# U.S. Army Corps of Engineers Louisville District

## Science and Concepts for Environmental Flows
## Licking River and Cave Run Lake

*Sustainable Rivers Program*

*Licking River, Cave Run Dam and Lake (USACE photo)*

Authors: Steele Mcfadden[1], Melanie Babin[1], Kristin Berger[1], Monte McGregor[2], Wendell Haag[3], Jeffrey Hawkins[1], Zac Wolf[1], Matthew Thomas[2], David Eisenhour[4], and Jonathan Matthews[1]

2025

[1]U.S. Army Corps of Engineers, [2]Kentucky Department of Fish and Wildlife Resources, [3]U.S. Forest Service, [4]Morehead State University

# Contents

## Figures



## Tables



## Appendix

## Introduction

The Nature Conservancy (TNC) and U.S. Army Corps of Engineers (USACE) have partnered to form the Sustainable Rivers Program (SRP) to examine opportunities to optimize reservoir releases and river flows to benefit river ecology while maintaining the federal mandates of the reservoir system in the United States. The mission of SRP is to improve the health and life of rivers by changing water infrastructure operations to restore and protect ecosystems, while maintaining or enhancing other project benefits. The founding objective of SRP is implementation of environmental flows (e-flows), which are defined as the quantity, timing, and quality of water flows required to sustain ecosystems. The SRP influences over 13,500 miles of U.S. waterways, including 90 associated reservoirs and 7 lock and dam facilities. This represents 25% of USACE water resource portfolio.

Dams, especially large ones, are the most common anthropogenic mechanism that alters flow regimes and their variability (Graf, 2006). The ecological and physical impacts of the damming of waterways are pervasive and persist well downstream. Dams encumber native species life cycles, decrease species richness, divorcing the river from its floodplain, and aid in the establishment of non-native species. (Acreman et al., 2009; Chen and Olden, 2017; Richter and Thomas, 2007; Risley et al., 2010; Warner et al., 2014). Dams cause hydrologic alterations that reduce peaks, prolong baseflows, smooth hydrographs, produce unseasonably high flows, and impact water quality, in particular water temperature and dissolved oxygen (DO). The USACE and TNC have joined efforts with local stakeholders to recommend a dam reoperation plan for Cave Run Lake, an impoundment on the Licking River in central Kentucky, through the SRP.

## History of Environmental Flows

The concept of e-flows emerged as a response to the widespread ecological consequences of altering natural river systems for human purposes such as agriculture, hydropower, and flood control. During the 20th century, dam construction and river regulation significantly disrupted natural flow regimes, resulting in habitat loss, reduced biodiversity, and the degradation of ecosystem services essential for both human and environmental health (Poff et al., 1997). Early efforts to address these impacts focused narrowly on maintaining "minimum flows" for specific species or uses, often without considering the broader ecological needs of river systems (Acreman & Dunbar, 2004).

In the 1970s and 1980s, scientific understanding of riverine ecosystems advanced, emphasizing the importance of flow variability to sustain ecological integrity. Researchers recognized that ecosystems depend on a full range of flows, from high flows that maintain channel structure and floodplain connectivity to low flows that sustain aquatic habitats during dry periods (Poff et al., 1997; Arthington et al., 2006). This shift led to the development of the "natural flow paradigm," which identifies the magnitude, frequency, duration, timing, and rate of change of flows as essential components of ecological health (Richter et al., 1996).

A significant milestone in the history of e-flows was the Brisbane Declaration of 2007, which provided a widely accepted definition of environmental flows as "the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods that depend on them" (Arthington et al., 2018). This global commitment emphasized the integration of e-flows into water management policies and underscored the need for interdisciplinary collaboration to address challenges such as climate change and competing water demands (Poff & Zimmerman, 2010).

In the United States, SRP is the largest scale and most comprehensive program for implementing environmental flows at USACE facilities. Initially focusing on eight river systems, SRP has expanded to more than 50, demonstrating the feasibility of balancing ecological and human water needs through collaborative management (Richter & Thomas, 2007). By integrating ecological science into reservoir operations, SRP has helped improve downstream ecosystems while maintaining project benefits such as flood control and water supply.

Today, e-flows are recognized as a cornerstone of sustainable water management. Advances in ecological science, hydrology, and adaptive management strategies continue to refine their implementation. As water systems face mounting pressures from climate change and increasing demands, e-flows offer a vital pathway to maintain the resilience and functionality of riverine ecosystems for the benefit of both nature and society (Poff et al., 2010).

## Goals and Objectives

The goal of this project is to determine e-flows for the Licking River below Cave Run Lake Dam that would support ecosystem health and resilience while aiding in the conservation of federally threatened and endangered species as well as other species of conservation concern. The objective of this report is to be a primer for attendees of the upcoming e-flows workshop by providing:

- Background on the Licking River basin,
- Details on Cave Run Lake Dam operations,
- Known impacts to Licking River hydrology, and
- A coordinated list of target species around which to develop e-flow recommendations.

## Licking River Basin Characteristics and Water Management

Cave Run Lake is in the Licking River basin of east-central Kentucky, 84 air miles from Cincinnati and 118 air miles from Louisville. The damsite is on the Licking River 1.9 miles upstream from U.S. Highway 60 and 173.6 miles above the confluence of the Licking and Ohio Rivers. Construction of the Project began in June 1965 and was placed in operation in February 1974. The Lake's catchment area is 826 square miles. The Lake is formed primarily from the Licking River and two of its main tributaries—Beaver Creek and North Fork Licking River. The nature of the terrain, together with the large number of branches and tributaries, has provided a shoreline with many coves and embankments. The terrain is generally characterized by steep slopes to the shoreline with moderately rolling terrain at the top. These steep shorelines provide varying degrees of difficulty to Lake access and generally become higher and steeper as one moves further upstream from the dam.

There are three pool elevations, measured based on the National Geodetic Vertical Datum of Year 1929 (NGVD29), that Cave Run Lake is managed for throughout the year. These include winter pool at 724 feet, summer pool at 730 feet, and flood control pool at 765 feet. The lake covers an area of 7,390, 8,270, and 14,870 surface acres at winter, summer, and flood pool levels respectively. The highest ever recorded water level for the lake was 761.12 feet on April 20, 2015.

The maximum allowable release of water into the Licking River is 5,500 cubic feet per second (cfs). Minimum release required to maintain water quality is 50 cfs during normal operation.

# Basin Climate

## Climate

Climate data for the lake were gathered from the nearest National Oceanic and Atmospheric Administration (NOAA) weather station located at the lake (38.12228° N, -83.5328° W). The 15-year period between 2006 and 2020 was used to summarize monthly normals for temperature and precipitation throughout this section (NOAA, 2021). The mean annual high temperature is approximately 65.5° Fahrenheit (F), and the mean low temperature is 44.6°F. Historically, the coldest month is January, which has an average daily temperature of 32.9°F, and the warmest month is July, with an average daily temperature of 74.6°F (NOAA, 2021). Approximately 64 percent of precipitation (34 inches) falls during the growing season (April – October), most of which falls between April and July. The driest average month is November, with 3.01 inches of precipitation. The wettest average month is July, with 6.3 inches of precipitation. Historically, storms that have the potential to cause serious flooding in the Licking River basin occur from late winter to spring.

## Physiology and Geology

As outlined in the Cave Run Lake Masterplan (2022), the catchment area is characterized by mountains and knobs with very narrow ridge tops and steep slopes. The lower portion of the lake near the dam has a wide floodplain with slopes averaging an approximately 40% gradient (USACE, 2022). In contrast, the upper extremities of this area of the lake have narrow flood plains and slope gradient averages of 65 to 75%. Due to the steep topography, lands suitable for public use are severely limited and major development would therefore be limited to a small number of sites (USACE, 2022).

Cave Run Lake is a unique recreational area because of its rugged character, primitive aspects, and the lack of development due to the substantial Forest Service ownership of the surrounding lands. Rocks of Cave Run Lake include consolidated sedimentary rocks of the Ordovician, Silurian, Devonia, Mississippian, and Pennsylvanian Periods, and from unconsolidated sediments of the Quaternary age (USACE, 2022). The oldest rocks at the surface are from the Ordovician Period and were deposited in shallow seas 490 million years ago (USACE, 2022). The New Albany Shale, an oil shale, was formed 400 million years ago when the sea floor became covered with an organic black sludge and is one of the most distinctive of all geologic formations in Kentucky (USACE, 2022). Mississippian-aged limestone was deposited 350 million years ago in the bottom of a shallow sea (USACE, 2022). The vast seas of the Mississippian began to recede 320 million years ago, and vast coastal swamps formed. As forests, swamps, and shallow seas were all establishing and receding during the Pennsylvanian Subperiod, many layers of sandstone, shale, and coal were deposited (USACE, 2022). Over the last million years unconsolidated Quaternary sediments have been deposited along the Licking River (USACE, 2022).

# Reservoir History, Operations, and Relevant Data

Cave Run is a multi-purpose reservoir with authorizations for flood risk management, water quality, fish and wildlife, recreation, and water supply. A primary function of the reservoir is to attenuate floods and release nondamaging flows when downstream gages are low. Multiple downstream control points restrict the reservoir releases during high water events. Table 1 presents a summary of control triggers that are monitored to know when to restrict flow from Cave Run Lake; however, it is important to note that operational decisions are more nuanced for releases than just the monitoring of these different gauges and restricting flow when a target is hit. For example, these stages and flow values are the minimum values that are considered, and stages and flows above these values would restrict releases even more.

For Blue Lick Springs, Catawba, and the Ohio River, the regulation allows for some increased releases when stages start falling (even when gages are still above these triggers) due to long travel times.

**Table 1**. Minimum stages and flows at USGS gauges that trigger a restriction in Cave Run Lake releases.

| **Gauge Name (location)** | **Minimum Trigger** | |
|---|---|---|
| | *Stage (ft)* | *Flow (cfs)* |
| Farmers Gauge (Licking River Tailwater + Hatchery) | 12 | - |
| North Fork Triplett Creek (Morehead) | - | 100 |
| North Fork Licking (Cynthiana) | - | 2,000 |
| Blue Lick Springs (Licking River) | 17 | - |
| Catawba (Licking River) | 19 | - |
| Cincinnati (Ohio River) | 40 | - |

The control tower at Cave Run is equipped with selective withdrawal gates that can be used while releasing small amounts of water through the bypass gates. This gate selection can be used to influence temperature and dissolved oxygen when the lake is stratified in the summer. Table 2 outlines the range of releases for the different gates.

**Table 2**. Cave Run gate release ranges.

| **Gate Name** | **Minimum Release (cfs)** | **Maximum Release (cfs)** | **Selective Withdrawal** |
|---|---|---|---|
| Bypasses | 11 | 228 | Yes |
| Main Gates | 485 | 5,415 | No |

For long periods of each summer/fall season, Cave Run will use the bypasses exclusively for releases. Summer storms and tropical systems can cause periodic use of the Main Gates in the summer/fall to manage the greater inflows, and this corresponds to a significant drop in temperature due to the fixed positions of the Main Gates. See the Water Quality section later in the report for more information about selective withdrawal.

# Recreation

## Daniel Boone National Forest

The Daniel Boone National Forest (DBNF) is owned and operated by the U.S. Forest Service (USFS). The DBNF is open for multi-use recreation and surrounds Cave Run Lake. DBNF was established in 1937 and comprises nearly 709,000 acres of land across 21 counties. There are 600 miles of multi-use recreation trails and 250 recreation sites throughout DBNF. Cave Run Lake is one of the most popular attractions located within the DBNF boundaries.

## Pioneers Weapons Wildlife Management Area

The Pioneers Weapons Wildlife Management Area is part of the Kentucky Department of Fish and Wildlife's (KDFWR) Wildlife Management Area (WMA) system and is a cooperative effort between KDFWR and the USFS. This 7,600-acre WMA is open for hunting using only primitive weapons (muzzleloaders and archery). While DBNF is maintained for multi-use, this area of the forest focuses on wildlife habitat with enhancements such as grassy openings and watering holes created and maintained on the WMA. Timber

management in this area also follows a wildlife emphasis. Ninety-four percent of the Pioneers Weapon WMA is forested land.

### Sport Fishing

The Muskellunge (*Esox masquinongy*) is an important recreational sport fishing resource at Cave Run Lake. The species native to the Green, Kentucky, Licking and Little Sandy drainages. The muskellunge population in Kentucky was almost destroyed due to pollution, siltation and poaching of the species; however, stocking the species in rivers and lakes with hatchery fish has restored the species to much of its historic range. Today, as a muskellunge fishery, Cave Run Lake is rated as excellent and is the best fishery in the state for the species. As a result, Cave Run Lake is one of the most popular fisheries in Kentucky for muskellunge. The Minor Clark Fish Hatchery located below the dam of Cave Run Lake is the sole hatchery responsible for stocked populations of the fish throughout Kentucky. The hatchery was built in tandem with the reservoir, in part to mitigate the riverine habit loss of the impounded upper Licking River.

A trout fishery is also maintained below Cave Run Lake and is a recreational resource managed by KDFWR. This fishery primarily supports rainbow trout (*Oncorhynchus mykiss*), which are stocked annually in the spring, typically from mid-March to early April, to coincide with water conditions favorable for trout survival and angler accessibility (KDFWR, 2024). Stocking occurs in the Licking River tailwaters, where cold water releases from the dam's hypolimnion create a suitable habitat during cooler months (USACE, 2023). However, as water temperatures rise in mid-summer due to the depletion of the reservoir's cold-water storage, maintaining trout survival becomes challenging. The fishery is thus primarily seasonal, offering excellent opportunities for anglers from spring through early summer. Beyond recreational benefits, this fishery contributes to local economic activity and supports ecological diversity by enhancing habitat complexity in the downstream ecosystem (KDFWR, 2024; USACE, 2023).

## Hydrology

The following analysis attempts to summarize broad characteristics of hydrologic dynamics for the upper Licking River above Cave Run Lake. It is well known that an average or mean value will often mask important details that are contained in the source data. The intent of this analysis is to help separate years and seasons of significance, using mean daily flows from water years 1983-2024. During later discussions on e-flows, it will be necessary to consider individual water years, and possibly sub-daily data, to make the best recommendations for aquatic environment in the Licking River. The following graphs and tables are provided to help guide the conversation and development of e-flows; more ecological and biological science will be needed to craft final recommendations.

Flood frequency analysis for Cave Run Dam is available in the 2017 Periodic Assessment, and thus was not re-created for this study (USACE 2018).

### Annual Streamflow

Pool elevations of Cave Run Reservoir are recorded by an electronic gage every 15 min, and this gage is verified with a manual measurement every month. Releases from Cave Run are calculated from gate openings and recorded at least every hour. These releases are verified with tailwater readings and USGS flow measurements. The Licking River valley was surveyed before the lake was impounded; this survey data is used as an elevation-storage curve for the reservoir. The calculated storage values are used with the outflows to calculate “inflows” into the reservoir. These “inflow” values can also be thought of as “natural” flow values that would have occurred if the reservoir was not present. Calculated inflow values

can be zero or negative on some occasions due to inaccuracies in the storage curve, gate ratings, or elevation measurements. There are too many sources of error to correct these values individually; negative values tend to occur in drought periods when most small tributaries are dry. Negative inflow values were changed to zero for this analysis, which may cause slight volume discrepancies in dry months.

**“Inflows” or “Natural” Flows and Hydrologic States (1984-2023)**

The corrected daily inflow records were used to calculate a mean daily inflow value for the purpose of sorting each water year into a “hydrologic state” of wet, average (ave), or dry. These “states” were selected based on the 25 and 75 percentile flows, such that roughly half of the years are average.

Table **3** presents wet, average, and dry mean average flows for Cave Run Lake.

**Table 3**. Cave Run Lake calculated mean daily "Inflows" or "Natural" flows.

| Rank | Flow Percentile | WY | Flow (cfs) | Hydrologic State |
|---|---|---|---|---|
| 1 | 0.02439 | 1994 | 1,923 | Wet |
| 2 | 0.04878 | 2004 | 1,846 | Wet |
| 3 | 0.07317 | 2020 | 1,772 | Wet |
| 4 | 0.09756 | 1989 | 1,749 | Wet |
| 5 | 0.12195 | 2019 | 1,727 | Wet |
| 6 | 0.14634 | 2015 | 1,643 | Wet |
| 7 | 0.17073 | 2021 | 1,551 | Wet |
| 8 | 0.19512 | 2003 | 1,495 | Wet |
| 9 | 0.21951 | 2018 | 1,493 | Wet |
| 10 | 0.24390 | 1991 | 1,423 | Wet |
| 11 | 0.26829 | 1997 | 1,375 | Ave |
| 12 | 0.29268 | 2022 | 1,348 | Ave |
| 13 | 0.31707 | 1990 | 1,306 | Ave |
| 14 | 0.34146 | 2005 | 1,266 | Ave |
| 15 | 0.36585 | 2011 | 1,244 | Ave |
| 16 | 0.39024 | 2014 | 1,243 | Ave |
| 17 | 0.41463 | 1996 | 1,191 | Ave |
| 18 | 0.43902 | 1987 | 1,103 | Ave |
| 19 | 0.46341 | 1998 | 1,099 | Ave |
| 20 | 0.48780 | 1995 | 1,083 | Ave |
| 21 | 0.51220 | 2013 | 1,075 | Ave |
| 22 | 0.53659 | 1993 | 1,056 | Ave |
| 23 | 0.56098 | 1985 | 1,024 | Ave |
| 24 | 0.58537 | 2012 | 1,024 | Ave |
| 25 | 0.60976 | 2016 | 968 | Ave |
| 26 | 0.63415 | 2009 | 967 | Ave |
| 27 | 0.65854 | 2002 | 963 | Ave |
| 28 | 0.68293 | 2010 | 934 | Ave |
| 29 | 0.70732 | 1984 | 901 | Ave |

| | | | | |
|---|---|---|---|---|
| 30 | 0.73171 | 2008 | 896 | Ave |
| 31 | 0.75610 | 2017 | 879 | Dry |
| 32 | 0.78049 | 1992 | 842 | Dry |
| 33 | 0.80488 | 2007 | 786 | Dry |
| 34 | 0.82927 | 1986 | 735 | Dry |
| 35 | 0.85366 | 2000 | 700 | Dry |
| 36 | 0.87805 | 2023 | 690 | Dry |
| 37 | 0.90244 | 2001 | 663 | Dry |
| 38 | 0.92683 | 1999 | 612 | Dry |
| 39 | 0.95122 | 2006 | 561 | Dry |
| 40 | 0.97561 | 1988 | 548 | Dry |

**Duration Curves for Annual Outflow and "Inflow" at Cave Run (1983-2024)**

The mean daily outflows and inflows (calculated and corrected) from 1983 to 2024 are show below as "duration curves". These curves represent the percentage of time that daily flows were at or above a specific flow rate. Figure 1 shows the duration curves, with the data on the left axis of the graph plotted on a log scale. Notably the inflows or "natural" flows reach values beyond 10,000 cfs at least some of the time, while only a handful of the regulated outflow values are greater than 5,000 cfs. Inflows and outflows are less than 1,000 cfs more than 50% of the time.

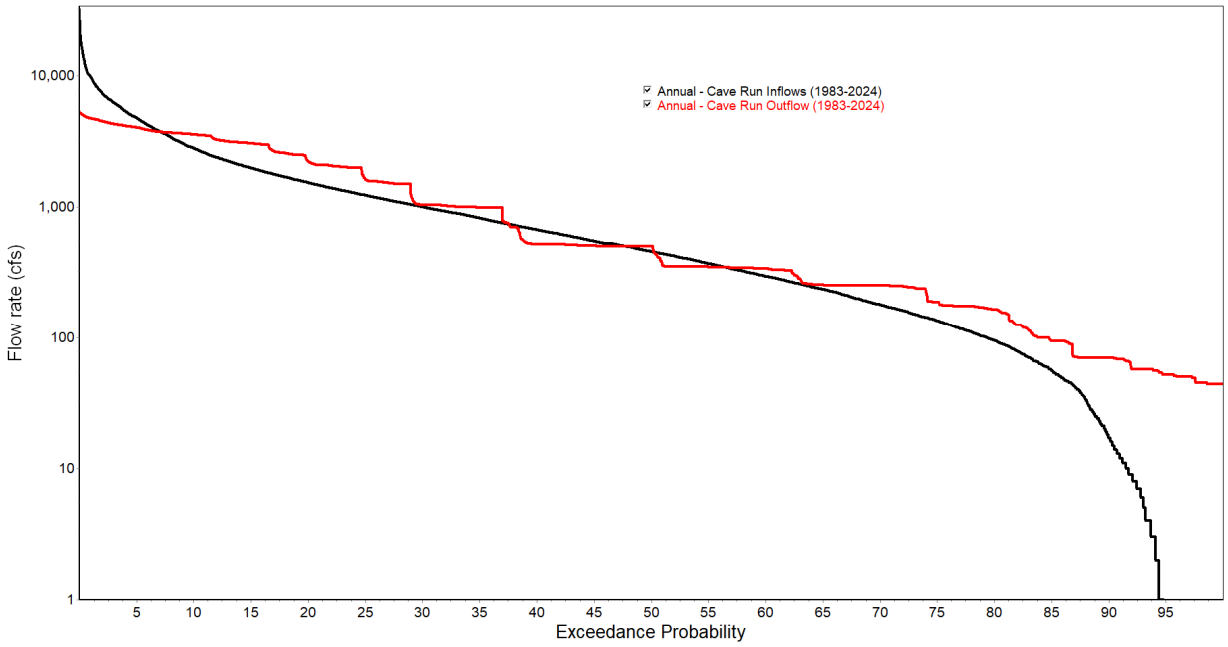


**Figure 1.** Cave Run Lake mean daily inflow and outflow duration curves.

## Seasonal Analysis

Flows vary seasonally for the Licking River. High flows are typically observed every February, March, and April. Additionally, some high flows can occur from thunderstorms or tropical storms in the summer months. September and October are typically the months with the lowest natural flows.

**Monthly Flows**

Mean daily inflows (calculated and corrected) from 1983 to 2024 are shown in Figure 2 as duration curves for each month of the year. The left axis of the graph is daily outflow values plotted on a log scale.

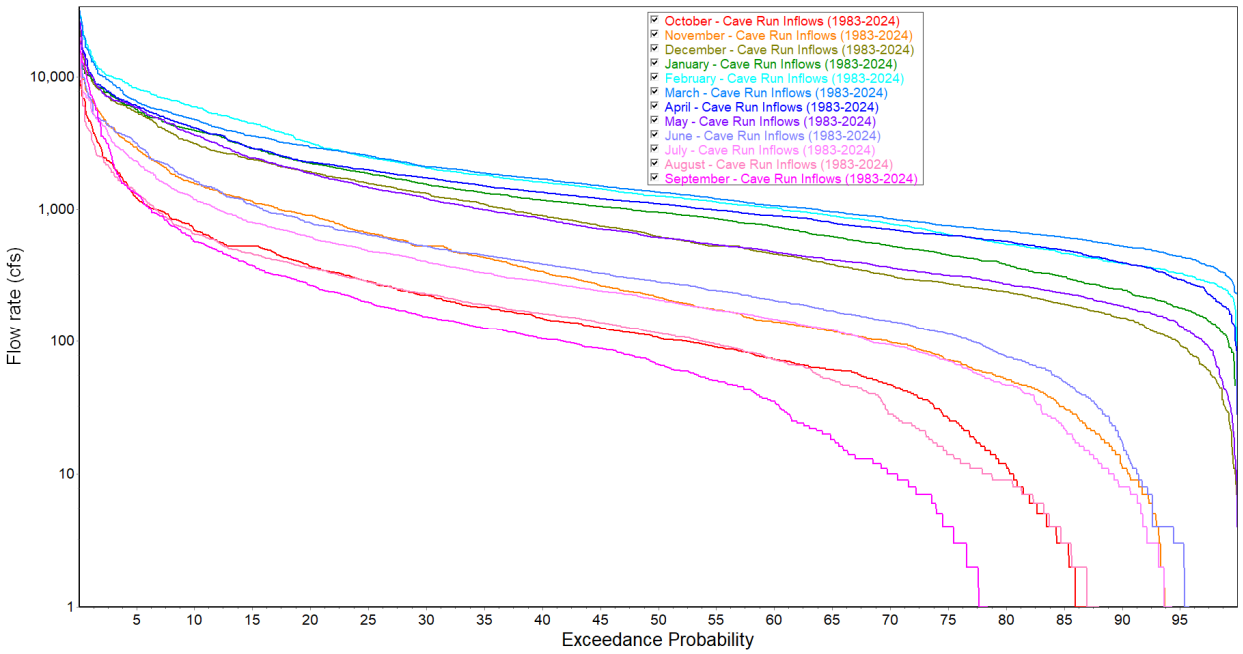


**Figure 2**. Cave Run Lake monthly mean daily inflow duration curves.

Duration curves for February, March, and April are at the top of the graph. Notice that flow values for those months are above 1,000 cfs for almost 90% of the time, while curves for August, September, and October show daily flows are above 1,000 cfs for less than 10% of the time.

Mean daily outflows from 1983 to 2024 are shown in Figure 3 as duration curves for each month of the year. The left axis of the graph is daily outflow values plotted on a log scale.

Notice that there are “flat” sections of each curve, these flow values correlate to frequently used gate settings at the reservoir. There are many factors that contribute to recurring outflows. To avoid wear and tear on the outlet structure and save on labor; gates are frequently set at the same opening for days at a time. Downstream flooding can trigger regulations that require specific flows and limited flexibility in gate settings (to prevent possible damage) can further constrain operations.

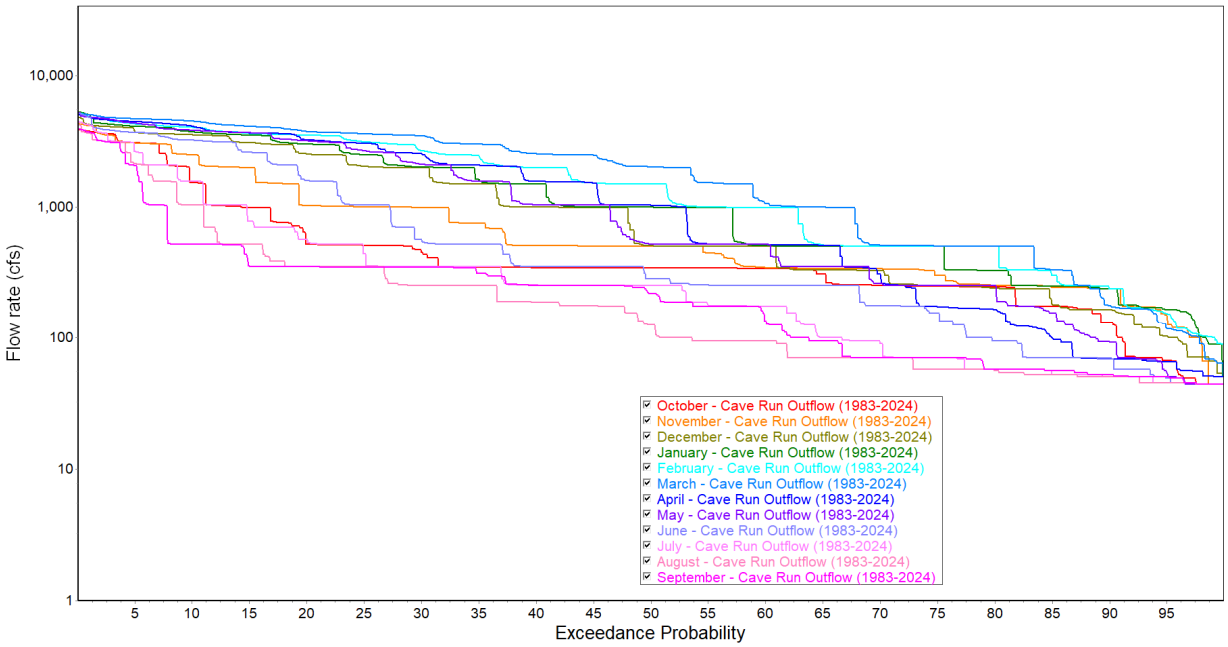


**Figure 3**. Cave Run Lake monthly mean daily outflow duration curves.

### Seasonal Flows

During the summer and winter seasons regulation is aimed at holding the pool at constant levels. There are also two specially regulated "seasons" of flow in between these periods. In spring, Cave Run is operated to store water from spring flows to raise the reservoir to summer pool for recreation. This summer pool level (elevation 730 feet) is 6 feet higher than the winter level and the fill increases the volume of the reservoir by approximately 27% each summer, filling 10% of the total flood storage. In fall, that storage is released - drawing the pool down to the wintertime level (elevation 724 feet) and allowing a minimum flow to be maintained during the natural dry period for downstream effluent dilution. An additional side effect of the drawdown release is high levels of manganese in reservoir outflows due to anoxic conditions within the stratified reservoir. The current mitigation practice is to delay the drawdown and use only selective withdrawal outlets while the reservoir remains stratified. Later in the season, large pulse releases are coordinated with Swift Water Rescue Training to make up for the delay of drawdown releases. This strategy allows the lake to mix naturally as the air temperatures cool, reducing the concentration of manganese in the lower levels of the reservoir, and provides a safe controlled environment for emergency response training.

Filling and drawdown periods can be affected by meteorological forecasts (drought/extreme floods) and by other more routine factors (maintenance, holidays) – so every year looks a little different. The target dates and pool levels can be seen in Table 4. Because of the impact of raising and lowering the pool on daily outflows, the seasonal analysis was done using the filling and drawdown schedule. While these "seasons" may not align perfectly with the natural hydrologic seasons, it is beneficial to acknowledge the regulation schedule to highlight the effect of the different release objectives. Please look to the monthly inflow values in Table 4 for a more naturalized flow reference.

Mean daily average flows for each season were calculated using the same data mentioned above, but instead of averaging over the water year, the data was separated into seasons. Also, due to incomplete data (seasons cross water year), only years 1984-2023 could be used for this seasonal analysis. Results for inflows and outflows are included in Table 4 for comparison.

**Table 4**. Seasonal mean average flows for Cave Run Lake by year.

| Season | Winter Dec 1 – Mar 16 | | Filling Mar 16 – May 1 | | Summer May 1 – Oct 15 | | Drawdown Oct 15 – Dec 1 | |
|---|---|---|---|---|---|---|---|---|
| Pool Target Elevation (feet) | 724 | | 724 - 730 | | 730 | | 730 - 724 | |
| WY | Outflow (cfs) | Inflow (cfs) | Outflow (cfs) | Inflow (cfs) | Outflow (cfs) | Inflow (cfs) | Outflow (cfs) | Inflow (cfs) |
| 1984 | 675 | 669 | 2,213 | 3,082 | 920 | 750 | 798 | 526 |
| 1985 | 2,168 | 2,162 | 357 | 710 | 476 | 525 | 525 | 940 |
| 1986 | 1,857 | 1,328 | 170 | 426 | 212 | 264 | 1,228 | 1,154 |
| 1987 | 1,726 | 1,695 | 1,884 | 2,151 | 290 | 297 | 301 | 107 |
| 1988 | 1,069 | 1,048 | 660 | 1,067 | 154 | 183 | 1,068 | 852 |
| 1989 | 2,211 | 3,194 | 3,578 | 1,681 | 1,024 | 994 | 2,029 | 1,771 |
| 1990 | 1,783 | 1,789 | 876 | 1,395 | 819 | 827 | 678 | 320 |
| 1991 | 3,107 | 3,204 | 2,088 | 2,438 | 303 | 324 | 596 | 253 |
| 1992 | 1,567 | 1,655 | 838 | 1,261 | 429 | 422 | 496 | 217 |
| 1993 | 1,518 | 1,668 | 2,226 | 2,332 | 612 | 630 | 1,212 | 890 |
| 1994 | 2,990 | 3,907 | 4,118 | 3,073 | 660 | 500 | 536 | 349 |
| 1995 | 1,875 | 1,864 | 1,049 | 1,192 | 780 | 967 | 430 | 143 |
| 1996 | 1,713 | 1,520 | 1,553 | 2,094 | 1,061 | 1,191 | 1,091 | 720 |
| 1997 | 1,738 | 2,450 | 2,266 | 1,414 | 940 | 950 | 388 | 128 |
| 1998 | 1,436 | 1,418 | 2,049 | 2,428 | 901 | 963 | 399 | 93 |
| 1999 | 1,704 | 1,635 | 136 | 761 | 44 | 80 | 172 | 112 |
| 2000 | 911 | 862 | 1,038 | 1,385 | 658 | 651 | 342 | 114 |
| 2001 | 1,083 | 1,041 | 255 | 758 | 662 | 654 | 401 | 138 |
| 2002 | 687 | 519 | 3,127 | 3,825 | 729 | 846 | 1,296 | 945 |
| 2003 | 2,285 | 2,352 | 1,716 | 1,609 | 886 | 1,081 | 1,723 | 1,049 |
| 2004 | 2,151 | 2,338 | 1,322 | 1,831 | 1,692 | 1,478 | 2,348 | 1,986 |
| 2005 | 1,819 | 2,118 | 2,054 | 2,378 | 171 | 340 | 305 | 44 |
| 2006 | 755 | 811 | 897 | 1,229 | 333 | 213 | 1,541 | 1,484 |
| 2007 | 1,162 | 1,136 | 917 | 1,314 | 68 | 166 | 546 | 118 |
| 2008 | 1,826 | 1,781 | 1,522 | 2,186 | 96 | 208 | 309 | 29 |
| 2009 | 1,221 | 1,112 | 1,865 | 1,843 | 861 | 1,012 | 914 | 291 |
| 2010 | 1,510 | 1,830 | 1,023 | 1,130 | 477 | 701 | 388 | 153 |
| 2011 | 1,354 | 1,516 | 2,472 | 4,069 | 1,205 | 696 | 1,362 | 863 |
| 2012 | 1,964 | 2,091 | 394 | 713 | 278 | 349 | 812 | 256 |
| 2013 | 1,825 | 1,781 | 939 | 1,692 | 693 | 821 | 919 | 152 |

| Season | Winter<br>Dec 1 – Mar 16 | | Filling<br>Mar 16 – May 1 | | Summer<br>May 1 – Oct 15 | | Drawdown<br>Oct 15 – Dec 1 | |
|---|---|---|---|---|---|---|---|---|
| Pool Target Elevation (feet) | 724 | | 724 - 730 | | 730 | | 730 - 724 | |
| WY | Outflow (cfs) | Inflow (cfs) | Outflow (cfs) | Inflow (cfs) | Outflow (cfs) | Inflow (cfs) | Outflow (cfs) | Inflow (cfs) |
| 2014 | 2,365 | 2,482 | 1,397 | 2,246 | 505 | 565 | 1,206 | 735 |
| 2015 | 1,486 | 2,158 | 3,684 | 3,925 | 1,333 | 980 | 405 | 114 |
| 2016 | 1,895 | 1,978 | 1,398 | 1,013 | 360 | 700 | 391 | 43 |
| 2017 | 1,345 | 1,151 | 816 | 1,248 | 825 | 999 | 592 | 346 |
| 2018 | 2,226 | 1,995 | 2,738 | 3,147 | 752 | 767 | 2,370 | 1,876 |
| 2019 | 2,952 | 3,644 | 1,652 | 911 | 712 | 861 | 1,213 | 516 |
| 2020 | 3,131 | 3,106 | 1,983 | 2,665 | 966 | 1,149 | 1,169 | 551 |
| 2021 | 2,505 | 2,910 | 1,744 | 1,798 | 962 | 967 | 767 | 196 |
| 2022 | 2,589 | 2,857 | 1,124 | 941 | 769 | 997 | 433 | 43 |
| 2023 | 1,624 | 1,480 | 308 | 1,098 | 217 | 297 | 285 | 24 |

It is important to note that differences between inflows and outflows may be attributed to more than just operational decisions made at the lake, it is also possible that these differences could be attributed to the timing of releases or calculation errors. As such, the average values shown in Table 4 should be used as a reference, with daily records being examined prior to drawing final conclusions on seasonal flow patterns.

The mean daily values for each season shown in Table 4 were used to compute the seasonal percents of annual flow, which are summarized in Table 5.

**Table 5**. Mean annual outflow and inflow, with seasonal flows shown as a percentage of total annual flow.

| WYs 1984-2023 | Annual Mean Daily Flow | Percentage of flow per Season | | | |
|---|---|---|---|---|---|
| | | Winter | Filling | Summer | Drawdown |
| Post-Dam (Outflows) | 1,135 | 46% | 17% | 27% | 9% |
| Post-Dam (Inflows) | 1,143 | 48% | 19% | 27% | 6% |

The effect of the filling and drawdown periods can be seen on average for all years from 1984-2023. Some individual filling and drawdown periods do not show a clear difference between inflows and outflows, but drought years tend to show the most distinct difference. This is intuitive since the reservoir volume increase is the same each year, while the total inflow is not.

## Low Stream flows

Mean daily flows were loaded into a statistical program created by The Nature Conservancy called Indicators for Hydraulic Analysis (IHA) (The Nature Conservancy, 2007). Low flows were sorted and compared for inflows and outflows, 1983 – 2024 (Figures 4 to 6).

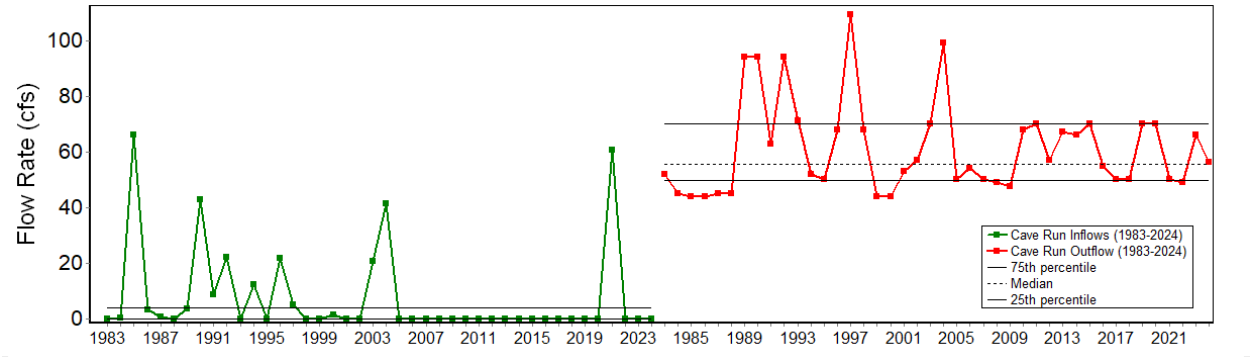


**Figure 4.** Cave Run Lake 3-day annual minimum flows.

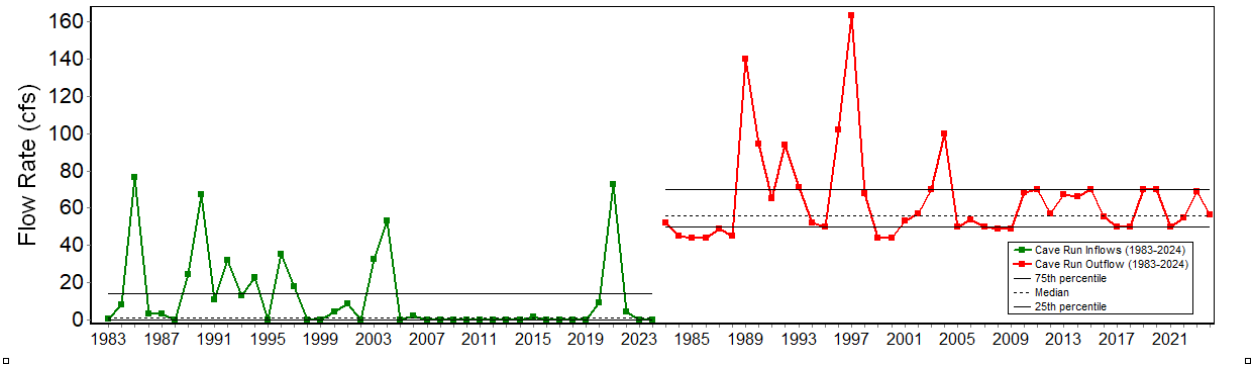


**Figure 5**. Cave Run Lake 7-day annual minimum flows.

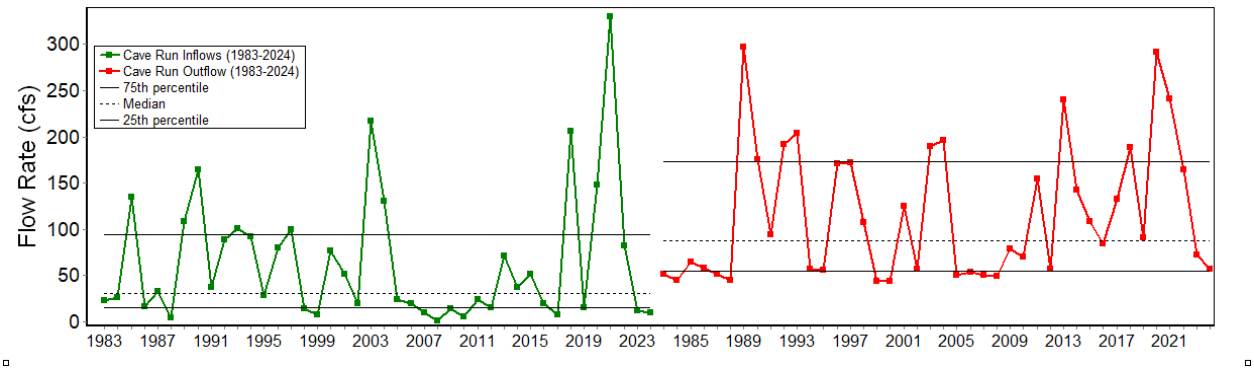


**Figure 6**. Cave Run Lake 30-day annual minimum flows.

The Licking River (at Cave Run Dam) can have extremely low flows in dry years. Without the reservoir, the natural river may even have zero flow for days or weeks of the year. As mentioned before, calculated inflow values can be zero or negative on some occasions; this is a result of inaccuracy in the storage curve, gate ratings, or elevation measurements. Negative values were changed to zero for this analysis. Cave Run has a minimum flow requirement of 50 cfs to provide effluent dilution downstream at all times of the year. This regulation can be seen clearly in 3-day (Figure 4) and 7-day (Figure 5) plots.

## Water Quality

According to Kentucky's list of impaired waters (303d list) for 2022, the following impairments exist upstream, downstream, and within Cave Run Lake:

- Licking River upstream of Cave Run Lake
    - Various stream segments were non-support or partial support of warm water aquatic habitat for one or more of the following: iron, lead, specific conductivity, nutrients/eutrophication, sedimentation siltation, and turbidity
- Cave Run Lake
    - Non-support of fish consumption for mercury in fish tissue
- Licking River downstream of Cave Run
    - Various segments were non-support of warm water aquatic habitat for iron and/or lead
    - One segment was partially supporting primary contact recreation for E. coli

Kentucky designated the Licking River below Cave Run as an Outstanding State Resource Water (OSRW). The Louisville District (LRL) Water Quality Team collects chemical data in the tailwater at Cave Run Lake typically once per year during stratification, as well as temperature and dissolved oxygen (DO) data in the reservoir and tailwater every two weeks during stratification. Data from 2012 through 2023 show that there were exceedances of water quality criteria for the OSRW designated use in the immediate tailwater of Cave Run Lake on four occasions:

- 9/8/2015: total zinc exceedance (result: 77.5 ug/L, criteria: <72.2 ug/L)
    - At the time of this exceedance, the project was releasing from the bypasses, blending equally from the epilimnion and upper-hypolimnion. Zinc levels measured in the lake ranged from 3.4-6.1 ug/L when sampled on the same day. It is unclear what caused this exceedance. In other sampling years, whether the project is releasing from the epilimnion or hypolimnion, there have not been any other exceedances of zinc in the tailwater. Due to the inconsistent nature of this result, this is possibly the result of an error rather than a true exceedance.
- 7/23/2014: pH exceedance (result: 9.07 standard units, criteria: <9 standard units)
    - Out of 12 pH measurements from 2012-2023, this is the only exceedance of criteria. At the time of the exceedance, the project was releasing from the bypasses, blending equally from the epilimnion and upper-hypolimnion. However, pH did not exceed 8.43 standard units in the reservoir when sampled on the same day.
- 7/27/2018 and 11/11/2022: dissolved oxygen (results 4.55 and 4.56 mg/L, respectively, criteria: >5 mg/L)
    - Out of 114 dissolved oxygen measurements from 2012-2023, 2 were below the criteria. At the time of these measurements, the project was releasing from the main gates at the bottom of the reservoir. Generally, DO levels below the water quality criteria are rare but possible especially when releasing low flows on the main gates.

### Temperature

The LRL Water Quality Team and project staff monitor temperature in Cave Run Lake near the dam and in the tailwater throughout the stratification period (approximately May through November) and funds a USGS gage in the tailwater, which records continuous temperature data. Both datasets are used to assess

compliance with the LRL-defined tailwater temperature guide curve, which was developed by LRL in coordination with project stakeholders when the reservoir was built. Because the control tower at Cave Run Lake has selective withdrawal capabilities, under certain conditions, the release settings can be changed to adjust the temperature downstream from the dam to better meet the guide curve. When a change is needed to increase or decrease temperature in the tailwater, the most recent temperature profile from the lake is analyzed to determine which level in the tower to release from to target specific temperatures. Figure 8 shows a photograph of the tower and its various release levels and a graph of temperature profiles throughout the year. The green bars on the graph represent the bypass inlet locations shown in the tower (see arrows). The gray bar at the bottom of the graph represents the main gates inlets which are much larger than the bypass inlets.

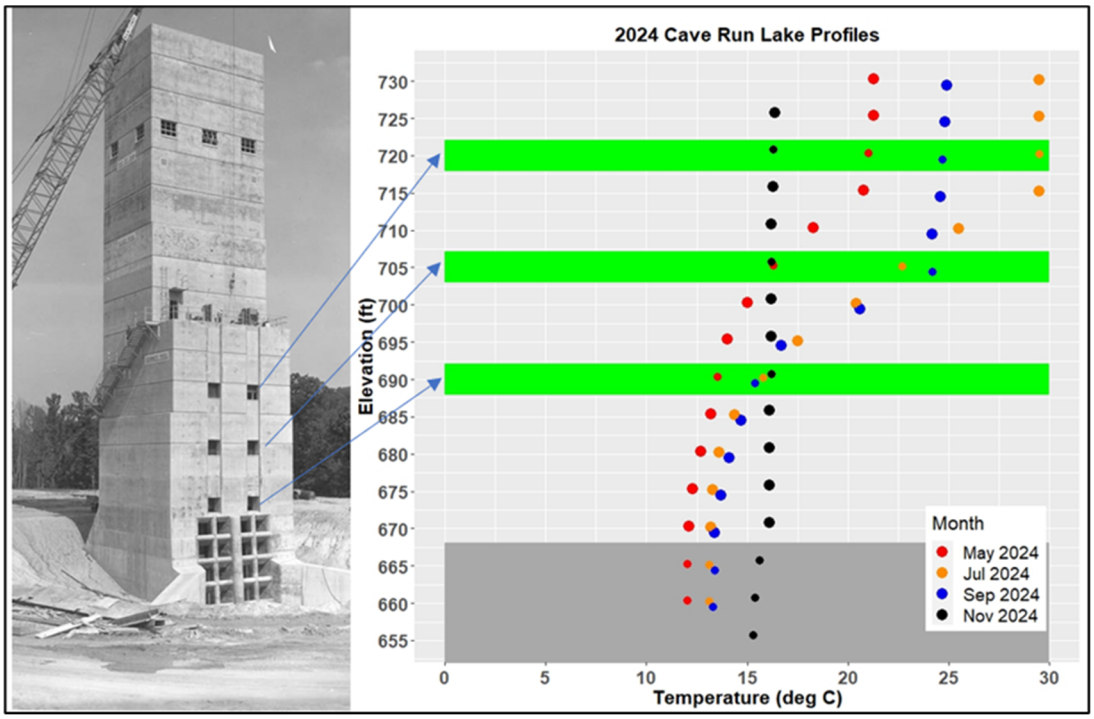


**Figure 7.** Cave Run Lake control tower during construction, showing outlet levels (left) and temperature profiles from 2024 (right). Green bars represent bypass levels and gray bar represents the main release gate.

Figure 8 shows the guide curve for Cave Run Lake's tailwater and the actual tailwater temperatures from 2024. In spring and early summer, an effort is made to keep temperatures in the tailwater below 20 degrees C (Figure 8, dashed red line) to support the stocked trout population instead of following the temperature guide curve (Figure 8, dashed gray lines). Around mid-July, due to difficulties with maintaining cold enough temperatures for trout to survive, stocking ceases and the guide curve is followed for the rest of the year as closely as possible. It is common that the reservoir runs out of cold-water storage and is unable to maintain cold enough temperatures to meet the guide curve in the fall and early winter, which is typical among all LRL reservoirs.

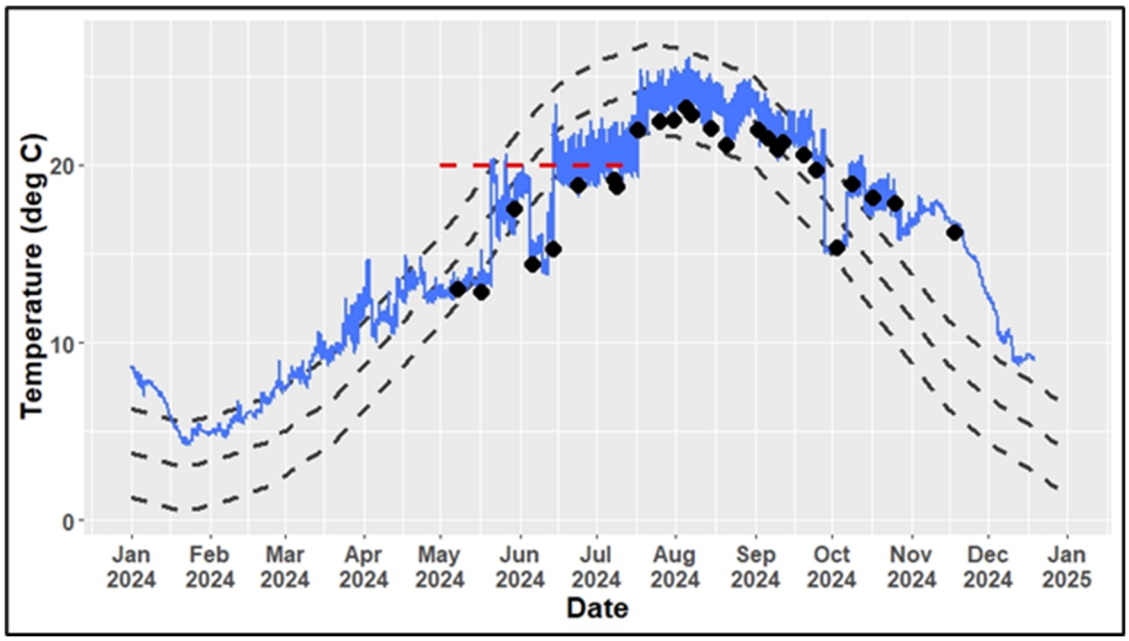


**Figure 8**. Graph showing temperature in the immediate tailwater (blue), tailwater temperature guide curve, maximum and minimum (gray dashed lines), and temperature maximum when regulating temperatures for trout in the tailwater (red dashed line).

## Dissolved Oxygen

Project staff in LRL collect dissolved oxygen data in the lake and the tailwater approximately every two weeks during stratification (roughly May through November). Dissolved oxygen levels in the lake vary throughout the year (Figure 9) and, when the lake is stratified, dissolved oxygen in the thermocline and hypolimnion is often very low or zero.

However, despite often releasing water from levels in the lake with little to no dissolved oxygen during stratification, dissolved oxygen in the immediate tailwater rarely falls under the state criteria of 5 mg/L (Figure 10).

In 2024, dissolved oxygen saturation was collected in the tailwater (Figure 11). As a general rule, approximately 82% is the minimum for fish and 90% is the minimum for mussels before seeing impacts to recruitment (Monte McGregor, KDFWR, pers. comm. 2024). LRL will continue collecting dissolved oxygen saturation data every two weeks during stratification in future years. Additionally, the LRL is considering deploying dissolved oxygen monitors to obtain continuous data to better assess project performance with respect to dissolved oxygen.

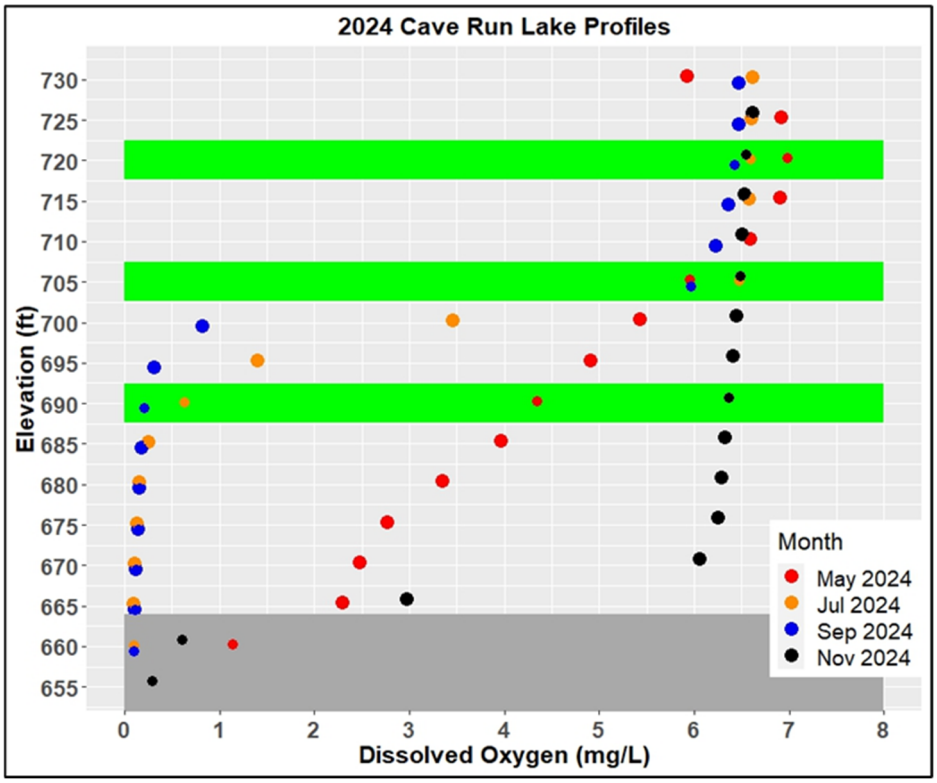


**Figure 9**. Dissolved oxygen profiles throughout 2024.

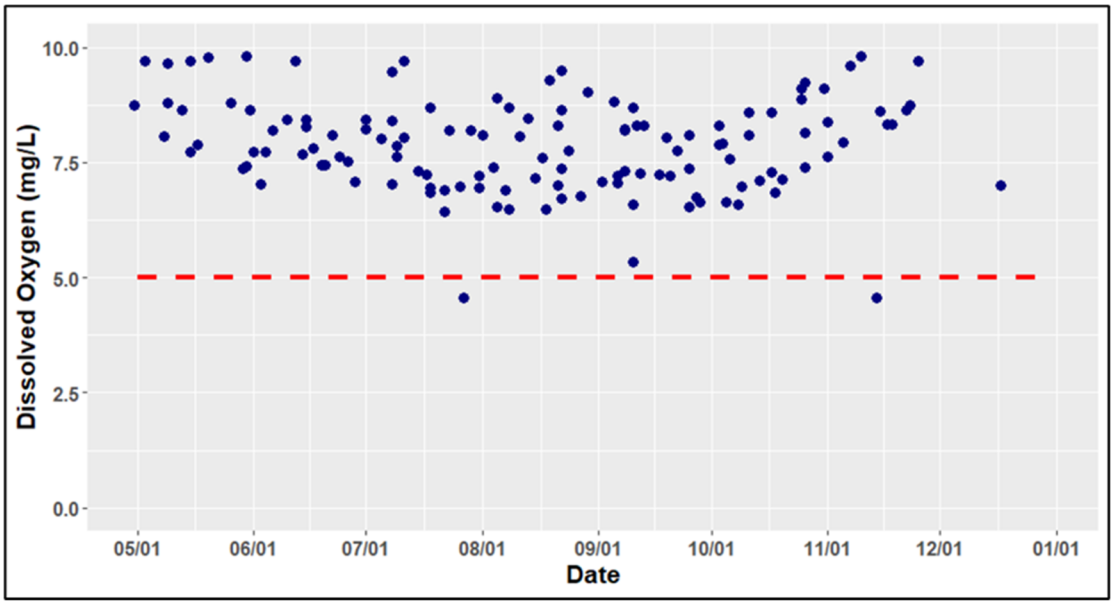


**Figure 10.** Tailwater dissolved oxygen data collected from 2012 through 2024 (blue dots) and water quality criteria for dissolved oxygen (red dashed line).

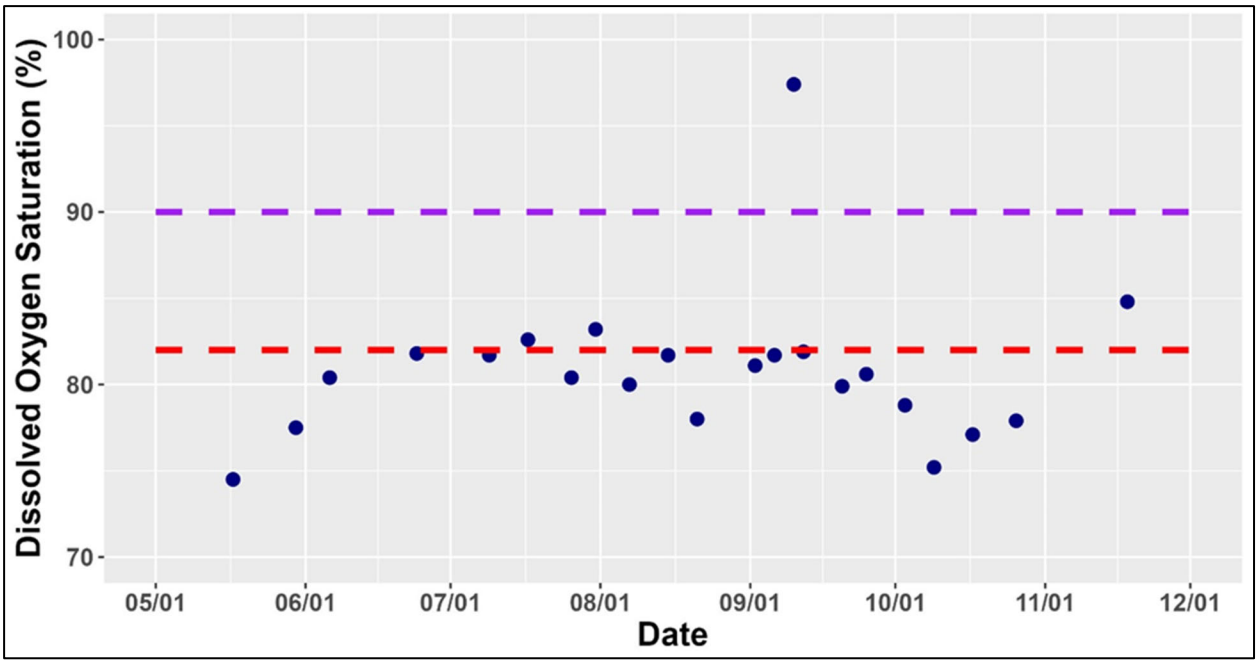


**Figure 11.** 2024 tailwater dissolved oxygen saturation (blue dots). The red and purple dashed lines represent the estimated minimum saturation requirements for fish (82%) and mussels (90%), respectively.

## Biological and Ecological Conditions

The goal of the Licking River SRP is to determine the most ecologically sound flows for the Licking River below the Cave Run Lake Dam that results in the establishment, maintenance, and magnification of physical processes that create and connect aquatic habitats, improve important life history conditions for downstream mussels and fishes, and the mitigation of potential thermal impacts of the dam releases on aquatic life.

### Mussel and Fish Assemblages of the Licking River

There are 55 native mussel species and 111 native fishes living in the Licking River. These include 12 federally listed mussel species as well as 24 mussel species and 13 fish species that are included as Species of Greatest Conservation Need (SGCN) on Kentucky's Wildlife Action Plan. Table 6 contains a list of mussel species known from the Licking River. Table 7 contains a list of fish species known from the Licking River.

**Table 6.** Mussel species of the Licking River.

| Scientific Name | Common Name | Endangered | Threatened | SGCN |
|---|---|---|---|---|
| *Actinonaias ligamentina* | mucket | | | |
| *Alasmidonta marginata* | elktoe | | | X |
| *Alasmidonta viridis* | slippershell | | | X |
| *Amblema plicata* | threeridge | | | |
| *Anodontoides ferussacianus* | cylindrical papershell | | | X |
| *Cambarunio iris* | rainbow | | | |

| Scientific Name | Common Name | Endangered | Threatened | SGCN |
|---|---|---|---|---|
| *Cyclonaias nodulata* | wartyback | | | |
| *Cyclonaias pustulosa* | pimpleback | | | |
| *Cyclonaias tuberculata* | purple wartyback | | | |
| *Cyprogenia stegaria* | fanshell | X | | X |
| *Ellipsaria lineolata* | butterfly | | | X |
| *Elliptio crassidens* | elephantear | | | X |
| *Epioblasma obliquata* | catspaw | X | | X |
| *Epioblasma rangiana* | northern riffleshell | X | | X |
| *Epioblasma triquetra* | snuffbox | X | | X |
| *Eurynia dilatata* | spike | | | |
| *Fusconaia flava* | wabash pigtoe | | | |
| *Fusconaia subrotunda* | longsolid | | X | X |
| *Lampsilis abrupta* | pink mucket | X | | X |
| *Lampsilis cardium* | plain pocketbook | | | |
| *Lampsilis fasciola* | wavyrayed lampmussel | | | |
| *Lampsilis ovata* | pocketbook | | | X |
| *Lampsilis siliquoidea* | fatmucket | | | |
| *Lampsilis teres* | yellow sandshell | | | |
| *Lasmigona complanata* | white heelsplitter | | | |
| *Lasmigona costata* | flutedshell | | | |
| *Leaunio lienosa* | little spectaclecase | | | X |
| *Ligumia recta* | black sandshell | | | X |
| *Megalonaias nervosa* | washboard | | | |
| *Obliquaria reflexa* | threehorn wartyback | | | |
| *Obovaria subrotunda* | round hickorynut | | X | X |
| *Paetulunio fabalis* | rayed bean | X | | X |
| *Plethobasus cyphyus* | sheepnose | X | | X |
| *Pleurobema clava* | clubshell | X | | X |
| *Pleurobema cordatum* | Ohio pigtoe | | | X |
| *Pleurobema plenum* | rough pigtoe | X | | X |
| *Pleurobema rubrum* | pyramid pigtoe | | | X |
| *Pleurobema sintoxia* | round pigtoe | | | |
| *Potamilus alatus* | pink heelsplitter | | | |
| *Potamilus fragilis* | fragile papershell | | | |
| *Potamilus ohiensis* | pink papershell | | | |
| *Ptychobranchus fasciolaris* | kidneyshell | | | |
| *Pyganodon grandis* | giant floater | | | |
| *Quadrula quadrula* | mapleleaf | | | |
| *Reginaia ebenus* | ebonyshell | | | |
| *Simpsonaias ambigua* | salamander mussel | | | X |

| Scientific Name | Common Name | Endangered | Threatened | SGCN |
|---|---|---|---|---|
| *Strophitus undulatus* | creeper | | | |
| *Theliderma cylindrica* | rabbitsfoot | | X | X |
| *Theliderma metanevra* | monkeyface | | | |
| *Toxolasma lividum* | purple lilliput | | | X |
| *Toxolasma parvum* | lilliput | | | |
| *Tritogonia verrucosa* | pistolgrip | | | |
| *Truncilla donaciformis* | fawnsfoot | | | |
| *Truncilla truncata* | deertoe | | | |
| *Utterbackia imbecillis* | paper pondshell | | | |

**Table 7.** Fish species of the Licking River.

| Family | Scientific Name | Common Name | SGCN |
|---|---|---|---|
| Petromyzontidae | *Ichthyomyzon bdellium* | Ohio lamprey | |
| Petromyzontidae | *Ichthyomyzon unicuspis* | silver lamprey | |
| Petromyzontidae | *Lampetra aepyptera* | least brook lamprey | |
| Petromyzontidae | *Lethenteron appendix* | American brook lamprey | X |
| Acipenseridae | *Scaphirhynchus platorynchus* | shovelnose sturgeon | |
| Polyodontidae | *Polyodon spathula* | paddlefish | X |
| Lepisosteidae | *Lepisosteus osseus* | longnose gar | |
| Amiidae | *Amia ocellicauda* | emerald bowfin | |
| Hiodontidae | *Hiodon alosoides* | goldeye | |
| Hiodontidae | *Hiodon tergisus* | mooneye | |
| Anguillidae | *Anguilla rostrata* | American eel | X |
| Alosidae | *Alosa chrysochloris* | skipjack herring | |
| Dorosomatidae | *Dorosoma cepedianum* | gizzard shad | |
| Dorosomatidae | *Dorosoma petenense* | threadfin shad | |
| Catostomidae | *Carpiodes carpio* | river carpsucker | |
| Catostomidae | *Carpiodes cyprinus* | quillback | |
| Catostomidae | *Carpiodes velifer* | highfin carpsucker | X |
| Catostomidae | *Catostomus commersonii* | white sucker | |
| Catostomidae | *Cycleptus elongatus* | blue sucker | X |
| Catostomidae | *Hypentelium nigricans* | northern hog sucker | |
| Catostomidae | *Ictiobus bubalus* | smallmouth buffalo | |
| Catostomidae | *Ictiobus cyprinellus* | bigmouth buffalo | |
| Catostomidae | *Ictiobus niger* | black buffalo | X |
| Catostomidae | *Minytrema melanops* | spotted sucker | |
| Catostomidae | *Moxostoma anisurum* | silver redhorse | |
| Catostomidae | *Moxostoma breviceps* | smallmouth redhorse | |
| Catostomidae | *Moxostoma carinatum* | river redhorse | |

| Family | Scientific Name | Common Name | SGCN |
|---|---|---|---|
| Catostomidae | *Moxostoma duquesnei* | black redhorse | |
| Catostomidae | *Moxostoma erythrurum* | golden redhorse | |
| Cyprinidae | *Carassius auratus* | goldfish | |
| Cyprinidae | *Cyprinus carpio* | common carp | |
| Xenocyprididae | *Ctenopharyngodon idella* | grass carp | |
| Xenocyprididae | *Hypophthalmichthys nobilis* | bighead carp | |
| Leuciscidae | *Alburnops blennius* | river shiner | |
| Leuciscidae | *Campostoma anomalum* | central stoneroller | |
| Leuciscidae | *Chrosomus erythrogaster* | southern redbelly dace | |
| Leuciscidae | *Clinostomus elongatus* | redside dace | X |
| Leuciscidae | *Clinostomus funduloides* | rosyside dace | |
| Leuciscidae | *Cyprinella spiloptera* | spotfin shiner | |
| Leuciscidae | *Cyprinella whipplei* | steelcolor shiner | |
| Leuciscidae | *Ericymba buccata* | silverjaw minnow | |
| Leuciscidae | *Erimystax dissimilis* | streamline chub | |
| Leuciscidae | *Hybopsis amblops* | bigeye chub | |
| Leuciscidae | *Luxilus chrysocephalus* | striped shiner | |
| Leuciscidae | *Lythrurus umbratilis* | redfin shiner | |
| Leuciscidae | *Macrhybopsis hyostoma* | shoal chub | X |
| Leuciscidae | *Macrhybopsis storeriana* | silver chub | |
| Leuciscidae | *Miniellus boops* | bigeye shiner | |
| Leuciscidae | *Miniellus stramineus* | sand shiner | |
| Leuciscidae | *Nocomis micropogon* | river chub | |
| Leuciscidae | *Notemigonus crysoleucas* | golden shiner | |
| Leuciscidae | *Notropis atherinoides* | emerald shiner | |
| Leuciscidae | *Notropis photogenis* | silver shiner | |
| Leuciscidae | *Notropis rubellus* | rosyface shiner | |
| Leuciscidae | *Paranotropis buchanani* | ghost shiner | X |
| Leuciscidae | *Paranotropis volucellus* | mimic shiner | |
| Leuciscidae | *Paranotropis wickliffi* | channel shiner | |
| Leuciscidae | *Phenacobius mirabilis* | suckermouth minnow | |
| Leuciscidae | *Pimephales notatus* | bluntnose minnow | |
| Leuciscidae | *Pimephales promelas* | fathead minnow | |
| Leuciscidae | *Pimephales vigilax* | bullhead minnow | |
| Leuciscidae | *Rhinichthys obtusus* | western blacknose dace | |
| Leuciscidae | *Semotilus atromaculatus* | creek chub | |
| Ictaluridae | *Ameiurus melas* | black bullhead | |
| Ictaluridae | *Ameiurus natalis* | yellow bullhead | |
| Ictaluridae | *Ameiurus nebulosus* | brown bullhead | |
| Ictaluridae | *Ictalurus furcatus* | blue catfish | |

| Family | Scientific Name | Common Name | SGCN |
|---|---|---|---|
| Ictaluridae | *Ictalurus punctatus* | channel catfish | |
| Ictaluridae | *Noturus eleutherus* | mountain madtom | |
| Ictaluridae | *Noturus flavus* | stonecat | |
| Ictaluridae | *Noturus miurus* | brindled madtom | |
| Ictaluridae | *Noturus stigmosus* | northern madtom | X |
| Ictaluridae | *Pylodictis olivaris* | flathead catfish | |
| Esocidae | *Esox americanus* | grass pickerel | |
| Esocidae | *Esox lucius* | northern pike | |
| Esocidae | *Esox masquinongy* | muskellunge | |
| Salmonidae | *Oncorhynchus mykiss* | rainbow trout | |
| Salmonidae | *Salmo trutta* | brown trout | |
| Percopsidae | *Percopsis omiscomaycus* | trout-perch | X |
| Gadidae | *Lota lota* | burbot | X |
| Atherinopsidae | *Labidesthes sicculus* | brook silverside | |
| Fundulidae | *Fundulus catenatus* | northern studfish | |
| Fundulidae | *Fundulus notatus* | blackstripe topminnow | |
| Poeciliidae | *Gambusia affinis* | western mosquitofish | |
| Centrarchidae | *Ambloplites rupestris* | rock bass | |
| Centrarchidae | *Lepomis auritus* | redbreast sunfish | |
| Centrarchidae | *Lepomis cyanellus* | green sunfish | |
| Centrarchidae | *Lepomis gibbosus* | pumpkinseed | |
| Centrarchidae | *Lepomis gulosus* | warmouth | |
| Centrarchidae | *Lepomis humilis* | orangespotted sunfish | |
| Centrarchidae | *Lepomis macrochirus* | bluegill | |
| Centrarchidae | *Lepomis megalotis* | longear sunfish | |
| Centrarchidae | *Lepomis microlophus* | redear sunfish | |
| Centrarchidae | *Micropterus dolomieu* | smallmouth bass | |
| Centrarchidae | *Micropterus nigricans* | largemouth bass | |
| Centrarchidae | *Micropterus punctulatus* | spotted bass | |
| Centrarchidae | *Pomoxis annularis* | white crappie | |
| Centrarchidae | *Pomoxis nigromaculatus* | black crappie | |
| Cottidae | *Cottus bairdii* | mottled sculpin | |
| Moronidae | *Morone chrysops* | white bass | |
| Moronidae | *Morone saxatilis* | striped bass | |
| Percidae | *Ammocrypta pellucida* | eastern sand darter | |
| Percidae | *Etheostoma blennioides* | greenside darter | |
| Percidae | *Etheostoma caeruleum* | rainbow darter | |
| Percidae | *Etheostoma flabellare* | fantail darter | |
| Percidae | *Etheostoma nigrum* | johnny darter | |
| Percidae | *Etheostoma spectabile* | orangethroat darter | |

| Family | Scientific Name | Common Name | SGCN |
|---|---|---|---|
| Percidae | *Etheostoma variatum* | variegate darter | |
| Percidae | *Etheostoma zonale* | banded darter | |
| Percidae | *Nothonotus camurus* | bluebreast darter | |
| Percidae | *Nothonotus maculatus* | spotted darter | X |
| Percidae | *Nothonotus tippecanoe* | tippecanoe darter | |
| Percidae | *Percina caprodes* | logperch | |
| Percidae | *Percina copelandi* | channel darter | |
| Percidae | *Percina evides* | gilt darter | |
| Percidae | *Percina maculata* | blackside darter | |
| Percidae | *Percina oxyrhynchus* | sharpnose darter | |
| Percidae | *Percina shumardi* | river darter | |
| Percidae | *Sander canadensis* | sauger | |
| Percidae | *Sander vitreus* | walleye | |
| Sciaenidae | *Aplodinotus grunniens* | freshwater drum | |
| Gasterosteidae | *Culaea inconstans* | brook stickleback | |

### Critical Habitat

The Licking River is classified as designated critical habitat below Cave Run Lake for the longsolid and round hickorynut mussels, as well as proposed designated critical habitat for the salamander mussel and the snuffbox mussel. Areas designated or proposed as critical habitat for the longsolid, salamander mussel, and snuffbox mussel occur from Cave Run Lake Dam to the mouth of the Licking River. Areas designated as critical habitat for the round hickorynut occurs from Cave Run Lake Dam to just downstream of the town of Butler, ending at the border of Pendleton and Campbell counties.

### Endemic Species

There are no species known to be endemic to the Licking River.

## Relationship Between Streamflow Alteration and Ecological Response

A natural flow or hydrologic regime, refers to the typical pattern of a river's flow, including quantity, timing, and variability. This flow regime plays a crucial role in shaping the river system's key characteristics and processes, such as physical habitat (channel structure and substrate types), water quality (including chemical composition and temperature), nutrient input and availability, and species interactions. The effects of the flow regime on ecosystems vary depending on whether the flow is low or high, but all conditions affect the ecological health of the river.

The amount and timing of stream flow are fundamental hydrologic factors that shape the structure and function of aquatic ecosystems. Natural flow patterns fluctuate over time based on landscape characteristics such as basin size, climate, geology, and topography (Poff et al., 1997). Stream-dwelling organisms are significantly influenced by key components of the natural flow regime, including magnitude, frequency, duration, timing, and rate of change (Poff and Ward, 1989; Knight et al., 2008). These flow regimes interact with ecosystems across various spatial and temporal scales, ultimately linking flow

variability to habitat conditions and the composition of biotic communities in streams (DiMaoi and Corkum, 1995; Poff and Allan, 1995).

When a river's flow pattern is altered by a dam, significant changes can occur in the natural flow regime including timing, duration, magnitude, frequency, and rate of change. The Licking River SRP project seeks to define the ideal flow regimes for fish, aquatic invertebrates (especially mussels), and overall aquatic ecosystem function.

## Streamflow and Temperature Regime Alteration and Effects on Mussels

The Licking River supports an outstanding mussel community, including at least five federally threatened and endangered species, and most species show evidence of robust recruitment in the lower and middle sections of the river. However, mussel populations have virtually disappeared in the tailwater reach, to at least 28 miles downstream of Cave Run Dam, since the 1980s. In the 1980s, this section supported large mussel populations, including the largest population of snuffbox (*Epioblasma triquetra*) in the river. At that time, most mussels were old, suggesting recruitment failure for approximately the last 10–20 years. Furthermore, although populations in the lower and middle river remain healthy, assemblage composition is radically different than the pre-1960 time period. For example, the federally threatened longsolid mussel formerly was a dominant species in the river but has declined precipitously and is now rare. Several other species appear to have been extirpated since that time, including the rabbitsfoot, northern riffleshell, pink mucket, clubshell, and rayed bean. These faunal changes suggest that operation of Cave Run Dam has had marked effects on mussel fauna of the river.

Life cycles and life history traits of freshwater mussels are complex. Reproduction within the mussel lifecycle is a crucial target for conservation efforts. Mussel reproduction is often limited to narrow periods of optimal conditions, and reproductive adults, juveniles, and gametes can be sensitive to environmental stressors (Galbraith and Vaughn, 2011). The four critical periods in mussel early life history are 1) gametogenesis and sperm release, 2) host fish attraction and infection; 3) development of glochidia on fishes, and 4) settlement and growth of juvenile mussels. The spawning strategy for freshwater mussels is unique in that males release sperm into the water column, which is collected by females during normal filter feeding. Upon fertilization, embryos are brooded by the female mussels where they develop into glochidia. Mussels may be either short-term or long-term brooders. In most short-term brooders, sperm is released and eggs are fertilized in late spring to early summer, embryos develop within two to six weeks, and glochidia are released immediately after maturation, usually in summer, and often during one or two brief periods. In most long-term brooders, sperm is released and eggs are fertilized in late summer or early fall, and embryos develop into glochidia by September or October. Mature glochidia are then brooded in the female over the winter and glochidia are released the following spring or early summer (Watters et al., 2009). Because of the sensitivity of breeding mussels to environmental perturbations, these periods of mussel reproduction and development need to be considered when designing and implementing flow recommendations.

Alteration of the natural temperature or flow regimes in a river can negatively affect mussel reproduction in several ways.

1. Unseasonably low temperatures can inhibit gametogenesis or release of sperm. In the Cumberland River, Kentucky, summer temperatures rarely exceed 20°C due to hypolimnetic release from an upstream dam. Mussels in the Cumberland River showed no evidence of gametogenic activity, but they resumed production of gametes when transplanted into streams

where summer temperatures exceeded 20°C (Heinricher and Layzer, 1999). Elimination of mussels from the Cumberland River and other rivers affected by suppressed summer water temperatures from dam release is attributed to recruitment failure due to a lack of gamete production (Layzer et al., 1993). Similarly, long-term brooders typically release sperm only when water temperature reaches 22–25°C (Jirka and Neves, 1982).

2. Unseasonably high flows can dilute sperm, resulting in poor egg fertilization, or they can interfere with transmittal of glochidia to host fishes. Mussel glochidia die if they do not encounter and attach to a suitable host soon after release from the female. Most mussel species have elaborate strategies for host infection that appear to target suitable fish species (see discussion of target mussel species). For example, mussels may use modified mantle lures to attract hosts, or they may release glochidia in conglutinates that resemble host prey items. Both strategies rely on visual encounters between host fishes and glochidia. Other species may release large numbers of glochidia freely or in mucus webs that rely on chance encounters with hosts as summarized in Haag (2012). High, turbid flows can interfere with sight-feeding fishes' ability to locate lures or conglutinates and dilute glochidia that rely on chance encounters with fishes.
3. Unseasonably low temperatures can inhibit or prevent glochidial transformation on fishes. For example, glochidia of Sheepnose (*Plethobasus cyphyus*) transformed robustly on suitable host fishes at 22–25°C, but most glochidia did not transform on the same fish species at 18–20°C (Hove et al., 2016).
4. Unseasonably high flows or unseasonably low temperatures can cause increased mortality of juvenile mussels. When mussels detach from a host fish, they must settle in a location with suitable, stable substrate and begin feeding. Most mussel species in the Licking River infect hosts and juveniles detach from fishes in late spring to summer. Sustained, high flows during this period can prevent juvenile mussels from settling. For most mussel species, significant juvenile growth occurs only at mean temperatures greater than about 20–22°C (Haag et al., 2019; 2021). Sustained periods of low temperatures can prevent juvenile mussels from growing and obtaining energy reserves for the coming winter.

Mussel declines or changes in assemblage structure may be due to different combinations of these factors in different parts of the river. In the tailwater reach, loss of the entire mussel community may be due primarily to unseasonably cold temperatures that may reduce gametogenesis, sperm release, glochidial growth on fishes, or juvenile growth. These factors would be expected to affect most species similarly. However, unseasonably high flows or reduced oxygen concentrations in late summer or fall also could reduce juvenile survival.

Reasons for changes in community structure in the lower and middle river are unknown. The lower and middle river are relatively unaffected by potential suppression of water temperature by Cave Run Dam, and summer temperatures regularly reach the mid- to high 20s°C (Haag et al., 2019). However, long periods of unseasonably high flows routinely occur throughout the river, particularly in wet years. In addition to longsolid mussel, other previously dominant species that release glochidia in conglutinates that drift in the current have declined precipitously since the 1950s or before (e.g., round pigtoe - *Pleurobema sintoxia*, and Ohio pigtoe - *P. cordatum*). Sustained high, turbid summer flows may dilute and wash away these conglutinates, as well as decrease visibility for their sight-feeding hosts (minnows). Furthermore, release of glochidia by these species often occurs in only one or two brief periods, such that an entire year's reproductive effort could be lost if release coincides with high flows. In contrast, species that use mantle lures to attract hosts typically display lures for extended periods and conglutinates released by other species are adhesive and stick to the bottom, potentially reducing downstream transport (Haag, 2012; see discussion of target mussel species). These traits may reduce effects of high flows on

those species. Annual recruitment strength of several mussel species is negatively correlated with summer and fall stream discharge, with little or no recruitment occurring in high-flow years, but the strength of this effect varies depending on life history traits (Howard and Cuffey, 2006; Jones and Neves, 2011; Haag, 2012).

### Streamflow and Temperature Regime Alteration and Effects on Fish

Dams in Kentucky have significant ecological impacts on aquatic ecosystems, especially on the fish species that inhabit the state's rivers and streams. The construction of dams disrupts natural hydrological processes, altering water flow, sediment transport, and temperature, which in turn affects the survival, migration, and reproduction of fish populations. One of the primary consequences of damming is the alteration of flow regimes, which are critical for the ecological health of river systems. In Kentucky, dams regulate the flow of water in rivers like the Kentucky River and the Licking River, altering the natural seasonal fluctuations in flow that many fish species rely on for spawning and migration (Jager et al., 2011). The reduction in seasonal flow variability can lead to habitat degradation (loss of stability and shifts in substrate concentration) and disrupted spawning cues (Baruch et al., 2024).

In addition to flow alterations, dams also affect water temperature, which is a crucial factor for fish survival and reproduction. Impoundment of water behind dams often leads to thermal stratification, creating a layer of warmer surface water and cooler, deeper water. When water is released downstream, it may be significantly warmer or cooler than the natural temperature, depending on the depth from which the water is drawn. Cold hypolimnetic releases of high magnitude and duration likely have the greatest negative impact on fish communities below the dam. Temperature shifts can also stress temperature-sensitive species, such as the river chub (*Nocomis micropogon*), which require cool, oxygen-rich waters to thrive (Arnot et al., 2008). Warmer water temperatures can also favor the establishment and proliferation of aggressive fish species, such as bluegill (*Lepomis macrochirus*), which can outcompete more typical assemblages of native species and further alter community dynamics (Rahel, 2007).

Dams also influence sediment transport, which affects fish habitats. Sediment carried by rivers plays an important role in maintaining riverbed structure, which provides spawning sites for many fish species. Dams trap sediment in reservoirs, reducing the amount of sediment that reaches downstream areas and leading to altered riverbed conditions. This can degrade habitats for many small benthic fishes adapted to riffle habitats in the middle and lower Licking River such as the shoal chub, northern madtom, Tippecanoe darter, and gilt darter. Moreover, the construction of dams creates barriers to fish migration, particularly for species that require access to both upstream and downstream habitats for different life stages. Species like the freshwater drum (*Aplodinotus grunniens*) and other migratory fish are unable to bypass dams, leading to population declines in certain areas (Poff et al., 1997).

## Defining Licking River Streamflow Alterations

The major streamflow alterations, as outlined in this report, that are caused by the Cave Run Lake Dam and are thought to significantly impact fish and mussel populations are:

1. Reduced frequency of high flows in the winter/spring (compare Figures 2 and 3).
2. Reduced magnitude of high flows in the winter/spring (compare Figures 2 and 3).

3. Elimination of low flows in fall, particularly in August, September, and October (compare Figures 2 and 3).

4. Decrease in summer water temperatures below normal, particularly June through mid-July (Figure 9).

5. Increase in fall/winter water temperatures above normal, particularly mid-October through January (Figure 9).

6. Although dissolved oxygen concentrations regularly meet state standards, there is potential for dissolved oxygen saturation levels within the tailwater to be insufficient for fish and mussel recruitment (Figure 12).

## Target Species to Model Flow Restoration

Through coordination with regional mussel and fish experts, we have developed a preliminary list of target species to focus on during the workshop. Modeling ecological flows out of a dam based on target species is an effective strategy because it tailors flow regimes to meet the specific habitat requirements of organisms that depend on stable environmental conditions for survival and reproduction (Poff et al., 1997). By focusing on key species—such as aquatic plants, invertebrates, or fish—this approach ensures that flow alterations account for critical needs, including water temperature, sediment transport, and the timing of flows necessary for spawning or migration (Arthington et al., 2010). Linking flow management to the life histories of target species supports ecosystem health by maintaining ecological functions and protecting biodiversity, especially for endangered or keystone species (Helfield et al., 2007). This species-specific model enhances the resilience of the entire ecosystem while balancing both ecological and human water needs (Poff et al., 2003).

For mussels, target species were identified according to the following criteria.

1. Species that are widely distributed in the Licking River from the tailwater reach downstream to nearly the mouth. This criterion is desirable because it allows us to assess the effects of flow management on both the tailwater reach, which likely is affected by altered temperature and flow regimes, and on the middle and lower river, which likely are affected mainly by altered flow.
2. Species that are abundant enough to support meaningful estimates of abundance or age structure both prior to and after any flow modifications are implemented. It is nearly impossible to make estimates of abundance of rare species with the precision necessary to detect changes over time.
3. A group of species that represents an array of life history strategies. Species with different life histories (e.g., host use, spawning or glochidial release timing) can be expected to respond differently to flow modification. Assessing species with different life history strategies allows us to assess effects of flow modification to the overall mussel assemblage.
4. Species that can serve as surrogate species for imperiled species (which may be too rare to monitor) because they have similar life history traits. For each target species, we list imperiled species for which they may serve as surrogates.

Below are the recommended target species with quick references to life history information for consideration during the Licking River e-flow workshop. See the Appendix for detailed mussel life history write ups and temporal life history graphs by Wendell Haag.

## Mussel Species

**Note:** All target mussel species occur in similar habitats. They most commonly occur in riffle or run habitats with gentle to moderate current in stable substrates composed of a mixture of gravel, sand, and silt. They occur only sparingly in pools with little current or extensive areas of deep, fine sediments.

**Longsolid (*Fusconaia subrotunda*)**

- **Habitat**: Found in medium to large rivers and streams, prefers clean, slow-moving waters. Commonly found in areas with stable flow and some cover, such as submerged vegetation or rocks (NatureServe, 2021)
- **Substrate Preference**: Typically prefers firm sand or gravel substrates for burrowing and feeding (NatureServe, 2021)
- **Water Temp**: Warm water streams, up to 25-30 C.
- **Reproduction:** Short-term brooders, spawn in May/June/July, gravid through July
- **Host Fish**: Unknown, but most likely minnows
- **Subsistence**: Spring temperatures in June are crucial to spawning and recruitment. Fall low flow conditions provide lots of food and stable habitats for new juveniles (< 5 mm). High oxygen levels (> 95%) recommended for young mussels
- **Base Flow:** Spring and summer base flows with no abrupt changes in temperature and oxygen provide optimal conditions for growth and spawning. Time window is much shorter for short-term brooders to provide optimum conditions

**Mucket (*Actinonaias ligamentina*)**

- **Habitat**: Typically found in flowing waters of medium to large rivers in main channels over firm sand and gravel substrates. Habitat is associated with its host fish, black basses
- **Substrate Preference**: Fine sand and gravel in riffles and runs
- **Reproduction**: Long-term brooders, spawn in August, gravid from Sept to May
- **Host Fish**: Bass, shad
- **Subsistence**: Fall low flow conditions provide lots of food and stable habitats for new juveniles (< 5 mm). High oxygen levels (> 95%) recommended for young mussels
- **Base Flow**: Fall base flows with no abrupt changes in temperature and oxygen provide optimal conditions for growth and spawning (usually in August)

**Spike (*Eurynia dilatata*)**

- **Habitat**: Typically found in flowing waters of medium to large rivers in main channels over firm sand and gravel substrates. Habitat is associated with its host fish, darters
- **Substrate Preference**: Sand and gravel in riffles and runs
- **Reproduction**: Short-term brooders, spawn in May/June/July, gravid through July
- **Host Fish**: Multiple darters, shad
- **Subsistence**: Spring temperatures in May/June are crucial to spawning and recruitment. Fall low flow conditions provide lots of food and stable habitats for new juveniles (< 5 mm). High oxygen levels (> 95%) recommended for young mussels
- **Base Flow:** Spring and summer base flows with no abrupt changes in temperature and oxygen provide optimal conditions for growth and spawning. Time window is much shorter for short-term brooders to provide optimum conditions

**Round Hickorynut (*Obovaria subrotunda*)**

- **Habitat**: Typically found in flowing waters of small, medium to large rivers
- **Substrate Preference**: Fine stable sand and gravel substrates. Habitat is associated with its host fishes, darters, especially sand darters
- **Reproduction**: Long-term brooders, spawn in August, gravid from Sept to May
- **Host Fish**: eastern sand darter, variegate darter, greenside darter, emerald darter
- **Subsistence**: Fall low flow conditions provide lots of food and stable habitats for new juveniles (< 5 mm). High oxygen levels (> 95%) recommended for young mussels
- **Base Flow**: Fall base flows with no abrupt changes in temperature and oxygen provide optimal conditions for growth and spawning (usually in August)

**Fanshell (*Cyprogenia stegaria*)**

- **Habitat**: Typically found in flowing waters of medium to large rivers in main channels over firm sand and gravel substrates. Habitat is associated with its host fishes, darters, especially logperch
- **Substrate Preference**: Fine sand and gravel in shallow runs
- **Reproduction**: long-term brooders, spawn in August, gravid from Sept to May
- **Host Fish**: logperch, sculpin, greenside darter
- **Flow Target**: Doing very well in Licking, so current flows make conditions highly favorable in the middle and lower Licking
- **Subsistence**: Fall low flow conditions provide lots of food and stable habitats for new juveniles (< 5 mm). High oxygen levels (> 95%) recommended for young mussels
- **Base Flow**: Fall base flows with no abrupt changes in temperature and oxygen provide optimal conditions for growth and spawning (usually in August).

## Fish species

**Northern Madtom (*Noturus stigmosus*)**

- **Habitat**: In the Licking River, the northern madtom inhabits riffles with moderate current (~0.5 m/sec) in depths of 20-23 cm over mixed substrates of sand, gravel, and cobble, with some vegetation. Individuals are frequently associated with riverweed (*Podostemum*), eelgrass (*Vallisneria*), or pondweed (*Potamogeton*). Juveniles occupy habitat similar to adults, but more often in shallower areas with slower current and more vegetative cover (Scheibly et al., 2008)
- **Spawning Season**: Spawning occurs from mid-June to late July when water temperatures range from 68°F and 72°F (20°C to 22°C) (Dunn & Cross, 2010; Scheibly et al., 2008)
- **Spawning Habitat and Behavior**: Nests are constructed in raceways above riffles in low to moderate flow (0.36-0.69 m/sec) in depths of 4-7 cm under large slab rocks surrounded by a substrate of cobble and gravel, with patches of pondweed (*Potamogeton*). Males guard the nest until the eggs hatch, then attends the larvae for a few days until they disperse (Taylor, 1969; Thomas and Burr, 2004; Scheibly et al., 2008)

**Shoal Chub (*Macrhybopsis hyostoma*)**

- **Habitat**: In small to medium-sized rivers, the shoal chub occurs immediately below riffles in deeper runs (0.5-1.5 m) with fast current over coarse sand and gravel. It is a strictly benthic minnow, occupying both turbid and clear waters (Eisenhour 2004, D.J. Eisenhour, pers. obs.)
- **Spawning Season**: Jenkins & Burkhead (2007) reported spawning occurring in late spring to early summer, typically from May to June, when water temperatures are between 64°F and 75°F (18°C to 24°C); however, nuptial males have been observed with breeding tubercules from late May to early August, indicating spawning may occur into later summer (D.J. Eisenhour, pers. obs.)

- **Spawning Habitat and Behavior**: Spawning has not been observed in this species. In related species of *Macrhybopsis*, males initiate the spawning event by nudging the female's abdomen. When the female is ready to spawn, the male encircles the female and both sexes expel gametes. Spawning location is unknown. Eggs are large (2.5-3.5 mm diameter) and semi-buoyant, drifting with the current as they develop. Eggs require significant flow to maintain buoyancy, otherwise they may sink to the benthos and be subject to being smothered by sediment, evisceration, or predation. Hatching occurs in 24-48 hrs at 23-28°C (Bottrell et al., 1964; Platania and Altenback, 1998). Because of these characteristics, it is likely shoal chubs expel fertilized eggs during summer storm pulses where there is enough flow to maintain buoyancy long enough for eggs to develop and hatch before flows recede, while also requiring sufficiently warm water temperatures for larval development to occur.

**Eastern Sand Darter (*Ammocrypta pellucida*)**

- **Habitat**: Inhabits clear, small to medium rivers. It occupies runs with clean sand or mixed sand and fine gravel, in areas of slight current at the edge of riffles or just below riffles. Like other sand darters, it buries in sand with only the snout and eyes exposed, darting out at passing prey (Forbes and Richardson, 1908; Simon and Wallus, 2006)
- **Spawning Season**: Spawning occurs from April to July at water temperatures of 17-26°C (Johnston, 1989; Simon and Wallus, 2006). Eggs are deposited in sand and fine gravel in shallow, slow riffles (Johnston, 1989; Simon and Wallus, 2006). Fecundity is relatively low, even for darters: females 39-50 mm SL had 30-170 mature ova (Spreitzer, 1979). Fertilized eggs are pale yellow, and average 1.4 mm in diameter (Simon and Wallus, 2006)
- **Spawning Habitat and Behavior**: Eggs are deposited in sand and fine gravel in shallow, slow riffles (Johnston, 1989; Simon and Wallus, 2006). There is no parental care for the eggs.

**Tippecanoe Darter (*Nothonotus tippecanoe*)**

- **Habitat**: Restricted to mid-sized rivers with moderate to high gradient, coarse substrates, and clear water. Adults occupy fast current over gravel and cobble, often adjacent to water willow (*Justicia*) beds (Warren et al., 1986)
- **Spawning Season**: Spawning occurs in July in Kentucky, and possibly throughout the summer (D.J. Eisenhour and M.R. Thomas, pers. obs.)
- **Spawning Habitat and Behavior**: In aquaria, females bury themselves in gravel, depositing eggs on a flat stone 4 cm below the surface. Eggs hatch in about 6-9 days at 22-25°C (Warren et al., 1986; Page and Simon, 1988)

**Gilt Darter (*Percina evides*)**

- **Habitat**: Occupies rocky riffles of small to medium-sized rivers. Adults occur in deep, fast riffles, usually among gravel, cobbles, and boulders (Burr and Warren, 1986; D.J. Eisenhour and M.R. Thomas, pers. obs.)
- **Spawning Season**: Spawning occurs from mid-April through early July at 14-22°C (Denoncourt, 1969; Page et al., 1982; Simon and Wallus, 2006)
- **Spawning Habitat and Behavior**: Spawns near the upstream end of rocky riffles. Spawning is initiated when a female enters a shallow depression in fine gravel or coarse sand in a male's territory. Males and females intertwine and move through the substrate, releasing eggs and sperm just below the surface. Parents do not guard the eggs, which hatch in about 5 days at 22°C (Simon and Wallus, 2006)

### Other aquatic organisms to consider

**Basking turtles (primarily northern map turtle (*Graptemys geographica)*, but also possibly pond slider (*Trachemys scripta)*, and painted turtle (*Chrysemys picta*).**

- **Rationale**: Basking turtles are conspicuous and ecologically important members of river ecosystems across much of Kentucky, including in the South Fork Licking River, where they are abundant. Accounts of local residents indicate that basking turtles were common in the mainstem Licking River prior to the 1970s, but they are largely absent today (W. Haag, unpublished observations)
- **Reproduction**: Basking turtles nest in late spring and summer. Nesting sites typically are in well-drained, sandy soils within 3 m of the water's edge and <1 m above water level. Females excavate a nest cavity into which are deposited up to 20 eggs, and the cavity is backfilled. Eggs hatch after about a 50 to 70-day incubation period, and hatchings emerge in August and September (Gordon and MacCulloch, 1980). Prolonged inundation of nests due to unseasonable high water can result in increased or total mortality of eggs (Bodie, 2001; Bárcenas-García et al., 2022)

## Conclusion

The Licking River's ecological health and biodiversity face significant challenges due to the alteration of natural flow regimes caused by the construction and operation of the Cave Run Lake Dam. This review highlights critical factors such as streamflow, temperature, and dissolved oxygen variations that impact aquatic habitats and the life cycles of key species, including federally endangered mussels and fish of conservation concern. It underscores the importance of implementing targeted environmental flows to restore and sustain ecological processes, enhance habitat connectivity, and support species resilience.

The Sustainable Rivers Program provides a collaborative framework to optimize reservoir operations, balancing ecological needs with federal mandates. Continued research, stakeholder engagement, and adaptive management are essential to achieving a sustainable flow regime that preserves the ecological integrity of the Licking River while maintaining its multifaceted benefits. This report serves as a foundational step toward informed decision-making and effective conservation strategies for one of Kentucky's vital waterways.

# References


Acreman, M.C. and M.J. Dunbar. 2004. Defining Environmental River Flow Requirements: A Review Hydrology and Earth System Sciences Discussions. European Geosciences Union, 8:861-876.

Acreman, M., J. Aldrick, J. Binnie, A. Black, I. Cowx, H. Dawson, M. Dunbar, C. Extence, J. Hannaford, A. Harby, N. Holmes, N. Jarrett, G. Old, G. Peirson, J. Webb, and P. Wood. 2009. Environmental flows from dams: the water framework directive. Proceedings of the Institution of Civil Engineers. 18:47:31.

Arnot, C.L., R.A. McKinney, and R.L. Weatherford. 2008. The effects of thermal stratification and dam releases on downstream fish populations: A case study of the Kentucky River. *Environmental Biology of Fishes*, *83*(2), 147–158. https://doi.org/10.1007/s10641-008-9375-5

Arthington A.H., S.E. Bunn, N.L. Poff, and R.J. Naiman. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications, 16:1311-1318.

Arthington, A.H., R.J. Naiman, M.E. McClain, and C. Nilsson. 2010. Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. Freshwater Biology, 55:1-16.

Arthington, A.H., J.G. Kennen, E.D. Stein, and J.A. Webb. 2018. Recent advances in environmental flows science and water management - Innovation in the Anthropocene. Freshwater Biology, 63:1022-1034.

Ashton, M.J. 2012. Ecological responses to flow alteration: A literature review within the context of the Maryland Hydroecological Integrity Assessment. Maryland Department of Natural Resources, Monitoring and Non-Tidal Assessment Division. RAS-MANTA-AIM-13-01, 45 p.

Bárcenas-García, A., F. Michalski, W.H Morgan, R.K. Smith, W.J. Sutherland, J.P. Gibbs, and D. Norris. 2022. Impacts of dams on freshwater turtles: a global review to identify conservation solutions. Tropical Conservation Science, 15:1–21.

Barnhart, M.C., and A. Roberts. 1997. Reproduction and fish hosts of unionids from the Ozark uplifts. Pages 16–20 in K.S. Cummings, A.C. Buchanan, C.A. Mayer, and T.J. Naimo, editors. Conservation & Management of Freshwater Mussels II: Initiatives for the Future. Proceedings of a UMRCC Symposium, St. Louis, MO: Upper Mississippi River Conservation Committee, Rock Island, IL.

Barnhart, C.E., W.R. Haag, and W. Roston. 2008. Adaptations to larval parasitism in the Unionoida. Journal of the North American Benthological Society, 27:370–394.

Baruch, E.M., S.M. Yarnell, T.E. Grantham, J.R. Ayers, A.L. Rypel, and R.A. Lusardi. 2024. Mimicking functional elements of the natural flow regime promotes native fish recovery in a regulated river. Ecological Applications, 34, e3413.

Bodie, J.R. 2001. Stream and riparian management for freshwater turtles. Journal of Environmental Management, 62:443–455.

Bottrell, C.E., R.H. Ingersol, and R.W. Jones. 1964. Notes on the embryology, early development, and behavior of Hybopsis aestivalis tetranemus (Gilbert). Trans. Amer. Microsc. Soc., 83:391-399.

Bruenderman, S. and R. Neves. 1993. Life history of the Endangered Fine rayed Pigtoe Fusconaia cuneolus (Bivalvia, Unionidae) in the Clinch River, Virginia. American Malacological Bulletin.

Burr, B.M. and M.L. Warren. 1986. A distributional atlas of Kentucky fishes. Kentucky State Nature Preserves Commission, Scientific and Technical Series Number 4.

Chen, W. and J.D. Olden. 2017. Designing flows to resolve human and environmental water needs in a dam-regulated river: Nature Communications, 8:2158. https://doi.org/10.1038/s41467-017-02226-4.

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

Culp, J.J., W.R. Haag, D.A. Arrington, and T.B. Kennedy. 2011. Seasonal and species-specific patterns in abundance of freshwater mussel glochidia in stream drift. Journal of the North American Benthological Society, 30:436-445.

Denoncourt, R. F. 1969. A systemactic study of the gilt darter, Percina evides (Jordan and Copeland) (Pisces, Percidae). Ph.D. dissert., Cornell Univ., Ithaca, New York.

Di Maio, J. and L.D. Corkum. 1995. Relationship between the spatial distribution of freshwater mussels (Bivalvia: Unionidae) and the hydrological variability of rivers. Canadian Journal of Zoology, 73:663-671.

Dunn, S. E. and D.J. Cross. 2010. Spawning behavior and habitat selection of the Northern Madtom (*Noturus stigmosus*). American Midland Naturalist, 163(2):217–229. https://doi.org/10.1674/0003-0031-163.2.217

Eisenhour, D.J. 2004. Systematics, variation, and speciation of the Macrhybopsis aestivalis complex west of the Mississippi River. Alabama Mus. Nat. Hist., 23:9-48.

Forbes, S.A. and R.E. Richardson. 1908. The fishes of Illinois. Illinois Natural History Survey, Urbana.

Galbraith, H.S. and C.C. Vaugh. 2011. Effects of reservoir management on abundance, condition, parasitism and reproductive traits of downstream mussels. River Research and Applications, 27:193-201.

Gordon, D.M. and R.D. Macculloch. 1980. An investigation of the ecology of the map turtle, Graptemys geographica (Le Sueur), in the northern part of its range. Can. J. Zool., 58:2210-2219.

Graf, W.L. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology, 29:336-360.

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

Haag, W.R. and M.L. Warren. 1997. Host fishes and reproductive biology of 6 freshwater mussel species from the Mobile Basin, USA. Journal of the North American Benthological Society, 16:576-585.

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

Haag, W.R. 2012. *North American freshwater mussels: Natural history, ecology, and conservation*. Cambridge University Press. https://doi.org/10.1017/CBO9781139048217

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

Haag, W.R., J.J. Culp, A.N. Drayer, M.A. McGregor, D.E.J. White, and S.J. Price. 2021. Abundance of an invasive bivalve, Corbicula fluminea, is negatively related to growth of freshwater mussels in the wild. Freshwater Biology 66:447-457. DOI: 10.1111/fwb.13651

Helfield, J.M., S.J. Capon, C. Nilsson, R. Jansson, and D. Palm. 2007. Restoration of rivers used for timber floating: Effects on riparian plant diversity. Ecological applications: a publication of the Ecological Society of America. 17(3):840-851.

Hove, M., B. Sietman, M. Berg, S. Bump, M. Davis, H. Hansen, S. Keogh, C. Luebke, S. Marr, A. Maynard, K. Murphy, Z. Secrist, and D. Hornbach. 2013. Pleurobema sintoxia early life history. Ellipsaria, 15(3):14-16.

Hove, M., B. Davis, E. Wanner, P. Leonard, G. Van Susteren, B. Sietman, S. Bump, S. Marr, K. Murphy, M. Berg, A. Handy, A. Thoreen, K. Rod, M. Hanson, R. Pochman, S. Nelson, and W. LaMere. 2014.

Laboratories show Lasmigona costata metamorphose on several fish species. Ellipsaria, 16(2):21-23.

Hove, M.C., B.E. Sietman, M. Berg, T. Brady, E. Guenther, S.L. Boyer, and D.J. Hornbach. 2016. Early life history of the sheepnose (Plethobasus cyphyus) (Mollusca: Bivalvia). Journal of Natural History, 50(9-10):523-542.

Hove, M., K. Carrow, S. Taylor, J. Donna, C. Rounds, S. Binkley, S. Deetz, A. Rager, J. Loegering, D. Zerwas, Jr., and D. Hornbach. 2020. Natural Hosts for St. Croix River Epioblasma triquetra, Fusconaia flava, Pleurobema sintoxia, Strophitus undulatus, and Theliderma metanevra. Ellipsaria, 22(3):9-12.

Howard J.K., and K.M. Cuffey. 2006. Factors controlling the age structure of Margaritifera falcata in 2 northern California streams. Journal of the North American Benthological Society, 25:677-690.

Jager, H.I., R.A. Efroymson, J.J. Opperman, and M.R. Kelly. 2011. Spatial design principles for sustainable hydropower development in river basins. River Research and Applications, 27(4):418-436. https://doi.org/10.1002/rra.1352

Jenkins, R. E., and N.M. Burkhead. 2007. Freshwater Fishes of Virginia. American Fisheries Society.

Jirka, K.J. and R.J. Neves. 1992. Reproductive biology of four species of freshwater mussels (Mollusca: Unionidae) in the New River, Virginia and West Virginia. Journal of Freshwater Ecology, 7(1):35-44.

Johnston, C.E. 1989. Spawning in the eastern sand darter, Ammocrypta pellucida (Pisces: Percidae), with comments on the phylogeny of Ammocrypta and related taxa. Tran. Illinois Acad. Sci., 82:163-168.

Jones, J.W., and R.J. Neves. 2011. Influence of life-history variation on demographic responses of three freshwater mussel species (Bivalvia: Unionidae) in the Clinch River, USA. Aquatic Conservation: Marine and Freshwater Ecosystems, 21:57-73.

Kentucky Department of Fish and Wildlife Resources (KDFWR). 2024. *2025 Fishing Forecast and Tips*. Retrieved from https://fw.ky.gov/Fish/Documents/currentfishingforecast.pdf

Knight, R.R., Gregory, M.B. and A.K. Wales. 2008. Relating streamflow characteristics to specialized insectivores in the Tennessee River Valley: a regional approach. Ecohydrology, 1:394-407.

Laudermilk, E.L. 1993. A survey of the unionids (Bivalvia: Unionidae) of the mainstem Licking River and selected tributaries below Cave Run Reservoir, Kentucky. Master's Thesis, Eastern Kentucky University, Richmond, Kentucky. 77 p.

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

Lefevre, G. and W.C. Curtis. 1910. Reproduction and parasitism in the Unionidae. Journal of Experimental Zoology, 9:79-116.

Lefevre, G., and W.C. Curtis. 1912. Studies on the reproduction and artificial propagation of fresh-water mussels. Bulletin of the U.S. Bureau of Fisheries, 30:105-201.

Leonard, P., M. Hove, B. Davis, E. Wanner, G. Van Susteren, B. Sietman, M. Berg, A. Handy, A. Thoreen, K. Rod, M. Hanson, R. Pochman, S. Nelson, W. LaMere, and D. Hornbach. 2014. Flutedshell (Lasmigona costata) natural hosts and glochidia release behavior. Ellipsaria, 16(4):29-32.

Luo, M. 1993. Host fish of four species of freshwater mussels and development of an immune response. Thesis, Tennessee Technological University, Cookeville, Tennessee, USA.

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

McMurray, S.E., G.A. Schuster, and B.A. Ramey. 1999. Recruitment in a Freshwater Unionid (Mollusca: Bivalvia) Community Downstream of Cave Run Lake in the Licking River, Kentucky. American Malacological Bulletin, 15(1) {1999):57-63.

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

National Oceanic & Atmospheric Administration (NOAA). 1981-2010 Normals. Web. 6 Sep. 2021 https://www.ncdc.noaa.gov/cdo-web/datatools/normals

NatureServe. 2021. *Fusconaia subrotunda*. NatureServe Explorer. Retrieved 8 Feb 2025, from https://explorer.natureserve.org/Taxon/ELEMENT_GLOBAL.2.118395/Fusconaia_subrotunda

Ortmann, A.E. 1910. The discharge of the glochidia in the Unionidae. The Nautilus, 24:94-95.

Ortmann, A.E. 1919. A monograph of the naiads of Pennsylvania. Part 111. Systematic account of the genera and species. Memoirs of the Carnegie Museum, 8:1-385.

Page, L.M., and T.P. Simon. 1988. Observations on the reproductive behavior and eggs of four species of darters, with comments on Etheostoma tippecanoe and E. camurum. Trans. Illinois Acad. Sci., 81:205-210.

Page, L.M. M.A. Retzer, and R.A. Stiles. 1982. Spawning behavior in seven species of darters (Pisces: Percidae). Brimleyana, 8:135-143.

Platania, S. P., C. S. Altenbach. 1998. Reproductive strategies and egg types of seven Rio Grande basin cyprinids. Copeia, 1998:559-569.

Poff, N.L. and J.V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of stream flow patterns. Canadian Journal of Fisheries and Aquatic Sciences, 46:1805-1818.

Poff, N.L. and J.D. Allan. 1995. Functional organization of stream fish assemblages in relation to hydrological variability. Ecology, 76:606-627.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience, 47: 769-784.

Poff, N.L., J.D. Allan, M.A. Palmer, D.D. Hart, B.D. Richter, A.H. Arthington, K.H. Rogers, J.L. Meyer and J.A. Stanford. 2003, River flows and water wars: emerging science for environmental decision making. Frontiers in Ecology and the Environment, 1:298-306.

Poff, N.L. and J.K.H. Zimmerman. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshwater Biology, 55:194-205.

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O'Keeffe, J.D. Olden, K. Rogers, R.E. Tharme, and A. Warner. 2010. The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. Freshwater Biology, 55(1):147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x

Rahel, F.J. 2007. Biogeographic barriers, connectivity, and biotichomogenization: it's a small world after all. Freshwater Biology, 52:696-710.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology, 10(4):1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x

Richter, B.D. and G.A. Thomas. 2007. Restoring Environmental Flows by Modifying Dam Operations. Ecology and Society, 12(1):12.

Risley, J., J.R. Wallick, I. Waite, and A. Stonewall. 2010. Development of an environmental flow framework for the McKenzie River basin, Oregon: U.S. Geological Survey Scientific Investigations Report 2010-5016, 94 p.

Ross, S.T. 2001. Inland fishes of Mississippi. University Press of Mississippi, Oxford.

Scheibly, J.F., D.J. Eisenhour, and L.V. Eisenhour. 2008. Reproductive biology of the northern madtom, Noturus stigmosus (Siluriformes: Ictaluridae) from the Licking River, Kentucky. J. Kentucky Acad. Sci., 69:178-186.

Schroeder, L., A. Edgcumbe, K. Murphy, S. Bump, A. Londo, B. Sietman, M. Hove, and G. Van Susteren. 2014. Host fishes and glochidia release behavior of Elliptio dilatata. Ellipsaria, 16(4):32-34.

Simon, T.P., and R. Wallus. 2006. Reproductive biology and early life history of fishes in the Ohio River drainage: Percidae – perch, pikeperch, and darters, Vol 4. CRC Press, New York.

Spreitzer, A.E. 1979. The life history, external morphology, and osteology of the eastern sand darter, Ammocrypta pellucida (Putnam, 1863), an endangered Ohio species (Pisces: Percidae). M.S. Thesis, Ohio St. Univ., Columbus.

Taylor, W.R. 1969. A revision of the catfish genus Noturus Rafinesque with an analysis of higher groups in the Ictaluridae. Bull. U.S. Natl. Mus., 281:1-315.

The Nature Conservancy. (2009). *Indicators of hydrologic alteration: Version 7.1 user's manual* (with rPurview LLC - Ted Rybicki, Totten Software Design, and Smythe Scientific Software).

Thomas, M.R., and B.M. Burr. 2004. Noturus gladiator, a new species of madtom (Siluriformes: Ictaluridae) from Coastal Plain streams of Tennessee and Mississippi. Ichthy. Explor. Freshwaters, 15:351-368.

Thomason, J., M. Hove, B. Sietman, M. Berg, S. Anderson, S. Bump, A. Lindeman, N. Ward, S. Morley, S. Berreth-Doran, and C. Poeschl. 2013. Laboratory trials show flutedshell (*Lasmigona costata*) transform on several fishes. Ellipsaria, 15(2):19-21.

U.S. Army Corps of Engineers (USACE). 1982. *Cave Run Lake and Dam: Operational management plan*. U.S. Army Corps of Engineers, Louisville District.

U.S. Army Corps of Engineers (USACE). 2018. *Cave Run Dam (KY03055) Dam Embankment and Spillway Periodic Assessment No. 1 Periodic Inspection No. 14.* U.S. Army Corps of Engineers, Louisville District.

U.S. Army Corps of Engineers (USACE). 2022. *Cave Run Lake Master Plan*. U.S. Army Corps of Engineers, Louisville District.

U.S. Army Corps of Engineers (USACE). 2023. Cave Run Lake. Retrieved from https://www.lrd.usace.army.mil/Missions/Projects/Article/3641194/cave-run-lake/

Warner, A.T., L.B. Bach, and J.T. Hickey. 2014. Restoring environmental flows through adaptive reservoir management: planning, science, and implementation through the Sustainable Rivers Project. Hydrological Sciences Journal, 59:3-4,770-785. https://doi.org/10.1080/02626667.2013.843777

Warren, M.L., Jr., B.M. Burr, and B.R. Kuhajda. 1986. Aspects of the reproductive biology of Etheostoma tippecanoe with comments on egg-burying behavior. Amer. Midl. Nat., 116:215-218.

Watters, Thomas G., M.A. Hoggarth, and D.H. Stansbery. 2009. The freshwater mussels of Ohio. Ohio State University Press, 345 p.

Watters, G.T., T. Gibson, and B. Kelly. 2009. Host identifications or confirmations. Ellipsaria, 11(1):19.

White, L.R., B.A. McPherson, and J.R. Stauffer, Jr. 1996. Molecular genetic identification tools for the unionids of French Creek, Pennsylvania. Malacologia, 38:181-202.

Yokely, P. 1972. Life history of *Pleurobema cordatum* (Rafinesque 1820) (Bivalvia: Unionacea). Malacologia, 11:351-364.

# Appendix A

# Supplemental Mussel Species Information

**Longsolid (*Fusconaia subrotunda*)/ Round Pigtoe (*Pleurobema sintoxia*)**

- **Rationale:** These species are combined as a single target because their life histories and distribution are similar and the current rarity of both species may make it more effective to monitor them as a group. The longsolid and round pigtoe are distributed throughout the Licking River downstream of Cave Run Dam (Haag and Cicerello 2016). Historically (~1900-1950), both species were dominant components of mussel assemblages in the middle and lower river, but they have declined precipitously and are now uncommon (Haag, W.R., M. Compton, J. Rech, unpublished data). However, both species appear to be recruiting in the river (M. McGregor unpublished data). The longsolid probably now is most abundant in the reach near Clay Wildlife Management Area (Bath and Fleming counties; Haag and Cicerello 2016). The longsolid is a threatened species under the U.S. Endangered Species Act.
- **Tribe:** Pleurobemini
- **Reproduction**: The longsolid and round pigtoe are short-term brooders (Ortmann 1919). The mode and timing of reproduction have not been studied in detail for either species but appear to be similar to most other species in the tribe Pleurobemini. In most Pleurobemini and other short term brooders, sperm is released and eggs are fertilized in late spring to early summer, generally in May and June, fertilized eggs are brooded by females and develop in two to six weeks, and females release glochidia shortly thereafter, from June to August; reproduction often is loosely synchronous among individuals in a population, and the period of gravidity may last only two to six weeks (Haag 2012). Observations for both species support these patterns. In Pennsylvania, female longsolid were gravid from mid-June to mid-July, but mature glochidia were found only during two weeks in July; female round pigtoe were gravid from mid-May to mid-July, mature glochidia were found from mid-June to July, and glochidial release began in mid-June (Ortmann 1919). In the Ohio pigtoe (*Pleurobema cordatum*) in northern Alabama, gametogenesis began in the fall, paused in winter, resumed in spring, and spawning occurred in April and May when water temperature reached about 20°C (Yokely 1972). Fertilized eggs developed into mature glochidia in 4–6 weeks, requiring temperatures >21°C, and glochidial release occurred mainly in June. In Virginia, fine-rayed pigtoe (*Fusconaia cuneolus*) were gravid from mid-May to early August, with the highest percentage of gravid females (>50%) from mid-June to early July (Bruenderman and Neves 1993). Development from embryos to mature glochidia required about two weeks at 20–24°C, and glochidia were released at temperatures between 21.2 and 23.0°C. Glochidia were present in stream drift from late May to early August, but abundance typically was low except during two brief peaks in abundance in mid-June and mid-July, indicating synchronous glochidial release during favorable conditions. In Alabama, gulf pigtoe (*Fusconaia cerina*) and southern clubshell (*Pleurobema decisum*) were gravid from late May to late July, and females were brooding

mature glochidia beginning in early June (Haag and Warren 2003). Glochidia of both species were present in stream drift from May to August (water temperature = 22.5–28.0°C), but abundance typically was low except during one to three brief peaks (Culp et al. 2011). Water temperatures during peak release periods were >25°C.

- **Host fishes**: Round pigtoe is a host specialist on minnows (Cyprinidae), including *Campostoma anomalum*, *Cyprinella* spp., *Luxilus cornutus*, *Notropis boops*, *Paranotropis volucellus*, *Pimephales notatus*, *Rhinichthys atratulus*, and *Semotilus atromaculatus* (Hove et al. 2013, 2020), but other minnows likely serve as hosts. In the Licking River, *Cyprinella* spp., *P. volucellus*, and potentially *N. atherinoides* and *N. rubellus* probably are the most important hosts because they are among the dominant minnows in the mid-water feeding guild (M. Thomas and D. Eisenhour, personal communication). These fishes are diurnal sight feeders that forage in the mid-water column on drifting insects and other small prey items (summarized in Ross 2001). Host fishes for longsolid are unknown, but it likely also is a specialist on minnows. All other species of *Fusconaia* and the closely related genus *Pleurobema* that have been studied are specialists on minnows (Haag 2012), and longsolid releases glochidia in conglutinates, which appear to target minnows (see host attraction strategy). **Host infection strategy:** Both species release glochidia in pelagic conglutinates (Ortmann 1910; Hove et al. 2013; M. McGregor, unpublished data), similar to all other studied species of *Fusconaia* and *Pleurobema* (Haag 2012). Pelagic conglutinates resemble small insect larvae or other invertebrates and are expelled forcibly from the female into the water column where they enter stream drift and are preyed upon by minnows; this strategy presumably makes them vulnerable to predation by sight-feeding minnows but reduces their vulnerability to benthic fishes like darters (Haag and Warren 2003; Haag 2012).

**Mucket (*Actinonaias ligamentina*)**

- **Rationale**: The Mucket is among the dominant species in mussel assemblages throughout the Licking River downstream of Cave Run Dam. It remains an abundant and dominant species in the middle and lower river, but it has declined precipitously since the 1980s in the tailwater reach (W. Haag, unpublished data).
- **Tribe:** Lampsilini
- **Reproduction**: The mucket is a long-term brooder (Ortmann 1919). In the New River, WV, gametogenesis began by early October, paused from October to June, and continued until spawning (Jirka and Neves 1982). Sperm is released and eggs are fertilized beginning in mid-August at water temperatures 22–25°C, and females are brooding mature glochidia by mid-September or October (Jirka and Neves 1982; Moles and Layzer 2008). Females brood glochidia over the winter. In the New River, females began releasing glochidia in late March, and release continued until mid-May (Jirka and Neves 1982). Similarly, in Pennsylvania, gravid females were found only until May (Ortmann 1919). However, in the Mississippi River, gravid females were found into July, suggesting a longer release period (LeFevre and Curtis 1912).
- **Host fishes**: Host use of muckets is poorly understood. Thirty-seven fish species in 11 families are reported as hosts, leading to the conclusion that the mucket is a host generalist (summarized in

Williams et al. 2008). However, the strength of evidence supporting glochidial metamorphosis is weak or cannot be evaluated for most sources. Robust metamorphosis is confirmed only on black basses (*Micropterus* spp.), gizzard shad (*Dorosoma cepedianum*), and sauger (*Sander canadensis*), but minnows, suckers, darters, and catfishes did not produce metamorphosis (J. Frommeyer and M. McGregor, unpublished data). **Host infection strategy:** The host infection strategy of the mucket is unknown. Females have no apparent modified mantle lure or other structure, and mature glochidia appear to be released freely and not in conglutinates or mucus; coupled with the species' high fecundity, these observations suggest that the species broadcasts glochidia and relies on chance encounters of glochidia with fishes (Haag 2012).

**Spike (*Eurynia dilatatus, formerly Elliptio dilatata*)**

- **Rationale:** The spike is among the dominant species in mussel assemblages throughout the Licking River downstream of Cave Run Dam. It remains an abundant and dominant species in the middle and lower river, but it has declined precipitously since the 1980s in the tailwater reach (W. Haag, unpublished data).
- **Tribe:** Pleurobemini
- **Reproduction**: The spike is a short-term brooder (Ortmann 1919). In the New River, WV, gametogenesis began in August, mature sperm and eggs were present by September or October, and mature gametes overwintered in males and females (Jirka and Neves 1982). Release of sperm and deposition of eggs in the female gills (i.e., spawning) began in late March at 9–10°C and continued through July. Gravid females were present from mid-April through early July, and mature glochidia were present beginning in May. Glochidia were present in stream drift from late April through early September, but abundance generally was low except for two large peaks, one in early June and another in early July. Similarly, in Pennsylvania, female spike were gravid from mid-May to mid-August, and mature glochidia were found beginning in early June (Ortmann 1919). In Alabama, Alabama spike (*Elliptio arca*) were gravid from late May to late July, and females were brooding mature glochidia beginning in late June (Haag and Warren 2003). Glochidia of Alabama spike were present in stream drift from May to early August (water temperature = 22.5–28.0°C), but abundance was low except during two brief peaks in abundance, one in May and another in July, indicating either synchronous glochidial release during favorable conditions, or production of two successive broods (Culp et al. 2011).
- **Host fishes**: Host use of the spike is unusual in that it shows characteristics of generalists and specialists. Glochidia transform robustly on darters, walleye (*Sander vitreus*), and sauger (*S. canadensis*, all Percidae) as well as black basses (*Micropterus* spp., Centrachidae) (Schroeder et al. 2014). Glochidia also transformed moderately well on American eel (*Anguilla rostrata*), sunfishes (*Lepomis* spp.), and longnose gar (*Lepisosteus osseus*). However, the most robust transformation occurred on Percidae, particularly darters. Transformation did not occur or was low on suckers, catfishes, and most minnows. Other confirmed hosts include sculpins (Cottidae) and gizzard shad (*Dorosoma cepedianum*) (Luo 1993, J. Frommeyer and M. McGregor, unpublished data). The most important hosts in the Licking River are unknown but may be darters, due to their abundance and frequent co-occurrence with spike. Sculpins do not occur in the Licking River downstream of Cave

Run Dam (Burr and Warren 1986). Many other reports of host fish use exist for spike (summarized in Williams et al. 2008), but the strength of evidence supporting glochidial transformation is weak or cannot be evaluated for most sources. Host use of the Alabama Spike (*Elliptio arca*) is similar to the spike, but the former species appears to be a strict specialist on darters (Haag and Warren 2003). **Host infection strategy:** The spike appears to infect fishes largely haphazardly by entangling them in mucus webs containing glochidia. The spike and the related Alabama spike (*Elliptio arca*) have no mantle lures or other modifications and do not release mature glochidia in conglutinates (Haag and Warren 2003; Schroeder et al. 2014; J. Frommeyer and M. McGregor, unpublished observations). Immature glochidia and eggs may be released in aggregations that resemble functional conglutinates, but these structures are not considered to be involved in host infection (i.e., puerile, or non-functional, conglutinates, see Barnhart et al. 2008). Instead, glochidia of both spike and Alabama spike are released in thick mucus strands or webs, which may entangle host fishes as well as reduce the likelihood that glochidia enter the drift, where they may encounter non-suitable hosts such as pelagic minnows (Haag and Warren 2003; Schroeder et al. 2014). Supporting this idea is the observation that glochidia of Alabama spike were less abundant in stream drift than predicted by glochidial production of adults (Culp et al. 2011).

**Flutedshell (*Lasmigona costata*)**

- **Rationale:** The flutedshell is a common and regular member of mussel assemblages throughout the Licking River downstream of Cave Run Dam. It remains widespread and common in the middle and lower river, but it has declined precipitously since the 1980s in the tailwater reach (W. Haag, unpublished data).
- **Tribe:** Anodontini
- **Reproduction**: The flutedshell is a long-term brooder (Ortmann 1919). The mode and timing of reproduction for flutedshell has not been studied in detail, but they appear to be similar to most other species in the tribe Anodontini. In Pennsylvania, release of sperm and fertilization of eggs appear to occur in July or August, gravid females are present by early August, and females are brooding mature glochidia by September. Glochidia overwinter in the female and are released in May; no gravid females were found in June or July (Ortmann 1919). In Minnesota, gravid females collected and returned to the laboratory in early April released glochidia in late May and early June at 21°C (Leonard et al. 2014).
- **Host fishes**: The flutedshell is a host generalist. Glochidial transformation has been confirmed on over 30 fish species in multiple fish families, and most fishes tested produced transformation (Thomason et al. 2013; Hove et al. 2014). Transformation of naturally infected fishes also was observed on minnows and suckers (Leonard et al. 2014). **Host infection strategy:** The host infection strategy of the flutedshell is unknown. It lacks mantle lures or other modifications and does not release mature glochidia in conglutinates (Leonard et al. 2014). Most host generalists in the tribe Anodontini release glochidia in mucus webs (Haag 2012), and this type of release is likely in flutedshell.

**Kidneyshell (*Ptychobranchus fasciolaris*)**

- **Rationale:** The kidneyshell is a common and regular member of mussel assemblages throughout the Licking River downstream of Cave Run Dam. It remains widespread and common in the middle and lower river, but it has declined precipitously since the 1980s in the tailwater reach (W. Haag, unpublished data).

- **Tribe:** Lampsilini

- **Reproduction**: The kidneyshell is a long-term brooder. The mode and timing of reproduction for kidneyshell has not been studied in detail. In Pennsylvania, release of sperm and fertilization of eggs appear to occur in July or August, gravid females were present by early August, and females were brooding mature glochidia by September. Glochidia overwinter in the female and are released as late as August but mainly in late spring and early summer (Ortmann 1919). In a Tennessee population of the fluted kidneyshell (*P*. *subtentus*), females were gravid by late August, developing glochidia began to appear by mid-September, and glochidia presumably overwintered in the females. Fully developed glochidia were present and glochidial release began by the middle of the following May, and all individuals had released glochidia by late June and early July (Davis and Layzer 2012).

- **Host fishes**: A comprehensive study of kidneyshell host use has not been conducted, but it likely is a specialist on darters (Percidae). Glochidial transformation has been reported on fantail darter (*Etheostoma flabellare*) and rainbow darter (*E*. *caeruleum*) (Watters et al. 2009), but methodological details and other information were not provided, and no other fish species appear to have been tested. Fantail darter produces robust transformation in the laboratory (A. Shepard, personal communication). Encysted glochidia of kidneyshell were found on wild greenside darter (*E*. *blennioides*), fantail darter, johnny darter (*E*. *nigrum*), and banded darter (*E*. *zonale*) (White et al. 1996). All other species of *Ptychobranchus* that have been studied (*greenii*, *jonesi*, *occidentalis*, *subtentus*) are strict specialists mostly on darters, and multiple other fish species did not support transformation (Barnhart and Roberts 1997; Haag and Warren 1997, Luo 1993; Davis and Layzer 2012; McLeod et al. 2017). *Ptychobranchus formanianus* and *P*. *subtentus* also appear able to use sculpins (Cottidae) as hosts (Luo 1993; Williams et al. 2008). Sculpins do not occur in the Licking River downstream of Cave Run Dam (Burr and Warren 1986). **Host infection strategy:** Like all *Ptychobranchus*, the kidneyshell releases glochidia in demersal conglutinates (reviewed in Barnhart et al. 1997; Haag 2012; see also McLeod et al. 2017). Demersal conglutinates resemble insect larvae or other prey items of small fishes and remain near the stream bottom after release (Haag 2012). Conglutinates of kidneyshell and other *Ptychobranchus* are complex, intricately pigmented structures that closely resemble insect larvae or pupae, larval fishes, or fish eggs (reviewed in Haag 2012; see also McLeod et al. 2017). The proximal end is strongly adhesive such that it sticks to pebbles or other objects on the stream bottom, making conglutinates vulnerable to benthic darters or sculpins but less vulnerable to pelagic feeding fishes such as minnows (Haag 2012).

Other potential target mussel species: Round hickorynut (*Obovaria subrotunda*), fanshell (*Cyprogenia stegaria*), snuffbox (*Epioblasma triquetra*).

- All three of these species are threatened or endangered under the U.S. Endangered Species Act. The round hickorynut historically occurred throughout the Licking River downstream of Cave Run Dam, but it is now rare in the lower river and relatively large populations exist only in the middle section, particularly near Clay WMA. The snuffbox historically occurred throughout the river downstream of Cave Run Dam, but it persists only as a small population in the middle section of the river near Clay WMA. Both species have declined precipitously in the tailwater reach since the 1980s and it is unknown if they persist there (W. Haag, unpublished data). The fanshell is restricted to the lower and middle river. It occurs as far upstream as the Clay WMA (river mile 145), but large populations exist only in the lower 120 miles of the river.
- All three species are in the tribe Lampsilini, all are long-term brooders, and all are host specialists on darters or sculpins. The reproductive period for all three species is similar to the kidneyshell, which can be considered a surrogate species expected to respond similarly to environmental conditions.

Figures A1 to A5 provide a visual presentation of mussel life histories and associated conditions.

Figure A1. Life histories and associated conditions for longsolid and round pigtoe mussels.

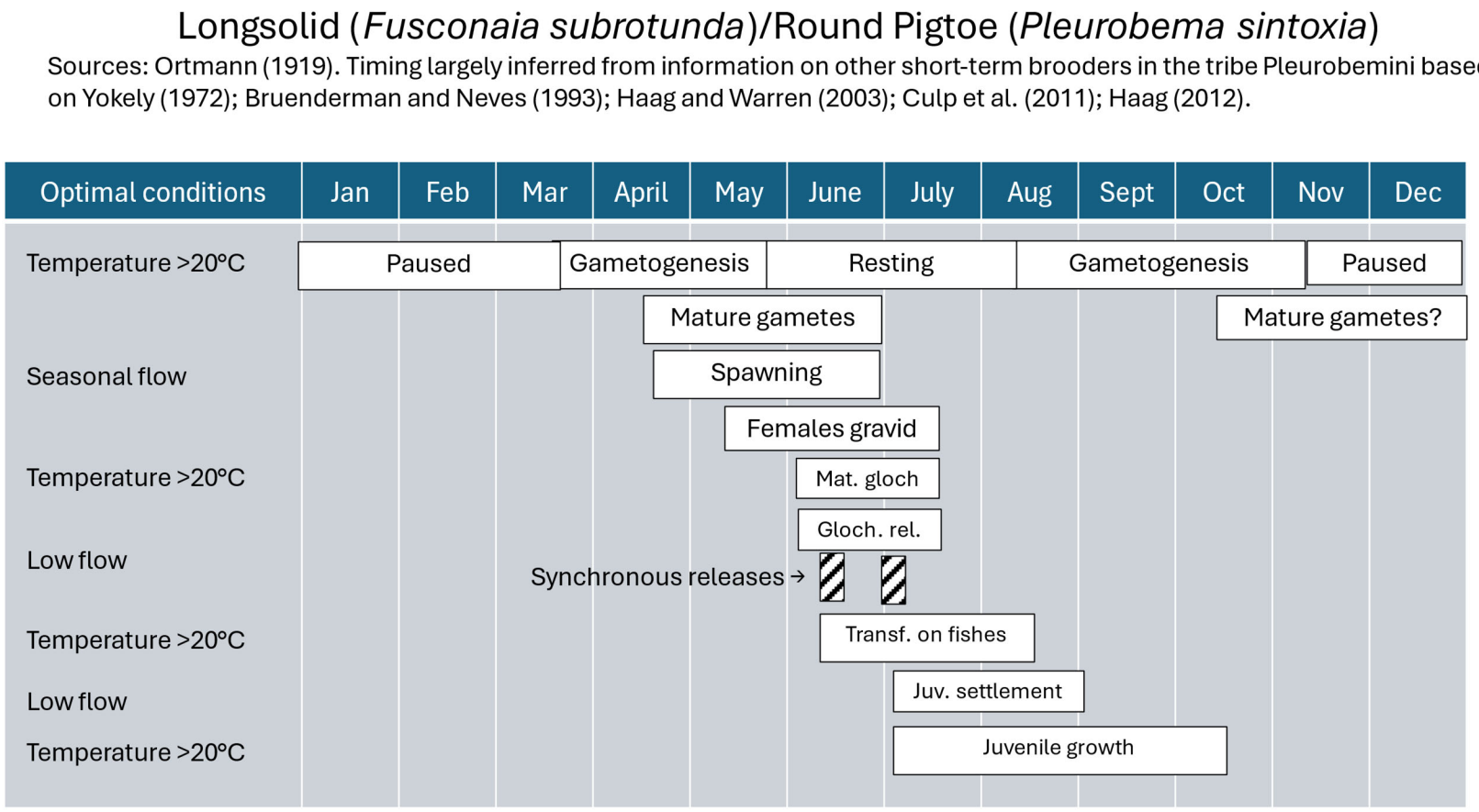

Figure A2. Life histories and associated conditions for spike mussels.

## Spike (*Eurynia dilatata*)

Sources: Ortmann (1919); Jirka and Neves (1982). Timing also inferred from information on other short-term brooders in the genus *Elliptio* or the tribe Pleurobemini based on Haag and Warren (2003); Culp et al. (2011); Haag (2012).

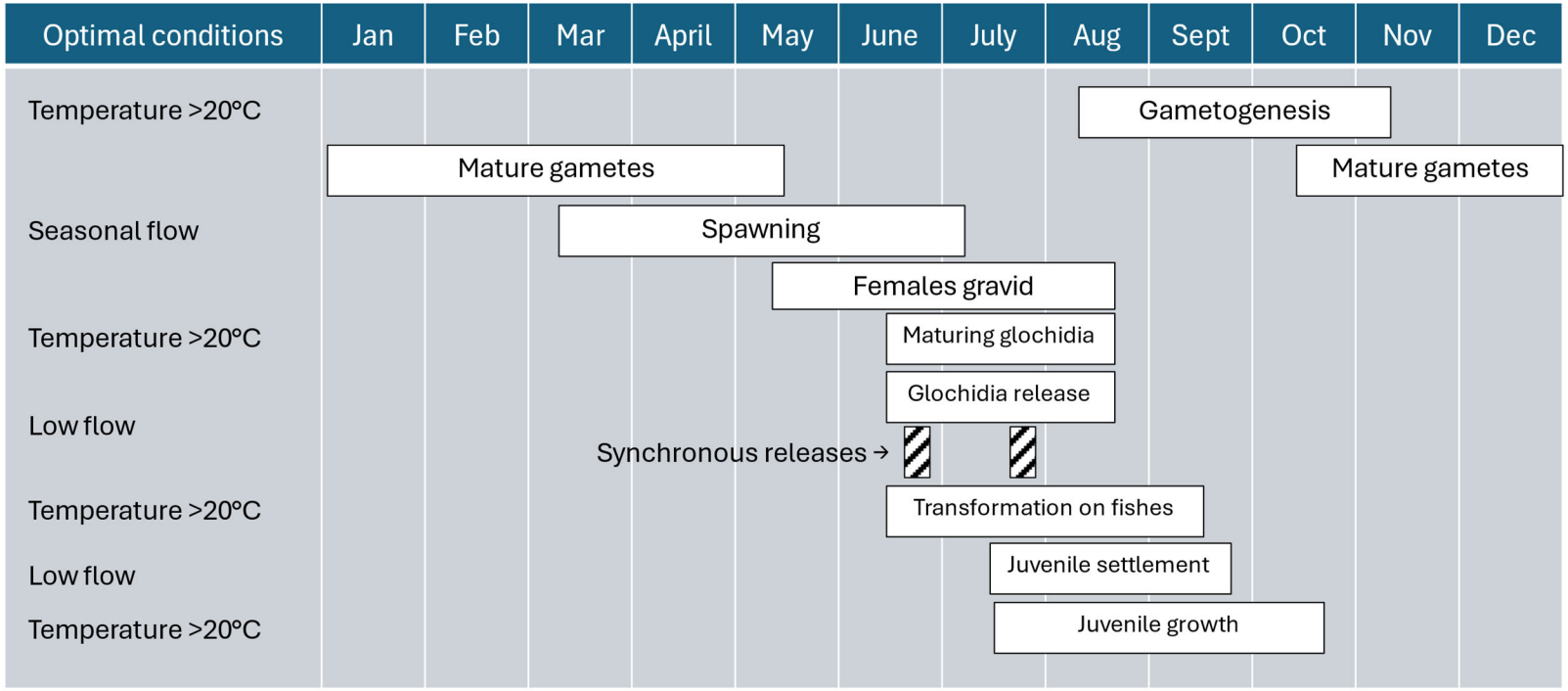

Figure A3. Life histories and associated conditions for mucket mussels.

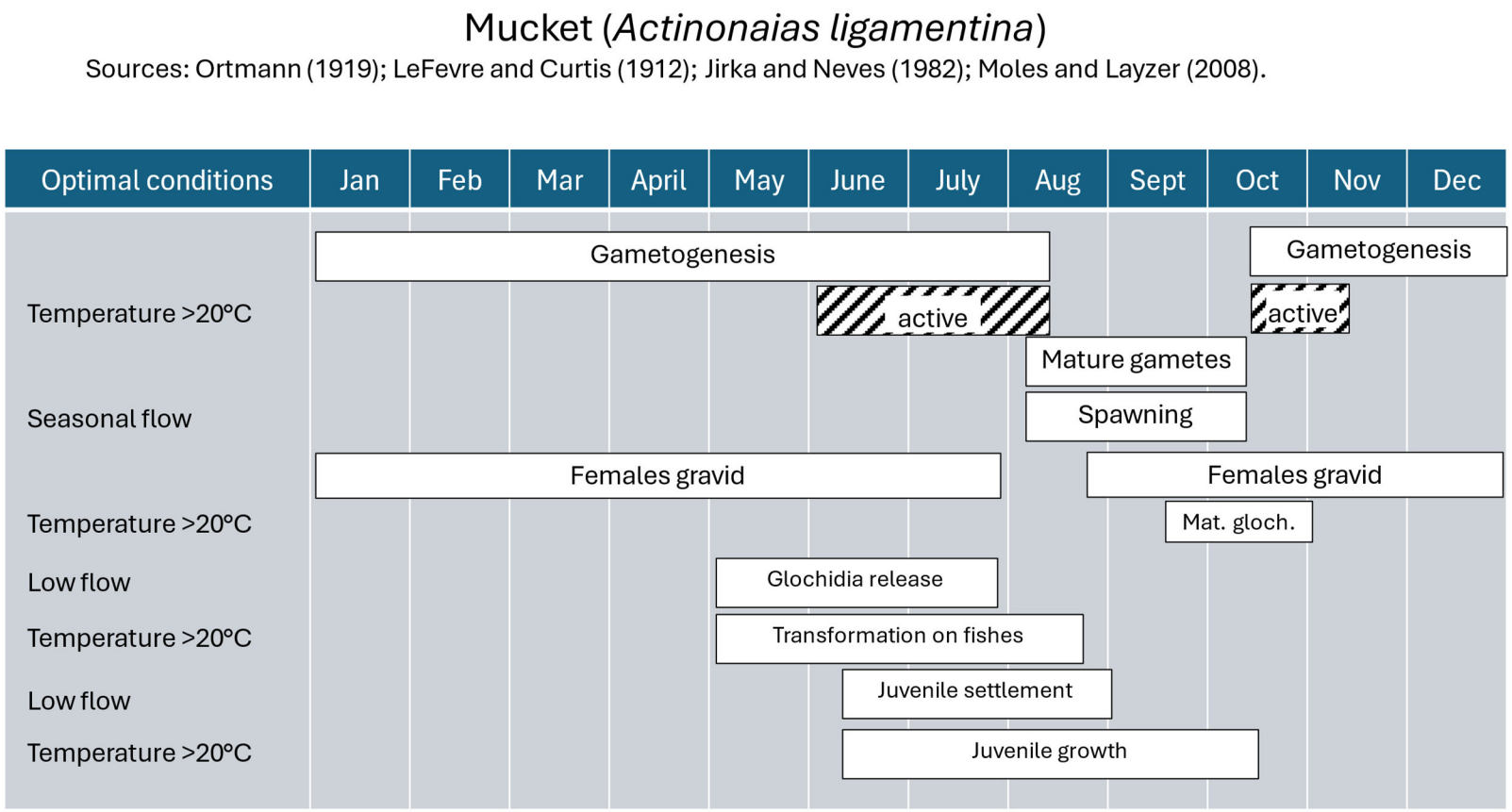

Figure A4. Life histories and associated conditions for flutedshell mussels.

## Flutedshell (*Lasmigona costata*)

Sources: Ortmann (1919); Leonard et al.( 2014). Timing also inferred from information on other long-term brooders in the tribe Anodontini based on Haag (2012).

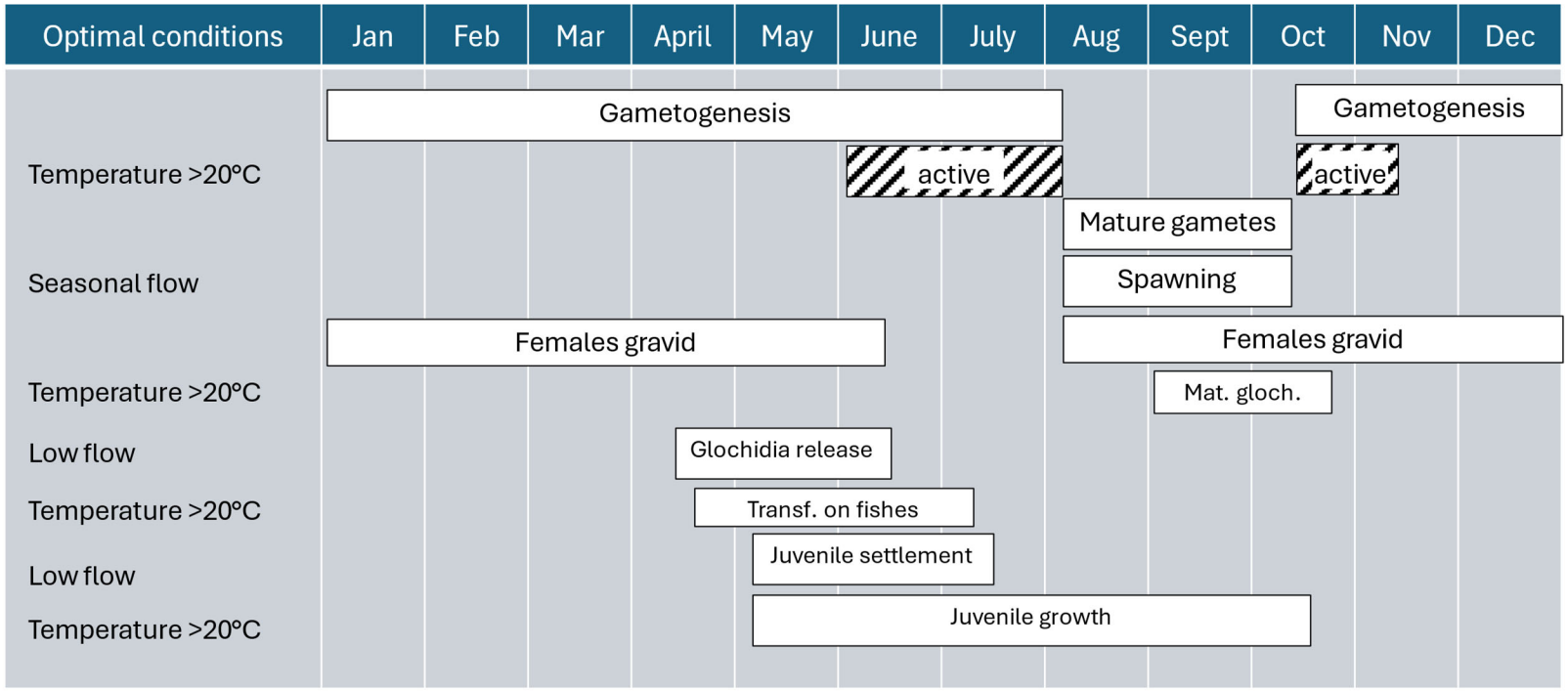

Figure A5. Life histories and associated conditions for kidneyshell mussels.