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# Comparative Analysis of the Bio-Acoustic Fish Fence (BAFF) and Underwater Acoustic Deterrent System (uADS) for Invasive Carp Deterrence at Lock and Dam #5

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**Final Report**

*Approved for public release; distribution is unlimited.*

Prepared for State of Minnesota

Under Project "Evaluation of Acoustics Deterrence in a Lock Approach Channel for Detering Upstream Movement of Invasive Fishes" (CRADA: C-2025-EL-6429).

Monitored by Environmental Laboratory
US Army Engineer Research and Development Center
Vicksburg, MS 39180-6199

# Executive Summary

Invasive carp species (silver, bighead, black, and grass) are progressing upstream in the Upper Mississippi River. Lock and Dam No. 5 (LD05) is a location where the dam gates open less frequently than other locks and dams in this stretch of the Mississippi River within the state of Minnesota's influence. The choice to deploy a deterrent system here will safeguard Minnesota's $1 billion fishery and ecosystem. This report provides a comprehensive engineering, biological, and decision-science evaluation of two leading deterrent technologies based on workshops and expert advice in the region: the Bio-Acoustic Fish Fence System (BAFF) and the Underwater Acoustic Deterrent System (uADS).

The BAFF system integrates broadband sound (0.1–3 kHz), strobing LED arrays, and pneumatic bubble curtains, achieving 53% in Silver Carp deterrence in full lock passage over a multi-year field trial (Barkley Lock). Its multimodal design reduces habituation and permits nearly complete passage of native species such as Freshwater Drum, Smallmouth Buffalo, though results indicated an impact on Paddlefish full lock passage (43% reduction). The uADS system delivers complex acoustic beams through submerged weldments, achieving 61% in Silver Carp, 75% Grass Carp and no change in Bighead carp full passage (Lock and Dam No. 19) at lower cost and with simpler installation, but lacks multimodal redundancy.

The site-specific design recommends a deployment approach that encourages operation flexibility:

- Deployment of the uADS lock approach channel, where the carp challenge the i-wall of the approach channel, at a low slope angle for several identified reasons

- Deployment of an air-bubble curtain or second uADS at a low slope angle for several identified reasons

An "unofficial" estimated cost for the first installation is $3.8M US (±15%), with implementation phased over winter closures from 2027 to 2029. This is a preliminary planning-level estimate (±15%) subject to final USACE cost engineering. A Real Estate Agreement is anticipated along with an Endangered Species Act (ESA) Section 7 clearance which should be supported by surrogate audiogram data.

Lastly, we highly recommend for this LD05 several lines of effort:

- Removal options to be pursued as LD05 is a preferred location for invasive carp deterrence in Minnesota and the upper Midwest against invasive carp.

- Follow-on analysis focuses on carbon dioxide and a second culvert deterrent option.

- Follow-on analysis focuses on several options for when the dam is in open river conditions to examine deterrents that are used for these infrequent, yet severe conditions.

- The monitoring plan should incorporate an NLT 12-receiver array, and possible monthly environmental DNA (eDNA) sampling, and real-time adaptive acoustic signal modulation.

# Acknowledgements

We extend our sincere thank you to the Minnesota Department of Natural Resources (MN-DNR) for its leadership in protecting the Upper Mississippi River and Great Lakes ecosystems from invasive carp. MN-DNR collaborators **Grace Loppnow, Carli Wagner, Kelly Pennington, Mike Noreen, and Heidi Wolf.** We appreciate the US Army Corps of Engineers (USACE), especially the St. Paul District team (MVP)— **Lee Ann Glomski, Lief Johnson, Geoffrie Kramer, Michelle Processor, Elliot Stefanick, and Nathan Wallerstedt**—and the Lock and Dam No. 05 team— **Lock Master Judy Denzer and Shift Head Dylan Duellman**— for their site-specific assessments. And to MN-DNR and MVP for their partnership through the Cooperative Research and Development Agreement (CRADA), which enabled detailed evaluations of the Bio-Acoustic Fish Fence System (BAFF) and Underwater Acoustic Deterrent System (uADS). Foundational field trials and performance data were provided by MN-DNR, the US Army Engineer Research and Development Center (ERDC), US Fish and Wildlife Service (USFWS), and US Geological Survey (USGS), including multi-year evaluations of the BAFF at Barkley Lock, the uADS at Lock and Dam NO. 19, the Electric Dispersal Barrier System (EDBS), and the ongoing design of the Brandon Road Interbasin Project (BRIP) managed by Rock Island (MVR), Chicago (LRN) and now Detroit (LRE) Districts. Their rigorous research has been essential in advancing deterrence strategies that minimize impacts on native species.

# Contents

# Report Documentation Page

# Figures

# Tables

# Preface

This study was conducted for the State of Minnesota, Department of Natural Resources, under the project agreement, C-2025-EL-6429, titled "Evaluation of Acoustics Deterrence in a Lock Approach Channel for Deterring Upstream Movement of Invasive Fishes".

The work was performed by the Water Quality & Contaminant Modeling Branch (EPW) of the Environmental Processes and Engineering Division (CEERD-EP) within the Environmental Laboratory (EL), US Army Engineer Research and Development Center (ERDC).

At the time of publication, the EPW Branch Chief was Dr. Brooke Stevens (EPW), and the EP Division Chief was Mr. Warren Lorentz. The Deputy Director of ERDC-EL was Dr. Brandon J. Lafferty, and the Director of ERDC-EL was Dr. Edmond J. Russo.

# Unit Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| acres (ac) | 4,046.873 | square meters ($m^2$) |
| atmosphere (standard) (atm) | 101.325 | kilopascals (kPa) |
| bars (b) | 100 | kilopascals (kPa) |
| cubic feet ($ft^3$) | 0.028 | cubic meters ($m^3$) |
| cubic inches ($in^3$) | 1.639 E-05 | cubic meters ($m^3$) |
| cubic yards ($yd^3$) | 0.765 | cubic meters ($m^3$) |
| dB re 1µPa | | dB re 20µPa |
| degrees (angle) (deg; °) | 0.017 | radians (rad) |
| degrees Fahrenheit (°F) | (°F-32)/1.8 | degrees Celsius (°C) |
| feet (ft) | 0.3048 | meters (m) |
| foot- pounds force (lbf) | 1.3568 | joules (J) |
| gallons (gal) | 3.785 E-03 | cubic meters ($m^3$) |
| hectares (ha) | 1.0 E+04 | square meters ($m^2$) |
| horsepower (hp) | 745.700 | watts (W) |
| inches (in) | 0.025 | meters (m) |
| inch- pounds (force) | 0.113 | newton meters (Nm) |
| knots (kn) | 0.514 | meters per second (m/s) |
| megapixel (MP) | | pixel (px) |
| microinches (µin) | 0.025 | micrometers (µm) |
| microns (µm) | 1.0 E-06 | meters (m) |
| miles (mi) | 1,609.347 | meters (m) |
| miles per hour (mph) | 0.447 | meters per second (m/s) |
| ounces (mass; oz) | 0.028 | kilograms (kg) |
| ounces (fluid; oz) | 2.957 E-05 | cubic meters ($m^3$) |
| parts per billion (ppb) | 1.0 E-06 | parts per million (ppm) |
| pints (pt) | 4.732 E-04 | cubic meters ($m^3$) |
| pints (pt) | 0.4736 | liters (L) |
| pounds (force; lb) | 4.448 | newtons (N) |
| pounds (force) per foot | 14.594 | newtons per meter (N/m) |
| pounds (force) per inch | 175.1268 | newtons per meter (N/m) |
| pounds (force) per square foot | 47.880 | pascals (Pa) |
| pounds (force) per square inch | 6.895 | kilopascals (kPa) |

| Multiply | By | To Obtain |
|---|---|---|
| pounds (mass) (lb) | 0.454 | kilograms (kPa) |
| pounds (mass) per cubic foot (lbs/ft$^3$) | 16.018 | kilograms per cubic meter (kg/m$^3$) |
| pounds (mass) per cubic inch (lbs/in$^3$) | 2.758 E+04 | kilograms per cubic meter (kg/m$^3$) |
| pounds (mass) per square foot (lbs/ft$^2$) | 4.882 | kilograms per square meter (kg/m$^2$) |
| pounds (mass) per square yard (lbs/yd$^2$) | 0.542 | kilograms per square meter (kg/m$^2$) |
| quarts (qt) | 9.464 E-04 | cubic meters (m$^3$) |
| square feet (ft$^2$) | 0.093 | square meters (m$^2$) |
| square inches (in$^2$) | 6.452 E-04 | square meters (m$^2$) |
| square miles (mi$^2$) | 2.589 E+06 | square meters (m$^2$) |
| square yards (yd$^2$) | 0.836 | square meters (m$^2$) |
| yards (yd) | 0.914 | meters (m) |

# Acronyms

| | |
|---|---|
| ABCD | automatic barge clearing device |
| ABCs | air bubble curtains, Fish Guidance Systems |
| AIS | automatic identification system |
| BAFF | bioacoustic fish fence, Fish Guidance Systems |
| BRIP | Brandon Road Interbasin Project |
| BRLD | Brandon Road Lock and Dam |
| $CO_2$ | carbon dioxide |
| CSSC | Chicago Sanitary and Ship Canal |
| EDBS | electrical dispersal barrier system |
| eDNA | environmental DNA |
| EIS | environmental impact statement |
| EL | Environmental Laboratory |
| ERDC | United States Army Engineer Research and Development Center |
| ESA | Endangered Species Act |
| FPS | feet per second |
| GIS | Geographic information systems |
| GLRI | Great Lakes Restoration Initiative |
| IC | Invasive Carp |
| ICRCC | Invasive Carp Regional Coordinating Committee |
| LBD | longitudinal bubble deterrent |
| L19 | Lock No. 19 |
| LD | Lock and Dam No. |
| LD05 | Lock and Dam No. 05 |
| LED | light-emitting diode |
| KPI | key performance indicator |
| MICAP | Minnesota Invasive Carp Action Plan |
| MICMRP | Minnesota Invasive Carp Monitoring and Response Program |
| MILs | modulated intense lights, Fish Guidance Systems |
| MSL | mean sea level |
| MN-DNR | Minnesota Department of Natural Resources |
| MUM | Modified Unified Method |
| MVP | St. Paul District, USACE |
| MVR | Rock Island, USACE |
| NEPA | National Environmental Policy Act |
| NIOSH | National Institute for Occupational Safety and Health |
| NOAA | National Oceanic and Atmospheric Administration |
| NSD | non-structural device |
| O&M | Operations and maintenance |
| OSHA | Occupational Safety and Health Administration |
| ROV | remote-operated vehicle |
| RDT&E | research, development, test and evaluation |

| | |
|---|---|
| SPA | sound projector array system, Fish Guidance Systems |
| T&E | threatened and endangered species |
| TRL | technology readiness level |
| TTS | temporary threshold shifts |
| WI-DNR | Wisconsin Department of Natural Resources |
| WIIN | Water Infrastructure Improvements for the Nation Act |
| WRDA | Water Resources Development Act |
| uADS | underwater acoustic deterrent system |
| UMR | Upper Mississippi River |
| UMRR | Upper Mississippi River Restoration |
| USCG | US Coast Guard |
| USACE | US Army Corps of Engineers |
| USFWS | US Fish and Wildlife Service |
| USGS | US Geological Survey |

# 1. Introduction

## 1.1 Background

Freshwater ecosystems are particularly vulnerable to human activities (e.g., water pollution, water extraction, aquatic and riparian habitat degradation, river regulation, and flow alterations) and, more recently, to rapid and extreme weather changes, which are responsible for increased frequency and magnitude of drought and flood events. Historically, river fragmentation due to river regulation has reduced river connectivity, leading to decreased flow, increased flow variability, conversion of lotic to lentic habitat, lowered habitat quality, and reduced habitat heterogeneity (Parasiewicz et al. 2016).

The US Army Corps of Engineers (USACE) is the primary federal agency responsible for building, operating, and managing civil works projects that aim to improve navigation, mitigate flood and storm damage, and restore ecosystems (CRS IF11666; EO 13751; PL 116-9, PL 116-188, PL 16 USC 661 et seq; WRDA 2022). While not the sole cause of native fish declines, lock-and-dam infrastructure has undeniably contributed to habitat loss for federally endangered and threatened species such as paddlefish, lake sturgeon, and Higgins' eye pearly mussel (Frett et al. 2025, Turney et al. 2022, USFWS 2004).

Superimposed on these long-term stressors is the rapid spread of aquatic invasive species (AIS). The introduction of AIS (e.g., bigheaded carps, zebra mussels, hydrilla, and sea lamprey) is a stressor to native aquatic species that can exacerbate existing habitat issues. Without significant competition and predation, invasive species can spread quickly and disrupt entire ecosystems by competing for resources, preying on other species, restructuring food webs, and causing secondary and tertiary impacts (e.g., increased turbidity and human health issues). Changes in AIS density or spread can take years in stable habitats, but environmental perturbations, such as river fragmentation or climatic events, can rapidly favor AIS (Beric and MacIsaac 2015). The economic costs of AIS are substantial, with studies estimating annual damages exceeding $100 million in the Great Lakes region (Lauber et al. 2020). Additionally, AIS can hinder civil works projects, damage infrastructure, and affect flood risk, hydropower, and water supplies. AIS can cause long-term environmental, structural, human welfare, and economic impacts.

To mitigate the impacts of AIS, considerable effort has been invested in preventing AIS range expansion without impeding commercial and recreational vessel travel, lock operations safety, and preserving the natural environment. The USACE allocated an estimated $165 million for AIS activities in fiscal year 2020 and $237 million in fiscal year 2022, compared with an estimated annual federal agency spending of $2.3 billion overall. The costliest invasive species affecting the USACE missions are invasive carp (IC), zebra and quagga mussels, sea lamprey, and round goby. Among the methods used by the USACE to control IC spread is the electrical dispersal barrier (“e-barrier” or EDBS), which is the only non-structural deterrent (NSD) with over 15 years of Research, Development, Test, and Evaluation (RDT&E) at Technology Readiness Level (TRL) 9 or higher (Woodley et al. 2025). The USACE EDBS in the Chicago Sanitary and Ship Canal (CSSC) in Romeoville, IL, were designed to prevent the migration of AIS fish between the Mississippi River and Great Lakes basins; however, they pose significant risks to navigation and human welfare and require considerable maintenance costs.

In the area of USACE RDT&E, innovative technologies such as Underwater Acoustics (uADS), Carbon Dioxide ($CO_2$), Lights, Automatic Barge Clearing Device (ABCD), and Longitudinal Bubble (LBD) deterrents are being deployed on a large scale to deter IC effectively. These technologies are specifically designed to combat IC, including bighead carp (*Hypophthalmichthys nobilis*), silver carp (*H*. *molitrix*), grass carp (*Ctenopharyngodon idella*), common carp (*Cyprinus carpio*), and black carp (*Mylopharyngodon piceus*). Emphasizing the impact of NSDS on the *environment, human safety, navigation, and deterring efficiency,* these innovative deterrents are vital in controlling the spread of IC. While they may currently appear less effective than existing EDBS, their potential to slow down the spread of IC is significant. However, due to their technological maturity levels (TRL 5-8), there is a need for more data on physics-based processes, structural elements, non-targeted biological impacts, and installation, operations, and maintenance (O&M) costs.

Managing native, threatened, and endangered (T&E) species and AIS in complex habitats and around infrastructure is an ever-present, complex issue, as native species require habitat connectivity. In contrast, IC needs an active deterrent (disrupted connectivity). Where NSDs are a feasible option providing selective fish passage, in this case for IC management, managers can mitigate the impacts of habitat fragmentation and the effects on T&E and other desirable fish species. There is growing interest in further developing the use of physiological and behavioral stimulants as an approach to control and influence AIS, while limiting impacts on T&E and native species. This requires the development of technology to elicit sensory or physiological responses shared by an AIS species or a group of fish (Noatch and Suski 2012). Since NSDs tend to target altered behavior, the primary response variable often is movement-based.

NSDs are often not 100% effective at blocking AIS. The efficacy of NSDs typically ranges from 60-95% due to differences in deployment equipment, locations, and site-specific challenges (Noatch and Suski 2012; Jones et al. 2021; Cupp et al. 2023; Woodley et al. 2024). The efficacy of NSDs varies with the sensory capabilities of fish species, changes within population dynamics and life history patterns, and with the fish's experiences (i.e., learning) (Noatch and Suski 2012; Holliman 2011; Woodley et al. 2024). Thus, it is critical to evaluate the response of multiple species and life stages to understand the whole ecosystem impact of NSDs.

Because NSDs are rarely 100% effective and because native threatened and endangered species require upstream–downstream connectivity, any deterrent deployed at Lock and Dam No. 05 (herein as LD05) must be selective: it should strongly repel invasive carp, while allowing safe passage of paddlefish, lake sturgeon, walleye, and other desirable natives. This selectivity is possible because invasive carp possess unusually sensitive hearing in the frequency range targeted by uADS and BAFF systems, whereas most Upper Mississippi River natives do not have the capability to hear higher frequency ranges. The challenge at LD05 is therefore clear: design, permit, fund, and construct a high-efficacy, low-risk, navigation-compatible, and environmentally selective non-structural deterrent before invasive carp establish self-sustaining populations upstream. The multi-deterrent Bioacoustics Fish Fence (BAFF) and underwater Acoustics Deterrent System (uADS) are currently the top alternatives, with a proposed placement in the LD05 downstream lock approach.

## 1.2 Purpose

This report reviews the proposed UMR design, installation, and assessment of invasive carp deterrents at LD05. While removal technologies are in the conservation plan, we have not included it in this report due to scope and limitations to meet MN-DNR timelines.

This report is not scoped for recommendations on culverts and dam deterrents. However, based on the data and analyses within this report, we highly recommend the following to be further pursued:

- *Removal options to be pursued as LD05 is a preferred location for invasive carp deterrence in Minnesota and the upper Midwest against invasive carp.*

- *Follow-on analysis focuses on carbon dioxide and a second culvert deterrent option.*

- *Follow-on analysis focuses on several options for when the dam is in open river conditions to examine deterrents that are used for these infrequent, yet severe conditions.*

- *The monitoring plan should incorporate a 12-receiver array for fish implanted surgically with an active transmitter, possible weekly/monthly environmental DNA (eDNA) sampling for abundance above and below LD05 to better guide management, and real-time adaptive signal modulation. The deterrent efficacy target is at 50% deterrence with less than 5% native species avoidance.*

This report is expected to evolve as the State of Minnesota Department of Natural Resources (MN-DNR), US Fish and Wildlife Service (USFWS), US Geological Survey (USGS), and US Army Corps of Engineers (USACE) teams examine placement and data at a more detailed level. The MN-DNR LD05 invasive carp prevention and management program will be further developed to evaluate the program's effectiveness with the development of the deterrent and therefore is not included in this report. Collaboration with partners include the Wisconsin DNR (WI-DNR), US Fish and Wildlife Service (USFWS), US Geological Survey (USGS), and US Army Corps of Engineers (USACE).

## 1.3 Invasive Carp Progression Timeline for Upper Mississippi River

Below is a brief review of the overarching efforts that are on-going or have been completed to address the movement of Invasive Carp into the Upper Mississippi River. Much of this information has been pulled into this report to provide the basis of our analyses (compiled from MN-DNR records; Accessed 2025 NOV 21: www.dnr.state.mn.us/invasives/ais/carp/index.html; www.mndaily.com, www.stcroix3360.com; and www.lccmr.mn.gov).

The history of invasive carp in Minnesota begins with the first accidental introductions, but coordinated statewide response did not truly initiate until the 2010s. In 1977, the first Grass Carp is reported in Minnesota, found in a private pond near Winona. In 1996, the first Bighead Carp is discovered in Lake St. Croix. Finally, in 2008, the first Silver Carp is confirmed in Minnesota, captured in Pool 8 of the Mississippi River.

In response to these early detections, Minnesota established a formal program in 2011, beginning with the Minnesota Invasive Carp Action Plan (MICAP). This plan created a structured, step-by-step approach focused on early detection, prevention, deterrence, response, management, and public outreach. In April 2012, the

Minnesota Department of Natural Resources (MN-DNR) hired a dedicated invasive fish consultant to lead these prevention and control efforts. In July 2012, the Minnesota Invasive Carp Monitoring and Response Program (MICMRP) was developed, supported by the first Legislative-Citizen Commission on Minnesota Resources -Environment and Natural Resources Trust Fund grants (Accessed 2025 Nov 12; www.lccmr.mn.gov). The program prioritized commercial fishing contracts, targeted sampling, public reporting, tagging and tracking, and testing new removal strategies.

In 2014, the MICAP was significantly updated with input from state, federal, local, and nongovernmental partners. In June 2015, federal legislation led to the permanent closure of the Upper St. Anthony Falls Lock in Minneapolis, restoring a historic natural barrier and preventing further upstream movement toward the Mississippi headwaters. In 2016, five physical deterrents were installed in the Little Sioux River watershed. The following year, the MN-DNR conducted a movement study involving invasive carp, specifically bighead carp, which required state regulations to amend regulations for tracking fish and facilitated the removal of seven additional carp.

Research studies and new removal efforts accelerated in the late 2010s and early 2020s. In 2018, two significant studies were completed: one assessed the feasibility of an acoustic deterrent at Lock and Dam No. 05 and another focused on hydrology for management opportunities. In 2019, a final report was released on fish passage through Locks and Dams 2 and 8, indicating that high-water events in April and May facilitated upstream migrations of invasive carp and recommended that the dam undergo "open river" operations. In 2020, commercial fishing efforts removed 51 invasive carp from Pool 8 in a single event. That same year, the MN-DNR hosted an “Invasive Carp Data Dive” to review the status, science, and coordination across programs. In 2021, the first of the spring and fall Modified Unified Method (MUM) removal efforts captured 31 silver carp in Pool 8. This effort occurred for a few years but have stopped in recent years. In 2022, the USGS completed the FluEgg modeling for the lower St. Croix River, examining the potential survival and development of invasive carp eggs and larvae if spawning occurred there.

In 2024, MN-DNR updated the MICAP based on 2023 structured decision-making process, and LD05 was identified as a location of interest for a deterrent; and spearheaded the LD05 Invasive Carp Deterrent Project, funded by a $12 US million appropriation by the Minnesota Legislature from the state's Outdoor Heritage Fund. This project is a collaborative effort involving multiple agencies, including the US Army Corps of Engineers (USACE), the US Fish and Wildlife Service

(USFWS), the US Geological Survey (USGS), the Wisconsin Department of Natural Resources (WI-DNR), and others. The goal is to design, install, and monitor a selective deterrent system by June 30, 2029.

The primary technology employed is a sound-based deterrent, such as either an underwater Acoustic Deterrent System (uADS) or a Bubble Barrier and Fish Filter (BAFF). These systems will be placed at the downstream entrance of the lock chamber. They emit sounds, bubbles, and lights to create an aversive environment specifically targeting the auditory sensitivities of invasive carp, while having a lesser effect on native species, such as walleye and bass. The inclusion of lights and bubbles affects the vision and lateral line senses of all fish, making it less specific than the underwater acoustic emissions.

Additionally, the project may incorporate a "trap and sort" mechanism to attract invasive carp and other fish into a containment area for removal, while allowing the selective passage of native species. Other efforts are also pursued under separate funding lines, though complimentary to this effort. One example is the enhanced commercial fishing operations below LD05 to help reduce invasive carp populations and ongoing discussions to develop deterrents for the six roller gates and 28 tainter gates, which together span over 1,600 feet and present a significant risk for fish passage during floods.

In July 2024, in effort to organize and develop a design for LD05, an interagency team was assembled, and fish tagging and acoustic telemetry monitoring initiated in May 2025 to track invasive carp movements. In 2025, a Cooperative Research and Development Agreement with the USACE's Engineer Research and Development Center (ERDC) was signed to assess feasibility, and with St. Paul District (USACE) finalize designs in 2026, paving the way for construction.

## 1.4 Legislative Drivers

Lock and Dam 5, located near Minnesota City, MN, serves as a critical barrier against the advance of invasive carp into Pools 4–1, as well as the St. Croix and Minnesota Rivers, and the headwaters of the Mississippi River. The potential ecological and economic damage caused by invasive carp could exceed $4 billion (https://www.mprnews.org/story/2012/06/08/report-adds-up-economic-harm-from-carp-spread). Federal and state legislation establishes clear mandates, funding sources, and authorities for the design, construction, and operation of an NSD system at LD05. These initiatives prioritize prevention over response (i.e., capture them after entering the area) and employ multimodal NSDs while maintaining navigational access and allowing passage for native species (https://fmr.org/updates/water-legislative-land-use-planning/2024-legi-session-invasive-carp).

The Water Infrastructure Improvements for the Nation (WIIN) Act (P.L. 114-322, 2016) authorizes the US Army Corps of Engineers (USACE) to enhance measures against aquatic invasive species (AIS), specifically targeting the spread of invasive carp in the Upper Mississippi and Ohio Rivers through means beyond traditional electric deterrents. (Accessed on 2025 Nov 07: www.congress.gov/114/plaws/publ322/PLAW-114publ322.pdf). Sections 1123 and 506 establish a regional AIS prevention program, funding research, development, and deployment of innovative NSDs (including acoustic devices and bubble curtains) at high-risk sites like LD05. It also mandates interagency coordination between USACE, US Geological Survey (USGS), and the US Fish and Wildlife Service (USFWS), while prioritizing deterrents that minimize navigation disruptions and impacts on endangered species. The WIIN Act enables USACE to incorporate LD05 into the broader Great Lakes protection and restoration frameworks. Without this act, USACE would lack the authority to implement NSDs at LD05.

The Great Lakes Restoration Initiative (GLRI), authorized under the Water Resources Development Act (WRDA) and funded annually, supports AIS prevention across the Great Lakes basin, which includes Upper Mississippi River (UMR) pinch points like LD05. (Accessed on 2025 Nov 07: www.glri.us; www.whitehouse.gov/presidential-actions/2025/05/protecting-the-great-lakes-from-invasive-carp/). The GLRI Action Plan IV (2021–2025) allocates $21 million per year for invasive carp control, emphasizing telemetry monitoring, environmental DNA (eDNA) surveillance, and pilot programs for deterrents. It requires deterrents to meet a minimum efficacy of 90% and promotes adaptive management to protect native species such as paddlefish and sturgeons.

Additionally, Minnesota Laws 2024, Chapter 106 (from House File 4124) appropriates $12 million from the Outdoor Heritage Fund to the Department of Natural Resources for the project “Protecting Upper Mississippi River from Invasive Carp.” This funding supports the design, construction, and initial operation and maintenance of a structural deterrent for invasive carp at Lock and Dam No. 5 on the Mississippi River. The law requires deterrent design to be completed within two years of the appropriation and installation to be completed by June 30, 2029 (ML 2024, Ch. 106, Art. 1, Sec. 2, Subd. 5(aa)). Accessed May 17, 2026. https://www.revisor.mn.gov/laws/2024/0/Session+Law/Chapter/106/. This state investment complements federal efforts on invasive carp management in the Upper Mississippi River basin. The relevance of Lock and Dam No. 05 is further underscored by this legislation, which directly funds the baseline cost estimate for the hybrid deterrent, including operations and maintenance for 10 years. It builds on the captures of over 30 invasive carp near Winona in 2023 and mandates phased installations during winter to avoid navigation delays (estimated 2,783 average annual LD05 lockages). HF 4124 positions Minnesota as an agency forward thinking to reduce invasive carp passage, collaborating with federal agencies, and indirect support through technology transfer from regional programs.

## 1.5 Why Lock and Dam No. 05 for Invasive Carp Deterrence

Lock and Dam No. 5 (LD05), located on the Mississippi River at river mile 738.1 near Minnesota City, Minnesota (approximately 10 miles northwest of Winona), functions as a critical control structure on the Upper Mississippi River. It serves as a point to limit upstream movement of invasive carp into Navigation Pools 4 through 1, Lake Pepin, and connected tributaries including the Chippewa, St. Croix, and Minnesota Rivers, as well as the Mississippi River reach extending to the Twin Cities metropolitan area.

Recent monitoring has documented increasing captures of adult invasive carp in Pools 5A and 6, including substantial removals during high-water periods agency (https://www.dnr.state.mn.us/invasives/ais/carp/lock-and-dam-5-invasive-carp-deterrent-project.html). Reproduction has not been confirmed in Minnesota waters to date, and thus the position of LD05 makes it a candidate location for deterrent measures. A combination of management actions that include deterrents and removal will be needed to slow invasive carp migration into Minnesota and minimize the impact of the invasive carp that are present in Minnesota (https://files.dnr.state.mn.us/natural_resources/invasives/aquaticanimals/invasivecarp/invasive-carp-action-plan-2024.pdf).

In contrast to some other locks and dams on the Mississippi River, LD05 possesses a design that is inherently challenging for fish to bypass, as it lacks significant side channels or bypasses that would facilitate circumvention. Although implementing a multi-deterrent system is currently beyond the immediate project scope (this report focuses only on the lock approach only of a single deterrent), such an approach would enable the deployment of non-structural deterrents (NSDs) in the lock and spillways without frequent disruptions from flooding events. LD05 comprises 34 gates (including both roller and tainter types), culverts, and a navigation lock chamber (as well as an archived lock chamber), all of which can be retrofitted with NSDs, such as acoustic deterrents in the lock approach, hydraulic modifications to create high-velocity water zones, and $CO_2$ enhancements to culverts. Hydrographic data indicates that LD05 experiences relatively infrequent "open river" conditions, defined as periods of high water when gates are fully open, and fish passage is more likely (waterdata.usgs.gov). When these conditions do occur, they prompt significant upstream movement of invasive carp, as demonstrated by data from comparable sites such as LD15, where nearly half of tagged invasive carp passed through spillway gates during high-flow years (Fritts et al. 2024).

With effective monitoring, targeting, and removal of invasive carp in coordination with the deterrent system, MN-DNR has a forward-thinking approach to minimize the impacts of invasive carp. This integrated approach reduces the risk of spawning and population establishment more effectively than in other pools that lack combined deterrent and active removal efforts. Additionally, designing an invasive carp deterrent to ensure minimal impacts on navigation operations will minimize disruptions to commercial barge traffic—a key consideration for the navigation industry, the U.S. Coast Guard, and the U.S. Army Corps of Engineers.

## 1.6 Expected Challenges of NSDs at LD05

Although recent advancements have been made, significant challenges persist in developing non-structural deterrents (NSDs) to achieve a key performance indicator (KPI) of at least 50% deterrence. This report focuses on the underwater acoustic deterrent system (uADS) and Bioacoustic Fish Fence (BAFF) (which utilizes sound, bubbles, and light) to deter or guide fish. Despite their potential, these technologies have documented limitations and may fail under certain conditions. Drawing on feasibility studies, field trials, and comparable installations, this report details known conflicts and limitations of these systems, categorized as operational, environmental, behavioral, and maintenance. These categories also inform the location assessments presented in this report.

### 1.6.1 Lock Operations

Ensuring compatibility with lock operations is essential to prevent disruption of navigation and lock functionality. System placement must not compromise lock safety, such as by avoiding proximity to lock wall edges, ensuring cables are properly embedded in concrete, and protecting communication and control cables. Long-term funding for maintenance and monitoring will be required beyond the initial structural maintenance appropriation. A formal agreement should be established to address potential damage or issues related to the deterrent, with responsibility assigned to the USACE or MN-DNR.

### 1.6.2 Navigation

Commercial (4–7 daily) and recreational vessels generate noise spikes up to 35-50 dB above ambient levels by 80–110 dB re 1µPa$^2$/Hz between broadband 10-1,000 Hz) and <90 dB re 1µPa/Hz at frequencies > 1,000 Hz (Putland and Mensinger 2019, USGS 2025). The ambient median background sound levels ranged from 50 – 70 dB re 1µPa/Hz across 10–12,000 Hz. Over the total deployment period, broadband SPL (200 – 5,000 Hz) was shown to increase when the lock has vessels passing through and when machinery was in action (such as at the lock gates) at all recording stations (Putland and Mensinger 2019, USGS 2025).

Based on these results, some fish species in the region (both native and invasive) are able to detect vessel sound. In addition, the ambient and commercial navigation may overwhelm deterrent signals within the carp's hearing range (100–6,000 Hz). The BAFF system relies on bubble curtains that can be disrupted by bow waves, docked vessels, propeller turbulence, and barge wakes. Vessel and barge “design”, loading, draft, and water elevation can all influence fish movement. Currently, no peer-reviewed data are available regarding BAFF performance in high-traffic environments such as LD05.

### 1.6.3 High Water

During flood or high-flow periods, dam gates (six roller and twenty-eight tainter gates at LD05) may be fully opened, resulting in open river conditions. Under these circumstances, carp can bypass the lock chamber by passing over or through the spillways, circumventing installed deterrents. Lock chamber discharge and dam gate openings produce noise and elevated bubble and total dissolved gas content, which may render acoustic-based deterrents (BAFF or uADS) ineffective, if positioned near the dam spill gates. Further examination during high-water events is warranted to determine the final design and structure. Although dam tainter full open gate are infrequent, they can persist for several days to weeks, allowing carp to migrate upstream. Elevated water levels can disrupt the uniformity of the bubble curtain, diminish sound containment, and permit fish to traverse weakened sections of the barrier. Frequent adjustments to air flow or compressor settings may be required, which could be impractical during peak navigation seasons.

LD05 features a three-tunnel culvert system (48” metal culverts controlled by sluice gates) and a single 38” metal culvert (controlled by stop logs and closer to LD05) on the Wisconsin side of the river, which is frequently submerged and with flow velocities ranging between 50-300 CFS and 0-70 CFS (respectively, based on 2023 data; Giblin et al. 2025; MN-DNR 2025). Flooding events could connect adjacent wetlands, creating alternative pathways for fish to bypass the dam and lock.

### 1.6.4 Ambient Noise

The ambient soundscape at LD05 fluctuates seasonally, with expected increases of approximately 3 dB re 1µPa SPL RMS (in water) during spring/summer due to anthropogenic and biological activity. Sound generated within the lock approach is subject to significant refraction at the lock walls and the approach sill, followed by rapid signal decay (6 dB per doubling of distance). Deterrent signals must exceed ambient noise by more than 10 dB and possess sufficient intensity to elicit a behavioral response. However, site-specific variables such as depth, flow, and interference may mask deterrent signals. Effective repulsion likely requires output levels of 165–180 dB re 1µPa SPL RMS (in water noting that the water-air transmission is quite low). Proprietary system designs may or may not align with carp auditory sensitivities and may not be tunable to the lock approach, potentially limiting behavioral impact. At related sites, acoustic systems may need to be deactivated during lock maintenance to facilitate communication and minimize temporary threshold shifts (TTS). Prolonged exposure may induce TTS in carp and native fish, reducing responsiveness, though this phenomenon is less studied in carp deterrence. During winter lock closure, NSDs are expected to function at reduced capacity. Cold water may destabilize bubble curtains, diminishing performance. The ability of a bubble curtain to refract and contain sound depends on precise air injection rates; fluctuations in river flow at LD05 can disperse bubbles, scatter acoustic energy, and could reduce deterrence by 20–30% compared to laboratory conditions.

### 1.6.5 Operations and Maintenance

Operation and maintenance costs for these systems are comparatively low compared to those of the CSSC EDBS. Accumulation of algae, sediment, or debris can foul speakers, necessitating visual inspection at least twice annually, with remote-operated vehicle (ROV) inspection considered acceptable. The proposed system requires a continuous power supply and "moist" grounding that well exceeds state and federal standards. Spatial constraints at locks, particularly the short lock approach and limited i-wall length, may necessitate suboptimal system placement, thereby increasing design complexity.

### 1.6.6 Habituation

Limited research exists on invasive carp habituation to repeated deterrent sounds, particularly in response to multiple complex stimuli. Short-term laboratory studies indicate rapid adaptation, and persistent exposure at LD05, such as during migration periods, may reduce system effectiveness over time. Silver carp are capable of jumping over barriers up to 2.24 meters high or following vessels into the lock. Highly motivated adults may disregard deterrent sounds, and low carp densities at LD05 make behavioral testing difficult. Although strategically placed bubble deterrents can enhance or dampen sound deterrence, they may inadvertently attract native species such as channel catfish or provide visual cues that silver carp exploit by jumping, especially when curtain visibility increases in shallow approaches during low water conditions.

In summary, while uADS and BAFF technologies can reduce carp passage by 50–90% under optimal conditions, several uncertainties necessitate adaptive management and, critically, operational flexibility[1]. Implementing adaptive designs, such as integrating gate modifications, is recommended to maximize operational flexibility, mitigate risks, and has demonstrated increased effectiveness, cost reduction, and decreased operations and maintenance requirements in fish passage projects in the Pacific Northwest. The following sections address these limitations, provide a comprehensive examination of the technologies, and offer detailed assessments of each system.

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[1] Operational flexibility refers to the capacity to modify and enhance deployed technologies over the next five to ten years as additional data on fish passage are collected.

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# 2. Site Characterization

## 2.1 Location

Lock and Dam No. 5 (LD05), completed in 1935, serves as a critical low-head navigation structure near Minnesota City, Minnesota (river mile 738.1[2]) (**Error! Reference source not found.**) and is operated by the US Army Corps of Engineers (USACE) St. Paul District. LD05 extends from Winona County, Minnesota, across the river to Buffalo County, Wisconsin. This lock and dam system is vital for maintaining a nine-foot navigation channel, especially during low to moderate river flows (USACE 2025a; USACE 2025b).

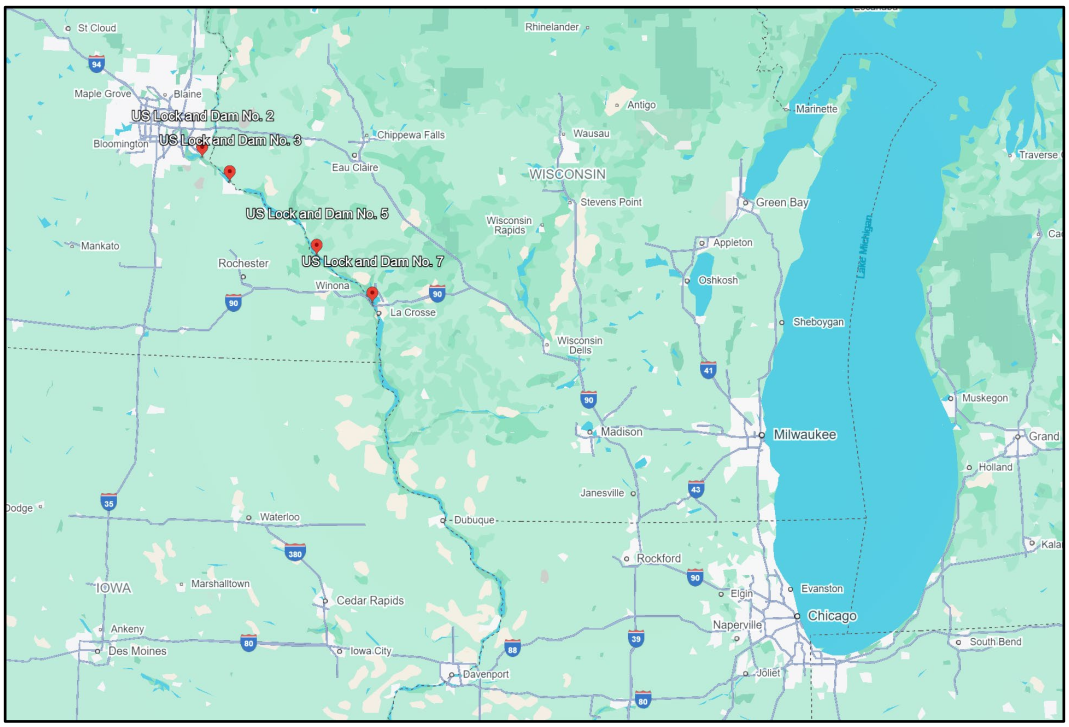


**Figure 2-1. Map of Lock and Dam No. 05 placement within the Upper Mississippi River**.

The dam adjusts to varying river flow conditions through controlled gate operations. Under normal conditions, the gates remain partially open to facilitate water flow, and their openings are modified as river conditions change to maintain target water levels. In the absence of flow in the pool, the water level remains

2 There is a discrepancy on the River Mile and coordinates of Lock and Dam 05. The USACE 2002 Water Control Manual provides River Mile as 715.6, and the coordinates as approximately latitude 44° 9' 42" N and longitude 91° 48' 42" W. The MVP website provides the River Mile referred to in the report and coordinates currently in the report. This is likely due to an older datum or measurement convention.

consistent throughout its length, establishing the "project pool" level that ensures a reliable nine-foot channel depth (further detailed in Section 2.5) (USACE 2002b). The project includes a main lock, an auxiliary lock, a movable dam section, and an earthen dike. Situated on the right bank of the river at approximately latitude 44° 9' 42” N and longitude 91° 48' 42” W, the facility is primarily designed to ensure safe navigation at a depth of nine feet. The authorized purposes of LD05 are navigation and recreation, as established under Public Laws PL 71-250 (1930 Rivers and Harbors Act) and PL 78-534 (1944 Flood Control Act). Although the USACE provides access and facilities for recreational activities, water levels are not managed for recreational purposes. Environmental management is coordinated with the US Fish & Wildlife Service (USFWS), the Minnesota and Wisconsin Departments of Natural Resources (MN-DNR and WI-DNR), and other relevant state and federal agencies, such as the US Geological Survey (USGS) (USACE 2002b, USACE 2025a).

## 2.2 Dam Characterization

The earth dike embankment dam spans 18,219 feet (estimated 5,553.2 m or 3.45 mi) and extends northwest from the removable dam section to the high ground on the Wisconsin side of the river. The elevation of the dam crest varies from 669.6 feet at the dam itself to 671.6 feet at the end of the dike, featuring a top width of 20 feet and a maximum height (USACE 2002b, USACE 2025a, USACE 2025b).

The dam is equipped with 28 tainter gates, each measuring 35 feet by 15 feet, located closer to the Wisconsin riverbank for higher flows and spillway discharge. Additionally, there are six large roller gates, sized 60 feet by 20 feet, that are used for low-flow control in conjunction with the auxiliary and lock chambers. The roller gate sill is set at an elevation of 640 feet, while the tainter gate sill is at 645 feet allowing for an estimated 12 ft head. Both types of gates can be submerged to depths of 3 feet and 2 feet below normal pool levels (657 feet and 658 feet, respectively) (USACE 2002b).

Lock and Dam No. 5 maintains a normal pool elevation of 660.0 feet (201.2 meters) above mean sea level (MSL) in Pool 5A upstream, with a tailwater elevation of approximately 678.6 feet (206.9 m) in Pool 5. This configuration creates a typical hydraulic head of approximately 9.3 feet (2.8 m) (Figure 2-4). The normal project upper pool is at 660 feet, while the lower pool stands at 651 feet, covering about 12,580 acres for a total pool area.

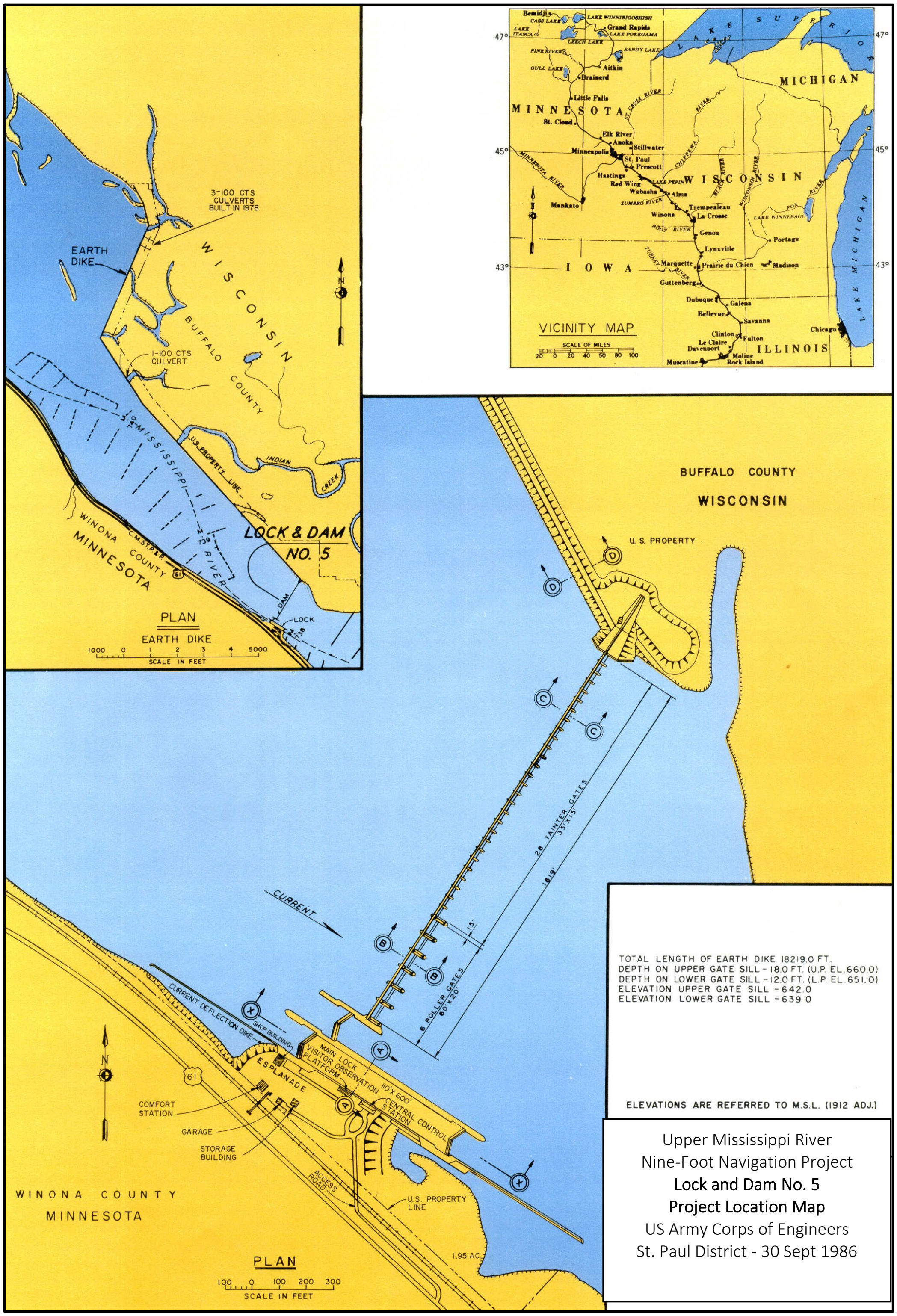


**Figure 2-2. Lock and Dam No. 05 Project Plan.** Plan shows the length of the dike, depth of sills and elevations of sills as planned in 1912 (USACE 2002b).

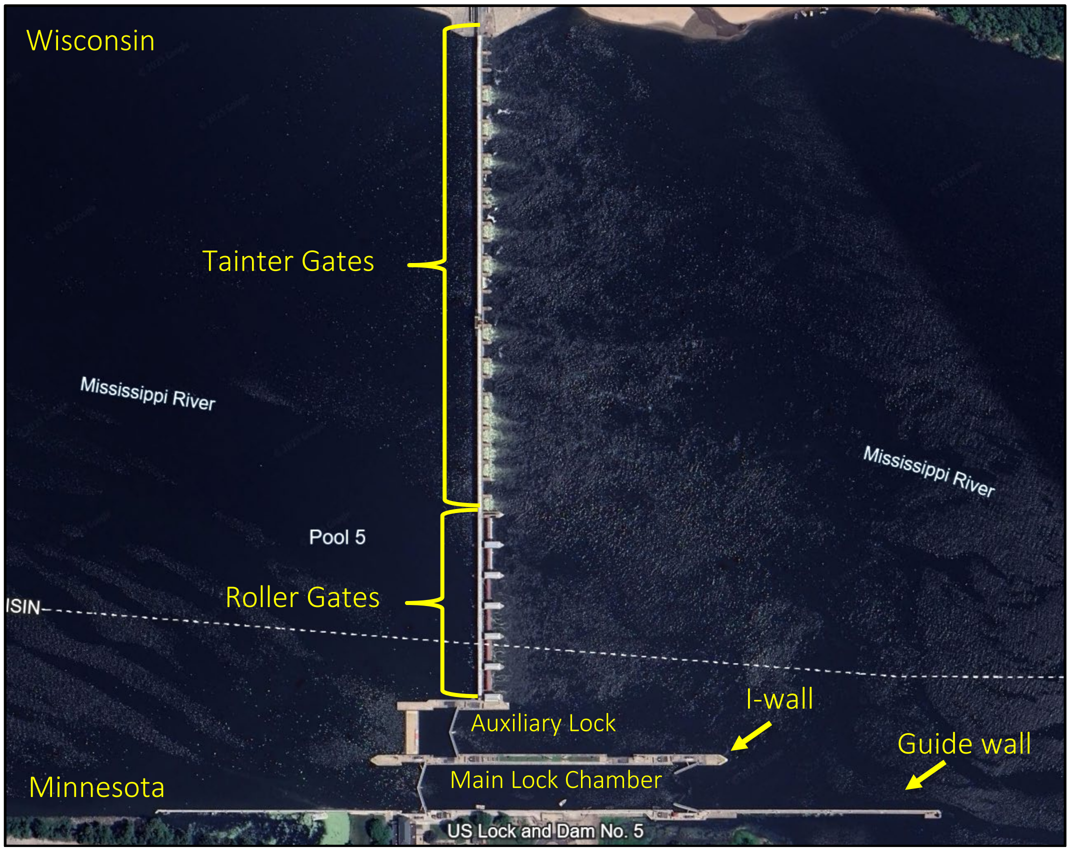


**Figure 2-3. Lock and Dam No. 05 Overview.** Overhead view of the LD05. From top to bottom, the tainter gates are closest to the Wisconsin shore, followed by the roller gates, an auxiliary lock, intermediate wall, main lock, and guidewall on the Minnesota side (Accessed 2025 Nov 01, 2:46 PM ET, www.earth.google.com).

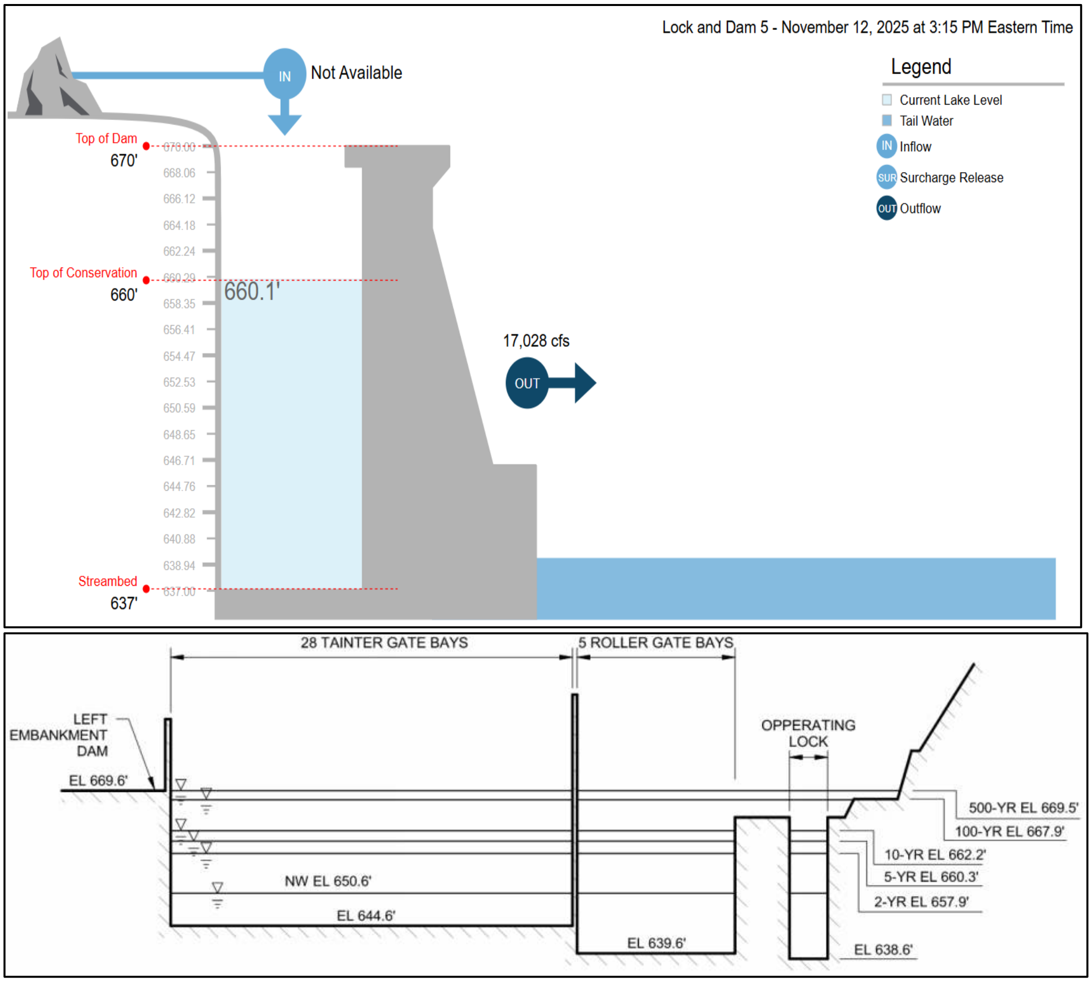


**Figure 2-4. Lock and Dam No. 05 Generalize Schematic.** (TOP) The actual elevations are as follows: Bottom of Conservation 659.5 ft, Bottom of Normal 659.5ft, Streambed 637 ft, Top of Conservation 660ft, Top of Dam 670ft, Top of Normal 660 ft, Bottom of Normal Stage 59.5 ft, Streambed Stage 37 ft, Top of Dam Stage 70ft, Top of Normal Stage 60 ft. (USACE 2025b). (BOTTOM) Please note the bottom figure lists the incorrect number of 6 not 5 roller gates (Barr Engineering 2022).

## 2.3 Main and Auxiliary Lock Characterization

The lock chamber measures 110 ft (33.5 m) in width and 600 ft (183 m) in length, accommodating approximately 10% of the river's cross-section during standard operations (Figure 2-5). The lock walls reach an elevation of 665.0 ft, with the main upper gate sill at 642 ft, the auxiliary gate sill at 639 ft, and the lower gate sill also at 639 ft. The upstream and downstream miter gates are 20 ft and 23 ft in height, respectively, while the auxiliary gate is 23 ft tall. A walkway, located three feet above the miter gates, supports small electric vehicles and enables crossover from the guidewall to the intermediate wall at an elevation of 665 ft (Table 2-1).

**Table 2-1. Lock and Dam No. 05 Dimensions and Characteristics.**

| | |
|---|---|
| Main Lock Chamber | 110 ft by 600 ft |
| Top of Lock Walls | Elevation 665.0 ft |
| Top of Upper Gate Sill (Main) | Elevation 642.0 ft |
| Top of Upper Gate Sill (Auxiliary) | Elevation 639.0 ft |
| Top of Lower Gate Sill: | Elevation 639.0 ft |
| Lock Chamber Floor | Elevation 637.0 ft |
| Height of Upper Miter Gates (Main) | 20.0 feet |
| Height of Upper Miter Gates (Auxiliary) | 23.0 feet |
| Height of Lower Miter Gate (Main)s | 23.0 feet |
| Upper Guidewall Length | 521 feet |
| Lower Guidewall Length | 504 feet |
| Average Filling/Emptying Time | 10 minutes |
| Average Double Lockage Time | 1.5 to 2.0 hours |
| Miter gate walkway weight Limit | *MNP verification required* |

Guidewalls are located upstream and downstream of the lock to provide a landing for downbound and upbound navigation (USACE 2002bError! Reference source not found.). The upper guide wall extends 521 ft upstream of the lock and the lower guide wall extends 504 ft downstream of the lock.

**Figure 2-5. Overhead View of Lock and Dam No. 05 Main and Auxiliary Lock Structure.** (Google Earth. Accessed: 2025 Nov 01, 2:46 PM ET).

The filling and emptying of the main lock are controlled by four tainter valves: two located at the upper end of the lock and two at the downstream end (USACE 2025c). During the filling operation, with the miter gates sealed, water flows into the culverts and the lock chamber through the upstream tainter valves until the water level in the lock chamber matches the pool elevation. Once this elevation is reached, the upstream tainter valves are closed, and the downstream tainter valves are opened. Under normal conditions, the filling process takes an estimated 10 minutes depending on water elevations differences. Similarly, the emptying process is also estimated to take 10 minutes (USACE 2002b; USACE 2025b).

(*See next page for Figure 2-6*)

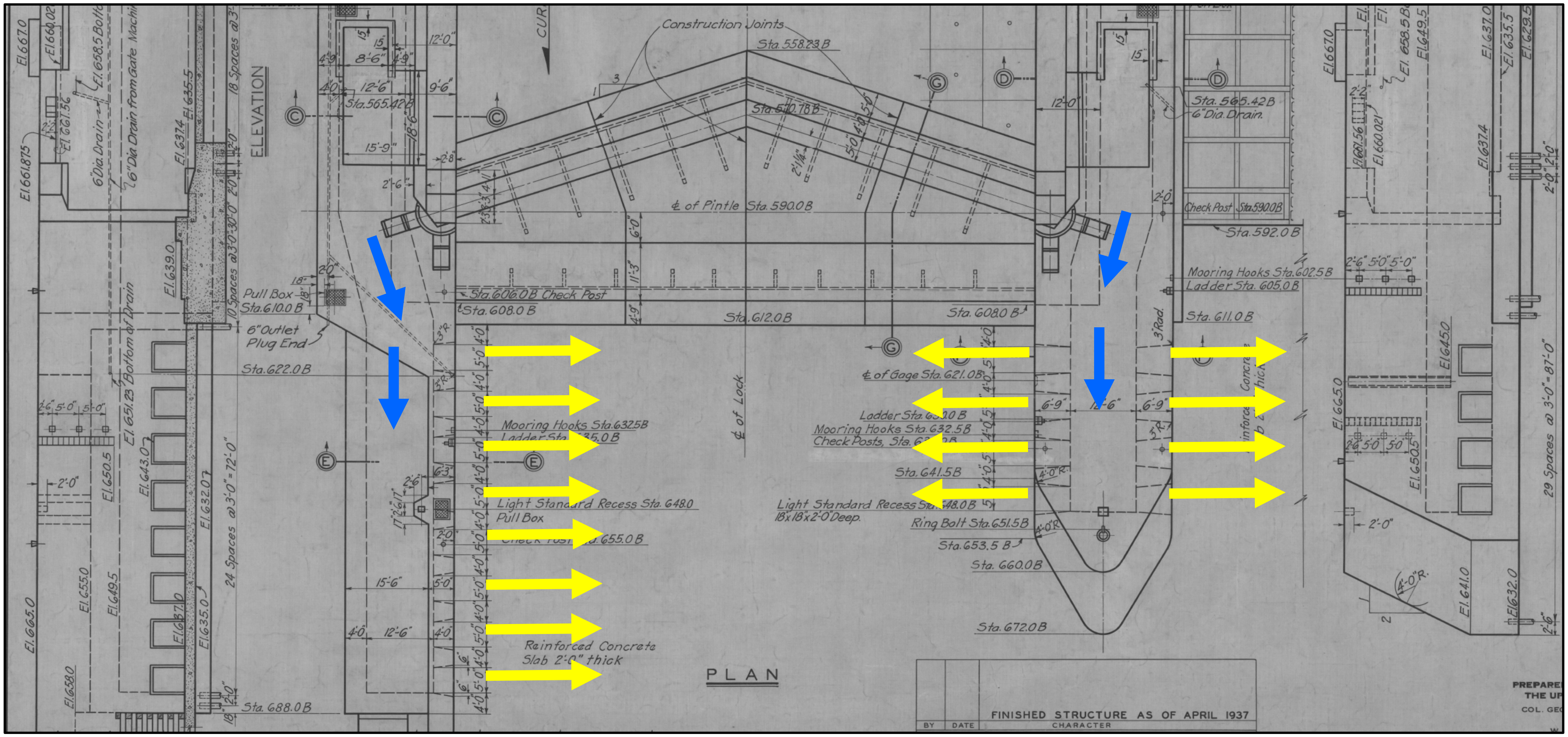


**Figure 2-6. Blueprint of Lock and Dam No. 05 Lock Intermediate Wall.** This blueprint image shows the eight emptying on the guidewall and four emptying discharge ports on the i-wall that empties into the downstream main lock approach and auxiliary lock approach. The yellow arrows indicate the direction of the discharge; blue arrows highlight the discharge culvert (USACE 2025c).

There are three sets of lock discharge ports that release water into the downstream lock approach channel, applicable to both the main downstream lock approach and the auxiliary lock approach channel. Specifically, there are eight discharge ports on the guide wall, four ports on the intermediate wall, and four connecting ports on the auxiliary side of the intermediate wall (USACE 2025c). The guidewall and i-wall discharge valves can be controlled to allow for varying percent open. There are no secondary control valves within the lock structure and thus water cannot be diverted to discharge into the river rather than the downstream lock approach (per Judy Denzer [LD05 Lock Master] and Dylan Duellman [LD05 Shift Head]).

The lock may undergo sediment and debris clearing events as needed, typically conducted during the fall season (per Judy Denzer [LD05 Lock Master]). This clearing process is often carried out at the end of the emptying cycle. With the lower miter gates recessed, the tainter valves are opened to allow water to flow through the system and into the lock chamber, which helps push sediment and debris into the mainstem river (USACE 2002b).

The original scour protection downstream of the lock and along the land guidewall consists of a combination of rock-filled cribs and derrick stone. A 20-foot-wide, 440-foot-long section of rock-filled cribs was placed on the riverward side of the intermediate lock wall (i-wall) (USACE 2020b, USACE 2025a, Barr Engineering 2022). Derrick stone, 3 feet thick, extends from the auxiliary lock to a point 100 feet downstream on the lower guidewall (USACE 2002b, USACE 2025c). The top of the rock elevation varies from 635.0 feet at the auxiliary lock to 637.0 feet downstream of the main lock (USACE 2002b, USACE 2025a, USACE 2025c).

Scour protection downstream was installed along the lock apron between the landward and intermediate lock walls. This protection consists of a 30-inch-thick layer of riprap underlain by a 12-inch-thick bedding layer, with the top of the rock elevation matching the apron elevation (USACE 2002b). The scour protection extends horizontally for 20 feet and then slopes down to meet the channel at a 1V:3H slope (USACE 2002b).

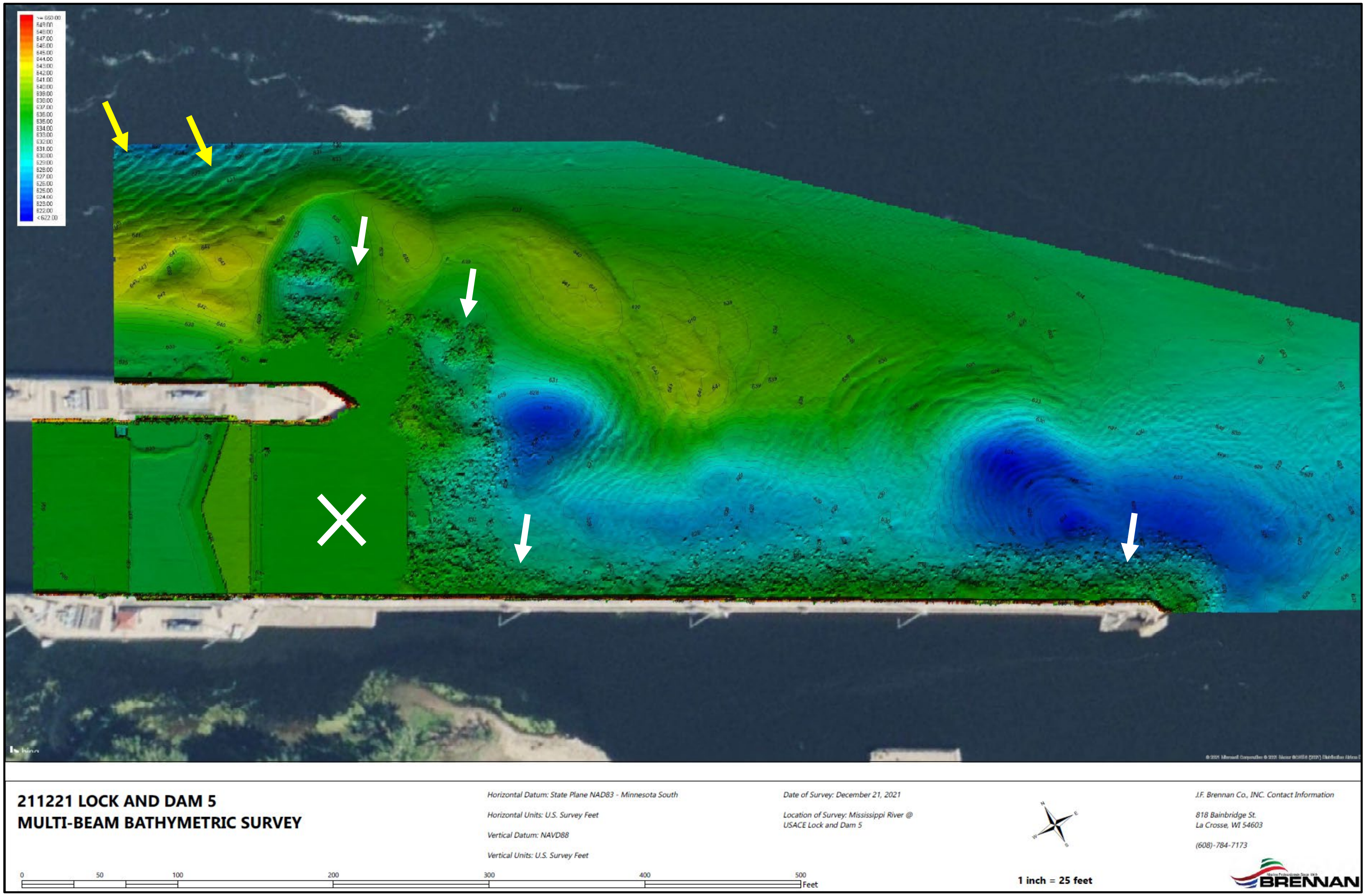


**Figure 2-7. Lock and Dam No. 05 Bathymetry.** (Barr Engineering 2022).

Due to the space limitation for Figure 2-7, the following further describes the bathymetric survey. The survey shows the bottom elevation of the LD05 main and (partial) auxiliary lock approach elevations. The survey shows the rock cribs that still exist, noting that some have been shifted with scouring (white arrows). The sill is relatively flat (white “X”). The discharge from the dam and river naturally move sediment and deposit it closer to the in and near the lock approach structures (yellow arrow points as “waves” of sediment).

## 2.4 Other Infrastructure

### 2.4.1 Debris Curtains (Bubble Curtains)

The Upper Mississippi features 29 locks and dams (Pools 1–26), managed by USACE districts in St. Paul (MVP), Rock Island (MVR), and St. Louis (MVS). Winters bring severe ice, closing navigation from December through March. Debris bubble curtains are standard in many lock chambers in cold-weather regions such as the Upper Mississippi River. These systems serve two main purposes. First, in winter, locks experience frazil ice and sheet ice buildup on gates and walls, which can jam mechanisms, reduce visibility, or damage structures. Ice loads can reach 10 to 20 tons within a lock chamber and approach. Bubblers keep water turbulent around critical areas, reducing ice loads to near zero and ensuring smooth gate operation and timely spring navigation (USACE 2022a). Second, bubble curtains assist with debris management. While some debris is removed through flushing (USACE 2002a), bubble curtains create upward currents that deflect floating debris, such as logs, trash, and aquatic plants, away from gates and sills, reducing clogs. They direct debris toward collection points or downstream, though this is less emphasized than ice control. In some designs, high-flow bubblers in lock approaches help move larger debris. USACE (2020a) recommends using bubblers in lock approaches during high-flow conditions to break ice sheets. During winter, LD05 bubblers operate nearly continuously (December through March) to keep the main and auxiliary locks functional (Figure 2-8, Figure 2-9). The debris curtain also helps reduce ice impact on the earthen dike. USACE (2020b) estimates that major maintenance on these systems is required approximately every 20 years.

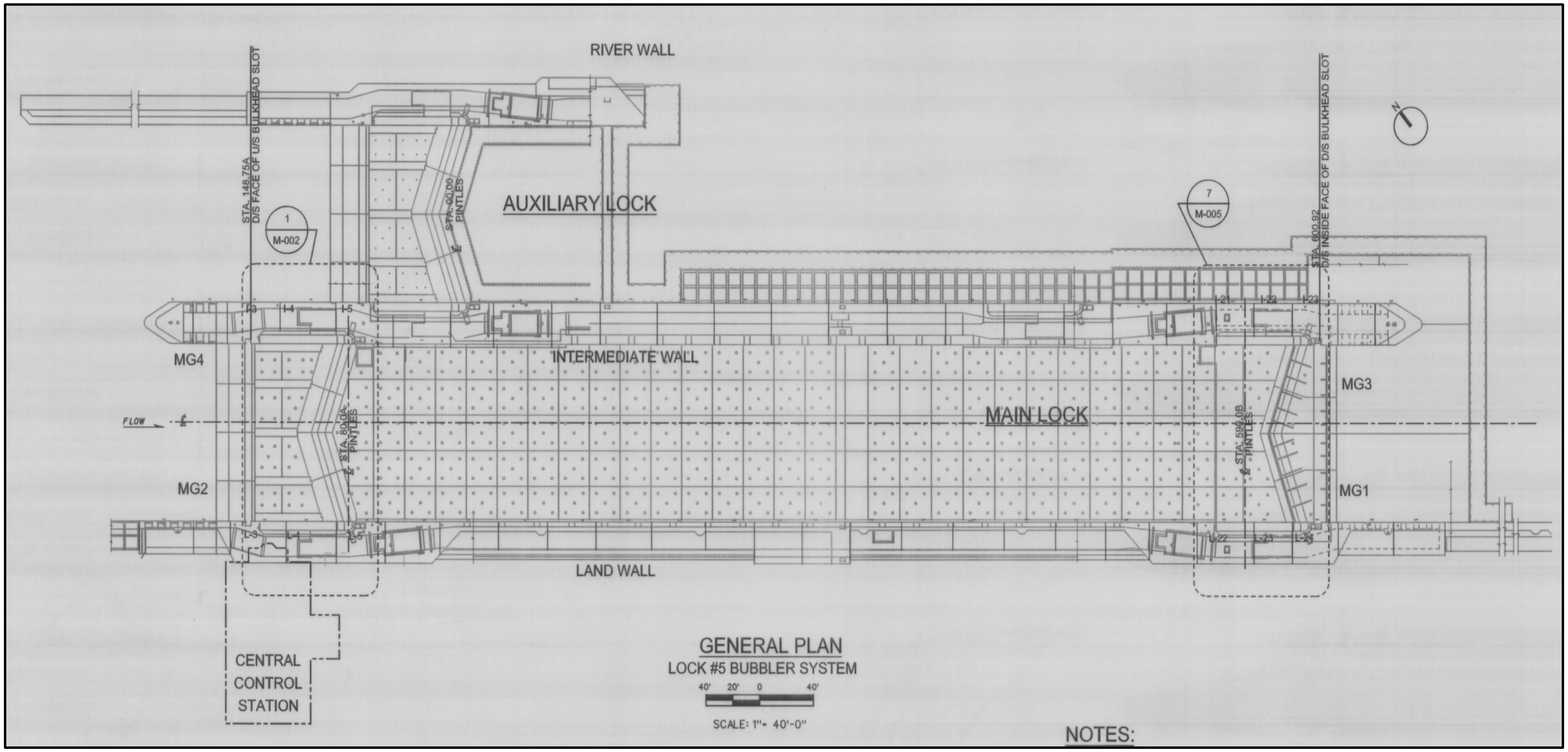


**Figure 2-8. Blueprint of Lock and Dam No. 05 Lower Lock Bubbler System.** (USACE 2025c)

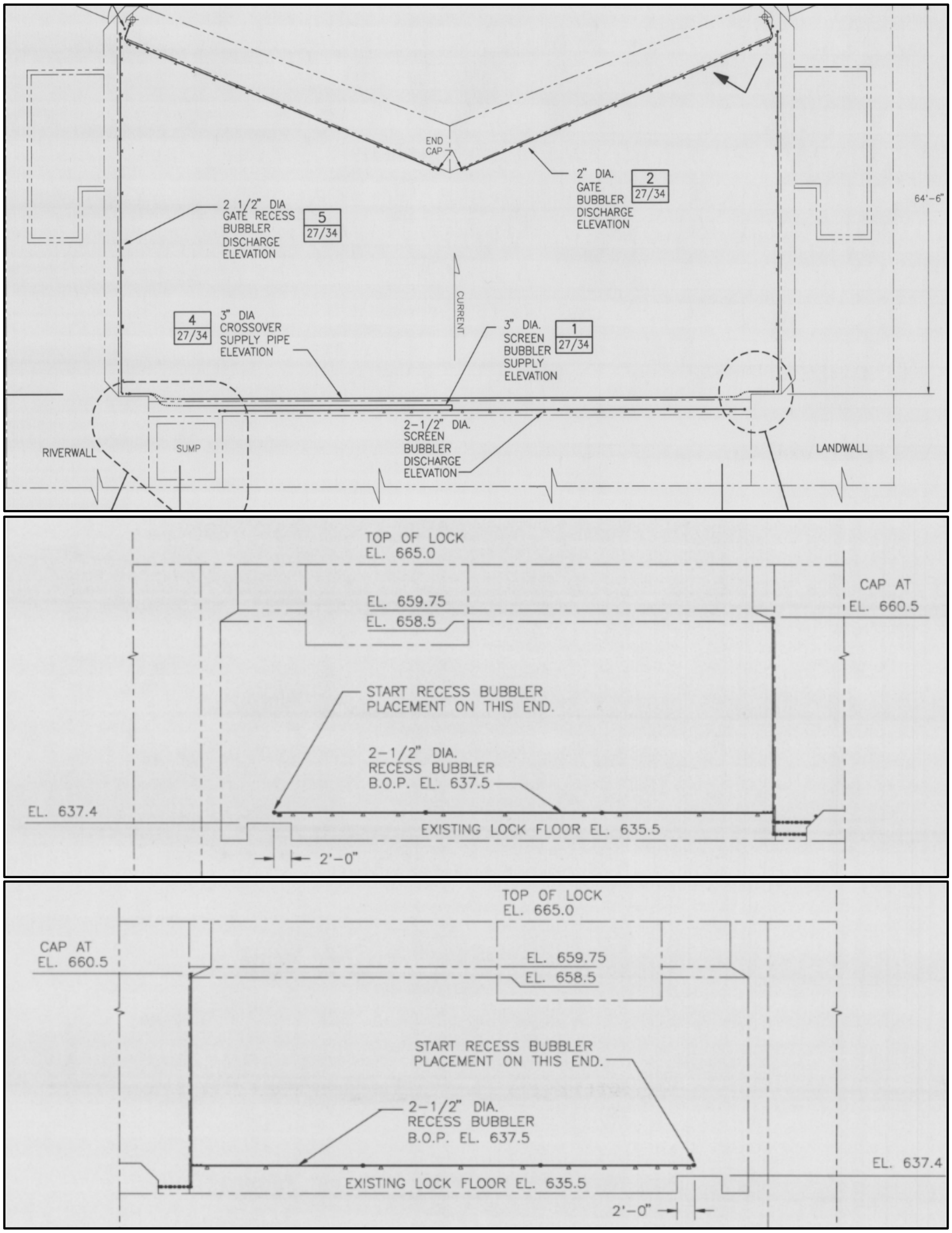


**Figure 2-9. Detailed view of Lock and Dam No. 05 Lower Lock Chamber Bubble System.** (USACE 2025c)

#### *2.4.1.1 Debris Curtains and Invasive Carp Passage*

Pending MVP approval, these debris bubblers could serve as a third purpose, that is as a bubble deterrent for invasive carp. There are several components to these systems including air lines (pipes) and nozzles (e.g., 2–4 inches diameter) that release air at low pressure (5–15 psi) to form loose bubble curtains. These are typically located on the lock chamber floors, walls, sills, and gate recesses. This infrastructure is placed within a few feet above the bottom for optimal agitation. The compressors for debris barriers may be electric- or diesel-powered units providing continuous or intermittent air supply (e.g., 100–500 scfm per nozzle). At LD05, the compressor is on the lock i-wall, with redundant units for reliability. All controls and associated sensors (e.g., temperature/flow triggers) are integrated lock into the SCADA (Supervisory Control and Data Acquisition) systems. Additional features like water jetting ports or culverts for enhanced sediment/ice flushing can also be used.

### 2.4.2 Aeration Culverts

The aeration culverts are a specific feature integrated into the earthen dike section of the dam structure. These culverts serve two purposes related to water quality improvement and structural/hydraulic efficiency. The earthen dike contains four aeration culverts, one 36-inch corrugated metal pipe (installed 1956, originally for flow to Indian Creek, controlled by stop logs, ~70 cfs at project pool) and three 48-inch corrugated metal pipes (installed 1977, sluice gate controlled, combined ~320 cfs at project pool). These are in the earthen dam section (crest 670–672 ft, etc.) are designed for environmental and operational enhancement (USACE 2022b, MN-DNR 2025). They are distinct from the lock's primary filling and emptying culverts, which handle water transfer during lockage operations. Water is routed through the culverts, where it is forced over or through designed drops, weirs, or diffusers, creating turbulence and air entrainment. This increases dissolved oxygen (DO) levels in the downstream pool (Pool 5A, below LD05), counteracting low-oxygen conditions caused by dam impoundment and stagnation in low-flow periods (USACE 2022b, Giblin et al. 2025). The culverts decrease indirect effects on navigation, and improve aquatic habitat in the project pool, supporting fish migration and reducing stress on species like walleye or sauger (coordinated with USFWS, MN DNR, and WI DNR). It also helps USACE meet the Clean Water Act standards, especially in summer low flows when DO can drop below 5 mg/L (USACE 2022b, Giblin et al. 2025).

## 2.5 Substrate and Geotech

As part of the 9-foot navigation channel system, LD05 experiences typical riverine challenges related to substrate (riverbed/bottom materials) and geotechnical conditions (soil/rock stability, foundations). Based on USACE 2002, hydrographic surveys from 2021

(Barr Engineering 2022), and related reports as of 2025 November 23 the primary known issues are sediment dynamics and scour over structural failures or foundation instability. Conversations with the Judy Denzer (Lock Master, LD05) led to the conclusion that at this time (November 2025) there were no major ongoing geotechnical crises (e.g., embankment slides or pile failures). The USACE St. Paul District will have an opportunity to investigate this further as a final technology and location is selected.

## 2.6 Existing Infrastructure (Spillway Gates, Tainter Valves)

As of November 2025, the request for technology comparison is for the Main and Auxiliary Locks and therefore will not address this section. This section as well as the operations of the gates under various flow conditions should be further addressed if a deterrent for the dam is of interest. If of interest, we will expand this section for other deterrent considerations.

## 2.7 References

Barr Engineering. 2022. Engineering Assessment of the Feasibility and Estimated Cost of Installing a State-of-the-Art BAFF Carp Deterrent at Mississippi Lock and Dam 5. Mississippi River Lock and Dam No. 5. Prepared for the University of Minnesota. 128 pp.

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# 3. Hydrology and Hydraulics

The operations of the US Army Corps of Engineers (USACE) at Locks and Dam 5 prioritize navigation, as required by the River and Harbor Act of 1930 (PL 71-250), rather than flood control (USACE 2002b; https://www.mvr.usace.army.mil/media/news-stories/article/476805/why-do-we-have-locks-and-dams). The dams primarily operate in a run-of-the-river manner, meaning that the inflow of water is approximately equal to the outflow, allowing for minimal water retention with a limited storage for operation flexibility (USACE 2002b). There are pools that extend approximately 14 miles, and the storage capacity above Lock and Dam No. 05 is limited (USACE 2002b). This setup emphasizes maintaining a continuous flow downstream instead of focusing on upstream water storage or elevation. The dam regulates all flow passing the structure (via gates/culverts/lock), but inflow is dominated by LD04 outflows + local tributaries to support 9-foot navigation depths (https://www.mvp.usace.army.mil/Home/Projects/Article/571102/upper-mississippi-river-9-foot-channel-navigation-project-locks-and-dams/). Data is monitored via USGS gauge 05378500 (Mississippi River at Winona, MN, est. 5 miles downstream; https://www.umesc.usgs.gov/data_library/ltrmp_data/sediment_nutrients/monitoring_sites/60001/b60001.txt) and USACE water control systems.

The outflows from LD05 are determined by upstream inflows, which include outflows from LD04 and various tributaries. Currently, the US Army Corps of Engineers (USACE) has limited control over drawdowns due to regulations imposed by the Water Resources Development Act (2022/2024) Anti-Drawdown Law (from 1934, amended 1946/1948) (also see Flood Control Act of 1944 (PL 78-534) and USACE 1110-2-240), which aimed to protect navigation and property upstream. Additionally, secondary priorities – such as recreation, water quality, and fish and wildlife considerations – include maintaining downstream aeration continuously at levels between 70 and 320 cfs for the health of backwater areas. Part of the Upper Mississippi River Wildlife and Fish Refuge is located in Pool No. 05. The Refuge (est. 1924; https://www.fws.gov/refuge/upper-mississippi-river/) preserves the Upper Mississippi River for fish, migratory birds, and other wildlife. The acreage was acquired by USFWS, and land acquisition by USACE for the construction of the nine-foot navigation channel. Currently, the refuge consists of est. 240,000 acres of wooded islands, forest, prairie, marsh, and water extending 261 miles southward from Wabasha, Minnesota, to just above Rock Island, Illinois. The refuge remains relatively native; despite the fact there are no specific upstream releases allocated for conservation purposes.

## 3.1 HEC-RAS Modeling

As noted, scouring is a significant issue at many dams on the Upper Mississippi River. The Hydrologic Engineering Center – River Analysis System (HEC-RAS) models are practical tools for simulating sediment transport and movable boundary calculations resulting from scour and deposition, particularly around locks and dams where concerns about scour, sediment deposition, and navigation maintenance are prevalent (Nelson et al. 2022). Currently, managing sediment and flow is less of a challenge at the lock approach compared to the dam and spillway areas.

Sediment loading affects the operation of underwater acoustic arrays that assess whether underwater sound propagation will be affected by burying the sound array (MN-DNR 2025). Therefore, significant variability in sediment load becomes a key factor to consider. At LD05, any sediment-flushing or spillway-release strategy that raises the suspended sediment concentration (SSC) for extended periods could compromise both the effectiveness of deterrents (without O&M) and the accuracy of hydroacoustic fish counting. We were unable to find a current HEC-RAS or model assessment of LD05 region giving time restrictions.

## 3.2 Flow Regimes

The normal elevation of the upstream pool is set at 660.0 ft (MSL 1912 adjustment). Unlike traditional storage reservoirs, LD05 does not provide significant flood-control storage and has no hydroelectric generation. Flow regulation is minimal; therefore, the dam is managed to allow water to flow as naturally as possible while maintaining navigation in Pool 5 (USACE 2002, USACE 2025b). Pools 5 and 5A have a minimal water storage capacity, holding very limited amount (< 1%) of the annual flow volume, and they lack upstream flood storage capabilities (USACE 2002). Flow through LD05 is predominantly over the spillway gates during normal and high-water conditions, with lock filling/emptying cycles contributing minor, pulsed flows (e.g., est. 1,000–2,000 cfs per cycle, lasting est. 10-15 min). Consequently, the flow regime in Pool 5 is driven by discharge and is highly variable, shifting dramatically between lake-like (lentic) conditions at low flows and free-flowing riverine (lotic) conditions at high flows (Figure 3-1, Figure 3-2) (USACE 2002, USGS gauge 05378500). The LD05 structure primarily regulates inflows from upstream structures and local tributaries (e.g., from LD04) to support 9-foot navigation depths.

(*See next page for Figure 3-1, and Figure 3-2*)

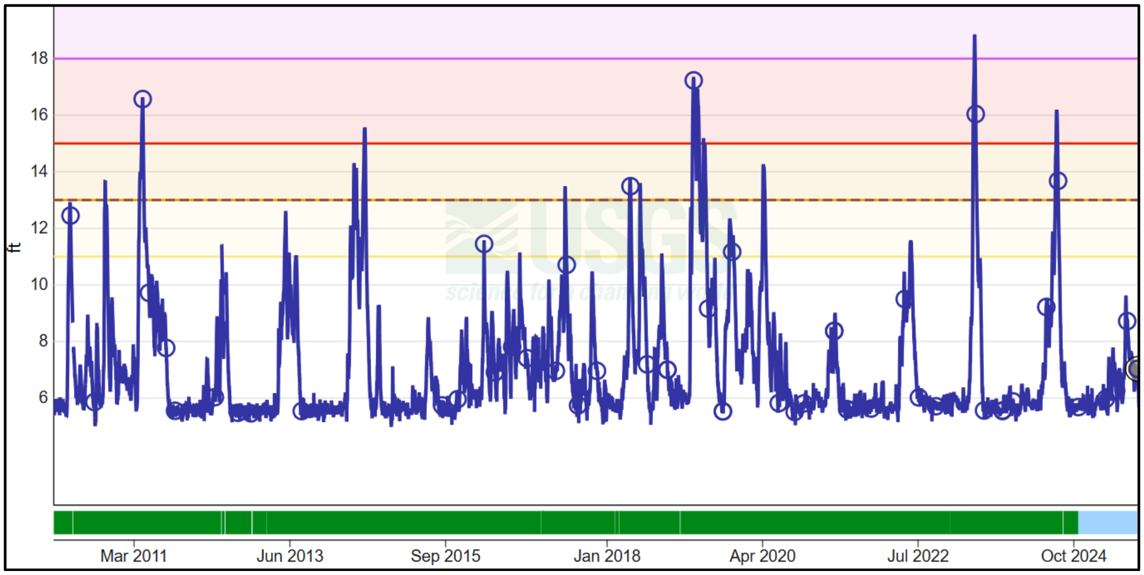


**Figure 3-1. Water Elevation at Winona, MN.** Based on data collected between 01 JAN 2010 through 01 NOV 2025, the dates in green are "approved" data points, and those in blue are "provisional". There are four flood stages highlighted: 11 ft (action stage for pre-flooding; yellow), 13 ft (minor flood stage; orange), 15 ft (moderate flood stage; red), and 18 ft (major flood stage; purple). The flood stage is 13 ft for this river reach. (Accessed 2025 NOV 25; www.waterdata.usgs.gov).

**Figure 3-2. Average Monthly Discharge (cfs) between 2010-2024.** USGS 05378500 Mississippi River at Winona, MN. Values rounded to nearest 1 cfs for readability. Annual mean estimated to be approximately 42,245 cfs. (Accessed 2025 NOV 25; www.waterdata.usgs.gov/nwis/uv?site_no=05378500).

| | Mean Discharge (cfs) | Std Dev (cfs) | Maximum Recorded (cfs) | Environmental Condition |
|---|---|---|---|---|
| January | 23,548 | 10,871 | 49,630 (2019) | Ice / low flow, Lentic |
| February | 20,951 | 8,974 | 45,580 (2017) | Ice / low flow, Lentic |
| March | 40,807 | 18,022 | 73,480 (2019) | Snowmelt onset, Transitioning |
| April | 73,990 | 36,253 | 155,600 (2019) | Spring flow / flood, Lotic |
| May | 72,686 | 26,399 | 120,900 (2019) | Spring flow / flood, Lotic |
| June | 62,591 | 23,382 | 104,900 (2014) | Spring/Summer flow / flood, Lotic |
| July | 52,281 | 23,660 | 97,950 (2024) | Peak Recreation, Transitioning |

| | | | | |
|---|---|---|---|---|
| **August** | 31,705 | 13,515 | 56,610 (2016) | Late Summer recession, Transitioning |
| **September** | 30,730 | 16,488 | 60,760 (2016) | Fall low flow, Transitioning |
| **October** | 38,794 | 27,406 | 95,300 (2019) | Grain harvest – Variable, transitioning |
| **November** | 32,594 | 15,270 | 62,470 (2019) | Falling, transitioning |
| **December** | 26,266 | 11,391 | 46,350 (2019) | Ice Onset, Lentic |

The Water Control River Manager (within USACE) prints the Regulation Sheets containing all the input from the lock and dam sites. Regulation for LD05 begins at LD04. Gate changes at LD04 directly influence action needed at LD05. After regulating LD04, inflow to Pool No. 05 is determined. Inflow consists of outflow from LD04, inflow from the Zumbro River, and any miscellaneous inflow.

At low discharge levels, typically below 20,000 cfs, the pool is maintained at elevation 660.0 ± 0.2 feet (1912 adjustment[3]) at the primary control point near Alma, Wisconsin. At low discharge levels, typically below 20,000 cfs, the roller and tainter gates of the dam are only partially open (Figure 3-3) (USACE 2002; www.waterdata.usgs). Water velocities throughout most of Pool 05 are slow, usually less than 0.1 ft/s in the main channel (Figure 3-4) (USACE 2002), bordering channels, and backwaters. In this scenario, the pool resembles a shallow lake, characterized by extensive submerged and emergent aquatic vegetation, deep isolated backwaters, and minimal current. This lentic through transitional environment dominates during low-flow periods (typically < 40,000 cfs, occurring a substantial portion of the year based on discharge-duration curves) (Figure 3-4) and supports centrarchid fish populations (such as largemouth bass, bluegill, and crappie) and northern pike spawning in the vegetated shallows (Holland and Huston 1984). The biological productivity in UMR navigation pools has declined as pools aged, motivating drawdown management. Summer growing-season drawdowns were identified by the multiagency Water Level Management Task Force (WLMTF) as the most promising tool for large-area habitat restoration in St. Paul District pools including Pool 5. In 2005 and 2006, Pool 5 was subject to pool-wide ecological drawdowns that exposed approximately

[3] Survey of Mississippi River Between Missouri River and Minneapolis, Letter from The Secretary of War, 72 Congress, 1st Session, House Document No. 137, Part 1 – Report, 9 December 1931

1,000 acres of mudflats. This effort resulted in increased marsh plant and submersed vegetation cover and elevated waterfowl use; and thus decreasing

(*See next page for Figure 3-3, and Figure 3-4*)

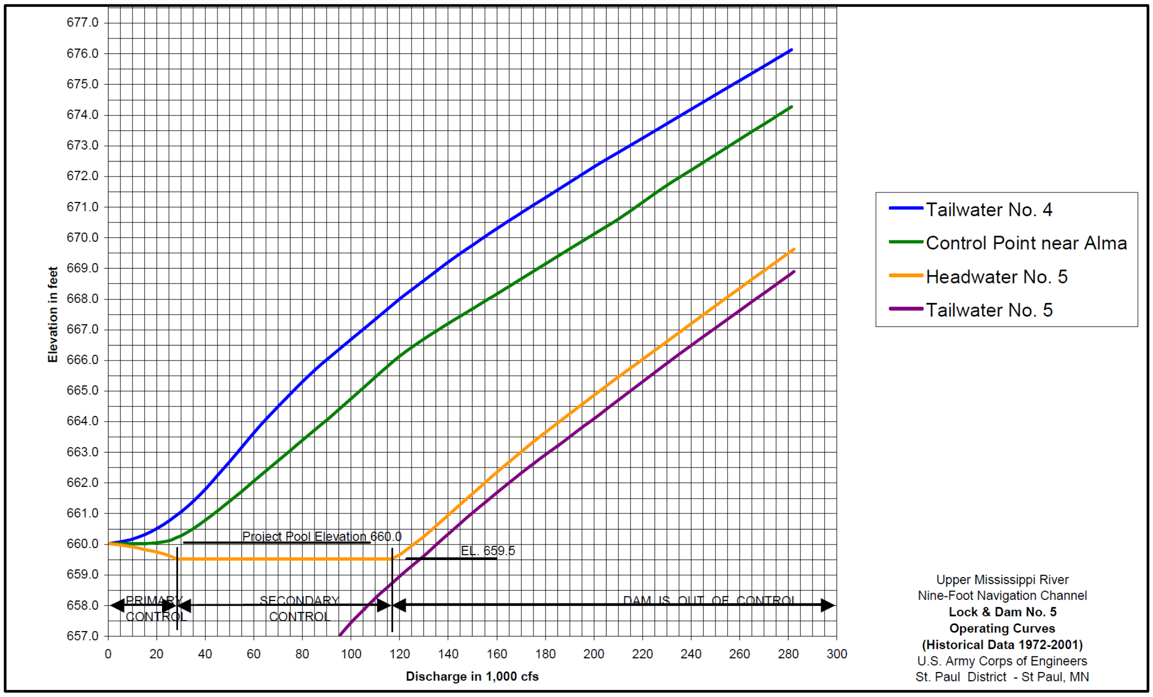


**Figure 3-3. Lock and Dam No. 05 Operating Curves.** The operation of discharge through the dam uses the elevations of LD04, Pool 5/5A. The black arrows show the overall control approach for LD05 (USACE 2022).

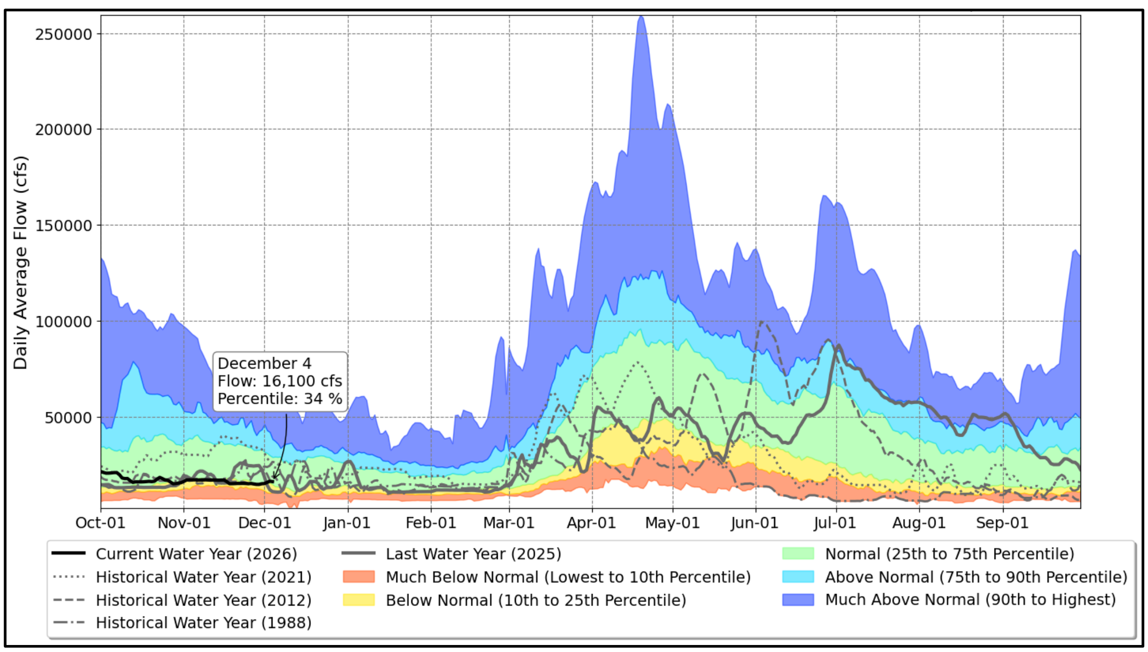


**Figure 3-4. Lock and Dam No. 05 Outflow Historical Percentiles Up to Current Year.** Based on data collected between 01 JAN 2010 through 04 DEC 2025.

As discharges increase, there is a “drawdown” in the water surface elevation at the dam. The drawdown elevation is based on necessary navigation depths upstream of the dam. Drawdown at the dam was first established at 2.5 feet below the project pool level. This was reduced to 1.5 feet in 1960 to ensure more stable water surface elevations for river-front property owners and conservation interests. Because of adverse effects on navigation due to the reduced dredging effort by the USACE in 1970, it was further reduced to 0.5 feet. Therefore, drawdown at the dam is constrained to elevation 659.5 ± 0.2 ft.

As discharge increases to a moderate range of 20,000 to 60,000 cfs, the USACE begins to lower the submersible tainter gates and open the roller gates (Figure 3-5) (USACE 2022; www.waterdata.usgs). Current velocities in the main navigation channel rise to between 0.5 and 2 ft/s, secondary channels reconnect with the main stem, and floodplain forests experience seasonal inundation. The pool transitions to a mixed lotic-lentic system, with riverine habitats expanding at the expense of still-water areas. This transitional regime is the dominant annual condition, occurring approximately 50% of the year (±10% annually, roughly March and July–November) and supports a greater diversity of fish species, including smallmouth bass, sauger, walleye, and freshwater drum, which prefer moderate current and clean gravel or sand substrates.

When discharge rates exceed approximately 60,000 to 70,000 cfs, all gates are fully opened, and the minimal storage level of Pool 5 effectively disappears as the tailwaters rise to match the upstream pool elevation. Velocities throughout the former pool increase to between 2 and 5 feet per second or higher, leading to intense sediment transport, and the area returns to natural, un-impounded river conditions (USGS 2025 water data). This open-river regime typically occurs for approximately 15–20% of the year (~55–75 days) (derived from the discharge-duration curve), primarily in spring and early summer, but during wet years such as 2019, it can last for four to six months.

During major floods that exceed 100,000 cfs, which occur in less than 5% of years, water velocities may reach 5 to 8 feet per second. Under these conditions, the dams (LD05 and LD05A) function similarly to an open river around 116,000 cfs, and there is a differential head less than one foot (USACE 2022, USACE 2025 MVP). To manage this situation, the gates are raised early to allow flows to pass and minimize "swellhead," which is the rise in backwater levels. This action helps reduce water pressure on the dams and their equipment, such as tainter and roller gates. When gates are put back in the water, the total gate openings are 96 feet on roller gates and 280 feet on tainter gates. Accordingly, high flow conditions lead to extensive overbank flows across floodplain forests and agricultural levee districts, significantly reshaping side channels and point bars due to scour and deposition. Additionally, backwater lakes and isolated wetlands are temporarily submerged under the fast-moving water.

Based on a meeting with the USACE and MN-DNR team, we also included the LD05 roller and tainter gate discharge estimated for operations of the dam. This will become more critical, as the team begins to examine how to operate the gates during moderate-high flows (excluding flows great than 116,000 cfs, open river conditions). Further descriptions on this data and pulling through the lock operations and water control manual have not been pursued further.

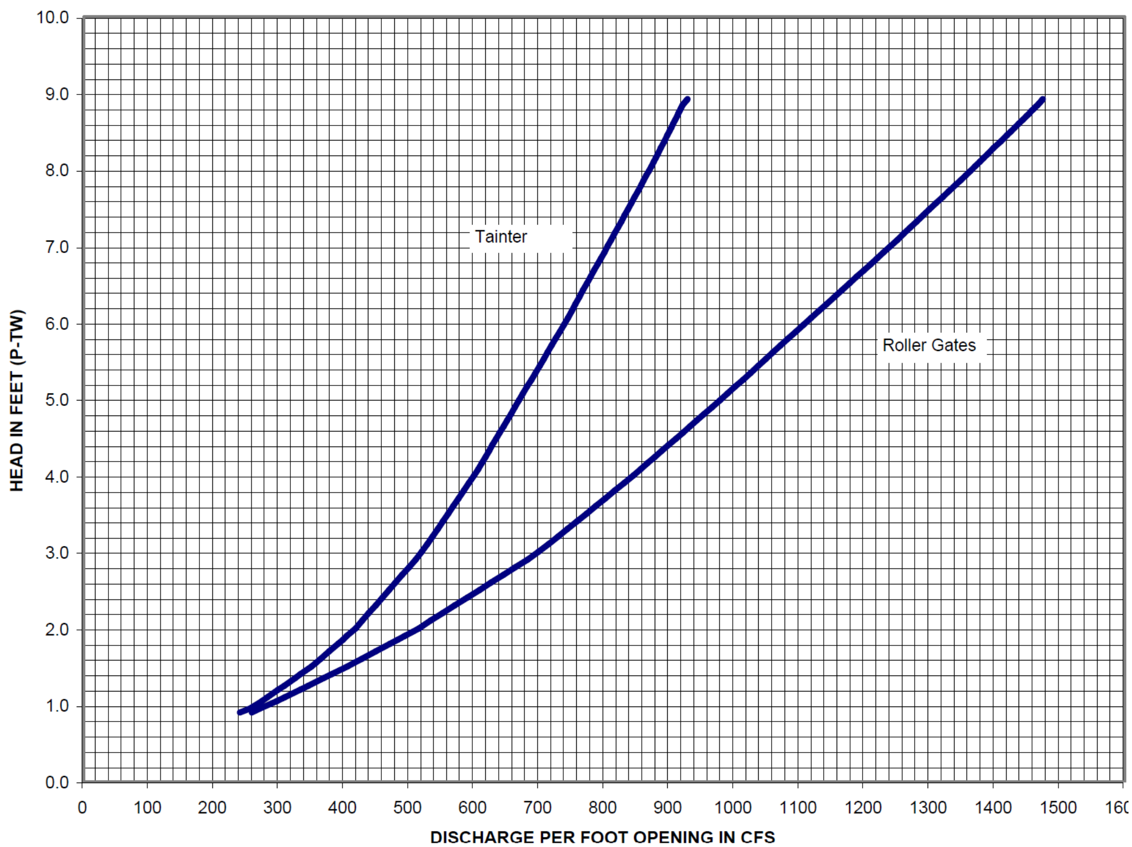


**Figure 3-5. Lock and Dam No. 05 Roller and Tainter Gate Discharge (cfs).** Roller and tainter gate discharge for a single gate. (USACE 2022).

Each fall/winter, the US Army Corps of Engineers (USACE), St. Paul District, conducts a modest drawdown of Pool 5, lowering the water level by approximately 0.5 to 2 feet below normal levels from late fall until ice-out. This drawdown slightly increases current velocity, consolidates aquatic vegetation, exposes mudflats to freeze-thaw cycles, and reduces the risk of ice damage to private shoreline properties. These drawdowns may be more than mandated but often coordinated with partners (e.g., states, USFWS).

Reviewing flow regimes between 1959 to the present, the Upper Mississippi basin has experienced above-average precipitation and runoff (Figure 3-4). As a result, open-river conditions at LD05 are now occurring more frequently and for longer durations than the historical average. This shift is transforming Pool 05, leading to extended periods of riverine habitat and shorter intervals of the stable, lake-like conditions that historically favored centrarchid-dominated fisheries.

## 3.3 Outflow and Outdraft

Downstream scour protection is designed to withstand and dissipate the outflow velocities from the roller and tainter gates. The original design plan set maximum outflow velocities at 4.5 feet per second (fps) for standard operating procedures with an allowance to go to 6.0 fps for an emergency. In 1983 and 1984, additional riprap was placed upstream and downstream of the dam. Since this time, routine maximum gate openings have been computed based on a maximum outflow velocity of 6.0 fps. Flow velocities are allowed to exceed 6.0 fps for short periods of time (15 to 20 minutes, standard operational recommendation, may vary) during emergency operations (e.g. barge incident, passing of debris) (USACE 2002b).

A well-documented outdraft hazard exists for downbound tows whenever total river discharge exceeds 70,000 cfs. Strong crosscurrents pull tows toward the dam as they exit the lock or approach from upstream. The USACE maintains a permanent warning sign on the upstream guidewall that is uncovered and displayed any time flows are above 70,000 cfs. Tow (flotilla) pilots are required to use assist boats, reduce speed, and square up early when the sign is visible.

## 3.4 CFD Models

As part of an ongoing project with the University of Minnesota, several computational fluid dynamics models have been developed to determine whether modified gate positions might reduce passage probability. The models were built using OpenFOAM and the solver interFoam. Flows from 44,000 to 115,000 cfs have been modeled. Representative gate positions were used and were provided by MVP.

The model in this study utilizes OpenFOAM, version 8. The solver, interFoam, solves the discrete Reynolds-Averaged Navier-Stokes (RANS) equations for two incompressible, isothermal, immiscible fluids—water and air—using a volume-of-fluid (VOF) phase-fraction-based interface-capturing method. The governing equations are specified below, and additional details of their implementation may be found in (Heynes et al. 2014). The continuity equation is defined as:

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

and the momentum equation is defined as:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{tij}) + \rho g_i + f_{\sigma i} \tag{2}$$

where $u$ is the velocity, $g_i$ is the gravitational acceleration, $p$ is the pressure, $\tau_{ij}$ and $\tau_{tij}$ are the viscous and turbulent stresses, $f_{\sigma i}$ is the surface tension, and $\rho$ is the density. For two-phase flows, the density is determined by:

$$\rho = \alpha\rho_1 + (1-\alpha)\rho_2 \tag{3}$$

where $\alpha$ is equal to 1 inside the water volume with density $\rho_1$ and 0 inside the air volume with density $\rho_2$. At the interface between the two fluids, the value of $\alpha$ varies between 0 and 1. In addition to the continuity and momentum equations, an additional equation is solved for the interphase between the two fluids:

$$\frac{\partial\alpha}{\partial t} + \frac{\partial(\alpha u_j)}{\partial x_j} = 0 \tag{4}$$

The two-equation realizable *k-ε* model is used for turbulence closure, which offers a more accurate calculation of turbulent viscosity than the standard *k-ε* model. Detailed descriptions of the following equations are found in Shih et al. (1994b) and Shaheed et al. (2019). The transport equation for turbulent kinetic energy, $k$, is expressed as:

$$\frac{\partial k}{\partial t} + \frac{\partial k u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left(Dk_{eff}\frac{\partial k}{\partial x_i}\right) + 2v_t S_{ij}^2 - \varepsilon \tag{5}$$

and the transport equation for dissipation rate, ε, is expressed as:

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial \varepsilon u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left(D\varepsilon_{eff}\frac{\partial \varepsilon}{\partial x_i}\right) + \sqrt{2}C_1 S_{ij}\varepsilon - C_2\frac{\varepsilon^2}{k + \sqrt{v_t\varepsilon}} \tag{6}$$

where constant $C_1$ is determined by:

$$C_1 = max\left(\frac{\eta}{5+\eta}, 0.43\right) \tag{7}$$

and $\eta$, the mean strain, is:

$$\eta = \frac{k\sqrt{2S_{ij}S_{ij}}}{\varepsilon} \quad (8)$$

The remaining constants are determined to be $C_2 = 1.9$ and $\sigma_\varepsilon = 1.2$ as prescribed in (T.-H. Shih et al., 1994a). The effective diffusivity for $k$ and $\varepsilon$, are:

$$Dk_{eff} = \nu + \nu_t \quad (9)$$

$$D\varepsilon_{eff} = \nu + \frac{\nu_t}{\sigma_\varepsilon} \quad (10)$$

and the rate of strain tensor defined as:

$$S_{ij} = 0.5\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) \quad (11)$$

The turbulent viscosity is calculated using:

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (12)$$

While the standard *k-ε* model assumes a constant for $C_\mu$, the realizable *k-ε* model considers an experimentally derived formulation. A more detailed view of the formulation of $C_\mu$ may be found in (T.-H. Shih et al., 1994) and (Shih et al. 1995). In the present study, the density of water, $\rho$, was assumed to be 1000 kg/m$^3$ with a kinematic viscosity, ν, of 1E-06 m$^2$/s. The density of air was assumed to be 1.2 kg/m$^3$, with a kinematic viscosity of 1.48E-05 m$^2$/s.

The model suggests that river flow approaches the i-wall at a 20-degree angle and does not run parallel to the i-wall. As the flow passes the i-wall, it encounters the guide wall approximately 60 m to 120 m downstream of the i-wall. This area is a prominent shear line separating the approach channel from the main river. As the river flow increases, the distance downstream of the flow connection point between i-wall and guidewall increases, see *Figures 3-6 to 3-9* that highlight this pattern.

The area between the miter gates and the shear line is hydraulically isolated from the main river flow. It is characterized by slow (0 to 0.2 m/s), complicated flow patterns.

Preliminary modeling of fish movement suggests most fish (90% or more) follow the shear line and do not enter the approach channel. However, for fish that follow the shearline, there are more complex behaviors evident reflecting the complicated flow lines. Based on the data generated, thus far, the lock emptying events will greatly change flow patterns disrupting the shear line patterns from the main river. In addition, the presence of commercial navigation will change the flow patterns in the lock approach channel. Additional modeling is required to further refine the forecasting of fish behavior.

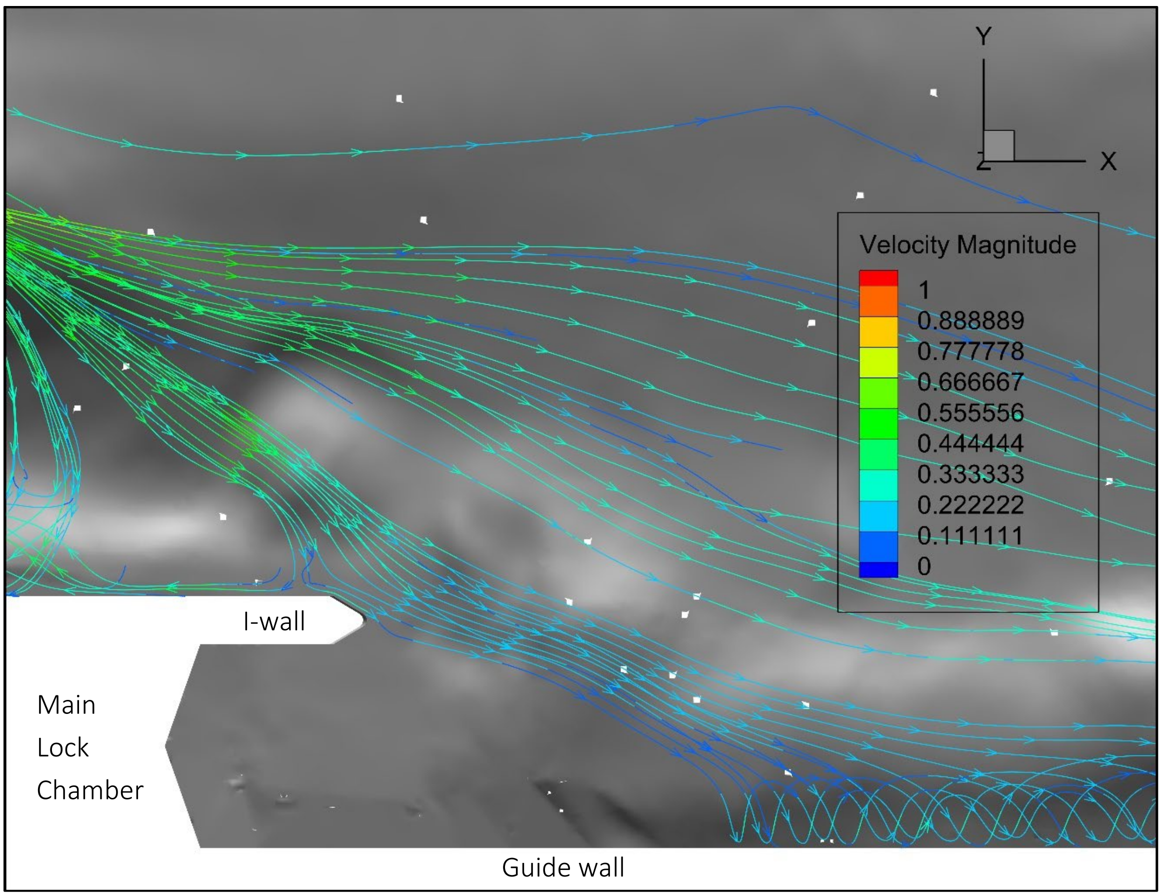


**Figure 3-6. Lock and Dam No. 05 River Reattachment Point on the Guidewall at 44,000 cfs.** Three-dimensional computation fluid dynamic model output. All units are m/s in the legend.

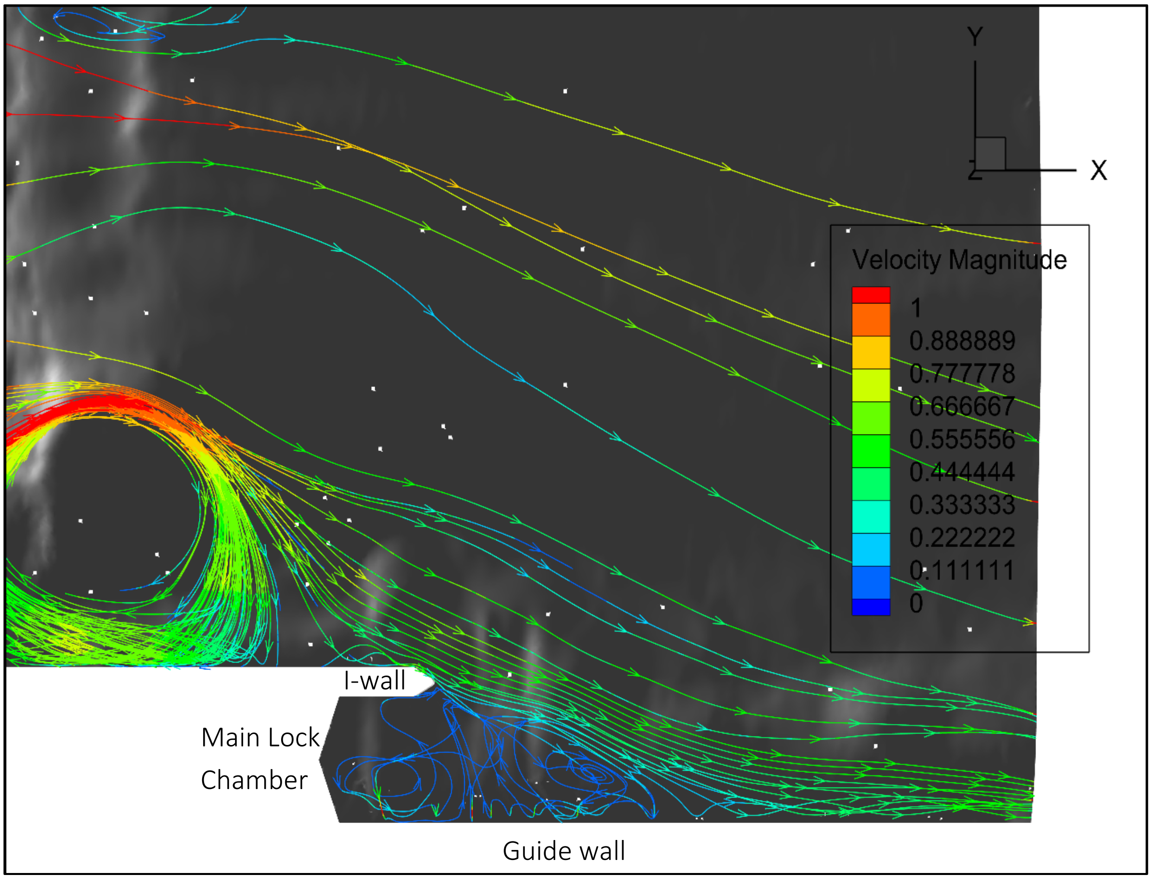


**Figure 3-7. Lock and Dam No. 05 River Reattachment Point on the Guidewall at 62,000 cfs.** Three-dimensional computation fluid dynamic model output. All units are m/s in the legend.

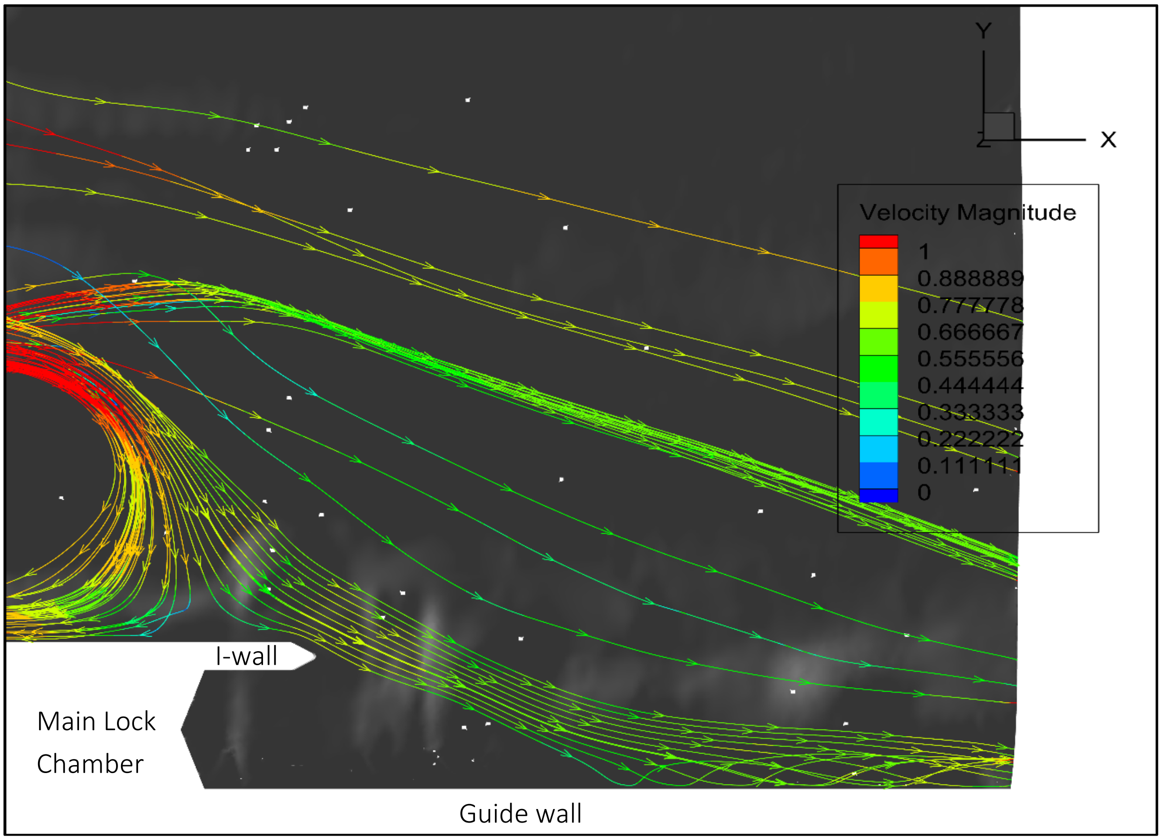


**Figure 3-8. Lock and Dam No. 05 River Reattachment Point on the Guidewall at 78,000 cfs.** Three-dimensional computation fluid dynamic model output. All units are m/s in the legend.

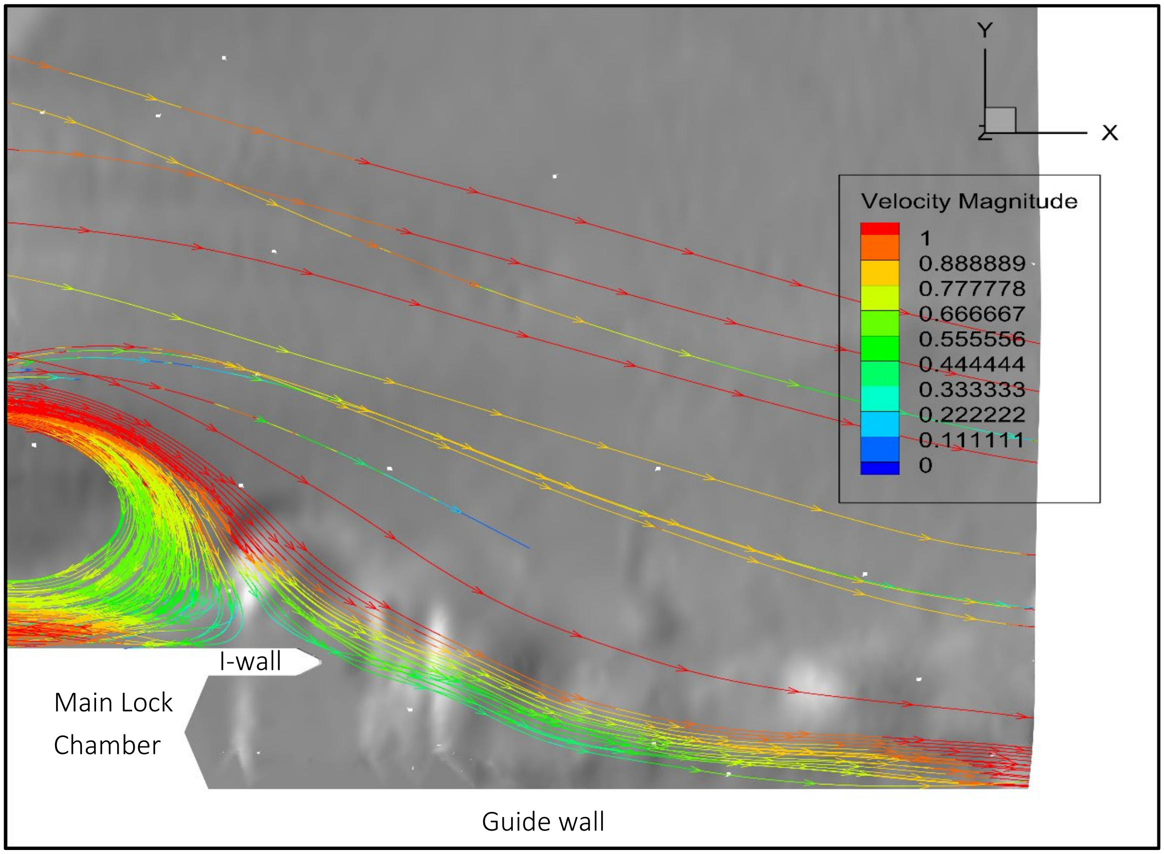


**Figure 3-9. Lock and Dam No. 05 River Reattachment Point on the Guidewall at 115,000 cfs.** Three-dimensional computation fluid dynamic model output. All units are m/s in the legend.

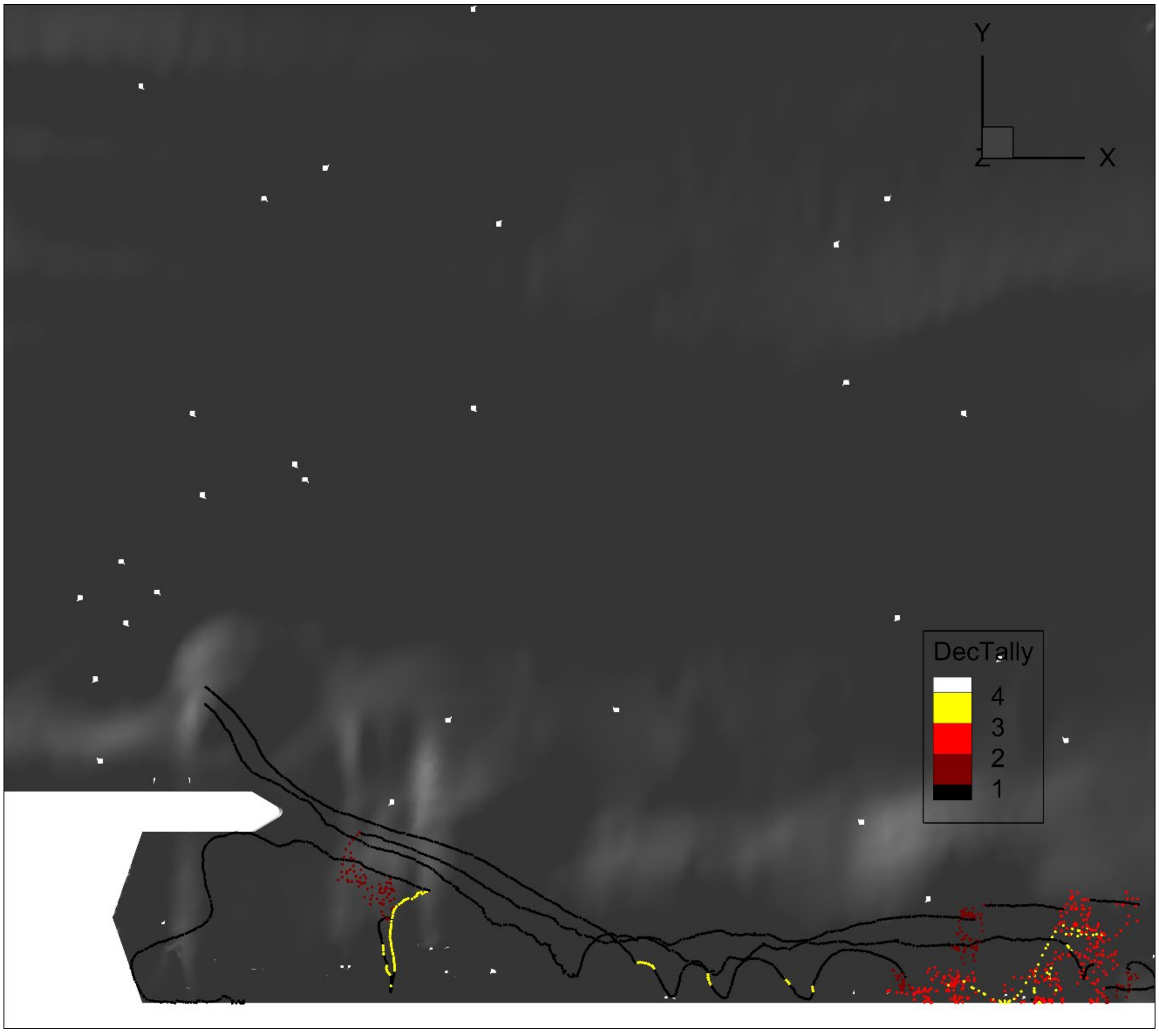


**Figure 3-10. Example of Lock and Dam No. 05 Modeled Fish Approaching the Lock.** LD05 model of fish movement shows that positive rheotactic behavior tends to move fish along the shear line and past the approach channel. However, some fish change behavior and may enter the approach channel and display complicated movement patterns indicative of the complicated flow in this location. DecTally (black) is swim upstream. DecTally (rust) is swim toward decreasing water velocity, DecTally (red) is swim toward increasing water velocity and DecTally (yellow) is swim toward increasing depth. Three-dimensional computation fluid dynamic model output.

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# 4. Navigation

## 4.1 Closures

It is expected that navigation will be reduced or closed during times on maintenance. Navigation will also close due to high or even extremely low water conditions. As part of the major rehabilitation work from 1987 through 1998, the lock can now technically remain open to navigation provided until water reaches the top of the lock wall (665.0 ft) or spills over the miter gates. While this is the physical constraint, closure will often happen before the water level gets this high due to wave action over the miter gates. For this reason, the lock closes when the pool elevation is half a foot from the top of the lock wall or elevation 664.5 ft (per Judy Denzer, Lock Master LD05). The US Coast Guard (USCG) during extreme high-water event like this, will "close" or "encourage" the river to recreational vessels, though commercial navigation will often continue.

The lock is also closed when ice is too thick to permit tow traffic (per Judy Denzer, Lock Master LD05). As winter approaches, the lock remains open as long as towboats and barges can travel. Water temperatures are monitored to predict lock closure. When temperatures approach the low 30's, ice can form overnight and can impact the entire pool. Typically, in March the ice becomes thin enough for some tow traffic and the lock is opened. The ice thickness on Lake Pepin (Pool No. 4) is monitored weekly. When the ice is thinner, tow (if tows are icebreaking) traffic can soon be expected.

Annual closures vary by year based on winter ice/maintenance often 90–120+ days for northern pools.

## 4.2 Traffic Patterns

LD05 is a moderate-traffic lock on the Upper Mississippi. With the auxiliary lock not functional, all navigation travels through the main lock. Using data pulled from AIS transponders (USACE Nav Portal) and the Lock Performance Monitoring System (LPMS) (Accessed November 2025; www.ndc.ops.usace.army.mil/ords; www.navportal.usace.army.mil), there are mismatches when the data is compared, likely because not all vessels use AIS transponders. Each table caption (Table 4-1, Table 4-2, Table 4-3, Table 4-4) note the data used. The primary focus on this section is related to commercial traffic as that will be more disruptive to the functioning of bubble curtains and underwater acoustics.

### 4.2.1 Number of Lockages by Type

Annually, the average number of vessels (all types) using the lock is 4,316 vessels (± 699) (Table 4-1). Of these vessels, annually, the average number of commercial lockages are 1,566 ± 253. This comprises an estimated commercial 350 ± 102 vessels (non-flotillas), and 1,217 ± 194 flotillas. The remaining 2,938 vessels are recreational craft that are handled in 1,175 recreational lockages (multiple boats are routinely locked together). Significant recreational traffic occurs during May–September, representing about 65% of the total vessels passing the lock, but only 42% of total lockages because of the group lockages.

Adding the small number of government and workboat lockages, the main chamber performs about 2,783 ± 337 total lock cycles per year, or an average of 8.2 lockages every 24 hours (based on annual average number of closed LD05 days). Thus, LD05 operates well below its capacity with the current traffic levels if one was to use the practical limit of 4,500 lockages per year for a single 600-ft chamber.

**Table 4-1. Summary of Lock and Dam No. 05 Usage.** The following table uses data from 2015 to 2024. (Accessed Nov 25, 2025; www.ndc-navapps.ops.usace.army.mil).

| Lock usage Description | Average Annual No. | Std Dev. |
|---|---|---|
| Annual Average Delay Tows | 1.05 (63 min) | 0.30 (18 min) |
| Annual Average Processing Time | 0.38 (23 min) | 0.03 (1.8 min) |
| Annual Count of Empty Barges | 1,812.10 | 625.58 |
| Annual Count of Loaded Barges | 5,440.20 | 1,279.04 |
| Annual Commercial Vessels | 1,335.70 | 151.98 |
| Annual Commercial Flotillas | 1,216.90 | 194.36 |
| Annual Commercial Lockages | 1,566.70 | 253.07 |
| Annual Commercial “Cut” Lockages | 1,796.3 | -- |
| Annual Non-commercial Vessels | 42.20 | 9.02 |
| Annual Non-commercial Flotillas | 40.80 | 9.17 |
| Annual Non-commercial Lockages | 40.90 | 9.29 |
| Annual Average Percent of Delayed Vessels | 31.11 | 7.38 |
| Annual Recreational Vessels | 2,938.40 | 723.74 |
| Annual Recreational Lockages | 1,175.40 | 177.72 |
| Annual Total Vessels | 4,316.30 | 699.76 |

| | | |
|---|---|---|
| Annual Total Lockages | 2,783.00 | 336.81 |

### 4.2.2 Commodities

Using the LPMS data, LD05 is overwhelmingly an agricultural lock, and thus seasonal traffic is to be expected. Grain and fertilizer/chemical movements dominate, reflecting the rich farmland of southeast Minnesota, southwest Wisconsin, and northeast Iowa that feed into the river at Red Wing, Winona, and La Crosse. Commercial vessel traffic is heavily dominated by grain and farm products (nearly 3.87 ± 1.91 million tons annually) (Table 4-2), followed by agricultural chemicals and fertilizers (estimated 1.70 ± 0.19 million tons) and sand/gravel/aggregates (1.41 ± 0.23 million tons). Coal movement is negligible at this lock. Knowing the commodity type helps better understand the tow, flotilla and vessel type most often transiting the lock. Grain and farm products dominate (≈52 % of all tonnage), followed by chemicals (23 %) and aggregates (19 %).

**Table 4-2. Summary of Lock and Dam No. 05 Commodities.** The following table uses data from 2015 to 2024. (Accessed Nov 25, 2025; www.ndc-navapps.ops.usace.army.mil).

| Commodity Code | Average | Standard Dev. | Average Percent |
|---|---|---|---|
| Coal, Lignite and Coke | 32,520.00 | 12,523.12 | 0.4 |
| Petroleum and Petroleum Products | 431,184.40 | 230,481.79 | 55.2 |
| Chemicals and Related Products | 1,700,287.40 | 192,696.10 | 20.4 |
| Crude Materials, Inedible, except Fuels | 1,408,861.50 | 228,444.14 | 16.9 |
| Primary Manufactured Goods | 871,440.60 | 75,726.04 | 10.4 |
| Food and Farm Products | 3,869,466.80 | 1,905,549.34 | 46.3 |
| All Manufactured Equipment and Machinery | 25,108.50 | 11,808.55 | 0.3 |
| Waste Material, Garbage, Landfill, Sewage Sludge and Wastewater | 7,433.33 | 6,079.75 | 0.1 |
| Others, NEC | 2,457.14 | 1,153.05 | 0.0 |

### 4.2.3 Dwell Times

The traffic throughput of this lock is very efficient averaging just under an hour when long delay times are removed (e.g., maintenance, weather delays, vessel breaks) (Table 4-3).

The delays are minimal (average < 1 tow per year; Table 4-4) according to the LPMS data. The AIS data (Table 4-3, Table 4-4) indicates about 31 vessels have delays greater than 4-hours and this could be related to several events. This confirms that > 95% of commercial lockages at LD05 are completed in under 2 hours, including cut lockages. *Due to limited time for reporting & Q1 complications, we did not flesh this data further.*

**Table 4-3. Lower Lock Approach Dwell Time Summary of Lock and Dam No. 05.** The following table is a summary using data from 2021 November 01 and 2025 November 01. (Accessed Nov 05, 2025; www.ndc.ops.usace.army.mil/ords).

| | Count | Average | Max | StdDev |
|---|---|---|---|---|
| Fishing | 30 | 1:06:38 | 2:05:31 | 0:34:15 |
| Other | 514 | 2:15:15 | 23:46:27 | 4:17:24 |
| Passenger | 79 | 0:24:23 | 23:11:32 | 3:30:24 |
| Pleasure | 54 | 0:10:50 | 21:00:25 | 2:49:50 |
| Sailing | 1 | 0:15:00 | 0:17:57 | NA |
| Spares for local vessels | 96 | 1:00:35 | 2:24:42 | 0:33:46 |
| Towing | 1282 | 1:08:47 | 23:50:32 | 2:49:45 |
| Towing astern | 3 | 0:51:17 | 1:16:50 | 0:25:00 |
| Tugs | 415 | 1:06:38 | 22:30:35 | 2:43:44 |
| NA | 49 | 2:41:34 | 16:39:45 | 3:58:39 |
| Grand Total | **2523** | **1:20:48** | **23:50:32** | **3:11:23** |

**Table 4-4.Lower Lock Approach Dwell Time Summary at Lock and Dam No. 05, 4-hr Window.** The following table is a summary using data from 2021 November 01 and 2025 November 01. (Accessed Nov 05, 2025; www.ndc.ops.usace.army.mil/ords).

| | Count | Average | Max | StdDev |
|---|---|---|---|---|
| Fishing | 30 | 1:06:38 | 2:03:29 | 0:34:17 |
| Other | 438 | 0:54:09 | 3:59:40 | 0:50:20 |
| Passenger | 79 | 0:24:23 | 1:13:32 | 0:09:48 |
| Pleasure | 54 | 0:10:50 | 0:17:04 | 0:03:47 |
| Sailing | 1 | 0:15:00 | 0:15:00 | |
| Spares for local vessels | 96 | 1:00:35 | 2:22:40 | 0:33:44 |
| Towing | 1268 | 0:57:46 | 3:46:09 | 0:38:52 |
| Towing astern | 3 | 0:51:17 | 1:14:31 | 0:25:00 |
| Tugs | 398 | 0:57:36 | 3:42:30 | 0:40:58 |

| | | | | |
|---|---|---|---|---|
| NA | 39 | 1:04:32 | 3:35:49 | 0:50:38 |
| **Grand Total** | **2406** | **0:55:14** | **3:59:40** | **0:41:29** |

## 4.3 Navigation by Season and Flow

When aligning the navigation data to the flow data, January–March has the lowest low flow and vessel traffic). The outflows typically range from 20,000 to 40,000 cubic feet per second (cfs). Commercial traffic is lightest at 0–5 lockages per day, with no recreational use. Ice may occasionally slow operations or cause closures (Table 4-5).

In the spring and early summer, April–June, the snow melt and rain increase the outflows. Commonly, outflows range between 60,000–120,000 cfs, with flood peaks occasionally exceeding 150,000 cfs. Northbound fertilizer and ammonia barges increase, while recreational traffic begins by mid-May. Daily lockages rise to 10–12 on weekends. Higher flows can require cautious gate adjustments, extending average commercial processing to 50–55 minutes, though delays remain rare.

In the mid-summer to early fall, July–September, peak recreation, moderate to high flow): Outflow averages 35,000–100,000 cfs. Weekend recreational lockages can surpass 24 cycles, accommodating hundreds of pleasure craft batched up to 40 per cycle (this ignores a single event of 99 in LPMD which could have been a QA issues or perhaps a canoe gathering event). Commercial traffic is steady at 4–6 lockages per day. Commercial tows maintain priority, with minimal delays.

Lastly in fall, October–December, grain harvest rush, falling stages: This period sees the highest tonnage. Outflow generally falls to 20,000-35,000 cfs. Downbound grain tows of 15 barges become routine (requiring a cut barge passage), boosting daily commercial lockages to 6–9. Recreational use drops after Labor Day weekend.

**Table 4-5. Summary of Navigation Exceedance Probability (Q10, Q50, and Q90).** Based on long-term record ~1929 to present.

| Exceedance Probability | Discharge (cfs) | Typical Conditions |
|---|---|---|
| Q10 | 94,500 (90,000 - 100,000) | High-flow conditions. Occurs mainly during spring snowmelt/flood peaks. Outdraft hazards likely, cautious gate ops, slower lockages. |
| Q50 | 31,200 (30,000 - 35,000) | Normal/average conditions. Typical baseflow, fall through early spring. No major outdraft issues. |
| Q90 | 14,800 (14,000 - 16,000) | Low-flow conditions. Common in winter. Light commercial traffic, possible ice issues. |

## 4.4 References

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# 5. Biology of Invasive Carp

## 5.1 Hearing Capabilities

Invasive carp, primarily referring to four species introduced to North America (i.e., silver carp [*Hypophthalmichthys molitrix*], bighead carp [*H. nobilis*], grass carp [*Ctenopharyngodon idella*], and black carp [*Mylopharyngodon piceus*]), belong to the family Xenocyprididae (ostariophysan fishes). Invasive carp and other Ostariophysi have specialized sensory adaptations that contribute to their ecological success as invaders. Weberian ossicles, a series of modified vertebrae that connect the swim bladder to the inner ear, enhance their auditory sensitivity compared to fish lacking this structure. As filter-feeding or predatory planktivores (bigheaded carps), herbivorous, macrophagous feeders (grass carps), molluscivores benthic feeders (black carp), their hearing and vision play key roles in predator avoidance, feeding, and orientation (Nissen and Mensinger 2023).

Carp has been studied extensively over the years due to their easy access. Popper (1972) examined pure-tone auditory thresholds in *Cyprinus carpio* and determined that this species could hear pure tones from 50 to 3000 Hz, with maximum sensitivity between 300 and 1000 Hz, where thresholds were below −34 dB (*re* 1 µbar). The thresholds for this species from 50 to 1500 Hz are similar to thresholds determined by a number of other species in the same superorder of the teleosts (Ostariophysi) (Popper 1974, Fay and Popper 1974). Using auditory brainstem response (ABR) techniques, it was established that goldfish (*Carassius auratus*), when presented with tone bursts delivered through a transducer mounted in air above the holding tank, produced reliable ABR responses from approximately 100 Hz to 5,000 Hz, and that the resulting ABR audiograms closely matched audiograms obtained through behavioral/psychophysical methods, validating the ABR approach as a non-invasive electrophysiological tool for characterizing fish hearing sensitivity (Kenyon et al. 1998, Yan et al. 2000).

Within bigheaded carps, Silver and Bighead carp hearing have been extensively studied due to interest in acoustic deterrents for invasion control (Nissen 2023). Lovell et al. (2006) served as a basis for the potential of acoustic fish guidance systems and for the development of a Bio-acoustic Fish Fence (BAFF) as an acoustic fish deterrent. In this study, Auditory Brainstem Response (ABR, a form of auditory evoked potentials or AEPs) in a pressure-dominated design was used to measure thresholds (N = 10 fish per species). They reported peak sensitivity at 750–1500 Hz, with lowest thresholds around 104–106 dB re 1 µPa SPLrms, and detection up to ~2000–3000 Hz in both species.

In the Vetter et al. (2018), study emphasized the role of particle acceleration in low-frequency detection and highlighted methodological improvements to produce more accurate audiograms for deterrent design. Vetter et al. (2018) reexamined Silver and Bighead carp hearing using the evoked auditory potential (AEP) method and included particle acceleration (N=5 fish per species) testing 100 Hz to 9 kHz tones. They found broader detection (responses to 5 kHz) and lower thresholds, with the lowest at 500 Hz (Silver carp: 80.6 ± 3.3 dB re 1 µPa SPLrms, Bighead carp: 90.5 ± 5.8 dB re 1 µPa SPLrms). Silver carp were more sensitive than bighead carp at multiple mid-frequencies (500–3000 Hz). Thresholds rose sharply above 3000 Hz, but responses persisted to 5000 Hz (~140–142 dB re 1 µPa). Silver carp thresholds were generally lower than common carp (European or Eurasian carp, *C. carpio*) at comparable frequencies. Vibration (or particle motion) aspects are integrated into these AEP studies, highlighting that at low frequencies, these species hear using particle motion (acceleration) induced overpressure. Vetter et al. (2018) confirmed that Silver and Bighead carp detect particle motion effectively below ~500 Hz, which is relevant to boat motor or propeller vibrations that trigger jumping (Silver carp) or avoidance (Bighead carp).

As a follow-up by Nissen et al. (2019), temporary threshold shifts (TTS) were examined to determine safe, effective sound levels for long-term deterrents, avoiding habituation or injury. To a 30-minute broadband sound exposure at 155.7 ± 4.7 dB re 1 µPa SPLrms, Bighead carp exhibited greater TTS and slower recovery than silver carp, though both recovered within hours without permanent damage (using the AEP method).

Grass carp and black carp have received far less attention for their auditory capabilities. As Xenocyprididae, they possess Weberian ossicles and are presumed to have comparable hearing range and sensitivity to bigheaded carps, but behavioral trials show they are much less responsive to broadband deterrent sounds. In mixed-species tests, grass carp rarely exhibit the strong avoidance or jumping seen in silver carp, suggesting either higher thresholds or weaker behavioral coupling to auditory stimuli. ERDC has tested all four species using a rapid assay approach to better understand their response to different stimuli (patent pending). For grass carp, the lowest SPL threshold was at 0.3 kHz (87.0 ± 3.6 dB re 1 µPa SPLrms). For black carp, the lowest SPL threshold was also at 0.3 kHz (93.4 ± 3.0 dB re 1 µPa SPLrms), with AEP responses detectable from 0.2 to 4 kHz in both species (Nissen and Messinger 2023). ERDC has continued to find acoustics stimuli for adding signals to the signal playback at Lock No. 19.

### 5.1.1 100 Hp Outboard Playback

There are various descriptions of the 100 Hp playback used in Murchy et al. 2016 and 2017 and Vetter et al. 2015 and 2017. In conversations, ERDC determined that the same

100 Hp outboard motor playback was used for each publication (personal communications with Vetter and Murchy, 2017). The spectrogram provided illustrates a characteristic underwater acoustic recording of a vessel passage, known in the above literature as a "100 Hp outboard motor" playback (Figure 5-1). Analysis reveals that the signal is representative of an outboard motor noise (a light watercraft likely recreational, e.g., small boat or similar) near a surface-deployed hydrophone gear noise.

The waveform (top panel of Figure 5-1 A) shows a gradual amplitude ramp-up over approximately the first 19 seconds, peaking around the closest point of approach (CPA) by the vessel, followed by a decay. This envelope reflects geometric spreading loss as the source approaches, passes, and recedes from the receiver.[4] The amplitude increases from low levels (~0.15 V) to a maximum (~1 V) near CPA, then decays asymmetrically to ~0.18 V.

The spectrogram (bottom panel of Figure 5-1) displays broadband frequency content consistent with the published characterization of this recording (~60 Hz to 10 kHz; 0.06–10 kHz as reported in Murchy et al. 2016, 2017 and Vetter et al. 2015, 2017), with energy concentrated in lower- to mid-frequencies during approach and passage. Prominent curved streaks in the mid-to-high frequencies are indicative of Doppler-shifted engine harmonics: as the vessel's range changes, the continuous tonal harmonic components of the engine sweep upward in frequency during approach (Doppler upshift) and downward in frequency post-CPA (Doppler downshift), producing the characteristic curved bands in the spectrogram. These Doppler-induced tonal sweeps are distinct from propeller cavitation noise, which contributes broadband non-tonal energy but does not produce the discrete curved streak patterns.

Post-passage, distinct vertical bands (Figure 5-1 Top) highlight white arrows in similar recordings) appear as broadband impulses or bursts, primarily in the lower frequencies. These arise from water lapping, splashing, or turbulence interacting with the hydrophone's surface-mounted tethering/anchoring platform and wake-induced surface disturbances. Such hydrodynamic noise introduces irregularities and artifacts that are not attributable solely to the propulsion system of the vessel.

Additionally, the signal exhibits amplitude distortion artifacts consistent with either digital clipping — hard saturation occurring when the signal level exceeded the maximum input range of the analog-to-digital converter at the time of recording — or dynamic range

[4] Note is not equivalent to a Doppler effect. A Doppler effect applies exclusively to frequency shifts, not amplitude. Often due to confusion on the underpinning of a Doppler effect compared to perceived auditory effects.

compression introduced by automatic gain control (AGC) circuitry in the recording equipment. These are distinct phenomena: clipping produces hard waveform truncation and harmonic distortion, while AGC produces level-dependent gain modulation across the signal. Either artifact would have been present at the time of original data collection and is not attributable to anti-aliasing filtering, which removes frequencies above the Nyquist limit but does not affect amplitude fidelity. This processing signature distorts the acoustic fidelity to some extent.

The total duration is approximately 35 seconds, encompassing the full approach, passage, and wake sequence. In summary, the 100 hp playback used in Murchy et al. (2016, 2017) and Vetter et al. (2015, 2017) is not a pure representation of the noise from a 100-horsepower outboard motor in isolation; rather, it represents a light watercraft passing a near-surface hydrophone, incorporating Doppler frequency shifts on engine harmonics, geometric spreading amplitude variation, hydrodynamic wake noise, and recording artifacts. This distinction is critical for interpreting behavioral responses in invasive carp studies, as the effective stimulus includes both non-propulsive elements (e.g., surface splashes, wake turbulence) and propulsive elements (e.g., engine broadband noise, propeller cavitation).

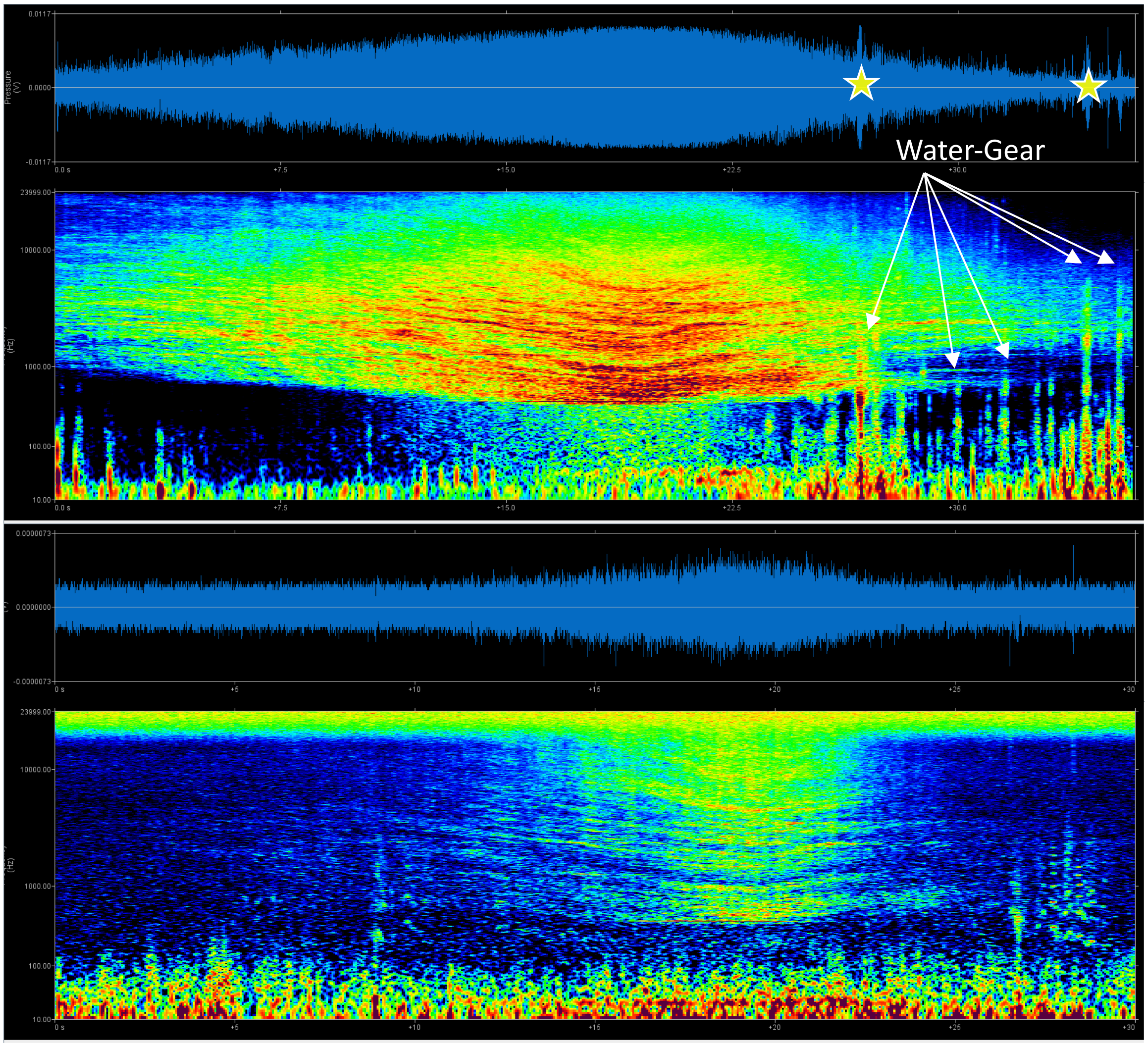


**Figure 5-1. Spectrogram of 100 Hp Outboard Recorded Playback.**

### 5.1.2 ERDC Engineered Signal Development

For the underwater acoustics deterrent system (uADS), experiments conducted at the U.S. Army Engineer Research and Development Center (ERDC), Cognitive Ecology and Ecohydraulics Research Facility (CEERF) flume, heat maps were generated to visualize the spatial distribution and behavioral responses of bighead carp (*Hypophthalmichthys nobilis*) to developed acoustic signals. These signals, designed as broadband stimuli mimicking vessel passages (e.g., incorporating Doppler-shifted harmonics and hydrodynamic noise), were projected underwater to elicit avoidance behaviors relevant to invasive species management. The flume setup consisted of a linear channel with partitioned sections, including a central constriction or baffle to simulate flow dynamics, allowing for controlled observation of fish movement under quasi-natural conditions.

In Figure 5-2, the panels provide a baseline grayscale view, highlighting structural elements such as vertical dividers and the hourglass-like constriction that may influence hydrodynamic cues. Each heat map panel overlays color-coded density contours on grayscale photographic images of the flume, where cooler colors (blue) represent low occupancy or transient passage, while warmer colors (yellow to red) indicate high-density hotspots corresponding to prolonged aggregation or hesitation points. For instance, in the first example, the Left Top panel (Figure 5-2) reveals dispersed low-density trails along the flume's length, with focal hotspots (yellow-red) near the central baffle and downstream sections, suggesting exploratory behavior. In a subsequent trial (Figure 5-2), intensified clustering is evident in the downstream regions, with red hotspots denoting strong avoidance responses proximal to the signal source, potentially reflecting particle motion sensitivity at lower frequencies (< 500 Hz). This pattern aligns with electrophysiological data indicating elevated thresholds in bighead carp compared to silver carp, leading to delayed or clustered retreats. Another variant (Figure 5-2, Right), displays fragmented trails with isolated red nodes, indicative of erratic movements post-signal onset, possibly due to temporary threshold shifts.

These visualizations show fish clustered downstream of the signal source in trials 2 and 3, consistent with avoidance of the high intensity zone, with hotspots correlating to signal nodes (e.g., via geometric spreading and multipath interference). Quantitative analysis via kernel density estimation confirmed statistically significant shifts in occupancy ($p < 0.05$, Kolmogorov-Smirnov test), supporting refined signal designs for field applications in riverine barriers (Woodley et al. 2019).

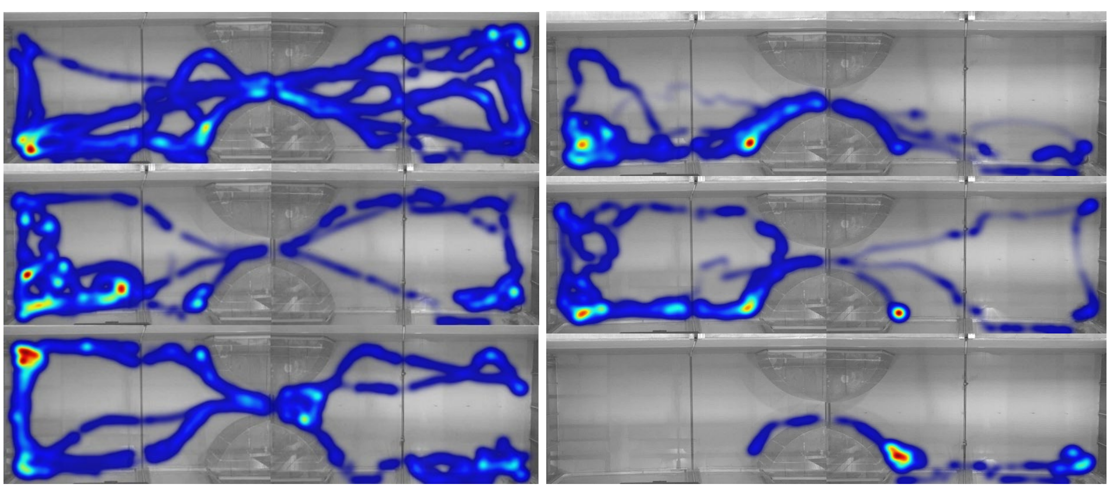

**Figure 5-2. Heatmaps of Bighead carp movement relative to several engineered playbacks at 140 dB re 1µPa.** (Left Top) Ambient. (Left Middle) 100 Hp Playback 0-19 secoNSDs. (Left Bottom) Square waveform, low pass 6000 Hz. (Right Top) Square waveform Low Pass

6000Hz). (Right Middle) Sine waveform Low Pass 6000 Hz. (Right Bottom) Chirp Log Low Pass 5000 Hz.

## 5.2 Vision

Vision in bigheaded carps is adapted for the turbid, plankton-rich waters they inhabit. Spectral sensitivity data specific to invasive carps are limited, but as xenocypridids, they possess a duplex retina with multiple cone types (likely UV, blue [460 nm], green [520 nm], and red-sensitive cones [620 nm]) plus rods, conferring potential tetrachromatic color vision like common carp (*Cyprinus carpio*) (Kaneko & Tachibana 1985, Zaunreiter et al. 1991). Behavioral responses to strobe lights and colored LEDs in deterrent trials confirm functional photopic (bright light) vision. High-intensity light is a relatively inexpensive, easy to deploy and NSD that can be used in low turbidity or shallow waterways. Dennis & Sorensen (2020) demonstrated that light-response as a behavioral NSD can be species- and situation-specific, and that high-intensity constant light has promise to block Bighead Carp in both dark and dimly lit environments without strongly blocking largemouth bass (*Micropterus salmoides*). In dimly lit environments, constant light was more effective that strobing light.

Electroretinography (ERG) studies of dark-adapted visual sensitivity reveal rapid dark adaptation and high scotopic (low light) sensitivity. Dark-adapted *H. molitrix* and *H. nobilis* possess broad visual sensitivity between 470–620 nm, with peak scotopic spectral sensitivity at 540 nm for *H. molitrix* and 560 nm for *H. nobilis* — valves reflecting rod-dominated sensitivity and distinct from the photopic cone peak wavelengths described above (Vetter 2018, 2019). After exposure to strobe light, both silver and bighead carp recover baseline sensitivity within 30–45 minutes, faster than many freshwater fishes. Threshold irradiance for detectable responses was extremely low ($\sim 10^{-6}$ μmol $m^{-2}$ $s^{-1}$), indicating excellent rod-dominated vision under dim conditions. The results suggest that strobe lights can temporarily depress visual sensitivity, which may render optical barriers less effective (Vetter et al. 2018, 2019).

Grass carp, being primarily herbivorous, may rely more on vision for locating macrophytes in clearer waters than the planktonic bigheaded carps. Retinal morphology studies on related cyprinids suggest a higher cone: rod ratio in grass carp, potentially favoring better acuity in brighter conditions, but no ERG or behavioral threshold data exist specifically for invasive populations. Black carp, as molluscivores, likely have vision tuned for benthic prey detection, but peer-reviewed sensory studies are absent.

Bubble deterrents (often called bubble or oblique curtains or screens) are non-physical barriers that release air bubbles to create a "wall" in water, deterring fish movement.

These deterrents engage auditory (from bubble oscillation and collapse, generating broadband acoustic fields that overlap carp hearing ranges), visual (from semi-opaque wall produced) and lateral line/tactile (from microcurrents of the moving bubbles, causing water turbulence and pressure changes, disorienting fish and making crossing uncomfortable) sensory systems. In lab trials using common carp as a proxy for Bigheaded carps and later bigheaded carps, graded- and coarse-bubble curtains reduced upstream and downstream passage by 75–85% (Zielinski et al. 2014). The curtains generated acoustic fields overlapping carp hearing frequencies, contributing to avoidance (Zielinski et al. 2014). Similarly, Zielinski and Sorensen (2016) showed that laboratory tests with a bubble curtain deflection screen diverted 73–83% of invasive carp from crossing. Effectiveness was attributed to a combination of sound, fluid motion, and visual cues, making it a simple, safe option for reducing passage in streams or channels. This was further supported in Martin et al. (2021), where laboratory experiments conducted on common carp showed bubble curtains with resonant bubbles deterred common carp more effectively, influencing passage rejection via acoustic and hydrodynamic stimuli.

Overall, sensory research on invasive carps is focused on bigheaded species (Silver and Bighead), because of the urgent need for non-physical barriers. Silver carp emerge as the most acutely sensitive to both sound and light changes, while bighead carp are slightly less responsive. Based on extremely limited data, grass and black carp appear less amenable to acoustic or visual light deterrents, highlighting the challenge of developing one-size-fits-all controls for the invasive carp complex.

Based on invasive carp sensory auditory and visual capabilities, the use of broadband sound spanning approximately 0.06–10 kHz (60–10,000 Hz) effectively repels bigheaded carps, and combined sound-light-strobe systems show additive deterrent effects. Understanding species-specific differences is critical for optimizing deterrents within lock structures, while minimizing impacts on native fishes.

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# 6. Technology Deep-Dive

## 6.1 BAFF System

Fish Guidance systems offer four options for fish deterrence (Accessed 2025 OCT 30; www.fgs.world). The Sound Projector Array (SPA) system deters fish with acoustic signals, encouraging movement away from the array. This system uses underwater speakers that produce a repellent sound gradient to block intakes and channels. High Intensity Light (HIL) systems function with acoustic solutions to provide secondary stimulus for some species. Synchronized Intense Light and Sound (SILAS) systems use light bars and acoustic stimuli to guide or deter multiple species. The Bioacoustics Fish Fence (BAFF) uses acoustic signals, directional strobe lighting, and an air-bubble curtain to create a locally contained sound field.

The BAFF is a multi-stimulus fish deterrent that integrates high-intensity LEDs, modulated intense lights (MILs), air bubble deterrents (ABDs), and a sound projector array (SPA) for bioacoustics (Bowen et al. 2009, Bowen and Bark 2015, Fritts et al. 2023), distinguishing it from the uADS (Cupp et al. 2021). The ABD refracts and “contains” sound (according to the FGS) producing a sharply defined sound field that fish detects only when they are near the deterrent. The MILs are oriented so their beams project onto the bubble curtain, enabling fish to identify the bubbles and locate the sound. The narrow, vertical MIL beam also minimizes light saturation in the experimental area. The BAFF allows for steady or flash rates of SPA and MILs to be adjusted to match the sensory sensitivities of different fish species.

Research shows that the most effective acoustic deterrents for various fish operate in the 30–600 Hz frequency range (Bowen and Bark 2015); however, for invasive carp, this range could be extended up to 5000 Hz (Vetter et al. 2018). Studies involving Chinook salmon demonstrate at Georgiana Slough, California, that adjusting sound and strobe light flash rates to species-specific sensitivities significantly increases deterrence or guidance of the BAFF, especially for juvenile Chinook salmon (Bowen et al. 2009).

### 6.1.1 Patent review (FGS UK patents)

The Bio-Acoustic Fish Fence (BAFF) system, developed by Fish Guidance Systems, Ltd. (FGS) in the United Kingdom, represents one of the first non-structural fish deterrence technologies. FGS was co-founded by Dr. Andy Turnpenny, a fisheries scientist who had led fish screening research at UK power stations from the 1980s, and Dr. Jeremy Nedwell, an underwater acoustician. The system's principles emerged from two converging lines of work: Turnpenny's need to protect fish from large water intakes — where traditional physical screens were impractical — and Nedwell's naval acoustics research into communicating with submarines without detection. A founder of FGS realized these acoustic principles could be applied to fish guidance, leading to the development of the BAFF, which was awarded a Queen's Award for Innovation in 2001. The core technology leverages the acoustic impedance contrast created by an air bubble curtain to contain and localize a sound field — a mechanism FGS describes as creating a "wall of sound" — producing a sharply defined acoustic boundary that fish detect only when they are near the deterrent. This innovation was patented as part of FGS's early work on acoustic deterrents[5], with core patents filed under the UK Intellectual Property Office (UK-IPO) intellectual property framework.

The primary UK patent underpinning the BAFF is GB9913896.8 (Accessed 28 November 2025; www.search-for-intellectual-property.service.gov.uk/GB9913896.8), documents titled "Electroacoustic transducer units for underwater use," though it is in a "Not in Force" status – likely due to upgrades the company was making and placed the IP on hold.

In 2010, a second patent, titled "Deterring underwater animals from an underwater region," was filed (GB2469603; Accessed 28 November 2025; www.search-for-intellectual-property.service.gov.uk/GB2469603). This patent describes a system combining lights and underwater sound that are intermittently pulsed with modulated repeatability and the ability to synchronize. The US counterpart to this patent, US2013139761A1, was published in 2013 as part of the same patent family. At the time, it was believed that light and sound synchronization had a synergistic effect on the deterrence of underwater animals.

> "In order to deter underwater animals from an underwater region such as adjacent the entrance to an offtake pipe or channel from a river, sound and light are produced in the underwater region and are intermittently pulsed and/or at least one characteristic of the sound and light is repetitively modulated. At least some of the pulses of light and/or the occurrences of at least one feature in at least some of the light modulation repetitions are substantially synchronized with at least some of the pulses of sound and/or the occurrences of at least one feature

[5] In review of the FGS websites, associated literature, and patents, the BAFF is often referred to as a barrier. For our purposes, since the system is non-structural, we will refer to it as a "deterrent". To date, all non-structural systems have a weakness in the technology and thus should not be considered a "barrier" as the term "barrier" infers blocking or 100% effectiveness.

> in at least some of the sound modulation repetitions," (Nedwell JR, 2010. GB2469603. Fish Guidance Systems Ltd., UK Intellectual Property Office).

In July 2016, UK patent application GB1613141.9 was filed, subsequently published as GB2552780, describing an acoustic device for forming a wall of sound underwater using an acoustic waveguide — compressible projections (typically neoprene, arranged in a fan or frond shape) connected to a transducer — that propagates sound along the projections without requiring a bubble curtain. Later, a similar-titled patent was filed in the US (US2013139761A1; Accessed 28 November 2025; www.worldwide.espacenet.com/patent/search/family/042777054/publication/US2013139761A1?q=pn%3DUS2013139761A1) with more descriptions, claims, and drawings than the prior patent[6]. The "patent family" indicated that this patent had been filed with several countries between 2010 and 2015, and that some changes were noted between applications. The US counterpart to this patent, US10388267 (published as US20180033423 in February 2018), contains expanded descriptions, claims, and drawings:

> "The acoustic device comprises an acoustic transducer 2 connected to an acoustic waveguide 16, 18. The waveguide comprises one or more projections, whereby sound generated by the transducer travels along the projection or projections to form the wall of sound. The waveguide may comprise compressible projections formed from neoprene and arranged in a fan or frond shape. Alternatively, the projections may be laminar. The projections could be of different lengths. The location, arrangement and lengths of the projections are all suited to the underwater location to maximize the effectiveness of the wall of sound," per (Nedwell JR, 2018. US20180033423 / US10388267. Fish Guidance Systems Ltd., US Patent and Trademark Office).

As of 2025, a system and method for deterring or guiding fish was filed GB2514426.2 with no further details available.

Challenges in patent enforcement include proving efficacy in variable riverine conditions, where flow velocities (> 1 m/s) can disperse bubbles, reducing the evanescent field's integrity. FGS has defended these in opposition proceedings, citing field data from sites

[6] The second US patent is likely an expansion of the prior patent. There were more details and drawing were likely computer generator. It is possible that the site used to access the UK patent data did not have a full holding of the original patent and thus, we were unable to see all the details.

such as the Hinkley Point C nuclear plant (Accessed 02 DEC 2025; www.fgs.world/hinkley-fish-deterrent/).

In summary, FGS's UK patents have been in place for two decades of iterative design to develop a versatile tool for ecosystem protection. Their emphasis on modularity and multi-sensory stimuli positions BAFF as a scalable solution, though ongoing R&D addresses site-specific adaptations.

### 6.1.2 Component specifications

The BAFF system comprises several components, according to its website, data releases, and patents. It is reasonable to assume that the number and specifications of components would be tailored to Lock and Dam No. 05, depending on placement and desired effects. In addition, due to the pending patent, the component specifications below may have been upgraded. The entire system is engineered for 24/7 unattended operation, remote monitoring, and fault detection. Annual maintenance is required (diver inspection/cleaning of projectors and bubble pipes). Note, below are the general components and thus each system is designed to the goal and deployment scenario.

- Proprietary System. Some components of the BAFF are proprietary. Non-disclosure agreements will need to be negotiated between federal and state partners for this system to be leased, installed, operated, and maintained.

- SILAS® Central Control Unit. The BAFF uses a rack-mounted industrial controller that continuously monitors every subsystem, provides real-time status, logs faults, and generates visual/audible alarms. The unit is equipped with Ethernet and cellular telemetry, so lock operators can view system health and, if needed, turn the deterrent on/off from the existing Barkley control room (Figure 6-1). Remote monitoring could be done from on-site, or remotely.

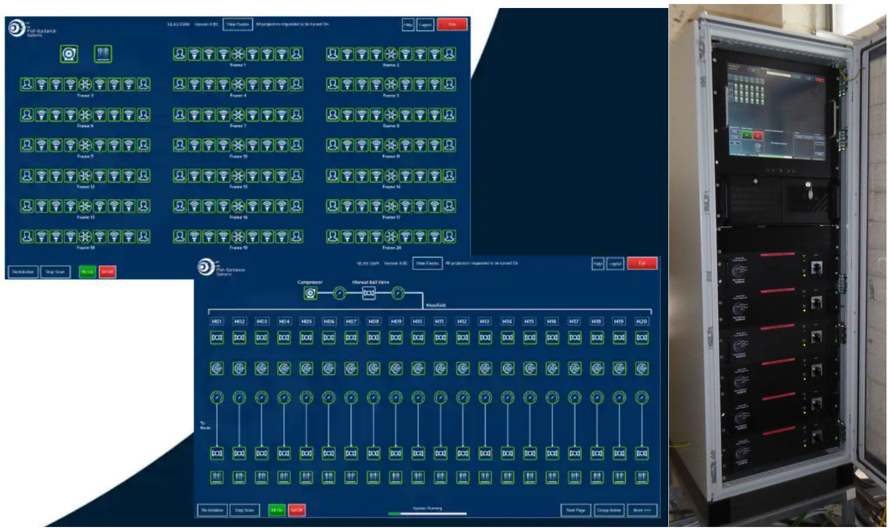


**Figure 6-1. Example of the BAFF SILAS Central Control Unit.** The equipment is housed in a control enclosure (Accessed 2025 DEC 07; Lambert 2023).

- Control Equipment Enclosure. The BAFF uses NEMA-4X stainless or painted steel cabinet located on the lock wall or guidewall containing the SILAS controller, all Model 1500 PSUs, circuit breakers, surge protection, and cooling/heating to ensure year-round operation in the Cumberland River climate (Figure 6-1).

- Power Control Units, such as Model 1500 Power Supply Units (PSUs). The BAFF uses single-phase, shore-based, weatherproof 120/208 V AC → 48 V DC power converters. Each Model 1500 PSU powers and communicates with up to six (6) underwater sound projectors. Multiple PSUs are installed in parallel inside the control enclosure to serve the full array.

- Underwater Power & Communication Hubs. The BAFF uses sealed submersible junction boxes that are mounted directly on each deployment frame. Each hub distributes 48 V DC power and digital audio signals to (maximum) 6 sound projectors and serves as the collection point for sensor feedback.

- Armored Power and Signal Cabling. In order to power and control the subsurface structure, the BAFF uses main power trunks from shore enclosure to each underwater hub. Two redundant SILAS data cables daisy-chained hub-to-hub for continuous system diagnostics.

- Flying Leads. The flying leads are short (3–5 m), heavily armored, wet-mateable cables connecting each hub port to an individual sound projector.

- **FGS MkIII 30–600 Sound Projectors.** The BAFF uses third-generation broadband underwater loudspeakers with integrated DSP amplifiers. These units generate the complex, high-intensity acoustic field proven to elicit strong avoidance in invasive carp (based on 2012 Georgiana Slough report and a Kaveh Someah presentation, sound production maximum *could be* 150-170 160 dB re 1 µPa across the target frequency band) (Figure 6-2).

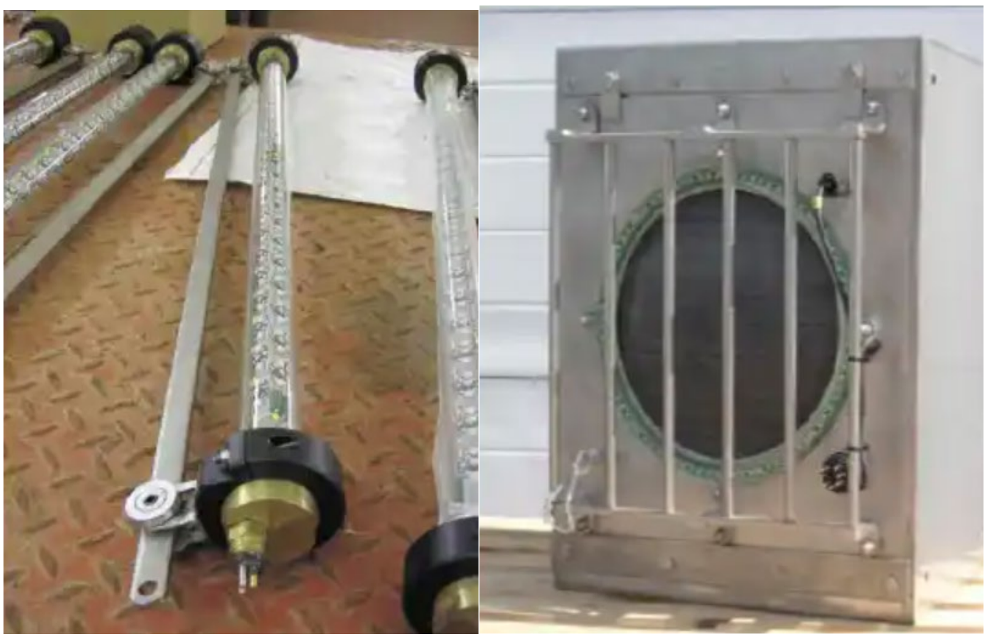


**Figure 6-2. Example of the FGS MkIII 30–600 Hz Sound Projectors and High-Intensity LED Strobe Light Bars.** (Accessed 2025 DEC 07; Photo credit: Turnpenny 2016)

  - **Acoustic Deterrent Signals.** The FGS acoustic signals used are proprietary, so their specifications are not available for discussion.

    - Based on Pegg and Chick (2004), they used two frequency ranges associated the test of the SPA-driven BAFF system that ranged between 20-500 Hz (repelled about 57% of Bighead carp from crossing the BAFF). They also tested 20-2000 Hz and found the repulsion rate increased to about 95% of the bighead carp attempts to cross the BAFF in a captive laboratory setting.

- **High-Intensity LED Strobe Light Bars.** Horizontally mounted LED arrays positioned immediately upstream of the sound projectors to create a continuous, blinding wall of light (Figure 6-2). Light bars are synchronized with the acoustic signal for maximum multimodal deterrence. Final placement and flash patterns will be reviewed and approved by USACE Navigation and the US Coast Guard to ensure no interference with vessel traffic.

- **Perforated Bubble Pipes.** Stainless-steel pipes running the length of the BAFF is drilled with precision orifices to produce a dense, uniform bubble curtain that couples low-frequency sound into the water column and provides a secondary visual and physical stimulus. Figure 6-6 provides an example of bubble curtain from overhead view at Georgiana Slough, CA) that uses two parallel flexible hoses per frame section. We assume that, due to velocity loss across a series of orifices, FGS would increase the compressor or pressure regulators through the system to achieve the flow rate (cfm) to offset the loss[7].

    - **For the BAFF at Barkley Lock and Dam,** six bubble pipes were deployed to provide the required bubble curtain. The initial estimate for the 197' BAFF system was estimated to require approximately 200 cfm. For the bubble pipe to be "self-cleaning" the air supply will need to be supplied by a constant flow compressor.

    - **For the BAFF at Georgiana Slough,** we do not have data on this, currently.

- **Shore-Based Air Compressors & Pipework.** For the BAFF system, rotary-screw three-phase compressors (one primary, one 100 % redundant) are used with receivers, dryers, filters, and high-pressure polyethylene delivery lines feeding the underwater bubble pipes.

- **Modular Deployment Frame System.** Lastly, the BAFF is deployed on a heavy-duty galvanized or stainless-steel frame that bolts together end-to-end across the downstream lock approach. Frames hold the sound projectors, light bars, bubble pipes, and underwater hubs at the optimal depth and alignment. Frames are lowered into

---

[7] The pressure loss in bubble aeration systems follows fundamental fluid dynamics principles. As air flows through the supply pipe and perforated diffusers, there are two primary sources of head loss: Frictional losses along the pipe walls (major losses), commonly calculated using the Darcy-Weisbach equation: $\Delta P = (f * L/D * \rho v^2/2)$ where $\Delta P$ is the pressure drop, f is the Darcy friction factor, L is the pipe length, D is the internal diameter, ρ is air density, and v is velocity. Minor losses from fittings, valves, and especially the diffuser orifices. At each diffuser orifice, the flow is governed by the orifice discharge equation: $Q = (C_d * A * (\mathrm{sqrt}(2\{\Delta P/\rho\})))$ where Q is the volumetric flow rate through the orifice, $C_d$ is the discharge coefficient (typically 0.6–0.8 for sharp-edged orifices in diffusers), A is the orifice area, and $\Delta P$ is the pressure difference across the orifice. Because flow through an orifice is proportional to the square root of the pressure difference (derived from Bernoulli's principle), a significant drop in internal manifold pressure from the first to the last diffuser causes uneven air distribution.

position, and placed so that underwater hubs are at the optimal depth and alignment.
to be raised individually for maintenance without dewatering the chamber.

The next section addresses some details and variations that we were able to locate of the BAFF deterrence at Georgiana Slough and Barkley Lock and Dam, respectively.

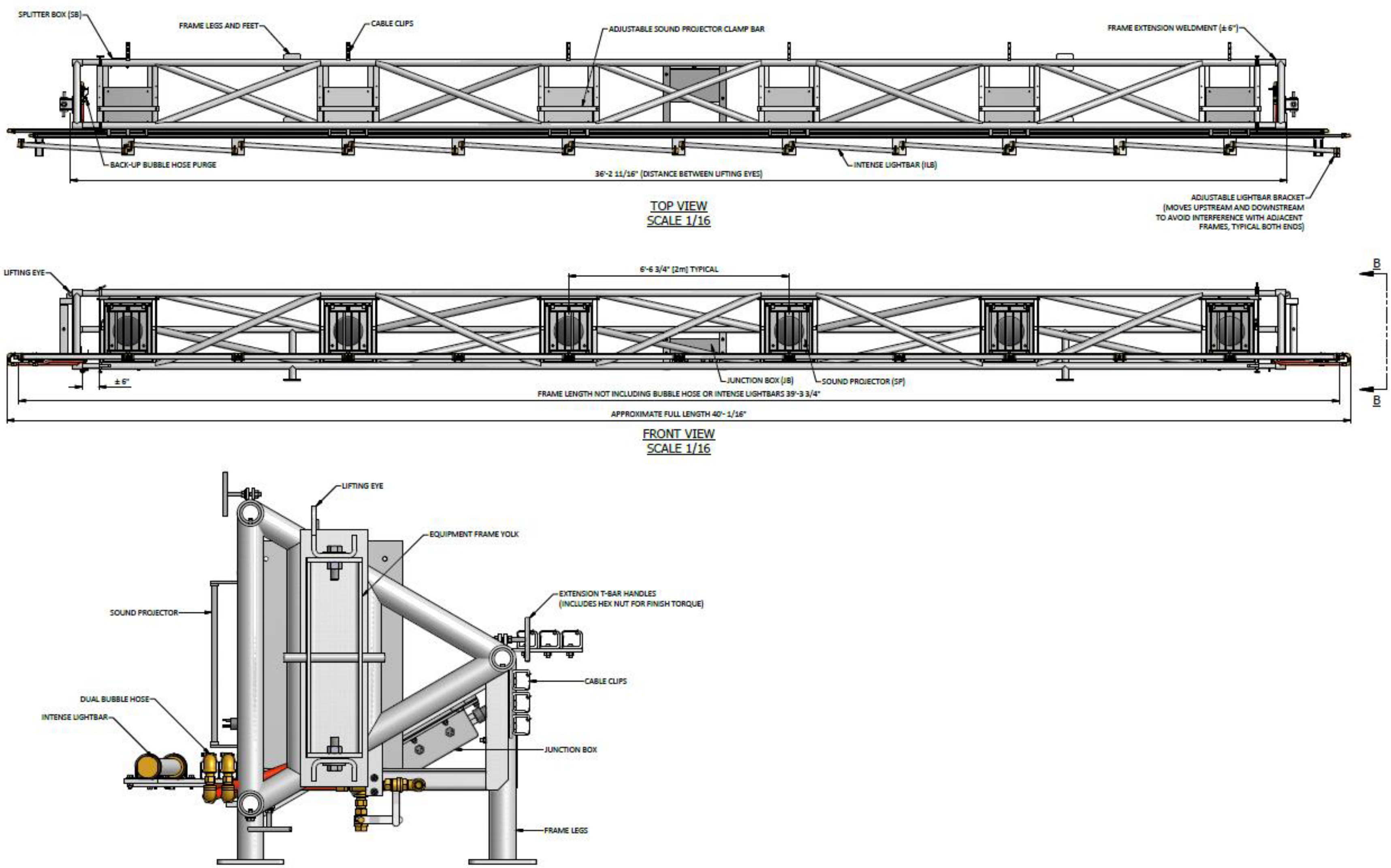



**Figure 6-3. Example of the BAFF modular deployment frame.** (TurnPenny 2016)

## 6.2 BAFF Deployment at Georgiana Slough, CA

The overall function of the BAFF at Georgiana Slough is quite different from that of the Barkley LD or LD05. The Georgiana Slough project involves installing and operating a BAFF at the Georgiana Slough junction for 8 years. The BAFF would be operated as a behavioral deterrent to prevent juvenile winter-run Chinook salmon and spring-run Chinook salmon from entering Georgiana Slough during emigration (primarily between October 1 through June 1). The Georgiana Slough Salmonid Migratory Barrier (GSSMB) is intended to reduce impacts of the State Water Project (SWP) and Central Valley Project (CVP) operations by deterring emigrating juvenile salmonid from entering Georgiana Slough and thereafter the central and south Delta, wherein survival is lower relative to remaining in the main-stem Sacramento River (ICF ESA JV D140883.38, May 2022).

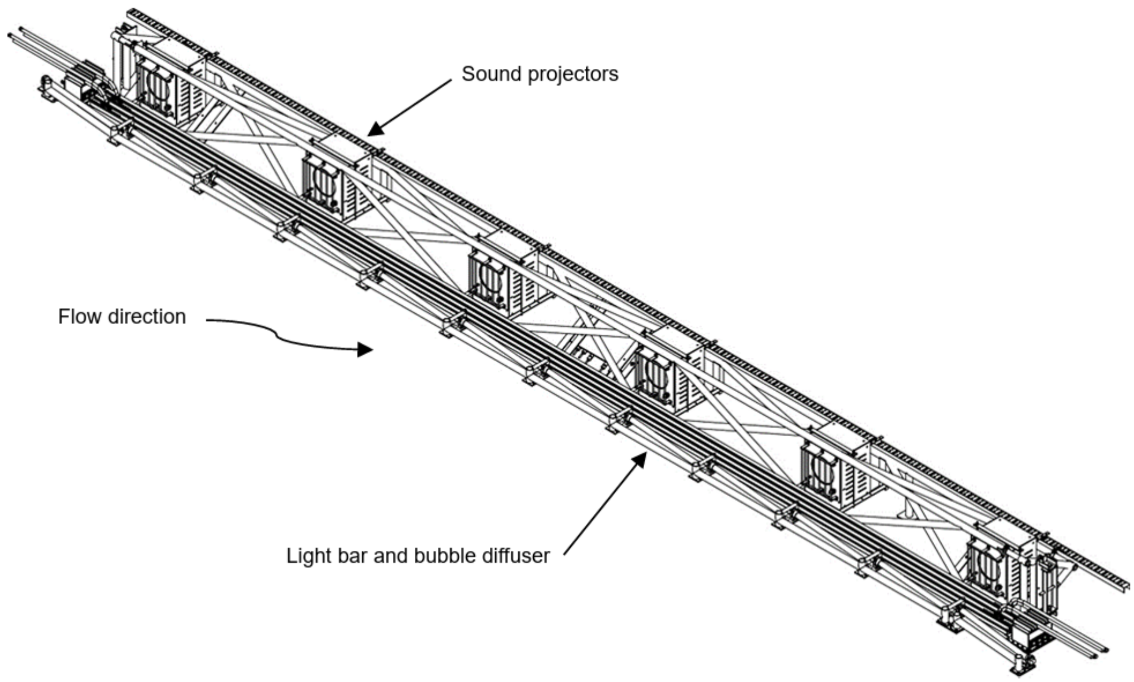
At this time, we are waiting for more data on the final design of the BAFF at Georgiana Slough. However, we have attached a brief description and figures that may spark ideas for installing non-structural devices at LD05.

Per the GSSMB Operations Plan (ICF ESA JV D140883.38, May 2022):

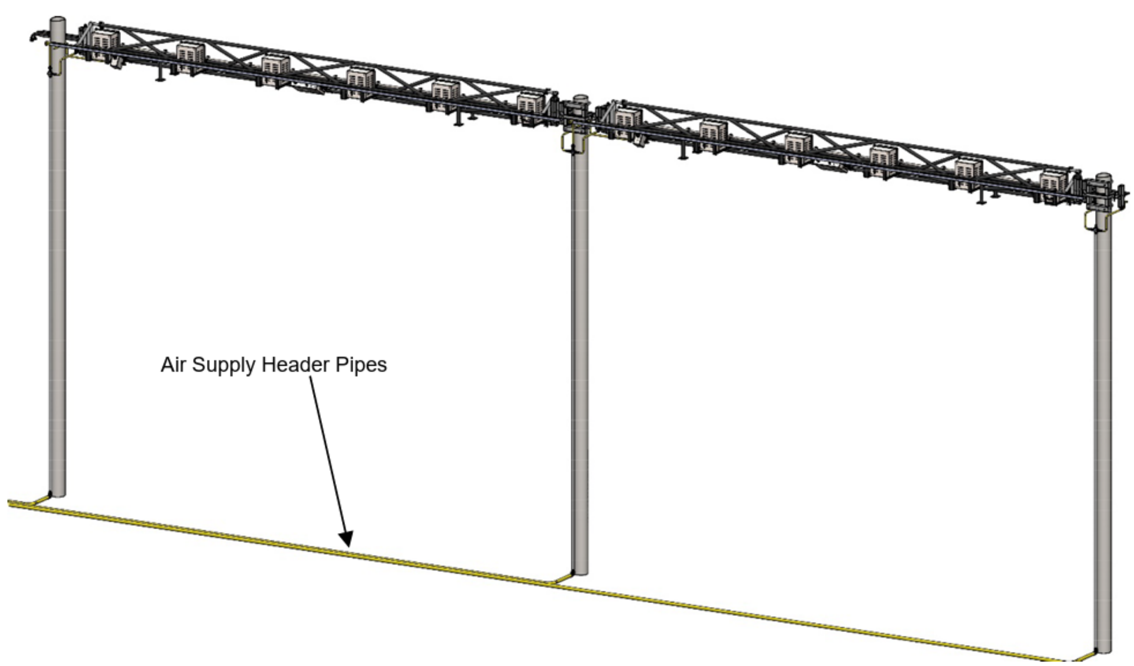
> "The BAFF, installed at the divergence of the Sacramento River and Georgiana Slough, would be up to approximately 800 feet long, comprising up to 20 separate 40-foot frame sections. Each frame section would have approximately six sound projectors, 12 MILs, and a perforated "bubble" pipe (Figure 6-4A). The bubble pipe would be positioned along each frame below and upstream of the sound projectors. A bubble curtain would be created by passing compressed air into the perforated pipe. Air flow rate would typically be 1.38 cubic feet per minute (cfm) per linear foot length of barrier. The MILs would be powered from an "accumulator" positioned on each frame section.
>
> A mounting plate would be attached to the support tray to house the accumulators. The junction of each frame section can pivot with the adjacent section, and where needed each frame section can be supported at either end with a piling or support column to a pier block. The frame sections could be adjusted vertically at the pile attachments to adjust for the uneven riverbed contour. The sections would be positioned along the barrier line such that its GSSMB Operations Plan 8 ICF ESA JV / D140883.38 (May 2022) Project Description effectiveness would be optimized. In the main portion of the channel, this is approximately 12 feet from the channel bottom (Figure 6-4B). The top of the frame sections would be at least 6 feet below the water surface elevation at low tide. The barrier frame would be supported by up to 31 piles (up to 24-inch-

diameter) in the riverbed. Up to four concrete pier blocks (up to 24-inchdiameter) would be situated in shallow water to ensure the system remains in alignment."

(*See next page for Figure 6-4, Figure 6-5*)




A) Three-dimensional rendering of BAFF frame with light, sound, and bubble diffuser components.




B) Three-dimensional rendering of BAFF frame suspended off riverbed on piles.

**Figure 6-4. Example of the BAFF modular deployment at Georgiana Slough, CA.**

**Figure 6-5. Installation of the BAFF at Georgiana Slough, CA.** (Top) BAFF Testing for Georgian Slough in Hood, CA (water.ca.gov/News/Blog/2023/Sep-23/DWR-Installs-Illuminated-Bubble-Barrier-to-Help-Young-Salmon-Migrate-Safely-Through-Delta). (Left) BAFF Components before installation at Georgian Slough. (Photo credit: Fish Guidance Systems, LTD). (Right) Seasonal removal of the BAFF at Georgian Slough (Photo credit: California Dept. of Water Resources; Accessed on 07 DEC 2025 https://x.com/CA_DWR/status/1930705561542066274).

Figure 6-6 highlights the overhead visibility of the BAFF at Georgiana Slough. The pulsating light bar functioning may also be seen in the following link for nighttime impacts (www.youtube.com/watch?v=VDkFh4Dz5hI California Department of Water Resources, 2023) and the following link for daytime impacts (x.com/CA_DWR/status/1930705561542066274) (California Department of Water Resources, 2025). From the Permit applications:

> "Based on DWR observations during the installation of a similar structure at Georgianna Slough in 2011 and 2012 and the Head of Old River in 2009 and 2010, and

the lighting for the proposed BAFF, substantial changes in visible light are not expected. Observations at the Head of Old River barrier concluded that nighttime lighting returned to ambient levels approximately 33 feet from the barrier. The turbid nature of the Sacramento River combined with the fast flows is expected to dissipate light emitted from the BAFF. No nighttime lighting would occur after the removal of the barrier." (https://water.ca.gov/-/media/DWR-Website/Web-Pages/News/Public-Notices/Files/DWR-GSSMB-IS-MND_Oct2021.pdf).

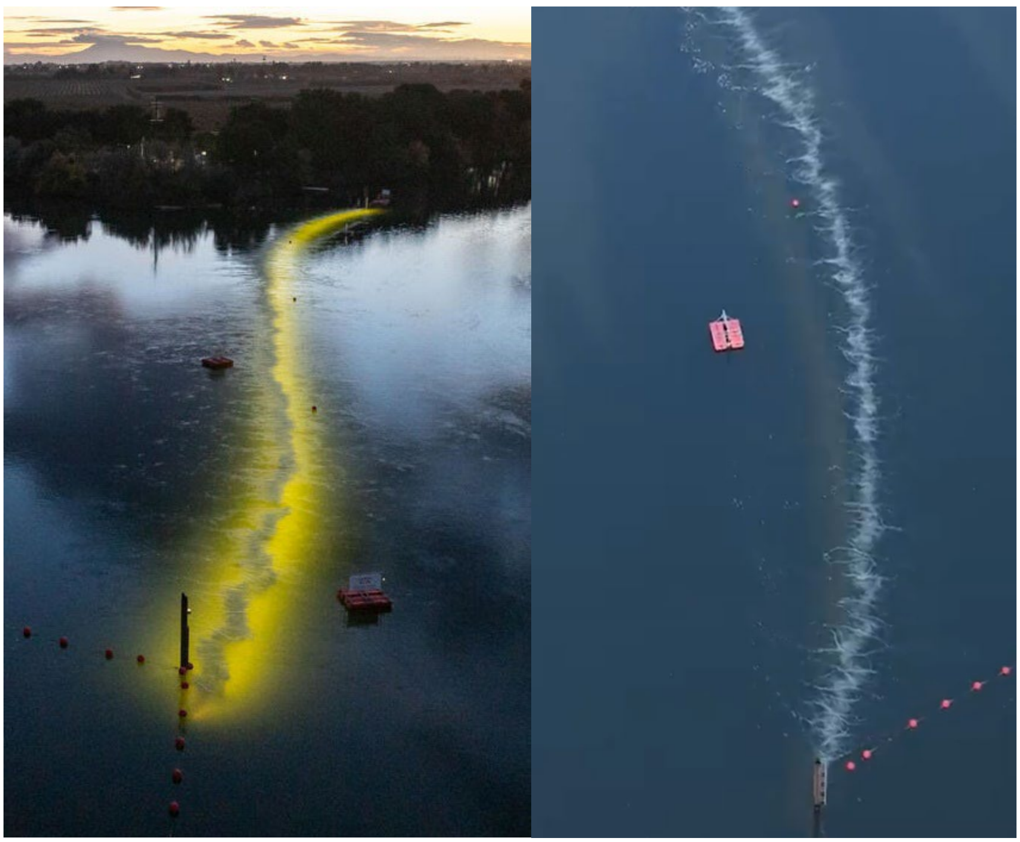


**Figure 6-6. Installed BAFF lightbar functioning at Georgiana Slough.** (Left) Nighttime light bar pulse ("on"). (Right) Daytime light bar pulse "on". California Department of Water Resources. (Accessed 07 DEC 2025; www.youtube.com/watch?v=VDkFh4Dz5hI; x.com/CA_DWR/status/1930705561542066274, respectively).

It is worth noting that the flow conditions at this location are quite different from those at Barkley LD and LD05; however, they are worth reviewing to better understand the design versus *in-situ* function. Where Georgiana Slough meets the Sacramento River, there is a possibility of a flow reversal due to tidal action. In the figure below (Figure 6-7), the top three diagrams illustrate how tides change around the BAFF. The time series plots in the lower section highlight the discharge at the BAFF related to Georgiana Slough. The typical discharge range for the BAFF in this study is 1200–3800 cfs.

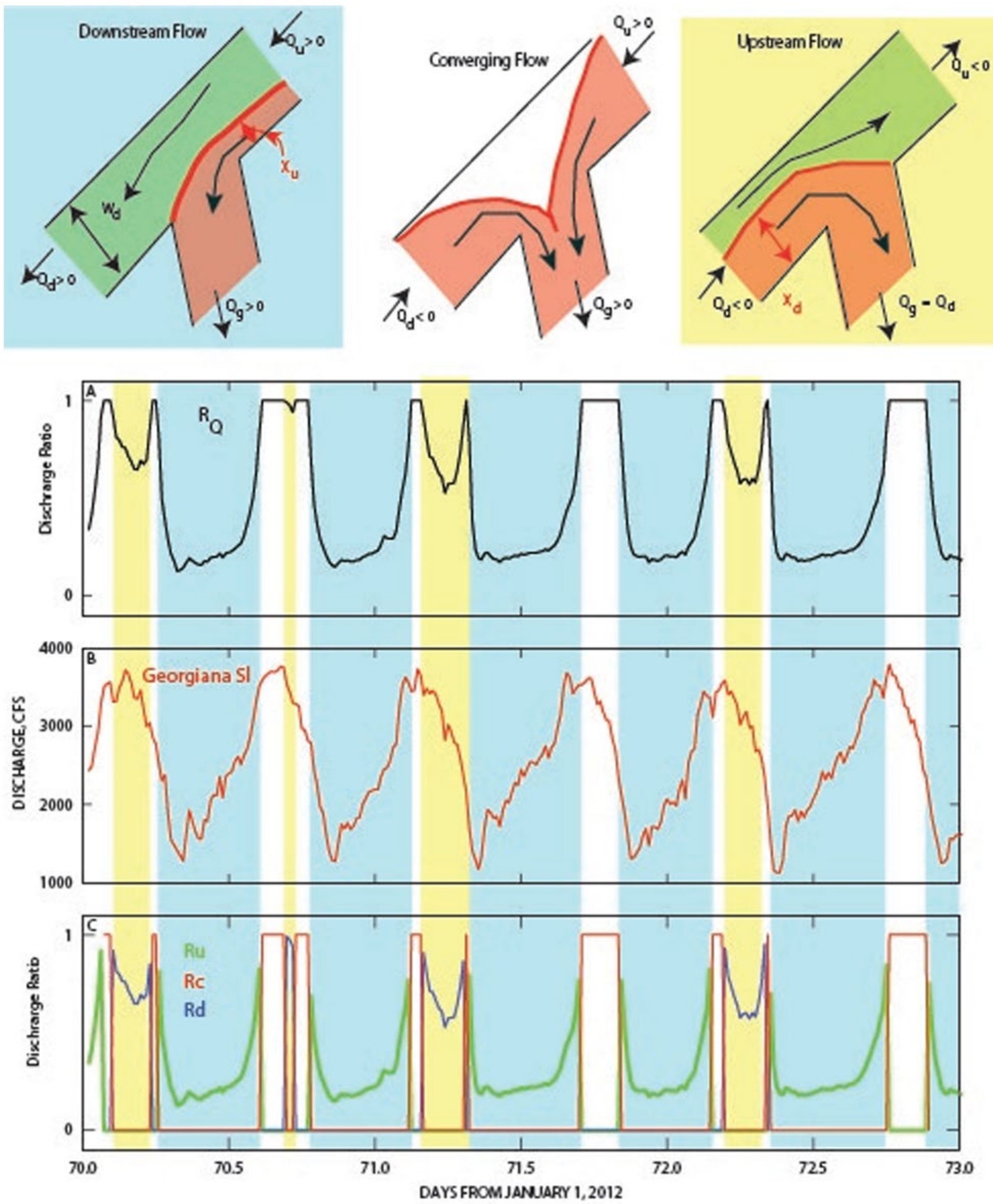



**Figure 6-7. Time Series plots of Geogina Slough, CA.** Time series plots of (A) the total discharge ratio, R, (B) the discharge in Georgiana Slough, and (C) the component discharge

ratios RU (flow entering Georgiana Slough from upstream, green), RD (flow entering Georgiana Slough from downstream, blue) and RC (converging flow into Georgiana Slough) during low Sacramento River flow period. (Accessed 07 DEC 2025; https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/State-Water-Project/Endangered-Species-Protection/2024-FEIR-Long-Term-Ops/Appendices/App-2F/SWP_LTO_FEIR_App2F_GSSMB-Operation-Plan_20220506-Final_508).

It should be noted that according to the Fish Guidance Systems (FGS) "Georgiana Slough" case study (Accessed 2026 JAN 21 on https://fgs.world/casestudy/georgiana-slough-2/) on overall deflection efficiency of the system for Chinook salmon with the barrier 'ON' was 91%.

In-air noise was assessed during the permit phase. There was no in-air study to validate the permit request. The following was described:

> “Project operation would cause noise due to the use of generators, air compressors, trucks, and in-water barge and workboat operation, over a period of up to 150 days per year during the 8-year period. Project-related operational noise is estimated to be 88 dB Leq to 89 dB Leq at 50 feet. The distance between proposed project operation activities and the closest acoustically sensitive receptors would be approximately 350 feet. Assuming a standard reduction of 6 dB per doubling of distance, the project-related operation noise levels at the nearest sensitive receptors would be approximately 71 dB Leq to 72 dB Leq at 350 feet. These levels of noise are above daytime noise levels typical of residential buildings, which is 55 dB Leq. Therefore, a substantial temporary increase in ambient noise levels resulting from temporary operation activities may occur.” (https://water.ca.gov/-/media/DWR-Website/Web-Pages/News/Public-Notices/Files/DWR-GSSMB-IS-MND_Oct2021.pdf).

According to the impact assessment, the operational costs were through to be the following:

> “Electricity use at the project site during the November through April period will depend on the BAFF operations schedule. If the BAFF were to operate 24 hours a day for 7 days per week, the electrical operating costs are estimated to be $50,000 per month. As a result, operating costs alone could easily exceed $300,000 for one season (i.e., November through April period). If the BAFF is

operated outside of this period (e.g., May), additional costs would be incurred associated with diesel generator acquisition and fuel consumption, totaling approximately $126,000/month.” (https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/State-Water-Project/Files/DEIR-Long-Term-Ops/2024/App2F_GSSMB-Operation-Plan_20220506-Final_508.pdf)

## 6.3 Old River Deployment

The Old River efforts have less available data on them. (https://filelib.wildlife.ca.gov/Public/Adult_Sturgeon_and_Striped_Bass/Staff%20Report%20---%20Literature%20Cited/Bowen%20et%20al%202009.pdf) the BAFF was noted to be heard beyond the wall of sound.

> “The US Department of the Interior/Bureau of Reclamation (Reclamation) worked in coordination with Fish Guidance Systems (Fareham, Hampshire, England), Jacobs Engineering (Southampton, England), EIMCO Water Technologies (Salt Lake City, UT), Hydroacoustic Technology Inc. (Seattle, WA), the San Joaquin River Group Authority (Davis, CA) and the California Department of Water Resources (Sacramento, CA) to design, implement, and monitor a non-physical barrier called the Bio-Acoustic Fish Fence (BAFF). The BAFF was deployed upstream of the divergence (Divergence) of the San Joaquin River (SJR) and Old River (OR). The BAFF intends to deter anadromous salmonid juveniles from entering Old River. The BAFF is comprised of three components: sound, bubble curtain, and hi-intensity light-emitting diode (LED) strobe lights. The BAFF was deployed in the San Joaquin River immediately upstream of the Old River and it will be referred to in this document as the Old River Barrier (ORB) or BAFF.”

> “Fish Guidance Systems (FGS) investigated the sensitivities of different fish species and found the most effective acoustic deterrents for multiple species applications fall within the sound frequency range of 5 to 600 Hz. The combined fish barrier generated frequencies within this range at source levels of around 160 dB re 1 µPa @ 1m. The signals were delivered by electromechanical transducers, or sound projectors. For the ORB installation, FGS Model 15-100 MkII sound projectors were used, allowing fine control of sound levels within the experimental arena. The sounds were generated by an FGS Model 1-08 Signal Control Unit which fed an FGS Model 400 (400 watt) Power Amplifier, which was linked by cable to the sound projectors.”

"Measurements of sound emitted by the barrier were measured at 0.5 m depth and are shown in Appendix 1. Sound measurements were taken adjacent to the four piles (Pile 1, nearest to the onshore origin, Pile 4 near terminus), and nominally at the pile itself (shown as "0 m") and at distances of 1 and 3 m upstream and downstream, orthogonal to the barrier. Waypoints are shown and were recorded at the water surface using a hand-held GPS unit. Ambient sound level measurements (barrier off) were made only at Pile 1. Sound pressure levels (SPLs) were measured using a Bruel and Kjaer Model 2204 hydrophone connected to Bruel and Kjaer Charge Amplifier and mV meter; millivolt readings were then 7 converted to SPLs (dB re 1 µPa) using calibration curves for the hydrophone. All instruments were calibrated to international standards."

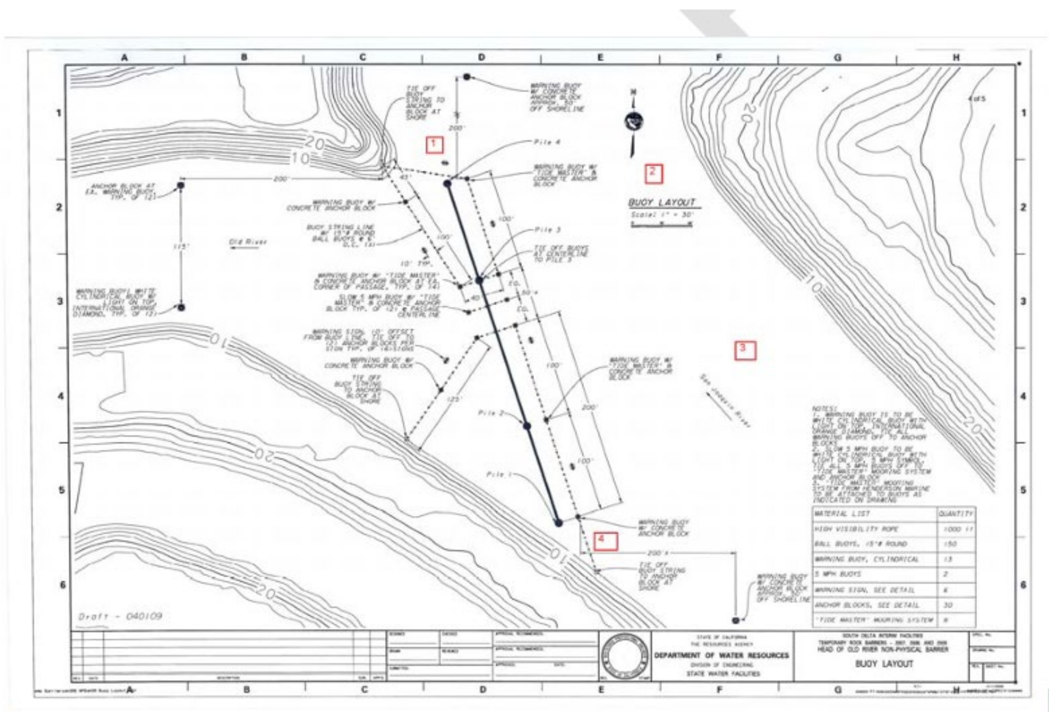



Figure 4. Divergence of Old River and San Joaquin River, CA. The bold black line indicates the BAFF location. The red squares exhibit the locations of HTI hydrophones and inside the boxes are their corresponding number.

Appendix 1. Sound pressure levels measured along the non-physical barrier. The ambient readings with barrier off were made at Pile 1: 98-104 dB re 1µPa.

| Measuring Position | | Sound Measurements dB re 1µPa, Barrier On | |
|---|---|---|---|
| Pile 1 Upstream | Waypoint | Upstream | Downstream |
| 0 m | 647258/4185772 | 144 | |
| 1 m | 647260/4185773 | 142 | 144 |
| 3 m | 647260/4185775 | 104 | 104 |
| | | dB re 1µPa, Barrier On | |
| Pile 2 Upstream | Waypoint | Upstream | Downstream |
| 0 m | 647250/4185801 | 102 | |
| 1 m | 647250/4185802 | 100 | 102 |
| 3 m | 647249/4185804 | 98 | 98 |
| | | dB re 1µPa, Barrier On | |
| Pile 3 Upstream | Waypoint | Upstream | Downstream |
| 0 m | 647235/4185847 | 90 | |
| 1 m | 647235/4185846 | 123 | 112 |
| 3 m | 647237/4185844 | 119 | 118 |
| | | dB re 1µPa, Barrier On | |
| Pile 4 Upstream | Waypoint | Upstream | Downstream |
| 0 m | 647222/4185876 | 151 | |
| 1 m | 647223/4185876 | 127 | 138 |
| 3 m | 647225/4185876 | 86 | 92 |



## 6.4 BAFF System at Barkley Lock and Dam

BAFF system was installed on the river bottom in the downstream lower lock approach and designed to reduce impeding navigation passage and decrease risk to the system and to commercial vessels (See design variation between Figure 6-4, Figure 6-5 and Figure 6-8). The final design used customized sound signals, directional strobe lighting, and an air bubble curtain to create an underwater linear deterrent to fish movement. USFWS, USGS, the State of Kentucky, USACE, and stakeholders used telemetry receivers and electronic fish tags to assess the extent of invasive carp movement through the Barkley Lock, including whether invasive carp move through the lock's emptying/filling system over the next two years.

The BAFF system was planned to be removed from the approach channel after the three-year test period (August 2023), subject to conditions. The USFWS extended the lease, and the final determination of its placement will occur in 2026.

*(See next page for Figure 6-8)*

**Figure 6-8. Installation of the BAFF at Barkley Lock and Dam, KY.** Installation of the BAFF at Barkley Dam (Top Photo Credit: Accessed 2025 DEC 07; https://fgs.world/invasive-carp/; Bottom Photo Credit: Leon Roberts, USACE).

### 6.4.1 Reported Issues

Results of the BAFF study will be presented in JAN 2026. We did not request access for early reporting of the results due to complex nature of the study. There were two note-worthy issues during the study, one of which was power due to storms (unavoidable due to storm severity). The second was an issue with the continuity of the bubble curtains. This could have been related to biofouling, mechanical issues or hydraulic turbulence from the riverbank and i-wall working up the lock approach (Figure 6-9). A change oc-curred during the project that was noticed in photos but not reported formally on by the lead federal agencies. The speaker projectors were pulled, repaired, but also modified compared to the initial deployment (Figure 6-10). Given the locations of the BAFF at Barkley LD and at Georgiana Slough, the weather normally does not warrant severe icing issues.

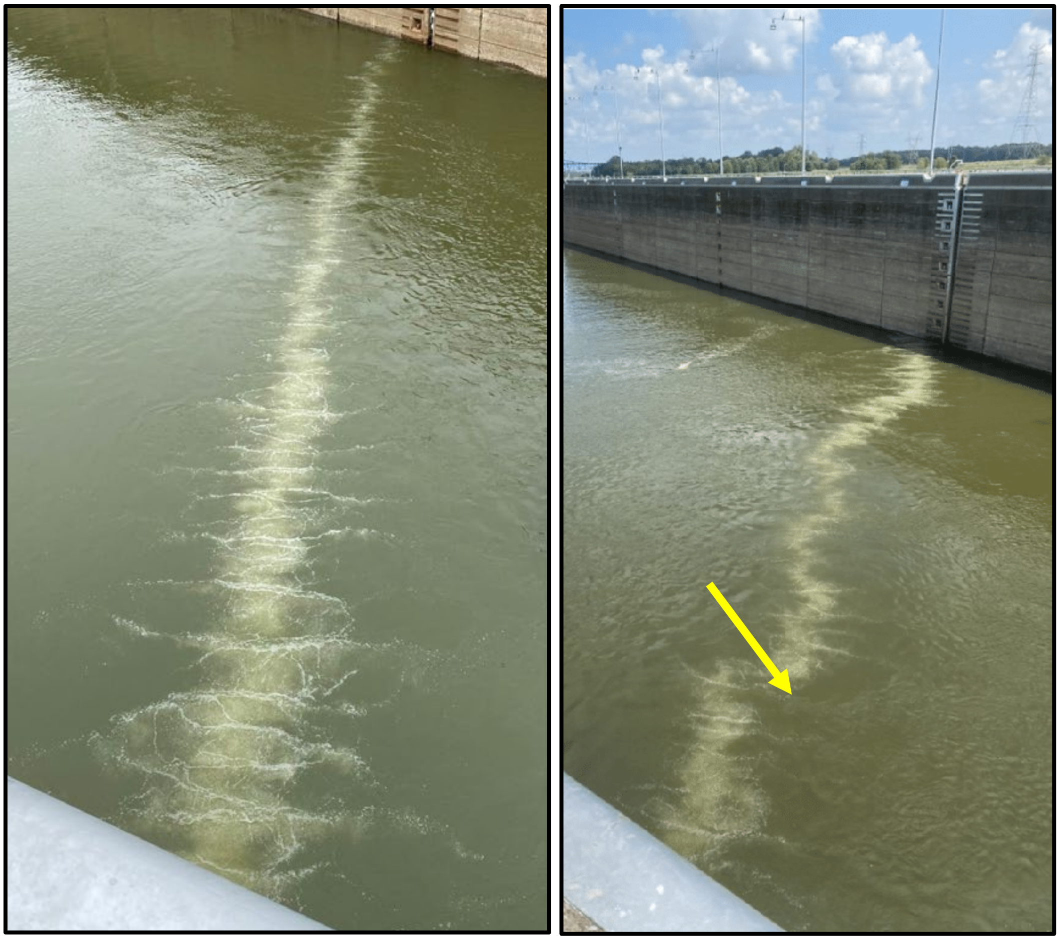


**Figure 6-9. View of BAFF from Barkley Land wall.** (Left) BAFF at time of installation OCT 2019 (Photo Credit: USACE fact sheet OCT 28, 2019). (Right) BAFF later during the study. The yellow arrow indicates the area of a persistent issue with inability to keep a continuous line of linear bubbles (Photo Credit: Cupp et al. 2021).

**Figure 6-10. BAFF SPA at installation and after repair.** (Left) BAFF Installation Lake Barkley (Photo credit: Kentucky Department of Fish and Wildlife Resources, Used by Permission, https://www.fws.gov/media/baff-installation-lake-barkley). (Right) The projector design changed to include a 5 “window” interface. Accessed 2025 DEC 07; https://www.mainstreamdivers.com/MoranSharedCmsContent/CaseStudyView.asp?NewsID=79)

### 6.4.2 Sound Field (Water or Air) Modeling

This activity was scoped within the USFWS contract; however, it was either not conducted or a summarized product not provided to the USFWS.

### 6.4.3 Barkley Lock BAFF Costing

According to USASpending.gov, the total cost of the BAFF between 2018 AUG through Sept 2026 has approached about $13.1M US (Accessed 2025DEC05; usaspening.gov/search/?hash= 16a1e837691af6b020c067faf75fed51) across the three contracts awarded to FGS (Award 140F0318C0006, 140F0422C0003, and 140FNR24C0021: $8,786,944.71 of $10,401,282.71 2: $3,163,861.16 of $3,866,911.16 3: $1,173,878.72 of $2,970,620.70, respectively). These costs were paid directly to FGS, and thus not reflective of the internal USFWS, USGS, USACE, U of MN, State of Kentucky costs for project management, contracting, travel, supplies (e.g., ultrasonic transmitters and receiver array for fish monitoring through the lock channel). It is not clear at this time if there was redundancy included for components systems (i.e., compressors, lights, sound projectors, etc.).

Costs are detailed in Table 6-1 for costs for installation and **Error! Reference source not found.**Table 6-2 for recurring costs.

*(See next page for Table 6-1 and Table 6-2)*

**Table 6-1. Design and installation costs for the BAFF at Barkley.** Design and installation costs for the BAFF at Barkley: $5.609M in FY2019. Data from Fritts et al. OFR 2023.

| Cost Category | Sub-Category/Description | Amount ($K) | Period/Details | Notes/Source |
|---|---|---|---|---|
| Engineering & Design | Planning, Design, & Bedrock Survey (frame, buildings, cable routing, sound projectors) | $342 | pre-2019 install | Contracted services; core design phase. ~7% of design/install total. |
| Fabrication and Installation | Construction, Equipment, & Deployment (concrete housing, bedrock recess excavation, air compressor/lines, cargo container, multimodal system & telemetry install, oversight) | $3,757 | July – Oct 2019 | Includes fabrication and on-site setup; excludes telemetry equip costs (only dives). ~93% of design/install total; |
| | Add-On: new electrical line; high-water dredging/diver adjustments | $1,510 | July – Oct 2019 | Power line: +$192,000; high water: +$1,318,000. |
| Design & Installation Total | | **$5,609** | | |

**Table 6-2. Annual (recurring costs) for the BAFF at Barkley.** Operations and maintenance costs for the BAFF at Barkley: $1.344M in FY2021-2025. Data from USASpending.gov.

| Cost Category | Sub-Category/Description | Amount ($K) | Period/Details | Notes/Source |
|---|---|---|---|---|
| Lease | Equipment Lease (multimodal deterrent system, incl. remote monitoring by FGS) | $654 Annual | Ongoing (research rate: $54,500/month) | Optional; avoids purchase. Not incurred if bought outright. ~12% of annual recurring if leased. |
| O&M | Annual System Operations (electricity, fixed maintenance for AC, compressor, CCTV, network) | $96 Annual | Ongoing ($6,000/month electricity + $24,000/year maintenance) | Basic runtime costs. |
| O&M | Annual Maintenance Event (sound projector cleaning, routine checks) | $437 Annual | Annual/18-month cycle | Includes dive-based work; FGS recommends 18-month trips. |
| | Add-On: silt removal [5 days]; sound survey [4 days]; telemetry repairs [2 days]) | $157 per event | During maintenance | Silt: +$91,000; survey: +$36,000; repairs: +$30,000. |
| Annual (estimated) Total | | **$1,344** | | |

## 6.5 uADS System

The underwater Acoustic Deterrent System (uADS) is an experimental prototype collaboratively developed by the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers (USACE), U.S. Geological Survey (USGS), and additional partners. In contrast to the BAFF, the uADS remains a prototype and is not commercially available. The uADS is designed to deter invasive carp by emitting underwater sound signals amplified within specific portions of the carp hearing range, thereby inhibiting their upstream movement. This system has been installed for testing at navigation locks such as Lock No. 19 (Keokuk, Iowa; Hamilton, Illinois) on the Mississippi River (since February 2021). The primary objective of the uADS is to restrict the spread of invasive carp into uninvaded regions, including the Great Lakes, while minimizing effects on native fish populations and ensuring compatibility with navigation infrastructure such as locks and dams. This non-lethal strategy is based on laboratory research that identified acoustic frequencies capable of eliciting avoidance behaviors in carp, thereby addressing a critical need identified by the Invasive Carp Regional Coordinating Committee (see Chapter 5).

Prior to installation, the USACE conducted multiple acoustic analyses to develop a sound propagation model, evaluate design configurations for ensonification of the lock approach, and assess ambient noise pollution. The deployed uADS features a soundbar containing 16 co-located transducers within a discharge lateral (US-12439199-B2). Stakeholders identified Lock No. 19 as an appropriate site for evaluating the effects of underwater acoustics on invasive carp behavior, given the existing carp population; therefore, neither invasive non-native species (INNS) introductions nor surrogate species were required for the large-scale field assessment (Brey et al 2023). Previous research on the fish community in and around Lock No. 19 demonstrated that both invasive carp and native fish frequently use the lock for upstream passage (Fritts et al 2021). The evaluation at Lock No. 19 is ongoing and is primarily conducted during the typical navigation season (March through early December) to assess the influence of navigation and seasonal factors on uADS operation and effectiveness. The system is engineered to be non-lethal, to minimize impacts on native fish species, and to maintain compatibility with lock operations and vessel traffic, such as by being recessed into a discharge trough.

uADS have been reviewed at several locations on a meso-scale, such as in the Morris Pits and as a maintenance deterrent to the EDBs in the CSSC.

### 6.5.1 Patent review (uADS US)

There is only one patent for the underwater acoustics deterrent systems (uADS) underpinning the uADS (US-12439199-B2) (Accessed 30 Nov 2025; https://ppubs.uspto.gov) titled "Sound bar for deterrence of Asian carp". The patent abstract is as follows:

> "One embodiment is directed to a sound bar for producing engineered acoustic signals for keeping an animal away from one or more specific areas. The sound bar includes: a weldment having a weldment top, a weldment bottom, a front weldment side, and a rear weldment side; a plurality of speakers disposed inside the weldment and spaced from each other; at least one acoustic doppler current profilers (ADCP) disposed inside the weldment; at least one hydrophone disposed inside the weldment; and a mounting mechanism configured to be attached to a discharge lateral, the mounting mechanism including a plurality of bottom supports spaced from each other to support the weldment bottom at a plurality of locations and position the weldment top below a top surface of the discharge lateral and position the rear weldment side adjacent a front side of the discharge lateral." (Figure 6-13).

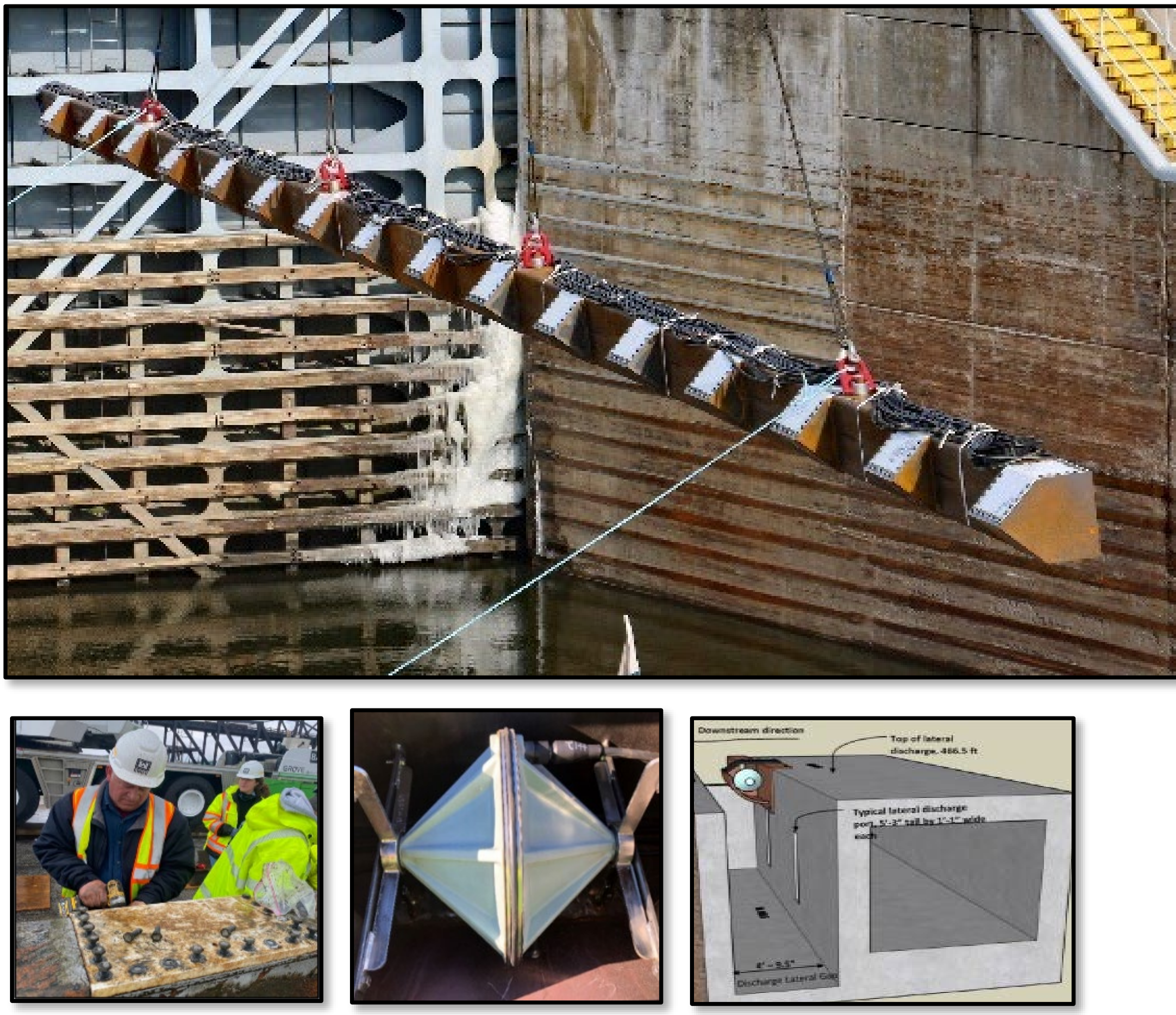



**Figure 6-11. Weldment (aka "Soundbar") during Deployment at Lock No. 19.**

### 6.5.2 Component specifications

The uADS system consists of multiple components, as detailed in data releases and patents. The number and specifications of these components are likely tailored to Lock and Dam No. 05, based on placement and intended outcomes. Notable upgrades have been implemented in the Brandon Road Multi-deterrent System, also known as the Brandon Road Interbasin Project (BRIP), informed by lessons learned at Lock No. 19. The system is designed for continuous, unattended operation, remote monitoring, and potential fault detection. As a prototype, certain aspects of the uADS differ by location and have evolved throughout the study. Annual maintenance, such as diver inspections, is necessary to maintain the integrity of the soundbar, while component replacements are performed as needed and may not occur every year.

- **Non-proprietary System.** All materials and equipment are commercial-off-the-shelf equipment.

- **Control Units.** There is no hardware control unit specific to the uADS. The software currently in use is maintained by commercial products, and control screens produced through ERDC-ITL (information Technology Laboratory).

- **Equipment Enclosure.** The uADS uses air-conditioned server rack located on in a trailer with a large HVAC unit. The server rack, which includes surge protections per amp, amplifiers, switch boxes, and cooling/heating to ensure year-round operation (Figure 6-12).

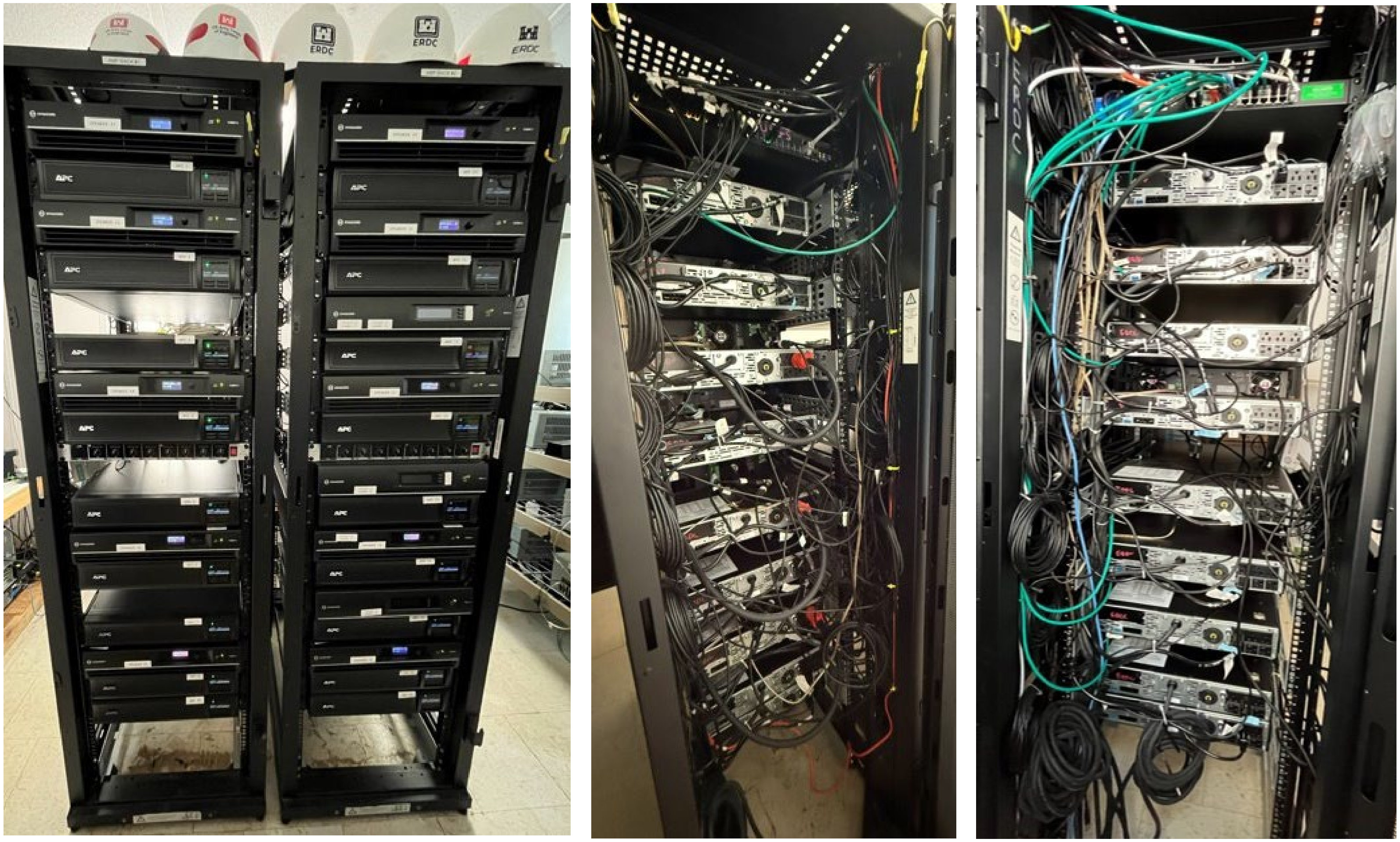



Figure 6-12. uADS Control Racks at Lock No. 19.

- Dynacord IPX 10:4. "IPX Series are dedicated amplifiers for fixed install application such as e.g. stadiums, arenas, houses of worship, concert halls, theaters and other applications that require high-power multichannel amplifiers with sophisticated speaker processing. Each channel can be individually operated in low impedance mode, or 70V/100V Direct Drive mode. By bridging also 140V/200V Direct Drive is available. By the possibility to parallel two channels and parallel-bridge four channels all kind of loudspeakers can be driven (Accessed 2026 JAN 04, https://products.dynacord.com/na/en/ipx-series)." The uADS has evolved towards the amplifiers for large-scale applications. IPX amplifiers have integrated OMNEO networking (Dante audio and OCA/AES70 control) and can be configured, controlled and operated from both IRIS-Net as well as SONICUE Sound System Software suite. The specifications and details have been provided to MN-DNR and MVP for design consideration (Figure 6-13).


**Figure 6-13. Front Face of Dynacord Amplifiers.** (TOP) C Series 3600. (BOTTOM) IPX 10:4.

- Dynacord C-Series 3600 2-channel. "C Series power amplifiers provide robust power, linear amp design, with protection circuitry ensures safe, reliable operation under all conditions. Currently in testing is the C3600FDi which supply 1800W at 4 ohms per channel and up to 6000 W in bridged mode at 4 ohms using a direct drive application with 70V and/or 100V speaker. SONICUE Sound System Software supports C Series, elevating them to the top league of professional amplifiers. The feature-rich onboard DSP gets a boost under SONICUE with 10 band PEQs and a dedicated array processing section. The amplifiers feature Euroblock connectors for convenient wiring, remote power-on delay, and GPIOs to interface with third-party controls." (Accessed 2026 JAN 04, https://products.dynacord.com/na/en/c3600fdi) The specifications and details have been provided to MN-DNR and MVP for design consideration. (https://products.dynacord.com/na/en/c3600fdi) (Figure 6-13).

- APC SMX2KR2UX145. "The 2000VA line interactive 2U rack/tower UPS provides pure sine wave power to support critical electronics during power disruptions. The SMX comes with NEMA 5-20P input, 3x NEMA 5-15R, 3x NEMA 5-20R and 1x NEMA L5-20R outlets. The UPS has a SmartSlot for optional Network Management Card that enables graceful shutdown of physical servers, virtual machines & HCI Clusters via PowerChute Network Shutdown. This uninterrupted power supply can connect to EcoStruxure IT or third-party centralized management platforms. The Emergency Power Off feature enables the UPS to remotely shutdown during emergencies." (Accessed 2026 JAN 04, https://www.se.com/us/en/product/SMX2KR2UX145/apc-smartups-x-line-interactive-2000va-rack-tower-2u-100v127v-3x-515r+3x-520r+1x-l520r-nema-smartslot-extended-runtime-10ft-input-cord/)

- Lubell Labs LL1424HP. "1424HP are high-power piezoelectric Underwater Acoustic Transducer (UAT) designed for use in Underwater Acoustic Deterrent Systems (uADS), Diver Deterrent Systems (DDS), Acoustic Sub-Bottom Profiling (SBP) systems, and general military and scientific applications. The Lubell Labs LL1424HP has a useful frequency range of 200 Hz - 9 kHz, a maximum SPL of 197dB/uPa/m at 600Hz, and a nominal impedance of 4 ohms (varies with frequency). The LL-1424HP is intended for use in rivers, lake, and ocean by virtue of its rugged MIL-A-8625 Type III hard coat anodize, and 8 mil PPG Amerlock II epoxy finishes. The LL1424HP comes mounted in a heavy duty 316 stainless steel cage with an isolation mounting system." (Figure 6-14). (Accessed 2026 JAN 04, https://www.lubell.com/products/ll1424hp-2/).

**Figure 6-14. Lubell Labs LL1424HP Underwater Acoustics Transducer.**

- Communication Hub. *Digi AnywhereUSB 24 Plus*: "Connect USB peripheral devices anywhere on a Local Area Network (LAN) without a locally-attached host computer. 24-port USB over IP remote USB 3.1 hub with dual 10 M/100 M/1 G/10 G Ethernet, dual 100-240 VAC power, dual SFP+ modules support and optional cellular Digi CORE module. The Digi Anywhere USB is used to connect the amplifiers to the main control tower" (Accessed 04 JAN 2026, https://www.digi.com/products/models/aw24-g300). The *Linksys LGS116P 16-Port Business Desktop Gigabit PoE+ Switch* is an unmanaged 16-port switch with PoE+ support that connects the amplifiers to the main control tower. (Accessed 04 JAN 2026, https://support.linksys.com/kb/article/4963-en/?section_id=189) (Figure 6-15).


**Figure 6-15. Communication Equipment.** (Top) Digi AnywhereUSB 24 Plus. (Bottom) Linksys LGS116P 16-Port Business Desktop Gigabit PoE+ Switch.

- Acoustic Deterrent Signals. The uADS acoustic signals used are not proprietary (see Chaper5).

## 6.6 Lock No. 19 uADS Areal Noise

In 2021, a prototype underwater Acoustic Deterrent System (uADS) was deployed at Lock No. 19 on the Mississippi River in Keokuk, Iowa, to assess its impact on invasive carp passage. The placement of the uADS within the lock infrastructure resulted in an acoustic stimulus that was detectable from land. To evaluate the potential for noise pollution in nearby communities resulting from deterrent technologies, an aerial acoustic analysis was conducted to distinguish the ambient sounsdscape from anthropogenic activities and the uADS. Sound level analyzers were positioned at several strategic locations to record ambient noise, uADS output, barge activity, lock operations, railway, and traffic noise profiles. These sound sources established a baseline ambient noise level (*LAeq*[8]), which was then compared to the sound output of the uADS. The investigation sought to quantify changes in ambient noise levels surrounding the lock during the operational ('on') and inactive ('off') cycles of the uADS, thereby informing future impact assessments for other proposed uADS installations. Within 1,000 ft of the uADS, there are two railways and a large vehicle bridge. Residential homes are situated on a bluff approximately 600 ft away, and a hydroelectric dam, owned and operated by Ameren, is located at the north, upstream end of the lock chamber (Figure 6-16). The results indicated that the uADS had no measurable impact on the surrounding community (Jarabica *in review*). *LAeq* analyses revealed significant variation across sampling points, with stations closest to the uADS (L02, L03, R02, and R03) exhibiting higher noise levels than those located mid-way and near the end of the lock approach (L01 and R01) (Figure 6-17) (Jarabica *in review*). The test encompassed both day and night activities, normal lock operations, vessel traffic, trains, and vehicle bridge noise. The study also evaluated the effectiveness of in-air noise attenuation during the operational cycles of the uADS (Table 6-1) (Jarabica *in review*). In terms of the overall noise levels at LOCK NO. 19, Figure 6-20, helps to illustrate the captures *LAeq* valves relative to common noises one hears on a near-daily basis (Jarabica *in review*).

[8] **LAeq (A-weighted):** This is a specific type of LEQ where "A-weighting" is applied to the sound, filtering it to mimic how the human ear hears, emphasizing mid-frequencies and reducing low/high frequencies. It is the most common metric for environmental and industrial noise monitoring.


**Figure 6-16. uADS Location of Areal Noise Sampling Stations.**

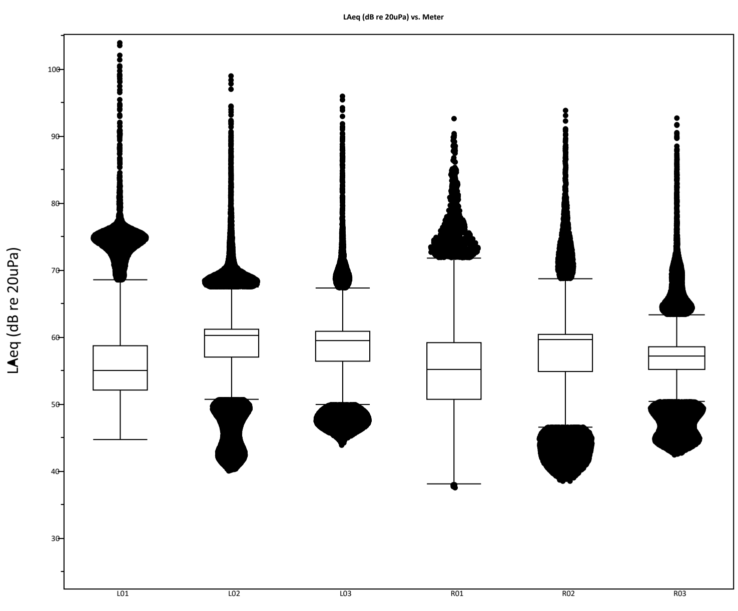



**Figure 6-17. uADS Areal Noise Estimates by Sampling Station.** The data includes the uADS operation, night/day activities, normal lock operations, vessel traffic, trains, and the vehicle bridge.

**Table 6-3. uADS Off and On Averages of Areal Noise.** Stars indicate significant difference between OFF and ON Cycles. The data includes the uADS operation, night/day activities, normal lock operations, vessel traffic, trains, and the vehicle bridge.

| Location | uADS OFF ($LA_{eq}$ dB re 20 µPa) | uADS ON ($LA_{eq}$ dB re 20 µPa) |
|---|---|---|
| ALL | 56.5 ± 5.6 | 57.4 ± 5.0* |
| L01 | 54.8 ± 4.5 | 56.4 ± 5.5 |
| L02 (uADS) | 57.9 ± 6.3 | 59.6 ± 4.9* |
| L03 | 58.1 ± 5.0* | 58.3 ± 3.8 |
| R01 | 54.8 ± 6.1 | 55.0 ± 5.5 |
| R02 (uADS) | 57.2 ± 5.5 | 57.7 ± 4.5* |
| R03 | 55.9 ± 4.6 | 56.9 ± 3.7* |

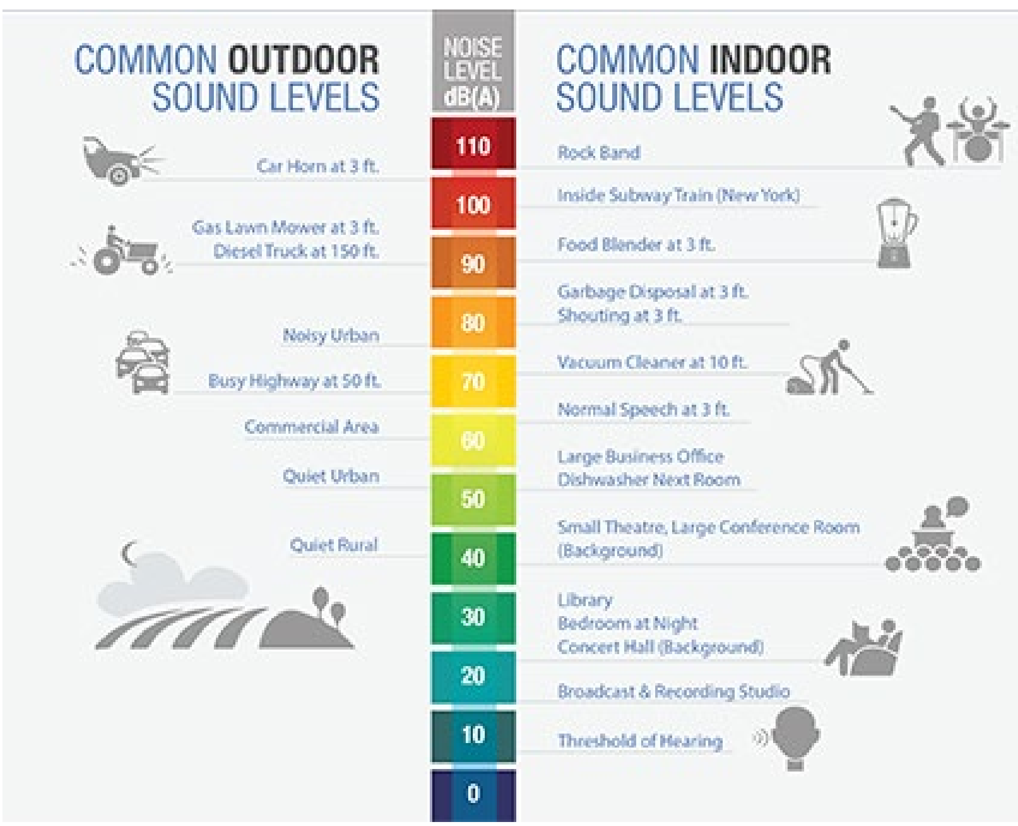


**Figure 6-18. Comparative Noise Levels (dBA[9]) Scale using A-weighted.** Accessed 20 DEC 2026: https://www.osha.gov/noise.

## 6.7 Lock No. 19 uADS Costing

The design, acquisition, install and operations/maintenance approach of the uADS is quite different from the approach taken by USFWS for the BAFF at Barkley Lock and Dam. The design and installation costs for the uADS included a payment to USACE from USGS and ERDC (est. $342K). Many installation costs were funded through USGS by GRLI, and secondary costs of government supplied equipment were acquired by ERDC and USGS These installation costs are not reflective of the internal ERDC, USACE, USGS, and States of Iowa and Illinois costs for labor, coordination, project management, contracting, travel, supplies (e.g., ultrasonic transmitters and receiver array for fish monitoring through the lock channel). The first year of O&M was most costly due ($.91M) which was mitigated in the future by changes to the design. Costs are detailed in Table 6-4 for costs for installation and Table 6-5 for recurring costs.

[9] **dBA (A-weighted Decibels)** The unit of measurement for A-weighted sound. When a is measured using the A-weighting filter, the result is expressed in dBA (e.g., LAeq = 70 dBA).

**Table 6-4. Design and Installation Costs for the uADS at Lock No. 19.**

Design and installation costs for the uADS at LOCK NO. 19: $2.29 M in FY2020 & FY2021.

| Cost Category | Sub-Category/Description | Amount ($K) |
|---|---|---|
| Engineering & Design | Planning, Design (frame, buildings, cable routing, permitting) | $370 |
| Fabrication and Installation | Construction, Equipment, & Deployment (concrete housing, bedrock recess excavation, air compressor/lines, cargo container, multimodal system & telemetry install, oversight) | $1,530 |
| Add Ons | Add-On: transformer, cabling and mics. parts | $68 |
| Equipment provided by the government | Fabrication of miter gate friendly hangers, sound projectors, rack mounts, signal conditionings, monitoring systems | $325 |
| **Estimated Total Costs** | | **$2.2M** |

**Table 6-5. Annual (reoccurring costs) for the uADS at Lock No. 19.**

Operations and maintenance costs for the uADS at LOCK NO. 19: $.91 M in FY2021-2022.

| Cost Category | Sub-Category/Description | Amount ($K) |
|---|---|---|
| O&M (5-yrs) | 5-Yr Cycle System Operations (O&M, sound projector cleaning and cable inspection and maintenance) | $506 |
| O&M (1-yrs) | Annual System Operations (includes dive inspections, electricity, and about 50% operations.) (Not included are the site visits which need to made quarterly for testing the projectors and costs of post processing; and the associated costs of fish monitoring through the lock) | $78 |
| Estimated Total Costs for 5 years | Note this estimate is for 5 years, not annual as detailed in Table 6-3 for the BAFF | $818 |

## 6.8 References

Barr Engineering. 2022. Engineering Assessment of the Feasibility and Estimated Cost of Installing a State-of-the-Art BAFF Carp Deterrent at Mississippi Lock and Dam 5. Mississippi River Lock and Dam No. 5. Prepared for the University of Minnesota. 128 pp.

Bowen, M. D., & Bark, R. (2015). *2012 Georgiana Slough non-physical barrier performance evaluation project report* [Final project report]. California Department of Water Resources. https://www.noaa.gov/sites/default/files/legacy/document/2020/Oct/07354626712

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# 7. Technology Comparison Specific to LD05

This chapter presents a comprehensive comparative analysis of the Bio-Acoustic Fish Fence (BAFF) and Underwater Acoustic Deterrent System (uADS) technologies for deterring invasive carp at Lock and Dam No. 05 (LD05) on the Mississippi River. The analysis integrates previously detailed hydrodynamic modeling, bathymetric data, discharge trensds, and navigation impacts to determine the optimal locations and cost estimates for both BAFF and uADS deployments.

## 7.1 Priority Concerns

The analysis began with the base United States Army Corps of Engineers (USACE) requirements for a non-structural deterrent (NSD):

- Lock Operation: Non-structural deterrent systems cannot interfere with lock operations nor delay navigation. NSDs must integrate seamlessly with chamber emptying via culverts and withstand the forces exerted on them by the chamber emptying process.

- Navigation Safety: NSDs should not slow down nor create hazardous situations for recreational or commercial navigation. Systems should prevent or provide safety measures to address sound amplification or structural hazards during vessel passage, dwells, and stalls.

- Operating Needs: NSD design should include remote monitoring, deterrents, adjustable operational control, and modular expansions, which are essential for adapting to variable flows.

- Inefficiencies and O&M Reduction: NSDs currently undergo annual maintenance events to deal with corrosion, damage, sediment issues, and quarterly inspections (uADS). Any design should include ways to improve the existing structures at Barkley Lock and Lock No. 19.

Building on the USACE requirements, we evaluated six optional locations varying in length from 34-164 m and assessed specific challenges for each location, including structural and physical forces, such as elevation variation, flow engagement, scour risks, discharge exposure, navigation, navigation dwell times, and costs. Because the BAFF combines sound with a bubble curtain, while the uADS uses targeted acoustic signals from speaker arrays (Table 7.1), it is expected that each NSD will perform differently based on the structural and physical challenges. To conduct a side-by-side assessment, a simple ranking system was developed for further discussion. Not included in the analyses but recommended for the final design is the knowledge base provided by the 95% design of Increment IA and the 35% design of Increment IIB of the Brandon Road Interbasin Project (BRIP).

**Table 7-1. BAFF, hybrid, and uADS deployment locations.**

| Site | River | Location | Current Status | Length of device | Depth |
|---|---|---|---|---|---|
| Barkley Lock | Cumberland | Mouth of the downstream lock approach | BAFF Pilot Testing (2019-2024)<br><br>BAFF Operational (planned start 2027) | 180 ft | 15–25 ft |
| Lock No. 19 | Mississippi | Lock approach | uADS Pilot testing (2021- current) | 110 ft | 12–24 ft |
| Lock & Dam 05 | Mississippi | Proposed (Pool 5A) | Design phase (2026 - 2028) | TBD | 12–20 ft |
| Brandon Road Lock and Dam | Illinois | Des Plaines River | Under construction (2025 - 2030) | Variable | 15–30 ft |

## 7.2 Proposed Locations

Assessment of BAFF and uADS at LD05 involved examination of six potential placement locations. These locations are preliminary, as modifications to the insertion point, insertion angle, and final touchpoints on the lock land wall are expected as the design project delivery team (PDT) advances. Current placements were selected based on lock structure, cable protection from navigation, safety considerations for lock staff, and the presence of active electrical infrastructure. Location estimates are based on Google Earth imagery with an accuracy of approximately ±1 meter. The following are the lengths and angles of insertion, with the insertion point beginning at the i-wall bullnose (Figure 7-2). Location No. 6 was added for placement on the exterior of the lower lock approach sill apron to minimize concrete costs related to trenching.

- Location No. 1 is 34 m, 90°
- Location No. 2 is 36 m, 99°
- Location No. 3 is 55 m, 113°
- Location No. 4 is 88 m, 123°

- Location No. 5 is 164 m, 132°
- Location No. 6 is 48 m, 132°, 90°

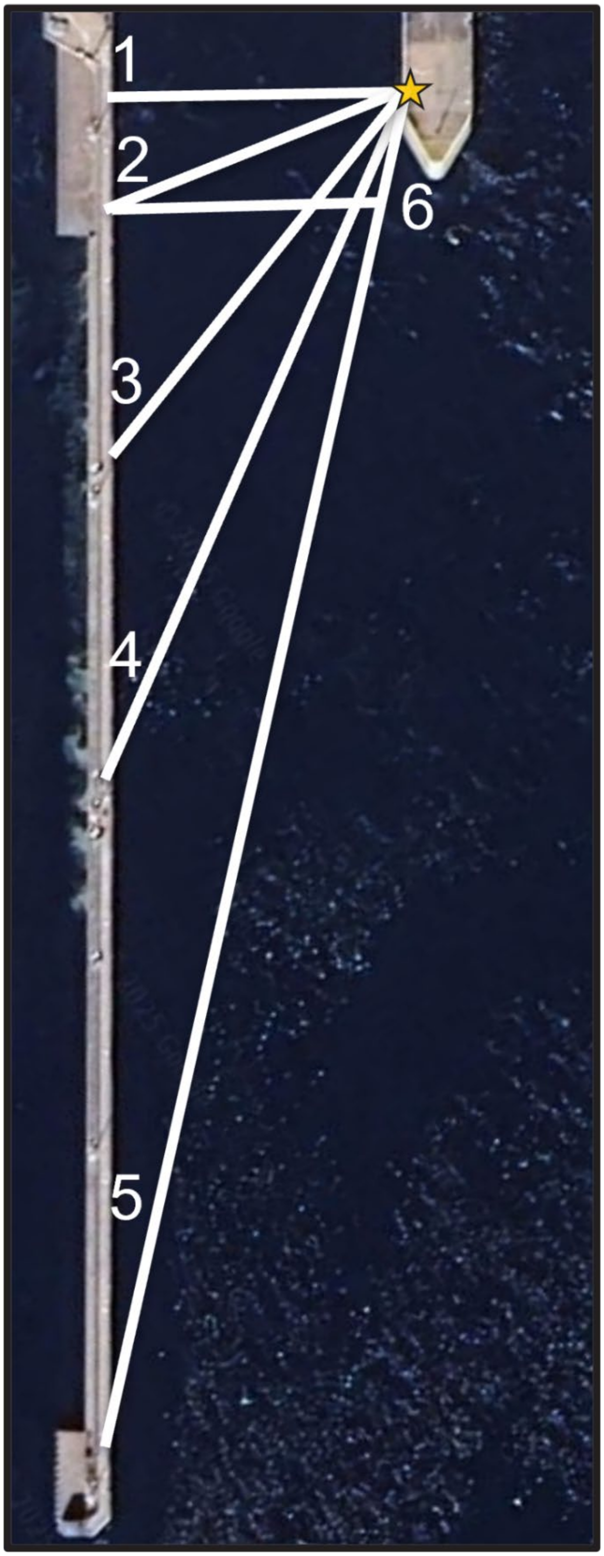


**Figure 7-1. Proposed NSDS Locations at Lock and Dam No. 05.** There are 5 proposed locations, with a 6th location added to reduced concrete trenching costs as the location line follows the lower lock approach concrete sill apron and then inserts at the same angle of Location No. 05. The "star" is the proposed insertion points for comparison of lengths and angles.

## 7.3 Bathymetric Impacts

Bathymetric data show significant substrate variability, affecting installation costs, structural stability, and fish bypass risk. Surveys indicate concrete slabs near the lock, transitioning to rock crib and benthos farther away. Scouring is caused by river flows and navigation prop wash. The benthos forms natural "waves" around the structure, creating higher elevations that affect array height. Scour patterns result from both lock chamber culvert discharge and natural river scouring (Figure 7-3). The benthos varies by about 4.5 m in elevation, which impacts the BAFF and uADS based on structure length (Table 7-1). Table 7-1 outlines the changes of elevation changes each structure must address in its design. Locations No. 4 and No. 5 will require additional planning for the lower portion of the NSD (the "footings") to ensure that

1) there is additional structural support to withstand scouring and increased turbulence in the scour zones, and

2) the NSD is constructed with a blocking shield to prevent fish from swimming underneath the structure if it is deployed without excavation.

In summary, Location No. 5 has the greatest elevation variation at 4.3 m (14 ft) due to its length. This increases the risk of fish passage beneath the structure and raises installation costs for lower shielding, larger footings, additional excavation, and long-term operations and maintenance. The cost estimates in Section 7.7 are based only on length and do not include these additional risks.

(*See next page for Figure 7-3*)

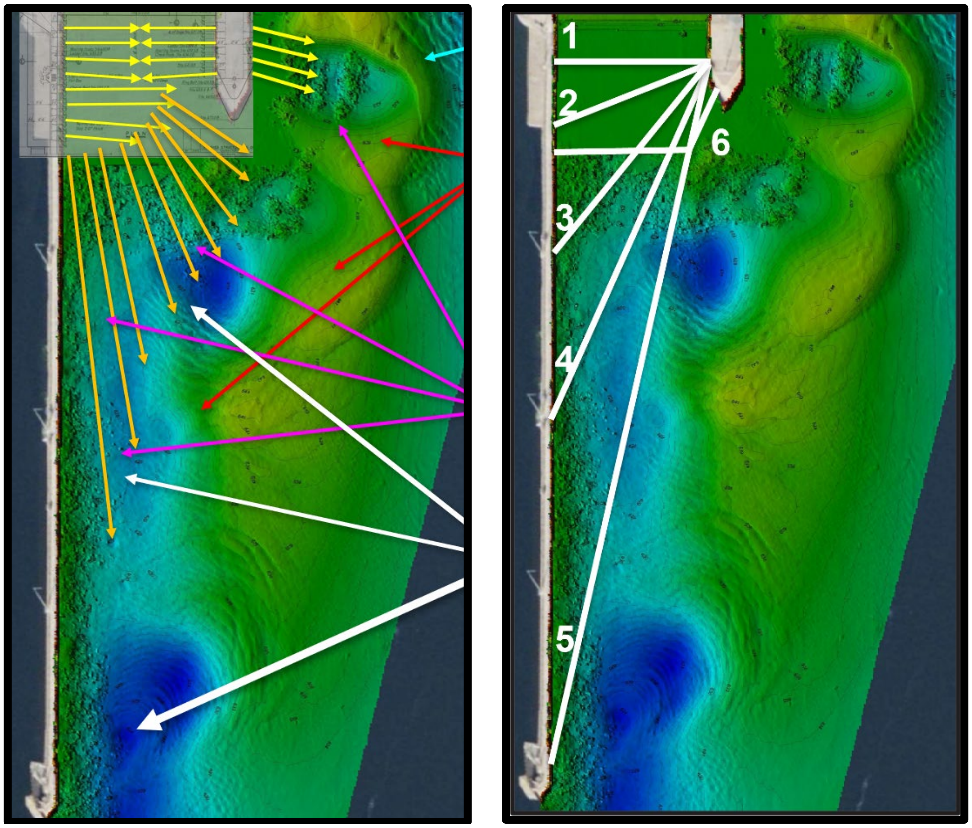


**Figure 7-2. NSD elevation status and likely impacts from lower lock discharge.** The survey presents the bottom elevations of the LD05 main lock approach. Most rock cribs remain intact; however, some have shifted due to scouring (expected scouring is indicated in purple, while unexpected scouring severity is shown in white). Discharge from the dam and river transports sediment, resulting in deposition near the in-lock and near-lock approach structures (sediment deposited by river wave action is marked in aqua).

(*See next page for Table 7-2*)

| Location No.[1] | Length (m) | Substrate Type | Estimated Elevation Variability[2] m (ft) | Comments |
|---|---|---|---|---|
| 1 | 34 | 34 m Concrete slab | 0 (0) | Need to consider the height of the array and impacts on navigation and navigation impacts on the structure. |
| 2 | 36 | 36 m Concrete slab | 0 (0) | Need to consider the height of the array and impacts on navigation and navigation impacts on the structure. |
| 3 | 55 | 23 m Concrete slab<br>32 m Rock cribs & benthos | Minor, 0.6 (2) | Need to consider the height of the array and impacts on navigation and navigation impacts on the structure. *USACE may be more protective of the rock cribs in this area protecting land wall.* |
| 4 | 88 | 20 m Concrete slab<br>68 m rock cribs & benthos | Some, 3.1 (10) | Need to consider the height of the array and impacts on navigation and navigation impacts on the structure. USACE may be more protective of the rock cribs in this area protecting land wall. *This structure will require careful planning for footing as the benthos due to some scouring from river (major impact) and navigation (minor). Accommodations should ensure the fish do not swim underneath the NSD.* |
| 5 | 164 | 19 m Concrete slab<br>145 m Rock cribs & benthos | Severe, 4.3 (14) | Need to consider the height of the array and impacts on navigation and navigation impacts on the structure. USACE may be more protective of the rock cribs in this area protecting land wall. *This structure will require careful planning for footing as the benthos due to severe scouring from river (major impact) and navigation (minor). Accommodations should ensure the fish do not swim underneath the NSD* |
| 6 | 44 | 19 m Concrete slab<br>25 m Rock cribs & benthos | Minor, 0.6 (2) | *This option allows for dredging to compensate for height of array, reducing navigation conflicts. The 19 m section is partially outside of the approach channel; USACE must meet minimum height for navigation.* |

[1]Lengths are estimated (± 1 m) from Google Earth.
[2]Bathymetry was collected in 2021 & 2022. We should expect greater variation in 2027.

**Table 7-2. NSD location by elevation, substrate types, and concerns.**

## 7.4 Hydrologic Flow Impacts

The LD05 structure regulates approximately 80 to 90 percent of the unregulated upstream inflow to maintain a 9-foot navigation channel depth. Flow data are collected using USGS gauge 05378500 (Mississippi River at Winona, MN, located about 5 miles downstream) and USACE water control systems. LD05 exhibits significant variability in flow, with a general trend of increasing annual water volumes (see Figure 7-4). Analysis shows an average annual discharge of approximately 42,409 cubic feet per second (cfs), and a maximum monthly value in April of 73,990 cfs (±36,253). Historical records from 1959 to 2025 indicate that 75 percent of discharges are below 44,000 cfs. However, recent years have shown upward trends in peak flows, with 2023 and 2024 exceeding the 90th percentile.

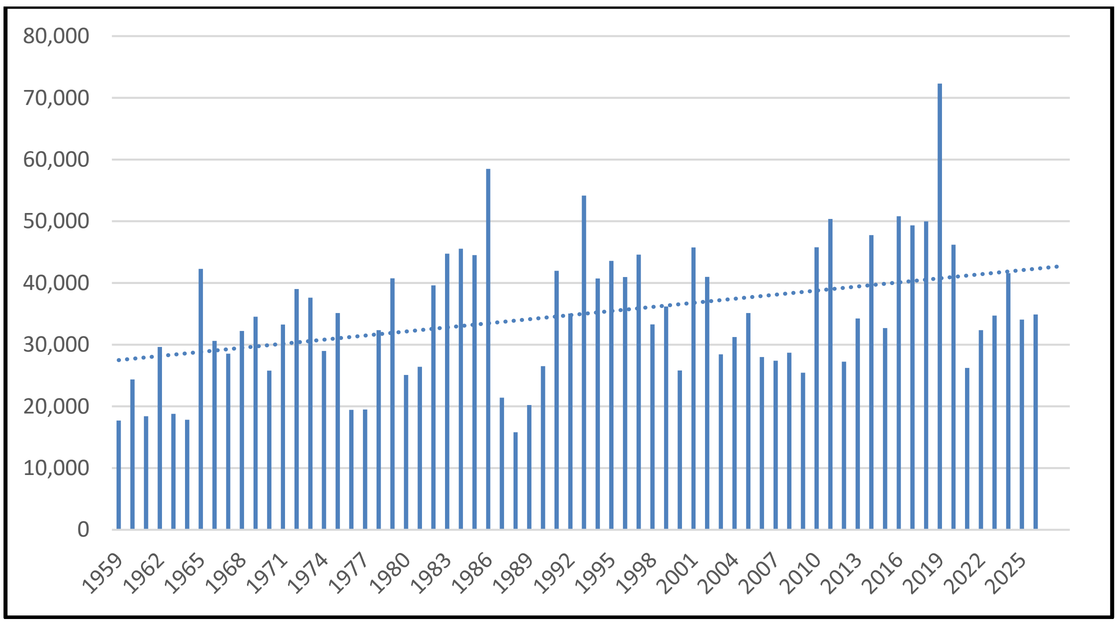


**Figure 7-3. Annual Discharge from 1959-2026.** Data from: www.mvp-wc.usace.army.mil/data/LockDam_05.Data.shtml

Computational fluid dynamics model results demonstrate that river flow approaches the main lower lock chamber i-wall at a 20-degree angle, rather than parallel to the structure. After passing the i-wall, the flow encounters the guide wall located approximately 60 to 120 meters downstream (Figure 7-5, Top Row). In this region, a distinct shear line forms between the approach channel and the main river at all modeled flow rates. As river discharge increases, the distance downstream from the flow connection point between the i-wall and the guide wall also increases, reinforcing this pattern. The area between the miter gates and the shear line remains more “hydraulically isolated” from the main river flow and is characterized by slow (0 to 0.2 m/s) and complex flow patterns.

Model results for river flow and river connectivity with the land wall indicate that the proposed NSD locations will experience varying impacts (Figure 7-5, Bottom Row). Location No. 1 is projected to experience the least impact from river flow past the i-wall, with approximately 25% minor flow turbulence (0.0–0.3 m/s). In contrast, Location No. 5 is expected to experience impacts along its entire length, with flow velocities ranging from 0.4 to 1 m/s. The longer arrays at Locations No. 4 and 5 extend further into the main channel, where computational fluid dynamics (CFD) analysis indicates progressively worsening turbulence and flow conditions.

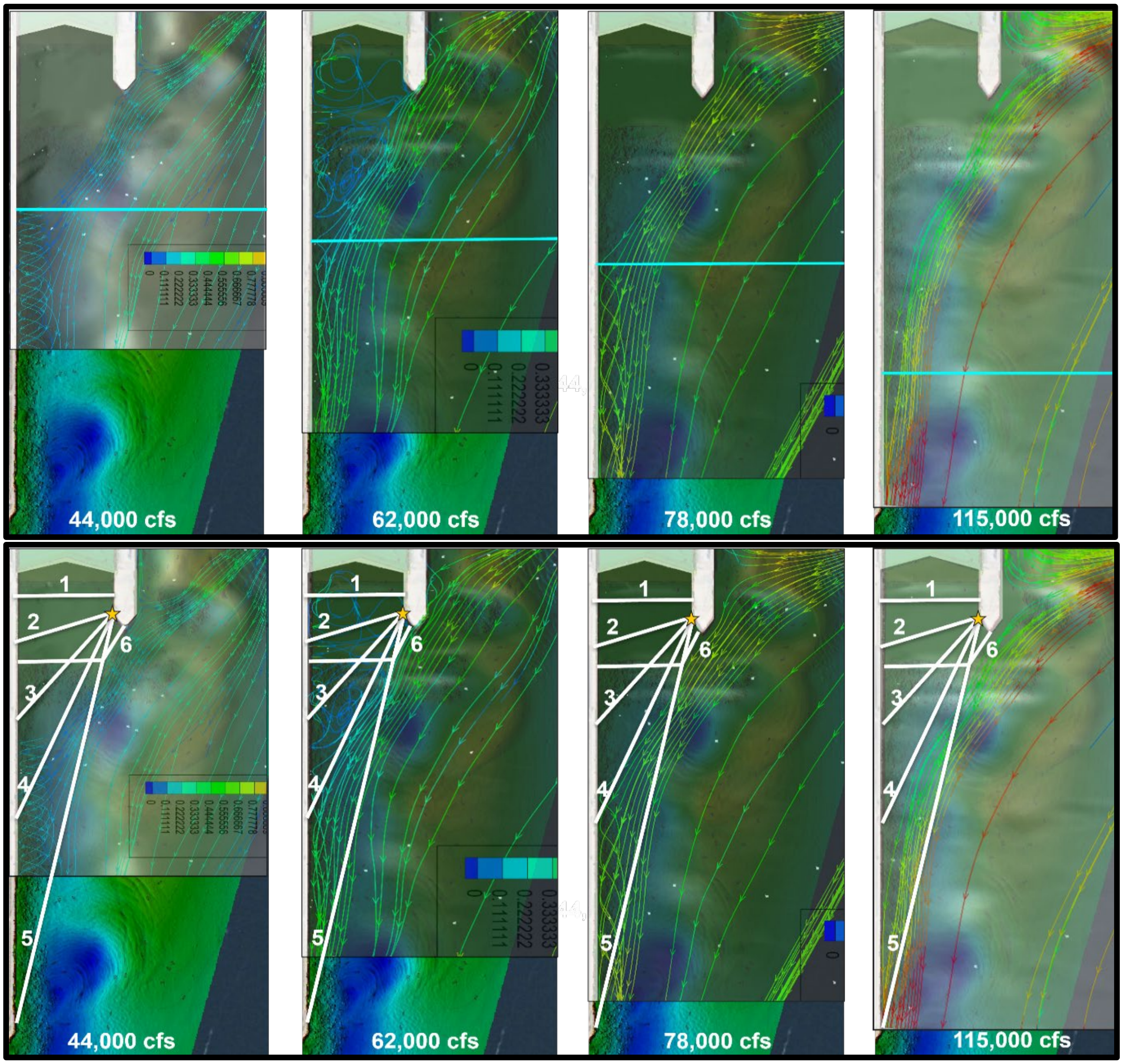


**Figure 7-4. Flow Reattachment Points, Shear Lines and Location Engagement.**

At 44,000 cubic feet per second (cfs), the river reattachment point shifts closer to the i-wall, accelerating the flow, causing shear along the wall. Shorter arrays at Locations 1, 2, and 6 avoid this effect. When discharge increases to 62,000–78,000 cfs, the reattachment point moves downstream, resulting in stronger vortices and shear layers, with mid-channel velocities reaching 0.4 to over 0.6 meters per second. Under these conditions, Location 4 experiences approximately 48% exposure, while Location 5 (164 meters) is fully exposed. At 115,000 cfs, which corresponds to flood peaks, extreme shear, high turbulence, and high-velocity streamlines dominate the outer channel. Full exposure at Location 5 results in flow across the entire array, while partial exposure at Location 4 occurs in an essential area for fish passage.

For both the Bio-Acoustic Fish Fence (BAFF) and Air Bubble Deterrent (ABD) systems, the bubble curtain is likely to be disrupted or collapse at velocities greater than 0.3 meters per second, as tests indicate instability at approximately 44 centimeters per second. In shear zones, bubbles are transported downstream, creating gaps that permit carp to bypass the barrier. This process reduces the effectiveness of multimodal deterrence (sound and bubbles) to nearly zero during high flows, which coincide with peak carp passage. United States Geological Survey (USGS) data indicate that carp detections increase significantly during discharges greater than 44,000–78,000 cfs, typically during spring or flood events. Although Zielinski et al. (2014) demonstrated that fine-, graded-, and coarse-bubble curtains reduced carp passage by 75–85% in indoor channel tests, these experiments were conducted at low velocities. Additional hydrodynamic studies have shown that bubble curtains breakdown under the influence of combined currents and waves, consequently reducing recirculation and mixing efficiency (Covarrubias-Contreras *et al.,* 2025; Woodley and Smith, unpublished data) (Figure 7-5, Table 7-3).

The presence of bubble curtains can induce a primary recirculation cell, where the upward movement of bubbles generates a return flow near the riverbed. Incoming currents displace the curtains downstream, while river-generated waves introduce oscillatory perturbations that alter the strength, size, and position of the recirculation cell. Consequently, the combined effects of wave and current forcing can either enhance sediment movement through increased turbulence or disrupt it through advection and deformation of the curtain (Covarrubias-Contreras *et al.,* 2025; Woodley and Smith, unpublished data) (Figure 7-5, Table 7-3).

Longer proposed locations overlap more extensively with vessel dwell and stall zones, resulting in cavitation exposure ranging from 10 to 51 minutes at Locations 4 and 5. This overlap increases exposure to prop wash, which further degrades the consistency of the bubble curtain. Additionally, vessel activity, prop wash, and propeller cavitation generate noise that can mask sound signals (Table 7-3).

*(See next page for Table 7-3, Figure 7-5)*

| Location No. | Length (m)[1] | % Exposed to Modelled Flow | Range of Modelled Flow | Comments |
|---|---|---|---|---|
| 1 | 34 | 25% | 0.0 – 0.3 m/s | Turbulence should be expected within the lower lock approach between the i-wall and guide wall, varies with discharge. |
| 2 | 36 | 25% | 0.0 – 0.3 m/s | Turbulence should be expected within the lower lock approach between the i-wall and guide wall, varies with discharge. Expect minor efficacy issues on the angle between March – July. |
| 3 | 55 | 25% | 0.1 – 0.3 m/s | Turbulence should be expected within the lower lock approach between the i-wall and guide wall, varies with discharge. Expect minor to moderate efficacy issues on the angle between March – July. |
| 4 | 88 | 48% | 0.1 – 0.6 m/s | Turbulence should be expected within the lower lock approach between the i-wall and guide wall, varies with discharge. This option will be challenged by the shear flow off the i-wall. While it may "function", the efficacy will be reduced. Expect moderate efficacy issues on the angle between March – November. |
| 5 | 164 | 100% | 0.4 – 1 m/s | Turbulence should be expected within the lower lock approach between the i-wall and guide wall, varies with discharge. This option will be greatly challenged by the shear flow off the i-wall. While it may "function", the efficacy will be reduced. Expect Minor to severe efficacy issues between March – October. |
| 6 | 48 | 25% | 0.1 – 0.3 m/s | Turbulence should be expected within the lower lock approach between the i-wall and guide wall, varies with discharge. Expect minor efficacy issues on the angle between March – July. |
| [1]Lengths are estimated (± 1 m) from Google Earth, final length TBD by MN-DNR location preference, USACE restrictions. | | | | |

**Table 7-3. Modelled Range of Flow and Exposure of Deterrent Placement at Lock and Dam No. 05.**

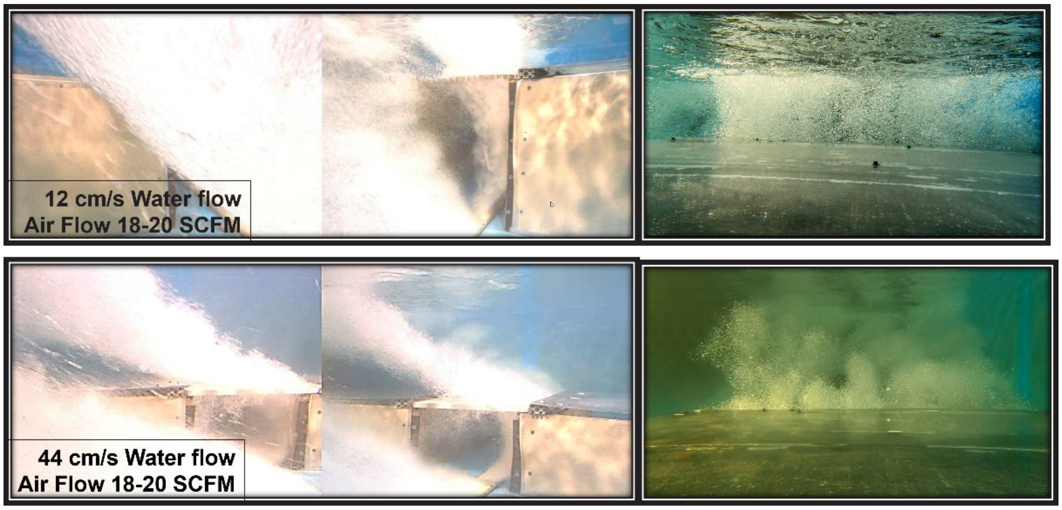


**Figure 7-5. Air Bubble Curtains Testing at 12 & 44 cm/s.** Photographs from the Brandon Road Interbasin Project, taken at a depth of 3.5 feet within a 32-inch trench, illustrate the effects of varying water velocities. The top-right panel (12 cm/s) demonstrates the initial breakdown of the curtain caused by water-flow forces, with further degradation observed as velocity increases to 44 cm/s.

Fish passage data (e.g., Fritts et al. 2024, Figure 7-6) indicate that upstream movements predominantly occur during periods of high discharge. Under high-flow shear conditions, acoustic components such as uADS may be partially masked, while bubble-dependent systems experience the greatest impact. Shorter proposed locations (Locations No. 1, 2, and 6) mitigate these effects, providing improved deterrence, as evidenced by reductions exceeding 50% in comparable low-flow sites such as Barkley BAFF or Lock No. 19 uADS.

*(See next page for Figure 7-6)*

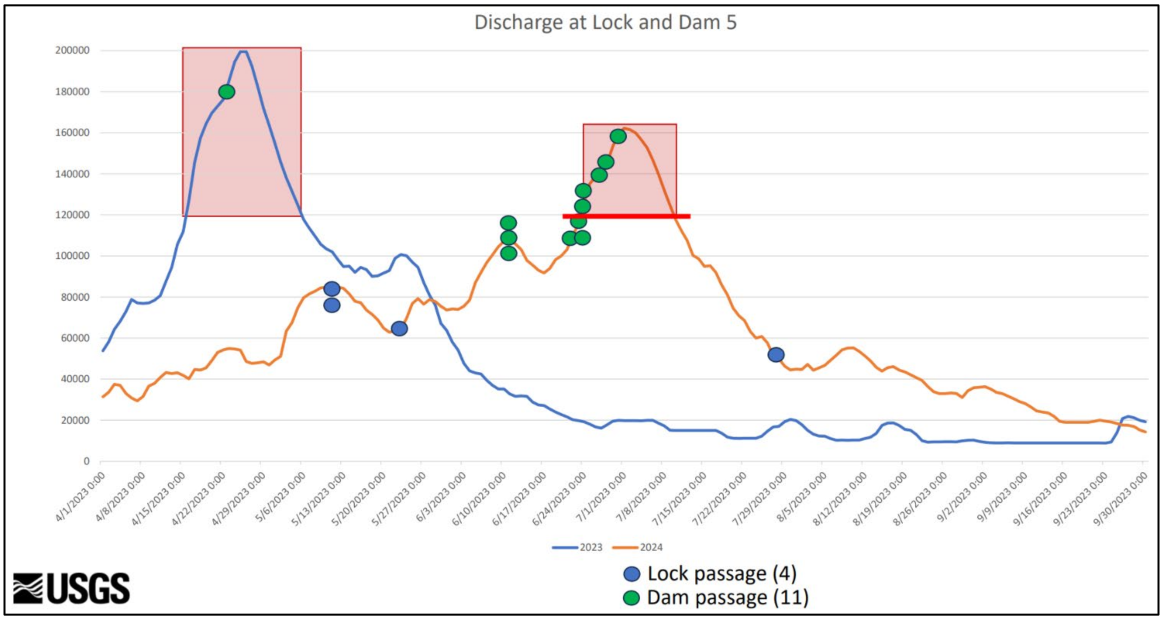


**Figure 7-6. USGS data.** Upstream passage of silver carp implanted with ultrasonic transmitters through LD05. Blue circle indicted LD05 Lock passage, whereas green circle indicates LD05 dam passage. Red boxes indicated open river conditions (Figure from Fritts et al. 2024, LD05 meeting presentation).

## 7.5 Navigation

Navigation is the primary consideration in the placement and operation of NSDs, aligning with the United States Army Corps of Engineers (USACE) mission to maintain navigable waterways and ensure safe passage. As detailed in the introduction to Chapter 7, USACE requirements for uninterrupted lock operations, navigation safety, daily operational continuity, and minimized installation and operations and maintenance (O&M) burdens establish the foundation for prioritizing navigation safety and lock operations. Therefore, any NSD placement that elevates the risk of vessel strikes, propeller wash disruption, or communication interference is unlikely to be approved by USACE.

Navigation within the area was evaluated as described in Chapter 4 and depicted in Figure 7-7. Vessel track density is highest near the land wall (guide wall) and the i-wall bullnose. The shorter proposed deterrent locations (Locations No. 1, 2, and 6) are positioned adjacent to primary vessel passage routes. In contrast, the longer proposed locations (Locations No. 4 and 5) extend further into the main channel, where vessel traffic is less concentrated; however, these locations still overlap substantially with critical dwell and stall zones. Figure 7-8, which provides a heatmap of the lower lock approach, illustrates this overlap. Bright red and orange hotspots identify areas where vessels spend the most time directly above the proposed deterrent footprints. The most intense red core downstream and the darker orange hex-bins correspond to typical mooring and dwell positions for cut-barge tows. In these zones, stationary or slow-moving vessels can increase deterrent sound (uADS) to levels that interfere with onboard communication, disrupt bubble curtains (BAFF/ABD) due to propeller wash, and obscure acoustic signals with engine or propeller noise. The area near the miter gates of the lower lock approach is also where upstream tows frequently execute strong reversing maneuvers to prevent barges from striking the upstream gates.

*(See next page for Figure 7-7 and Figure 7-8*)


**Figure 7-7. Plot of Every Recorded Tow, Barge, Commercial Vessel, and Recreational Vessel Passing LD05 using AIS Capabilities.**

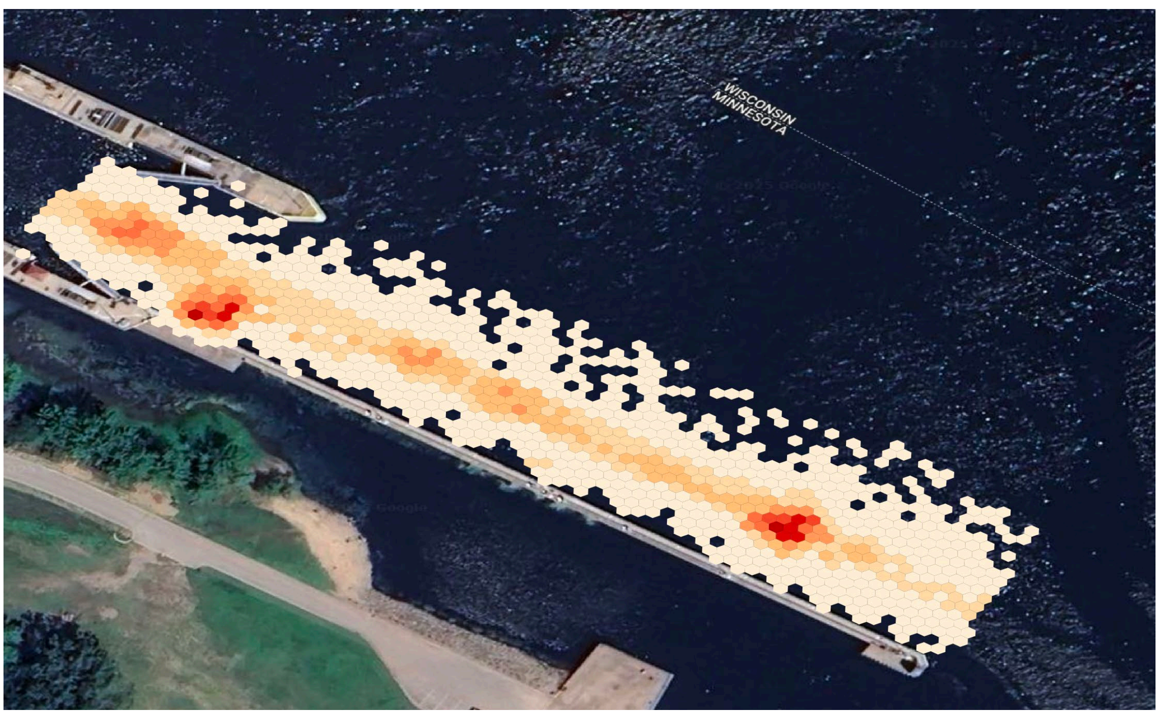


**Figure 7-8. Plot of a Hex-bin Density Map of the Lower Lock Approach.** The Bright red/orange hotspots show where vessels dwell, which is precisely over the proposed deterrent foot-prints. (Data from AIS, https://navportal.usace.army.mil, 2021-2024)

To clarify the temporal patterns observed in the hex-bin data, an analysis was conducted to examine navigation vessel type and the time required to pass. The vessel types included were: 0 and NA (Default), 30 (Fishing), 31 and 32 (Tug/Tow), 37 (Sailing), 65 (Passenger), and 90 (Commercial Vessel). Towing vessels (32 and 90) and tugs accounted for the majority of time spent in the approach (Figure 7-9). After excluding outliers exceeding four hours (approximately 4.6% of the data), the mean dwell time in the approach remained 55 minutes overall, with towing vessels and tugs averaging 57 to 58 minutes (Figure 7-10). The removal of outliers is justified, as it excluded rare instances of extended moorings or mechanical issues.

For comparison, the uADS at Lock No. 19 installed downstream of the miter gates and experiences minimal navigation conflict due to its recessed weldment and short effective length. However, large tows or adverse weather conditions can generate significant cavitation and turbulence when vessels slow using engine reverse over the uADS. In contrast, the BAFF is deployed in an environment characterized by lower traffic and reduced water velocity, but it is not an area challenged by prop wash and cavitation.

Navigation impacts are anticipated to be greater at the longer proposed array locations (Locations 4 and 5) because cavitation exposure, as measured by prop wash duration, increases with array length. Longer arrays result in more time spent in the high-turbulence zone near the i-wall bullnose, where tows frequently stall or dwell (Figure 7-11, Table 7-4). Prop wash from moored or stalling tows will repeatedly fragment the curtain during the approximately 58-minute dwell window. This effect is particularly pronounced during high-traffic seasons, such as spring and fall grain or coal movements. Concerns regarding hull amplification and engine noise masking within the tow are heightened during dwell periods, with longer arrays further increasing exposure duration. In contrast, Locations 1, 2, and 6 experience minimal dwell exposure because they are primarily upstream of the main stall zone, which reduces repeated bubble disruption (BAFF/ABD) and sound masking or amplification (uADS). Furthermore, the longer proposed locations may increase the risk of noise-related navigation impacts, potentially creating safety risks that require further verification through modeling. Consequently, Locations 1, 2, or 6 are recommended for any uADS or hybrid ABD-uADS deployment, as these sites minimize vessel-induced degradation of the deterrent while maintaining lock operations and navigation safety.

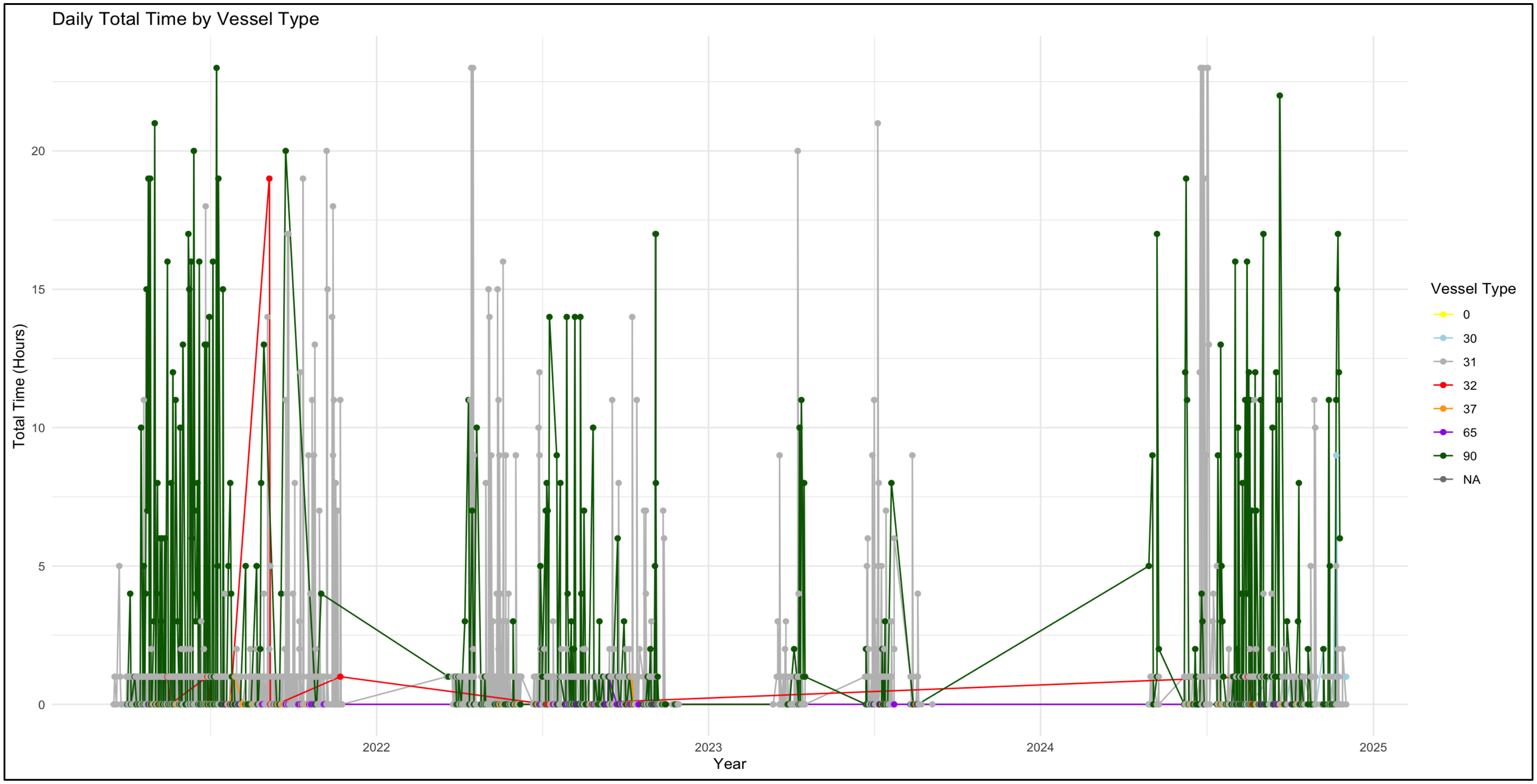


**Figure 7-9. Plot of Daily Total Time a Vessel Type for the Lower Lock Approach of Lock and Dam No. 05.** Vessel types are as follows: 0 and NA (Default), 30 (Fishing), 31 and 32 (Tug/Tow), 37 (Sailing), 65 (Passenger), and 90 (Commercial Vessel).

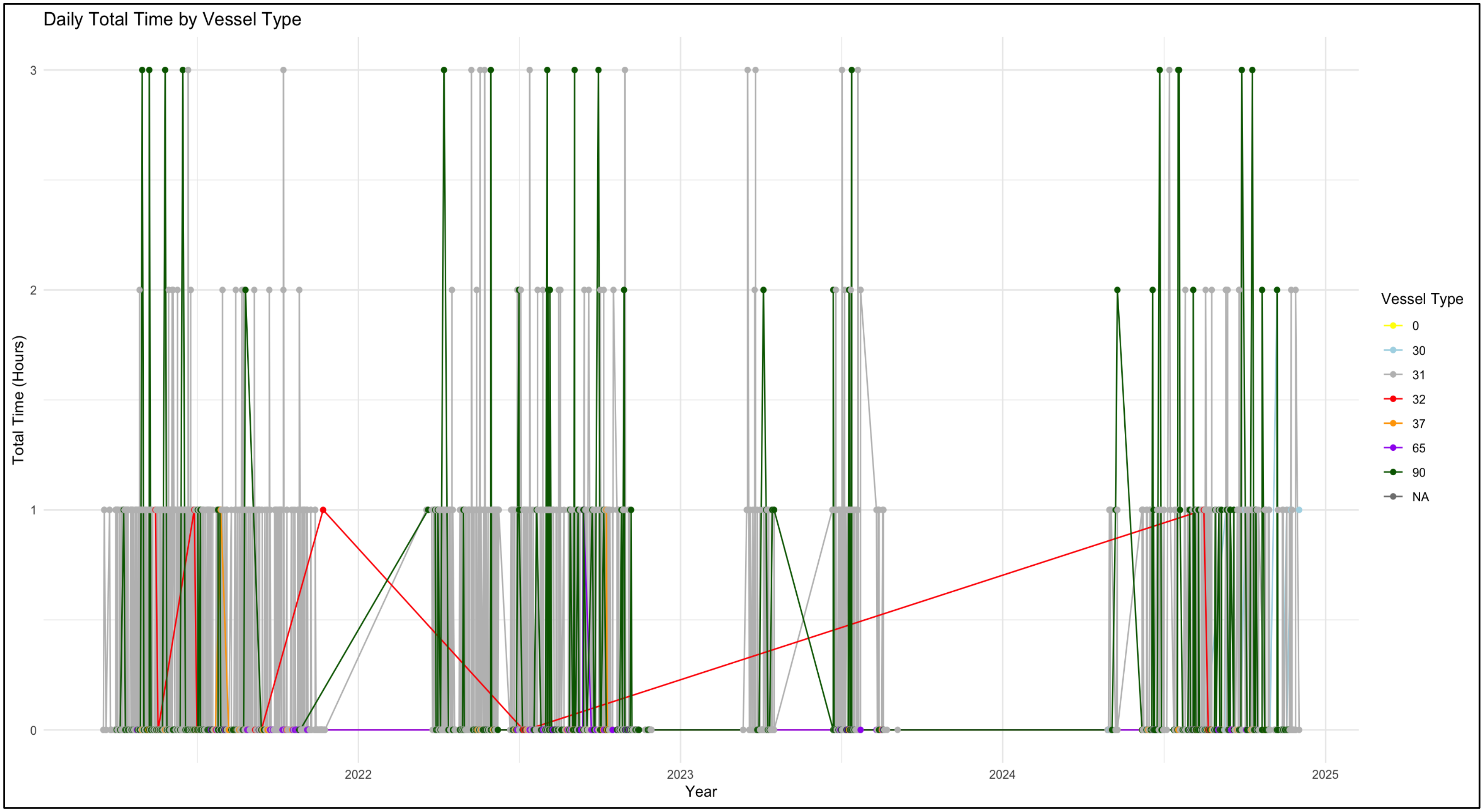


**Figure 7-10. Plot of Daily Total Time (max. 4 hrs) a Vessel Type for the Lower Lock Approach of Lock and Dam No. 05.** In this plot, all data greater than 4 hours were removed to examine the dwell time and vessel time at a finer scale and more typical of normal lock operations. Vessel types are as follows: 0 and NA (Default), 30 (Fishing), 31 and 32 (Tug/Tow), 37 (Sailing), 65 (Passenger), and 90 (Commercial Vessel).

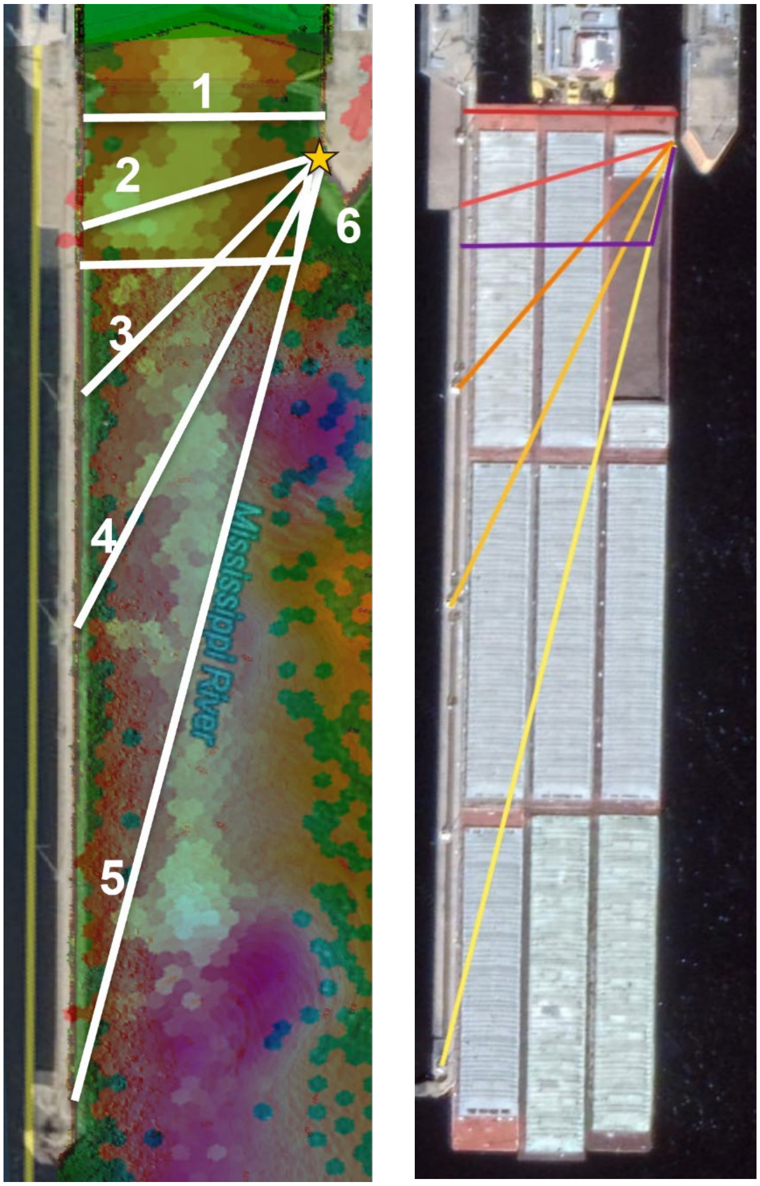


**Figure 7-11. Navigation Dwell and Coverage example.** The red, purple, orange, and yellow lines mark the proposed locations a deterrent array would sit relative to the gates and bullnose. The lines fall squarely in the red-hot dwell zones shown in the heatmap.

| Location No. | Length (m) | Percent Exposed ($m^2$) | Estimated exposure time (min) "cavitation" (max time) | Estimate time of exposure to "dwell time" | Comments |
|---|---|---|---|---|---|
| 1 | 34 | 100% | 2 | Minimal | Shortest exposure time to navigation passing |
| 2 | 36 | 100% | 3.8 | Minimal | Dwell overlaps with the deterrent; forth longest exposure time top navigation passing |
| 3 | 55 | 100% | 13.8 | Minimal, cut barges mooring | Third longest exposure time to navigation passing |
| 4 | 88 | 100% | 26.0 | Cut barges moored | Dwell overlaps with the deterrent; second longest exposure time to navigation passing |
| 5 | 164 | 100% | 51.3 | Cut barges moored | Dwell overlaps directly with the deterrent; longest exposure time to navigation passing |
| 6 | 48 | 100% | 1 – 4.4 | Minimal | Dwell overlaps with the deterrent; closer to third longest, depending on that final angle. |

**Table 7-4. Assessment of Navigation Impacts on Proposed Locations.** Several notes on this table include that the AIS units are typically above wheelhouse, this represents the tow not the front edge of the vessel; and requires that we assume vessel is in the middle of the channel.

## 7.6 Technology Specifications

The Bio-Acoustic Fish Fence (BAFF) and the underwater Acoustic Deterrent System (uADS) are both designed to modify fish behavior (Table 7-5). The BAFF is a well-established technology, having been implemented in several fisheries, while the uADS is a prototype currently under evaluation for its ability to reduce or prevent the passage of invasive carp through the LD05 lock chamber. The BAFF, a proprietary system developed by Fish Guidance Systems Ltd., uses a multimodal approach combining broadband sound, an air-bubble curtain, and strobe lights. In contrast, the uADS, developed by ERDC, USACE, and USGS, is an open-source, acoustic-only system that uses commercial-off-the-shelf (COTS) components. The BAFF has demonstrated deterrence efficacy ranging from 50% to 98% at Barkley during low-velocity tests (Fritts et al. 2023, unpublished presentation Jan 2026), features mature software, and maintains operational reliability when sediment is managed. However, its limitations include dependence on a UK-based vendor, ongoing sediment issues (which could be an artifact of Barkley Lock), and operations and maintenance (O&M) requirements. The uADS provides advantages such as COTS flexibility, lower costs, modularity through individual speaker replacement, and adaptability via open-source signals. As a prototype, its software is less mature and may require additional investment to develop effective, remotely operated systems, potentially through contractors with expertise in remote operations that meet USACE criteria.

| Category | BAFF | uADS | Benefits | Cost |
|---|---|---|---|---|
| Off-the-shelf Equipment | No (proprietary components & signals) | Yes (COTS speakers, amplifiers, e.g., Lubell LL-1424HP) | uADS easier procurement & upgrade. | BAFF risks vendor lock-in or obsolescence (i.e., risk of brand change or model change as this is vendor controlled and associated specification issues). uADS requires more procurements. |
| Proprietary Elements | Partial (full system + signals from one vendor) | No (open signals; patent tied USACE) | BAFF: One vendor, one contract<br>uADS: multi-vendor flexibility | Components are one vendor, and thus reliant on one vendor. Signals are proprietary – one must request to change the signal list if desired. uADS requires integration to be conducted by an experienced contractor. |
| Signals & Customization | Proprietary signals (changes require vendor request/approval) | Government-developed/open signals (customizable with funding) | BAFF: more "set-it-and-forget-it"<br>uADS: adaptive tuning (for other spp) | BAFF less agile |
| Software Matured | High (mature remote interface; vendor updates available) | Developing (functional but needs funding for full remote/flexibility) | BAFF: Matured software (with updates likely), esp. if O&M is procured through vendor | BAFF: Less likely or will require funding to adapt for operation flexibility.<br>Both: Requires boots on the ground to interface with equipment should remote connection fail |
| Remote Operation | Yes (via vendor network; Starlink possible for non-Federal) | Yes (COTS-based; ERDC network/Starlink feasible but quarterly boots-on-ground likely without contractor development) | | Remote access by any non-Federal group will be conducted through a non-Federal government network. Some flex in ERDC RDE's network with Starlink for state and federal teams but closed to external vendors. |
| Maintenance | Yes | Yes | uADS is less expensive to maintain annually still requires a dive inspection every few years. | BAFF experiences sediment issues annually – this could be a location issue or a BAFF issue. uADS is a COTS and thus more software feeding into one interface. |

**Table 7-5. Technology Comparison of the BAFF and uADS.**

## 7.7 Costs

The cost estimates presented are preliminary. It is strongly recommended that a final assessment be conducted by a USACE Cost Engineer subject matter expert.

Cost estimates were developed by forecasting from available BAFF data at Barkley and uADS data at Lock No. 19. Due to COVID the time lapse between the deployment of the BAFF and the uADS significantly changes for costs, the forecasts remain outside USACE guidelines. Per USACE Engineer Manual EM 1110-2-1304, using index valves to update project costs more than two consecutive years is not recommended for costs escalation if more than two consecutive years require adjustment. The following indices were applied for cost forecasting: Civil Works Construction Cost Index System (CWCCIS), Construction Analytics (historical 2019–2024 trends), CBRE (2023–2024 forecasts), and the Mortenson Construction Cost Index (2024 stabilization), supplemented by AGC workforce and market data. Many site-specific conditions were not considered in these estimates; therefore, this section should be used solely for general estimation purposes.

Table 7-6 is based on the 180-foot (55 m) BAFF. Analyses predicted compounded inflation between 48.3% and 55.6% from 2019 to 2027. The Consumer Price Index (CPI) and CBRE were used to estimate recurring costs, which were approximately 34% from 2019 to 2027. Contract documentation and discussions with USFWS indicate that the lower approach at Barkley Lock was excavated, and the BAFF was placed directly on the substrate rather than on a concrete slab. The Barkley i-wall is notably long relative to its guidewall (1:8.3). The entire lower lock approach is characterized by a low-flow environment because the Barkley Lock can discharge into the river channel instead of the lock approach.

Table 7-7 applies the per-meter costs from the uADS at Lock No. 19 to estimate the costs of the NSDs at the proposed locations for Lock and Dam No. 05. These costs include the deployment, installation, the reoccurring 5-year operations and maintenance (this is every 5 years), and reoccurring 1-year operations and maintenance (this is for the 4 years between each 5-year large maintenance).

Table 7-8 detains the cost comparison between the proposed locations for the BAFF and uADS at LD05.

| Cost Category | Sub-Category/Description | Actual Costs ($K US) | Est. 2027 Costs ($K US) |
|---|---|---|---|
| Engineering & Design | Planning, Design, & Bedrock Survey (frame, buildings, cable routing, sound projectors) | $342 | $532 |
| Fabrication and Installation | Construction, Equipment, & Deployment (concrete housing, bedrock recess excavation, air compressor/lines, cargo container, multimodal system & telemetry install, oversight) | $3,757 | $5,846 |
| Add Ons | Add-On: new electrical line; high-water dredging/diver adjustments | $1,510 | $2,350 |
| | **TOTAL** | **$5,609 Deployment** | **$8,728 Deployment** |
| | **PER METER** | **$102 Deployment** | **$159 Deployment** |

| Cost Category | Sub-Category/Description | Actual Costs ($K US) | Est. 2027 Costs ($K US) |
|---|---|---|---|
| Lease | Equipment Lease (multimodal deterrent system, incl. remote monitoring by FGS, software updates as needed) | $654 | $876 |
| O&M | Annual System Operations (electricity, fixed maintenance for AC, compressor, CCTV, network) | $96 | $129 |
| O&M | Annual Maintenance Event (sound projector cleaning, routine checks) | $437 | $586 |
| | **TOTAL** | **$1,187 Annual** | **$1,591 Annual** |
| | **PER METER** | **$22 Annual** | **$29 Annual** |

**Table 7-6. BAFF-Barkley LD Cost Forecast.** This is based on the Design and installation costs which were $5.609M in FY2019. Data from Fritts et al. OFR 2023. Operations and maintenance costs for the BAFF at Barkley: $1.344M in FY2021-2025. Data from USASpending.gov.

| Cost Category | Sub-Category/Description | Actual Costs ($K US) | Est. 2027 Costs ($K US) |
|---|---|---|---|
| Engineering & Design | Planning, Design (frame, buildings, cable routing, permitting) | $370 | $562 |
| Fabrication and Installation | Construction, Equipment, & Deployment (concrete housing, bedrock recess excavation, air compressor/lines, cargo container, multimodal system & telemetry install, oversight) | $1,530 | $2,326 |
| Add Ons | Add-On: transformer, cabling and mics. parts | $68 | $103 |
| Equipment provided by the government | Fabrication of miter gate friendly hangers, sound projectors, rack mounts, signal conditionings, monitoring systems, etc. | $325 | $494 |
| | TOTAL | $2,293 Deployment | $3,486 Deployment |
| | PER METER | $68 Deployment | $103 Deployment |

| Cost Category | Sub-Category/Description | Actual Costs ($K US) | Est. 2027 Costs ($K US) |
|---|---|---|---|
| O&M (5-yrs) | 5-Yr Cycle System Operations (O&M, sound projector cleaning and cable inspection and maintenance) | $506 5-Yr | $581 5-Yr |
| O&M (1-yrs) | Annual System Operations (including dive inspections, electricity, and about 50% operations) (Not included: quarterly site visits, data processing) | $78 1-Yr | $86 1-Yr |
| | TOTAL OVER 5-YEARS | | $668 Reoccurring Over 5 yrs |
| | ANNUAL 5-YEAR AVERAGE[10] | | $134 Annual 5-Yr |

**Table 7-7. uADS Lock No. 19 Cost Forecast.** These costs include the deployment, installation, the reoccurring 5-year operations and maintenance (this is every 5 years), and reoccurring 1-year operations and maintenance (this is for the 4 years between each 5-year large maintenance).

[10] *This total either over-represents (Year 1 through 4) or underrepresents (Year 5) the estimated yearly cost.*

| Location | Length | Design & Installation | | | Annual O&M | | | |
|---|---|---|---|---|---|---|---|---|
| | | BAFF | uADS | | BAFF | uADS Years 1- 4[11] | uADS Year 5 | uADS Annual 5Yr Average |
| 1 | 34 | $5,406,000.00 | $3,502,000.00 | | $986,000.00 | $85,986.00 | $580,992.00 | $133,396.00 |
| 2 | 36 | $5,724,000.00 | $3,708,000.00 | | $1,044,000.00 | $91,044.00 | $615,168.00 | $141,243.00 |
| 3 | 55 | $8,745,000.00 | $5,665,000.00 | | $1,595,000.00 | $139,095.00 | $939,840.00 | $215,787.00 |
| 4 | 88 | $13,992,000.00 | $9,064,000.00 | | $2,552,000.00 | $222,552.00 | $1,503,744.00 | $345,260.00 |
| 5 | 164 | $26,076,000.00 | $16,892,000.00 | | $4,756,000.00 | $414,756.00 | $2,802,432.00 | $643,438.00 |
| 6 | 48 | $7,632,000.00 | $4,944,000.00 | | $1,392,000.00 | $121,392.00 | $820,224.00 | $188,324.00 |

Table 7-8. Costs Applied to Lock and Dam No. 05 Proposed Location Lengths.

[11] Note that the uADS, based on Lock No. 19, requires a dive maintenance once every 1-4 years, and a larger maintenance about every 5-years.

## 7.8 Rapid Assessment of Technology Comparisons

The following section focuses on comparing technologies across known challenges for design, deployment and O&M of an NSD at Lock and Dam No. 05. The process is drawn from site-specific data (i.e., bathymetry, hydrodynamic modeling, navigation statistics), analogous field deployments (i.e., Barkley BAFF and Lock No. 19 uADS), and project priorities to inform technology selection and deployment strategy.

The following tables present rankings of the locations (Table 7-10), the impacts on the BAFF at each location (Table 7-11), and the uADS at each location (Table 7-12). Costs generally increase with array length and are higher for multi-modal systems, with BAFF being more expensive than uADS. The lock approach concrete impact on the lower lock approach apron sill (Locations 1 and 2) is greater for infrastructure than at Locations 3 through 6. Rock crib impacts are more significant at Locations 3 to 6, as these sites would require alteration or additional support for existing rock cribs. Scour exposure is higher for the longer proposed locations (Locations 3 to 5) compared to Locations 1, 2, and 6. BAFF and ABD are more affected by river discharge exposure (bubble integrity issues above 0.3 m/s shear and gaps during high flow), while uADS performs slightly better overall due to the absence of bubbles and reduced flow penalty; however, potential masking from turbulence should be further examined. River discharge exposure time, defined as the percentage of the year the array is impacted by river discharge, is minor between March and July for Locations 1, 2, 3, and 6, but greater from March to November for Locations 4 and 5. The longer arrays at Locations 4 and 5 are exposed to passing navigation for the greatest total time compared to the in-lock arrays (Locations 1, 2, and 6). Similarly, navigation dwell time (mooring during cuts) is also higher at the longer locations. This presents challenges for BAFF and ABD, as both are more susceptible to bubble wall deformation. In-air acoustic noise assessment is limited due to the lack of direct data for BAFF at Barkley; however, data from previous projects in California suggest BAFF produces 66–85 dBA in-air, scaling with length. uADS data indicate a similar trend. Consequently, longer proposed locations (04 and 05) are expected to emit greater noise than shorter locations, though these levels are considered safe and not sufficient to impede navigation. Regarding masking of sound in the water column due to navigation, shorter proposed locations will experience less exposure and therefore less masking overall.

Table 7-13 presents the combined scores to provide a detailed comparison between BAFF and uADS. The results confirm that Locations 1, 2, and 6 are the top performers, while the longer locations (4 and 5) receive significantly lower rankings.

| Category | Description | #1 (34m) | #2 (36m) | #3 (55m) | #4 (88m) | #5 (164m) | #6 (48m) | Comments |
|---|---|---|---|---|---|---|---|---|
| Cost | Based on annual total | 1 | 2 | 4 | 5 | 6 | 3 | Lowest est. cost: 1 |
| Lock Approach Concrete Impact | Costs associated with cutting the concrete apron of the lock approach | 5 | 6 | 4 | 3 | 1.5 | 1.5 | Based on meters |
| Lock Approach Rock Crib Impact | Costs associated with constructing around and possibly reinforcing the infrastructure | 1.5 | 1.5 | 4 | 3 | 6 | 5 | Based on meters |
| Scour Exposure | Cost associated with instability near structure, and ability of fish to pass under structure | 2 | 2 | 3 | 4 | 6 | 2 | Based on feet |
| River Discharge Exposure | % of the surface area the device is exposed to river current | 1.5 | 1.5 | 3.5 | 5 | 6 | 3.5 | Not inclusive of efficacy |
| River Discharge Exposure Time | % of the year flow ranges would impact the device | 2.5 | 2.5 | 2.5 | 5.5 | 5.5 | 2.5 | |
| Navigation Exposure | Estimated time of "cavitation" exposure (min) | 1 | 2 | 4 | 5 | 6 | 3 | #6 could be weighed the same as number 2 |
| Navigation Dwell Time Exposure | Based on where barges dwell, and cuts are moored | 2 | 2 | 4 | 5.5 | 5.5 | 2 | Check on #3 with LM |
| Audible Noise (no vessels) | SME estimate based on Old River and Georgiana Slough without adequate noise suppression | 1 | 2 | 4 | 5 | 6 | 3 | 66-72-85 dBa (20µPa) |
| Masking Noise (vessels) | Drafted analyses | 3.5 | 3.5 | 1.5 | 5 | 6 | 1.5 | |
| Rank (Sum/Variables) | Estimate function over a range of conditions | 21 | *25* | 34.5 | 46 | 54.5 | *27* | No specific to a technology |

**Table 7-7. Rapid Assessment of Challenges per Proposed Location.**

| Category | Description | #1 (34m) | #2 (36m) | #3 (55m) | #4 (88m) | #5 (164m) | #6 (48m) | Comments |
|---|---|---|---|---|---|---|---|---|
| Cost | Based on annual total | 1 | 2 | 4 | 5 | 6 | 3 | Lowest est. cost: 1 |
| Lock Approach Concrete Impact | Costs associated with cutting the concrete apron of the lock approach | 5 | 6 | 4 | 3 | 1.5 | 1.5 | Based on meters |
| Lock Approach Rock Crib Impact | Costs associated with constructing around and possibly reinforcing the infrastructure | 1.5 | 1.5 | 4 | 3 | 6 | 5 | Based on meters |
| Scour Exposure | Cost associated with instability near structure, and ability of fish to pass under structure | 2 | 2 | 3 | 4 | 6 | 2 | Based on feet |
| River Discharge Exposure | % of the surface area the device is exposed to river current | 1.5 | 1.5 | 3.5 | 5 | 6 | 3.5 | Not inclusive of efficacy |
| River Discharge Exposure Time | % of the year flow ranges would impact the device | 2.5 | 2.5 | 2.5 | 5.5 | 5.5 | 2.5 | |
| Navigation Exposure | Estimated time of "cavitation" exposure (min) | 1 | 2 | 4 | 5 | 6 | 3 | #6 could be weighted the same as number 2 |
| Navigation Dwell Time Exposure | Based on where barges dwell, and cuts are moored | 2 | 2 | 4 | 5.5 | 5.5 | 2 | Check on #3 with LM |
| Audible Noise (no vessels) | SME estimate based on Old River and Georgiana Slough | 1.5 | 1.5 | 4 | 5 | 6 | 3 | |
| Masking Noise (vessels) | *Drafted analyses* Based on exposure to vessel noise | 0 | 0 | 0 | 0 | 0 | 0 | |
| Rank (Sum/Variables) | | **18** | **21** | **33** | **41** | **48.5** | **25.5** | |

**Table 7-8. Rapid Assessment of Challenges for the BAFF at Each Proposed Location.**

| Category | Description | #1 (34m) | #2 (36m) | #3 (55m) | #4 (88m) | #5 (164m) | #6 (48m) | Comments |
|---|---|---|---|---|---|---|---|---|
| Cost | Based on annual total | 1 | 2 | 4 | 5 | 6 | 3 | Lowest est. cost: 1 |
| Lock Approach Concrete Impact | Costs associated with cutting the concrete apron of the lock approach | 5 | 6 | 4 | 3 | 1.5 | 1.5 | Based on meters |
| Lock Approach Rock Crib Impact | Costs associated with constructing around and possibly reinforcing the infrastructure | 1.5 | 1.5 | 4 | 3 | 6 | 5 | Based on meters |
| Scour Exposure | Cost associated with instability near structure, and ability of fish to pass under structure | 2 | 2 | 3 | 4 | 6 | 2 | Based on feet |
| River Discharge Exposure | % of the surface area the device is exposed to river current | 0 | 0 | 0 | 0 | 0 | 0 | |
| River Discharge Exposure Time | % of the year flow ranges would impact the device | 0 | 0 | 0 | 0 | 0 | 0 | |
| Navigation Exposure | Estimated time of "cavitation" exposure (min) | 1 | 2 | 4 | 5 | 6 | 3 | |
| Navigation Dwell Time Exposure | Based on where barges dwell, and cuts are moored | 2 | 2 | 4 | 5.5 | 5.5 | 2 | |
| Audible Noise (no vessels) | SME estimate based on Old River and Georgiana Slough | 1 | 2 | 4 | 5 | 6 | 3 | |
| Masking Noise (vessels) | *Drafted analyses* Based on exposure to vessel noise | 3.5 | 3.5 | 1.5 | 5 | 6 | 1.5 | |
| Rank (Sum/Variables) | | **17** | **21** | **28.5** | **35.5** | **43** | **21** | |

**Table 7-9. Rapid Assessment of Challenges for the uADS at Each Proposed Location.**

| Category | #1 (34m) | #2 (36m) | #3 (55m) | #4 (88m) | #5 (164m) | #6 (48m) |
|---|---|---|---|---|---|---|
| BAFF | (#2) 18 | (#3) 21 | 32.5 | 41 | 48.5 | 26 |
| uADS | (#1) 17 | (#3) 21 | 28.5 | 35.5 | 43 | (#3) 21 |

**Table 7-10. Rapid Assessment Summary of Challenges for the BAFF and uADS at Each Proposed Location.** Note, the results for AB would be more similar to the BAFF results.

## 7.9 Operational Flexibility Considerations

Based on our experiences with the NWP and lessons learned, we strongly recommend implementing operational flexibility by deploying several deterrents in coordination. This strategy supports best practices in the design, deployment, and operation of engineering system[12], while allowing for reduced costs in the future. ERDC also advises designing and gradually deploying 1-3 systems at Lock and Dam No. 05 over several years, rather than committing to a single system at the outset.

Building multiple systems (or variants) allows for the intentional flexibility customization (tailored features in each deterrent) much like at Brandon Road Lock and Dam. This approach allows MN-DNR to adapt to uncertainties that are likely to arise, support adaptive management of the ecosystem, mitigate risks as they arise, and enhance the value of the effort. Factors such as variable invasive carp behavior, evolving environmental conditions, technological advancements, regulatory changes, or performance data from the initial deployment could reveal that one configuration performs better than expected, while other required adjusting. By designing for two of the 1-3 systems, MN-DNR retains the 'option' to scale the most effective one, modify others, or abandon those less effective without overhauling a single large-scale implementation. A single system locks MN-DNR into one path, and maybe suspectable to “outages” due to navigational damage. Multiple systems enable staged testing and learning, reducing risks (e.g., ineffective deterrence), while capturing potential (e.g., optimized multi-mode operation).

A phased approach increases the risk of long-term adaptability and performance, as demonstrated in other infrastructure projects with phased deployments (see NWP fish passage efforts). Operational flexibility enables an iterative, learn-by-doing approach that is essential for adaptive management. Deploying 1-3 systems allows for testing and refining resilient designs, monitoring real-world performance, and making data-driven adjustments to ensure long-term robustness. Similarly, as invasive species adapt or new threats emerge, multiple systems support parallel experimentation or changes, enabling rapid response to ecological changes rather than being limited by a single, inflexible solution. Although this approach may require a higher initial investment, the building in flexibility typically results in better O&M outcomes by reducing the need for costly changes in the future.

[12] Defined as the ability to adapt swiftly and cost-effectively to changing requirements, uncertainties, and disruptions throughout the lifecycle.

This report does not comprehensively address other potential deterrents or activities that could improve deterrent placement within the lower lock approach at Lock and Dam No. 05. Current priority strategies at LD05 and similar locks include:

- Retaining the Acoustic Bubble Deterrent (ABD) or Bio-Acoustic Fish Fence (BAFF) in the unused auxiliary chamber as a secondary or backup deterrent.
- Installing flush-gate acoustic and water-jet systems at the dam's tainter and roller gates. These systems operate independently of lock cycles and do not interfere with navigation.
- Installing a small electrical deterrent system on the Wisconsin side of the lock, where carp tend to pass during elevated river flows. This system would likely operate for up to two weeks annually and could be designed to effectively prevent carp from crossing.
- Deploying downstream herding sound arrays on the lock approach walls to direct fish away from the chamber before they reach it.
- Testing fully retractable or mobile underwater Acoustic Deterrent System (uADS) units that can be removed from the chamber within minutes, although these remain costly and operationally complex.

## 7.10 References

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Report Documentation Page