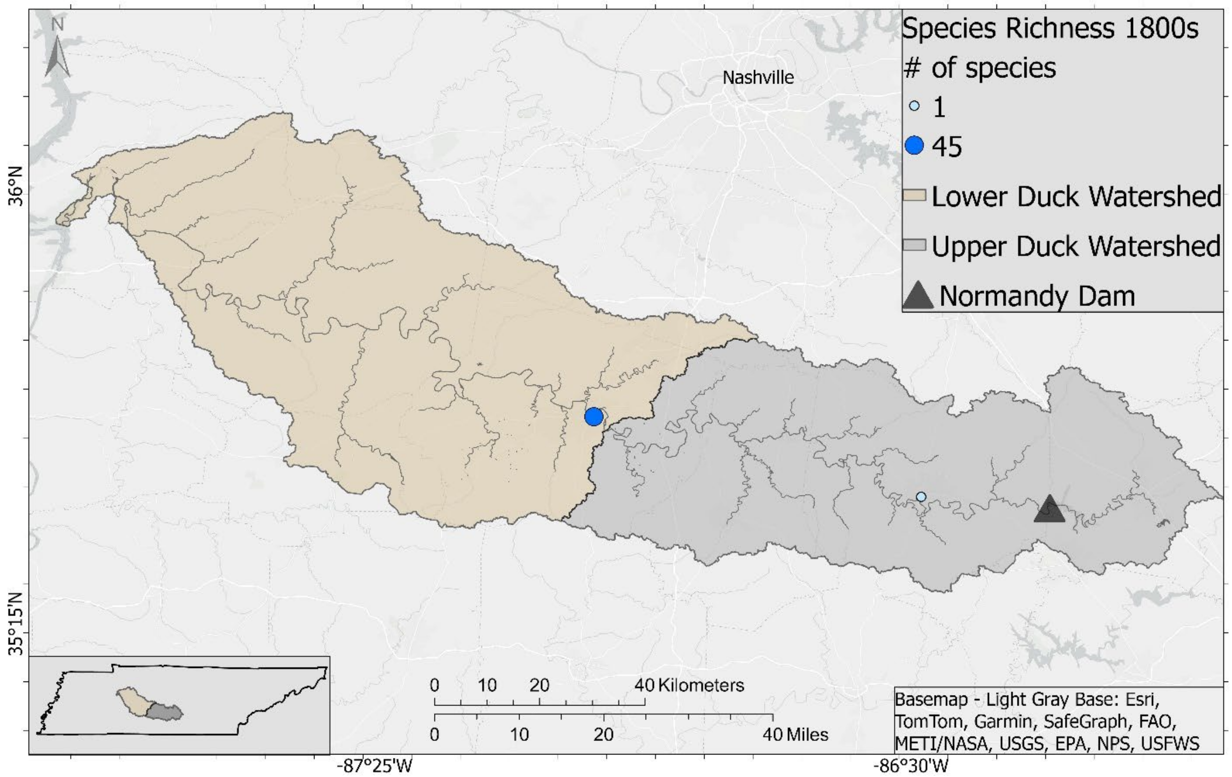


Figure 6. Freshwater mussel species richness documented in the Duck River in the 1800s.

1920-1929

The first drainage-wide mussel survey of the Duck River was conducted in the early 1920s and included sites on the main stem from Centerville to Manchester (Ortmann 1924). Forty-seven species were reported, and the highest species richness was downstream of Columbia near the mouth of Rutherford Creek (N=32; Figure 7). This site was approximately three river miles below the site surveyed by Hinkley and Marsh in 1884, and reported richness declined by 13 species in this area compared to the previous surveys. Although water quality data were not collected during the 1920s survey, Arnold Ortmann anecdotally attributed lower levels of richness below Centerville to phosphate and iron ore mining between Centerville and Columbia.

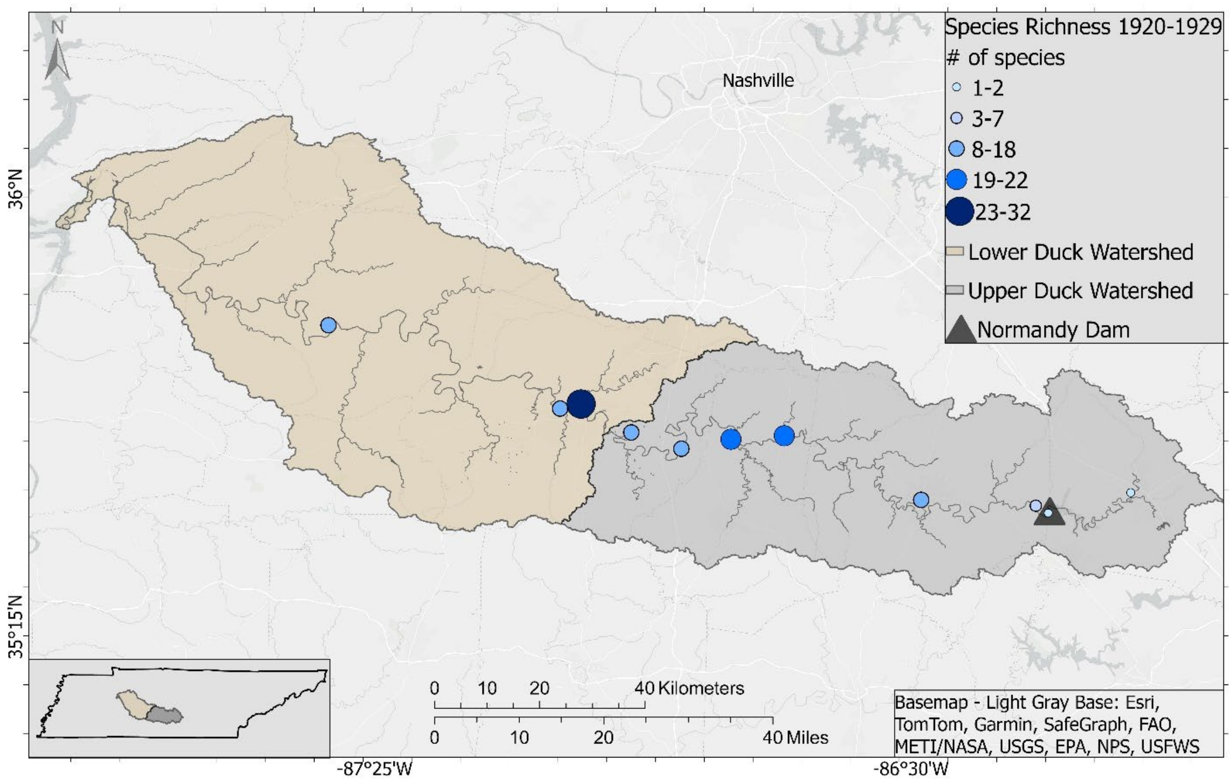


Figure 7. Freshwater mussel species richness documented in the Duck River from 1920 to 1929.

1930-1939

The highest species richness in the Duck River in the 1930s was reported near Hardison Mill (N=32; Figure 8). Reported species richness continued to decline near Columbia, with only 25 species reported compared to 32 in the 1920s. In contrast, mussel species richness in the upper Duck River watershed at Wilhoite Mills remained stable compared to previous surveys.

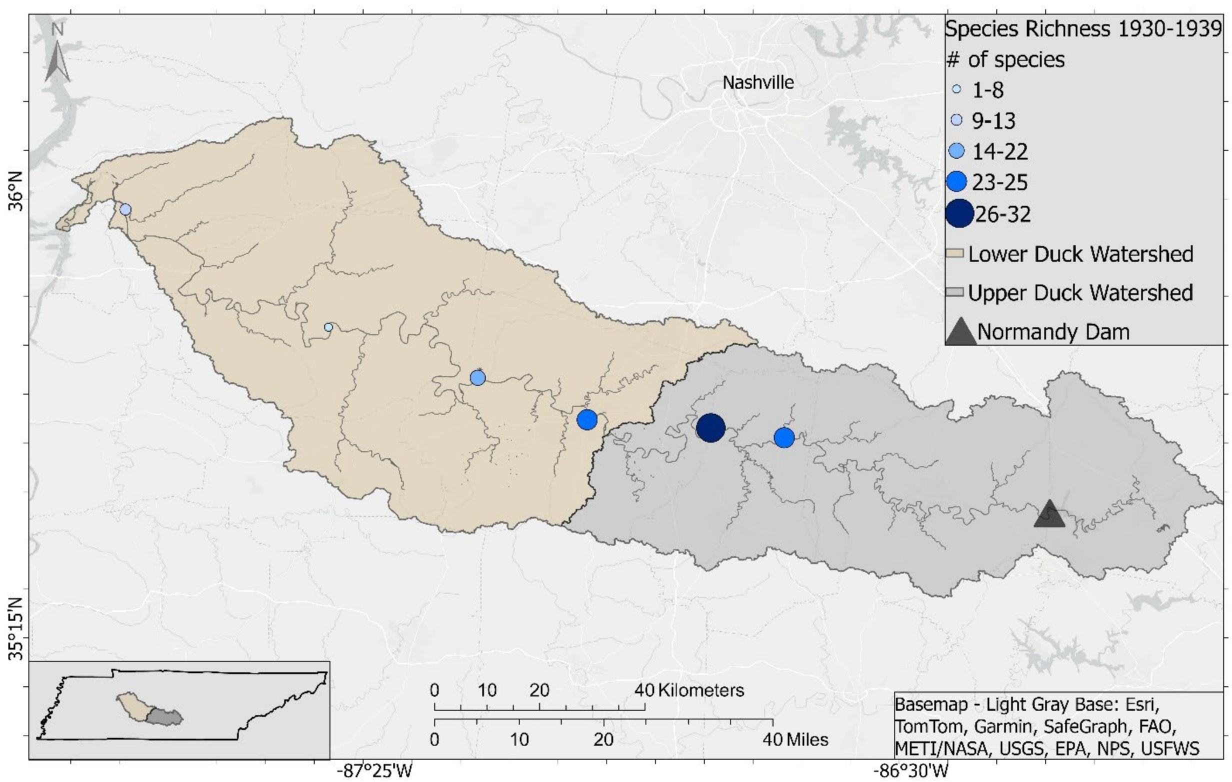


Figure 8. Freshwater mussel species richness documented in the Duck River from 1930 to 1939.

1940-1959

Data gaps in the 1940s and 1950s limit our ability to assess changes in mussel species richness in the Duck River during these decades. We found no mussel records from the 1940s while building the comprehensive Duck River mussel database (Womble and Rosenberger 2025). Records from the 1950s are sparse and restricted to less than 50 lots of shell material housed in museum collections (Figure 9). Therefore, this period was removed from our temporal assessment.

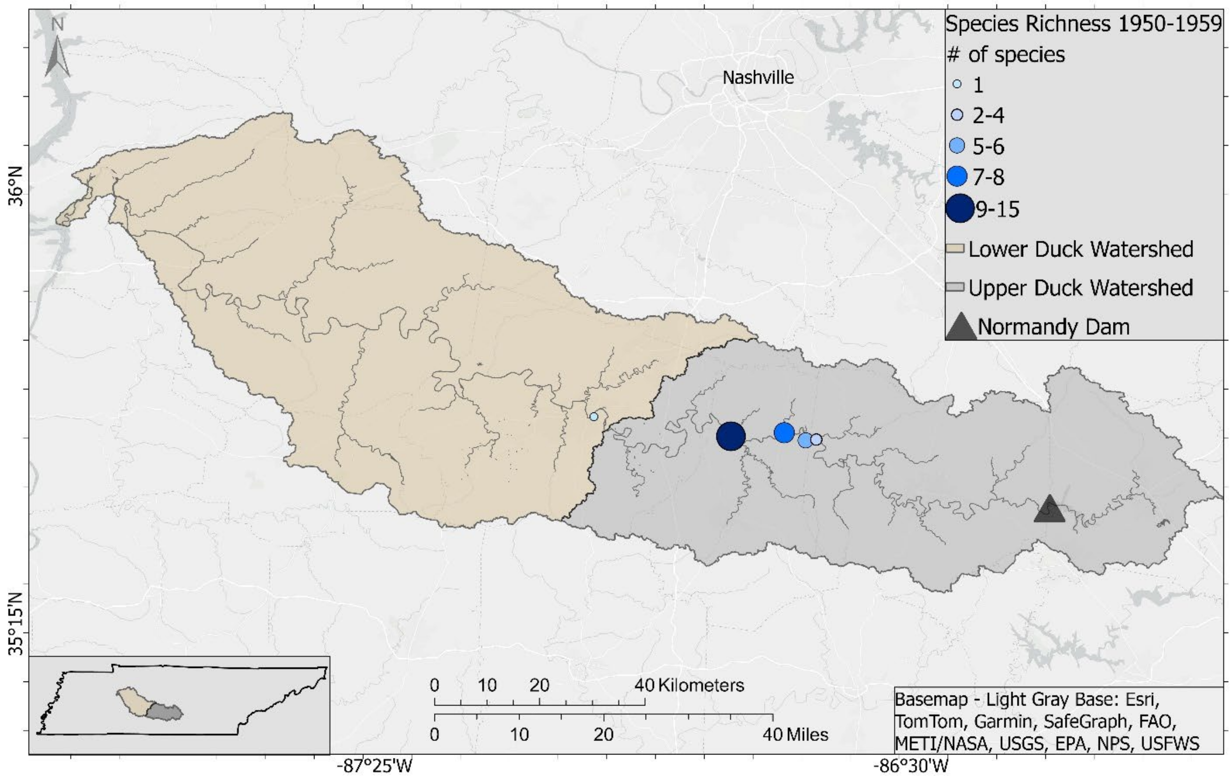


Figure 9. Freshwater mussel species richness documented in the Duck River from 1950 to 1959.

1960-1969

Arnold Ortmann's 1920s survey sites were revisited in 1965 (Isom and Yokley 1968). Overall, mussel species richness declined by 16% from 51 to 43, although reductions were observed at only three sites: Alexander Bend, Columbia, and Lillard Mill (Figure 10). Notably, observed species richness increased below Centerville from 13 in the 1920s to 21 in the 1960s. While the authors noted that physical habitat did not appear heavily altered, they cited municipal sources of pollution, including industry, phosphate ore mining, and sedimentation, as likely contributors to species declines throughout the river.

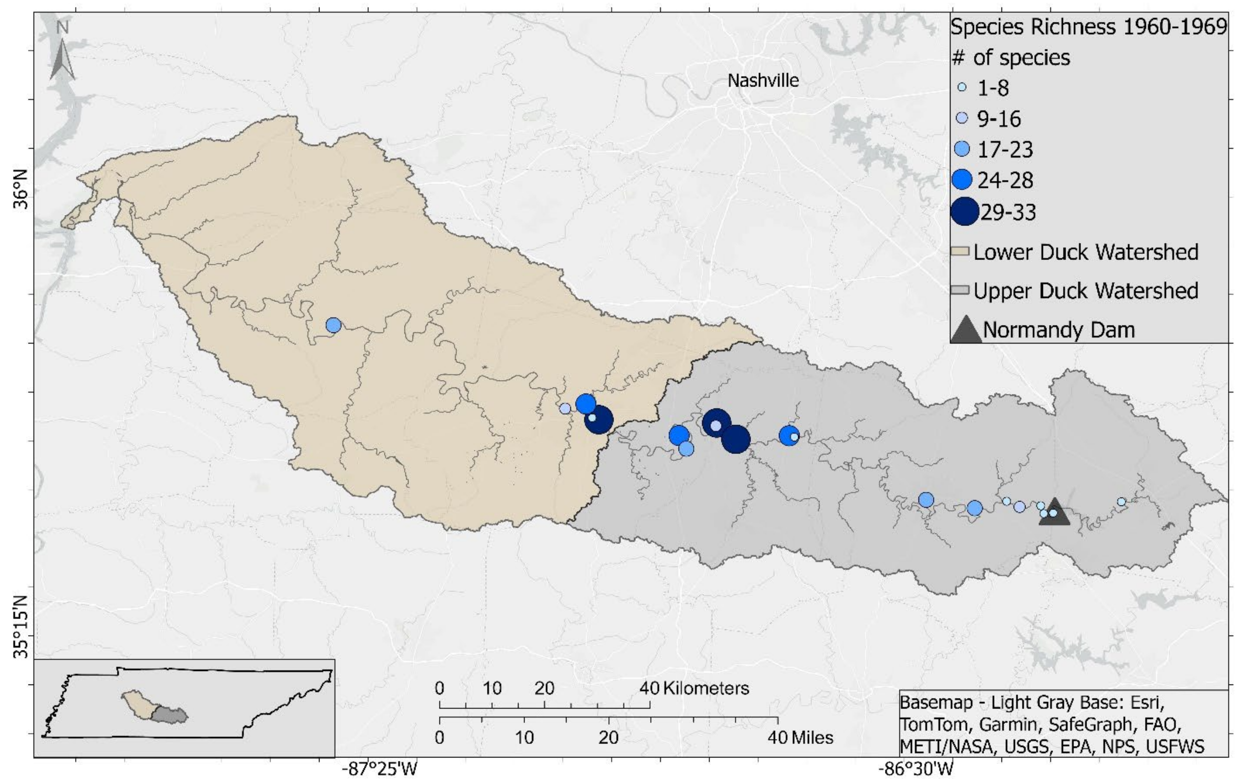


Figure 10. Freshwater mussel species richness documented in the Duck River from 1960 to 1969.

1970-1979

Declines in freshwater mussel species richness were observed in the early 1970s and were primarily attributed to pollution from phosphate ore mining (Van der Schalie 1973). Although the evidence linking specific pollution sources to these declines is anecdotal, no other major causes were documented at the time. These declines overlap temporally with enigmatic mussel declines observed throughout North America beginning in the 1960s (Haag 2019). In the 1970s, the Clean Water Act (1972) and the Endangered Species Act (1973) were enacted in response to worsening water quality and biodiversity loss in the United States. Normandy Dam was completed in 1976 in the upper Duck River watershed (mile 248.6), impounding the river and blocking migratory fish passage. The Tennessee Valley Authority conducted a large-scale mussel survey in 1979, and, despite sampling almost 100 sites from above Normandy Dam downstream to Columbia, they only observed 35 species, and richness at most sites had declined since the 1960s (Ahlstedt 1991) (Figure 11).

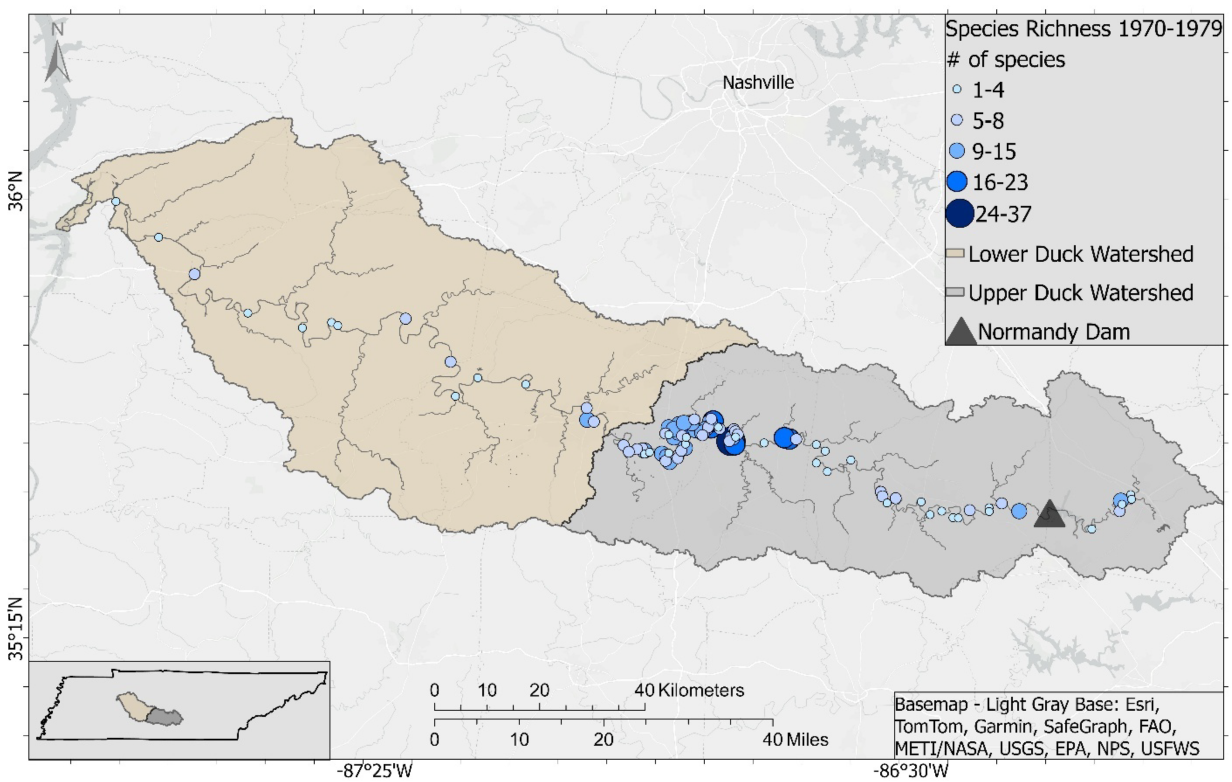


Figure 11. Freshwater mussel species richness documented in the Duck River from 1970-1979.

1980-1989

Continued monitoring of mussels between Columbia and Lillard Mill in 1988 indicated that species richness remained generally stable from the 1970s to the end of the 1980s, both in terms of overall richness and site-specific richness (Jenkinson 1988) (Figure 12). One exception was increased species richness below Cheek Bend (DRM 155).

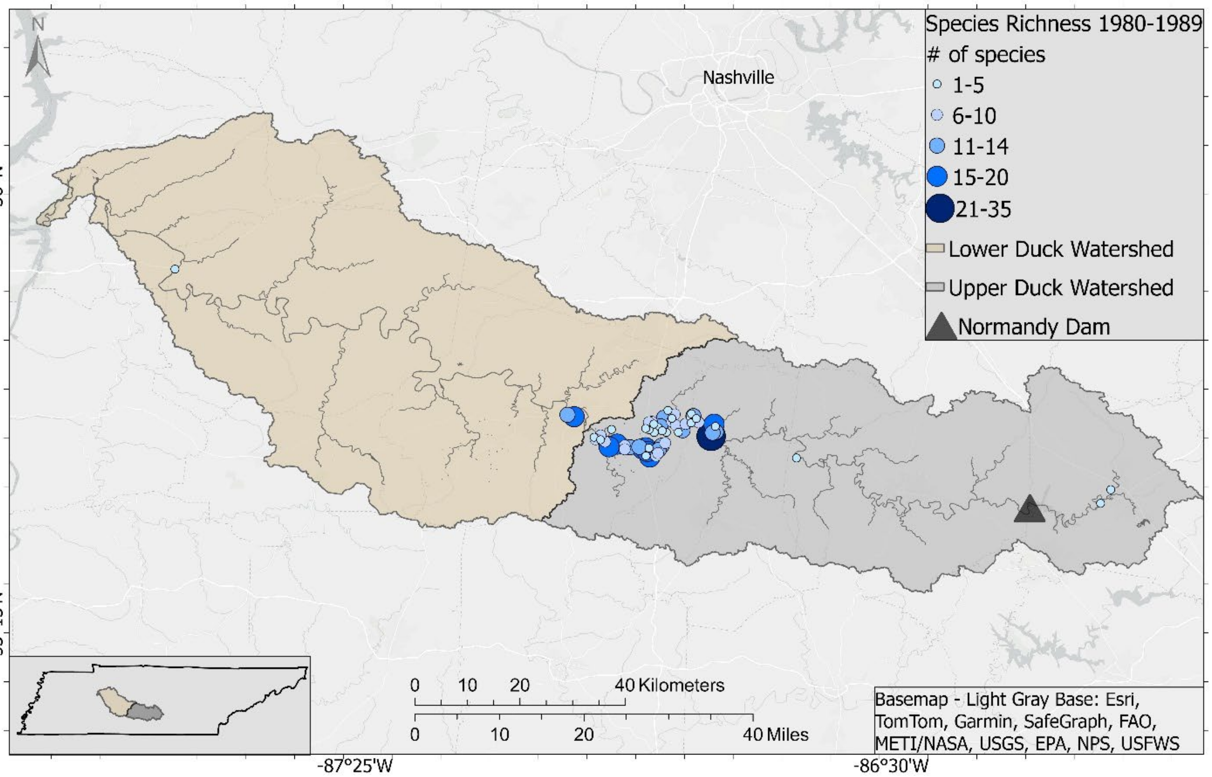


Figure 12. Freshwater mussel species richness documented in the Duck River from 1980 to 1989.

1990-1999

Available data on mussels from the Duck River in the 1990s are limited and primarily composed of shell records from museum databases (Figure 13). The Tennessee Valley Authority initiated reservoir release improvements at Normandy Dam in 1991, which regulated discharge to improve minimum flows and dissolved oxygen levels below the dam (TDRDA 2013).

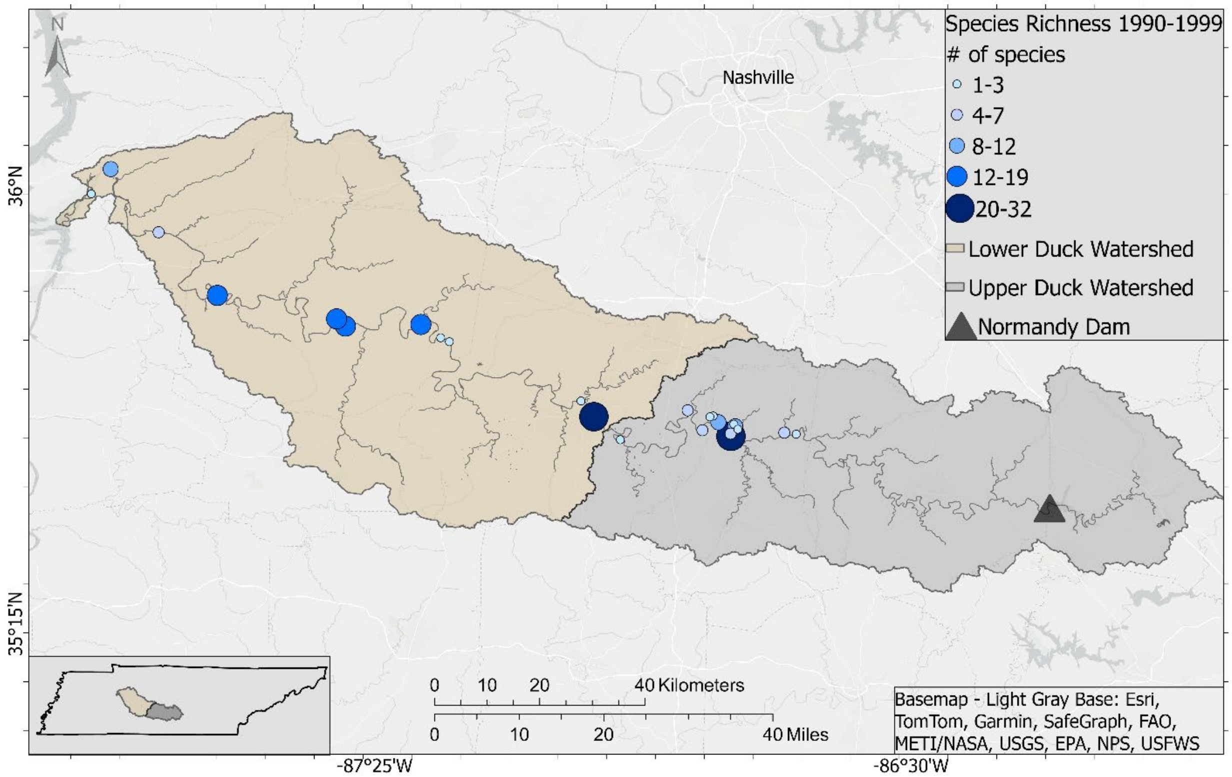


Figure 13. Freshwater mussel species richness documented in the Duck River from 1990 to 1999.

2000-2009

A drainage-wide survey in 2001-2002 documented 54 species throughout the Duck River watershed (Ahlstedt et al. 2017), and a concurrent survey of the lower Duck River reported 32 species below Centerville (Schilling and Williams 2002) (Figure 14). This represents an overall loss of 21 species since historical surveys began; however, statistically significant increases in species richness were found in 2001-2002 when compared to previous monitoring by the Tennessee Valley Authority (TVA) in 1979 and 1988 (Ahlstedt et al. 2017). Mussel species richness in the early 2000s was not statistically different from reported richness across 12 sites from 1922 and 1965, indicating that some rebound of richness may have occurred over this time span. Improvements in mussel communities were attributed to reservoir release enhancements at Normandy Dam, reduction of point source pollution, farmland acquisition and removal, and channel recovery from past destabilization events (Ahlstedt et al. 2017). A severe drought occurred in the Duck River watershed in 2007-2008, and one mortality event involving 30 mussels of eight species was documented due to apparent stranding at Hardison Mill (TWRA 2008).

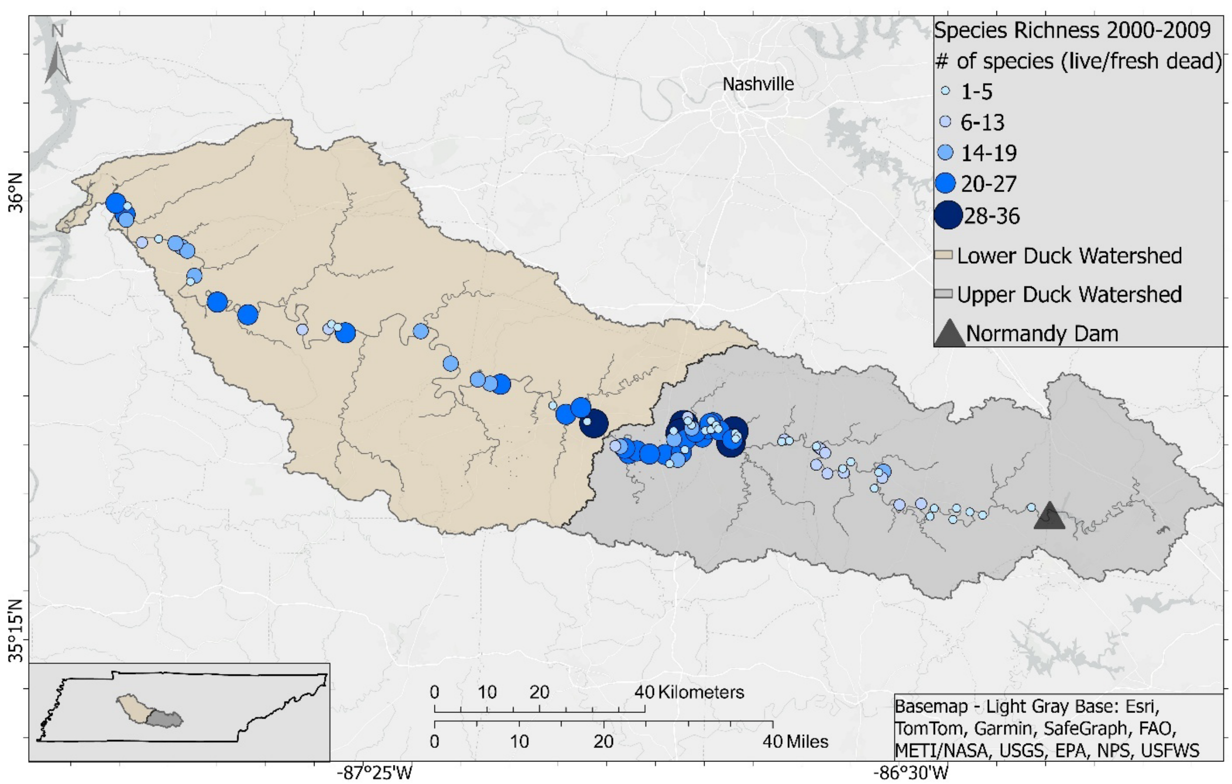


Figure 14. Freshwater mussel species richness documented in the Duck River from 2000 to 2009.

2010-2019

Mussel surveys in the 2010s in the mainstem Duck River were limited compared to the previous decade; however, drainage-wide tributary surveys were completed between 2013 and 2018 (Reed et al. 2019; Irwin and Alford 2018). Mussel species richness trends in the Duck River tributaries are summarized in the following section. A mussel reintroduction and augmentation plan for the Cumberlandian region (including the Duck River) was finalized during this decade (CRMRC 2010). Species reintroductions and population augmentations were initiated for mussels in the Duck River beginning in 2013.

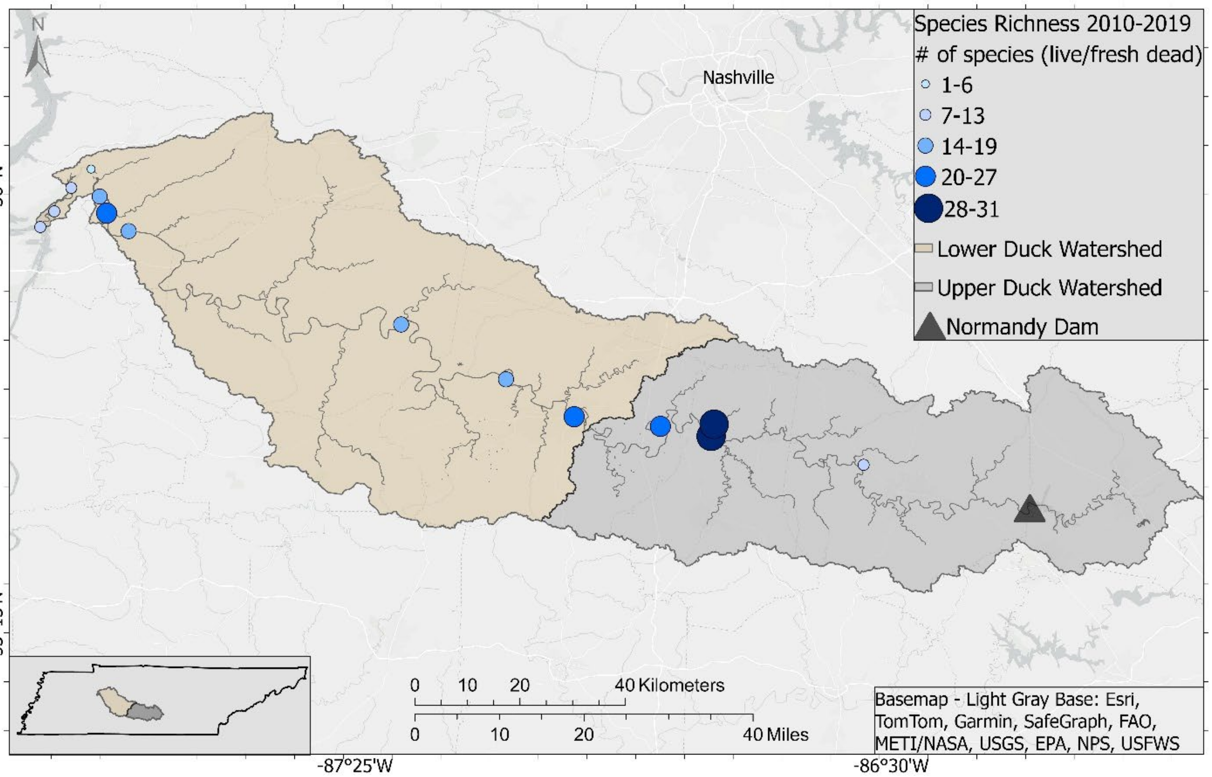


Figure 15. Freshwater mussel species richness documented in the Duck River from 2010 to 2019.

2020-2023: Recent Freshwater Mussel Monitoring in the Duck River

Quantitative monitoring conducted by the Tennessee Wildlife Resources Agency (TWRA) at five to six sites every five years indicates that species richness has remained generally stable in the middle portion of the Duck River since long-term monitoring began in 2010 (Wisniewski 2020) (Figure 16). In response to growing concerns over increased water withdrawal pressure, additional mussel surveys were conducted throughout the lower and middle Duck River in 2022–2023 (Stantec 2023; AST 2024). Surveys were conducted at twelve sites between Centerville (DRM 72.5) and Tugas Bend (~DRM 166) in 2022 "to assess potential effects of flow alteration" (Stantec 2023). Forty-one species were observed, with the highest species richness recorded at the upper end of the study reach at Carpenter Bridge (N=25) and Leftwich (N=25). Species richness in the lower Duck River was generally lower than reports from the early 2000s, potentially indicating further species loss in that area (Stantec 2023). AST Environmental surveyed four sites in the middle of the drainage between Carpenter Bridge (DRM 165.4) and Slick Shoals Island (DRM 178.2) in 2023 to assess mussel and habitat conditions in shallow reaches. Thirty-one species, including four endangered, were observed in the study reach. Endangered species made up over 32% of the mussels found during quadrat sampling (Birdwing Pearlymussel [*Lemiox rimosus*], Slabside Pearlymussel [*Pleuronaia dolabelloides*], Cumberland Rockshell [*Theliderma intermedia*], Duck River Dartersnapper [*Epioblasma ahlstedti*]). Although not included in Figure 16, a mussel mark-recapture study initiated in 2022 is ongoing at Lillard Mill, Venable Spring, and Hooper Island. In 2024, these sites supported 35, 15, and 18 species, respectively (Bajo-Walker 2024) (Figures 17, 18).

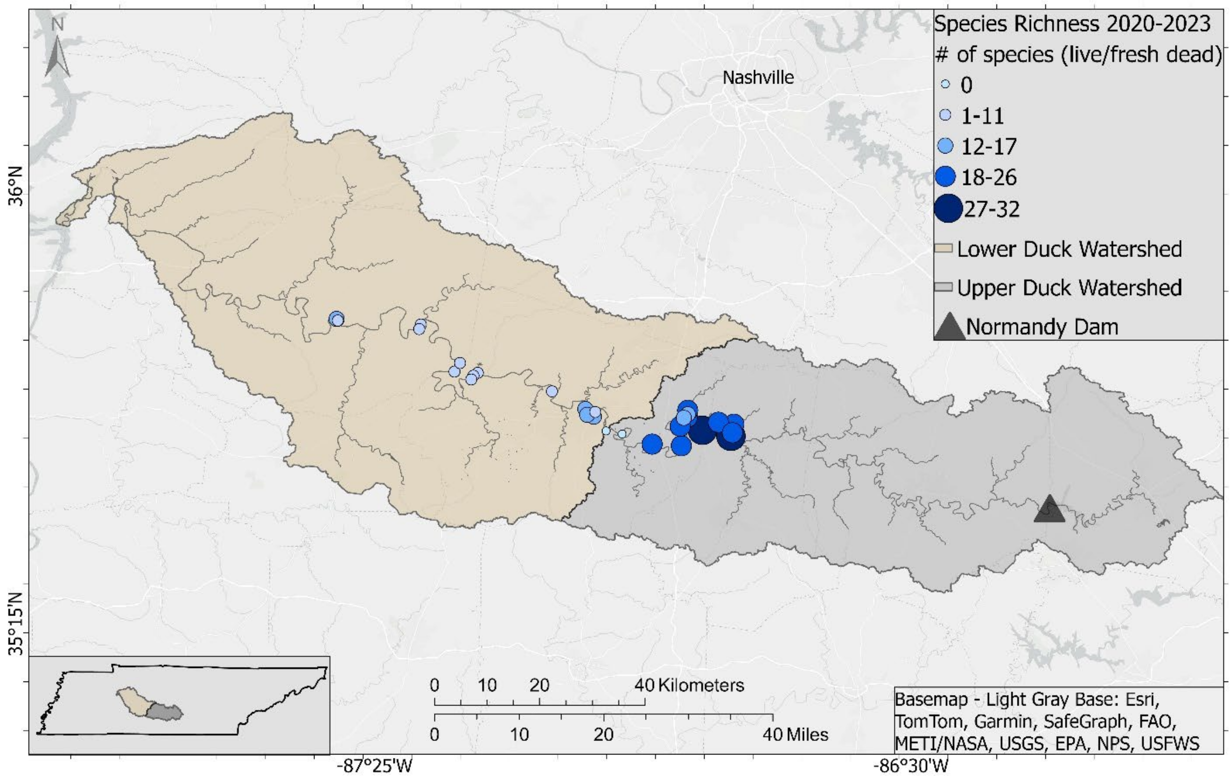


Figure 16. Freshwater mussel species richness documented in the Duck River from 2020 to 2023. We included places with zero live/fresh dead individuals to reflect recent conditions more comprehensively.

Figure 17. Mussels collected during the 2024 Tennessee Wildlife Resources Agency (TWRA) Mark-Recapture study in the Duck River. Photographs provided by Brittany Bajo-Walker, TWRA.

Figure 18. The federally endangered Cumberland Rockshell (*Theliderma intermedia*) collected in the Duck River, 2024. Photograph provided by Brittany Bajo-Walker, Tennessee Wildlife Resources Agency (TWRA).

Tributary Species Richness

Smaller tributary streams are generally underrepresented in freshwater mussel surveys when compared to mid-to-large river systems. Mussel diversity and abundance are positively related to stream size (Daniel and Brown 2013), and this often deters monitoring efforts in smaller tributary streams when resources are limited. Headwater streams, however, provide unique aquatic habitats, including for threatened and endangered mussels, and can be particularly vulnerable to human impacts (Downing et al. 2012; Wohl 2017; Irwin and Alford 2018). From 2013 to 2021, drainage-wide tributary surveys were conducted in the Duck River watershed (Irwin and Alford 2018; Reed et al. 2019; Womble and Rosenberger 2025).

Buffalo River

The Buffalo River is the largest tributary of the Duck River; it enters the mainstem at river mile 15.5 and remains largely unimpounded. Historically, it harbored a diverse mussel fauna of 51 species (Reed et al. 2019). In the 1920s, Ortmann (1924) described mussels in the Buffalo River at Riverside as “abundant everywhere, on gravelly, sandy, and muddy bottom.” However, by the 1960s, species richness had declined, despite no direct evidence of pollution (Isom and Yokley 1968). Due to this apparent decline in mussel diversity, surveys in the Buffalo River were lacking until a drainage-wide survey effort was initiated in 2012. Reed et al. 2019 reported 36 species from the Buffalo River, 29 of which were found live or fresh dead. Mussel diversity in the Buffalo River is primarily restricted to the lower portion of the river; no live mussels were observed in the middle reaches or tributaries, which may be attributed to agricultural land use practices, metal toxicity, and gravel dredging (Denton 2007; Reed et al. 2019). The lower Buffalo, particularly between Buffalo River Mile (BRM) 3.2 to 4.9, harbors diverse mussel beds with viable populations of listed species such as the Slabside Pearlymussel (*Pleuronaia dolabelloides*) and Rabbitsfoot (*Theliderma cylindrica*) (Reed et al. 2019).

Despite historical mussel population declines and anthropogenic stressors, the Buffalo River plays a vital role in supporting mussel diversity in the Duck River watershed. Recent survey efforts highlight the river’s potential for recovery. Continued monitoring and conservation actions in the Buffalo River are essential to ensure the long-term viability of mussels in the Duck River watershed.

Other tributaries

Historical mussel data from the Duck River tributaries are limited. Arnold Ortmann sampled Garrison Fork in Wartrace during a survey of the Duck River basin in the early 1920s, describing the stream as “fordable, with a great variety of conditions of current, bottom” (Ortmann 1924). He collected seven species from one shallow riffle, and all species except for *Lampsilis ovata* were observed live. Recent surveys indicate widespread declines throughout the Duck River tributaries (Figure 19; Figure 20). Mussels have been mostly extirpated from Garrison Fork since Ortmann’s survey, with the exception of the Painted Creekshell (*Cambarunio taeniatus*) (Ahlstedt et al. 2017; Irwin and Alford 2018). Big Rock Creek historically contained 12 species but now contains six, although this includes the endangered Slabside

Pearlymussel (*Pleuronaia dolabelloides*) and Tennessee Pigtoe (*Pleuronaia barnesiana*) (Irwin and Alford 2018). The Nature Conservancy (TNC) is currently conducting a long-term restoration project in the Big Rock Creek drainage. In the last decade, restorative actions in the drainage have included bank stabilization, riparian buffer improvement, and riffle construction (Rob Bullard, The Nature Conservancy, oral comm., 2025). Continued monitoring of the mussels in Big Rock Creek will not only help document additional outcomes of this restoration but may inform future tributary restoration in the Duck River watershed. Lick Creek in the lower Duck River watershed currently harbors six species, including the endangered Pale Lilliput (*Toxolasma cylindrellus*). Surveys of the lower Duck River tributaries below Centerville in 2021 indicate mussels are extirpated; however, a lack of historical survey effort in this area precludes us from knowing how diverse, if at all, the populations were historically (Womble and Rosenberger 2025).

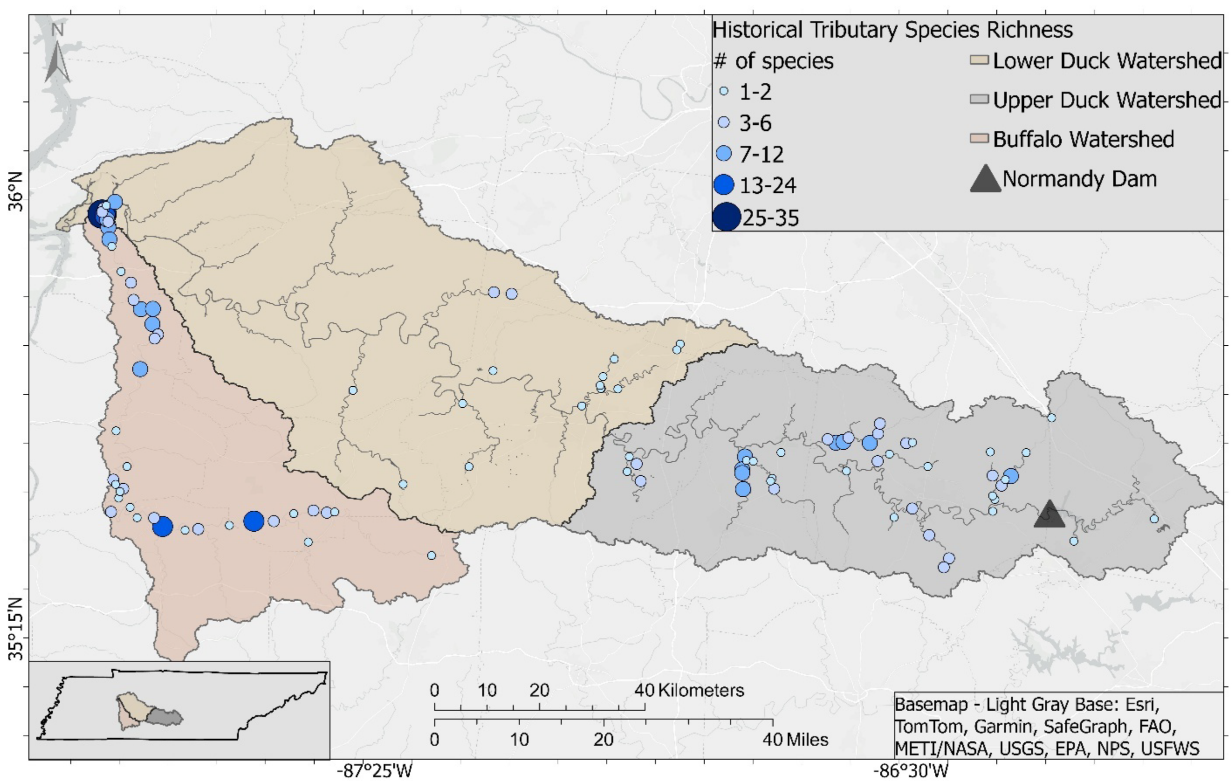


Figure 19. Historical freshwater mussel species richness documented in the Duck River tributaries (early 1800s-2023).

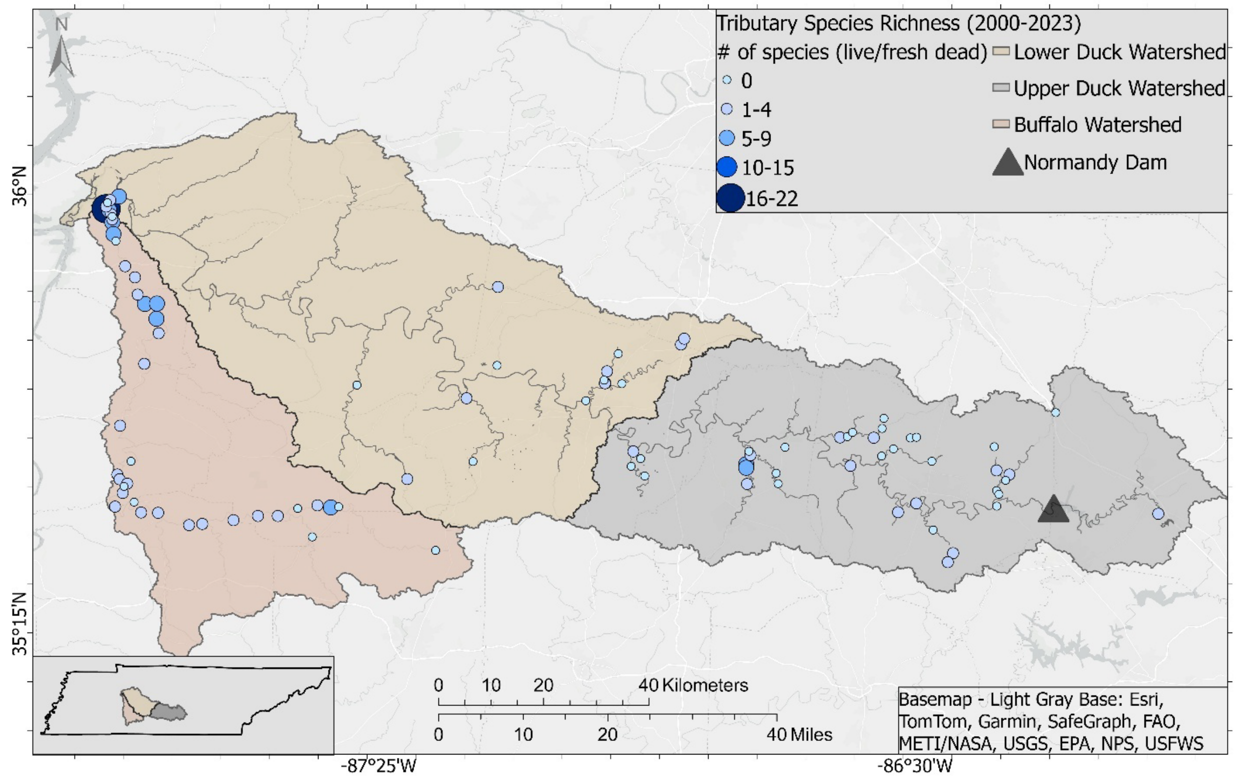


Figure 20. Freshwater mussel species richness documented in the Duck River tributaries (2000-2023).

Historical Species Richness Assessment Summary

Since historical mussel collections began, mussel species richness has declined on a drainage-wide basis in the Duck River. However, our analysis indicates that 62 mussel species are extant in the Duck River watershed (Appendix 1). Species that are extirpated from the Duck River are primarily extinct (Yellow Blossom [*Epioblasma florentina*] and Turgid Blossom [*Epioblasma turgidula*]) or endangered species that are rare in general (Cracking Pearlymussel [*Hemistena lata*], Golden Riffleshell [*Epioblasma aureola*], and Littlewing Pearlymussel [*Pegias fabula*]). Some generally widespread species that appear extirpated from the system (Lilliput [*Toxolasma parvum*) and Flat Floater [*Utterbackiana suborbiculata*]) may occur in the Duck River at densities low enough to inhibit detection, especially in the lower Duck River where survey effort is limited. Historically and presently, the core area of species diversity is restricted to approximately 50 river miles in the middle of the drainage between the two most species-rich sites of Columbia and Lillard Mill. Data suggest that mussel species richness declines began in the Duck River as early as the 1960s, coinciding with other enigmatic declines of freshwater mussels throughout the southeastern United States (Haag 2019). Rebounds of mussel communities were observed in the early 2000s, and species richness was higher than in the late 1970s and late 1980s (Ahlstedt et al. 2017). While overall species richness was lower in the early 2000s than in the 1920s, site-specific declines in richness were not statistically significant (Ahlstedt et al. 2017), indicating a potential return toward historical species richness for some river reaches. Recent data since 2000 suggest that Lillard Mill remains the most diverse site, with a richness of 46 species. Available data indicate that overall mussel richness has declined within the core area of diversity and throughout the drainage compared to historical richness values (Figure 5).

Surveys in the Buffalo River from 2012-2013 revealed a diverse and abundant mussel community in the lower Buffalo, in contrast to reports from 2001-2002 (Ahlstedt et al. 2017). Viable populations of threatened Rabbitsfoot (*Theliderma intermedia*) and endangered Slabside Pearlymussel (*Pleuronaia dolabelloides*) were collected in the lower Buffalo River (Reed et al. 2019). Widespread declines in mussel species richness have been documented in the other tributaries to the Duck River; however, Big Rock Creek harbors populations of the endangered Slabside Pearlymussel (*Pleuronaia dolabelloides*) and Tennessee Pigtoe (*Pleuronaia barnesiana*). Mussels appear to be extirpated from the lower Duck River tributaries below Centerville, although the lack of historical data limits our ability to determine the former species richness of these streams (Womble and Rosenberger 2025).

The mussel community improvements observed in the early 2000s were likely attributed to reservoir release improvements at Normandy Dam, reduction of point source pollution, farmland acquisition and removal, and channel recovery from past destabilization events (Ahlstedt et al. 2017). Historically and currently, the core area of species diversity in the Duck River is restricted to approximately 50 river miles in the middle of the drainage. Mussel community conditions in some river reaches, such as Shelbyville and above Normandy Dam, have not rebounded, although these areas are under surveyed. Since the early 2000s, mussel species richness has generally remained stable in the middle portion of the main stem Duck River but appears to have declined in the upper and lower portions of the river. Most mussel survey work has been concentrated above Columbia; therefore, conditions outside of the core area of diversity, especially in the lower Duck River, are generally unknown based on current data availability. Continued drainage-wide monitoring would document future trends in mussel species richness and ensure the protection of the Duck River's freshwater mussel fauna**.**

2. Historical Density and Abundance Assessment

Consistent monitoring of freshwater mussel communities enables robust assessment of changing assemblage health and species recovery. Quantitative surveys can estimate mussel densities and document the presence of juveniles, which are not easily found in qualitative surveys (Dunn and Strayer 2010). Mussel abundance is generally reported as Catch Per Unit Effort (CPUE), the number of mussels observed divided by effort (person-hours, person minutes), and these values are used to assess population status when quantitative surveys are not possible. Sampling bias and error are inherent in mussel sampling methods, which limit assessment of community changes through time, especially with shorter-term monitoring (Strayer and Smith 2003). Additionally, detection is often low or unknown for mussel species; therefore, species may not be captured in mussel surveys with limited survey effort. Mussel density within sampled quadrats is typically extrapolated to the site scale, where incomplete detection is even higher due to habitat heterogeneity (Downing and Downing 1992; Strayer and Smith 2003; MacKenzie 2006). With these caveats in mind, in this section, we compare reported mussel densities and abundances through time in the Duck River. Similar to our historical species richness assessment, variation in survey methods and effort limits the direct comparison of many studies reported here. Despite this, we have summarized current knowledge based on available data.

Density

Information regarding mussel densities in the Duck River before the late 1970s is limited. However, during surveys in 1939, the stream bottom of the Duck River and the Buffalo River was described as “paved” with mussels, suggesting that historical mussel densities were high (Van der Schalie 1973). The Tennessee Valley Authority (TVA) quantitatively sampled 21 sites from Duck River mile 147.9 to 179.2 in 1979 and resurveyed 14 sites from Columbia to Milltown in 1988; however, sites did not overlap consistently (Jenkinson 1988; Ahlstedt 1991). Three sites were revisited in the early 2000s to assess changes in mussel density (Ahlstedt et al. 2017). The Tennessee Wildlife Resources Agency (TWRA) began a five-year quantitative monitoring program at six sites on the Duck River in 2010 (Hubbs 2010). Additional quantitative monitoring was conducted in the Duck River in 2023 (AST 2024). Methods and effort were not standardized between these studies, except for TWRA’s 2010, 2015, and 2020 monitoring. The sample size of quadrats varied from 8 to 40 in 1979, 12 to 41 in 1988, 20 in 2000, 80 in 2010-2020, and ranged from 80 to 90 in 2023. Despite this, we discuss general trends in reported mussel densities for all years. Mussel densities for eight sites on the Duck River are summarized in Table 1.

Overall, mussel abundance was higher in 1988 (9.33 mussels/m^2) than in 1979 (3.89 mussels/m^2); however, quadrats in 1988 were focused on the most optimal habitats, and effort was generally lower than the surveys conducted in 1979. Mussel densities were reported to be significantly higher at three locations (Lillard Mill, Hooper Island, and Venable Spring) in 2000 compared to 1979 and 1988 (Ahlstedt et al. 2017). For the most consistently monitored localities, densities increased between 1979 and 2000 but have declined since 2000 (Table 1). TWRA's long-term monitoring has documented a decline in reported overall mussel densities since 2010 at Columbia, Hooper Island, Venable Spring, and Lillard Mill; however, the densities of some species have increased dramatically (Wisniewski 2020). For example, a 376% increase in Round Hickorynut (*Obovaria subrotunda*) abundance was observed at Venable Spring in 2020. The recovery of the Duck River mussel fauna documented in the early 2000s was attributed mainly to improved spring and summer flows created by reservoir release improvements at Normandy Dam (Ahlstedt et al. 2017) (refer to section 1). More recent data indicate that mussel densities may have declined since 2000, although the Duck River still harbors globally significant, abundant, and diverse mussel beds containing multiple threatened and endangered species.

Table 1. Freshwater mussel densities (mussels/m^2) reported in the Duck River, Tennessee from quantitative surveys (1979-2023). Only results from 2010, 2015, and 2020 are directly comparable – other years vary in sampling method used and number of quadrats sampled.

Locality	1979	1988	2000	2010	2015	2020	2023
Columbia		3.6		10.5	7.4	5.0	
Hooper Island	10.0		24.4	22.2	20.2	19.1	
Old Trap Island		2.0					20.1
Cundiff Island	1.33						10.5
Venable Spring	1.67	7.81	19.6	12.6	14.2	14.1	
Slick Shoals Island		7.67					12.3
Milltown	17.8	26.8	36.6	37.4	30.3	18.1	
Tarpley Bluff			2.2	4.9	1.8		

Reported mussel densities in tributaries to the Duck River are limited to the lower Buffalo River and two sites on Big Rock Creek. In 2013, a density of 1.8 mussels/0.25m^2 quadrat was reported from the lower Buffalo River (Reed et al. 2019). In Big Rock Creek, densities of 0.33 and 1.27 mussels/0.25m^2 were reported at two separate sites in 2018 (Irwin and Alford 2018). No mussel density data are available for the remaining tributaries of the Duck River.

Abundance

Mussel abundance is typically estimated through Catch Per Unit Effort (CPUE) reported as mussels/hour. This metric is commonly collected during qualitative timed searches, which is a practical survey method for documenting species richness and for observing rare species, as it allows surveyors to cover a more extensive area (Vaughn et al. 1997; Strayer and Smith 2003). Abundance values can be estimated for some freshwater mussel data in the Duck River dating back to 1988; however, temporal comparisons of CPUE are limited to eight sites (Table 2). While changes are minimal for several sites, CPUE has decreased greatly at Littlelot since 1999 (DRM 88.9). Surveys indicate that reported mussel abundance has increased dramatically below Columbia (DRM 131.7), at Leftwich (DRM 156.2), and Tugas Bend (DRM 166.1). In 1988, mussel abundance was significantly higher in DRM 175-179 compared to downstream areas, and this pattern continues with the most recent surveys (Jenkinson 1988; Ahlstedt et al. 2017).

Table 2. Changes in Catch Per Unit Effort (CPUE)(mussels/hour) in the Duck River, Tennessee.

DRM	Pre-2000	Post-2000	Change (%)
Mile 72.5	89.5	74.7	-16.5
Mile 88.9	286.3	82	-71.4
Mile 133.5	37.2	123.3	+231.5
Mile 155.7	27	52.7	+95.2
Mile 156.2	33.5	188	+461.2
Mile 164.3	38	27.3	-28.2
Mile 166.1	9	181.3	+1914.4
Mile 168.5	11	37.3	+239.1

Historical mussel abundance information in the tributaries of the Duck River is similarly scarce. Abundance information is available for some tributaries but dates from 2012-2018, limiting our ability to assess how mussel abundances have changed over time (Irwin and Alford 2018; Reed et al. 2019). In Big Rock Creek, mussel abundance has increased since 2001, indicating that the restoration methods used by TNC may be benefiting the freshwater mussel community (Ahlstedt et al. 2017; Irwin and Alford 2018).

Historical Density and Abundance Assessment Summary

While available data provide insights into general temporal trends in mussel density and abundance in the Duck River, inconsistencies in survey methods and effort limit direct comparisons for most of the watershed. Quantitative surveys since 1979 suggest that mussel densities generally increased in the core area of mussel diversity from the late 70s to the early 2000s (Lillard Mill, Hooper Island, and Venable Spring) (Ahlstedt et al. 2017). However, long-term monitoring by TWRA (2010-2020) indicates that densities in this area have declined since 2000. Despite this, some species, such as the Round Hickorynut (*Obovaria subrotunda*), have experienced localized population increases (Wisniewski 2020). While not included in the above analysis, results from TWRA's 2024 mark-recapture study suggest that abundances remain high at Lillard Mill, Hooper Island, and Venable Spring, as 945, over 1,119, and over 322 mussels were collected at these sites, respectively (Bajo-Walker 2024). Trends in mussel abundance outside of the core area are mixed: while some sites (e.g., below Columbia Dam, Leftwich, Tugas Bend) show documented increases in mussel abundance, others, like Littlelot, have experienced what may be precipitous declines.

This analysis highlights the importance of consistent survey methods for robust assessments of long-term trends in mussel density and abundance. While quantitative surveys are time-intensive, they provide insight into temporal dynamics in mussel density, recruitment, and species composition, allowing robust assessments of changes through time, estimates of baseline variability expected for mussel populations in this system, and the effectiveness of changing management practices in the drainage. Standardizing methods and survey effort across years is critical for comparing these data, and the TWRA long-term monitoring program provides a robust framework for documenting changes in mussel community conditions. While the Duck River has been surveyed more extensively than most rivers in Tennessee, data on mussel abundances are limited and may not be directly comparable due to inconsistency in survey efforts and methods, or a lack of reporting to derive CPUE values. Consistent documentation and reporting of survey time and number of surveyors would enable the calculation of CPUE and improve the utility of existing data. These findings underscore the benefits of standardized, repeatable monitoring protocols to assess and support mussel recovery in the Duck River effectively.

3. Mussel Assemblage Health Index (MAHI)

The Mussel Assemblage Health Index (MAHI) is a recently published tool that integrates fundamental aspects of mussel communities (species richness, abundance, recruitment, and population growth) to assess overall assemblage health (Haag et al. 2024). This tool was developed for streams in the eastern United States and was designed to address data consistency issues, allowing for the incorporation of mussel data collected from multiple sources. MAHI provides an objective assessment of mussel health in the Duck River that is independent of regional context and individual perception, while still incorporating expert judgment that is often challenging to quantify in analyses. The tool covers fundamental aspects of mussel assemblages: relative density and population growth, different indicators of abundance, and assemblage recruitment strength and historical richness, which are additional relevant information on assemblage health (Haag et al. 2024).

Due to inconsistencies in the collection methodologies of freshwater mussel data in the Duck River, direct temporal comparisons of population metrics such as richness and abundance cannot be obtained in a statistically robust manner drainage-wide. We therefore employed this tool to supplement our assessment of mussel community changes throughout the Duck River, allowing us to depict mussel community health at long-term monitoring sites.

The MAHI is comprised of four primary metrics: proportion of historical richness, relative density, assemblage recruitment strength, and population growth (Table 3). MAHI is designed to be robust to missing data; therefore, the tool can be used if one of the four metrics is missing. The proportion of historical richness represents the proportion of the historical mussel species richness that remains extant at a site based on recent survey efforts and can be informed from a variety of data sources, from organized surveys to best professional judgement. Relative density describes mussel density relative to stream size and is calculated using the observed mussel density at a site and the watershed area upstream of the site. Assemblage recruitment strength is the estimated proportion of individuals in the assemblage that are recent recruits (<10 years old). This metric is calculated using the proportion of species in the assemblage that show evidence of recent recruitment and mean species recruitment strength (proportion of individuals estimated to be <10 years old). Mean species recruitment strength requires shell lengths from quadrat sampling and an $N \geq 5$; therefore, this metric often requires obtaining mussel length information directly from sources. While recruitment measurements are generally more restrictive in other mussel bioassessments, the liberal use of <10 years is considered beneficial since very young (small) individuals are challenging to detect in most mussel surveys (Haag et al. 2024). To mitigate the risk of underrepresenting recruitment, we used professional opinion to contribute to our recruitment designations, which is a recommended method by the MAHI tool. Population growth describes the change in mussel density over time and can be calculated using either density or catch per unit effort over at least two years. The tool outputs individual scaled metric scores of increasing health (0-10) and a composite health score based on scaled individual metric scores (the unweighted mean of all metric scores, 0-10). A detailed description of each metric, its requirements, and limitations can be found directly in the MAHI publication and Excel application (Haag et al. 2024).

Table 3. Description of metrics used to derive a mussel assemblage health score with the Mussel Assemblage Health Index (MAHI) (Haag et al. 2024).

Metric	Description
Species richness	Proportion of historical richness retained at the site. Historical richness represents the probable original fauna before anthropogenic alteration. Current richness reflects the probable current fauna based on recent survey efforts. Both can be gathered from a variety of sources.
Recruitment	Assemblage recruitment strength is the estimated proportion of individuals in the assemblage that are recent recruits, <10 years old. This metric is a combination of the proportion of species recruiting and mean species recruitment strength. The proportion of species recruiting represents the best professional opinion based on observations of live or fresh dead individuals from a variety of sources.
Abundance	Density or abundance relative to stream size, or the difference between observed mussel density at the site and the predicted density in a stream of that size. Density is the number of mussels/m^2, and stream size is the watershed area upstream of the site in (km^2)
Population growth	Change in mussel density over time. The slope of the linear regression of natural log (ln) density on year to show an estimate of instantaneous rate of change (*r*) in density/year. Can be estimated from catch-per-unit-effort (CPUE) (number/hour). This metric requires estimates from at least two years.

The long-term monitoring program led by the TWRA presents an opportune dataset to use MAHI to assess mussel community conditions at four sites on the Duck River: Columbia, Venable Spring, Hooper Island, and Lillard Mill. Although Tarpley Bluff and Littlelot are also long-term monitoring sites, these areas were not sampled in 2020 and were omitted from this analysis. For historical species richness, we used the richness values calculated in Section 1 above. For current species richness, we used verified observations of live or fresh dead individuals at the location since 2010. Relative densities were restricted to samples collected during TWRA's long-term monitoring program in 2010, 2015, and 2020. We retrieved and digitized length measurements from the quantitative surveys for each year. We note that propagated individuals have been released at several of these sites, which may be bolstering assemblage health scores (as intended). It is often not possible to discern which increases or sustainment of richness/abundance are directly due to these efforts versus ‘natural’ recovery. Regardless, these reintroductions and augmentations represent a necessary effort to protect and sustain these mussel species and therefore their inclusion would benefit any assessment of mussel health. The following figures and tables summarize the results from the MAHI tool for mussel assemblages at Columbia, Venable Spring, Hooper Island, and Lillard Mill. All figures are direct output from the MAHI Excel application (Haag et al. 2024).

Columbia Mill Dam

The site at the Columba Mill Dam (Columbia) scored the lowest of the four quantitative survey localities with a composite score of 5.4, placing this site in the middle of the assemblage health range seen in comparable mussel communities from Haag et al. 2024. (Figure 21; Table 4). This moderate score reflects a large decline in species richness (from 49 to 27), moderate assemblage recruitment strength, and a low population growth score driven by a decrease in mussel density from 10.5 to 4.98 mussels/m^2 from 2010 to 2020. The full MAHI input values, raw scores, and score components are listed in Appendix 2.

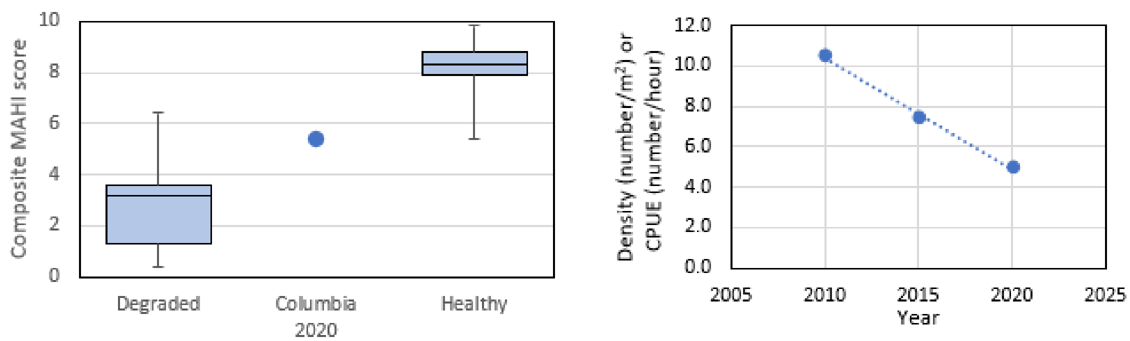


Figure 21. The Mussel Assemblage Health Index (MAHI) (Haag et al. 2024) analysis for the Columbia Site on the Duck River, Tennessee, by the Tennessee Wildlife Resources Agency (TWRA). On Left: MAHI composite score for Columbia (Score = 5.4) (blue dot) presented in relation to value ranges for degraded and healthy mussel assemblages in comparable systems in the southeastern United States (Haag et al. 2024). Boxes represent the 25th and 75th percentiles, with the horizontal line within the box indicating the median. Whiskers represent the minimum and maximum values. On Right: Changes in mussel density over time at Columbia from 2010 to 2020.

Table 4. Final scaled metric scores for the Columbia site on the Duck River, Tennessee, based on guidance from Haag et al. (2024) and data collected by the Tennessee Wildlife Resources Agency (TWRA). Composite score = 5.4.

Proportion Historical Richness	Relative Density	Assemblage Recruitment Strength	Population Growth
5.5	7.0	6.0	3.1

Venable Spring

The site at Venable Spring scored the highest of the four quantitative survey localities with a composite score of 8.4 (Figure 22; Table 5). The health of this assemblage falls high within the "healthy" range assigned by the index. This high score is driven by only a moderate decline in richness (36 to 29), high assemblage recruitment strength, and a slight increase in mussel density from 12.65 to 14.12 mussels/m^2 from 2010-2020. The full MAHI input values and raw scores and score components are listed in Appendix 3.

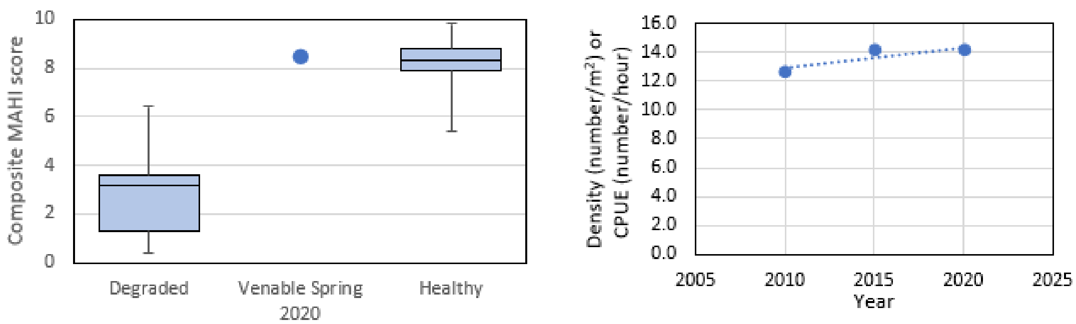


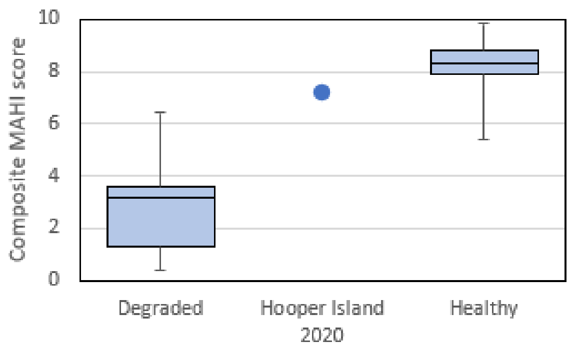
Figure 22. The Mussel Assemblage Health Index (MAHI) (Haag et al. 2024) analysis for the Venable Spring site on the Duck River, Tennessee, by the Tennessee Wildlife Resources Agency (TWRA). On Left: MAHI composite score for Venable Spring (Score = 8.4) (blue dot) in relation to value ranges for degraded and health mussel assemblages in comparable systems in the southeastern United States (Haag et al. 2024). Boxes represent 25th and 75th percentiles, and the horizontal line within the box is the median, and whiskers are minimum and maximum values. On Right: Changes in mussel density over time at Venable Spring from 2010-2020.

Table 5. Final scaled metric scores for the Venable Spring site on the Duck River, Tennessee, based on guidance from Haag et al. (2024) and data collected by the Tennessee Wildlife Resources Agency (TWRA). Composite score = 8.4.

Proportion Historical Richness	Relative Density	Assemblage Recruitment Strength	Population Growth
8.1	8.4	10	7.2

Hooper Island

The site at Hooper Island received a moderate to high composite score of 7.2 (Figure 23; Table 6). This score is driven by a decline in species richness (36-25), a moderate assemblage recruitment strength, and a small decrease in mussel density from 22.2 to 19.08 mussels/m^2 from 2010-2020. The full MAHI input values and raw scores and score components are listed in Appendix 4.



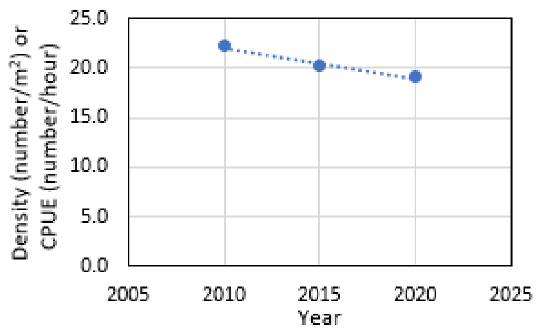


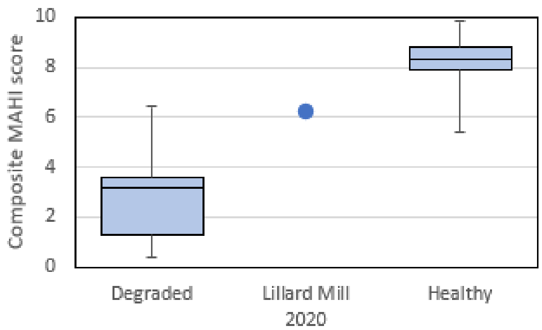
Figure 23. The Mussel Assemblage Health Index (MAHI) (Haag et al. 2024) analysis for the Hooper Island site on the Duck River, Tennessee, by the Tennessee Wildlife Resources Agency (TWRA). On Left: MAHI composite score for Hooper Island (Score = 7.2) (blue dot) in relation to value ranges for degraded and health mussel assemblages in comparable systems in the southeastern United States (Haag et al. 2024). Boxes represent 25th and 75th percentiles, and the horizontal line within the box is the median, and whiskers are minimum and maximum values. On Right: Changes in mussel density over time at Hooper Island from 2010-2020.

Table 6. Final scaled metric scores the Hooper Island site on the Duck River, Tennessee, based on guidance from Haag et al. (2024) and data collected by the Tennessee Wildlife Resources Agency (TWRA). Composite score = 7.2

Proportion Historical Richness	Relative Density	Assemblage Recruitment Strength	Population Growth
6.9	8.7	7.3	5.9

Lillard Mill

The site at Lillard Mill scored a composite score of 6.3, placing this mussel assemblage in the middle of the health range defined by the index (Figure 24; Table 7). This lower-than-expected score is driven by a substantial loss of species richness (57 to 39) and a large decline in reported mussel density from 37.4 to 18.14 mussels/m^2 from 2010-2020. Despite this decline in reported species richness and density, 33 species are recruiting at the site; however, overall assemblage recruitment strength is moderate based on length measurement of the community. The full MAHI input values and raw scores and score components are listed in Appendix 5.



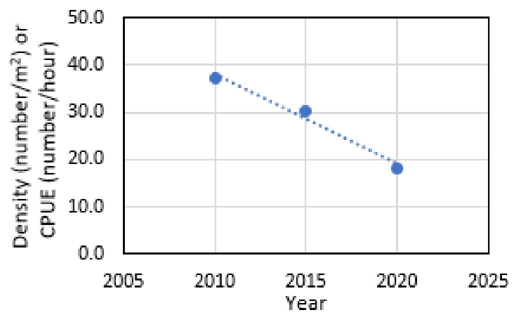


Figure 24. The Mussel Assemblage Health Index (MAHI) (Haag et al. 2024) analysis for the Lillard Mill site on the Duck River, Tennessee, by the Tennessee Wildlife Resources Agency (TWRA). On left: MAHI composite score for Lillard Mill (Score = 6.3) (blue dot) in relation to value ranges for degraded and healthy mussel assemblages in comparable systems in the southeastern United States (Haag et al. 2024). Boxes represent 25th and 75th percentiles, and the horizontal line within the box is the median, and whiskers are minimum and maximum values. On Right: Changes in mussel density over time at Lillard Mill from 2010-2020.

Table 7. Final scaled metric scores for the Lillard Mill site on the Duck River, Tennessee, based on guidance from Haag et al. (2024) and data collected by the Tennessee Wildlife Resources Agency (TWRA). Composite score = 6.3

Proportion Historical Richness	Relative Density	Assemblage Recruitment Strength	Population Growth
6.8	8.7	6.4	3.2

Duck River Mussel Assemblage Health

Application of the Mussel Assemblage Health Index to four long-term monitoring sites in the Duck River revealed composite scores ranging from 5.4 to 8.4, with all sites meeting or exceeding the minimum threshold for healthy mussel assemblages in comparable southeastern systems. The intermediate to high health scores reflect the continued significance of Duck River mussel communities within a regional context, while simultaneously highlighting ongoing conservation concerns that warrant sustained monitoring and management attention.

Venable Spring scored highest with a composite score of 8.4, and Columbia scored the lowest at 5.4. These scores are in line with previous professional opinion regarding site and community quality, as Columbia has experienced declines and species densities have been reported to increase at Venable, such as a 376% increase in density of Round Hickorynut (*Obovaria subrotunda*) (Wisniewski 2020). The composite score of 6.3 at Lillard Mill was unexpected, as this site is generally considered to harbor a robust mussel assemblage that is used for propagation and reintroduction efforts (Hubbs 2019; Wisniewski 2020). In addition to the composite health scores, individual metric scores offer relevant information regarding mussel assemblage health. For example, while Lillard Mill has a higher current species richness than the other three sites, it also had higher historical richness, and this species loss lowers its composite score. While Lillard has comparable relative density to the higher scoring Venable and Hooper sites, its loss of overall richness and decline in density over time (declining population growth) leads to a lower overall health score than anecdotally expected. To assess the impact of a stable density at Lillard Mill on the composite score, we input a density of 30 mussels/m^2, and the composite score remained moderate at 7.0. This reflects MAHI ability to incorporate full assemblage health into the composite score.

Using MAHI in tandem with other monitoring data may assist with comprehensive assessment of mussel community conditions in the Duck River and provide insight regarding the effects of ongoing management decisions in the Duck River. During TWRA's mark recapture study in 2024, more mussels were recaptured at Lillard Mill (N=975) than Venable Spring (N=322), showing how sampling methods and timing can impact reported abundance (Bajo-Walker 2024). This TWRA survey indicates that, despite a decline in reported density at Lillard Mill in 2020, mussels may be persisting at Lillard Mill at high rates comparable to the Venable site, and this is not apparent when considering MAHI scores in isolation. Despite the fact that Lillard Mill's composite score was lower than expected, the site still harbors more extant species than any site and is a stronghold for propagation and reintroduction efforts in the Duck River and Tennessee. However, the MAHI highlights potential declines in species richness and abundance, underscoring the importance of monitoring the mussel community at Lillard Mill for future declines.

Sampling bias and error are inherent in mussel sampling methods, and species detection is typically low for mussels (refer to section 2). These limitations may influence observed trends in Duck River mussel communities since 2010, such as for Lillard Mill where a large density decline has been documented (Wisniewski 2020). Because natural fluctuations in mussel population demographics are poorly understood and repeat sampling data are limited in availability, it is challenging to determine whether observed changes in density fall within the range of natural variability or are driven by external stressors. These knowledge gaps hinder our ability to fully understand the population dynamics of species in the Duck River. Despite this, MAHI offers a science-based approach for assessing overall assemblage health. All four sites analyzed met or exceeded the minimum MAHI score for "healthy assemblages", reflecting the robustness of Duck River mussel communities related to overall mussel assemblage health in eastern North America. However, intermediate scores and declining densities in 3 of 4 sites highlight the importance of continued monitoring of these communities. Integrating MAHI into ongoing long-term monitoring in the Duck River may provide a more comprehensive description of mussel community health in this critical system.

4. Threats for Duck River Freshwater Mussels

The Duck River mussel fauna has faced multiple threats spanning over a century, beginning with mill dam construction in the 1800s and phosphate ore mining between Centerville and Columbia that was noted as early as the 1920s (Ortmann 1924). Mussel declines accelerated in the 1960s, coinciding with enigmatic declines observed throughout North America, and were primarily attributed to pollution from phosphate ore mining and municipal sources (Van der Schalie 1973; Isom and Yokley 1968; Haag 2019). The construction of Normandy Dam in 1976 further altered freshwater mussel habitat by impounding sections of river and blocking fish passage, contributing to species extirpations above the reservoir (Ahlstedt et al. 2017). Contemporary threats include dramatically increased water withdrawals along with associated wastewater effluent containing heavy metals and nutrients that can bioaccumulate in mussels and reduce reproductive success (USFWS 2025). Additional ongoing stressors include various land use impacts and drought events. Below we discuss some of the most pressing and/or persistent threats faced by the Duck River in greater detail.

Normandy Dam

Impoundments are among the most cited factors contributing to the loss of freshwater mussel diversity and abundance in North America (Haag 2012). In addition to altering physical habitat and water conditions, dams and impoundments can block fish passage, disrupting mussel reproduction by isolating populations from their fish hosts (Haag 2012; Haag et al. 2017). Normandy Dam was constructed in 1976 in the headwaters of the Duck River (DRM 248.6), covering 3,048 acres and altering freshwater mussel habitat by impounding the section of river above the dam. Dam release operations control flows in the Duck River below Normandy. The Tennessee Valley Authority implemented a Reservoir Release Improvement (RRI) program at Normandy Dam in 1991 to improve minimum flows and dissolved oxygen levels downstream. A river discharge evaluation conducted in 2002 compared spring and summer discharges from 1981-1991 (pre-RRI) and 1992-2002 (post-RR) at Shelbyville and Columbia (Ahlstedt et al. 2017). Differences in discharges between the two decades were not statistically significant; however, discharges were higher post-RRI implementation at both locations. Mussel recruitment typically occurs in the spring and summer, and higher discharges may increase habitat availability for reproducing mussels. Ahlstedt et al. (2017) primarily attributed the recovery of the Duck River mussel fauna in the early 2000s to the flow improvements established under the RRI.

Mussel species richness before and after the construction of Normandy Dam is depicted in Figures 21 and 22. The higher number of data points post-Normandy is an artifact of sampling bias, as most records in our database were collected after 1976. The absence of a data point denotes the absence of a record and not a verified absence of mussels. Species richness in the upper Duck River has declined since Normandy Dam was completed, particularly at and above Shelbyville. Reported richness at Shelbyville has declined by 15 species, and mussels are extirpated from some areas above Normandy Reservoir (Ahlstedt et al. 2017). While other environmental factors, such as point source pollution, could have also contributed to mussel declines in these areas, mussel communities in this section of the river have not recovered to the extent of downstream communities. Below Shelbyville, drainage-wide richness generally did not change throughout the Duck River following the completion of Normandy Dam. This indicates that many species extirpations likely occurred before dam construction due to other factors (e.g. habitat degradation, pollution, enigmatic declines). Reported mussel densities are generally higher post-Normandy construction, although there are limitations to those comparisons based on inconsistencies in survey methods and effort (refer to Section 2).

While the construction of Normandy Dam likely contributed to mussel declines above Shelbyville and upstream of the reservoir, the effect of the dam on mussel communities downstream of Shelbyville are less clear. Mussel recovery throughout the Duck River was attributed to flow improvements from TVA's Reservoir Release Improvement program at Normandy; however, current data limitations prohibit the conclusion of a direct causal link between RRI and mussel recovery. However, RRI likely increased habitat availability for mussels in the Duck River during the critical recruitment seasons of spring and summer, which may have contributed to the apparent rebound of mussel populations. Other temporally overlapping factors, such as water quality improvements from the Clean Water Act and physical habitat improvements from farmland restoration, likely also contributed to the recovery of the mussel fauna. Our assessment highlights the importance of standardized mussel monitoring before and after the construction of impoundments and the implementation of reservoir release management.

Although we cannot directly attribute the Duck River mussel recovery to the RRI program, our assessment indicates that Normandy Dam operations do not prohibit the persistence of diverse and abundant mussel beds in certain reaches of the river (i.e., the middle of the drainage). TVA has recently changed Normandy Dam's release strategy, shifting from instantaneous to weekly average flow targets to improve water conservation and operational flexibility (TVA 2025). The adjustments are expected to raise Normandy Reservoir levels up to two feet about 25% of the time, which will reserve water for release during drought and potentially benefit aquatic organisms like mussels. However, the new strategy may also slightly reduce wetted perimeters at key freshwater mussel monitoring sites. TVA modeling predicts minor, temporary reductions in wetted width, averaging less than a foot, which are considered within normal variation for the Duck River. They conclude that since the reductions in wetted perimeter would be small, temporary, and within historical variation for the Duck River, mussels will not be adversely affected during normal, non-drought conditions because most mussel species occupy the middle of the channel and non-juvenile mussels can move or burrow to avoid stranding. For the species that do occupy marginal stream habitats, effects of the proposed alternative are expected to be minimal, gradual, and temporary. The USFWS agreed with TVA's conclusion that the proposed changes are not likely to adversely affect mussels. However, the assessment's reliance on wetted width and stranding potential overlooks broader ecological impacts, such as juvenile recruitment and interactions with other stressors, potentially underestimating long-term risks to mussel populations. Continued monitoring of freshwater mussels will allow a better assessment of impacts on freshwater mussels if any changes to Normandy Dam release operations are implemented in the future.

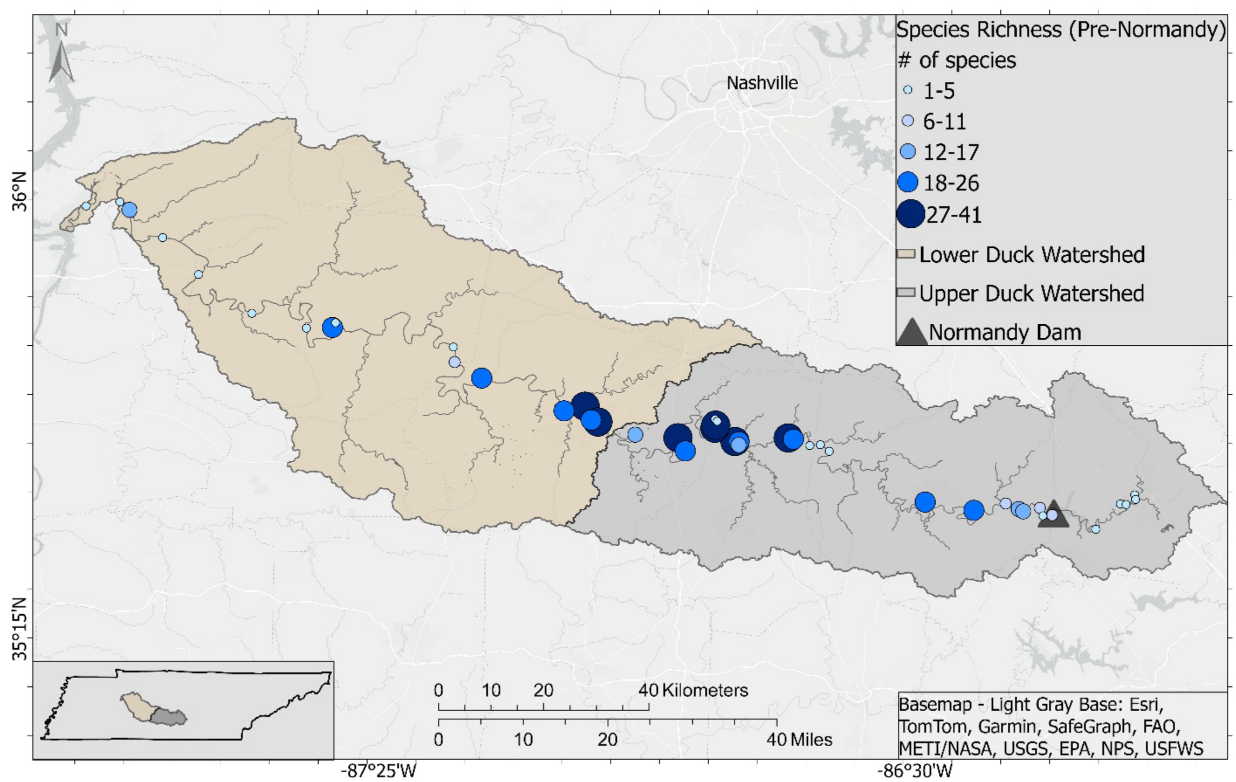


Figure 25. Freshwater mussel species richness documented in the Duck River before completion of Normandy Dam (1800s-1975).

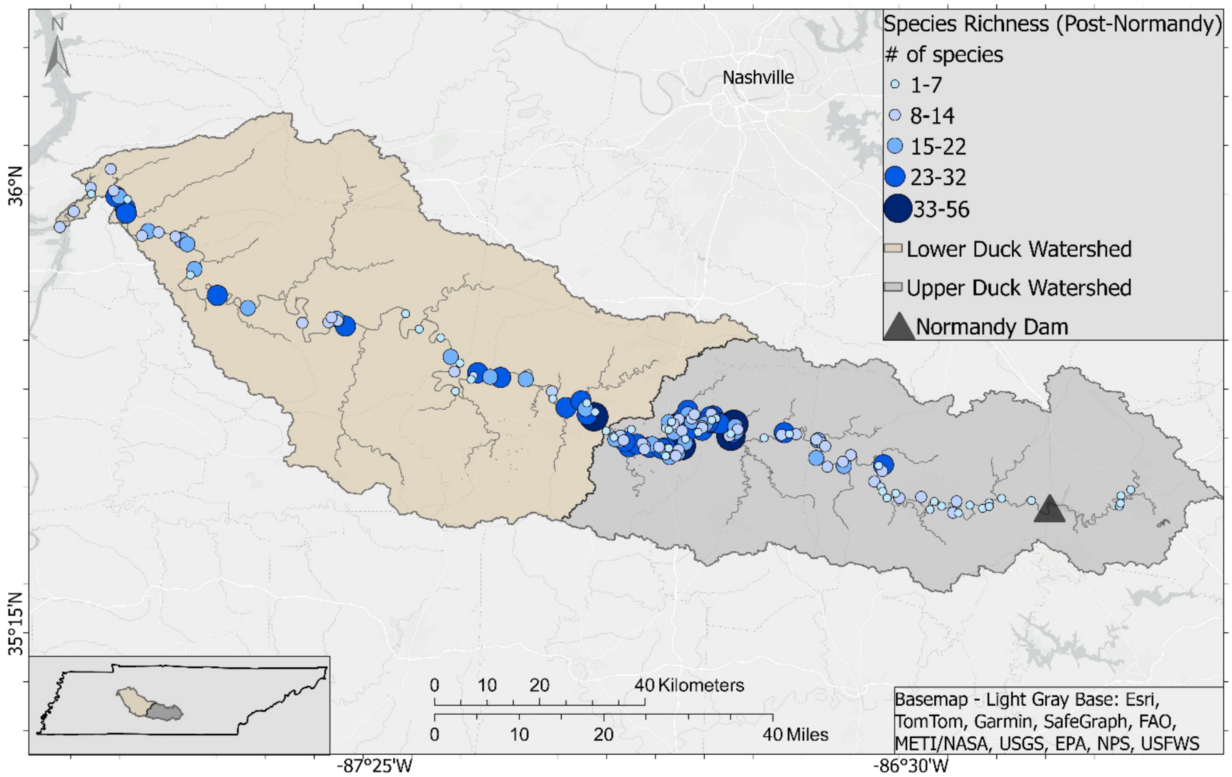


Figure 26. Freshwater mussel species richness documented in the Duck River following completion of Normandy Dam (1976-2023).

Human water use

Water supply planning in the Duck River is a critical component of water resource management in central Tennessee, as the river provides drinking water for over 250,000 people. The Tennessee Department of Environment and Conservation has recently permitted or proposed to permit eight water utilities to withdraw a total of 77 million gallons per day (mgd), representing an over 40% increase in permitted withdrawals (USFWS 2025). Effects of flow regime changes that reduce flows on mussels are multifaceted and complex (refer to Section 2b). Additionally, increased withdrawals lead to a subsequent increase in released effluents. Wastewater effluent can contain heavy metals and inorganic nutrients, such as ammonia, nitrate, and phosphate, that can negatively affect the viability of mussels and host fish (Augspurger et al. 2003; Haag 2012; Nobles and Zhang 2015; Gillis et al. 2017a). As sessile filter feeders, mussels can bioaccumulate heavy metals, which can lead to DNA damage in hemocytes (Naimo 1995; Khan et al. 2019). Inorganic pollutants can reduce mussel reproductive success and juvenile survival and even lead to local extirpation (Cope et al. 2008; Moore and Bringolf 2018; Gillis et al. 2017b).

Interacting land use effects

Land use in the Duck River watershed is composed of approximately 66.1% forest, 20.5% pasture/hay/grasses, 9.9% cropland, 1.2% commercial/residential, 0.9% woody/emergent wetlands, 0.8% mines/rock/cleared areas, and 0.6% water (USACE 2018). Over 300 stream miles within 40 streams in the Duck River watershed are listed on the Tennessee 303(d) List for biological integrity loss and suspended sediment (TDEC 2024). Multiple reaches in the Duck River are impacted by nutrient enrichment, *Escherichia coli* bacteria, and low dissolved oxygen from multiple human water use impacts and agricultural inputs (TDEC 2024).

Anthropogenic land use has both direct and indirect effects on water quality and physical habitat available for freshwater mussels in the Duck River. Water quality in the Duck River watershed is impaired by high nutrient loading and bacteria counts from livestock waste, failing septic tanks, failing or inadequate wastewater collection systems, and wastewater plant discharges (USACE 2018). While mussels have evolved behavioral adaptations to avoid short-term physical stressors, their sessile nature makes them susceptible to the effects of surrounding land use and sensitive to long-term exposure to poor water quality and contaminants. Mussels are more sensitive than other aquatic organisms to contaminants such as ammonia and may be particularly sensitive during the larval or juvenile stage (USEPA 2013; Salerno et al. 2020). Agriculture may have an adverse effect on mussel diversity and abundance; however, it may also have a positive effect on mussel growth (Hornbach et al. 2021). Chronic exposure to herbicides can reduce the growth and survival of juvenile mussels (Bringolf et al. 2007). Excessive nutrients such as phosphate from mining and nitrogen from agricultural practices can lead to algal growth (Xia et al. 2020), which, after die-offs, can lower dissolved oxygen levels and harm mussels (Sparks et al. 1998). Excessive algal growth may be particularly prevalent in the lower Duck River due to extensive cropland and a low river gradient lead to higher nitrogen and phosphate inputs (Kingsbury et al. 1999). Increased turbidity and suspended solids can inhibit the filter-feeding of mussels and negatively affect aspects of their life cycle, including the host-fish relationship (Goldsmith et al. 2021).

The full synergistic effects of these summarized threats on the Duck River mussel fauna are not fully understood. More knowledge regarding the tolerance of Duck River mussel species to flow alterations and various water quality parameters, such as temperature, dissolved oxygen, and contaminants would benefit our understanding of potential synergistic effects of these conditions on freshwater mussel health. Addressing these data gaps would help managers ensure that future land use and water management will meet anthropogenic needs while also protecting the ecological integrity of the Duck River for mussel populations.

Drought

Drought conditions occurred in 2024, during which several mussel stranding events were documented (Hubbs 2024). An extended low flow event was recorded between July 4 and July 16 based on below-median daily flow measurements at the USGS Milltown stream gage (03599240). In response, Don Hubbs surveyed eight sites near existing or proposed water intakes between Shelbyville and Centerville (DRM 222-51) in July and September 2024 to assess the effects of this low flow event on freshwater mussel populations. They observed 777 fresh dead individuals of 36 species between Shelbyville and Centerville. Federally protected species were observed from DRM 221-51 and accounted for 58.4% of total collected mussels. The endangered Birdwing Pearlymussel (*Lemiox rimosus*) and the threatened Round Hickorynut (*Obovaria subrotunda*) comprised 24.6% and 19.65% of the sample between Shelbyville and Columbia, respectively. Many individuals had soft tissue remaining in their shells, indicating recent mortality (Figure 27). At Venable Spring, a TWRA long-term monitoring site, 277 fresh dead mussels were collected. Mussels were observed stranded or attempting to move horizontally to deeper water within marginal habitats. Numerous live mussels were found in extremely shallow water—less than four inches deep—further highlighting their vulnerability during low-flow conditions.

Figure 27. Fresh dead mussel shells collected in the Duck River, Tennessee during mussel stranding surveys in 2024 (from Hubbs 2024, permission from author obtained).

Figure 28. Photographs from Venable Spring site on the Duck River, Tennessee "looking downstream at 100 flags placed next to live mussels in < 4-inch-deep water over a 40 m stretch of bank along the right descending bank immediately upstream from the spring confluence at the downstream site boundary" (from Hubbs 2024, permission from author obtained).

Figure 29. Drought conditions during Summer 2024 in the Duck River, Tennessee. Photographs provided by Don Hubbs.

5. Conclusions

The Duck River is one of the most thoroughly studied rivers for freshwater mussels in Tennessee. Our recent compilation of over 7,000 mussel records throughout the watershed (Womble and Rosenberger 2025) enabled a detailed analysis on the history of mussel communities in the system. Historically, the Duck River harbored over 70 mussel species, and our results indicate that 62 of those remain extant, underscoring the importance of this river for freshwater mussel conservation in Tennessee. Although overall species richness has declined at 85% of sites surveyed throughout the drainage, the Duck River continues to harbor one of the most diverse mussel communities in North America. Mussel species extirpated from the Duck River are predominantly either extinct, such as the Yellow Blossom (*Epioblasma florentina*) and Turgid Blossom (*Epioblasma turgidula*), or federally endangered taxa that are naturally rare across their range, including the Cracking Pearlymussel (*Hemistena lata*), Golden Riffleshell (*Epioblasma aureola*), and Littlewing Pearlymussel (*Pegias fabula*). Several species that are common in other systems, such as the Lilliput (*Toxolasma parvum*) and Flat Floater (*Utterbackiana suborbiculata*), may persist in the Duck River at densities below detection thresholds, particularly in the lower mainstem where survey coverage has been limited.

Our analysis indicates that the mussel fauna of the Duck River was described to be robust as early as the 1920s however, data suggest that mussel declines began as early as the 1960s. By the early 2000s, the mussel fauna recovered to a condition comparable to that observed in early surveys. Although data limitations preclude assessment of which factors contributed directly to this recovery, reservoir release improvements at Normandy Dam, reduction of point source pollution, farmland acquisition and removal, and channel recovery from past destabilization events likely influenced mussel community condition. Historically and currently, the core area of species diversity in the Duck River is restricted to approximately 50 river miles in the middle of the drainage between Columbia and Lillard Mill. Although recent quantitative surveys indicate declining mussel density at several sites in this stretch of river since 2000, these communities still harbor moderate to high relative densities of mussels. Further investigation into potential causal relationships between water chemistry and mussel abundance, persistence, and community structure could improve our understanding of the concentration of the most diverse and abundant mussel communities in the Duck River immediately downstream of zones where limestone and karst geochemical processes dominate. Mussel communities in other sections of the river have not shown the same resilience. Reaches near Shelbyville and upstream of Normandy Dam have not rebounded, and available data indicate that mussel richness and abundance have declined in the lower Duck River. However, this analysis highlighted large data gaps in the lower portion of the river (Figure 30; Appendix 6), highlighting the potential benefits of additional targeted surveys.

Despite extensive survey coverage in the Duck River, this analysis highlights the inherent challenges of monitoring freshwater mussel communities and assessing long-term trends in community health. Many historical and recent mussel surveys are affected by sampling bias, and this challenge is compounded by a general lack of standardization in survey intensity, methods, and spatial coverage. These limitations warrant consideration when interpreting our reported temporal changes in species richness, density, and abundance in the Duck River watershed. To strengthen our analysis, we incorporated the Mussel Assemblage Health Index (MAHI) as a science-based assessment of mussel community health, which supports our observation of a general and ongoing, though not wholesale or precipitous, decline of mussel richness and health in the Duck River system. Use of MAHI in concert with ongoing monitoring data (e.g. TWRA long-term monitoring and mark-recapture studies) will enhance our ability to continue assessing the conditions of Duck River mussel communities. The mussel communities in the Duck River have been impacted by a wide variety of threats, including mining, the construction of Normandy Dam, water withdrawals, interacting land use impacts, and drought conditions. While these threats and others have been affecting mussels for centuries, our directly comparable, long-term monitoring data only extend back to 2010. Establishing longer-term datasets, such as 30 years or more, would improve our ability to more accurately assess temporal changes in mussel communities in response to environment changes (Vaughn and Atkinson 2025). This is particularly important given that mussel populations are prone to dynamic lags; therefore, factors affecting mussel communities may not be apparent for several decades (Strayer 2024).

Standardized and consistent monitoring of mussel communities throughout the entirety of the Duck River watershed will contribute to understanding baseline variability in mussel community dynamics in the system, ongoing effects of land use changes and management decisions, and opportunities for intervention or assemblage improvements. This analysis identifies priority areas for protection, such as the core area of diversity between Columbia and Lillard Mill, as well as regions that would benefit from further study, including the lower Duck River. Prioritizing survey methods that reduce bias and allow for the estimation of abundance will improve the accuracy and comparability of future mussel assemblage assessments.

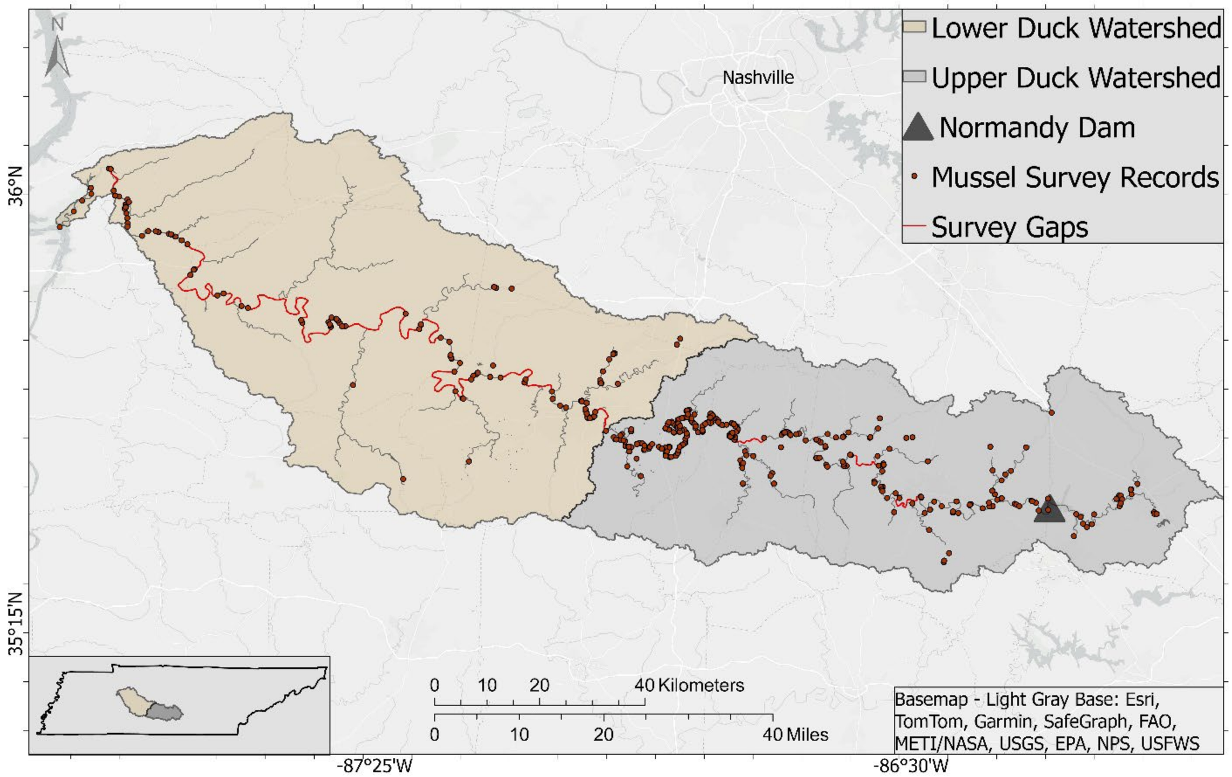


Figure 30. Mussel survey gaps (>3 river miles) in the Duck River, Tennessee according to available data from Womble and Rosenberger 2025.

Appendices

Appendix 1. Mussel species reported historically in the Duck River drainage, Tennessee (N=75). Federal Status is the status of the species under the Endangered Species Act (ESA) at the time of this report. “Prop. End” refers to species that have been proposed for listing under the ESA at the time of this report. Extant refers to whether the species has been collected live or fresh dead from the watershed since 2000 (Y=Yes, N=No). Taxonomic assignments follow the Freshwater Mollusk Conservation Society’s 2025 Checklist of Bivalve Names (FMCS 2025).

Species	Common Name	Federal Status	Extant (Y/N)
Ortmanniana ligamentina	Mucket	Not Listed	Y
Lampsilis pectorosa	Pheasantshell	Not Listed	Y
Alasmidonta marginata	Elktoe	Not Listed	N
Pressodonta viridis	Slippershell Mussel	Not Listed	Y
Amblema plicata	Threeridge	Not Listed	Y
Arcidens confragosus	Rock Pocketbook	Not Listed	Y
Cambarunio dactylus	Cumberland River Rainbow	Not Listed	Y
Cambarunio taeniatus	Painted Creekshell	Not Listed	Y
Cumberlandia monodonta	Spectaclecase	Endangered	Y
Pustulosa nodulata	Wartyback	Not Listed	Y
Pustulosa pustulosa	Pimpleback	Not Listed	Y
Cyclonaias tuberculata	Purple Wartyback	Not Listed	Y
Cyprogenia stegaria	Fanshell	Endangered	Y
Ellipsaria lineolata	Butterfly	Not Listed	Y
Elliptio crassidens	Elephantear	Not Listed	Y
Epioblasma ahlstedti	Duck River Dartersnapper	Endangered	Y
Epioblasma aureola	Golden Riffleshell	Endangered	N
Epioblasma brevidens	Cumberlandian Combshell	Endangered	Y
Epioblasma florentina	Yellow Blossom	Extinct	N
Epioblasma obliquata	Catspaw	Endangered	Y
Epioblasma triquetra	Snuffbox	Endangered	Y
Epioblasma turgidula	Turgid Blossom	Extinct	N
Eurynia dilatata	Spike	Not Listed	Y
Fusconaia cuneolus	Finerayed Pigtoe	Endangered	Y
Fusconaia flava	Wabash Pigtoe	Not Listed	Y
Fusconaia subrotunda	Longsolid	Threatened	N
Hemistena lata	Cracking Pearlymussel	Endangered	N
Lampsilis abrupta	Pink Mucket	Endangered	Y
Lampsilis cardium	Plain Pocketbook	Not Listed	Y
Lampsilis fasciola	Wavyrayed Lampmussel	Not Listed	Y
Lampsilis ovata	Pocketbook	Not Listed	Y

Lampsilis teres	Yellow Sandshell	Not Listed	Y
Pterosyna complanata	White Heelsplitter	Not Listed	Y
Lasmigona costata	Flutedshell	Not Listed	Y
Platynaias sp.	Barrens Heelsplitter	NA	Y
Leaunio vanuxemensis	Mountain Creekshell	Not Listed	Y
Lemiox rimosus	Birdwing Pearlymussel	Endangered	Y
Ligumia recta	Black Sandshell	Not Listed	Y
Medionidus conradicus	Cumberland Moccasinshell	Prop. End	Y
Megalonaias nervosa	Washboard	Not Listed	Y
Obliquaria reflexa	Threehorn Wartyback	Not Listed	Y
Obovaria subrotunda	Round Hickorynut	Threatened	Y
Paetulunio fabalis	Rayed Bean	Endangered	N
Pegias fabula	Littlewing Pearlymussel	Endangered	N
Plectomerus dombeyanus	Bankclimber	Not Listed	Y
Plethobasus cyhypus	Sheepnose	Endangered	Y
Pleurobema clava	Clubshell	Endangered	N
Pleurobema cordatum	Ohio Pigtoe	Not Listed	Y
Pleurobema oviforme	Tennessee Clubshell	Prop. End.	Y
Pleurobema sintoxia	Round Pigtoe	Not Listed	Y
Pleuronaia barnesiana	Tennessee Pigtoe	Prop. End.	Y
Pleuronaia dolabelloides	Slabside Pearlymussel	Endangered	Y
Potamilus alatus	Pink Heelsplitter	Not Listed	Y
Potamilus fragilis	Fragile Papershell	Not Listed	Y
Potamilus ohiensis	Pink Papershell	Not Listed	Y
Ptychobranchus fasciolaris	Kidneyshell	Not Listed	Y
Ptychobranchus subtentus	Fluted Kidneyshell	Endangered	Y
Pyganodon grandis	Giant Floater	Not Listed	Y
Quadrula fragosa	Winged Mapleleaf	Endangered	N
Quadrula quadrula	Mapleleaf	Not Listed	Y
Reginaia ebenus	Ebonyshell	Not Listed	Y
Sagittunio subrostratus	Pondmussel	Not Listed	N
Simpsonaias ambigua	Salamander Mussel	Prop. End.	Y
Strophitus undulatus	Creeper	Not Listed	Y
Theliderma cylindrica	Rabbitsfoot	Threatened	Y
Theliderma intermedia	Cumberland Rockshell	Endangered	Y
Theliderma metanevra	Rockshell	Not Listed	Y
Toxolasma cylindrellus	Pale Lilliput	Endangered	Y
Toxolasma lividum	Purple Lilliput	Not Listed	Y
Toxolasma parvum	Lilliput	Not Listed	N
Quadrula verrucosa	Pistolgrip	Not Listed	Y

Truncilla donaciformis	Fawnsfoot	Not Listed	Y
Truncilla truncata	Deertoe	Not Listed	Y
Utterbackia imbecillis	Paper Pondshell	Not Listed	Y
Utterbackiana suborbiculata	Flat Floater	Not Listed	N

Appendix 2a. Inputs for the Mussel Assemblage Health Index (MAHI) score for the Columbia site on the Duck River, Tennessee.

Proportion Historical Richness	
Historical Richness	49
Current Richness	27
Density Relative to Stream Size	
Mussel Density (number/m2)	4.98
Watershed Area (km2)	3124.9
Assemblage Recruitment Strength	
Number of Species Recruiting	27
Mean Species Recruitment Strength	*Amblema plicata*, *Cyclonaias tuberculata*, *Pustulosa pustulosa*, *Quadrula verrucosa*
Population Growth	
2010 Mussel Density (number/m2)	10.5
2015 Mussel Density (number/m2)	7.4
2020 Mussel Density (number/m2)	4.98

Appendix 2b. Final scaled metric scores and raw scores and score components for the Columbia site on the Duck River in Tennessee using the Mussel Assemblage Health Index (MAHI) Tool (Composite score=5.4).

Final Scaled Metric Scores	
Proportion Historical Richness	5.5
Relative Density	7.0
Assemblage Recruitment Strength	6.0
Population Growth	3.1
Raw Scores and Score Components	
Proportion Historical Richness	0.551
Predicted Density (number/m2)	12.6
Observed Density (number/m2)	5.0
ln Density Residual	-0.93
Proportion of Species Recruiting	1.000
Mean Species Recruitment Strength	0.094
Assemblage Recruitment Strength	0.094
Population Growth (*r*)	-0.075

Appendix 3a. Inputs for the Mussel Assemblage Health Index (MAHI) score for the Venable Springs site on the Duck River in Tennessee.

Proportion Historical Richness	
Historical Richness	36
Current Richness	29
Density Relative to Stream Size	
Mussel Density (number/m2)	14.12
Watershed Area (km2)	2454.3
Assemblage Recruitment Strength	
Number of Species Recruiting	29
Mean Species Recruitment Strength	*Amblema plicata, Cyclonaias tuberculata, Eurynia dilatata, Epioblasma ahlstedti, Pleuronaia barnesiana, Cambarunio taeniatus, Theliderma cylindrica, Lasmigona costata, Lemiox rimosus, Pleuronaia dolabelloides, Obovaria subrotunda, Pleurobema sintoxia*
Population Growth	
2010 Mussel Density (number/m2)	12.65
2015 Mussel Density (number/m2)	14.15
2020 Mussel Density (number/m2)	14.12

Appendix 3b. Final scaled metric scores and raw scores and score components for the Venable Spring site on the Duck River in Tennessee using the Mussel Assemblage Health Index (MAHI) Tool (Composite score=8.4)

Final Scaled Metric Scores	
Proportion Historical Richness	8.1
Relative Density	8.4
Assemblage Recruitment Strength	10
Population Growth	7.2
Raw Scores and Score Components	
Proportion Historical Richness	0.806
Predicted Density (number/m2)	11.6
Observed Density (number/m2)	14.1
ln Density Residual	0.19
Proportion of Species Recruiting	1.000
Mean Species Recruitment Strength	0.193
Assemblage Recruitment Strength	0.193
Population Growth (*r*)	0.011

Appendix 4a. Inputs for the Mussel Assemblage Health Index (MAHI) score for the Hooper Island site on the Duck River, Tennessee.

Proportion Historical Richness	
Historical Richness	36
Current Richness	25
Density Relative to Stream Size	
Mussel Density (number/m2)	19.08
Watershed Area (km2)	2636.8
Assemblage Recruitment Strength	
Number of Species Recruiting	25
Mean Species Recruitment Strength	*Amblema plicata, Pustulosa pustulosa, Cyclonaias tuberculata, Epioblasma ahlstedti, Eurynia dilatata, Lampsilis fasciola, Lasmigona costata, Lemiox rimosus, Cambarunio taeniatus, Medionidus conradicus, Obovaria subrotunda, Theliderma intermedia, Pleurobema oviforme, Pleurobema sintoxia, Pleuronaia barnesiana, Pleuronaia dolabelloides, Theliderma cylindrica*
Population Growth	
2010 Mussel Density (number/m2)	22.2
2015 Mussel Density (number/m2)	20.15
2020 Mussel Density (number/m2)	19.08

Appendix 4b. Final scaled metric scores and raw scores and score components for the Hooper Island site on the Duck River, Tennessee using the Mussel Assemblage Health Index (MAHI) Tool (Composite score=7.2)

Final Scaled Metric Scores	
Proportion Historical Richness	6.9
Relative Density	8.7
Assemblage Recruitment Strength	7.3
Population Growth	5.9
Raw Scores and Score Components	
Proportion Historical Richness	0.694
Predicted Density (number/m2)	11.9
Observed Density (number/m2)	19.1
ln Density Residual	0.47
Proportion of Species Recruiting	1.000
Mean Species Recruitment Strength	0.115
Assemblage Recruitment Strength	0.115
Population Growth (*r*)	-0.015

Appendix 5a. Inputs for the Mussel Assemblage Health Index (MAHI) score for the Lillard Mill site on the Duck River, Tennessee.

Proportion Historical Richness	
Historical Richness	57
Current Richness	39
Density Relative to Stream Size	
Mussel Density (number/m2)	18.14
Watershed Area (km2)	2370.9
Assemblage Recruitment Strength	
Number of Species Recruiting	33
Mean Species Recruitment Strength	*Amblema plicata, Pustulosa pustulosa, Cyclonaias tuberculata, Cambarunio taeniatus, Epioblasma ahlstedti, Quadrula verruosa, Eurynia dilatata, Theliderma cylindrica, Lasmigona costata, Lemiox rimosus, Ptychobranchus subtentus, Pleuronaia dolabelloides, Pleuronaia barnesiana*
Population Growth	
2010 Mussel Density (number/m2)	37.4
2015 Mussel Density (number/m2)	30.26
2020 Mussel Density (number/m2)	18.14

Appendix 5b. Final scaled metric scores and raw scores and score components for the Lillard Mill site on the Duck River, Tennessee using the Mussel Assemblage Health Index (MAHI) Tool (Composite score=6.3).

Final Scaled Metric Scores	
Proportion Historical Richness	6.8
Relative Density	8.7
Assemblage Recruitment Strength	6.4
Population Growth	3.2
Raw Scores and Score Components	
Proportion Historical Richness	0.684
Predicted Density (number/m2)	11.5
Observed Density (number/m2)	18.1
ln Density Residual	0.45
Proportion of Species Recruiting	0.846
Mean Species Recruitment Strength	0.118
Assemblage Recruitment Strength	0.100
Population Growth (*r*)	-0.072

Appendix 6. Mussel survey gaps (>3 river miles) in the Duck River, Tennessee according to available data from Womble and Rosenberger 2025.

Duck River Mile Reaches	Coordinates Start	Coordinates End
12.0-15.0	36.0421909, -87.8474266	36.0063205, -87.8432165
28.5-32.1	35.9136400, -87.7168154	35.8722439, -87.7044289
33-42.7	35.8609063, -87.7122159	35.8265710, -87.6663009
43.5-48.4	35.8300005, -87.6541967	35.8092217, -87.6245820
49.1-64	35.8053080, -87.6125989	35.7848521, -87.5224231
64.5-70.7	35.7790824, -87.5206478	35.7721427, -87.4720699
74-82.5	35.7735549, -87.4453601	35.7958668, -87.3434434
82.7-87.3	35.7948985, -87.3443714	35.7687132, -87.3212121
89.5-95	35.7842065, -87.3149180	35.7545514, -87.2847383
100.5-108	35.6963560, -87.2612679	35.6645724, -87.2594564
108.3-112.8	35.6626786, -87.2584683	35.6826463, -87.2320368
116.4-121	35.6865163, -87.1809854	35.6835932, -87.1381269
121.5-125	35.6772118, -87.1402266	35.6636255, -87.0941156
134.1-137.8	35.6283012, -87.0194734	35.5952413, -87.0007409
180-183.9	35.5789097, -86.7814025	35.5832047, -86.7305750
202.5-206.5	35.5523498, -86.5817025	35.5354073, -86.5356442
216.3-221.3	35.4796756, -86.5002310	35.4835868, -86.4645361

Literature Cited

Ahlstedt, S.A. 1991. Cumberlandian mollusk conservation program activity 1: Mussel surveys in six Tennessee Valley streams. Walkerana 5(13):123-160.

Ahlstedt, S.A., J.R. Powell, R.S. Butler, M.T. Fagg, D.W. Hubbs, S.F. Novak, S.R. Palmer, and P.D. Johnson. 2017. Historical and current examination of freshwater mussels (Bivalvia: Margaritiferidae: Unionidae) in the Duck River Basin, Tennessee. Malacological Review 45(46):163.

Allan, J.D., M.M. Castillo, and K.A. Capps. 2021. Stream ecology: structure and function of running waters. Springer Nature, Cham, Switzerland.

American Rivers. 2024. America's most endangered rivers of 2024. A call to action for clean water. Final Report. 24pp. Accessed at: https://www.americanrivers.org/wp-content/uploads/2024/04/v8_AR_2024-Most-Endangered-Rivers-FINAL.pdf

AST Environmental (AST). 2024. Duck River Mussel Survey and Habitat Assessment Report: Slick Shoals, Old Trap Island, Cundiff Island, Carpenter Bridge Shoal, Marshall and Maury Counties, Tennessee. Report prep. for Civil and Env Consultants, Inc. and TDEC. 58 pp.

Atkinson, C.L., J.P. Julian, and C.C. Vaughn. 2014. Species identity dominates over environment in shaping the mussel-associated macroinvertebrate community. Freshwater Science 33:675-687.

Atkinson, C. ., C.C. Vaughn, K.J. Forshay, and J.T. Cooper. 2018. Consumer-driven nutrient dynamics in freshwater ecosystems: from individuals to ecosystems. Biological Reviews 93:309-329.

Augspurger, T., A.E. Keller, M.C. Black, W.G. Cope, and F.J. Dwyer. 2003. Water quality guidance for protection of freshwater mussels (Unionidae) from ammonia exposure. Environmental Toxicology and Chemistry 22:2569-5775.

Bajo-Walker, B. 2024. Freshwater Mussel Capture-Mark-Recapture on the Duck River. Presentation given at the 2024 Duck River Symposium. Pages 72-96. Accessed online at: https://webgen1files1.revize.com/theduckriveragencytn/Document%20Center/Symposium/2024%20Symposium/2024%20Symposium%20Presentations.pdf

Bringolf, R.B., W.G., Cope, C.B. Eads, P.R. Lazaro, M.C. Barnhart, and D. Shea. 2007. Acute and chronic toxicity of technical-grade pesticides to glochidia and juveniles of freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10):2086-2093.

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

Cumberlandian Region Mollusk Restoration Committee (CRMRC). 2010. Plan for the population restoration and conservation of imperiled freshwater mollusks of the Cumberlandian Region. 144 pp.

Daniel, W.M. and K.M. Brown. 2013. Multifactorial model of habitat, host fish, and landscape effects on Louisiana freshwater mussels. Freshwater Science 32(1):193-203.

Denton, G.M. 2007. Mercury levels in Tennessee fish. Tennessee Department of Environment and Conservation, Division of Water Pollution Control, Nashville, TN.

Downing, J.A., and W.L. Downing. 1992. Spatial aggregation, precision, and power in surveys of freshwater mussel populations. Canadian Journal of Fisheries and Aquatic Sciences 49:985- 991.

Downing, J., J. Cole, C. Duarte, J. Middelburg, J. Melack, Y. Prairie, P. Kortelainen, R. Striegl, W. McDowell, and L. Tranvik. 2012. Global abundance and size distribution of streams and rivers. Inland Waters 2:229–236.

Dunn, H.L., and D.L. Strayer. 2010. Overview of sampling techniques for freshwater mussels. Freshwater Mollusk Conservation Society 2010 workshop: regional fauna identification and sampling.

Ford, D., and P.D. Williams. 2007. Karst hydrogeology and geomorphology. John Wiley & Sons, Chichester, UK.

Ford, D.F., A.D. Walters, L.R. Williams, M.G. Williams, and N.B. Ford. 2016. Mussel assemblages in streams of different sizes in the Neches River Basin of Texas. Southeastern Naturalist, 15(1):26-40.

Freshwater Mollusk Conservation Society (FMCS). 2025. The 2025 FMCS checklist of freshwater mussels (Mollusca: Bivalvia: Unionida) of the United States and Canada. https://molluskconservation.org/Library/Committees/Names/Appendix_1_Bivalves_Revised_Names_List_wo_Sphaeriidae_20250803.pdf

Gillis, P.L., R. McInnis, J. Salerno, S.R. de Solla, M.R. Servos, and E.M. Leonard. 2017a. Freshwater mussels in an urban watershed: Impacts of anthropogenic inputs and habitat alterations on populations. Science of the Total Environment 574:671-679.

Gillis, P.L., R. McInnis, J. Salerno, S.R. de Solla, M.R. Servos, and E.M. Leonard. 2017b. Municipal wastewater treatment plant effluent-induced effects on freshwater mussel populations and the role of mussel refugia in recolonizing an extirpated reach. Environmental Pollution 225:460-468.

Goldsmith, A.M., F.H. Jaber, H. Ahmari, and C.R. Randklev. 2021. Clearing up cloudy waters: a review of sediment impacts to unionid freshwater mussels. Environmental Review 29:100-108.

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

Haag, W.R. 2019. Reassessing enigmatic mussel declines in the United States. Freshwater Mollusk Biology and Conservation 22(2): 43-60.

Haag, W.R., D.J. Berg, D.W. Garton, and J.L. Farris. 2017. Novel technique to identify large river host fish for freshwater mussel propagation and conservation. Aquaculture Research, 48(12):6253-6264.

Haag, W.R., and J.D. Williams. 2014. Biodiversity on the brink: an assessment of conservation strategies for North American freshwater mussels. Hydrobiologia 735(1):45-60.

Haag, W.R., A.K. Burrow, T.P. DuBose, and S.J. Price. 2024. A broadly applicable, objective freshwater mussel assemblage health index (MAHI). Freshwater Science 43(2):150-168.

Hinkley, A.A., and P. Marsh. 1885. List of shells collected in central Tennessee with notes on species. Published privately by the author, Aledo, Illinois. 10 pp.

Hornbach, D.J., H.N. Stutzman, M.C. Hove, J.L. Kozarek, K.R. MacGregor, T.J. Newton, and P.R. Ries. 2021. Influence of surrounding land-use on mussel growth and glycogen levels in the St. Croix and Minnesota River Basins. Hydrobiologia 848:3045-3063.

Hubbs, D.W. 2010. 2010 Duck River quantitative mussel survey. Tennessee Wildlife Resources Agency Fisheries Division Report 11-04. 47 pp.

Hubbs, D.W. 2015. 2015 Duck River quantitative mussel survey. Tennessee Wildlife Resources Agency Fisheries Division Report 16-06. 59 pp.

Hubbs, D.W. 2019. 2018 Annual Mussel Recovery Activity Report for Project 7775. Tennessee Wildlife Resources Agency Fisheries Division Report 19-05. 80 pp.

Hubbs, D. 2024. Duck River Low Flow Mussel Mortality Survey Bedford, Marshall, Maury and Hickman Counties, Tennessee July 16 – 17, September 5, 2024. Ellipsaria Vol. 26(2):14-22.

Inoue, K., D.M. Hayes, J.L. Harris, N.A. Johnson, C.L. Morrison, M.S. Eackles, T.L. King, J.W. Jones, E.M. Hallerman, A.D. Christian, and C.R. Randklev. 2018. The *Pleurobemini* (Bivalvia: Unionida) revisited: Molecular species delineation using a mitochondrial DNA gene reveals multiple conspecifics and undescribed species. Invertebrate Systematics, 32(3): 689-702.

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

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

Jenkinson, J. 1988. Resurvey of freshwater mussel stocks in the Duck River, Tennessee. Tennessee Valley Authority Report, 32pp.

Johnson, N. A., A.R. Henderson, J.W. Jones, C.E. Beaver, S.A. Ahlstedt, G.R. Dinkins, N.L. Eckert, M.J. Endries, J.T. Garner, J.L. Harris, P.D. Hartfield, D.W. Hubbs, T.W. Lane, M.A. McGregor, K.R. Moles, C.L. Morrison M.D. Wagner, J.D. Williams, and C.H. Smith. 2024. Glacial vicariance and secondary contact shape demographic histories in a freshwater mussel species complex. Journal of Heredity, 115(1):72-85.

Johnson, P.D. and K.M. Brown. 2000. The importance of microhabitat factors and habitat stability to the threatened Louisiana pearl shell, *Margaritifera hembeli* (Conrad). Canadian Journal of Zoology 78:271–277.

Khan, M.I., M. Zahoor, A. Khan, N. Gulfam, and M. Khisroon. 2019. Bioaccumulation of Heavy Metals and their Genotoxic Effect on Freshwater Mussel. Bulletin of Environmental Contamination and Toxicology 102:52–58.

Kingsbury, J. A., A.B. Hoos, and M.D. Woodside. 1999. Environmental setting and water-quality issues in the lower Tennessee River basin. U.S. Geological Survey Water-Resources Investigations Report 99-4080. 44 pp.

Knight, R.R. and J.A. Kingsbury. 2007. Water resources of the Duck River watershed, Tennessee. U.S. Geological Survey Scientific Investigations Report 2007-5105, 46pp.

LaForest, M.J. and L.L. Oliveira. 1979. An inventory of mills on the Duck River. Tennessee Valley Authority, Office of Natural Resources, Knoxville, Tennessee. 31 pp.

MacKenzie, D.I., J.D. Nichols, J.A. Royle, K.H. Pollock, J.E. Hines, and L.L. Bailey. 2006. Occupancy estimation and modeling: inferring patterns and dynamics of species occurrence. Elsevier, San Diego, CA. 324pp.

Moore, A.P. and R.B. Bringolf. 2018. Effects of nitrate on freshwater mussel glochidia attachment and metamorphosis success to the juvenile stage. Environmental Pollution 242(Part A):807-813.

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

Noble, M., P. Duncan, D. Perry, K. Prosper, D. Rose, S. Schnierer, G. Tipa, E. Williams, E., R. Woods, and J. Pittock. 2016. Culturally significant fisheries: keystones for management of freshwater social-ecological systems. Ecology and Society 21(2):22 pp.

Nobles, T. and Y. Zhang. 2015. Survival, growth and condition of freshwater mussels: Effects of municipal wastewater effluent. PLoS One, DOI:10.1371/journal.pone.0128488.

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

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

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

Reed, M.P., G.R. Dinkins, and S.A. Ahlstedt. 2019. Freshwater mussels (Bivalvia: Margaritiferidae and Unionidae) of the Buffalo River drainage, Tennessee. Southeastern Naturalist 18:346-372.

Salerno, J., P.L. Gillis, H. Khan, E. Burton, L.E. Deeth, C.J. Bennett, P.K. Sibley, and R.S. Prosser. 2020. Sensitivity of larval and juvenile freshwater mussels (Unionidae) to ammonia, chloride, copper, potassium, and selected binary chemical mixtures. Environmental Pollution 256:113398.

Sansom, B.J., S.J. Bennett, J.F. Atkinson, and C.C. Vaughn. 2020. Emergent hydrodynamics and skimming flow over mussel covered beds in rivers. Water Resources Research 56(8): 17pp.

Schilling, E.M. and J.D. Williams. 2002. Freshwater mussels (Bivalvia: Margaritiferidae and Unionidae) of the lower Duck River in middle Tennessee: a historical and recent review. Southeastern Naturalist 1(4):403-414.

Shea, C. P., J.T. Peterson, J.M. Wisniewski, and N.A. Johnson. 2011. Misidentification of freshwater mussel species (Bivalvia: Unionidae): Contributing factors, management implications, and potential solutions. Journal of the North American Benthological Society, 30(2):446-458.

Smith, R.K., P.L. Freeman, J.V. Higgins, K.S. Wheaton, T.W. FitzHugh, K.J. Ernstrom, and A. A. Das. 2002. Priority areas for freshwater conservation action: a biodiversity assessment of the southeastern United States. The Nature Conservancy 3.

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

Spooner, D.E., and C.C. Vaughn. 2006. Context-dependent effects of freshwater mussels on stream benthic communities. Freshwater Biology 51:1016-1024.

Stantec Consulting Services, Inc. (Stantec). 2023. Duck River mussel survey for proposed Columbia Power and Water Systems Long-Term Water Supply Program. 04ET1000-2021-SLI-0621. Draft Report Prepared for Columbia Power and Water Systems. 123 pp.

Strayer D.L. 2024. Better Population Monitoring and Understanding of Dynamic Lags Could Aid Freshwater Mussel Conservation. American Malacological Bulletin 41(1):22-34.

Strayer, D.L. and D.R. Smith. 2003. A guide to sampling freshwater mussel populations. No. 8 American Fisheries Society. 103pp.

Stephenson, C. 2024. Environmental group calls for water conservation as drought saps Duck River. Tennessee Lookout. Accessed at https://tennesseelookout.com/2024/09/10/environmental-group-calls-for-water-conservation-as-drought-saps-duck-river/

Stueber, A.M., and R.E. Criss. 2005. Origin and transport of dissolved chemicals in a karst watershed, Southwestern Illinois. Journal of the American Water Resources Association 41:267-290.

Tennessee Department of Environmental and Conservation (TDEC). 2024. List of Impaired and Threatened Waters in Tennessee. April 2024. Accessed at https://www.tn.gov/content/dam/tn/environment/water/watershedplanning/wr_wq_impaired-waters-list-2024-final.xlsx

Tennessee Department of Environment and Conservation (TDEC). 2025. Tennessee Scenic Rivers. Tennessee Department of Environment and Conservation. Accessed at https://www.tn.gov/environment/program-areas/na-natural-areas/na-sr-scenic-rivers-list.html

Tennessee Duck River Development Agency (TDRDA). 2011. Duck River Comprehensive Regional Water Supply Plan: Report. 40pp.

Tennessee Duck River Development Agency (TDRDA) 2013. Optimization of Normandy Reservoir Releases: Final Report. 17pp.

Tennessee Valley Authority (TVA). 2025. Normandy Reservoir Optimization of Reservoir Releases: Final Environmental Assessment. 254pp.

Tennessee Wildlife Resources Agency. (TWRA) 2008. Memo from David McKinney to Duck River Interagency Project. Subject: Duck River Mussel Stranding, Before August 16, 2008, Duck River mile 165.8- Lower Hardison Mill Dam.

U.S. Army Corps of Engineers (USACE). 2018. Duck River Watershed Plan: Final Watershed Assessment. U.S. Army Corps of Engineers, Nashville District, Nashville, Tennessee. 153pp.

U.S. Environmental Protection Agency (USEPA). 2013. Aquatic Life Ambient Water Quality Criteria for Ammonia – Freshwater. EPA 822-R-18-002/EPA-822-R-13-001. 242pp.

U.S. Fish and Wildlife Service (USFWS). 2025. Biological Opinion/Conference Opinion: Environmental Protection Agency Columbia Power and Water System Long-term Water Supply Program, FWS ECOSphere Project Code: 2022-0002767. 106pp.

Van der Schalie, H. 1973. The mollusks of the Duck River drainage in central Tennessee. Sterkiana 52:45-55.

Vaughn, C.C. and C.L. Atkinson. 2025. The Importance of Long-Term Data for Understanding How Environmental Change Impacts Mussel Communities and Their Ecosystem Effects. American Malacological Bulletin 41(1):1-10.

Vaughn, C.C., C.N. Taylor, and K.J. Eberhard. 1997. A comparison of the effectiveness of timed searches vs. quadrat sampling in mussel surveys. Conservation and Management of Freshwater Mussels II: Proceedings of a UMRCC Symposium. 8pp.

Vaughn, C.C., and C.C. Hakenkamp. 2001. The functional role of burrowing bivalves in freshwater ecosystems. Freshwater Biology 46:1431-1446.

Vaughn, C.C., K.B. Gido, and D. E. Spooner. 2004. Ecosystem processes performed by unionid mussels in stream mesocosms: species roles and effects of abundance. Hydrobiologia 527:35-47.

Williams, J., M. Warren, K. Cummings, J. Harris, and R. Neves. 1993, Conservation Status of Freshwater Mussels of the United States and Canada. Fisheries 18(9):1-17.

Wisniewski, J. 2020. 2020 Duck River quantitative mussel survey. Tennessee Wildlife Resources Agency, Nashville, TN. Fisheries Report 16-06. 38 pp.

Wohl, E. 2017. The significance of small streams. Frontiers in Earth Science 11:447–456.

Womble, K.I. and A.E. Rosenberger. 2025. A comprehensive freshwater mussel database for the Duck River Drainage, Tennessee. U.S. Department of Interior, Fish and Wildlife Service, Cooperator Science Series FWS/CSS-166-2025, Washington, D.C. https://doi.org/10.3996/css36499787

Xia, Y., M. Zhang, D.C. Tsang, N. Geng, D. Lu, L. Zhu, A.D. Igalavithana, P.D. Dissanayake, J. Rinklebe, X. Yang, and Y.S. Ok. 2020. Recent advances in control technologies for non-point source pollution with nitrogen and phosphorous from agricultural runoff: current practices and future prospects. Applied Biological Chemistry 63(1):8.